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Greenhouse gases (CH_4, CO_2 and N_2O) emissions from a newly flooded hydroelectric reservoir in subtropical South Asia: case of Nam Theun 2 Reservoir, Lao PDR

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Chapter 7
Net GHG footprint of a newly impounded subtropical hydroelectric reservoir: Nam Theun 2 case study

Abstract: Rising concern over the contribution of hydroelectric reservoirs to increased atmospheric concentration of greenhouse gases (GHGs) led to quantify the net GHG footprint of a hydroelectric reservoir. We present here the first comprehensive assessment of GHGs footprint associated with the creation of a hydroelectric reservoir Nam Theun 2 (NT2) in subtropical region of the Lao People's Democratic Republic. This is the results of a large scale study that have been conducted over 4 year (2008-to date). The major GHG sources and sinks of the terrestrial and aquatic components of the pre-impoundment landscape where quantified. Similar estimate of these various emission pathways were made at the reservoir scale since the May 2009.

Ecosystems existing on the reservoir footprint before flooding were a sink of carbon dioxide (-73 ± 225 $GgCO_2eq.year^{-1}$), roughly neutral in terms of methane (7 ± 11 $GgCO_2eq.year^{-1}$), and a source of nitrous oxide (345 ± 158 $GgCO_2eq.year^{-1}$). Post-impoundment GHG budget reveal that the same footprint has become a more significant source of CO_2 and CH_4, and a much smaller source of N_2O. For the year 2010, with 1307 ± 244 $GgCO_2eq.year^{-1}$ and 768 ± 206 $GgCO_2eq.year^{-1}$ respectively, CH_4 and CO_2 have contributed around 60% and 35%) to the total GHG budget. With 93 ± 163 $GgCO_2eq.year^{-1}$, N_2O accounts for less than 5% of the total emission. While CH_4 emissions declined a bit the second year of study (473 ± 91 $GgCO_2eq.year^{-1}$ in the year 2011), CO_2 emissions increased (1551 ± 197 $GgCO_2eq.year^{-1}$) in the same time, while N_2O emissions remained constant. Our results indicate that upstream GHG emissions (emissions from the reservoir water surface and drawdown area) contributed around 87% and 92% of total GHG emissions for the years 2010 and 2011, respectively. Remaining total GHG emissions were contributed from downstream emissions (degassing and diffusive emissions from the downstream), a percentage lower than reported for tropical reservoirs.

With a total gross emissions of 2168 ± 358 and 2133 ± 276 $GgCO_2eq.year^{-1}$ for the years 2010 and 2011, gross NT2 emissions are about an order of magnitude higher than pre-impoundment emissions (276 ± 343 $GgCO_2eq.year^{-1}$). With a net GHG emissions of 1889 ± 496 (2010) and 1854 ± 440 (2011) $GgCO_2eq.year^{-1}$, and an annual power generation of about 6 TWh, GHG emission factor equal to 0.31 (2010) and 0.30 (2011) $MgCO_2eq.MWh^{-1}$ for the NT2 Reservoir. This is lower than a typical thermal coal based power plant emission factor of 0.96 Mg of $CO_2eq.MWh^{-1}$. GHG emission factor for the year 2010 corresponds to the initial years after impoundment for NT2, and as such, can be considered as the maximum value that would be reached for this reservoir. Work is in progress to predict the trends of GHG emissions over the projected life span (e.g. 100 years) of the reservoir yields integrated long-term net GHG emissions per energy generation. It will allow comparing with alternate energy sources over the projected life span (100 years) of the reservoir.

7.1. Introduction

The identification and accurate quantification of sinks or sources of greenhouse gases (GHGs) have become a key challenge for scientific and policy makers groups working on climate change or global warming. The contribution of freshwater hydroelectric reservoirs to

the increasing atmospheric GHGs concentrations is of rising concern. The major GHGs related to reservoir creation are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Eggletion et al., 2006). A recent meta-analysis of published data on GHG emissions from hydroelectric reservoirs covering a worldwide distribution suggests that globally, hydroelectric reservoirs emit annually about 48 TgC-CO_2, and 3 TgC-CH_4 (Barros et al., 2011). This is significantly less than previous estimates (St. Louis et al. 2000), mostly due to differences in the estimate of global reservoir surface (0.34 vs. 1.50 Million km^2). The second main reason of the large range of GHG emissions estimates is lack of representative regional GHG areal flux.

Most current estimates are based on gross GHG fluxes from reservoirs alone. They may be biased because they do not consider the pre-impoundment GHG sinks and sources (St. Louis et al., 2000; Teodoru et al., 2012; Tremblay et al., 2005, 2010). A realistic assessment of the net GHG footprint of hydroelectric reservoirs requires, in addition to reliable estimates of reservoir GHG emissions taken over space and time, robust estimates of the GHG sinks and sources from the terrestrial and natural aquatic ecosystems that existed in the pre-impoundment landscape, and which disappear due to flooding (Teodoru et al., 2012; Tremblay et al., 2010), i.e. net emissions = post impoundment emissions - pre impoundment emission. Thus, to predict the impact on emissions of greenhouse gases needed to be measured precisely, before and after the impoundment of reservoirs. In spite of the increasing awareness of the significance of reservoir GHG emissions for these two last decades, only one such pre-and-post impoundment GHG balance has ever been carried out (Eastmain 1 Reservoir, Quebec; Teodoru et al., 2012; Tremblay et al., 2010).

For the governing bodies (e.g. Intergovernmental Panel on Climate Change (IPCC), United Nations Educational, Scientific and Cultural Organization (UNESCO), etc.) and the energy sector (International Hydropower Association (IHA), International Energy Agency (IEA), etc.), the evaluation of net GHG emissions from hydroelectric reservoirs is becoming more and more relevant to ensure that methods of energy production are adequately compared. This is a necessary step for assessing carbon credits.

Around 25% of the existing 45000 large dams are used for electricity production, while the other 75% are used exclusively for other purposes (e.g., irrigation, flood control, navigation and urban water supply schemes). The number of reservoirs continues to increase at fast pace specially in the tropical or sub-tropical regions which still hold significant amount of undeveloped hydropower resources to be exploited (Kumar et al., 2012). As a matter of fact, tropical or subtropical hydroelectric reservoirs have been considered as more significant source of GHG than boreal or temperate one (Barros et al., 2011; St. Louis et al., 2000; Varis et al., 2012). Notably, no study dedicated to "net emissions" has ever been conducted in tropical or subtropical regions which is believed to be the "hot spot" for GHG emissions (Barros et al, 2011; DelSontro et al, 2011; Demarty and Bastien, 2011; Kemenes et al, 2011; St. Louis et al., 2000).

In this context, we studied a subtropical hydroelectric reservoir, Nam Theun 2 (NT2), a complex-structural-designed, created on the Nam Theun River in Laos PDR. This reservoir

has 1070 MW installed capacity, and an annual production of about 6 TWh. The overall aims of our study were to: (1) determine the complete GHG budget of the pre-impoundment landscapes; (2) determine the post-impoundment GHG budget including spatial and temporal variability; and finally, (3) combine these two estimates to assess the net GHG footprint of the NT2 reservoir.

Considering the above objectives, a major part of this chapter deals with the quantification of pre-impoundment GHG budget. Afterwards, net GHG emissions were quantified by combining this pre-impoundment GHG emission assessment with gross post GHG emissions estimated in Chapter 4, Chapter 5 and Chapter 6. Finally, we compared the net NT2 GHG emissions with alternative conventional energy sources.

These results represent, to the best of our knowledge, the first comprehensive, pre- and post-flooding net GHG balances ever carried out for a tropical/subtropical hydroelectric reservoir, and provide a robust estimate of the net GHG footprint directly associated with hydroelectricity generation.

7.2. Site description and methodology

7.2.1. Site description

The Nam Theun 2 (NT2) hydroelectric dam (17˚59'49" N, 104˚57'08" E) is built on the Nam Theun River in the subtropical region of Lao People's Democratic Republic (Figure 7.1). NT2 hydroelectric plant delivers an annual production of 6 TWh with a maximum flooded area of 450 km^2 at full water level (538 m msl). This leads to a high ratio of energy density (or annual production by maximum flooded area) of 13.34 $GWh.km^{-2}$. The project area experiences a tropical monsoon climate with distinct wet and dry (initial cold, then warm) seasons. Since the water inputs are directly related to rainfall, filling typically occurs during the wet season (mainly May to September). Owing to the hydrological conditions and reservoir operation planning, a large drawdown area, up to 80% of total 450 km^2 can be observed in normal years during the dry season (March to June) when the reservoir is at its minimal operating level (525.5 m msl).

With an annual average rainfall of 2400 mm, NT2 reservoir receives an average annual runoff of 7527 million m^3 from six major tributaries (Nam Xot, Nam Mon, Nam Theun, Nam Noy, Nam Yang and Nam On), an amount that represent more than twice the NT2 reservoir full capacity (3530 Mm^3).

Filling of the reservoir began in April 2008 and full water level (538 m msl) was first reached in October 2009. Commercial operation of the NT2 hydroelectric plant began in March 2010. The 450 km^2 area of terrestrial landscape was originally covered by dense, medium, light, degraded and riparian forests, as well as agricultural soils and swamps (Descloux et al., 2011). Dense, medium, and light forests represented 59% of the 450 km^2, whereas agricultural lands and swamps accounted only for 11% and 2% respectively. A small fraction of the vegetation was partially burnt or removed before the impoundment. The total amount of flooded organic carbon was around 5.1 ± 0.7 MtC, with 2.2 MtC from above

ground biomass, litter and dead wood, and 2.9 MtC from below ground biomass and soil organic carbon (Descloux et al., 2011).

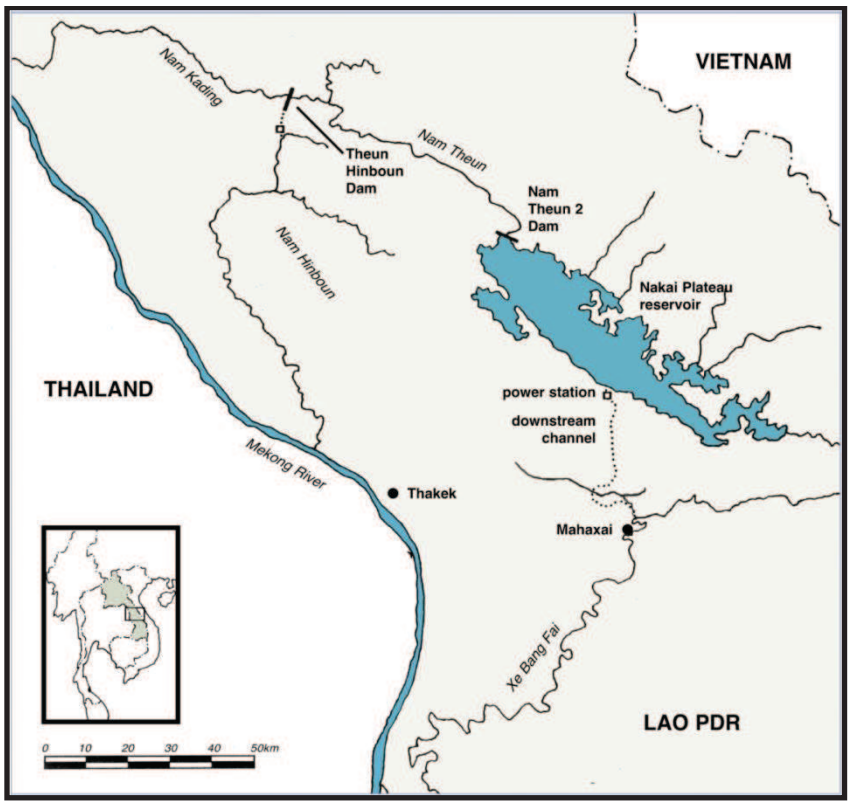

Figure 7.1. Location map of the Nam Theun 2 (NT2) Reservoir. The reservoir is shown at its full capacity (538 m above sea level). Map available on International Rivers Organization website (http://www.internationalrivers.org/campaigns/nam-theun-2-dam)

The NT2 reservoir is characterized as a warm monomictic lake, completely mixed from top to bottom once a year (Chanudet et al., 2012). During the dry season, the lake water body remains stratified with an oxic epilimnion overlying an anoxic hypolimnion, destratification occurring during the wet and cold dry season (Chanudet et al., 2012). An important feature of the reservoir concern is the turbine intake. This intake is located at the bottom of the reservoir between 506 and 524 m msl and receives a mixture of epilimnitic and hypolimnitic water due to its conceptual design. NT2 reservoir is a trans-basin diversion hydroelectric reservoir that takes water from the Nam Theun River and turbines release it after turbines into the Xe Bang Fai River through a 27 km long artificial downstream channel (Figure 7.1). Before being released into the Xe Bang Fai River, and to control the flow, turbined water is stored in an 8 Mm^3 artificial regulating pond. A continuous ecological flow (2 $m^3.s^{-1}$), and occasionally spillway release is released from the Nakai Dam to the Nam Theun River.

7.2.2.General approach

The net reservoir GHG footprint corresponds to the net changes in GHG flux. This includes the GHG emissions after impoundment to which are subtracted the sinks or sources

of GHG that were present in the pre-impoundment landscape. This represents the "excess" emissions directly associated with the creation of the reservoir (UNESCO-IHA, 2009; World Commission on Dams, 2000). CO_2, CH_4 and N_2O emissions to the atmosphere were quantified and estimated for each of the individual ecosystems existing in the pre-impoundment landscape. Similarly, GHG emissions from the NT2 system (reservoir water surface + drawdown area + downstream) were estimated post-impoundment (see Chapter 4, Chapter 5 and Chapter 6). The overall impact of reservoir creation on the GHG source/sink balance, i.e. net GHG footprint of the reservoir, is calculated as:

Net reservoir GHG footprint = reservoir GHG sink/source balance - pre-impoundment GHG sink/source balance (Teodoru et al., 2012; Tremblay et al., 2010).

The quantification of pre-impoundment and post-impoundment GHG emissions is elaborated from six intensive field campaigns (one before, and five after impoundment, between May 2008 and June 2011) measurements, and from a continuous fortnightly monitoring program on going since the NT2 flooding. Pre-impoundments GHG balance was quantified for year 2008, and reservoir GHG sink/source balance was calculated for first two years after full-impoundment i.e. year of 2010 and 2011.

There is an imbalance in the sampling effort pre-impoundment and post-impoundment, with in the order of ten days of sampling during one season and using a limited number of techniques before flooding and a much more ambitious sampling program during all seasons and using multiple methods after flooding. It was because of the severe practical constraints in terms of funding, timing and access that have caused this imbalance. However, forests occupied about 80% of the surface area prior to the filling of the reservoir and that the pre-impoundment CO_2 budget for forests was derived from a literature value, it could be apparent that the pre-impoundment values are highly tentative. It is to be mentioned that our estimate of CH_4, CO_2 and N_2O exchanges were in the upper range. CH_4 exchange has very low contribution to GHG pre-impoundment emissions. Globally, estimates of CO_2 (sink) and N_2O (source) exchanges were probably compensated by each other. Therefore, our estimates on GHG pre-impoundment emissions can be considered as conservative values.

Next section deals with the GHG budget assessment for the pre-impoundment period.

7.2.3. Pre-impoundment GHG exchange

GHG emission from the different pre-impoundment ecosystems were estimated during a field campaign conducted from 11th to 21st May 2008, at the beginning of the wet season, together with some additional N_2O flux measurements conducted in June 2010. GHG emission from pre-impoundment riverine ecosystems were derived using the thin boundary layer technique from GHG concentrations in the surface water sampled from the pristine rivers sampled by AELab within the continuous monitoring program (see details on that technique in Chapter 2).

7.2.3.1. CO_2 exchange

CO_2 exchange, or more exactly the Net Ecosystem Exchanges (NEE) were measured using the Eddy Covariance (EC) technique, a direct micrometeorological method (see details in Chapter 2). Given the various constraints (see below) related to the implementation of the EC technique, CO_2 flux measurements were conducted primarily in the former Nam Theun River floodplain. This area was used for agriculture (rice cultivation) before the impoundment. Estimate of the NEE for the different types of forest was beyond our possibility in the context of this program. Indeed, among others, eddy covariance technique requires measurements to be done above a flat and horizontal uniform surface. Forests in the reservoir footprint were on sloppy terrain, and would a tower exceeding the forest canopy has not been present, measurements would have not complied with EC constraints. Literature values were used to complete the database on different forest types, extracted from the study on CO_2 fluxes in the tropical forests from the most comprehensive study currently available (Luyssaert et al., 2007).

7.2.3.2. CH_4 exchange

CH_4 emissions were measured using static chamber technique (see the detail in Chapter 2). These measurements were done on six of the most representative ecosystems (primary forest, degraded forest, riparian forest, slash and burnt, agricultural land, swamps, see locations in Figure 7.2) in the reservoir footprint.

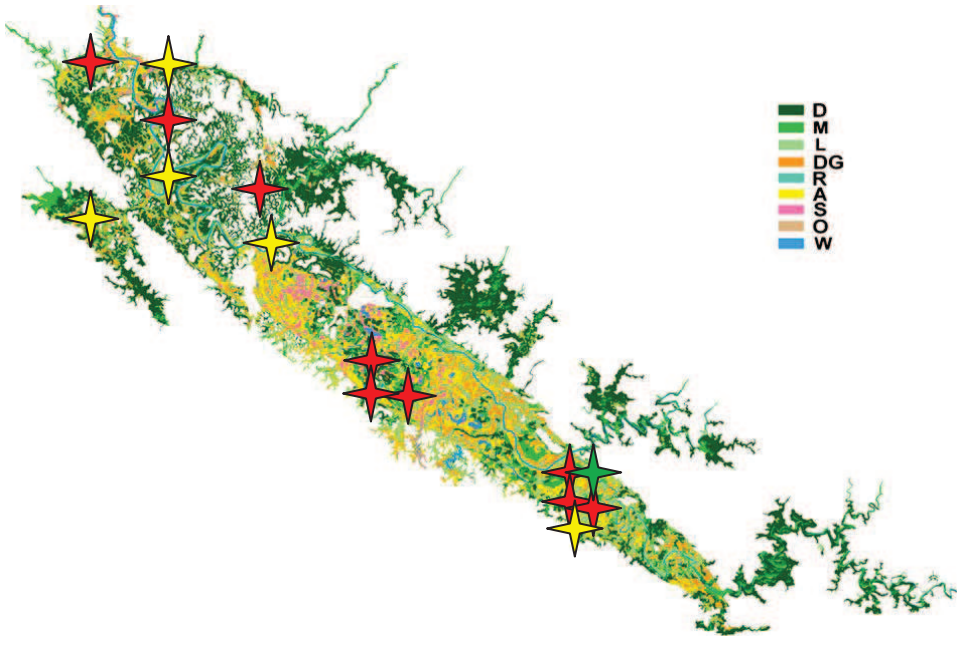

Figure 7.2. Locations of the sampling sites investigated for CH_4 (red symbol), CO_2 (green symbol) and N_2O (yellow symbol) fluxes pre-impoundment of the NT2 reservoir (source of the map: Descloux et al., 2011). Note: D: dense forest, M: medium forest, L: light forest, DG: degraded forest, R: riparian forest, AG: agricultural land, SW: swamps, S: soils, and W: water.

The sum of the investigated ecosystems represented 96.6% of the total area flooded by the reservoir creation (Table 7.1, Descloux et al, 2011).

A total of nine different sampling stations were investigated (2 swamps sites, 3 degraded forest sites and one site each in other ecosystems, see locations in Figure 7.2). Similar to CO_2, CH_4 emissions from the water surface were determined from surface CH_4 concentration measured in pristine river sites of the monitoring network and estimated via the thin boundary layer technique.

Table 7.1. Distribution of the major ecosystems existing before flooding the NT2 Reservoir and the number of flux measurements of CO_2, CH_4 and N_2O. SC: static chamber flux measurements; EC - eddy covariance flux measurement; TBL - thin boundary layer flux calculation.

Type of ecosystem	Surface area (km^2)	Surface (%)	No. of flux measurements (technique used)		
			CO_2	CH_4	N_2O
Primary forest	154.5	34.6	-	3 (SC)	12 (SC)
Degraded forest	207.9	46.6	-	19 (SC)	20 (SC)
Agricultural land	48.7	10.9	218 (EC)	45 (SC)	6 (SC)
Swamps	10.7	2.4	-	38 (SC)	-
Bare Soils	5.3	1.2	-	8 (SC)	-
Riparian forest	4.0	0.9	-	8 (SC)	-
Water	15.3	3.4	150 (TBL)	150 (TBL)	150 (TBL)
Total	**450**	**100**	**368**	**271**	**188**

7.2.3.3. N_2O exchange

N_2O emissions were measured in June 2010 using static chamber technique. Measurements were performed on three types of ecosystems present in the pre-impoundment landscape: primary forest, degraded forest and agricultural land. The sum of the investigated ecosystems represented 92.1% of the total flooded area. Flux measurements were done together with soil moisture content and temperature measurements. Note that N_2O flux measurements were not done on bare soil and in riparian forest. For this latter ecosystem, data from the literature (Groffman et al, 2000, McSwiney et al, 2001) were used to complete the assessment. For bare soils, it was assumed that N_2O emissions were null because moisture conditions on such soil types are generally not favorable to denitrification, the process primarily responsible for emissions of N_2O in such ecosystem. Similar to CO_2 and CH_4, N_2O emission from the water surface were determined from surface N_2O concentration measured in pristine river sites of the monitoring network and estimated via the thin boundary layer technique.

7.3. Results

7.3.1. Pre-impoundment GHG exchange

7.3.1.1. CO_2 exchanges

Figure 7.3 shows half-hour CO_2 fluxes measured in the Nam Theun River floodplain during the May 2008 field campaign. A total of 234 half-hours (about 5 days of measurements) were acquired. After post processing and quality control on the measured fluxes, 218 half-hour samples were considered for the final calculation of the CO_2 fluxes (see Figure 7.3).

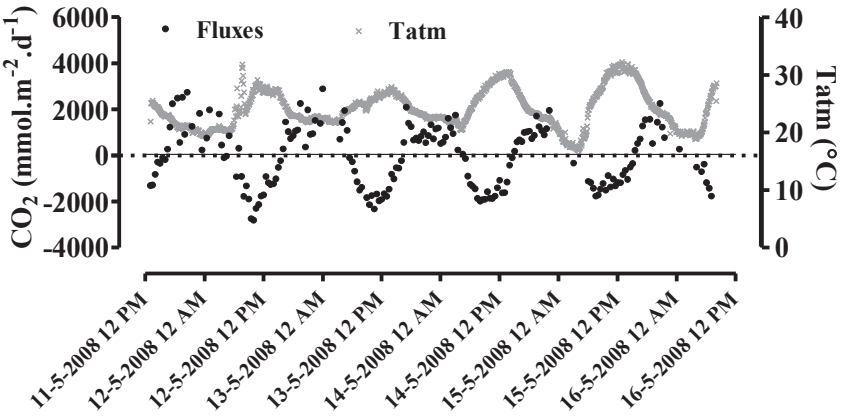

Figure 7.3. Diurnal pattern of CO_2 fluxes measured in May 2008 using eddy covariance technique at the floodplain of the Nam Theun River.

7.3.1.2. CH_4 exchange

A total of 121 hourly measurements of CH_4 fluxes were conducted, only 119 fluxes were actually considered for the final calculation (Figure 7.4). For each measurement site (excepted for the primary forest and bare soil sites), a minimum of 8 replicates of flux measurements were performed, which allows us to obtain a reliable and robust statistically mean.

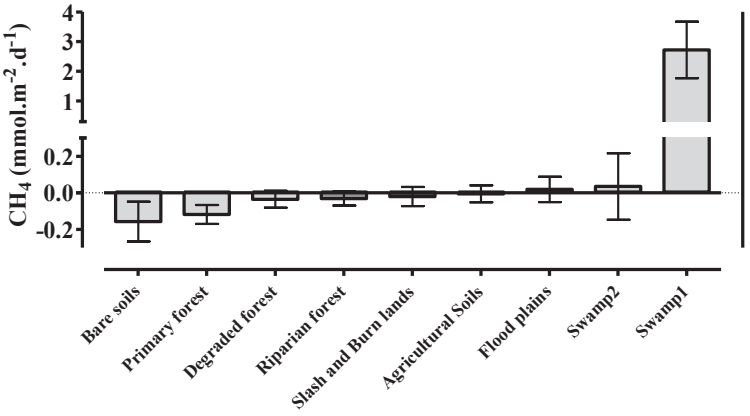

Figure 7.4. Average (± standard deviation) CH_4 fluxes at the nine sampling sites investigated in the pre-impoundment landscape of NT2 reservoir.

A statistical analysis showed that among the 6 sampling sites with mean negative fluxes, only two sites (bare soil and primary forest) were significant sinks of CH_4, which was not the case for the other four sites (degraded forest, riparian forest, slash and burn farming, rice fields). From the three sites showing positive mean CH_4 flux, only Swamp 1 was a significant source of CH_4, while the two other sites (floodplain and Swamp 2) were not significantly source of CH_4 at the time of measurement.

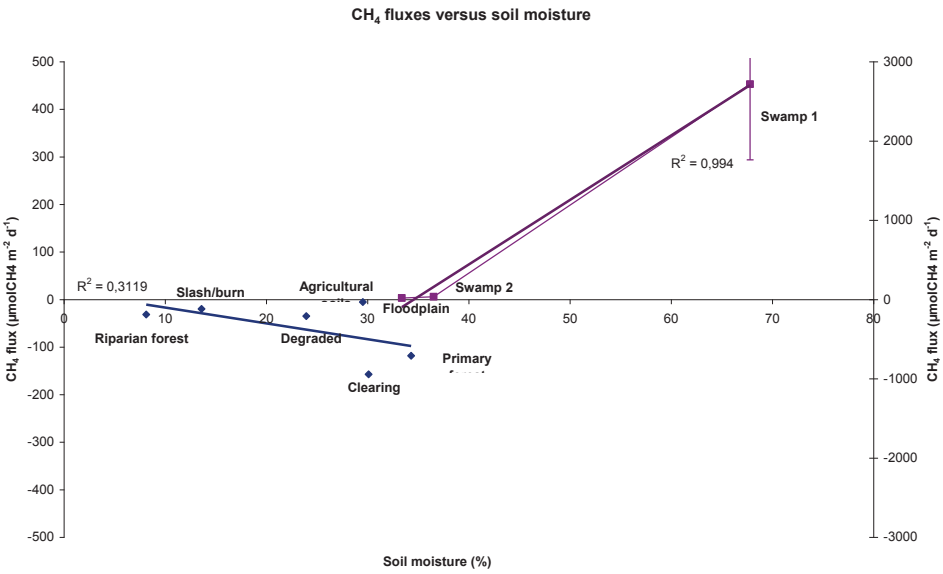

Figure 7.5. Average fluxes of CH_4 for each type of flooded ecosystems depending on the soil moisture content. Fluxes from swamps are plotted on the right Y-axis.

A significant relationship between CH_4 fluxes and soil moisture content was found for sampling sites that were acting as a source of CH_4 (see Figure 7.5, right Y-axis). CH_4 emission was positively correlated with the soil moisture content in 35 to 68% soil moisture range ($r^2 = 0.998$), while CH_4 sink appears to be more or less independent from soil moisture content ($r^2 = 0.3$) in the 10 to 35% soil moisture range. It seems that comparatively low CH_4 emission from swamp 2 (36.5% soil moisture content) than from swamp 1 (68% soil moisture content) appears to be linked to soil moisture, rather than ecosystem differences.

7.3.1.3. N_2O exchanges

A total of 39 hourly N_2O flux measurements were conducted, 38 of them being considered for final calculation (Table 7.2). According to the soil moisture contents at the time of the measurements, three different groups can be defined: dry soils (20 ± 7% vol.), representing the warm dry season; intermediate soils (29 ± 11% vol.) representing the cold dry; saturated soils (45 ± 4% vol.), representing average condition of the wet season. Since we could not perform the measurement over swamps, we considered N_2O fluxes from saturated agricultural soils for swamp areas in the subsequent flux up-scaling.

Table 7.2. N_2O mean flux values in the four investigated ecosystems.

Sites	Dry soils (20 ± 7% vol.)	Intermediate moisture content (29 ± 11% vol.)	Saturated Soils (45 ± 4% vol.)
Degraded forest	38 ± 22	195 ± 129	214 ± 274
Primary forest	35 ± 21	708 ± 171	62 ± 6
Agricultural soils	64 ± 86	103 ± 75	29 ± 48
Swamp	29 ± 48	29 ± 48	29 ± 48

7.3.1.4. Spatial and temporal integration of fluxes

Several assumptions were made for each GHG to extrapolate measured fluxes at the scale of the total flooded area. Note that all calculations of spatial and temporal integration fluxes were made at the scale of the reservoir footprint at its full level i.e. 450 km^2.

7.3.1.4.1. CO_2 budget

It has been considered that evolution of the swamp area along the wet season was the result of agricultural soils flooding (Chanudet, personal communication, EDF) of the Nam Theun river floodplain. Areas of all other ecosystems remain constant throughout the year. All types of forests (primary, medium, light, degraded and riparian) listed in the inventory (Descloux et al., 2011) are lumped in a same "forest" category (362.4 km^2 or 81% of the total area). For the "forest" category, CO_2 fluxes of -403 ± 102 $gC\text{-}CO_2.m^{-2}.year^{-1}$ were considered from Luyssaert et al, 2007. CO_2 flux for the water surface was calculated from CO_2 surface concentrations determined in sampling stations NXT0, NXT1, NTH2 and NON1 (pristine sections of the Nam Xot, Nam Theun and Nam On rivers respectively). These fluxes were calculated via the thin boundary layer technique using a constant k_{600} of 10 $cm.hr^{-1}$. From this, an average annual CO_2 flux of 9393 ± 9403 $gC\text{-}CO_2.m^{-2}.year^{-1}$ from the water surface was estimated. One should note that this estimate does not consider any seasonal variability in CO_2 fluxes since we used annual mean surface water concentrations for this purpose. CO_2 fluxes used for interpolation on the whole pre-impoundment landscape are summarized in Table 7.3.

Table 7.3. Average (± standard deviation) CO_2 flux values used for spatial extrapolation (all fluxes in $gC\text{-}CO_2.m^{-2}.year^{-1}$).

Type of ecosystem	Average ± SD	References
All type of forests	-403 ± 102	Luyssaert et al., 2007, Global Change Biology
Agricultural soils	-1710 ± 927	this study (measured by eddy covariance)
Swamp	1963 ± 2164	Jauhiainen et al, 2005, Hirano et al, 2007
Water	9393 ± 9403	this study

Figure 7.6 shows integrated CO_2 exchanges for the different major ecosystems investigated, namely forest, agricultural land, swamp and water surface, using CO_2 exchanges and surface area of the different ecosystems.

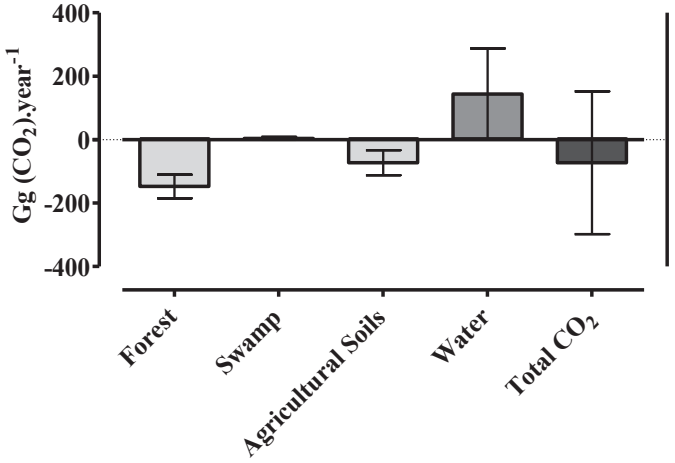

Figure 7.6. Average (± standard deviation) CO_2 fluxes for forest ecosystems, swamp, agricultural soils, surface water, and total emissions (all fluxes given in $GgCO_2.year^{-1}$).

At the whole pre-impoundment landscape, CO_2 uptake from the forest ecosystems was almost offset the CO_2 emissions from the river ecosystems, while CO_2 emission from the swamp is almost negligible. As a matter of consequences, total CO_2 fluxes are very similar to the CO_2 flux from the agricultural soils. Pre-impoundment NT2 footprint represents an annual sink of 72.6 ± 225 $GgCO_2.year^{-1}$), i.e. an average CO_2 uptake of -169 ± 504 $gC\text{-}CO_2.m^{-2}.year^{-1}$) (Figure 7.6).

7.3.1.4.2. CH_4 budget

Similar to CO_2, it has been considered that evolution of the swamp area along the wet season was the results of agricultural soils flooding. We considered that all the swamp area was in saturated conditions, and then attributed the emission value from swamp 1 sampling site. No seasonal variation in the area of primary forest (154.5 km^2, 34.6% of total flooded area) was considered. All ecosystems acting as CH_4 sinks (that is light, medium and degraded forests) are clustered in the category of degraded forest which represents then an area of 207.9 km^2 (or 46.6% of total flooded area). Statistically, this area is neutral in term of CH_4 exchange. CH_4 fluxes for the water surface was calculated from CH_4 surface concentrations determined in sampling stations NXT0, NXT1, NTH2 and NON1 (pristine sections of the Nam Xot, Nam Theun and Nam On rivers respectively). These fluxes were calculated via the thin boundary layer technique using surface CH_4 concentrations and a constant k_{600} of 10 $cm.hr^{-1}$. From this, we estimated an average daily CH_4 flux from the water surface of 1.44 ± 3.14 $mmol.m^{-2}.d^{-1}$. One should note that a probable seasonal variability in CH_4 fluxes was not considered for any of the studied ecosystems.

Since CH_4 fluxes were measured in the beginning of the rainy season, the soils moisture content must have been in an intermediate range. The sinks of CH_4 (bare soil and primary forest) might be the place, during the dry season, of a stronger (significant) consumption than the one measured. Further, ecosystems that were not significant sinks of CH_4 emission (degraded forest, riparian forest, burnt forest, rice fields) could be larger sinks of CH_4 (that is to say significant in the case of ecosystems neutral) if we would have done the measurements in the dry season. As a matter of consequence, net CH_4 flux presented here has to be considered as a value in the upper range. Table 7.4 summarizes the average fluxes from the different ecosystems used for spatial extrapolation.

Table 7.4. Average (± standard deviation) CH_4 flux values used for spatial extrapolation (all fluxes in $mmol.m^{-2}.d^{-1}$).

Type of Ecosystem	CH_4 flux
Bare soil	-0.16 ± 0.11
Primary forest	-0.12 ± 0.05
Swamp	2.70 ± 0.95
Water	1.44 ± 3.14

Figure 7.7 shows the annual CH_4 exchange from the different ecosystem prior to flooding. CH_4 uptake occurring in the primary forest soils is almost counterbalanced by CH_4 emissions from the water surface, while CH_4 exchange in the bare soils ecosystem is almost negligible. Therefore, total CH_4 emission is very close to the CH_4 emissions from the swamp area (i.e. 0.28 ± 0.43 Gg $CH_4.year^{-1}$).

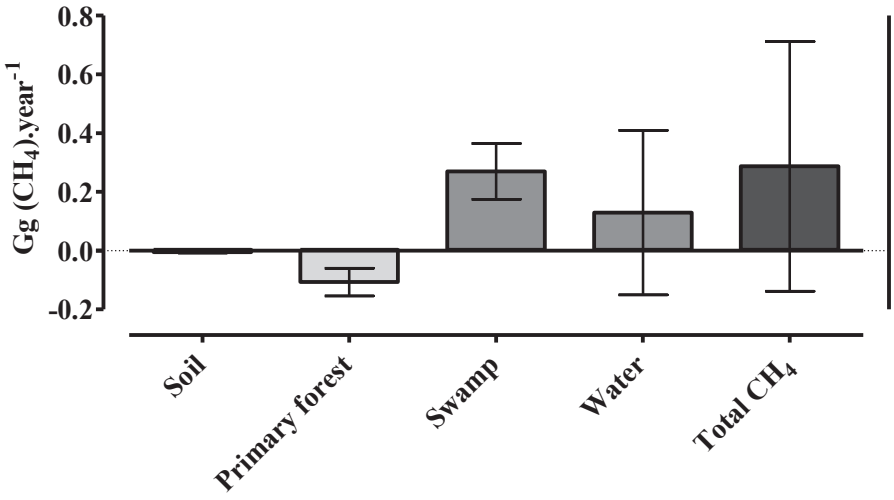

Figure 7.7. Average (± standard deviation) annual CH_4 exchanges in source (swamp, water surface), and sinks (primary forest, bare soil) ecosystems, and total budget.

7.3.1.4.3. N_2O budget

As for CH_4, we considered that all the swamp areas were in saturated conditions, and then attributed the emission value from swamp 1 site to the entire swamps surface. Evolution of the swamp area along the wet season was the results of agricultural soils flooding. No seasonal variation in the area of primary forest (154.5 km^2, 34.6% of total flooded area) was considered. Light, medium and degraded forest ecosystems were clustered into the degraded forest category which represents an area of 207.9 km^2 (or 46.6% of total flooded area). For the riparian forest ecosystem, an average flux of 0.61 ± 0.31 $mgN_2O.m^{-2}.d^{-1}$ from the literature (Groffman et al, 2000; McSwiney et al, 2001) was used. N_2O flux for the water surface was calculated from N_2O surface concentrations determined in sampling stations NXT0, NXT1, NTH2 and NON1 (pristine sections of the Nam Xot, Nam Theun and Nam On rivers respectively). Fluxes were calculated via the thin boundary layer technique using a constant k_{600} of 10 $cm.hr^{-1}$. From this, we estimated an average N_2O flux from the water surface of 4.8 ± 9.8 $mgN_2O.m^{-2}.day^{-1}$. A possible seasonal variability of the flux from the water surface has not been taken into account since we used annual mean surface water concentrations for this purpose.

Soil moisture is a very important and sensitive factor regulating N_2O emission from soils. Many studies have suggested that the soil moisture directly regulates oxygen availability in soil pores, which in turn determines the status of nitrification and denitrification and the ratios of N_2O to final products (Bandibas et al., 1994; Bateman et al., 2005; Cardenas et al., 1993; Conen, et al., 2000; Davidson, 1992; Hou et al., 2000; Maag and Vinther, 1996; Schindlbacher et al., 2004; Smith et al., 1998; Zheng et al., 2000). For N_2O fluxes up scaling at the whole pre-impoundment landscape, we considered that for all sampling sites, the fluxes measured in the driest soils (high toposequence) were representative of the dry season. The emissions measured under conditions of intermediate soil moisture (middle toposequence) were assigned to conditions during the wet season. The measurements made at the bottom of toposequence (saturated soils) were assigned to an area representing 10% of the area of primary forest ecosystems and degraded forest in the wet season, and 100% of swamp area.

The length of the season is determined from known statistics of precipitation over the past ten years. Around 5% of the annual precipitation occurs in the dry season (January, February, March, April, October, November and December, or 212 days). Around 80 to 90% of the rainfall occurs in the wet season (May to September, or 153 days). Table 7.5 summarizes the average flux values for different ecosystems deduced from these assumptions, and used for the spatial integration of N_2O emissions.

Figure 7.8 shows the annual N_2O emissions from the different ecosystems prior to flooding. This budget is dominated by emissions from primary and degraded forests, agricultural soils and surface water, whereas wetlands and riparian forests are only minor sources for N_2O. Pre-impoundment NT2 footprint was an annual N_2O source of 1156 ± 558 Mg $N_2O.year^{-1}$.

Table 7.5. Average (± standard deviation) N_2O fluxes used for spatial extrapolation (all fluxes given in $mgN_2O.m^{-2}.d^{-1}$)

Type of ecosystem	Dry soil	Soil with intermediate moisture level	Saturated soils	References
Primary forest	1.6 ± 0.9	31.1 ± 7.5	2.7 ± 0.2	This study
Degraded forest	1.7 ± 1.0	8.6 ± 5.7	9.4 ± 12.1	This study
Riparian forest	0.6 ± 0.3	0.6 ± 0.3	0.6 ± 0.3	Groffman et al., 2000; McSwinney et al., 2001
Agricultural soil	2.8 ± 3.8	4.5 ± 3.3	1.3 ± 2.1	This study
Swamp	1.3 ± 2.1	1.3 ± 2.1	1.3 ± 2.1	This study
Water	4.8 ± 9.8	4.8 ± 9.8	4.8 ± 9.8	This study

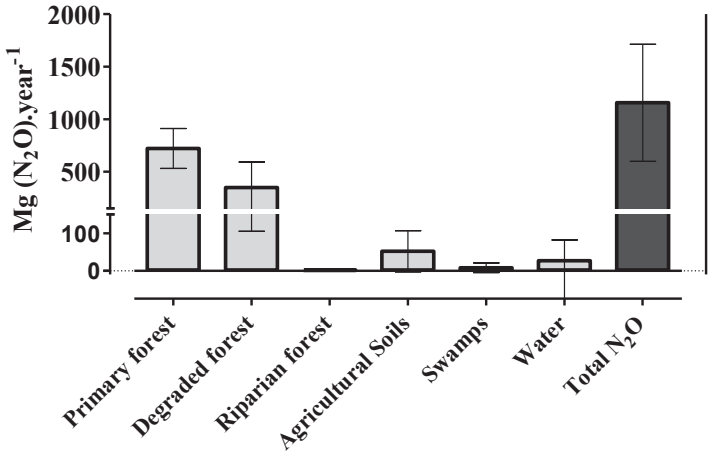

Figure 7.8. Average (± standard deviation) annual N_2O emitted by forests, swamp, agricultural ecosystems, water surface, and total budget (all terms in $MgN_2O.year^{-1}$).

7.3.1.5. Assessment of GHG exchange in CO_2 equivalent

The CH_4 and N_2O budgets were converted into CO_2-equivalent by multiplying the global warming potentials (GWPs) of CH_4 and N_2O. For this calculation, GWP values of 25 and 298 for CH_4 and N_2O respectively were used (IPCC 2007, 100 years time scale).

Table 7.6. Annual CO_2, CH_4, and N_2O budgets converted into CO_2-equivalent (all terms given in $Gg\ CO_2\text{-}eq.year^{-1}$)

GHG	Exchange, $GgCO_{2eq}.year^{-1}$
Total CH_4-CO_2eq	7 ± 11
Total N_2O-CO_2eq	345 ± 158
Total CO_2	-73 ± 225
Total CO_2eq	**279 ± 343**

Emissions of greenhouse gas from the pre-impoundment ecosystems within the NT2 footprint would represent a total of 279 ± 343 $GgCO_2$-eq.$year^{-1}$ (see Table 7.6), or an average flux of 620 ± 881 gCO_2-eq.m^{-2}.yr^{-1}. Table 7.6 shows that the two most significant terms in the total GHG budget are exchanges of N_2O and CO_2, while the influence of CH_4 is of secondary importance.

7.3.2. Post-impoundment GHG exchange

After the flooding of the NT2 Reservoir, the different GHG emission pathway terms from the NT2 reservoir footprint were quantified by integrating detailed spatial and temporal variability (see Chapter 3, Chapter 4, Chapter 5, and Chapter 6). This includes estimates of emissions from the drawdown area, diffusive and bubbling emissions from the reservoir water surface, and degassing and diffusive emissions from downstream (of the Nakai dam and the powerhouse). Sampling strategies with methodologies and results have been discussed in the previous chapters. Here are summarized the major findings regarding gross GHG emissions.

To calculate the post-impoundment gross GHG emissions from the NT2 Reservoir, estimates of the following pathways were established:

a. Upstream GHG emissions
    1. Diffusive GHG emissions from the reservoir water surface
    2. Diffusive GHG emissions from the drawdown area
    3. Ebullitive (bubbling) GHG emissions from the reservoir surface area corresponding to less than 13 m water depth
b. Downstream GHG emissions
    1. Diffusive GHG emissions downstream of the powerhouse (initial 30 km) and the Nakai Dam (initial 30 km)
    2. Degassing GHG emissions at five facilities: at the Nakai Dam (ecological flow and occasional spillway release), turbines outlet, regulating pond outlet, and aeration weir

In order to compare the contribution of each gas to gross GHG emissions, CH_4 and N_2O emissions were converted to CO_2 equivalent using GWPs as stated in pre-impoundment section. Estimates of post impoundment GHG budget for the different pathways of CO_2, CH_4 and N_2O are summarized in Table 7.7. Our results indicate that upstream GHG emissions (emissions from reservoir water surface and drawdown area) contributed around 87% and 92% of total GHG emissions for 2010 and 2011 respectively. With 13% and 8% for the year 2010 and 2011, downstream emissions (degassing and diffusion) show a percentage lower than reported for other reservoirs.

Table 7.7. Annual gross GHG budgets for the year 2010 and 2011 ($GgCO_2eq.year^{-1}$).

		Upstream emission			Downstream emission		Total
Year	Pathways	Diffusive fluxes from the drawdown area	Bubbling (water depth < 13m)	Diffusive fluxes from the reservoir water surface	Degassing	Diffusive fluxes from the downstream	
2010	CO_2	324 ± 48		892 ± 239	51 ± 8	40 ± 4	1307 ± 244 **(60%)**
	CH_4	20 ± 18	383 ± 28	173 ± 203	165 ± 18	28 ± 8	768 ± 206 **(35%)**
	N_2O	64 ± 162		24 ± 11	2 ± 2	3 ± 0.2	93 ± 162 **(4%)**
	All GHG	408 ± 170 **(19%)**	383 ± 28 **(18%)**	1089 ± 313 **(50%)**	218 ± 19 **(10%)**	70 ± 8 **(3%)**	**2168 ± 358**
2011	CO_2	243 ± 48		1192 ± 191	62 ± 8	54 ± 3	1551 ± 197 **(73%)**
	CH_4	23 ± 20	318 ± 25	73 ± 85	55 ± 8	5 ± 3	473 ± 91 **(22%)**
	N_2O	58 ± 170		48 ± 16		3 ± 0.5	109 ± 170 **(5%)**
	All GHG	324 ± 177 **(15%)**	318 ± 25 **(15%)**	1312 ± 210 **(62%)**	117 ± 11 **(5%)**	62 ± 4 **(3%)**	**2133 ± 276**

The following conclusions can be drawn from Table 7.7.

a. Major emission pathways for different GHGs:

1. CO_2: Diffusive fluxes from reservoir water surface and from drawdown area
2. CH_4: Bubbling, diffusive fluxes from the reservoir water surface and degassing.
3. N_2O: Diffusive fluxes from the drawdown area and from the reservoir water surface.

b. Significance of each gas to gross GHG emissions: CH_4 and CO_2 emissions contribute significantly to total gross GHG emissions, while N_2O has a small contribution.

c. Upstream vs. downstream GHG emission: most of the gross GHG emissions is contributed from upstream (emissions from drawdown, diffusion from reservoir water surface and bubbling), while relatively low GHG emissions come from the downstream (degassing and diffusion from downstream).

One can notice that pre-impoundment budget for CO_2 correspond to a sink, when the net footprint budget is a source for CH_4 and N_2O (Figure 7.9). Our GHG budget reveals that the NT2 Reservoir is a significant source of CO_2 and CH_4, and a much smaller source of N_2O

(Figure 7.9). For the year 2010, with 1307 ± 244 $GgCO_2eq.year^{-1}$ and 768 ± 206 $GgCO_2eq.year^{-1}$ respectively, CH_4 and CO_2 have contributed around 60% and 35% to the total GHG budget, N_2O accounting for less than 5% with 93 ± 162 $GgCO_2eq.year^{-1}$. While CH_4 emissions show around 40% decrease from the year 2010 to 2011 (473 ± 91 $GgCO_2eq.year^{-1}$ in the year 2011), CO_2 emissions increased around 15% (1551 ± 197 $GgCO_2eq.year^{-1}$) in the same time, when N_2O emissions remained constant.

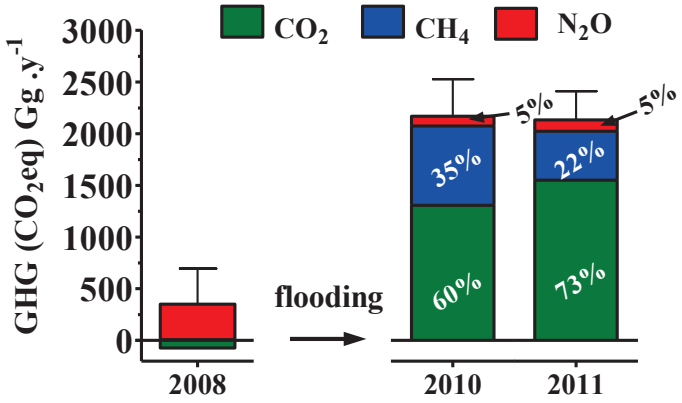

Figure. 7.9. Annual gross GHG budgets for the years 2008, 2010 and 2011.

Total GHG budget suggests that the footprint turned from a small source of total CO_2eq emissions (279 ± 343 $GgCO_2eq.year^{-1}$ in the year 2008) in pre-impoundment conditions, to a significant post impoundment source (2168 ± 358 and 2133 ± 276 $GgCO_2eq.year^{-1}$ for the years 2010 and 2011 respectively) (Figure 7.9).

7.4. Net GHG Emissions

The net GHG footprint of the NT2 Reservoir represents the actual CO_2, CH_4 and N_2O fluxes to the atmosphere that can be directly attributed to the creation and existence of the reservoir. As stated in the methodology section, annual net budgets were calculated by subtracting the pre-impoundment GHG budget from the post-impoundment GHG budget. Table 7.8 summarizes the estimates of net budgets for the different GHGs.

Table 7.8. Annual net GHG budgets for the years 2010 and 2011 (all values given in Gg $CO_2eq.year^{-1}$).

	Pre-impoundment exchange	Post-impoundment exchange		Net GHG footprint	
GHG	2008	2010	2011	2010	2011
Total CO_2	-73 ± 225	1307 ± 244	1551 ± 197	1380 ± 332	1624 ± 299
Total CH_4-CO_2eq	7 ± 11	768 ± 206	473 ± 91	761 ± 206	466 ± 92
Total N_2O-CO_2eq	345 ± 258	93 ± 162	109 ± 170	-252 ± 305	-236 ± 309
Total CO_2eq	279 ± 343	2168 ± 358	2133 ± 276	1889 ± 496	1854 ± 440

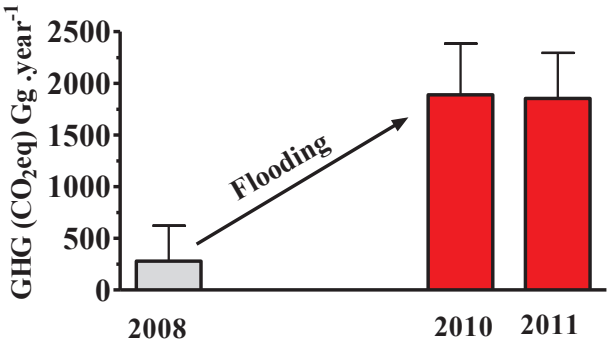

Figure. 7.10. Annual net GHG budgets for the years 2010 and 2011.

The difference between the pre-impoundment and post-impoundment emissions indicates that the net NT2 reservoir footprint is a10 times large source of GHG (1889 ± 496 and 1854 ± 440 Gg CO_2eq.year^{-1} respectively for the years 2010 and 2011; Table 7.8).

7.5. Net GHG emissions and energy generation

From the net GHG footprint of the NT2 Reservoir calculated in the previous section, and the annual power generation (6TWh), GHG emission factors of 310 and 300 gCO_2 eq.kWh^{-1} are calculated for the years 2010 and 2011, respectively. One can conclude that the net GHG emission factor from NT2 reservoir is significantly lower than the emission factors of power plants running on natural gas and all other current fossil-fuel based technologies (Figure 7.11).

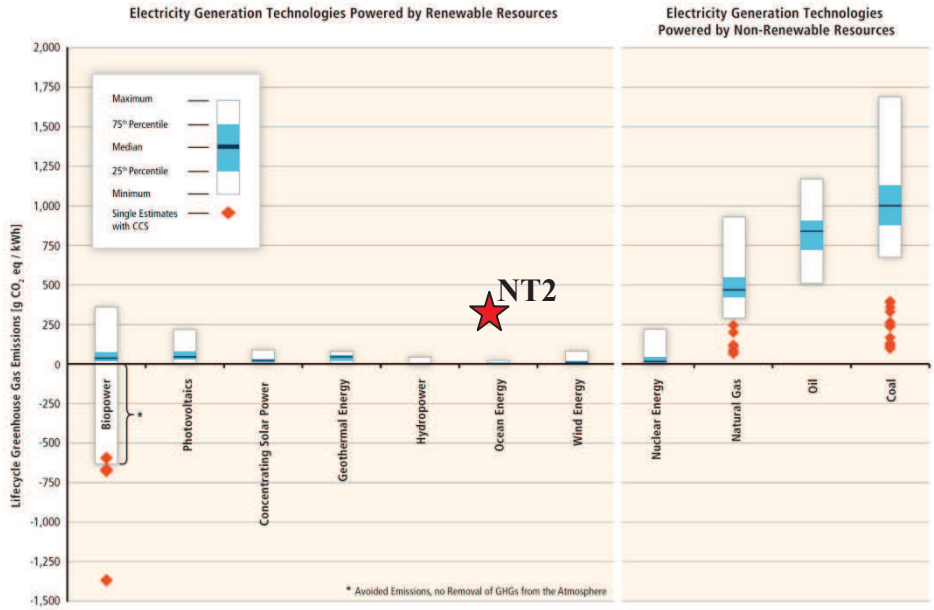

Figure 7.11: Estimates of lifecycle GHG emissions (gCO_2eq.kWh^{-1}) for broad categories of electricity generation technologies, plus some technologies integrated with CCS (IPCC, 2012). It must be noted that red star corresponds to GHG emissions factor for the first 2 years after impoundment of the NT2 Reservoir (which is not the lifecycle GHG emissions).

Those rate are about more than 3 times lower than the mean emission factor of thermal power plant using coal (generator types with scrubbing), and 1.5 times lower than of the GHG emission factor of thermal power plant using natural-gas combined cycle (Figure 7.11).

For more direct comparison of GHG emission factors related to power generation, it is more relevant to use the cumulative GHG emissions throughout the lifespan of the generating facilities (e.g. 100 years for reservoirs). Literature suggests that these emissions will decline over the next following years (Barros et al., 2011; St. Louis et al., 2000). It is difficult at this point to accurately estimate the trend of the NT2 reservoir net GHG budget over the next 100 years, and this is the next step to be undertaken.

GHG emission factors from hydroelectricity vary from one climatic region to another. This result should only be attributed to sub-tropical or tropical reservoir, and not to temperate or boreal reservoirs. Further, GHG emission can also vary within a climatic region from one reservoir to another. This is related to differences in abiotic and biotic parameters in the reservoirs such as availability of carbon and nitrogen, residence time, average water depth, reservoir shape, design and location of the turbine intake (influence on downstream emissions). These estimated GHG emissions related to energy production are likely to vary with the actual reservoir operation and management (time, duration, seasonality of water release for example).

As a conclusion, one should note that the creation of the NT2 sub-tropical reservoir resulted in a significant shift in the GHG budget of the footprint that was flooded. The results of this work project highlights the importance of well documenting (both in term of assessment and process understanding) the GHG exchanges of the natural landscapes prior to flooding, and the post-impoundment GHG budget when determining the net GHG footprint of a hydroelectric reservoir.

Chapter 8
Conclusion and outlook

8.1. Methane (CH_4)

8.1.1. CH_4 dynamics

Experiments on the methanogenesis have shown that the CH_4 production rates were lower in the soils from the NT2 Reservoir as compared to some hydroelectric reservoirs studied in the Amazonian region. Our results hint that comparatively low flooded carbon leads to lower CH_4 production in the reservoir. Aerobic CH_4 oxidation at the top of the hypolimnion during the stratified period effectively regulates the CH_4 levels in the epilimnion. The fortnightly continuous monitoring of the CH_4 concentrations on the water column revealed that those concentrations and subsequent emissions to the atmosphere varied over four orders of magnitude. Maximum concentrations were observed during the warm dry season and minimum ones during the cold dry seasons. Our study clearly shows that the physical dynamics of the water column along with dissolved O_2 level in the water are the most important determinants of CH_4 concentration in the water column, rather than methanogenesis (production) at the bottom itself.

Our results show that seven out of nine sampling stations behaved similarly, suggesting a not strong spatial variation compared to the complexity in the system (i.e. different flooded ecosystems). However, embayment(s)/flooded forest (i.e. RES3 in our study) behaved differently than other sampling stations and had higher CH_4 concentration in the water column. Often such sampling stations have been overlooked. Interestingly, artificial mixing due to structural design (i.e. RES9 in our study) can build up very high surface CH_4 concentrations, and allows CH_4 outgassing and increase CH_4 oxidation via penetrating O_2 to the bottom of the water column. Therefore, it's very important to examine the whole reservoir considering the physical dynamics and pre-flooded ecosystems.

Owing to the large seasonal variation in the CH_4 concentrations, our sampling strategy warns that irregular/interrupted sampling could lead to a misunderstanding and wrong assessment of CH_4 emissions. A recommendation to avoid such errors is that sampling should be performed, at least, for all seasons.

8.1.2. Techniques for assessing CH_4 emissions

In the course of assessing CH_4 emissions from the water surface of the reservoir and their variations at different time scales, multiple approaches and techniques have been investigated. The micrometeorological technique, namely the one based on eddy covariance (EC) calculation was deployed during four field campaigns (between May 2009 and June 2011). Direct field measurement techniques included traditional ones, such as floating chambers (FC) for diffusive fluxes and submerged funnels (SF) for bubbling fluxes were

performed simultaneously. The EC method is a less invasive that was used for one of the first time on sub-tropical hydroelectric reservoir. The two approaches, the EC one on one side, and the FC and SF on the other one, are complimentary. Floating chamber and submerged funnel techniques are reliable and inexpensive, but they need continuous manpower. Their results are representative of small scale, which is interesting to study spatial heterogeneity, though inconvenient to extrapolate the results at a larger scale. On the other hand, EC technique is costly and some caution need to be taken for the deployment, for post-processing data and quality control criteria. First advantage of EC technique is the high spatial coverage it offers. Second, it allows for high temporal resolution and long-term automated monitoring - two factors not easy to reach with other traditional techniques. High frequent and long term measurements are useful to investigate the link between CH_4 emissions and their drivers (see next section). This may increase our understanding of the underlying processes regulating CH_4 fluxes on different time scales. When matching EC footprint with floating chamber and funnel measurements, it was observed that our EC methodology was able to capture both diffusive and bubbling fluxes together. For all the field campaigns, EC fluxes were very consistent with the sum of the two terms measured independently (diffusive fluxes + bubbling fluxes = EC fluxes). From the EC measurements, it was found that there is a clear semidiurnal pattern in the CH_4 emissions. Therefore, one should perform submerged funnel measurement on at least 24 hr time period to cover the entire daily variation, as done in this study. Short time measurement of bubbling can be overestimated or underestimated the CH_4 emissions significantly. Semidiurnal pattern warns that only day time measurement can lead an overestimation of CH_4 emissions.

8.1.3. Environmental drivers of CH_4 flux variability

The continuous and high resolution flux sampling provided by EC allowed us to evidence peak periods of CH_4 emissions on daily and seasonal time scales. It was revealed that atmospheric pressure changes, water depth, and water level changes played a critical role in temporal variability of CH_4 emission. We observed a semidiurnal variation of EC fluxes during all four campaigns. These two peaks per day - one in early morning and one in the afternoon, were clearly linked to the semi-diurnal atmospheric pressure variation (late morning and night pressure drop). Our daily EC CH_4 fluxes were weakly linked with near-surface temperature. This is not surprising since temperature did not affect emissions as strongly on daily/short-term basis as temperature could concern on seasonal basis. As for the seasonal variability, CH_4 fluxes from the reservoir were found to be mostly linked with the changes in the reservoir water level.

A comprehensive dataset allowed us to examine the factors regulating the ebullitive emissions of CH_4. Ebullitive CH_4 emission decreased non-linearly with the depth and atmospheric pressure. Further, it was discovered that ebullitive CH_4 emission was sensitive to changes in the water depth, change in the atmospheric pressure, and bottom temperature. All these factors changing concurrently in an environment such as a hydroelectric reservoir, consequently CH_4 ebullitive emission becomes a non-linear stochastic process. To explore such a process, we chose to develop an artificial neuron network model (ANN) which can

explain up to 50% of the ebullitive fluxes variability using water depth, atmospheric pressure, variations in the water level, atmospheric pressure change and bottom temperature as inputs.

8.1.4. Gross CH_4 emissions

We reported here the first assessment of gross CH_4 emissions from a newly flooded sub-tropical hydroelectric reservoir including all major emission pathways. Total gross emissions from NT2 were found to be lower than emissions reported in previous studies available, mainly conducted in South America. Our result confirms that CH_4 emissions experience a significant seasonal variability (see previous section).

Among the all emission pathways at the NT2 Reservoir, we have first evidenced a dominant contribution from ebullition, proportionally higher when compared to previously studied (sub) tropical reservoirs. We have evidenced a new hotspot of emission by diffusion just before the turbines water intake. Its existence in other reservoirs depends both on the design of the water intake and the physics of the water column upstream of the structure. In reservoirs with well mixed water column, the occurrence of mixing upstream of the turbines should not have impacted, whereas in stratified reservoir with high hypolimnetic CH_4 concentration such in the NT2 during the warm dry season, CH_4 diffusive fluxes could be overlooked if such stations are not included in the monitoring. The design of the water intake together with the design of the water release below the powerhouse (and regulating pond in the NT2 case) leads to a very low contribution of the downstream emissions compared to South American reservoirs.

Around 38% decrease of the emissions from the year 2010 to 2011 is probably because of significant increase in the CH_4 oxidation in the reservoir and thereby low diffusive and degassing emission. Further, higher emissions for the year 2010 resulted from the accumulation of CH_4 before the turbines went on operation in March 2010. The comparison of the contribution of each emission pathway to the total emissions from the NT2 Reservoir with other reservoirs evidences that the estimation of worldwide emission from hydroelectric reservoirs is challenging.

8.2. Carbon dioxide (CO_2)

8.2.1. Techniques for assessing CO_2 emissions

Direct flux measurements of CO_2 fluxes using the eddy covariance (EC) technique were consistent with CO_2 emissions measured with the conventional floating chamber (FC) (based on *in-situ* measurements and gas chromatography as well). This provided a cross-validation of the three methods for assessing diffusive CO_2 emissions. FC appears to be a reliable and inexpensive technique to measure diffusive CO_2 emissions when operated properly. This implies avoiding the creation of artificial turbulence by having FCs with walls extending into the water and performing measurements while drifting. Owing to continuous 30 min integration intervals, the eddy covariance technique allowed to capture all the temporal variability contained in biophysical processes and the linkage with their drivers.

8.2.2. Environmental drivers of CO_2 flux variability

CO_2 flux measurement from different deployments revealed a complex pattern which appears to be mainly a result of the interaction of physical processes in the water column and meteorological processes above the water surface. CO_2 fluxes appeared to be time-dependent over the NT2 Reservoir and changes from one season to another. Our results indicate that owing to the contribution of turbulent velocity scale to the turbulence at the water-air interface, CO_2 fluxes are much higher when $T_{water} > T_{air}$ with thermal and CO_2 gradient in the water column. On the opposite, when the water column exhibits a poor thermal stratification together with no CO_2 gradient, low CO_2 fluxes occur. Our results confirm that during heat gain by the water column (buoyancy > 0), CO_2 fluxes are linearly dependent on wind speed. Whereas, during heat loss from the water column (buoyancy < 0), (1) at low wind speed, fluxes do not show a clear dependency on the wind speed, and (2) at higher wind speed, fluxes increase exponentially with the wind speed.

8.2.3. Gross CO_2 emissions and carbon budget

From the gross CO_2 emissions assessment, it was found that emissions from upstream of the dam (drawdown area and diffusion from the reservoir water surface) contribute around 93% of the total gross CO_2 emissions for the years 2010 and 2011, while only 7% were coming from the downstream area (degassing and diffusion). The annual carbon balance calculation indicated that this reservoir was a significant carbon source to the atmosphere. Import and export carbon balance has revealed that around 85-90% of total annual carbon release (atmosphere + downstream) is fuelled by organic carbon flooded at the bottom of the reservoir during impoundment. Our results suggest that total carbon release within the first two years after impoundment correspond to around 15% of the initial flooded organic carbon in the first 30 cm layer of soils and above-ground biomass.

Our results show that the magnitude of diffusive CO_2 fluxes from the drawdown area varied in the same range as observed at the reservoir water surface, a pathway never investigated in previous CO_2 emissions studies. Considering the strong proportion of the drawdown area to the total reservoir surface, we suggest that this pathway should be accountable for future studies to avoid underestimate in assessing gross CO_2 emission from the hydroelectric reservoirs.

8.3. Nitrous oxide (N_2O) dynamics and gross emissions

We observed the wet season as a hot moment for the N_2O concentration in the reservoir water column. It was found that during the wet season, a significant amount of N_2O was carried in to the reservoir with the high water inflow from the watershed. Further, it seems that during water level rising, flooding of soils could increase the denitrification process in the flooded drawdown soils. Another probable reason could be an enhanced nitrification process during hydrodynamical mixing of NH_4^+-rich hypolimnatic water with oxygenated epilimnetic water.

Further, notably, it was discovered that soils of the drawdown area can be significant hot spot of N_2O emission. Significantly higher fluxes were observed in the mid zone of the drawdown area, this could be due to an enhanced nitrification process during water level falling when NH_4^+-rich anoxic soil are exposed to the air. During the increase in the water level, NO_3^--rich oxic soil becomes anoxic, both conditions that favor denitrification. This suggests that if the drawdown area represents a large portion of the reservoir surface, like in the NT2 case, it can represent a significant proportion (53-67% for the NT2) of the total N_2O emission. This is an important new result, specially keeping in mind that fluxes from the drawdown area have never been considered in previous studies.

8.4. Net GHG footprint

Our study has shown that natural ecosystems pre-existing of flooding were overall a low source of GHG. After flooding, the whole ecosystem has an almost ten times higher GHG footprint. This highlights the importance of understanding the GHG exchanges of the natural landscapes prior to flooding, and the post-impoundment GHG budget when determining the net GHG footprint of a hydroelectric reservoir.

For the two first years after impoundment (2010 and 2011), it was observed that CO_2 and CH_4 emissions contributed mostly to the total gross GHG emissions, 60-73% and 22-35% of the total gross GHG emission for CO_2 and CH_4 respectively. This study clearly indicates that N_2O emissions did not significantly contribute to the gross GHG emissions (~5%). N_2O emissions are probably not an issue in hydroelectric reservoirs with low nitrogen inputs like the NT2 Reservoir. In contrast to results from other large tropical reservoirs, we found that design of the water intake and the physics of the water column upstream of the turbine intake significantly lowered downstream GHG emissions. Indeed, most of the gross GHG emissions in NT2 were attributed to upstream (emissions from drawdown, diffusion from reservoir water surface and bubbling).

With net GHG emissions of 1889 ± 496 and 1854 ± 440 $GgCO_2eq.year^{-1}$, and an annual power generation of 6 TWh, net GHG emission factors of 0.31 and 0.30 Mg-CO_2 $eq.MWh^{-1}$ were calculated for the years 2010 and 2011 respectively. These GHG emission factors represent about one third of the mean emission factor (0.96 Mg-CO_2 $eq.MWh^{-1}$) of thermal power plant using coal (generator types with scrubbing) and generally, is well below the emissions of the power plant running on natural gas and all other current fossil fuel based technologies. If the results were extrapolated to the entire watershed, net emissions from the NT2 would have been even lower. Though NT2 net GHG emission factor is not negligible, it is considerably lower than emission factors for some South American reservoirs. This comes from a combination of higher annual power production and lower net emissions**.**

8.5. Outlook and implications for future GHG emission research

We have identified short and long term causes for temporal changes in CH_4 emissions that should be considered when attempting to predict or estimate CH_4 emissions from a hydroelectric reservoir. Ebullitive CH_4 emission is sensitive to change in the water level and

atmospheric pressure, normally such daily variation as seen at the NT2 are expected to cause large variations in CH_4 emissions; therefore, it appears that they must be taken into consideration when estimating emissions from a hydroelectric reservoir. Water depth and probably also temperature (as a proxy for CH_4 production) vary CH_4 emissions on seasonal or yearly timescale. Here only physical variables have been linked to CH_4 emissions. One should keep in mind that biological activity occurring at the sediment (i.e. decomposition of organic matter in the sediments) is responsible for the CH_4 fluxes observed over a period of reservoir life.

It is very clear from our study that ebullition deserves a lot more attention while assessing CH_4 emissions from hydroelectric reservoirs. We developed an ANN model to quantify the ebullition using water depth, atmospheric pressure, water level change, change in atmospheric pressure and bottom temperature of the reservoir. It would be beneficial to use our model in other (sub) tropical reservoirs to further develop the ANN ability to parameterize CH_4 ebullition in a wider range of conditions. However, in order to quantify the spatial variability in the bubble characteristics and their release in a better way, approaches based on hydroacoustics should be encouraged in such aquatic ecosystem. Measurements coupling submerged funnels and hydroacoustics on one hand, along with floating chambers and EC on the other hand should be tested in the future for intercomparison and cross validation.

A permanent and continuous deployment of eddy covariance and equilibrators would be appreciated to provide continuous discrimination of bubbling and diffusion. Further, it will allow us to examine the hot moments: (1) bubbling burst when total static pressure drops (e.g. water level drop in the warm dry season or sudden atmospheric pressure drop), (2) sudden and large outgassing by diffusion during overturn (e.g., thermal over turn in cold dry season or hydrological mixing in the wet seasons when a large mass of water inters in the reservoir).

We stress that our laboratory experiments aiming at the quantification of CH_4 production did not consider the seasonal changes in the temperature. For this reason, we used constant Q_{10} value for methanogenesis to mimic the seasonal changes in the temperature occurring in the sediment layer at reservoir bottom. We encourage that future work should consider such seasonal variation in temperature since methanogenesis is significantly influenced by temperature.

It is very important to precise identify the processes fuelling the GHG emissions for better prediction of GHG emissions from the reservoir. The internal cycling of C and N either in the water column or in the flooded soils and sediments has to be well understood. Therefore identification of sources of OM using of isotopes and OM tracers would be appreciated in the future works.

We found that the NT2 Reservoir does not exhibit stratification throughout the year. It exhibits an oxic upper layer of the sediment during wet season, leading to CH_4 oxidation in the upper layer of sediment which was not accounted for in this study. For future work, we suggest to consider CH_4 oxidation at the sediments for reservoirs that do not exhibit stratification throughout the year such as NT2.

Further, high frequency continuous monitoring of CO_2 concentration in the whole water column would be appreciated to improve the understanding on CO_2 dynamics in the water column at small time scale. A permanent and continuous deployment of eddy covariance, series of thermocouples and equilibrators which are capable to provide continuous measurements of temperature and GHG concentration at different depths in the water column would be appreciated. It will allow us to examine (1) sudden and large diffusion during overturn (e.g., thermal over turn in cold dry season or hydrological mixing in the wet seasons when a large mass of water inters in the reservoir (2) examine the proportional contribution of convective velocity scale and shear velocity scale to the actual turbulence at the water surface must be included to improve our understanding on buoyancy influence on gas exchange in the tropical hydroelectric reservoirs.

In this study we extrapolated the N_2O fluxes from the whole drawdown area by using soil moisture content, considering moisture content being the main controlling factor of the nitrification and denitrification processes responsible for N_2O emissions. We encourage future studies focusing on linking the other environmental variables in addition to soil moisture content to N_2O emissions and such assumptions should be better checked. This would help to better quantify the contribution of the drawdown area to the total N_2O emission at the reservoir scale.

Further, the comparison of the contribution of each pathway to the total emissions from the NT2 Reservoir with other reservoirs evidences that the estimation of worldwide emission from hydroelectric reservoirs is challenging because of following reasons: (1) is very high proportional contribution of bubbling to the total CH_4 emissions a common phenomenon in young reservoirs or was it overlooked in others studied done in older reservoir? (2) comparison of different emission pathways with other reservoirs suggest that each emission pathways vary significantly from one reservoir to another (3) unfortunately, very few detailed studies (i.e. considering spatial and temporal variability) are available.

For direct comparison of GHG emission factors related to power generation, it would be more relevant to calculate lifecycle GHG emissions of the generating facilities (e.g. 100 years for reservoirs). Literature suggests that these emissions will decline over the next following years (Barros et al., 2011; St. Louis et al., 2000). It is difficult at this point to accurately estimate the trend of the NT2 net GHG footprint over the next 100 years. This shall be the next step to be undertaken.

We estimated the GHG emissions for a newly flooded subtropical reservoir. This estimate corresponds to the period of the life cycle of the hydroelectric reservoir when maximum GHG emissions are expected. While comparing the hydroelectric power with alternative energy sources, these estimates can be considered as the upper values that would be reached for this reservoir. Knowing that GHG emission factors from hydroelectricity vary from one climatic region to another, the calculated GHG emission factor should only be attributed to sub-tropical or tropical reservoir.

There is an urgent demand from the industry, financial institutions and decision makers for reliable predictive tools able to estimate GHG emissions from unmonitored and/or future hydroelectric reservoirs. Development of this kind of tools will rely on comprehensive data set of GHG emission and proxies. This is particularly true for reservoirs from the tropical climatic region. This is even more sensitive for the Asian continent where data are particularly scarce, though this region has the potential of many new hydroelectric projects to come in the future. We hope that the whole data set built all along this three-year study will be used to validate those predictive models. First step could be to test our data set against the predictive tool developed under the UNESCO/IHA umbrella. The UNESCO/IHA predictive tool might not reproduce NT2 emission with the full spatial and temporal resolution acquired during this study, but rather produce a risk indicator (e.g. probable range of emissions with defined thresholds). After the development of the predictive tools, the development of guidance and assessment tools for mitigation should be pursued. Indeed, there is an urgent need to couple process-based model on greenhouse gases (i.e. biogeochemistry) and water quality (i.e. hydrodynamics).