

# A method for the assessment of long-term changes in carbon stock by construction of a hydropower reservoir

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**Abstract** Sustainability of hydropower reservoirs has been questioned since the detection of their greenhouse gas (GHG) emissions which are mainly composed of carbon dioxide and methane. A method to assess the impact on the carbon cycle caused by the transition from a natural river system into a reservoir is presented and discussed. The method evaluates the long term changes in carbon stock instead of the current approach of monitoring and integrating continuous short term fluxes. A case study was conducted in a subtropical reservoir in Brazil, showing that the carbon content within the reservoir exceeds that of the previous landuse. The average carbon sequestration over 43 years since damming was  $895 \text{ mg C m}^{-2}\text{day}^{-1}$  and found to be mainly due to storage of carbon in sediments. These results demonstrate that reservoirs have two opposite effects on the balance of GHGs. By storing organic C in sediments, reservoirs are an important carbon sink. On the other hand, reservoirs increase the flux of methane into the atmosphere. If the sediments of reservoirs could be used for long term C storage, reservoirs might have a positive effect on the balance of GHGs.

**Keywords** Carbon cycle · Fluxes · Sedimentation · Sequestration

## INTRODUCTION

Carbon emissions from reservoirs have been discussed since the pioneering paper by Rudd et al. (1993) showing that reservoirs are potential sources of greenhouse gas (GHG) emissions into the atmosphere, which consist mainly of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>). Since then, researchers have tried to assess the impacts on global warming of man-made reservoirs and especially of

hydropower reservoirs. Nowadays, hydroelectric sources produce 73% of total energy from renewable sources (REN21 2015) and the current capacity is expected to double by 2050 (WEC 2015). For this reason, understanding of the carbon cycle in hydropower reservoirs is essential to verify the sustainability of current trends of development.

Estimation of net GHG emission is the method suggested by IHA (2010) to evaluate the impact of a reservoir. The net GHG emission was defined as the change of GHG fluxes in a river basin resulting from the creation of a reservoir by evaluating pre- and post-impoundment states (IHA 2010; Goldenfum 2012). The reservoir will act as a source (or sink) of GHG, if gross emissions increase (decrease) after damming, thus allowing to estimate the role of reservoirs on global warming.

Traditional estimation of net GHG emissions requires comprehensive monitoring of GHG fluxes in the river basin, including measurements of (i) diffusive fluxes at the air–water interface, (ii) bubbling fluxes at the air–water interface, (iii) degassing after passage through turbines and/or spillways, (iv) fluxes from contributing rivers, (v) fluxes at the air–soil interface, (vi) fluxes of vegetation, and (vii) carbon sedimentation rate in the reservoir. Each process requires dedicated equipment and sometimes, standard measuring techniques are even lacking (IHA 2010). This is the case for measurements of diffusive fluxes at the air–water interface, where the methods applied (floating chamber, thin boundary layer and eddy covariance) produce large deviations within and among each other (Duchemin et al. 1999; Eugster et al. 2003; Matthews et al. 2003; Demarty et al. 2009; Vachon et al. 2010). Additionally, fluxes are subject to a high variability in time (Abril et al. 2005; Teodoru et al. 2012; Mannich 2013) and space (Teodoru et al. 2011). As a result, the appropriate

number of required samples increases considerably to guarantee a representative description of system behavior. All results of those flux measurements are usually averaged and integrated over time and compared to pre-impoundment fluxes. Unfortunately, no flux measurements are available for pre-impoundment conditions in most cases. The only known complete analysis using the flux method was reported in Teodoru et al. (2012), who estimated the net GHG emission of a Canadian hydropower reservoir based on intensive multidisciplinary work over 7 years.

This paper investigates the net carbon flux of a hydro-power reservoir without the traditional approach of measuring the fluxes, but by looking at the consequence of changing the flux, which is the alteration of carbon storage. The objective is to quantify the impact on the carbon cycle by the transition from a natural landscape to a man-made reservoir. Additionally, work is aimed at determining where carbon has been stored and from where it has escaped.

The carbon stock was estimated for the *Capivari* Reservoir in the south of Brazil. The carbon stock was estimated in soil, vegetation, water, and sediment. On this basis, the change of carbon stocks was studied comprehensively and the carbon stock estimation in the sediment used an innovative hydro-acoustic approach.

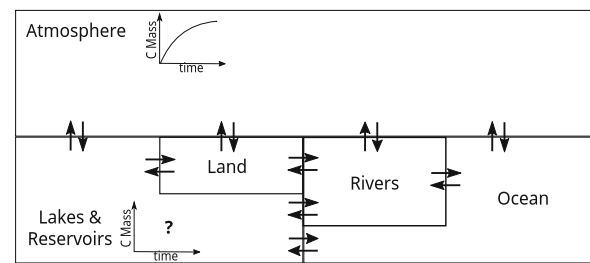
The carbon stock method and its derivation are described in next section. “Materials and methods” section highlights the study area and the measurement methods. The results are presented and discussed in “Results and discussion” section, and main conclusions are drawn in “Conclusions” section.

### CARBON STOCK AND CARBON GHG FLUX RELATIONSHIP

The carbon stock method is no new approach. IPCC (2013) already chose the increase in GHG concentration in the atmosphere (increasing mass storage) as a key indicator of climate change. The accumulation of carbon dioxide in the atmosphere indicated an increased trend of carbon dioxide fluxes into the atmosphere. There was no need to integrate gas emissions from the Earth’s surface to conclude that carbon dioxide fluxes increased. Similarly, the carbon stock estimates mean carbon flux of the reservoir without taking into account the fluxes.

The basic hypothesis is the constant content of carbon on Earth. This means that if the carbon content in the atmosphere increases, the carbon stored in another compartment is to decrease (Fig. 1). If no change in net flux is observed, no change of carbon storage is expected. The carbon stock will decrease in case of a negative (out) net flux, and the stock will increase in case of a positive (in) net flux into the system. As a result, the net impact on the

Earth (Constant Carbon Mass)



**Fig. 1** Simple schematic division of the Earth into five compartments: atmosphere, lakes and reservoirs, rivers, land, and ocean. The main assumption of the carbon stock method is the constant mass of carbon on the Earth. It is known that carbon in the atmosphere increases. Consequently, stored carbon is supposed to decrease in at least one of the remaining compartments. Estimations of carbon stock changes were made to evaluate the effects of hydropower reservoirs on the global carbon cycle. In the future, this method may be extended to also cover lakes and other compartments

global carbon cycle of a specific system can be estimated by the means of carbon stock method.

The carbon stock and GHG flux are directly related to the conservation of mass, i.e., the accumulation of carbon by the system within a given time period is the result of the integration in time of all mass fluxes at the boundaries:

$$\underbrace{\frac{\Delta M_C}{\Delta t}}_{t_1}^{t_2} = \underbrace{Q_{in} C_{WAT,in} - Q_{out} C_{WAT,out} + (F_{eb} + F_{dif}) \times A}_{\text{Integration of mass fluxes}}, \quad (1)$$

Accumulation

where the ratio between carbon mass change ( $\Delta M_C = M_{C,t_1} - M_{C,t_2}$ ) over time ( $\Delta t = t_2 - t_1$ ) in the system equals the time-averaged net carbon flux over this period through the control surface, represented here by the sum of all time-averaged (bar) mass fluxes, i.e., of the ebullitive flux ( $F_{eb}$ ), and the diffusive flux ( $F_{dif}$ ) through the reservoir surface area ( $A$ ) and the mass flux at inlets ( $in$ ) and outlets ( $out$ ), described by the product of discharge ( $Q$ ) and total carbon concentration ( $C_{WAT}$ ).

The carbon mass in the system ( $M_C$ ) is defined as the carbon stock, and can be described by the sum of carbon masses in soil ( $M_{SOIL}$ ), vegetation ( $M_{VEG}$ ), sediments ( $M_{SED}$ ), and water ( $M_{WAT}$ ), as is outlined in Eq. (2).

$$M_C = M_{SED} + M_{SOIL} + M_{VEG} + M_{WAT}. \quad (2)$$

The carbon mass in water is composed of dissolved inorganic carbon (DIC), total organic carbon (TOC), and methane ( $CH_4$ ). The organic fraction consists of dissolved organic carbon (DOC) and particulate organic carbon (POC). Equations (3) and (4) represent these carbon species.

$$M_{WAT} = M_{DIC} + M_{TOC} + M_{CH_4}, \quad (3)$$

$$M_{TOC} = M_{DOC} + M_{POC}. \quad (4)$$

The carbon stock method consists in measuring the quantities on the left side of Eq. (1), that is, all carbon masses in sediment, soil, vegetation, and water as described in Eqs. (2)–(4). The traditional flux method consists of measuring the fluxes on the right side of Eq. (1). Theoretically, both are equivalent and complementary.

The balance just accounts for carbon species ( $\text{CO}_2$  and  $\text{CH}_4$ ), ignoring other GHGs, such as  $\text{N}_2\text{O}$ . Hence, it is called carbon GHG flux. Compared to the flux method, the carbon stock method requires a smaller measurement effort. It is only needed to assess the total carbon mass at two instants of time, and complex and continuous monitoring of fluxes is not necessary.

Most of the estimates and field studies presented in literature are based on the flux method which represents the state of the art in monitoring GHG emissions from lakes and reservoirs. However, this method only provides a snapshot of the state of the reservoir and fluxes, i.e., only instantaneous information. A complete diagnosis of the GHG balance requires measurement of fluxes with high temporal and spatial resolutions. Such measurements are complicated, as there are difficulties in data acquisition due to logistical and accessibility aspects, diverse methods and instruments, the uncertainty of the measurement techniques, and laboratory analysis effort.

In contrast to this, the carbon stock method is based on the evaluation of the variation of the total carbon mass in the system. The associated time scale ( $\Delta t$ ) can be defined according to management needs, e.g., an annual scale. A result of usually coarse reservoir monitoring time scales is that the diurnal and seasonal variabilities are incorporated in the carbon mass change, and these variabilities do not need to be resolved in detail. Thus, from the perspective of a reservoir manager, this strategy combines the aims of net GHG emissions estimations with simplified logistics and low costs for the monitoring program.

This section showed that the carbon stock is directly related to the net carbon GHG flux by the carbon mass balance. The major drawback of the carbon stock method is the inability to take into account the global warming potential (GWP), because there is no way to differentiate the carbon forms. The advantage is that the carbon stock method just requires two extensive surveys at different times instead of measuring fluxes continuously and extensively.

## MATERIALS AND METHODS

The overall method consists in examining the carbon stock change over the pre-impoundment and the post-impoundment states (Fig. 2). The data for pre-impoundment were based on literature data and it was compared with current

data measured from reservoir surrounding area. Two field campaigns (at winter and summer) were conducted to measure carbon mass for the post-impoundment state (43 years after the damming). Additionally and just for comparison, bubbling and diffusive fluxes were measured during these campaigns.

The subsections below describe the study area and the methods applied to estimate carbon content in soil, vegetation, sediment, and water as well as the GHG flux at the surface. The last subsection discusses the assumptions made to estimate pre- and post-impoundment states.

### Study area

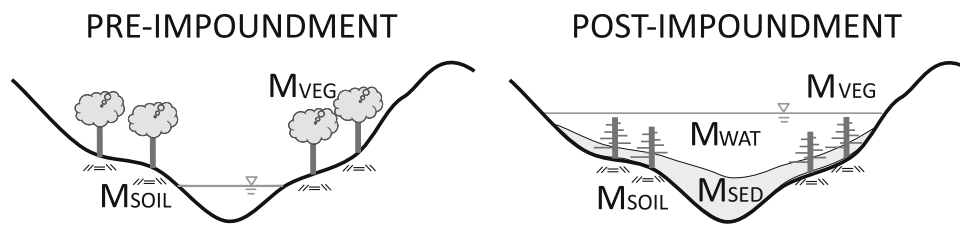
The carbon stock method was applied to assess the *Capivari* Reservoir, located in Paraná, South Brazil, (48.8729°W, 25.1405°S). The reservoir (Fig. 3) covers an area of 13 km<sup>2</sup> and has a total volume of 179 hm<sup>3</sup> with a mean water depth of 14 m. The drainage area of the associated watershed is 945 km<sup>2</sup> with a mean annual discharge of 20 m<sup>3</sup> s<sup>-1</sup> and a mean residence time of 103 days. The reservoir was built as a storage reservoir in 1970 for a downstream hydropower plant with an installed capacity of 250 MW, and up to 92% of the annual discharge flows through the turbines. This subtropical region is composed mainly by *Araucaria* moist forest, with a mean canopy height of 20 m. Soils in the basin are mainly acrisol and cambisol (IBGE 2001).

### Carbon stock in soils and vegetation

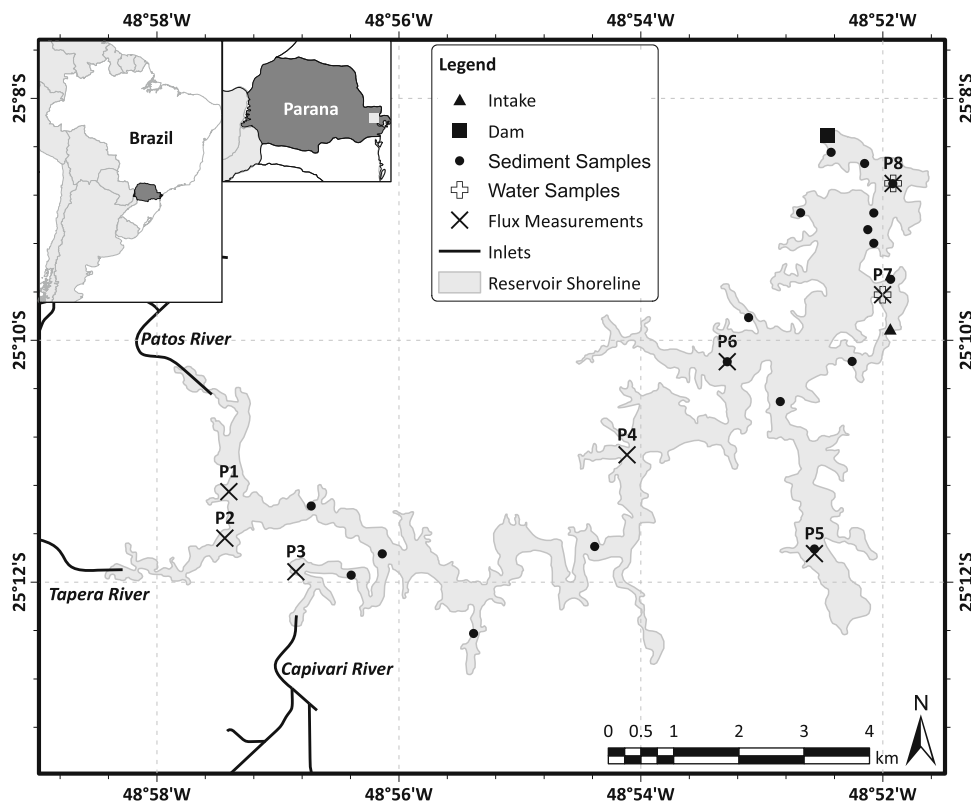
The carbon storage in soils was measured in three representative areas of the basin. Carbon concentration profiles down to 1 m depth in eight soil slices (0–2.5, 2.5–5.0, 5–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm). The organic carbon content (kg kg<sup>-1</sup>) was measured by the method of Walkley–Black dichromate oxidation. Dry density (kg m<sup>-3</sup>) and moisture content (kg kg<sup>-1</sup>) analysis followed the procedures described in Flint and Flint (2002).

The carbon stock in soil is estimated for each parcel by summing up the carbon stock of each layer, which is calculated by the multiplication of dry density, carbon content, and layer height.

The carbon stock above ground was estimated based on the data provided by the National System for Forest Data (SNIF). This tool summarizes the carbon-related data collected and published about Brazilian forests; it is available online. It is the most up-to-date compilation of below- and above-ground carbon stock data for many Brazilian biomes (SNIF 2015). The predominant vegetation surrounding *Capivari* Reservoir is the *Araucaria* moist forest (IBGE 1992).



**Fig. 2** Illustration of compartments where carbon mass is measured for pre-impoundment and post-impoundment states. Carbon mass content within vegetation ( $M_{VEG}$ ) and ( $M_{SOIL}$ ) were considered to be pre-impoundment. The post-impoundment state considered two additional compartments: carbon contents in water ( $M_{WAT}$ ) and sediment ( $M_{SED}$ )



**Fig. 3** Map of the Capivari Reservoir showing its geographical location, main inflows, outline, intake, dam, water sample points, sediment samples points, and flux measurement points

### Carbon stock in the water column

The carbon stock in the water was obtained from the evaluation of different species (POC, DOC, DIC,  $CH_4$ ). Concentration profiles of those species were measured at two points in the reservoir: one close to the intake (point P7 in Fig. 3) and another at the central and deepest point of the reservoir (P8 in Fig. 3). A vertical integration was performed to estimate the carbon stock.

Water samples were collected every 3 m in depth at P8 and at every 2 m depth at P7. DIC concentrations were estimated through alkalinity analysis (in situ) (APHA 1994); temperature and pH information was obtained using a Horiba U-53 multi-parametric probe. TOC was measured

in the laboratory with a Shimadzu corporation TOC-VCPH using a non-dispersive infrared detector based on high-temperature catalytic oxidation (680 °C). DOC and POC fractions were also measured in the laboratory using a 0.45  $\mu$ m cellulose acetate membrane as described by Hope et al. (1994).

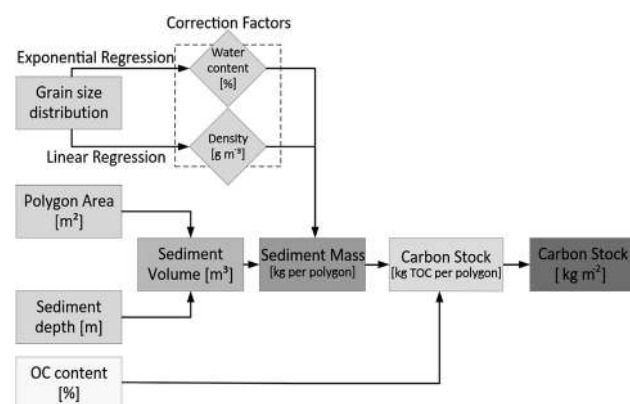
Methane profiles were obtained in situ with a tunaid laser spectroscopy probe made by Franatech with a measuring range from 1 to 40 000 (ppmv) and accuracy of  $\pm 2\%$  of reading or  $\pm 2$  ppmv. The dissolved gas concentration in water was further corrected based on measuring depth and water temperature. In addition to carbon stock parameters, dissolved oxygen (DO) was measured in the water column with a Horiba U-53 multi-parametric probe.

## Carbon stock in sediments

Echo sounding technology was used for high precision determination of the sediment carbon stock. The sediment thickness was determined according to Hilgert and Fuchs (2015). An EA 400 single-beam dual-frequency echo sounder (Kongsberg) with 200 and 38 kHz frequencies was used to ensonify the sediment. Two different procedures were performed. First, static measurements with the boat fixed using three anchors were carried out, leading to unbiased (no pitch, heave, roll) hydro-acoustic reflection data of all 18 coring positions. During the second phase, the reflectivity of the lakebed was measured by driving a raster on the entire reservoir. The distance of driven lines was approximately  $50 \times 100$  m. The static hydro-acoustic data set and the carbon content of the analyzed cores served as a basis to build a model predicting the sediment carbon content for the driven lines (Hilgert 2015; Hilgert et al. 2016). Then the entire reservoir surface was interpolated using inverse distance weighting.

The sediment magnitude was derived from the first bottom pick of the 200 kHz frequency and the highest reflectivity layer of the 38 kHz frequency. Fully consolidated sediment represents the lower boundary for this technique; therefore softer sediment layers can be measured precisely using this method. Based on the correlation between the measured carbon contents and the hydro-acoustic response, the carbon stock of the sediment was calculated according to the following scheme (Fig. 4).

To obtain input data, the sediment surface was separated into 45 000 single polygons using ArcGIS 10.2 (ESRI) covering an area of  $10.5 \text{ km}^2$ , which equals 88% of the Capivari Reservoir. Each polygon was combined with a sediment magnitude (depth) value. The resulting volume was corrected to obtain the dry sediment mass, which again



**Fig. 4** Schematic representation of the methods to determine carbon stored in sediment

was combined with the organic carbon content to receive the carbon stock per  $\text{m}^2$ . The TOC and the grain size distribution were averaged over the depth of the sediment. Calculating the average carbon content is important, since the first 15 cm of the sediment tend to contain more carbon than the layers below.

## Bubbling and diffusive GHG fluxes at the air–water interface

Diffusive fluxes were measured with floating chambers of 1 L headspace volume and an area of  $23 \text{ cm}^2$ . Measurements were made in the freely floating mode and close to the boat. Sufficient time was given after switching off the boat engine to prevent interference of boat motor gases. The air in the chambers was mixed by holding the latter opposite to wind direction. In this way, atmospheric conditions in the chamber headspace were ensured. Two chambers per sample point were deployed. After pressure stabilization, a valve was closed and the measurement started. Five gas samples were taken with syringes over a period of 8 min; these samples also included the initial condition. Gas concentrations were analyzed by gas chromatography (GC) with a flame ionization detector.

Bubbling emissions were measured with funnels of 1 m in diameter. Three funnels per sample point were submerged close to the water surface, anchored in a fixed position, and marked with a floating device for each monitoring point. The accumulated sample of air bubbles after 24 h of deployment was collected with syringes and analyzed by means of the GC technique.

## Pre- and post-impoundment states

The evaluation of net carbon fluxes by the carbon stock method consists in defining  $t_1$  and  $t_2$  as pre- and post-impoundment conditions, as illustrated by Fig. 2. Since there is no available data for the pre-impoundment state, a scenario was defined.

The pre-impoundment state was considered to be similar to the current state of land cover and soil uses near the reservoir, with the soil being covered mainly by natural forest. The carbon stock in this scenario was composed of soil and vegetation compartments, which were measured on an undisturbed site close to the reservoir. Thus, carbon stored in all other compartments, such as river water, river sediment, river fauna, and air, were neglected.

The post-impoundment condition comprises the total carbon in the water and sediment phase and the fraction of carbon that remains in the soil after the impoundment. It was assumed that the carbon stored in the soil top layer (15 cm) is totally degraded after damming due to the lower density and presence of more unstable carbon.

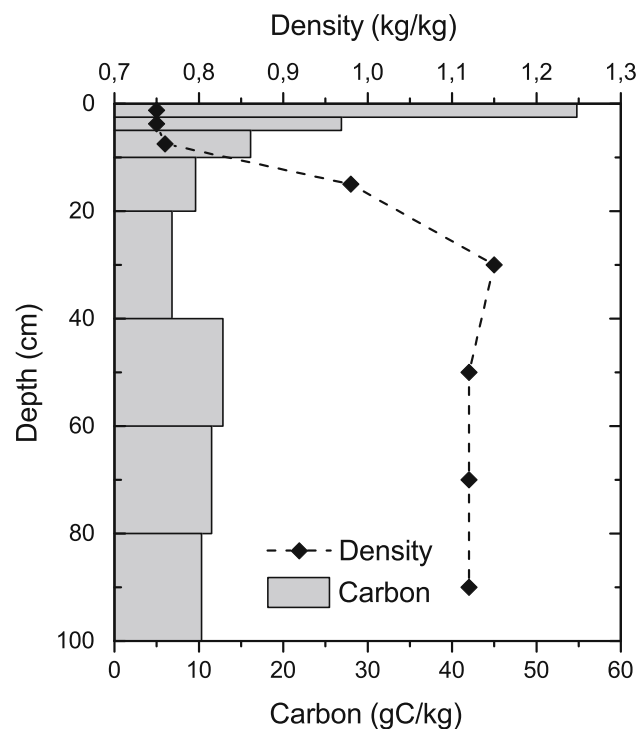
## RESULTS AND DISCUSSION

This section presents the carbon stock estimated for each compartment. The pre- and post-impoundment states are compared as well as the relative contributions of each compartment to the total carbon stock. From the change in stock, an average flux can be computed, which is then compared with the CO<sub>2</sub> fluxes measured at the air–water interface.

### Soil and vegetation carbon stock

The measured carbon concentration profiles (dry mass basis) and soil densities are shown in Fig. 5. The vertical integration of the concentration profile resulted in a carbon stock per unit area of  $9.0 \pm 3.0 \text{ kg C m}^{-2}$ , which represents the pre-impoundment state. Taking into account just the carbon in layers deeper than 15 cm, the carbon stock is  $6.5 \pm 2.5 \text{ kg C m}^{-2}$ .

The carbon stock above ground estimated by SNIF for Araucaria moist forest is  $3.5 \text{ kg C m}^{-2}$ , the carbon stock below-ground is  $10.8 \text{ kg C m}^{-2}$ , whereas the carbon in the soil amounts to  $8.6 \text{ kg C m}^{-2}$  which is consistent with the measurements and indicates that the above-ground carbon represents a good estimate. Moreover, these values are of the same magnitude as values found in other places over the world (Blais et al. 2005; Gibbs et al. 2007).



**Fig. 5** Measured soil density and soil carbon concentration profiles

### Carbon storage in sediments

Correlations with hydro-acoustic data were calculated to derive the carbon distribution of the reservoir based on the carbon content in 18 sediment cores sampled over the entire reservoir. Table 1 shows the sediment key data for the included sediment cores. The resulting mass of organic carbon is  $205\,129 \pm 60.8 \text{ Mg C}$ , which equals the average content of  $19.5 \pm 5.8 \text{ kg C m}^{-2}$ . The deviations of around 30% are due to uncertainties associated with the correction factor prediction based on the regression models. Variances originally caused by the measurement techniques, e.g., hydro-acoustic assessment, are not included in the calculation of the deviation. The average value of  $19.5 \text{ kg C m}^{-2}$  seems to be a reasonable value compared to other studies of tropical lakes and reservoirs (Cole et al. 2007; Tranvik et al. 2009; Ferland et al. 2012; Mendonça et al. 2014).

### Water carbon stock

Figure 6 shows the measured concentrations of DIC, CH<sub>4</sub>, DO, and temperature profiles. The methane profile is inversely related to DO, which is coherent to the expected behavior of CH<sub>4</sub> oxidation. DIC value is higher in the hypolimnion, which is mostly related to pH, because the alkalinity profile remained uniform through the water column.

TOC, DOC, and POC profiles are shown in Fig. 6. TOC values are lower than  $5 \text{ mg L}^{-1}$ , except those measured close to the bottom. Neither of the organic carbon fractions showed vertical stratification like the other water quality parameters. DOC decreased, while POC increased with water depth, which can be related to settling and resuspension processes.

The carbon stock in the water (Table 2) was obtained by vertically integrating TOC, DIC, and CH<sub>4</sub> profiles with respect to the volume, as is shown in Fig. 6. DIC is the most important fraction in the water carbon stock; its share being 66%. TOC is not representative, since it only makes up 13% of the water carbon stock. POC, a fraction of TOC, however, is important, because it settles and contributes to the carbon in the sediment. Below, POC relevance will be discussed with respect to the carbon budget. Methane is the smallest fraction of the carbon stored in water. Thus, the CH<sub>4</sub> contribution may be neglected in terms of storage. Regarding the fluxes, however, CH<sub>4</sub> should be evaluated due to its high GWP.

### Air–water fluxes

The fluxes measured by floating chambers and funnels at P1–P8 (Fig. 3) in spring-2012 and winter-2013 (Table 3) were compared. It was found that carbon dioxide fluxes by

**Table 1** Sediment key parameters as obtained from cores taken in the *Capivari* Reservoir (18 samples), SD is the standard deviation, CV is the coefficient of variation; the depth range only refers to the sediment sampling locations

	Mean	Max.	Min.	SD	CV
Depth (m)	13.7	32.5	0.4	8.8	0.6
LOI (%)	13.3	16.5	8.3	1.7	0.1
Organic carbon (%)	2.7	4.2	1.3	0.6	0.2
Bulk density (g cm <sup>-3</sup> )	1.3	1.8	1.1	0.1	0.1
Proportion of particles					
<63 μm (%)	78.3	99.9	34.7	17.5	0.2
<250 > 63 μm (%)	14.7	43.2	0	13	0.9
<500 > 250 μm (%)	4	19.5	0	4	1
<2 mm > 500 μm (%)	2.2	14.1	0	2.2	1
>2 mm (%)	0.5	2.6	0	0.6	1.2

bubbling processes correspond to less than 0.3% of total bubbling emission. The spatial variability was high, with maximum/minimum ratios higher than two. In addition, the temporal variability of CO<sub>2</sub> diffusive fluxes was high, showing positive fluxes in spring and negative fluxes in winter. Methane fluxes differed for diffusive and ebullitive processes at seasonal transitions.

IHA (2010) summarized results from studies where mean CO<sub>2</sub> diffusive fluxes at the water surface ranged from −276 to 5184 mg C m<sup>-2</sup> day<sup>-1</sup>, CH<sub>4</sub> fluxes ranged between −3.6 and 612 mg C m<sup>-2</sup> day<sup>-1</sup>, and fluxes for CH<sub>4</sub> bubbling amounted up to 1052 mg C m<sup>-2</sup> (IHA 2010). Fluxes are site-specific and depend on several variables (wind, temperature, hydrological conditions, DO, TOC, hydrodynamic issues, stratification, and biogeochemical cycles; IHA 2010).

The diurnal cycle of CO<sub>2</sub> fluxes was investigated by Eugster et al. (2003) and Mannich (2013). They observed differences of the day–night behavior of CO<sub>2</sub> fluxes in absorption and emission cycles. Mannich (2013) observed mean negative fluxes from −145 to 2 mg C m<sup>-2</sup> day<sup>-1</sup> at P8 of *Capivari* Reservoir (Fig. 3), using an automatic floating chamber.

### Net carbon balance

Table 4 compiles the carbon stock results for each compartment. Sediments are the main fraction (73%) of carbon stock after impoundment, whereas the vegetation is the main fraction (61%) before impoundment. The water compartment has the lowest share, it represents only 2% to the total carbon stock.

The general trend for *Capivari* is that drowned soil and vegetation release carbon, while water and sediment store carbon. The carbon soil and vegetation may be responsible

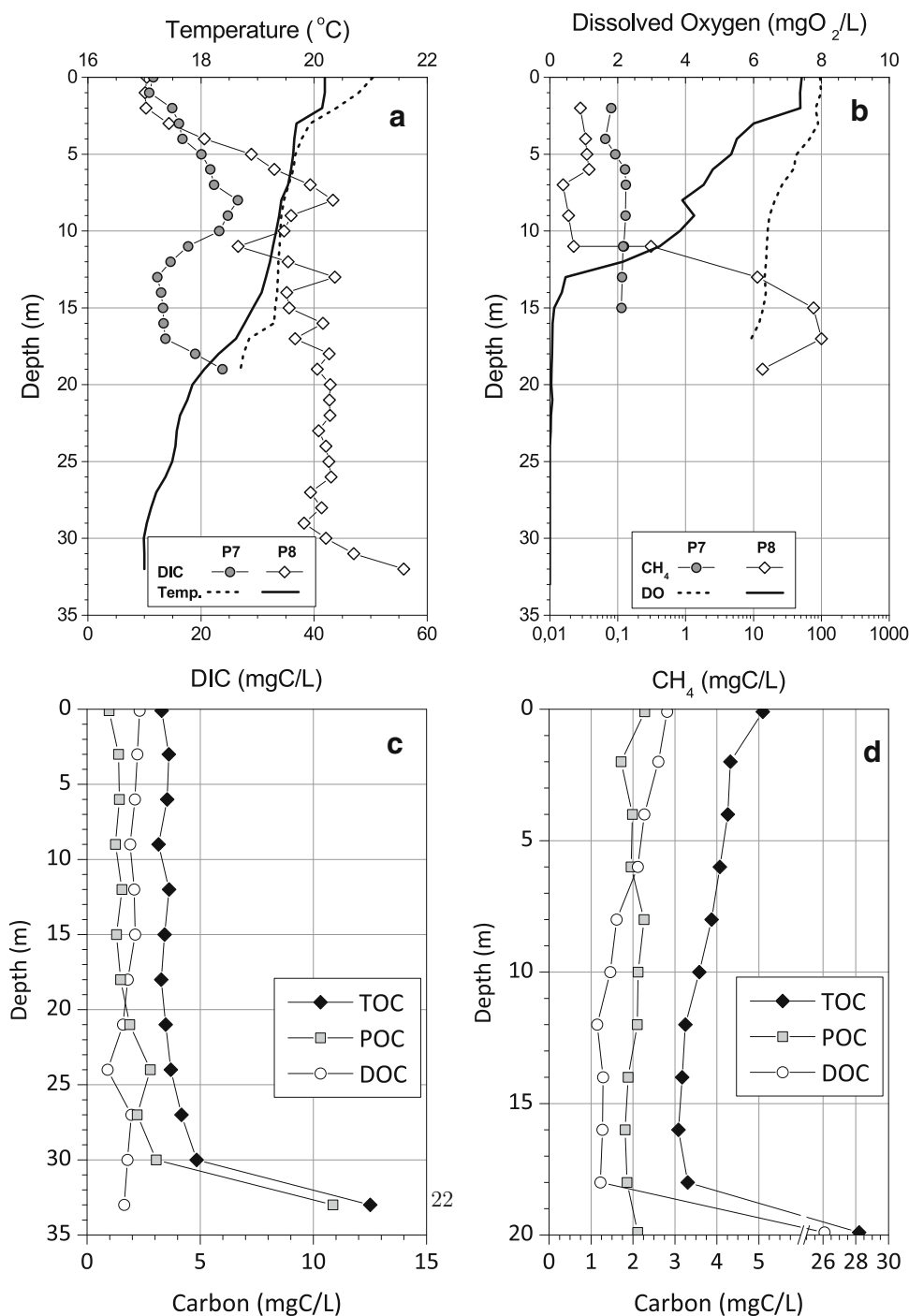
for the high amount of fluxes which are frequently detected in the early years after damming, as was reported by Teodoru et al. (2012). Based on our approach, approximately 50% of the current carbon stock were released. Hence, natural environments with a low carbon content are good areas to be flooded in terms of the carbon cycle. The same holds for reservoirs in which morphology and hydrodynamics favor carbon sedimentation and storage in the water (e.g., stable stratification).

The difference between the pre- and post-impoundment carbon stocks resulted in a net storage of 14.1 kg C m<sup>-2</sup> over 43 years, corresponding to a mean net sequestration rate of (−895 mg C m<sup>-2</sup> day<sup>-1</sup> ± 739). Consequently, *Capivari* Reservoir is a carbon sink, what is in contrast to the common behaviour of a reservoir which is usually classified as GHG source (Louis et al. 2000; Barros et al. 2011). However, those studies were mostly based on gross fluxes at the air–water interface, and they did not consider carbon loads from inflows and outflows.

The results obtained from flux measurements represent an instantaneous information, whereas the carbon stock method has all temporal dynamics embedded. Ideally, both methods should give the same results; however, temporal resolutions of fluxes are considered insufficient to estimate adequately the long-term changes in the carbon stock.

At *Capivari* Reservoir, the spatial average carbon fluxes at the surface (−59.7 to 289.4 mg C m<sup>-2</sup> day<sup>-1</sup>) suggest sequestration and emission depending on the season. This underlines the importance to properly resolve temporal and spatial variability when applying the flux method to assess GHG emissions from hydropower reservoirs and to pay the associated costs.

The sedimentation process is the most relevant sinking process in the *Capivari* Reservoir, because the carbon stock represents the biggest share in the total carbon stored after



**Fig. 6** Profiles of dissolved inorganic carbon and temperature (a), dissolved oxygen and methane (b), and organic carbon concentrations at P8 (c) and P7 (d)

the impoundment. Carbon settling took about 37 years to store the same amount as the previous forest landscape. Researchers already revealed that sedimentation processes in reservoirs can sequester a high amount of carbon, usually more than terrestrial and ocean systems (Cole et al. 2007; Mendonça et al. 2014). Consequently, the magnitude of the net long-term carbon flux ( $-895 \text{ mg C m}^{-2} \text{ day}^{-1}$ )

also is comparable to sedimentation rates found in literature. Dean and Gorham (1998) and Mulholland and Elwood (1982) suggested a global mean carbon sequestration rate by sediments of  $1100 \text{ mg C m}^{-2} \text{ day}^{-1}$ . Teodoru et al. (2013) observed POC sedimentation rates of  $30\text{--}548 \text{ mg C m}^{-2} \text{ day}^{-1}$  in Canadian lakes and reservoirs. Furthermore, they stated that reservoir carbon settling is



**Table 2** Carbon stock in the water column

Carbon species	Carbon stock (kg C m <sup>-2</sup> )
DIC	0.37 ± 0.018
TOC	0.07 ± 0.02
CH <sub>4</sub>	0.12 ± 0.12
Total	0.55 ± 0.31

three times higher than that in lakes. Apart from the differences of lakes, reservoirs, and soil, Kunz et al. (2011) identified higher carbon contents in the reservoir sediment than in the riverbed before flooding.

The relationship with GHG emissions and age found by Barros et al. (2011) is explained by the decomposition of organic matter present in soil and vegetation. However, another compartment should provide carbon while carbon within vegetation and soil became unavailable. The sediment is a good candidate because of its high availability of carbon. Thus, the reservoir would produce more or less methane depending on the spatial and time evolution of favorable areas to sedimentation.

Furthermore, this significant amount of carbon can be released during dam decommissioning and flushing of the reservoir to prevent silting. The viability of those actions is determined by the impact on global carbon balance.

Reservoirs do not only represent a carbon sink, and they also produce methane. The challenge is to include the methane production rate in the assessment presented here. This issue will be addressed in more detail in the next section.

### Carbon sink and methane producer

The results revealed that the construction of the *Capivari* Reservoir has opposite consequences on the greenhouse effect: (i) reduction of carbon availability in the surroundings caused by the storage of carbon in sediments and (ii) transformation of carbon forms into GHG as reflected by the GHG fluxes measured at the water surface (Table 3). Thus, the assessment of the impact of the reservoir on the greenhouse effect depends on the balance of those opposite effects.

**Table 4** Carbon stock for pre- and post-impoundment states

	Pre-impoundment Stock (kg C m <sup>-2</sup> )	Post-impoundment Stock (kg C m <sup>-2</sup> )	Trend
Soil	9.0 ± 3.0	6.50 ± 2.5	↓
Vegetation	3.5	0.0	↓
Water	Neglected	0.55 ± 0.31	↑
Sediment	Neglected	19.5 ± 5.8	↑
Total	12.5 ± 3.0	26.55 ± 8.6	↑

The GWP and other metrics can be used to compare GHG emissions, but it is impossible to compare emissions with sinks, because it is unknown which GHG was captured or which GHG is prevented from being released. Therefore, it still is a challenge to develop a metrics to compare sources and sinks as regards their impacts relating to the greenhouse effect. This type of metrics will be useful for systems similar to forests which produce GHG and store carbon at same time. It is not reasonable to compare the GWPs of different power sources, because major power plants, such as thermal power plants, are no carbon sinks.

This dual effect can be transferred to other reservoirs, since researchers also have detected high carbon sequestration as well as GHG fluxes there (Pace and Prairie 2005; Cole et al. 2007; Mendonça et al. 2014).

The time scale can play an important role when comparing carbon sinks and carbon changes with GHG emissions. In the first years, high GHG emissions are expected due to the decomposition of the carbon present in soil and vegetation (Barros et al. 2011). This means that there is a transition time, during which the release of GHG is not compensated by sequestration. For example, the *Capivari* Reservoir took approximately 37 years to accumulate the amount of carbon contained in the previous vegetation. This estimation was based on the average sedimentation rate until 43 years after damming. During this transition time, *Capivari* Reservoir reduced the impact on the global carbon cycle.

After this transition period, the major impact is the conversion of retained organic matter into methane. Methane emission is not high enough to decrease the carbon stored within the reservoir, and no carbon mass is spontaneously generated within the reservoir, which is why

**Table 3** Measurements of CO<sub>2</sub> and CH<sub>4</sub> fluxes at *Capivari* Reservoir, values in parentheses are the minimum and maximum, respectively

Process	Carbon species	Flux (mg C m <sup>-2</sup> day <sup>-1</sup> )	
		Spring 2012	Winter 2013
Diffusive	CO <sub>2</sub>	-69.5 ± 288.9 (-582/1180)	262.8 ± 268.6 (-67/914)
	CH <sub>4</sub>	8.1 ± 15.9 (-4/123)	2.4 ± 4.6 (-6/18)
Ebullitive	CH <sub>4</sub>	11.8 ± 19.4 (0/58)	24 ± 28.3 (0/99)

the extra carbon comes from the boundaries. The reservoir stores carbon and transforms part of the carbon species coming from the boundaries into methane.

In moderate approximation, the critical flux of methane may be at least 23 times less (GWP) than the sedimentation rate. However, it is assumed that the carbon is captured by the reservoir in the form of carbon dioxide, which is uncertain.

## CONCLUSIONS

Reservoirs may contribute to the greenhouse effect in two ways: (i) carbon is prevented from reaching the atmosphere by storing it in the sediment and (ii) carbon species are transformed into methane. Both processes do not exclude each other and depend on the time scale. In the long term, the reservoir is beneficial for the global carbon cycle, because it stores carbon. In the short term; however, the emission of methane may be more relevant than the sequestration of carbon.

The main drivers of carbon dynamics processes are found in the water phase (e.g., sedimentation, photosynthesis, and respiration). However, the carbon stock share in the water phase is just 2% for *Capivari* Reservoir. In this context, measurements of TOC, DIC, and CH<sub>4</sub> in the water can be neglected.

The disadvantages of the carbon stock method for assessing GHG emissions are as follows: (i) need of sufficient time after impoundment to observe sediment deposits in the reservoir, (ii) carbon species are not distinguished. The reliability of carbon storage estimation within sediments depends on the spatial variability of carbon content and sediment thickness.

The relation of carbon balance and GWP is not straightforward, because the carbon species have a distinct GWP. For example, if CH<sub>4</sub> emission is 28 times higher than CO<sub>2</sub> (IPCC 2013), the reservoir can enhance the greenhouse effect even under carbon sinking condition. For GHG diagnostics, other metrics should be developed to allow for a fair comparison with other power sources.

Usually, comparison of GHG emissions from different energy sources is based on GHG fluxes (dos Santos et al. 2006) as well as on parameters for the trade of carbon credits. We suggest to also consider the carbon stored in the system, mainly because this analysis takes into account the entire carbon cycle instead of focusing on one component (emissions) only. When flux is used as a parameter, the dynamics of the emissions and the capture of GHG should be measured, which still is a challenge. For example, a thermal power plant burning natural gas will release buried gas (carbon stock) in a long-term analysis, whereas

a reservoir will be full of sediment which usually contains high contents of carbon. Thus, comparison of carbon stock projections in the future simplifies analysis. Furthermore, the increasing CO<sub>2</sub> fluxes were explained by the rising concentration of this gas, that is an approximation of carbon stock in the atmosphere.

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