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Wood decomposition in Amazonian hydropower reservoirs: An additional source of greenhouse gases

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ABSTRACT

Amazonian hydroelectric reservoirs produce abundant carbon dioxide and methane from large quantities of flooded biomass that decompose anaerobically underwater. Emissions are extreme the first years after impounding and progressively decrease with time. To date, only water-to-air fluxes have been considered in these estimates. Here, we investigate in two Amazonian reservoirs (Balbina and Petit Saut) the fate of above water standing dead trees, by combining a qualitative analysis of wood state and density through time and a quantitative analysis of the biomass initially flooded. Dead wood was much more decomposed in the Balbina reservoir 23 years after flooding than in the Petit Saut reservoir 10 years after flooding. Termites apparently played a major role in wood decomposition, occurring mainly above water, and resulting in a complete conversion of this carbon biomass into CO_2 and CH_4 at a timescale much shorter than reservoir operation. The analysis of pre-impounding wood biomass reveals that above-water decomposition in Amazonian reservoirs is a large, previously unrecognized source of carbon emissions to the atmosphere, representing 26–45% of the total reservoir flux integrated over 100 years. Accounting for both below- and above-water fluxes, we could estimate that each km^2 of Amazonian forest converted to reservoir would emit over 140 Gg CO_2-eq in 100 years. Hydropower plants in the Amazon should thus generate 0.25–0.4 MW h per km^2 flooded area to produce lower greenhouse gas emissions than gas power plants. They also have the disadvantage to emit most of their greenhouse gases the earliest years of operation.

1. Introduction

Hydroelectric reservoirs, particularly those that flood tropical forests, in which the stores of organic carbon are among the highest in the world, emit greenhouse gases (GHGs) to the atmosphere (Galy-Lacaux et al., 1997; St Louis et al., 2002; Delmas et al., 2001; Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2007, 2011; Barros et al., 2011). Furthermore, anoxic conditions and high concentrations of CO_2 and CH_4 resulting from intense microbial activity have been consistently observed in Amazonian reservoirs (Galy-Lacaux et al., 1997; Abril et al., 2005; Kemenes et al., 2007, 2011). The flooded soil and litter rapidly decompose underwater to GHGs, which reach the atmosphere through four distinct pathways (Abril et al., 2005): (1) ebullition (mainly of CH_4), from shallow areas of the reservoir; (2) diffusion of CO_2 and CH_4 from the reservoir surface; (3) degassing at the turbines and immediately below the dam; and (4) degassing from downstream rivers. As the carbon pool from the flooded soil and biomass is progressively consumed, the emissions decrease with time (Abril et al., 2005; Guérin et al., 2008). Most information available from the literature are gross GHG emissions and very few studies attempt to quantify net emissions, that is the difference between pre-impounding and post-impounding fluxes (Delmas et al., 2001; Guérin et al., 2008). Even though projections at a 100-year horizon are approximates, they suggest that lowland Amazonian reservoirs with a low power density (the ratio between the energy produced and the flooded area) could emit amounts of GHGs similar to or even higher than those from a gas power plant (Delmas et al., 2001). However, all these estimates have only considered the gross fluxes from waters upstream and downstream from dams, and the fate of the standing

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dead wood has been ignored (Fearnside and Pueyo, 2012). In this paper, we attempt to describe the decomposition of wood that occurs above water in reservoirs, and to quantify its significance in terms of greenhouse gases emissions.

2. Material and methods

We studied two Amazonian reservoirs: Balbina in Brazil, flooded in October 1987, and Petit Saut in French Guiana, flooded in January 1994. Flooded area in both systems was dominated by tropical forest growing on the dissected Guianense Complex Formation (Fearnside, 1989; Galy-Lacaux et al., 1997). We base our qualitative analysis on observations and photographs taken during numerous cruises at different years, which correspond to different post-flooding ages of the wood in the reservoirs: one year (1995) and 9 years (2003) at Petit Saut, and 23 years (2010) at Balbina. Such analysis allowed us assessing the fate of flooded wood in tropical reservoirs over time. Concerning the quantitative approach, the transient character of the GHG emissions of reservoirs makes it difficult to compare reservoirs with thermal power plants. Because of the limited field data, no completely satisfactory method exists for the extrapolation of measured gas emissions during 100 years of reservoir operation (Delmas et al., 2001). We based our analysis on the comparison of two scenarios of "low" and "high" above- and below-water CO_2 and CH_4 emissions in Balbina, where GHG fluxes were measured in 2005 (Kemenes et al., 2007, 2011) and in Petit Saut, which has been intensively monitored since impounding (Galy-Lacaux et al., 1997; Abril et al., 2005). We first applied the 100-year extrapolation method previously developed at Petit Saut to both reservoirs; this method is based also on data from older African reservoirs and provides net GHG fluxes (Delmas et al., 2001). This model incorporates the pre-impounding fluxes from natural tropical forest and soils, and includes the assumption that the gross flux of CH_4 will remain significant over 100 years, based on the fueling by organic material carried by rivers and produced by the aquatic system itself. The model developed at Petit Saut was applied to Balbina by simply correcting for the reservoir surface area. A second type of estimates was derived by extrapolating the few available fluxes measured in the field (Abril et al., 2005; Kemenes et al., 2007, 2011) to a 100-year period. At Petit Saut, we applied the observed fluxes during the first 10 years (Abril et al., 2005). We assumed that the emissions of the reservoir would be 10-fold lower during the subsequent 90 years, consistently to the observed decreasing time course of emission (Abril et al., 2005). At Balbina, we assumed that, during the first 20 years, the reservoir had emitted at the rates measured at year 18 (Kemenes et al., 2007, 2011) and for the next 80 years, we applied fluxes that were 10-fold lower. Balbina's emission calculated that way is probably an underestimate of gross emission, as it does not account for the strong ebullition probably occurring the first 2 years after impounding (Fearnside and Pueyo, 2012).

The above-water emissions were computed as a loss of biomass, assuming a total decomposition of the wood above the water table, consistent with our qualitative observations (see Results). The above water wood biomass in each reservoir was calculated from the regional carbon density given by Saatchi et al. (2007), an average canopy height of 30-m as reported by Helmer and Lefsky (2006), and the reservoirs depths and the surface areas. The relative proportions of CO_2 and CH_4 produced were calculated from the reported rates of wood decomposition by termites (Seiler et al.,

Fig. 1. Above-water wood decomposing in tropical reservoirs. A: Aerial view of the Petit Saut Reservoir one year after complete flooding, showing the initial density of dead trees. Living, green trees remain only on the islands. B: Flooded dead forest in the Petit Saut Reservoir 9 years after flooding. C: A termite nest on a standing tree in the Petit Saut Reservoir 9 years after flooding. D: Flooded dead forest in the Balbina Reservoir 23 years after flooding, showing a broken hollow bole (diameter ~2 m) resulting from decomposition by termites. The trees generally break near the water level, whereas the submerged wood decomposes more slowly (6). E: Beached boles in the Balbina Reservoir, 23 years after flooding; falling wood can continue to float for months in the reservoirs but is finally transported by wind and decomposes on the reservoir banks. Photo credits: A: Hydreco, Kourou, B to E: G. Abril.

1984). For the low estimate, the biomass density was fixed at its lower range; the CO_2/CH_4 ratio was maximal (1000). For the high estimate, the biomass density was fixed at its higher range; the CO_2/CH_4 ratio was minimal (10). The CH_4 emissions were converted to CO_2 equivalents using a global warming potential of 23 ($kgCO_2/kgCH_4$) over a 100-year time horizon.

3. Results and discussion

During the trips in the reservoirs of different ages, we observed that the above-water dead wood was decomposing significantly over a relatively short time scale (Fig. 1). At 9 years and more, intense termite activity was attested by the abundance nests, and in the 23-year-old Balbina Reservoir, most of the remaining standing trees were completely hollow. At times depending on the wood's density and diameter, the trees generally break near the water level. This is consistent with the fact that wood decomposes slower below-water that above water, as reported in Amazonian floodplains (Martius, 1997). Although no quantitative data on wood density are available, the accounts by the local people indicate a continuous decrease of standing dead trees over time. Wind or the actions of the reservoir operators ultimately brings floating boles to the edge of the reservoir. Turnover time of dead wood in Amazonian forests and floodplains is typically 10–20 years, termites, fungi and microbes being the major decomposers (Martius, 1997; Chambers et al., 2000). From these qualitative observations, we can conclude that almost all of the above-water wood will disappear well before 100 years of reservoir operation and will be released to the atmosphere as CO_2 and CH_4.

CO_2 and CH_4 emissions are reported in Table 1 and lead to a flux of 140–227 Gg CO_2-eq per flooded km^2 in 100 years. These estimates imply that each km^2 of tropical forest converted to reservoir emits 22–46 Gg carbon in 100 years, even though it formerly contained only 13–26 Gg carbon biomass. This difference, particularly significant at Balbina, may be attributed to the carbon supply from watersheds from phytoplankton and from semi-aquatic plants upstream (Kemenes et al., 2011); In addition, in reservoir anoxic water bodies, the production and emission of CH_4 from

Table 1
Estimates CO_2 and CH_4 emissions from tropical reservoirs.

		Petit Saut		Balbina		Amazon basin	
		Low	High	Low	High	Low	High
Biomass in forest (10^6 gC km^{-2})							
Aboveground live[a]		15,000	20,000	12,500	17,500	10,000	20,000
Aboveground dead and belowground[a]		4500	6000	3750	5250	3000	6000
Total		19,500	26,000	16,250	22,750	13,000	26,000
Reservoir geometry							
Maximum flooded area (km^2)		365[b]	365[b]	2360[c]	2360[c]	1	1
Average water depth (m)		10[b]	10[b]	7[c]	7[c]	10	10
Biomass in forest before flooding (GgC)[d]							
Aboveground live		5480	7300	29,500	41,300	10	20
Aboveground dead and belowground		1640	2190	8850	12,390	3	6
Total		7120	9490	38,350	53,690	13	26
Biomass in reservoir after flooding (GgC)							
Above water[e]		3650	4870	22,620	31,660	6.7	13.3
Below water[f]		3470	4620	15,730	22,030	6.3	12.7
GHG emissions integrated over 100 years (GgC)							
Above water	Total C[e]	3650	4870	22,620	31,660	10	14
	C–CH_4	5[g]	490[h]	25[g]	3160[h]	0.01[g]	1[h]
	C–CO_2	3650	4380	22,595	28,490	10	13
	C-eq[i]	3690	8478	22,804	54,970	10	25
	CO_2-eq[i]	13,540	31,090	83,615	201,570	37	90
	Contribution to total (CO_2-eq)	31%	45%	30%	41%	26%	40%
Below water	Total C		4450[j]		72,910[k]	12[l]	32[m]
	C–CH_4		790[j]		2040[k]	2.1[l]	0.9[m]
	C–CO_2		3660[j]		70,870[k]	10[l]	30[m]
	C-eq[i]	8180[n]	10,220	52,900[n]	87,960	28	37
	CO_2-eq[i]	30,000[n]	37,480	193,970[n]	322,530	103	137
	Contribution to total (CO_2-eq)	69%	55%	70%	59%	74%	60%
Total	Total C		9320		107,730	22	46
	C–CH_4		1270		5200	2	2
	C–CO_2		8050		102,530	20	43
	C-eq	11,870	18,700	75,710	146,050	38	62
	CO_2-eq	43,540	68,570	277,590	535,530	140	227

[a] From Saatchi et al. (2007).
[b] From Abril et al. (2005).
[c] From Kemenes et al. (2007).
[d] Obtained by multiplying biomass density by reservoir surface area.
[e] Obtained by considering the average canopy height from Helmer and Lefsky (2006), the reservoir depth, the live biomass above water, assuming a homogeneous vertical distribution of wood.
[f] Obtained as the sum of live biomass below water, aboveground dead and belowground biomass.
[g] Assuming a high CO_2/CH_4 ratio of 1000 for wood decomposition by termites (Seiler et al., 1984).
[h] Assuming a low CO_2/CH_4 ratio of 10 for wood decomposition by termites (Seiler et al., 1984).
[i] Using a global warming potential of 23 ($kgCO_2/kgCH_4$) over a 100-year time horizon.
[j] Obtained by applying the observed fluxes during the first 10 years (Abril et al., 2005) and assuming that the emissions of the reservoir would be 10-fold lower during the subsequent 90 years.
[k] Assuming that, during the first 20 years, the reservoir had emitted at the rates measured at year 18 (Kemenes et al., 2007, 2011) and applying fluxes that were 10-fold lower for the next 80 years.
[l] Case of Petit Saut normalized to 1 km^2.
[m] Case of Balbina normalized to 1 km^2.
[n] Applying the model of Delmas et al. (2001).

autochthonous organic matter would increase gross GHG emission as expressed in CO_2-eq (Abril et al., 2005). As a consequence, GHG emission from Amazonian reservoirs is much higher than would be from deforestation of equivalent surface areas. Above water decomposition of wood accounts for 26–45% of this total flux in the Balbina and Petit Saut Reservoirs. Although hydroelectric reservoirs are currently a modest GHG source at the global scale, the Amazonian region has been highlighted as the largest source in the future, owing to its large hydropower potential (Barros et al., 2011). Because it is probable that above water decomposition occurs in a similar way in all tropical systems, our analysis suggests that the Amazonian Basin is even more unfavorable for clean energy production than previously hypothesized, as above water emissions must be added to previous estimates.

Because the Petit Saut and Balbina Dams both produce under 50% of their installed capacity (respectively 115 and 250 MW), they may emit 0.8 and 2.5 tons of CO_2-eq per MWh produced, respectively, a ratio that is higher than the 0.64 value for a gas power plant (Delmas et al., 2001). Conversely, our quantitative analysis reveals that new Amazonian hydropower plants should be able to produce a minimum of 0.25–0.4 MW h for each km^2 of tropical forest flooded to emit less GHG than a gas power plant. However, this comparison is made on a 100-year basis. The great disadvantage of reservoirs is that they predominantly emit GHGs during the first 5–10 years of operation (Fearnside, 2011).

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