

Greenhouse gases and initial findings on the carbon circulation in two reservoirs and their watersheds

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Introduction

For the past 12 years our group has been studying greenhouse gas emissions from hydroelectric reservoirs throughout Brazil. The purpose was to compare hydroelectric to thermoelectric power generation in their influence on the greenhouse effect. While all CO₂ emitted from fossil fueled thermal power plants contributes to the greenhouse effect, a hydroelectric reservoir is incorporated into the natural carbon circulation of a watershed. Its repercussion on the greenhouse effect is thus more subtle.

In the first phase of our work we measured CH₄, CO₂ and N₂O emissions from reservoir water surfaces and interpreted the fluxes as being a consequence of the reservoir itself. The importance of the carbon cycle (WEISSENBERGER et al. 1998) gradually became clear, and our point of view can now be summarized by the following statement: The influence of a hydroelectric reservoir lies in the difference in carbon circulation before and after impoundment. This difference can be ascribed to the presence of the reservoir. The ultimate aim of this study was to assess the environmental impact of the hydroelectric reservoirs from the point of view of greenhouse gas emission.

Key words: carbon budget, greenhouse effect, hydroelectric reservoir, methane

The “black box” model

Carbon circulation can readily be studied through the carbon budget of a reservoir’s watershed. We studied the carbon budget by establishing a black box around the reservoir. The black box’s boundaries are fairly intuitive, beginning at the inflowing river or rivers and ending immediately after the dam at the turbinated water outflow; the upper boundary is the air-water interface. The lower boundary is less intuitive: included is the fresh sediment layer, which receives settling particulate matter and gives off carbon in dissolved forms such as CO₂, CH₄, humic substances, etc., to

the overlying water. Bubbles containing mainly CO₂, and CH₄ also rise from this fresh sediment layer. We draw the lower boundary at the surface below which all carbon is permanent (i.e. not susceptible to mobilization and on its way to fossilization). We estimate that this boundary is somewhere between 5–20 cm below the water-sediment interface. At this depth humic substances are already resistant to further carbon decomposition, as can be seen from the constant C/Si ratio starting at about this depth. In fact, the lower boundary could be described as lying in the two-dimensional region where this ratio is constant from this point down.

Reservoir carbon inputs into the black box come through rivers, underground water, rainfall, and occasional diffusive absorption. Carbon outputs are effluent outflow, permanent sedimentation, and diffusive and bubbling emissions such as CH₄ and CO₂.

Studied reservoirs

The Brazilian hydroelectric reservoirs of *Serra da Mesa* (13°50’S, 48°18’W) and *Manso* (14°32’S, 49°09’W; Table 1) were sampled, and carbon fluxes measured in one-week survey stints during the dry season of November 2003 and again in the wet season of March 2004.

Upstream from the reservoir, river-surface gas fluxes and also soil gas fluxes in the near-reservoir area were measured in the wet season survey. These fluxes serve as a reference for “background” emissions before impoundment and are important for the proposed assessment of environmental impact.

Methods

Total dissolved and particulate organic carbon concentrations were measured with a carbon analyzer (Shimadzu, Japan). Underground water flow was measured *in situ* using a graduated pole on a styrofoam float in a mini-well 20 m from the reservoir.

Table 1. Water surface and water flows of Serra da Mesa and Manso during dry season of November 2003 and rainy season of March 2004 (data suppl. by Furnas Centrais Elétricas SA, † estimated by us).

Reservoir	Area (km ²)	Water flow (m ³ s ⁻¹)	Area (km ²)	Water flow (m ³ s ⁻¹)
	Nov. 2003		Mar. 2004	
Serra da Mesa	670	1765 (in)† 568 (out)†	948	1765 (in) 568 (out)
Manso	369	170	395	229

Gas-sample collecting equipment was developed by our group (MATVIENKO et al. 1998). An ECD (Varian, USA) chromatograph was used for N₂O analyses. A TCD (Construmaq, Brazil) chromatograph equipped with FID (Gow-Mac, USA) analyzed CH₄ and CO₂. Calibrations were performed using certified gas standards (Air Liquide). An exponential curve is fitted through concentration \times time data yielded by this technique. Gas flux is described by the derivative of this exponential equation with respect to time at instant $t = 0$ (ROSA et al. 2002).

Permanent carbon (C) sedimentation measurements used silica as a carbon tracer, as silica is insoluble in a sedimentation environment at pH 5.5. The essence of using silica as a carbon tracer is that "fresh" carbon (includes C that is subjected to further decomposition) is not taken into account in this permanent sedimentation measurement. Silica traps, PVC tubes 40 cm long and 7 cm diameter, were filled with chilled water and placed in the reservoir for a known period of time. Chilled water ensured capture of settling sedimentation and prevented unwanted initial thermal convection that would bring in particles. Silica trap water was filtered, and the filters (paper filters with 11 μ m particle retention) were analyzed for silica contents using the yellow silicomolibdate procedure. Sediment samples from a 20 cm depth were analyzed for silica content (% SiO₂) after undergoing alkaline fusion. Carbon content (% C) of these sediment samples was thermogravimetrically

determined. Permanent-carbon sedimentation rate was calculated by:

$$(\text{carbon content/silica content}) \times \text{silica sedimentation rate} \quad (1)$$

Results

High standard deviations (e.g. 737.5 t C d⁻¹ in Table 2 of *Serra da Mesa*'s March 318.5 \pm 737.5 t C d⁻¹ carbon emission from water surface) reflect gas emission variability of sampled reservoir sites. For instance, CO₂ emissions measured during this campaign ranged from -407 mg m⁻²d⁻¹ (absorption) to 38 128 mg CO₂ m⁻² d⁻¹ (emission).

Results in Table 4 show a consistent absorption of N₂O by soil (0.816 and 0.132 t N₂O d⁻¹ for *Serra da Mesa* and *Manso*, respectively) during the wet season of March 2004. Also during this season, soil in the *Manso* reservoir's surrounding absorbed CH₄ at a rate of 0.150 t C d⁻¹. Highest carbon budget imbalance was 36% for the November 2003 *Serra da Mesa* survey (2871.7 t C d⁻¹ input as opposed to 1827.8 t C d⁻¹ output). Measured underground waterflow of <500 L s⁻¹ at *Manso* was disregarded as carbon input because it represents <0.3% of carbon input by affluent.

Table 2. Carbon budgets for Serra da Mesa surveys.

Carbon fluxes	<i>Serra da Mesa</i> Nov. 2003	<i>Serra da Mesa</i> Mar. 2004
River inflow (t C d ⁻¹ input)	2851.7 \pm 1316.0 (100%) (7)*	1429.0 \pm 664.9 (100%) (14)
Total input (t C d⁻¹)	2851.7 \pm 1316.0 (100%)	1429.0 \pm 664.9 (100%)
C emission as CO ₂ and CH ₄ (t C d ⁻¹ output)	581.6 \pm 499.8 (31.8%) (43)	318.5 \pm 737.5 (31.3%) (62)
Permanent sedimentation (t C d ⁻¹ output)	35.5 \pm 40.2 (2.0%) (12)	50.2 \pm 56.9 (5.0%) (11)
Effluent (t C d ⁻¹ output)	1210.7 (66.2%) (7)	648.3 (63.7%) (14)
Total output (t C d⁻¹)	1827.8 \pm 501.4 (100%)	1017.0 \pm 739.7 (100%)

* number of sampled sites in italics

Table 3. Carbon budgets for *Manso* surveys.

Carbon fluxes	<i>Manso</i> Nov. 2003	Carbon fluxes	<i>Manso</i> Mar. 2004
River inflow (t C d ⁻¹ input)	342.1 ± 51.0 (100%) (6)*	River inflow (t C d ⁻¹ input)	154.7 ± 60.1 (57.3%) (6)
Total input (t C d⁻¹)	342.1 ± 51.0 (100%)	Net carbon diffusive absorption (t C d ⁻¹ input)	115.3 ± 641.1 (42.7%) (34)
C emission as CO ₂ and CH ₄ (t C d ⁻¹ output)	55.4 ± 77.9 (18.4%)(30)	Total input (t C d⁻¹)	270.0 ± 643.9 (100%)
Permanent sedimentation (t C d ⁻¹ output)	40.6 ± 32.5 (13.5%) (7)	Permanent sedimentation (t C d ⁻¹ output)	43.5 ± 34.8 (21.1%) (7)
Effluent (t C d ⁻¹ output)	205.6 (68.1%) (6)	Effluent (t C d ⁻¹ output)	162.6 (78.9%) (6)
Total output (t C d⁻¹)	301.6 ± 84.4 (100%)	Total output (t C d⁻¹)	206.1 ± 34.8 (100%)

* number of sampled sites in italics

Table 4. "Before impoundment" and March 2004 flux averages.

Fluxes from <i>Serra da Mesa</i>	948 km ² area similar to <i>Serra da Mesa</i> before impoundment (3)*	<i>Serra da Mesa</i> reservoir (62)	Carbon and N ₂ O emissions after impoundment compared to "before"
T C d ⁻¹ (CH ₄)	0.062 ± 0.285	6.06 ± 8.25	Emits 100 times more
T C d ⁻¹ (CO ₂)	344 ± 441	313 ± 737	Same
T N ₂ O d ⁻¹	-0.816 ± 2.911	0.141 ± 0.927	Emits 17% more than absorbed
Fluxes from <i>Manso</i>	395 km ² area similar to <i>Manso</i> before impoundment (2)	<i>Manso</i> reservoir (34)	-
T C d ⁻¹ (CH ₄)	-0.150 ± 0.128	29.57 ± 27.05	Emits 200 times more
T C d ⁻¹ (CO ₂)	2470 ± 2777	-145 ± 641	Absorbs 6% more
T N ₂ O d ⁻¹	-0.132 ± 0.565	0.051 ± 0.523	Emits 39% more than absorbed

* number of sampled sites in italics

Discussion

River inflows could have been overestimated, resulting in consistently higher carbon input than output. Although primary production was not directly measured (it is a process occurring within the black box) its contribution to the carbon balance was integrated into gas emissions from the water surface, which we routinely take into account.

Carbon emissions downstream from the dam were not included in the present carbon balance because these fluxes occur outside the black box. But they are a consequence of the reser-

voir itself and thus are relevant in our greenhouse effect study.

Years of gas emission field-measurements in tropical reservoirs have shown that although diffusive CO₂ absorption by a water body is infrequent, it can prevail and produce a net carbon diffusive absorption as happened during the March 2004 campaign at *Manso* when measured absorption was 115 t C d⁻¹, or 288 mg m⁻²d⁻¹.

The instantaneous (measurement duration was of a few days) nature of these carbon flow budgets is the probable cause of the 12%–36%

imbalances. Changes in reservoir resident carbon mass can not be accounted for by these flow budgets, although these changes can act as virtual sources or sinks of C. Carbon budgets that do take into account seasonal changes of resident carbon mass in the reservoir should yield improved balances.

Conclusions

In terms of the carbon budget, the main carbon input (>50%) is through river inflow into reservoir and the main carbon output (>60%) occurs in effluent outflow. The second most important carbon output (>15%) is as water-surface gas emission.

Compared to an equivalent area of watershed territory that has never been flooded, the reservoir emits an average of 150 times more C in the form of CH₄. The main effect of the reservoir seems to be replacement of part of the CO₂ emission by CH₄. In terms of proportion: after impoundment, 20% of carbon is emitted as CH₄, up from 0.02% before impoundment. An additional effect is that an average of 28% more N₂O is emitted than is hypothesized to have been absorbed by a like area in the pre-impoundment phase.

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