

# Greenhouse Gas Emissions from Hydroelectric Reservoirs: What Knowledge Do We Have and What is Lacking?

Raquel Mendonça<sup>1,2</sup>, Nathan Barros<sup>1</sup>, Luciana O. Vidal<sup>1</sup>,  
Felipe Pacheco<sup>1</sup>, Sarian Kosten<sup>2</sup> and Fábio Roland<sup>1</sup>

<sup>1</sup>Federal University of Juiz de Fora, Federal University of Rio de Janeiro

<sup>2</sup>Wageningen University

<sup>1</sup>Brazil

<sup>2</sup>The Netherlands

## 1. Introduction

*The question that motivated us to write this chapter was “How does hydroelectricity production contribute to the global emissions of greenhouse gases?”. Here, we present an overview of (i) scientific advances on the topic and (ii) aspects of hydroelectric reservoir ecology in the context of greenhouse gas production, consumption and emission.*

Electricity production is a challenging issue when it comes to mitigating greenhouse gases (GHG) emissions without risking development goals. Non-renewable energy sources, as fossil fuel burning, account for most of the global energy production (68% in 2007) and are responsible for most of the anthropogenic GHG emissions to the atmosphere (40%, International Panel on Climate Change - IPCC, 2007). Compared to fossil fuels, hydropower has been considered an attractive renewable energy source with the advantage of being less harmful in terms of GHG emissions (International Energy Agency - IEA, 2008). Hydropower currently provides about 16% of the world's electricity supply (IEA, 2008) with many countries depending on it for more than 90% of their supply. Indeed, hydropower is a proven, mature, predictable and typically price-competitive technology. Moreover, it has among the best conversion efficiencies of all known energy sources: 90% efficiency as opposed to up to 50% efficiency of e.g. fossil fuel burning. The historical perception of hydroelectricity as being GHG neutral (Hoffert et al., 1998), however, is now known to be flawed. The concern regarding the GHG emissions by hydroelectric reservoirs has steeply increased since the early 90's, even though it remains unclear what their actual emission is.

Although inland water systems naturally produce and emit carbon to the atmosphere (Cole et al., 2007) different characteristics of hydroelectric reservoirs cause that they often produce and emit more than natural systems, especially in the first twenty years after flooding (Barros et al., 2011). This is mainly due to the usually excessive availability of decomposable organic matter in hydroelectric reservoirs. Not only large amounts of soil and terrestrial vegetation are flooded by damming rivers, but terrestrial organic matter derived from land erosion is continuously flushed into reservoirs as well. The usually high water residence

time in reservoirs as compared to rivers, combined with high inorganic nutrient inputs, favors organic matter decomposition and, thus, the production of two major GHGs – carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>). The amount of CO<sub>2</sub> and CH<sub>4</sub> emitted varies (a) among reservoirs (as function of drainage basin characteristics, reservoir morphology, climate, etc.); (b) within reservoirs (along longitudinal gradients from the tributaries to the dam, before and after the dam, etc.); and (c) over time (with reservoir aging, seasonally, daily, with changes in anthropogenic activities in the drainage basin, and with dam operation depending on energy needs and precipitation regime). Attempts to estimate the amounts of CO<sub>2</sub> and CH<sub>4</sub> emitted to the atmosphere should consider such variability which makes it a complex task.

Despite the complexity of the GHG issue, the effect of damming rivers on the atmospheric GHG concentrations cannot be disregarded. The concern about the impacts of hydroelectric reservoirs on the global GHG budgets has been increasing in the same pace as the construction of new dams. Nowadays, there are at least 45,000 large hydroelectric reservoirs in operation worldwide (World Commission on Dams –WCD, 2000). Moreover, recent inventories estimate the total surface area of world's hydroelectric reservoirs at about 350,000 km<sup>2</sup> (Barros et al., 2011). The substantial size of some hydroelectric projects and the extensive total surface area globally covered by reservoirs require that research determining the impacts of these systems be done at ever-increasing spatial and temporal scales.

This chapter focuses on the GHG emissions that are due to the landscape transformation (damming a river to form a reservoir) and to reservoir operation to produce electricity. First, the scientific advances towards understanding the role of hydroelectric reservoirs and their environmental effects as sources of GHG are delineated. Then, the metabolic processes involved in GHG production and consumption are described with focus on the two major interacting compartments: the water column and the sediment. Next, the external factors influencing the emission rates from reservoirs are discussed. Finally, an overlook of future perspectives in terms of GHG emissions from hydroelectric reservoirs is presented.

## 2. Important scientific advances

The ever increasing global energy demand and the concern about the changes in environment have lead to an urge to assess the hydropower 'footprint' in terms of GHG emissions to the atmosphere. Since the early 90's the role of hydroelectric reservoirs as sources or, as the opposite, sinks of GHG has rapidly become a global topic of investigation (**Figure 1**). At least 85 globally distributed hydroelectric reservoirs have so far been studied with focus on GHG fluxes (Barros et al., 2011). The first scientific papers focused on reservoirs located in Canada (e.g. Rudd et al., 1993; Duchemin et al., 1995), Brazil (e.g. Rosa & Schaeffer, 1994; Fearnside, 1995, 1997), Panama (Keller & Stallard, 1994) and French Guiana (e.g. Galy-Lacaux et al., 1997; Galy-Lacaux et al., 1999). Later, reservoirs in Finland (e.g. Huttunen et al., 2002), USA (e.g. Soumis et al., 2004), Sweden (e.g. Aberg et al., 2004; Bergstrom et al., 2004) and Switzerland (e.g. Diem et al., 2007) were studied. Only very recently, GHG emissions from reservoirs located in China, the country with the largest installed capacity in the world, became focus of investigation (e.g. Chen et al., 2009; Wang et al., 2011; Zheng et al., 2011) (**Figure 2**).

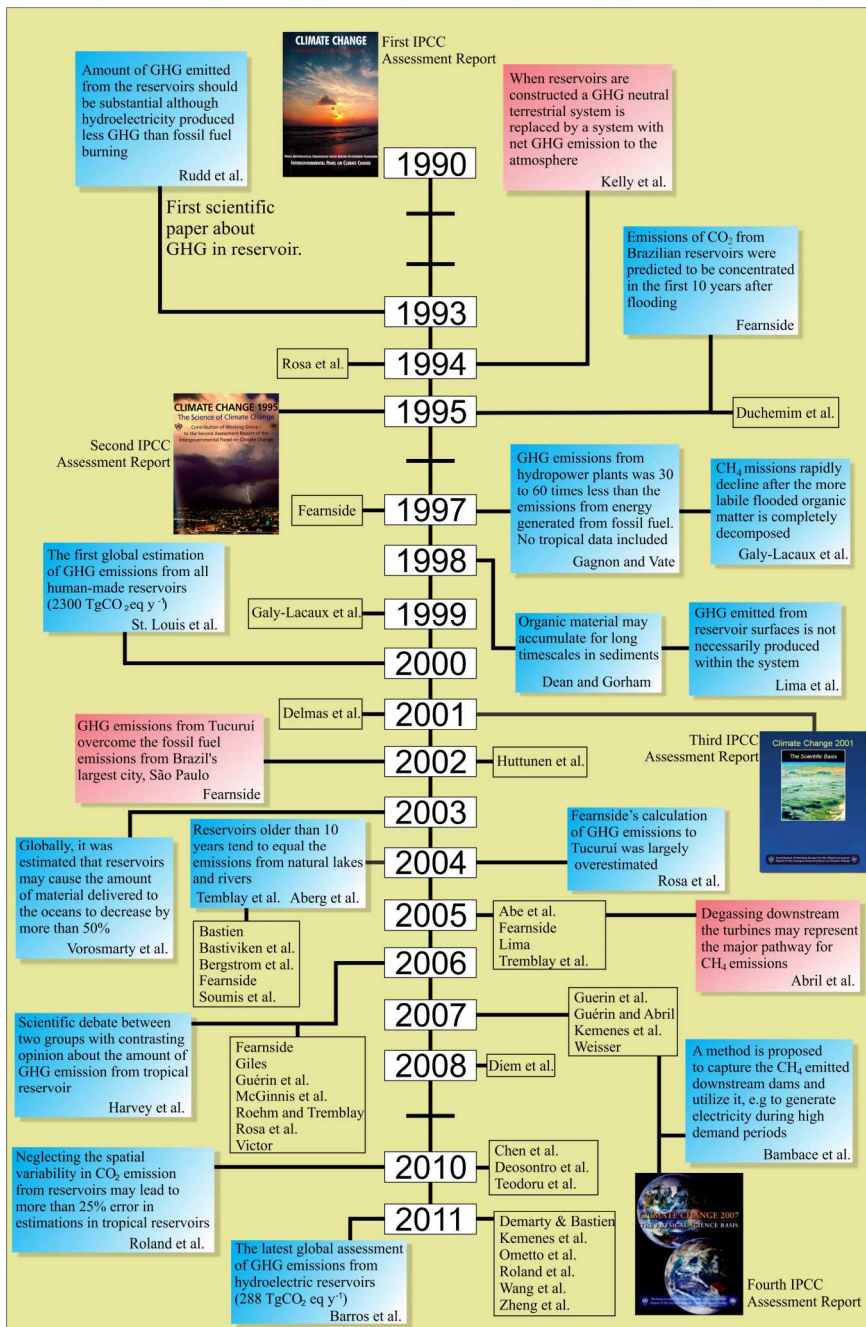


Fig. 1. Timeline of scientific advances regarding the role of hydroelectric reservoirs as sources of GHG to the atmosphere.

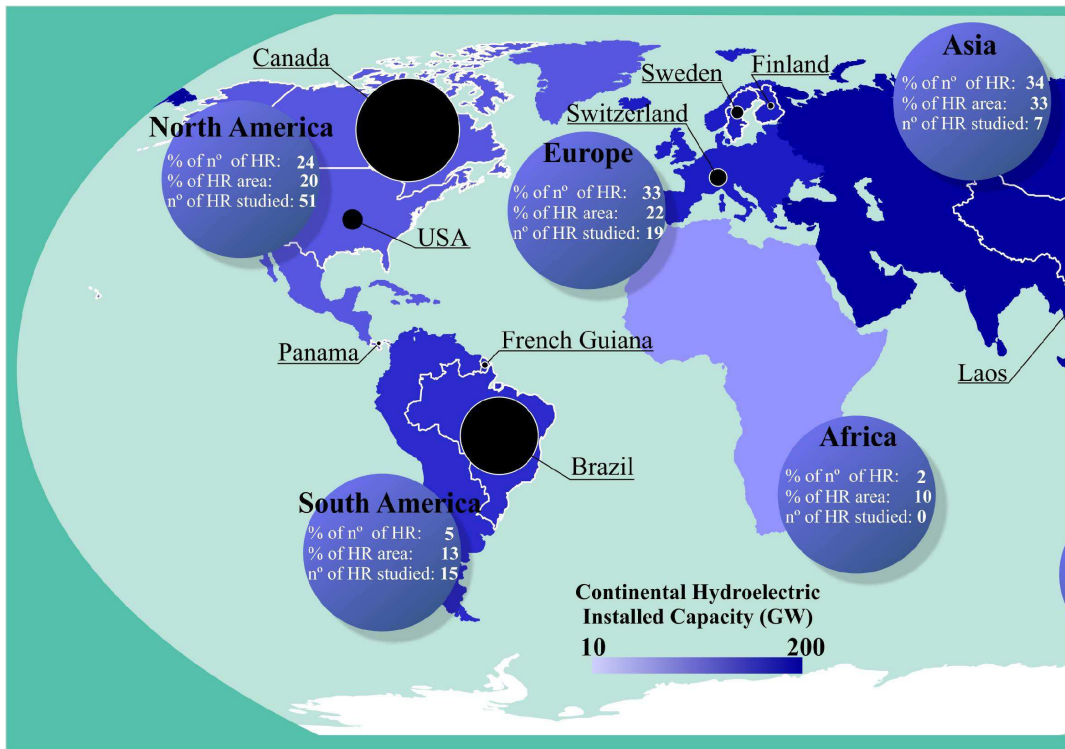


Fig. 2. Global distribution of hydroelectric reservoirs (HR), expressed as the proportion of the total n° constructed on each continent, the proportion of the global HR area on each continent and the number of papers published dealing with GHG emissions from reservoirs located in each country. The blue gradient indicates the hydroelectric installed capacity per continent. The black circles indicate the number of papers published dealing with GHG emissions from reservoirs located in each country. The number and total area of hydroelectric reservoirs were calculated based on ICOLD (2007). The number of papers published dealing with GHG emissions from hydroelectric reservoirs were extracted from Barros et al., 2011, Cerdas et al., 2011, and Zheng et al., 2011.

## 2.1 GHG emissions – hydropower versus other electricity sources

Historically, the question to which extent hydropower is a GHG-friendly source of energy has been an important one. A first study focusing on reservoirs in northern Canada suggested that the amount of GHG emitted from reservoirs was substantial when compared to emissions from fossil fuel burning (Rudd et al., 1993). A subsequent assessment estimated that GHG emissions from hydropower plants (considering their full lifecycle) was 30 to 60 times less than the emissions from energy generated from fossil fuel (Gagnon & Van de Vate, 1997). This assessment, however, did not include data from hydroelectric reservoirs in tropical climates which were later found to have relatively high emissions. Yearly GHG emissions from a large reservoir located in the Brazilian Amazon (Tucuruí reservoir), for example, was argued to overcome the fossil fuel emissions from Brazil's largest city, São Paulo (Fearnside, 2002). Others criticized this finding and considered the reservoir GHG emissions to be largely overestimated (Rosa et al., 2004). This critic triggered a scientific debate between two groups with contrasting opinions (Fearnside, 2004; Rosa et al., 2004; Cullenward & Victor, 2006; Fearnside, 2006; Giles, 2006). Although the groups disagree on the amount of GHG emitted from hydropower in relation to other energy sources, they do agree that GHG emissions from tropical reservoirs are large. Emissions from the Brazilian Curuá-Una reservoir, for instance, were argued to overcome the emissions from oil generated electricity (Fearnside, 2005). Later, Brazilian hydroelectric reservoirs were shown to emit less carbon per energy production than thermonuclear power plants, with the exception of some cases of low power density, i.e. low energy production/flooded area ratio (Dos Santos et al., 2006). Finally, a recent inventory including several Brazilian reservoirs located both in the Amazon and in other biomes showed that the GHG emissions per energy produced (GHG/MWh) are lower in most reservoirs, regardless of their age (Ometto et al., submitted). This inventory showed that the highest GHG/MWh rates occur in large Amazonian reservoirs with low energy production rates.

Overall, hydropower may thus produce electricity with one of the lowest life-cycle GHG emissions (Weisser, 2007), especially in non-tropical regions (Barros et al., 2011). Nevertheless, the important role of hydroelectric reservoirs in the global GHG dynamics is unquestionable.

## 2.2 Organic matter and GHG

The high GHG emissions from hydroelectric reservoirs were originally argued to be due to the decomposition of flooded organic soil and vegetation (Rudd et al., 1993; Abril et al., 2005). This understanding of the role of reservoirs needs to take into account the balance between GHG emissions and consumption prior to and after the impoundment of a certain area (Teodoru et al., 2010). Net GHG emission was considered close to zero prior to impoundment, as emissions from rivers would be compensated by the sink of terrestrial photosynthesis. After flooding, the GHG neutral terrestrial system is replaced by a system with net GHG emissions to the atmosphere (Kelly et al., 1994).

This focus on the flooded organic matter further lead to the understanding that with reservoir aging, the amount of decomposable flooded organic matter would be gradually reduced and, thus, GHG emissions from reservoir surfaces would decline. Indeed, a long-term assessment of GHG emissions from the tropical Petit Saut reservoir showed that CO<sub>2</sub> and CH<sub>4</sub> emissions are high in the first two years after impoundment after which emissions

rapidly decline when the more labile flooded organic matter is decomposed (Galy-Lacaux et al., 1997; Galy-Lacaux et al., 1999). Emissions of CO<sub>2</sub> from Brazilian reservoirs were predicted to be concentrated in the first 10 years after flooding (Fearnside, 1995, 1997). Later, evidence from Canadian systems showed a similar trend and suggested that CO<sub>2</sub> emissions from reservoirs older than 10 years tend to equal the emissions from natural lakes and rivers (Tremblay et al., 2004). Similar results were also reported for a Swedish reservoir which was compared with a natural lake (Aberg et al., 2004). Moreover, a significant negative relationship between age and GHG emissions was registered for temperate reservoirs (St Louis et al., 2000) and for reservoirs located all over the globe (Barros et al., 2011).

Nevertheless, other sources of carbon to reservoirs besides flooded organic matter should be taken into consideration. During their complete lifetime, organic matter and nutrients from the drainage basin are continuously flushed into the systems through tributary rivers (Fearnside, 1995; Roland et al., 2010) and aquatic primary production rates tend to increase (Bayne et al., 1983). Once in the reservoirs, organic matter derived from the drainage basin and from aquatic primary production mineralizes at different rates, the latest being usually more labile (Kritzberg et al., 2005; Vidal et al., 2011). Most of the organic matter mineralization and, thus, most of the GHG production in reservoirs occurs in the sediment (Aberg et al., 2004; Abe et al., 2005). Furthermore, it has become clear that GHG emitted from reservoir surfaces is not necessarily produced within the system, as tributary rivers may export large amounts of GHG to reservoirs (e.g. Lima et al., 1998).

### 2.3 Global emission estimates

From 2004 on, the studies were marked by a more holistic approach incorporating emissions from water passing through the turbines and downstream of dams, as has been done earlier in the tropical Petit Saut reservoir (Galy-Lacaux et al., 1997). Continuous measurements from Petit Saut reservoir lead to a 10-year assessment of GHG emissions which showed that degassing downstream the turbines may represent the major pathway for CH<sub>4</sub> emissions (Abril et al., 2005). High emissions downstream of dams were registered in other tropical (e.g. Guerin et al., 2006; Kemenes et al., 2007, 2011) and in temperate reservoirs as well (e.g. Soumis et al., 2004; Abril et al., 2005; Roehm & Tremblay, 2006). Motivated by the idea of mitigating CH<sub>4</sub> emissions from reservoirs, a method was proposed to capture the CH<sub>4</sub> emitted downstream dams and utilize it, for instance, to generate electricity during high demand periods (Bambace et al., 2007).

More recently, attention has turned to the spatial variability on GHG emissions within reservoirs. Measurements in tropical reservoirs suggested that neglecting the spatial variability in CO<sub>2</sub> emission from reservoirs may lead to more than 25% error in estimations (Roland et al., 2010). In the same year, spatial variability in CO<sub>2</sub> fluxes from temperate reservoirs was shown to decline with time after impounding (Teodoru et al., 2010). The importance of considering the spatial variability in CH<sub>4</sub> emissions was also addressed based on data from Chinese reservoirs (Zheng et al., 2011).

The first global estimation of GHG emissions from reservoirs was published in 2000 (St Louis et al., 2000). This assessment considered emissions from reservoirs of all uses, including irrigation, water supply, energy generation and others. Based on 21 systems located in temperate climate (i.e. Canada, United States, and Finland), the authors calculated

average emissions of  $1400 \text{ mg m}^{-2} \text{ d}^{-1}$  of  $\text{CO}_2$  and  $20 \text{ mg m}^{-2} \text{ d}^{-1}$  of  $\text{CH}_4$ . Their estimated emissions from tropical reservoirs ( $3500 \text{ mg m}^{-2} \text{ d}^{-1}$  of  $\text{CO}_2$  and  $300 \text{ mg m}^{-2} \text{ d}^{-1}$  of  $\text{CH}_4$ ), though, were based on data from a very small number of systems (four) and might have been overestimated due to the inclusion of young reservoirs (1-2 year old) which have high emissions. After estimating the global area occupied by all reservoirs types, the authors calculated the global emissions of GHG to be 273 Tg of  $\text{CO}_2$  and 48 Tg of  $\text{CH}_4$  per year. Considering that  $\text{CH}_4$  global warming potential is 25 times higher than that of  $\text{CO}_2$  (IPCC, 2007), these emissions corresponded to 2,600 Tg of  $\text{CO}_2$ -equivalents per year.

After 2000, there was an important increase in the amount of data on GHG emissions from reservoirs located in both temperate (e.g. Huttunen et al., 2002; Aberg et al., 2004; Bergstrom et al., 2004; Soumis et al., 2004; Tremblay et al., 2004; Duchemin et al., 2006) and tropical regions (e.g. Delmas et al., 2001; Fearnside, 2002; Rosa et al., 2004; Abril et al., 2005; Guerin et al., 2006 ; Guerin et al., 2007). Comparisons between emissions in different regions were applied as tools to understand the factors controlling emissions from reservoirs. For example,  $\text{CO}_2$  emissions from Swedish reservoirs were lower than those reported for other boreal regions, which was attributed to the fact that in Sweden often comparatively small areas with thin layers of organic soil are flooded for reservoir construction (Bergstrom et al., 2004). In 2011 a review of the achievements in 20 years of measurements of  $\text{CH}_4$  emission from tropical and equatorial reservoirs came out (Demarty & Bastien, 2011). The document claims that GHG emissions might have been underestimated in the tropics due to the neglect of  $\text{CH}_4$  emissions.

Finally, the latest global assessment of GHG emissions from hydroelectric reservoirs compiled data from 85 globally distributed systems which account for about 20% of the global area occupied by hydroelectric reservoirs (Barros et al., 2011). The authors estimated that hydroelectric reservoirs globally emit about 51 Tg of carbon per year (48 Tg per year as  $\text{CO}_2$  and 3 Tg per year as  $\text{CH}_4$  or 288 Tg of  $\text{CO}_2$ -equivalents per year) which is low compared to the first global estimation (321 Tg of carbon per year, St Louis et al., 2000). This difference is argued to be caused (i) by the greater amount of data currently available and (ii) by the smaller area occupied by hydroelectric reservoirs ( $350.000 \text{ km}^2$ , Barros et al., 2011) when compared to the area occupied by all types of reservoirs ( $1.500.000 \text{ km}^2$ , St Louis et al., 2000). Furthermore, this latest assessment showed that GHG emissions are correlated to reservoirs age and latitude, with the highest emission rates occurring in the Amazon region.

### **3. Environmental effects of hydroelectric reservoirs and the consequences for GHG emissions**

By definition, hydropower is a renewable source of electricity in which power is derived from the energy of water moving from higher to lower elevations. The amount of energy generated depends both on the accumulated water volume and on the difference in height between the water inlet and the outflow. While dams perform an important function, their effect on landscapes is remarkable: a fragment of river and its adjacent terrestrial environment are transformed in a new freshwater system, the reservoir. According to recent global inventories,  $10,800 \text{ km}^3$  of water were impounded in reservoirs (all kinds of reservoirs, e.g. irrigation, water supply, flood control, and aquaculture) in the last half century, causing the sea level to reduce by approximately 30 millimeters (Chao et al., 2008). The construction of reservoirs clearly represents, thus, one of the major human impacts on the hydrological cycle. The effects of such transformation, however, surpass the hydrological level. Impounded areas undergo a cascade of changes which influence, directly or indirectly, the local GHG fluxes (**Figure 3**).

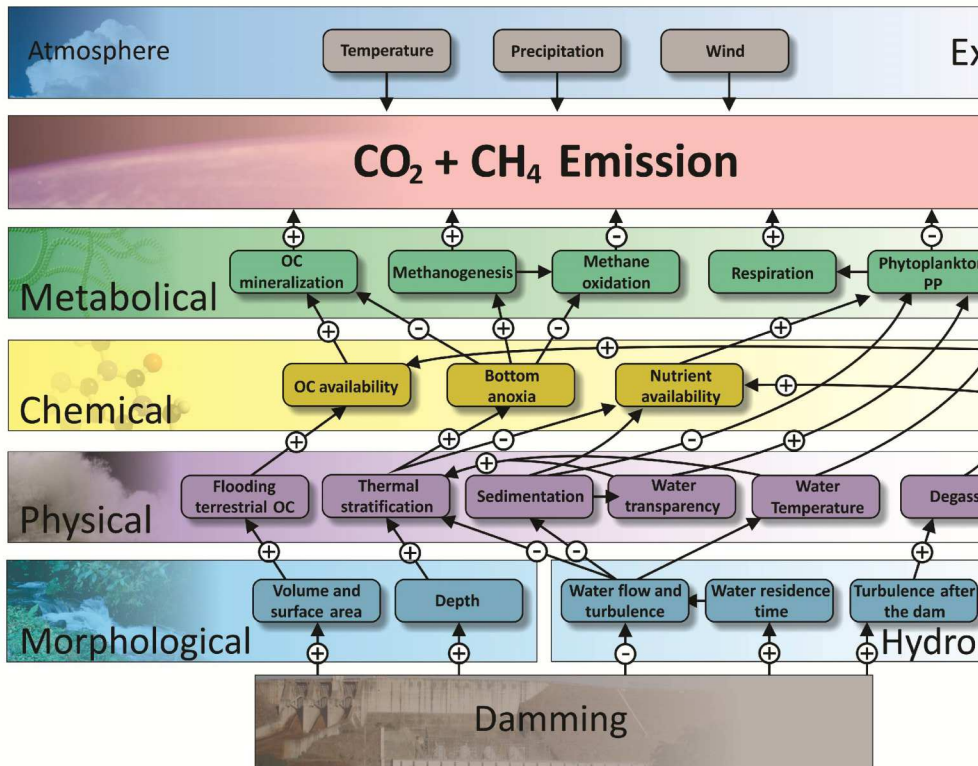


Fig. 3. Diagram illustrating some of the major impacts of damming rivers and their effects on GHG emissions. The hydrological impacts of damming rivers trigger a cascade of shifts in the physical and chemical environment, leading to indirect (through changes in metabolism) and direct changes in GHG fluxes. External factors like atmospheric conditions and drainage basin characteristics also influence GHG emissions. OC = organic carbon; PP = primary production. Arrows with the (+) symbol represent positive effect; arrows with the (-) symbol represent negative effect.



Prior to dam construction, rivers generally have rapid water flow rates which vary with drainage basin size and topography and respond to the seasonality in the upstream precipitation regime. Precipitation regimes also control variations in river water level, which usually varies within a predictable range. Rivers naturally emit large amounts of CO<sub>2</sub> due to terrestrial organic matter decomposition (Cole et al., 2007; Tranvik et al., 2009). Because the turbulent flow keeps oxygen concentrations high, CH<sub>4</sub> emissions hardly occur (Abril et al., 2005) except in highly organic matter-rich rivers (e.g. Lima et al., 1998). In compensation, terrestrial vegetation surrounding a river course usually functions as a CO<sub>2</sub> sink, since photosynthesis tends to exceed respiration. Furthermore, rivers play a crucial role in removing carbon from the global cycle by carrying large amounts of terrestrial material to the ocean (Schlesinger & Melack, 1981) where it is partially permanently buried (Hedges & Keil, 1995; Hedges et al., 1997).

The construction of dams implies the extension of flooded area. This implies that flooded terrestrial vegetation no longer performs photosynthesis. Instead, the organic matter stored in vegetation, as well as in flooded soil, becomes available for bacterial decomposition (with subsequent release of CO<sub>2</sub> and CH<sub>4</sub>). It means that the flooded terrestrial area shifts from being a net sink to a net source of carbon to the atmosphere. The amount of GHG emitted from decomposition of flooded vegetation depends on the size of the flooded area, as well as on the quantity and quality of organic matter.

Moreover, the enlargement of flooded area with reservoirs formation comes with an increase in water volume and causes water residence time (or turnover time) at individual impoundments to increase from less than one day to several years in the case of large dams. The reduction of river water velocity in the headwater of reservoirs results in a decreased sediment-carrying capacity and in the retention of particulate matter transported by rivers. Reservoirs are usually constructed at the lower end of large drainage basins, where rivers usually carry terrestrial material derived from the entire upstream drainage basin. Despite being energetically favourable – it guarantees maximal water inflow and, thus, enhances the potential for energy generation – this strategy implies that high amounts of terrestrial material constantly flow into and accumulate in the reservoirs. Globally, it has been estimated that reservoirs may cause the amount of material delivered to the oceans to decrease by more than 50% (Vorosmarty et al., 2003). Organic matter settled at the bottom of the reservoir has a higher chance to be mineralized than when it would have settled at the ocean bottom (see section 4 for details). As a consequence the net global emission of GHG is enlarged. Nevertheless, it should also be remarked that part of the organic material deposited in the sediment of reservoirs is not mineralized and may accumulate for long timescales (Dean & Gorham, 1998).

Due to the transition from a turbulent-shallow river to a relatively static-deep system, reservoirs tend to undergo thermal stratification, especially in warm regions. The process of thermal stratification is triggered by differences in water density and leads to the formation of water layers: epilimnion (top), metalimnion (intermediate) and hypolimnion (bottom). Once these layers are formed, there is no mixture between top and bottom layers unless some stress (e.g. wind, shift in temperature or increase in water inflow from rivers) breaks water column stability. The establishment of stratification has important effects on oxygen dynamics and, thus, on GHG emissions from reservoirs (see section 4 for details).

#### 4. GHG dynamics in reservoirs – an ecological assessment

The potential of any aquatic system as source or sink of GHG to the atmosphere is ultimately determined by (i) the concentration of GHG dissolved in the water as related to the atmospheric GHG concentration and (ii) the solubility of the gases in the water. The processes of production, consumption and emission of GHG in hydroelectric reservoirs are dependent on their hydrological characteristics, which make of them especial sites in terms of GHG dynamics when compared to other aquatic systems.

##### 4.1 Water column and sediment

Most of the routes of production and consumption of  $\text{CO}_2$  and  $\text{CH}_4$  are controlled by the aquatic biota metabolism (**Figure 4**). In a nutshell: aerobic respiration produces  $\text{CO}_2$  which is consumed through photosynthesis; methanogenic bacteria produce  $\text{CH}_4$  which is consumed by methanotrophic bacteria. An exception to the general pattern of biota mediating  $\text{CO}_2$  production is the process of photo-oxidation, i.e. the break-down of dissolved organic molecules by solar radiation with the production of several compounds among which  $\text{CO}_2$  is the more abundant (Soumis et al., 2007; Bastien, 2005). Production and consumption of GHG within reservoirs, however, are not the only processes controlling GHG stocks in the water column. Tributary rivers flowing into reservoirs may carry variable amounts of GHG

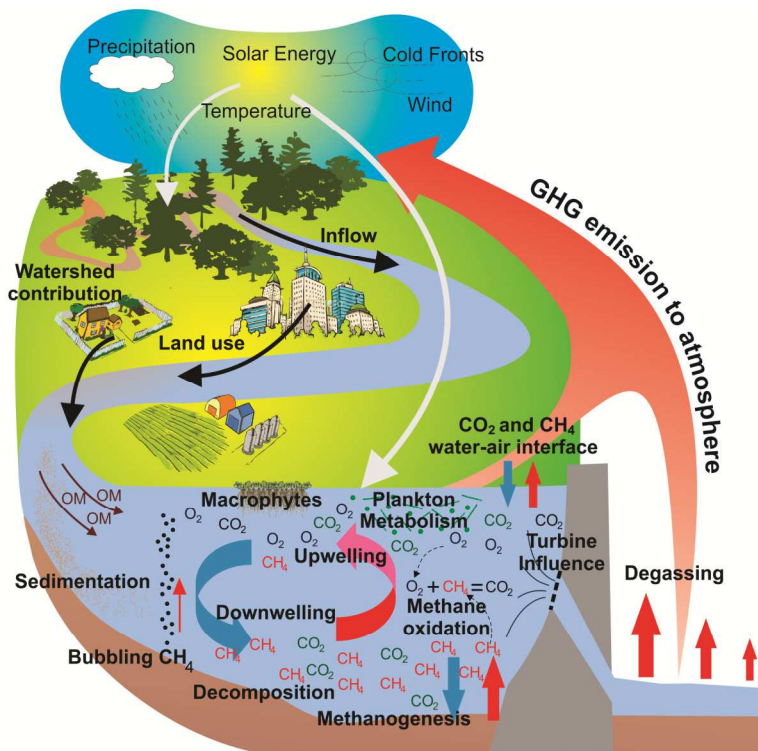


Fig. 4. Main pathways of GHG production, consumption and emission to the atmosphere.

(mostly CO<sub>2</sub> but also CH<sub>4</sub>). Moreover, dissolved CO<sub>2</sub> can flow into reservoirs from both surface and groundwater runoff.

A global assessment of lakes with a worldwide distribution showed that most of the lakes in the world are net sources of CO<sub>2</sub> to the atmosphere (Cole et al., 1994; Sobek et al., 2005). The frequently high CO<sub>2</sub> concentrations are argued to rely on the high influx of organic matter and the consequent excess respiration by heterotrophic bacteria. The high availability of terrestrial organic matter in hydroelectric reservoirs causes particularly high heterotrophic respiration in these systems. Especially in young reservoirs where the availability of decomposable organic matter is high, the respiration by aerobic planktonic bacteria is elevated (Roland et al., 2011).

Mineralization may also occur anaerobically in the water column of stratified reservoirs (Abril et al., 2005). With the establishment of stratification, the oxygen consumption due to organic matter mineralization in the bottom layers of reservoirs is no longer offset by water exchange with top oxygenated water layers (see section 3 for details). Thus, bottom water layers become gradually anoxic. Under anoxic conditions, methanogenic bacteria metabolize organic compounds, hydrogen and CO<sub>2</sub> into CH<sub>4</sub> (methanogenesis), leading to high CH<sub>4</sub> concentrations in the bottom layer of reservoirs (Abril et al., 2005). Due to the persistent stratification of reservoirs located in warmer regions, methanogenesis is usually an important pathway of GHG production in those systems (Demarty & Bastien, 2011). However, most of the CH<sub>4</sub> produced in the water column of reservoirs tend to be emitted to the atmosphere as CO<sub>2</sub> due to the oxidation by methanotrophic bacteria at the top oxygenated water layer (Guerin & Abril, 2007).

The overall GHG production in the water column of reservoirs is small compared to the production in the sediments. Great amounts of particulate organic matter transported through rivers tend to sedimentate in reservoirs. Sedimentation is also the fate of organic matter produced by algal photosynthesis in the water column. Once in the sediment, organic matter (i) is mineralized by aerobic or anaerobic bacteria and released as CO<sub>2</sub> and CH<sub>4</sub> (among other compounds) to the water column, (ii) is re-suspended, or (iii) remains buried. The relative importance of each of these processes is system-specific and influences the overall role of a reservoir as net sink or source of GHG to the atmosphere.

Mineralization leads to a general chemical-metabolic gradient within undisturbed sediment profiles. Aerobic mineralization is restricted to the top sediment layer, which may have variable thicknesses depending (i) on the hypolimnetic oxygen concentration, (ii) on the oxygen diffusion coefficient, which is a function of sediment density, sediment porosity, temperature and turbulence at the sediment-water interface and (iii) on the rate of oxygen consumption during organic matter mineralization. Below this top oxygenated sediment layer, anaerobic processes dominate sediment metabolism. While CO<sub>2</sub> is the only GHG gas produced as a result of aerobic decomposition, anaerobic processes produce CH<sub>4</sub> in addition to CO<sub>2</sub>. These gases accumulate in sediment pore-water and tend to be released in the water column as a consequence of the difference between concentrations in these two compartments.

Diffusive CH<sub>4</sub> tends to be oxidized into CO<sub>2</sub> by methanotrophic bacteria at the oxygenated top sediment layer or in the water column. The extent of CH<sub>4</sub> oxidation in the water column depends on oxygen availability and, thus, may be higher in deeper reservoirs (Lima, 2005).

It has been shown, e.g., that oxidation in the water column of Petit Saut reservoir can reduce CH<sub>4</sub> emissions at more than 85% (Guerin & Abril, 2007). However, in very organic-rich sediments, the high rates of mineralization combined with the hydrophobic characteristic of CH<sub>4</sub> molecule, can cause CH<sub>4</sub> to form bubbles which tend to be quickly emitted to the atmosphere (Bastviken et al., 2004; McGinnis et al., 2006). Even though the formation of CH<sub>4</sub> bubbles is favoured by high temperatures, temperate reservoirs may also emit significant amounts of CH<sub>4</sub> through bubbling (e.g. Delsontro et al., 2010).

Both aerobic and anaerobic mineralization of organic matter release large amounts of inorganic nutrients, in addition to CO<sub>2</sub> and CH<sub>4</sub>, in the water column of reservoirs. The availability of inorganic nutrients, especially phosphorus, combined to the usually high light penetration depth in reservoirs (due to sedimentation of suspended material) favours CO<sub>2</sub> uptake by photosynthesis. Photosynthesis in reservoirs, as in any other aquatic system, is performed by phytoplankton in the water column, attached algae (periphyton) and aquatic plants (macrophytes). However, due to the usually high depth (and high 'total volume/littoral volume' ratio) of reservoirs, the relative importance of periphyton and macrophyte tends to be low compared to the importance of phytoplankton. In eutrophic reservoirs (i.e. high nutrient concentrations and high phytoplankton production) photosynthesis can cause a strong reduction in CO<sub>2</sub> concentrations turning the reservoirs into a sink of atmospheric CO<sub>2</sub>. This occurs in reservoirs worldwide, regardless of age or latitude (Barros et al., 2011). The number of reservoirs acting as carbon sinks is, however, low as compared to CO<sub>2</sub> emitting reservoirs.

#### 4.2 GHG flux through the water-atmosphere interface

The excess GHG in the water column of reservoirs tend to be emitted to the atmosphere. Emissions can occur through (i) molecular diffusion at the water-air interface (e.g. Roland et al., 2010; Teodoru et al., 2010), (ii) bubbling from the sediment (e.g. Abe et al., 2005; Lima, 2005) (iii) degassing from water passing at the turbines (e.g. Kemenes et al., 2007, 2011) or (iv) turbulent degassing in downstream rivers (e.g. Guerin et al., 2006) (**Figure 4**).

Diffusive fluxes of CO<sub>2</sub> and CH<sub>4</sub> at the water-atmosphere interface are dependent on the existence of a concentration gradient between these two compartments. If the water at the surface of a reservoir is supersaturated with CO<sub>2</sub> or CH<sub>4</sub> in relation to the atmosphere, gas fluxes occur towards the atmosphere. If, on the other side, surface water is under-saturated in relation to the atmosphere, gas fluxes are from the atmosphere to the water. In the latter case, the reservoir surface represents a sink of atmospheric carbon. The amount of GHG flowing through water-atmosphere interfaces depends on gas solubility in water. Gas solubility is negatively related to temperature and positively related to pressure, according to Le Chatalier's principle. Thus, GHG emissions through diffusion tend to be higher in reservoirs located in warmer regions and at lower altitudes. The surfaces of reservoirs are usually dominated by diffusive fluxes of CO<sub>2</sub>, even in cases in which bottom anoxia leads to high CH<sub>4</sub> production (Barros et al., 2011). This is due to the intense oxidation of diffusive CH<sub>4</sub> by methanotrophic bacteria above the interface between anoxic and oxygenated water layers.

On the other hand, GHG emissions through bubbling are dominated by CH<sub>4</sub>. This is due to the very low CH<sub>4</sub> solubility in water, which permits the formation of bubbles varying in size

from 2 to 8 millimetres (Delsontro et al., 2010). The bubbles are usually formed in the sediment of reservoirs, under anoxic conditions. Most of the CH<sub>4</sub> emissions in shallow reservoirs occur through bubbling whereas CH<sub>4</sub> bubbles are usually dissolved in the water before reaching the surface in deep reservoirs.

The process of energy generation by the turbines of hydroelectric reservoirs leads to two pathways of GHG emission that do not occur in artificial reservoirs built for other purposes (e.g. irrigation, water supply, flood control, and aquaculture): turbulent degassing of water passing through turbines (energy generation unities) and degassing downstream of dams. The water inlet to generate energy is frequently located in medium or lower parts of the dam which means that water from deep layers of the reservoirs passes through the turbines. These deep water layers are usually CO<sub>2</sub> and CH<sub>4</sub>-rich due to both high mineralization rates and high water pressure (i.e. high gas solubility). By passing through the turbines, the gases are exposed to a low pressure and high temperature condition which favors rapid emissions to the atmosphere (Kemenes et al., 2007). Despite the usually high GHG emissions at the turbines, high amounts of both CO<sub>2</sub> and CH<sub>4</sub> remain dissolved in the water downstream the dams. GHG produced in reservoirs may be encountered at sites as far as 40 km downstream of the dam (Guerin et al., 2006).

## 5. External factors affecting the processes driving GHG emissions to the atmosphere

The great variation in GHG emissions from hydroelectric reservoirs in different parts of the globe is explained by the effect of climate and drainage basin characteristics on GHG dynamics. Climate affects the inputs of carbon from land to the aquatic environment and the rates of GHG production and consumption. Moreover, wind, precipitation and temperature may have important effects on the rates of gas exchange in the water-atmosphere interface. This section brings an overview of some important processes and external factors influencing GHG emissions from freshwater systems with focus on the dynamics of hydroelectric reservoirs.

### 5.1 Wind

Wind is the major source of energy for water movement in lakes and reservoir. The wind stress at the water surface can result in small turbulence, horizontal currents, vertical currents, surface waves and internal waves (seiches). Where and how those processes will emerge and behave depends on a series of factors such as the size and the shape of water surface, fetch, wind direction, temperature, and surrounding terrain. The response of reservoirs to wind stress depends mainly on the morphometric characteristics of the basin and its location. Reservoirs are typically built in valleys, after confluence of several tributaries. It usually results in long and dendritic water bodies (Ford, 1990), contrasting to the generally circular- or bowl-shaped natural lakes. Therefore, depending on the surrounding terrain, wind can blow aligned with the main-long fetch, increasing its effect over water surfaces. This effect, however, is limited by the dendritic geometry of reservoir, resulting in more complex circulation patterns in certain parts of reservoirs.

Wind effect strongly impacts on GHG emissions. Turbulence, for example, influences the velocity of gas transfer at the water-atmosphere interface (Wanninkhof, 1992). The role of

wind on GHG emissions, however, is not restricted to causing surface turbulence. Wind can also cause deep water circulation and transport of dissolved compounds.

The overall picture that emerges is that reservoirs are highly temperature stratified in summer and only weakly forced by wind, while in spring/winter the mixing process is enhanced by high wind velocity. During high velocity wind events surface water moves toward the shore, where the water piles up and sinks in the process known as downwelling. At the same time at the opposite side, surface water is replaced by water that wells up from below (upwelling) (Monismith, 1985; Stevens & Imberger, 1996; Macintyre et al., 2002; Farrow & Stevens, 2003). However, wind direction and persistency are of great importance as well. Persistent wind aligned with the main reservoir body – resulting in a large fetch – is able to promote downwelling/upwelling (d/u) even at low velocities (Assireu et al., 2011). At the downwelling side of a reservoir, CH<sub>4</sub> oxidation plays an important role, changing CH<sub>4</sub> into CO<sub>2</sub> during the downward dissolved oxygen transport and reducing the CH<sub>4</sub> emission to the atmosphere. At the upwelling side of reservoir, the GHG flux to the atmosphere is enhanced due to the high CO<sub>2</sub> and CH<sub>4</sub> concentrations of emerging water. This clearly influences the spatial variability of GHG emissions within reservoirs (Roland et al., 2010). It was suggested that frequent d/u events in the tropical Manso reservoir could enhance CO<sub>2</sub> emissions with approximately 12% (Assireu et al., 2005; Ometto et al., 2011).

## 5.2 Precipitation

Precipitation can vary markedly in intensity and frequency from one year to another. Such variability can generate different kinds of seasonal patterns, modifying water turnover time and changing the intensity of environmental processes occurring in the water column of aquatic systems (Armengol et al. 1999). Furthermore, the external loading of organic matter and other compounds to the system often increases with intensive precipitation events. The intensity of these loadings depends on land use, vegetation cover and landscape patchiness (Rybak, 2001). Rain-induced high primary productivity has been observed in some African lakes (Lemoalle, 1975; Melack, 1979; Thomas et al., 2000). In tropical regions, the first rains after the start of the rainy season are expected to a lot of carbon into the reservoir that can be assimilated by bacterioplankton or be buried in the sediment. However, if the residence time of the water is very short, with high flushing rate, most of this carbon and nutrients will not remain long in the system (Amarasinghe & Vijverberg, 2002).

Precipitation also affects CO<sub>2</sub> transfer at the air-water interface. Impinging raindrops causes turbulence, enhancing CO<sub>2</sub> flux across the air-water interface (Takagaki & Komori, 2007). This means that, depending on the difference of gas concentrations between water and atmosphere, the emission/absorption of GHG in aquatic systems can be enhanced by increasing precipitation rates. The rainfall effects can be significant to the local CO<sub>2</sub> budget between water and atmosphere during the rainy season but are not as important to the whole system budget as the wind share effect.

## 5.3 Temperature

Changes in temperature may affect, directly and indirectly, all processes involved in the production, consumption and emission of GHG in reservoirs. For example, respiration

(Sand-Jensen et al., 2007), primary production in the water column (Flanagan et al., 2003) are strongly influenced by temperature. Although both processes tend to increase with warming, it has been argued that respiration has usually a stronger response (Rivkin & Legendre, 2001; Biddanda & Cotner, 2002; Lopez-Urrutia et al., 2006; Sand-Jensen et al., 2007), leading to a net increase in CO<sub>2</sub> production under warmer conditions (Kosten et al. 2010). Moreover, evidences from lakes located in different climate regions have shown that more mineralization occurs (with further CO<sub>2</sub> and CH<sub>4</sub> production) and less carbon is buried in the sediment of warmer systems (Gudasz et al., 2010).

Indeed, GHG emissions are higher in reservoirs located in warmer latitudes (Barros et al., 2011). The positive relationship between GHG emissions and temperature implies that environmental changes causing temperature to vary affects the role of hydroelectric reservoirs as GHG sources. Based on the predicted scenarios of global change in temperature (IPCC, 2007) GHG emissions from reservoir will increase, especially in cold regions.

#### 5.4 Drainage basin and river input

Large impoundments may show different zones in terms of CO<sub>2</sub> emission because those fluxes are dependent on flooded biomass and watershed input of organic matter. Compared to natural lakes, reservoirs tend to have shorter water residence times and more complex heterogeneity due to the presence of one or more major water inlets, instead of multiple diffuse water sources characteristic for most natural lakes (Kennedy et al., 1985; Kennedy & Walker, 1990). Reservoirs are intrinsically linked to the rivers that feed them (Baxter, 1977), creating a river-reservoir continuum, in which water and sediment inputs are functions of the land use in the watershed (Kelly, 2001). Watershed land use is often highly correlated with algal cell and nutrients concentrations as has been shown for seven subtropical reservoirs (Burford et al., 2007). This clearly indicates that in order to understand and predict GHG emissions from reservoirs, features of the drainage basin have to be taken into account.

Another important factor to be considered is the difference between the densities of river and reservoir water. When a river reaches a reservoir the water plunges and can flow along the surface (overflow), intermediate (interflow) or deep (underflow) layer, depending on the difference between the water temperature and physical characteristics (e.g. total dissolved solids and suspended solids) (Martin & McCutcheon, 1999). The fate of organic matter influx largely depends on the way the incoming water flows into the reservoirs. If incorporated into deeper layers, anoxic conditions facilitate degradation of organic matter into CH<sub>4</sub>. The picture becomes more complicated when, due to the complexity of the system and hydrodynamic factors of the river entrance, waves arise in the interface between river/reservoir water. These waves cause transport of water from the nutrient-rich and GHG-rich deep layer to the surface layer (Assireu et al., 2011).

### 6. Future perspectives

It is now clear that hydroelectric reservoirs represent a renewable but not a carbon-free source of electricity. Attempts to determine the carbon footprint of hydropower production have led to significant scientific advances (see section 2 for details). However, it is still a

long way towards a full assessment of the role of hydroelectric reservoirs as sources of GHG to the atmosphere. The major gaps to be filled by future research are related to the quality of current carbon budget estimations. However, other issues need attention, e.g. the outcomes of removal of dams and the development of mitigation strategies.

The assessment of the net role of reservoirs as sinks or sources of GHG to the atmosphere requires more than measurements of carbon fluxes at the water-atmosphere interface of reservoirs. For example, the net change in the carbon cycle due to reservoir construction should consider pre-impoundment carbon sinks and sources from the original river course and the adjacent terrestrial landscape (Teodoru et al., 2010). Scenarios of pre- and post-impoundment fluxes, however, are neglected by most estimates of emissions. Even more importantly, there is a need to evaluate the net effect of reservoir as sink of atmospheric carbon (St Louis et al., 2000; Barros et al., 2011), by comparing carbon burial in reservoirs with carbon burial prior to impoundment (i.e. in the ocean).

The role of reservoirs sediment in the global carbon cycle is still poorly understood. Despite the importance of sediment as the main site for organic matter mineralization and GHG production (especially CH<sub>4</sub>) sediment carbon fluxes in reservoirs are restricted to few measurements (e.g. Aberg et al., 2004; Abe et al., 2005). Additionally, reservoirs accumulate large amounts of carbon in the sediment, which compensates at least part of the emissions. It has been estimated that approximately 400 gC m<sup>-2</sup> y<sup>-1</sup> is buried in reservoirs (Dean & Gorham, 1998; Mulholland et al., 2001). This estimation, however, is based on non-standardized methods which consider, e.g. loss in water storage capacity of reservoirs in the USA and constant values for carbon content and sediment density. There is an urgent need, thus, for research focusing on this potential carbon sink pathway.

Another important source of errors in carbon budgets relies on neglecting variability. Both the neglected variability among and within reservoirs as well as variability over time impacts the precision of carbon flux estimates. The persistent increase in the amount of data, by itself, may contribute to equal out the errors of local and global estimations. Nevertheless, addressing all possible sources of variability is an important task for future research on GHG emissions from reservoirs.

Regarding the variability among reservoirs, the limited amount of data from reservoirs located in the tropics was, until recently, severely limiting the precision of GHG emission estimations from reservoirs (e.g. St Louis et al., 2000). Within the last decade, many tropical reservoirs have become focus of study, permitting a better evaluation of the latitudinal effect on emissions (Barros et al., 2011). Nevertheless, there is still a great need for research in the tropics, since this is where most of the potential for new dams remains (Figure 2). Future research on tropical reservoirs should seek for better estimations of CH<sub>4</sub> emissions, which seems to have been seriously underestimated in the last two decades (Demarty & Bastien, 2011; Wehrli, 2011) in spite of its greater warming potential (more than 20 times more) when compared to CO<sub>2</sub>.

Neglecting variability in GHG emissions over time may equally cause great errors in estimations. Especially because GHG emissions reduce as reservoirs age (Barros et al., 2011). Furthermore, fluctuations in carbon cycling may occur on a seasonal (Wang et al., 2011) and even on a daily basis (Roland et al., 2010). The changes in GHG emission rates with time makes the full assessment of the carbon budget in a reservoir is a difficult task. Future studies



of GHG emissions from reservoirs should, thus, seek for a better understanding of the patterns of variation on GHG dynamics with time. Both long-term measurements (including several years) and intensive measurements (in a more frequent basis, e.g. hours) are needed.

Overcoming the issues related to variability of GHG emission in space and time becomes even more challenging due to extreme events (e.g. upwelling). Such events which are very hard to 'catch' may account to a major portion of the GHG emissions from a reservoir (Roland et al., 2010).

Most of the GHG assessments in hydroelectric reservoirs have looked at emissions from decaying biomass after impoundment, as related to the previous emissions (see section 2 for details). Some studies have used a full life-cycle assessment, which considers the emissions during the construction phase of dams (e.g. Chamberland & Levesque, 1996; Gagnon & Van de Vate, 1997; Pacca & Horvath, 2002). However, little attention has been given to the fact that every hydropower plant has an intrinsic operation life-time after which its dam should be deactivated (Pacca, 2007). Moreover, dams may be deactivated and removed due to failures (e.g. error during construction, geological instability, poor maintenance, excess internal erosion etc.). It has been estimated that about 600 dams were removed in the last 100 years in the USA alone (Gleick et al., 2009). The removal of dams was the subject of a special issue published by Bioscience in 2002 which did not mention the effects on GHG emission.

With dam removal, part of the sediment accumulated at the reservoirs will be flushed down river if not otherwise controlled (e.g. dredged). Sediment fate is an important factor determining the amount of carbon returning to the atmosphere – a greater fraction of dredged sediment becomes available for mineralization whereas organic carbon flushing downstream rivers may ultimately accumulate the ocean (Pacca, 2007). Despite the many uncertainties regarding the effects of dam removal, it is now clear that this issue should not be disregarded by future assessments. Answering questions as “how permanent is carbon accumulation in the sediment of reservoirs?” is mandatory to a better understanding of reservoirs' role in the global carbon cycle.

With the continuous and integrated research focusing on revealing the actual role of hydroelectric reservoirs in the global carbon cycle, the gaps in knowledge tend to be reduced at a rapid pace. Recent advances have resulted in important tools for reducing GHG emissions from reservoirs through changes in reservoir management and, even more importantly, through the GHG-intelligent design and location of new hydropower plants. It is now known, for example, that future hydropower projects should seek for better GHG emission/MWh ratios by reducing flooded area to the maximum extent, removing terrestrial vegetation prior to impounding and preserving the vegetation in the drainage basin to avoid soil erosion. The research about hydroelectric projects has been promoting a new generation of scientist that are able to apply fundamental environment sciences – ecology, biology, chemistry, physics and mathematics – to issues representing global concerns. We believe that the scientific community is strongly prepared to discuss the needs for energy and environmental wellness in the future.

## 7. References

Abe, D.S.; Donald D. Adams; Galli, C.V.S.; Sikar, E. & Tundisi, J.G. (2005). Sediment greenhouse gases (methane and carbon dioxide) in the Lobo-Broa Reservoir, São

- Paulo State, Brazil: Concentrations and diffuse emission fluxes for carbon budget considerations. *Lakes & Reservoirs: Research and Management*, Vol.10. No.4, pp. 201-209, 1440-1770
- Aberg, J.; Bergstrom, A.K.; Algesten, G.; Soderback, K. & Jansson, M. (2004). A comparison of the carbon balances of a natural lake (L. Ortrasket) and a hydroelectric reservoir (L. Skinnmuddselet) in northern Sweden. *Water Research*, Vol.38. No.3, Feb, pp. 531-538, 0043-1354
- Abril, G.; Guerin, F.; Richard, S.; Delmas, R.; Galy-Lacaux, C.; Gosse, P.; Tremblay, A.; Varfalvy, L.; Dos Santos, M.A. & Matvienko, B. (2005). Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). *Global Biogeochemical Cycles*, Vol.19. No.4, Oct, 0886-6236
- Amarasinghe, P.B. & Vijverberg, J. (2002). Primary production in a tropical reservoir in Sri Lanka. *Hydrobiologia*, Vol.487. No.1, Nov, pp. 85-93, 0018-8158
- Armengol, J.; Garcia, J.C.; Comerma, M.; Romero, M.; Dolz, J.; Roura, M.; Han, B.H.; Vidal, A. & Simek, K. (1999). Longitudinal processes in canyon type reservoir: the case of Sau (N.E. SPAIN), pp. 313-345. In: *Theoretical reservoir ecology and its applications*, Tundisi, J.G. & Straskraba, M. (eds.), Brazilian Academy of Sciences and Backhuys Publishers, 585p. ISBN 85-87418-02-5, Barcelona
- Assireu, A.T.; Alcântara, E.; Novo, E.M.L.M.; Roland, F.; Pacheco, F.S.; Stech, J.L. & Lorenzetti, J.A. (2011). Inside the hydro-physics processes at the plunge point location: an analysis by satellite and in situ data. *Hydrol. Earth Syst. Sci. Discuss.*, Vol.8. pp. 1-31
- Assireu, A.T.; Stech, J.L.; Marinho, M.M.; Cesar, D.E.; Lorenzetti, J.A.; Ferreira, R.M.; Pacheco, F.S. & Roland, F. (2005). Princípios Físicos e Químicos a Serviço da Limnologia - Um Exercício. In: *Lições de Limnologia.*, Rima Editora, ISBN: 8576560593, São Carlos
- Bambace, L.A.W.; Ramos, F.M.; Lima, I.B.T. & Rosa, R.R. (2007). Mitigation and recovery of methane emissions from tropical hydroelectric dams. *Energy*, Vol.32. No.6, Jun, pp. 1038-1046, 0360-5442
- Barros, N.; Cole, J.J.; Tranvik, L.J.; Prairie, Y.T.; Bastviken, D.; Huszar, V.L.M.; Del Giorgio, P. & Roland, F. (2011). Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nature Geoscience*, Vol.4. No.9, Sep, pp. 593-596, 1752-0894
- Bastien, J. (2005). Impacts of ultraviolet radiation on aquatic ecosystems: greenhouse gas emissions and implications for hydroelectric reservoirs. In: *Greenhouse Gas Emissions - Fluxes and Process. Hydroelectric Reservoirs and Natural Environments*, Tremblay, A., Varfalvy, L., Roehm, C. & Garneau, M., 509-527, Springer-Verlag, ISBN 978-3-540-23455-5, New York
- Bastviken, D.; Cole, J.; Pace, M. & Tranvik, L. (2004). Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate. *Global Biogeochemical Cycles*, Vol.18. No.4, Oct 20, 0886-6236
- Baxter, R.M. (1977). Environmental Effects of Dams and Impoundments. *Annual Review of Ecology and Systematics*, Vol.8. pp. 255-283, 0066-4162
- Bayne, D.R.; Lawrence, J.M. & McGuire, J.A. (1983). Primary productivity studies during early years of West-Point reservoir, Alabama Georgia. *Freshwater Biology*, Vol.13. No.5, pp. 477-489, 0046-5070
- Bergstrom, A.K.; Algesten, G.; Sobek, S.; Tranvik, L. & Jansson, M. (2004). Emission of CO<sub>2</sub> from hydroelectric reservoirs in northern Sweden. *Archiv Fur Hydrobiologie*, Vol.159. No.1, Jan, pp. 25-42, 0003-9136

- Biddanda, B.A. & Cotner, J.B. (2002). Love handles in aquatic ecosystems: The role of dissolved organic carbon drawdown, resuspended sediments, and terrigenous inputs in the carbon balance of Lake Michigan. *Ecosystems*, Vol.5. No.5, Aug, pp. 431-445, 1432-9840
- Burford, M.A.; Johnson, S.A.; Cook, A.J.; Packer, T.V.; Taylor, B.M. & Townsley, E.R. (2007). Correlations between watershed and reservoir characteristics, and algal blooms in subtropical reservoirs. *Water Research*, Vol.41. No.18, Oct, pp. 4105-4114, 0043-1354
- Chamberland, A. & Levesque, S. (1996). Hydroelectricity, an option to reduce greenhouse gas emissions from thermal power plants. *Energy Conversion and Management*, Vol.37. No.6-8, Jun-Aug, pp. 885-890, 0196-8904
- Chanudet, V.; Descloux, S.; Harby, A.; Sundt, H.; Hansen, B.H.; Brakstad, O.; Serça, D. & Guerin, F. (2011). Gross CO<sub>2</sub> and CH<sub>4</sub> emissions from the Nam Ngum and Nam Leuk sub-tropical reservoirs in Lao PDR. *Science of The Total Environment*, Vol.in press. No.0, pp. 0048-9697
- Chao, B.F.; Wu, Y.H. & Li, Y.S. (2008). Impact of Artificial Reservoir Water Impoundment on Global Sea Level. *Science*, Vol.320. No.5873, April 11, 2008, pp. 212-214,
- Chen, H.; Wu, Y.Y.; Yuan, X.Z.; Gao, Y.H.; Wu, N. & Zhu, D. (2009). Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir. *Journal of Geophysical Research-Atmospheres*, Vol.114. Sep, pp. 0148-0227
- Cole, J.J.; Caraco, N.F.; Kling, G.W. & Kratz, T.K. (1994). Carbon-Dioxide Supersaturation in the Surface Waters of Lakes. *Science*, Vol.265. No.5178, Sep 9, pp. 1568-1570, 0036-8075
- Cole, J.J.; Prairie, Y.T.; Caraco, N.F.; Mcdowell, W.H.; Tranvik, L.J.; Striegl, R.G.; Duarte, C.M.; Kortelainen, P.; Downing, J.A.; Middelburg, J.J. & Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems*, Vol.10. No.1, Feb, pp. 171-184, 1432-9840
- Cullenward, D. & Victor, D.G. (2006). The dam debate and its discontents. *Climatic Change*, Vol.75. No.1-2, Mar, pp. 81-86, 0165-0009
- Dean, W.E. & Gorham, E. (1998). Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology*, Vol.26. No.6, Jun, pp. 535-538, 0091-7613
- Delmas, R.; Galy-Lacaux, C. & Richard, S. (2001). Emissions of greenhouse gases from the tropical hydroelectric reservoir of Petit Saut (French Guiana) compared with emissions from thermal alternatives. *Global Biogeochemical Cycles*, Vol.15. No.4, Dec, pp. 993-1003, 0886-6236
- Delsonro, T.; McGinnis, D.F.; Sobek, S.; Ostrovsky, I. & Wehrli, B. (2010). Extreme Methane Emissions from a Swiss Hydropower Reservoir: Contribution from Bubbling Sediments. *Environmental Science & Technology*, Vol.44. No.7, Apr 1, pp. 2419-2425, 0013-936X
- Demarty, M. & Bastien, J. (2011). GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH<sub>4</sub> emission measurements. *Energy Policy*, Vol.39. No.7, Jul, pp. 4197-4206, 0301-4215
- Diem, T.; Koch, S.; Schwarzenbach, S.; Wehrli, B. & Schubert, C.J. (2007). Greenhouse-gas (CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub>) emissions from hydroelectric reservoirs in Switzerland.
- Dos Santos, M.A.; Rosa, L.P.; Sikar, B.; Sikar, E. & Dos Santos, E.O. (2006). Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants. *Energy Policy*, Vol.34. No.4, Mar, pp. 481-488, 0301-4215
- Duchemin, E.; Lucotte, M.; Canuel, R. & Chamberland, A. (1995). Production of the greenhouse gases CH<sub>4</sub> and CO<sub>2</sub> by hydroelectric reservoirs of the boreal region. *Global Biogeochem. Cycles*, Vol.9. No.4, pp. 529-540,

- Duchemin, E.; Lucotte, M.; Canuel, R. & Soumis, N. (2006). First assessment of methane and carbon dioxide emissions from shallow and deep zones of boreal reservoirs upon ice break-up. *Lakes & Reservoirs: Research & Management*, Vol.11. No.1, pp. 9-19, 1440-1770
- Farrow, D.E. & Stevens, C.L. (2003). Numerical modelling of a surface-stress driven density-stratified fluid. *Journal of Engineering Mathematics*, Vol.47. No.1, Sep, pp. 1-16, 0022-0833
- Fearnside, P.M. (1995). Hydroelectric dams in the Brazilian amazon as sources of greenhouse gases. *Environmental Conservation*, Vol.22. No.1, Spr, pp. 7-19, 0376-8929
- Fearnside, P.M. (1997). Greenhouse-gas emissions from Amazonian hydroelectric reservoirs: the example of Brazil's Tucuruí Dam as compared to fossil fuel alternatives. *Environmental Conservation*, Vol.24. No.1, Mar, pp. 64-75, 0376-8929
- Fearnside, P.M. (2002). Greenhouse gas emissions from a hydroelectric reservoir (Brazil's Tucuruí Dam) and the energy policy implications. *Water Air and Soil Pollution*, Vol.133. No.1-4, Jan, pp. 69-96, 0049-6979
- Fearnside, P.M. (2004). Greenhouse gas emissions from hydroelectric dams: Controversies provide a springboard for rethinking a supposedly 'clean' energy source - An editorial comment. *Climatic Change*, Vol.66. No.1-2, Sep, pp. 1-8, 0165-0009
- Fearnside, P.M. (2005). Do hydroelectric dams mitigate global warming? The case of Brazil's Curuá-Una dam. *Mitigation and Adaptation Strategies for Global Change*, Vol.10. No.5, pp. 675-691,
- Fearnside, P.M. (2006). Greenhouse gas emissions from hydroelectric dams: Reply to Rosa et al. *Climatic Change*, Vol.75. No.1-2, Mar, pp. 103-109, 0165-0009
- Flanagan, K.M.; McCauley, E.; Wrona, F. & Prowse, T. (2003). Climate change: The potential for latitudinal effects on algal biomass in aquatic ecosystems, Canadian. *Journal of Fisheries and Aquatic Sciences*, Vol.60. No.6, Oct 20, pp. 635-639, 0706-652X
- Ford, D.E. (1990). Reservoir transport processes. In: *Reservoir limnology: ecological perspectives*, Thornton, K.W., Kimmel, B.L. & Payne, F.E., 256, JohnWiley & Sons, New York
- Gagnon, L. & Van de Vate, J.F. (1997). Greenhouse gas emissions from hydropower - The state of research in 1996. *Energy Policy*, Vol.25. No.1, Jan, pp. 7-13, 0301-4215
- Galy-Lacaux, C.; Delmas, R.; Jambert, C.; Dumestre, J.F.; Labroue, L.; Richard, S. & Gosse, P. (1997). Gaseous emissions and oxygen consumption in hydroelectric dams: A case study in French Guyana. *Global Biogeochemical Cycles*, Vol.11. No.4, Dec, pp. 471-483, 0886-6236
- Galy-Lacaux, C.; Delmas, R.; Kouadio, G.; Richard, S. & Gosse, P. (1999). Long-term greenhouse gas emissions from hydroelectric reservoirs in tropical forest regions. *Global Biogeochemical Cycles*, Vol.13. No.2, Jun, pp. 503-517, 0886-6236
- Giles, J. (2006). Methane quashes green credentials of hydropower. *Nature*, Vol.444. No.7119, Nov, pp. 524-525, 0028-0836
- Gleick, P.H.; Cooley, H.; Cohen, M.J.; Marikawa, M.; Morrison, J. & Palanappn, M. (2009). Dams Removed or Decommissioned in the United States, 1912 to Present. In: *The World's Water 2008-2009*, Gleick, P.H., 239-264, Pacific Institute for Studies in Development, Environment, and Security, Island Press, Washington, D.C.
- Gudasz, C.; Bastviken, D.; Steger, K.; Premke, K.; Sobek, S. & Tranvik, L.J. (2010). Temperature-controlled organic carbon mineralization in lake sediments. *Nature*, Vol.466. No.7305, Jul, pp. 478-U3, 0028-0836
- Guerin, F. & Abril, G. (2007). Significance of pelagic aerobic methane oxidation in the methane and carbon budget of a tropical reservoir. *Journal of Geophysical Research-Biogeosciences*, Vol.112. No.G3, pp.

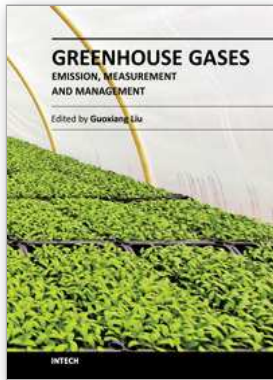
- Guerin, F.; Abril, G.; Richard, S.; Burban, B.; Reynouard, C.; Seyler, P. & Delmas, R. (2006). Methane and carbon dioxide emissions from tropical reservoirs: Significance of downstream rivers. *Geophysical Research Letters*, Vol.33. No.21, Nov, pp. 0094-8276
- Guerin, F.; Abril, G.; Richard, S.; Burban, B.; Reynouard, C.; Seyler, P. & Delmas, R. (2006 ). Methane and carbon dioxide emissions from tropical reservoirs: Significance of downstream rivers. *Geophysical Research Letters*, Vol.33: L21407. Nov 14, pp. 0094-8276
- Guerin, F.; Abril, G.; Serca, D.; Delon, C.; Richard, S.; Delmas, R.; Tremblay, A. & Varfalvy, L. (2007). Gas transfer velocities of CO<sub>2</sub> and CH<sub>4</sub> in a tropical reservoir and its river downstream. *Journal of Marine Systems*, Vol.66. No.1-4, Jun, pp. 161-172, 0924-7963
- Hedges, J.I. & Keil, R.G. (1995). Sedimentary organic-matter preservation - an assessment and speculative synthesis. *Marine Chemistry*, Vol.49. No.2-3, Apr, pp. 81-115, 0304-4203
- Hedges, J.I.; Keil, R.G. & Benner, R. (1997). What happens to terrestrial organic matter in the ocean? *Organic Geochemistry*, Vol.27. No.5-6, Oct-Nov, pp. 195-212, 0146-6380
- Hoffert, M.I.; Caldeira, K.; Jain, A.K.; Haites, E.F.; Harvey, L.D.D.; Potter, S.D.; Schlesinger, M.E.; Schneider, S.H.; Watts, R.G.; Wigley, T.M.L. & Wuebbles, D.J. (1998). Energy implications of future stabilization of atmospheric CO<sub>2</sub> content. *Nature*, Vol.395. No.6705, Oct, pp. 881-884, 0028-0836
- Huttunen, J.T.; Vaisanen, T.S.; Hellsten, S.K.; Heikkinen, M.; Nykanen, H.; Jungner, H.; Niskanen, A.; Virtanen, M.O.; Lindqvist, O.V.; Nenonen, O.S. & Martikainen, P.J. (2002). Fluxes of CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O in hydroelectric reservoirs Lokka and Porttipahta in the northern boreal zone in Finland. *Global Biogeochemical Cycles*, Vol.16. No.1, Mar, pp. -, 0886-6236
- IEA (2008). International Energy Agency. Electricity/Heat in World in 2008. available via <http://go.nature.com/6mAANK>
- IPCC (2007). Intergovernmental Panel on Climate Change's Fourth Assessment Report
- Keller, M. & Stallard, R.F. (1994). Methane Emission by Bubbling from Gatun Lake, Panama. *Journal of Geophysical Research-Atmospheres*, Vol.99. No.D4, Apr 20, pp. 8307-8319, 0148-0227
- Kelly, C.; Rudd, J.W.M.; St. Louis, V.L. & Moore, T. (1994). Turning attention to reservoir surfaces, a neglected area in greenhouse studies. *Eos Trans. AGU*, Vol.75. No.29, pp. 332,
- Kelly, V.J. (2001). Influence of reservoirs on solute transport: a regional-scale approach. *Hydrological Processes*, Vol.15. No.7, May, pp. 1227-1249, 0885-6087
- Kemenes, A.; Forsberg, B.R. & Melack, J.M. (2007). Methane release below a tropical hydroelectric dam. *Geophysical Research Letters*, Vol.34. No.12, Jun, pp. 0094-8276
- Kemenes, A.; Forsberg, B.R. & Melack, J.M. (2007 ). Methane release below a tropical hydroelectric dam. *Geophysical Research Letters*, Vol.34: L1 2809. Jun 23, pp. 0094-8276
- Kemenes, A.; Forsberg, B.R. & Melack, J.M. (2011). CO<sub>2</sub> emissions from a tropical hydroelectric reservoir (Balbina, Brazil). *Journal of Geophysical Research-Biogeosciences*, Vol.116. Jul, pp. 0148-0227
- Kennedy, R.H.; Thornton, K.W. & D.E., F. (1985). Characterization of the reservoir ecosystem. In: *Microbial Processes in Reservoirs.*, Gunnisson, D., Dr. W. Junk Publishers, Dordrecht
- Kennedy, R.H. & Walker, W.W. (1990). Reservoir nutrient dynamics. In: *Reservoir Limnology: Ecological Perspectives*, Thornton, K.W., B.L., K. & F.E., P., John Wiley and Sons, New York

- Kosten, K.; Roland, F.; Motta Marques, D.M.L.; Van Nes, E.H.; Mazzeo, N.; Sternberg, L.S.L.; Scheffer, M. & Cole, J.J. (2010). Climate-dependent CO<sub>2</sub> emissions from lakes. *Global Biogeochemical Cycles*, Vol.24. May 8, 0886-6236
- Kritzberg, E.S.; Cole, J.J.; Pace, M.M. & Graneli, W. (2005). Does autochthonous primary production drive variability in bacterial metabolism and growth efficiency in lakes dominated by terrestrial C inputs? *Aquatic Microbial Ecology*, Vol.38. No.2, Feb, pp. 103-111, 0948-3055
- Lemoalle, J. (1975). L'activité photosynthétique du phytoplancton en relation avec le niveau des eaux du Lac Tchad (Afrique). *Verh. int. Ver. Limnol.*, Vol.19. pp. 5,
- Lima, I.B.T. (2005). Biogeochemical distinction of methane releases from two Amazon hydroreservoirs. *Chemosphere*, Vol.59. No.11, Jun, pp. 1697-1702, 0045-6535
- Lima, I.B.T.; Novo, E.M.L.M.; Ballester, M.V.R. & Ometto, J.P.H.B. (1998). Methane Production, Transport and Emission in Amazon Hydroelectric Plants. *Veranstaltungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie.*, pp.
- Lopez-Urrutia, A.; San Martin, E.; Harris, R.P. & Irigoien, X. (2006). Scaling the metabolic balance of the oceans. *Proceedings of the National Academy of Sciences of the United States of America*, Vol.103. No.23, Jun, pp. 8739-8744, 0027-8424
- Macintyre, S.; Romero, J.R. & Kling, G.W. (2002). Spatial-temporal variability in surface layer deepening and lateral advection in an embayment of Lake Victoria, East Africa. *Limnology and Oceanography*, Vol.47. No.3, May, pp. 656-671, 0024-3590
- Martin, J.L. & Mccutcheon, S.C. (1999). Hydrodynamics and transport for water quality modeling. Boca Raton
- McGinnis, D.F.; Greinert, J.; Artemov, Y.; Beaubien, S.E. & Wuest, A. (2006). Fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere? *Journal of Geophysical Research-Oceans*, Vol.111. No.C9, Sep, pp. 0148-0227
- Melack, J.M. (1979). Photosynthetic Rates in 4 Tropical African Fresh Waters. *Freshwater Biology*, Vol.9. No.6, pp. 555-571, 0046-5070
- Monismith, S.G. (1985). Wind-Forced Motions in Stratified Lakes and Their Effect on Mixed-Layer Shear. *Limnology and Oceanography*, Vol.30. No.4, pp. 771-783, 0024-3590
- Mulholland, P.J.; Fellows, C.S.; Tank, J.L.; Grimm, N.B.; Webster, J.R.; Hamilton, S.K.; Marti, E.; Ashkenas, L.; Bowden, W.B.; Dodds, W.K.; McDowell, W.H.; Paul, M.J. & Peterson, B.J. (2001). Inter-biome comparison of factors controlling stream metabolism. *Freshwater Biology*, Vol.46. No.11, Nov, pp. 1503-1517, 0046-5070
- Ometto, J.P.; Cimleris, A.C.P.; Santos, M.A.; Rosa, L.P.; Abe, D.S.; Tundisi, J.G.; Stech, J.L.; Barros, N.O. & Roland, F. Patterns of carbon emission as a function of energy generation in hydroelectric reservoirs. . *Submitted to Climatic Changes (2011)*, pp.
- Ometto, J.P.; Pacheco, F.S.; Cimleris, A.C.P.; Stech, J.L.; Lorenzetti, J.A.; Assireu, A.; Santos, M.A.; Matvienko, B.; Rosa, L.P.; Galli, C.S.; Abe, D.S.; Tundisi, J.G.; Barros, N.; Mendonça, R.F. & Roland, F. (2011). Carbon dynamic and emissions in Brazilian hydropower reservoirs. In: *Energy Resources: Development, Distribution, and Exploitation*, Alcântara, E., Nova Science Publishers, New York
- Pacca, S. (2007). Impacts from decommissioning of hydroelectric dams: a life cycle perspective. *Climatic Change*, Vol.84. No.3-4, Oct, pp. 281-294, 0165-0009
- Pacca, S. & Horvath, A. (2002). Greenhouse gas emissions from building and operating electric power plants in the upper Colorado River Basin. *Environmental Science & Technology*, Vol.36. No.14, Jul, pp. 3194-3200, 0013-936X
- Rivkin, R.B. & Legendre, L. (2001). Biogenic carbon cycling in the upper ocean: Effects of microbial respiration. *Science*, Vol.291. No.5512, Mar, pp. 2398-2400, 0036-8075

- Roehm, C. & Tremblay, A. (2006). Role of turbines in the carbon dioxide emissions from two boreal reservoirs, Quebec, Canada. *Journal of Geophysical Research-Atmospheres*, Vol.111. No.D24, Dec, pp. 0148-0227
- Roland, F.; Cimbliris, A.C.P.; Lobão, L.M. & Vidal, L.O. (2011). Bacterioplankton Metabolism in Hydroelectric Reservoirs. *Oecologia Australis*, Vol.15. pp. 605-617,
- Roland, F.; Vidal, L.O.; Pacheco, F.S.; Barros, N.O.; Assireu, A.; Ometto, J.; Cimbliris, A.C.P. & Cole, J.J. (2010). Variability of carbon dioxide flux from tropical (Cerrado) hydroelectric reservoirs. *Aquatic Sciences*, Vol.72. No.3, Jun, pp. 283-293, 1015-1621
- Rosa, L.P.; Dos Santos, M.A.; Matvienko, B.; Dos Santos, E.O. & Sikar, E. (2004). Greenhouse gas emissions from hydroelectric reservoirs in tropical regions. *Climatic Change*, Vol.66. No.1-2, Sep, pp. 9-21, 0165-0009
- Rosa, L.P. & Schaeffer, R. (1994). Greenhouse-Gas Emissions from Hydroelectric Reservoirs. *Ambio*, Vol.23. No.2, Mar, pp. 164-165, 0044-7447
- Rudd, J.W.M.; Harris, R.; Kelly, C.A. & Hecky, R.E. (1993). Are hydroelectric reservoirs significant sources of greenhouse gases. *Ambio*, Vol.22. No.4, Jun, pp. 246-248, 0044-7447
- Rybak, J. (2001). Long-term and seasonal dynamics of nutrient export rates from lake watersheds of diversified land cover pattern. *International Association of Theoretical and Applied Limnology*, Vol 27, Pt 5, *Proceedings*, Vol.27. pp. 3132-3136, 0368-0770
- Sand-Jensen, K.; Pedersen, N.L. & Sondergaard, M. (2007). Bacterial metabolism in small temperate streams under contemporary and future climates. *Freshwater Biology*, Vol.52. No.12, Dec, pp. 2340-2353, 0046-5070
- Schlesinger, W.H. & Melack, J.M. (1981). Transport of organic-carbon in the worlds rivers. *Tellus*, Vol.33. No.2, pp. 172-187, 0040-2826
- Sobek, S.; Tranvik, L.J. & Cole, J.J. (2005). Temperature independence of carbon dioxide supersaturation in global lakes. *Global Biogeochemical Cycles*, Vol.19. No.2, Apr 5, pp. -, 0886-6236
- Soumis, N.; Duchemin, E.; Canuel, R. & Lucotte, M. (2004). Greenhouse gas emissions from reservoirs of the western United States. *Global Biogeochemical Cycles*, Vol.18. No.3, Sep, pp. 0886-6236
- Soumis, N.; Lucotte, M.; Larose, C.; Veillette, F. & Canuel, R. (2007). Photomineralization in a boreal hydroelectric reservoir: a comparison with natural aquatic ecosystems. *Biogeochemistry*, Vol.86. pp. 123-135, s10533-007
- St Louis, V.L.; Kelly, C.A.; Duchemin, E.; Rudd, J.W.M. & Rosenberg, D.M. (2000). Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. *Bioscience*, Vol.50. No.9, Sep, pp. 766-775, 0006-3568
- Stevens, C. & Imberger, J. (1996). The initial response of a stratified lake to a surface shear stress. *Journal of Fluid Mechanics*, Vol.312. Apr 10, pp. 39-66, 0022-1120
- Takagaki, N. & Komori, S. (2007). Effects of rainfall on mass transfer across the air-water interface. *Journal of Geophysical Research-Oceans*, Vol.112. No.C6, Jun 8, pp. 0148-0227
- Teodoru, C.R.; Prairie, Y.T. & Del Giorgio, P.A. (2010). Spatial Heterogeneity of Surface CO<sub>2</sub> Fluxes in a Newly Created Eastmain-1 Reservoir in Northern Quebec, Canada. *Ecosystems*, Vol.14. No.1, Jan, pp. 28-46, 1432-9840
- Thomas, S.; Cecchi, P.; Corbin, D. & Lemoalle, J. (2000). The different primary producers in a small African tropical reservoir during a drought: temporal changes and interactions. *Freshwater Biology*, Vol.45. No.1, Sep, pp. 43-56, 0046-5070
- Tranvik, L.J.; Downing, J.A.; Cotner, J.B.; Loiselle, S.A.; Striegl, R.G.; Ballatore, T.J.; Dillon, P.; Finlay, K.; Fortino, K.; Knoll, L.B.; Kortelainen, P.L.; Kutsar, T.; Larsen, S.; Laurion, I.; Leech, D.M.; McCallister, S.L.; McKnight, D.M.; Melack, J.M.; Overholt,

- E.; Porter, J.A.; Prairie, Y.; Renwick, W.H.; Roland, F.; Sherman, B.S.; Schindler, D.W.; Sobek, S.; Tremblay, A.; Vanni, M.J.; Verschoor, A.M.; von Wachenfeldt, E.; Weyhenmeyer, G.A. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography*, Vol. 54. No.6, Nov 09, pp. 2298-2314, 0024-3590
- Tremblay, A.; Lambert, M. & Gagnon, L. (2004). Do hydroelectric reservoirs emit greenhouse gases? *Environmental Management*, Vol.33. Jul, pp. S509-S517, 0364-152X
- Vidal, L.O.; Graneli, W.; Daniel, C.B.; Heiberg, L. & Roland, F. (2011). Carbon and phosphorus regulating bacterial metabolism in oligotrophic boreal lakes. *Journal of Plankton Research*, Vol.33. No.11, pp. 1747-1756,
- Vorosmarty, C.J.; Meybeck, M.; Fekete, B.; Sharma, K.; Green, P. & Syvitski, J.P.M. (2003). Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change*, Vol.39. No.1-2, Oct, pp. 169-190, 0921-8181
- Wang, F.; Wang, B.; Liu, C.Q.; Wang, Y.; Guan, J.; Liu, X. & Yu, Y. (2011). Carbon dioxide emission from surface water in cascade reservoirs-river system on the Maotiao River, southwest of China. *Atmospheric Environment*, Vol.45. No.23, Jul, pp. 3827-3834, 1352-2310
- Wanninkhof, R. (1992). Relationship between Wind-Speed and Gas-Exchange over the Ocean. *Journal of Geophysical Research-Oceans*, Vol.97. No.C5, May 15, pp. 7373-7382, 0148-0227
- WCD (2000). World Commission on Dams. Dams and Development: A New Framework for Decision-Making. Earthscan Publications. Available via <http://go.nature.com/rnFEBI>
- Wehrli, B. (2011). Renewable but not carbon-free. *Nature Geoscience*, Vol.4. No.9, pp. 585-586, 1752-0894
- Weisser, D. (2007). A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy*, Vol.32. No.9, Sep, pp. 1543-1559, 0360-5442
- Zheng, H.; Zhao, X.J.; Zhao, T.Q.; Chen, F.L.; Xu, W.H.; Duan, X.N.; Wang, X.K. & Ouyang, Z.Y. (2011). Spatial-temporal variations of methane emissions from the Ertan hydroelectric reservoir in southwest China. *Hydrological Processes*, Vol.25. No.9, Apr, pp. 1391-1396, 0885-6087





## **Greenhouse Gases - Emission, Measurement and Management**

Edited by Dr Guoxiang Liu

ISBN 978-953-51-0323-3

Hard cover, 504 pages

**Publisher** InTech

**Published online** 14, March, 2012

**Published in print edition** March, 2012

Understanding greenhouse gas sources, emissions, measurements, and management is essential for capture, utilization, reduction, and storage of greenhouse gas, which plays a crucial role in issues such as global warming and climate change. Taking advantage of the authors' experience in greenhouse gases, this book discusses an overview of recently developed techniques, methods, and strategies: - A comprehensive source investigation of greenhouse gases that are emitted from hydrocarbon reservoirs, vehicle transportation, agricultural landscapes, farms, non-cattle confined buildings, and so on. - Recently developed detection and measurement techniques and methods such as photoacoustic spectroscopy, landfill-based carbon dioxide and methane measurement, and miniaturized mass spectrometer.

### **How to reference**

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Raquel Mendonça, Nathan Barros, Luciana O. Vidal, Felipe Pacheco, Sarian Kosten and Fábio Roland (2012). Greenhouse Gas Emissions from Hydroelectric Reservoirs: What Knowledge Do We Have and What is Lacking?, Greenhouse Gases - Emission, Measurement and Management, Dr Guoxiang Liu (Ed.), ISBN: 978-953-51-0323-3, InTech, Available from: <http://www.intechopen.com/books/greenhouse-gases-emission-measurement-and-management/greenhouse-gas-emissions-from-hydroelectric-reservoirs-what-do-we-have-and-what-is-lacking->

**INTECH**  
open science | open minds

### **InTech Europe**

University Campus STeP Ri  
Slavka Krautzeka 83/A  
51000 Rijeka, Croatia  
Phone: +385 (51) 770 447  
Fax: +385 (51) 686 166  
[www.intechopen.com](http://www.intechopen.com)

### **InTech China**

Unit 405, Office Block, Hotel Equatorial Shanghai  
No.65, Yan An Road (West), Shanghai, 200040, China  
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元  
Phone: +86-21-62489820  
Fax: +86-21-62489821

© 2012 The Author(s). Licensee IntechOpen. This is an open access article distributed under the terms of the [Creative Commons Attribution 3.0 License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.