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Nitrous oxide emissions from tropical hydroelectric reservoirs

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[1] We report original data on nitrous oxide (N_2O) fluxes from two tropical reservoirs, their rivers below the dam, and from natural aquatic ecosystems and rainforest soils in French Guiana and Panama. We also review published N_2O fluxes from other tropical reservoirs and natural environments. We show that: (1) N_2O emissions from tropical reservoirs occur mainly at the reservoir surface, fluxes downstream of dams being minor; (2) Because pre-flooding natural N_2O fluxes are significant, the net N_2O emissions from reservoirs are less than $\sim$50–70% of gross N_2O emissions; (3) the contribution of N_2O to the global warming potential of emissions from reservoirs could be significant for gross emissions, but less than 10% for net emissions, disregarding N_2O degassing emissions. **Citation:** Guérin, F., G. Abril, A. Tremblay, and R. Delmas (2008), Nitrous oxide emissions from tropical hydroelectric reservoirs, *Geophys. Res. Lett.*, *35*, L06404, doi:10.1029/2007GL033057.

1. Introduction

[2] Nitrous oxide (N_2O) is one of the major greenhouse gases (GHG) in the Earth's atmosphere [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. Anthropogenic and natural emissions consist mostly of biogenic N_2O. N_2O is mainly produced as an intermediate compound during denitrification and nitrification processes which occur in anoxic and oxic conditions, respectively [*Bouwman et al.*, 1995]. Tropical hydroelectric reservoirs generally show anoxic water bodies, an oxic-anoxic interface [e.g., *Guérin et al.*, 2006] and high ammonium (NH_4^+) turnover [*Collos et al.*, 2001], and thus appear as potential sources of N_2O.

[3] In recent years, there has been an increasing concern about atmospheric emissions of CH_4 and CO_2 from boreal and tropical hydroelectric reservoirs [*Huttunen et al.*, 2002; *Abril et al.*, 2005; *Guérin et al.*, 2006; *Kemenes et al.*, 2007]. N_2O emissions from reservoirs were recently documented for the boreal region and their contribution to global warming appear as very minor [*Huttunen et al.*, 2002; *Hendzel et al.*, 2005]. It is however still unclear if N_2O emission from tropical reservoirs is an environmental issue, because data are sparse and the contribution of fluxes downstream of the dams are not documented [*Lima et al.*, 2002; *Sikar et al.*, 2005].

[4] In this paper, we present a first analysis of the significance of gross N_2O emissions from tropical reservoirs, based on original data upstream and downstream from dams of two tropical reservoirs (Petit Saut and Fortuna), and on previously published data in other sites. We also compare N_2O fluxes to CO_2 and CH_4 emissions in terms of global warming potential. Finally, we review literature data on N_2O fluxes from natural tropical aquatic and terrestrial systems, in order to assess net N_2O fluxes from reservoirs.

2. Sites and Methods

[5] We studied N_2O emissions from the reservoir surface of two tropical reservoirs located in French Guiana (Petit Saut) and in Panama (Fortuna). The two reservoirs are very different in terms of age, surface area, residence time of water and depth (Table 1). The Petit Saut Reservoir (PSR) and the Sinnamary River below the dam were described in several papers [eg., *Abril et al.*, 2005; *Guérin and Abril*, 2007]. The Fortuna Reservoir (FR) is a valley-type reservoir with a seasonal drawdown of 15 m. In contrast with the PSR, the water column of the FR is well oxygenated from the top to the bottom throughout the year.

[6] At the PSR, N_2O fluxes ($F(N_2O)$) were measured in May and December 2003 corresponding to the wet and the dry seasons, respectively. During each campaign, $F(N_2O)$ were measured along a longitudinal transect from the Sinnamary River upstream of the reservoir to the dam including open water (OW) and flooded forest (FF) sites. Our sampling strategy included 5 OW stations and 3 FF stations in May 2003 and 6 OW stations and 1 FF station in Dec. 2003. $F(N_2O)$ were also measured in the downstream river, from the dam to the Sinnamary Estuary during each field trip. In addition, in May 2003, $F(N_2O)$ were also measured from natural aquatic ecosystems in French Guiana for comparison: in the Sinnamary River upstream of the reservoir; in the Pri-Pri Yi-Yi, a freshwater marsh; and in the Kourou tidal River, the catchment of which is very similar to that of the Sinnamary River. In Dec. 2003, $F(N_2O)$ were measured from soil of the forest surrounding the PSR. In February 2003 during the dry season in Panama, $F(N_2O)$ from the FR surface were measured at 5 OW sites and at a site located $\sim$1 km below the Fortuna dam in the Chiriqui River. In Feb. 2003, $F(N_2O)$ were also measured at the air-water interface of the Arena and Mellizas Rivers, two pristine tropical rivers in Panama.

[7] The $F(N_2O)$ at the air-water interface were measured as described by *Guérin et al.* [2007] with a plastic floating chamber (volume 20 L, surface 0.2 m^2). The chamber, connected to the gas analyzer for N_2O was deployed during 10 minutes, with 2 to 5 replicates at each station. N_2O was

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Table 1. Relevant Characteristics of the Petit Saut and Fortuna Reservoirs

Reservoir	Petit Saut	Fortuna	Tucurui	Samuel	Serra de Mesa	Manso
Country	France	Panama	Brazil	Brazil	Brazil	Brazil
State	French Guiana	Chiriqui	Pará	Rodônia	Goiás	Mato Grosso
River	Sinnamary	Chiriqui	Tocantins	Jamari	Tocantins	Cuiabá
Date of impoundment	1994	1983	1983	1988	1996	2000
Lat.	05°04′N	08°45′N	3°49′S	08°44′S	13°50′S	14°32′S
Long.	53°03′W	82°11′W	49°38′W	63°30′W	48°18′W	49°09′W
T_{air}, deg C	26	23	26.5	27.3	25	26
Precipitation, mm	2965	4380	2427	2280	1700	1750
Watershed area, km^2	6900	1995	758000	29700		
Water discharge, $m^3.s^{-1}$	267	27	11000	350	1247	200
Reservoir surface, km^2	300	10	2800	420	1784	427
Volume, km^3	3.5	0.17	46	4.5	54.4	7.3
Residence time, month	5–6	2.4	1.6	3.5	26	14
Mean depth, m	10	15	19	5.7	6.7	

detected with a Fourier Transformation Infra Red Gas Analyzer (FTIR-GA) (Gasmet DX-4010, Temet Instruments). Fluxes were accepted when r^2 of the linear regression of the partial pressure versus time was higher than 0.85, $p < 0.002$ and $F(N_2O) > 5$ μmol m^{-2} d^{-1} resulting in the rejection of 30% of the fluxes. Because N_2O and CH_4 fluxes were measured simultaneously with the same chamber and the same FTIR-GA, and CH_4 concentrations were measured at each station, we could compute the gas transfer velocity at the PSR, as described by *Guérin et al.* [2007] and normalize the N_2O fluxes to a constant gas transfer velocity of 10 cm h^{-1}. These normalized fluxes are proportional to the N_2O concentration gradient at the air water interface and do not depend on the turbulence during the measurements. At the air-soil interface, $F(N_2O)$ were measured using the same FTIR-GA connected to a stainless steel chamber (volume 12L, 0.08 m^2) described by *Serça et al.* [1994]. The collar was installed 1 hour prior to measurement.

3. Results and Discussion

3.1. Gross Emissions From the Reservoir Surfaces

[8] $F(N_2O)$ from OW and FF sites of the PSR were not significantly different and showed no clear seasonal variations (Table 2 and Figure 1a). The annual average $F(N_2O)$ from the reservoir surface was 97 ± 61 μmol m^{-2} d^{-1}. Because of lower gas transfer velocities, normalized fluxes are significantly higher at the PSR reservoir surface (OW and FF) than in the Sinnamary River upstream the PSR (Figure 1b). This clearly indicates that N_2O production is higher within the water column of the PSR than in the pristine Sinnamary River upstream of the PSR and in the Sinnamary River below the dam. In the reservoir, most of the N_2O is believed to be produced around the oxycline and in the epilimnion, as previously observed in lakes with an oxic-anoxic interface in the water column [*Mengis et al.*, 1997]. At the FR during the dry season, $F(N_2O)$ was 7 ± 11 μmol m^{-2} d^{-1}, that is one order of magnitude lower than fluxes at the PSR (Table 2). The diffusive fluxes from the PSR are similar to those from the Tucurui and Samuel Reservoirs and diffusive fluxes from FR were twice the diffusive fluxes from Manso and Serra de Mesa Reservoirs (Table 2). Hence, from one reservoir to another, $F(N_2O)$ differed and did not correlate with the age of the studied reservoirs. $F(N_2O)$ from tropical reservoir surfaces are in the upper range of emissions from natural aquatic ecosystems in the tropics (Table 3).

3.2. Gross Emissions Below Tropical Dams

[9] Emissions from the Chiriqui River below the Fortuna dam (Table 2) were in the middle of the range of emissions from natural tropical rivers (Table 3). Unfortunately, we have no data from the Chiriqui River upstream the FR, in order to assess the impact of the reservoir on N_2O emissions below the Fortuna dam. In the tidal river below the Petit Saut dam, N_2O fluxes were similar during the dry and the wet season (Table 2). Along the first 40 km below the dam, $F(N_2O)$ and normalized fluxes were respectively 35% and 100% higher than fluxes from the Sinnamary River upstream of the dam (Figure 1), which indicates the presence of an additional source of N_2O below the dam.

Table 2. Nitrous Oxide Fluxes ($F(N_2O)$) From Tropical Reservoirs

			$F(N_2O)$, μmol m^{-2} d^{-1}						
			Reservoir Surfaces						
			Open Water		Flooded Forest		Downstream River		
Reservoir	Country	Season	Mean ± SD (n)	Range	Mean ± SD (n)	Range	Mean ± SD (n)	Range	Reference[a]
Petit Saut	French Guiana	Wet	103 ± 77 (33)	−135–219	124 ± 37(11)	65–189	128 ± 41 (16)	78–230	1
		Dry	84 ± 41 (27)	18–162	138 (1)		140 ± 67 (20)	51–281	1
Fortuna	Panama	Dry	7 ± 11 (10)	−18–22			31 ± 26 (2)	13–50	1
Tucurui	Brazil	Dry	125 ± 82 (8)		130 ± 109 (8)				2
Samuel	Brazil	Dry	157 ± 148 (8)		255 ± 141 (9)				2
Serra de Mesa	Brazil	Wet	3 ± 22 (62)[a]						3
Manso	Brazil	Wet	3 ± 30 (34)[a]						3

[a]References: 1, this study; 2, *Lima et al.* [2002]; 3, *Sikar et al.* [2005].

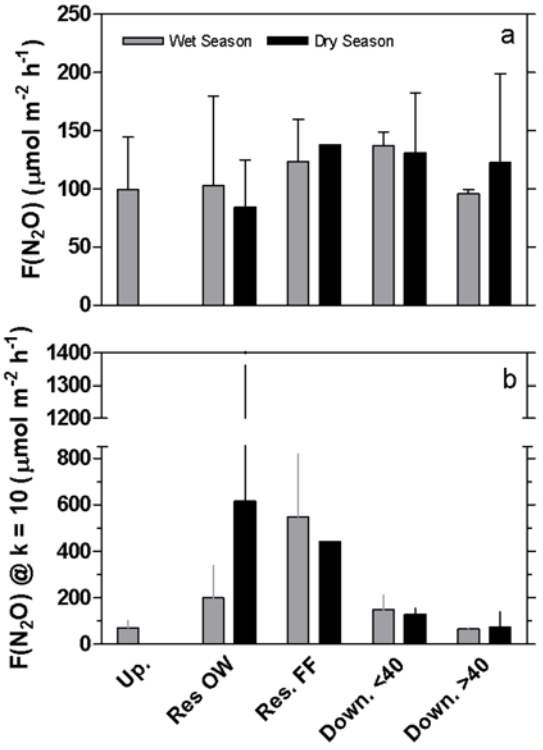

Figure 1. (a) Nitrous oxide fluxes and (b) normalized fluxes at a gas exchange (k) of 10 cm h^{-1} in the Sinnamary River upstream of the PSR (Up.); at open waters (Res. OW) and flooded forest (Res. FF) sites in the reservoir; along the first 40 km below the dam (Down <40); and downstream 40 km (Down >40 km) below the dam in wet (May) and dry season (Dec.).

[10] We assume that lateral transport of N and N_2O from the forest surrounding the river course is similar upstream and downstream of the dam since the Sinnamary watershed is solely man-impacted by the PSR. Therefore, the additional N_2O emitted from the river below the dam might have the following origins: (1) the N_2O produced in water column of the PSR that passes through the turbine and do not degas at the aerating weir; (2) in situ production in the river, by denitrification in the sediments and/or nitrification in the water column or the surface sediment. N_2O was probably produced in the epilimnion and at the oxicline of the PSR, as evidenced by the high normalized fluxes from the reservoir surface. The water passing through the turbines is a mixture of epilimnetic and hypolimnetic waters, and N_2O produced in the PSR reaches the downstream river. Thus, as it occurs for CH_4 and CO_2 [*Abril et al.*, 2005; *Guérin et al.*, 2006], a part of the N_2O passing through the turbines degasses at the weir and the remaining is supposed to be emitted to the atmosphere downstream. As for CH_4, N_2O fluxes reached the values similar to the natural background in the Sinnamary River 40 km below the dam (Figure 1). Waters passing through the turbines are poor in nitrate (<1 μmol L^{-1}) and enriched in NH_4^+ (30–175 μmol L^{-1}). Thus, nitrification probably exceeded denitrification as N_2O producer in the first 40 km reach of the Sinnamary River. N_2O production could also be enhanced by nitrification by methanotrophs [*Roy and Knowles*, 1994] as the Sinnamary River below the PSR is a hot spot for aerobic CH_4 oxidation [*Guérin and Abril*, 2007].

3.3. Contribution of N_2O to Gross Greenhouse Gas Emissions

[11] In order to compare the contribution of N_2O to GHG emissions from tropical reservoirs, fluxes of CO_2, CH_4 and N_2O were calculated in CO_2 equivalent using the 100-year GWP of 25 and 298 for CH_4 and N_2O respectively [*IPCC*, 2007]. For all studied reservoirs in the tropics, the contribution of N_2O to global warming potential of emissions from reservoir surfaces range from <1% to 30% (Table 4). Downstream of the PSR, the contribution of N_2O is less than 2%. The total contribution of N_2O emissions downstream of the FR cannot be assessed as fluxes were measured only at one station 1 km below the dam. The contribution of 29% for N_2O to global warming potential of emissions from the Samuel Reservoir is clearly an overestimate since the degassing of CO_2 and CH_4 below the dam are not available (Table 4). N_2O emissions downstream of the dam are also missing but as shown at the PSR, they are probably not significant.

[12] For all the quantified GHG emission pathways at the PSR, the global warming potential of N_2O contributed to 16% of the total GWP of the GHG emissions (Table 4). The potential degassing of N_2O in the vicinity of the dam was not quantified directly with our sampling strategy. The difference between the degassing efficiency of two gases depends mainly on their solubility in water and the concentration gradient between the water and the air. The solubility of N_2O in water is similar to that of CO_2 [*Wanninkhof*, 1992]. The degassing efficiency at the weir is 40% for CO_2 and 60% for CH_4 [*Abril et al.*, 2005]. A few hundreds meters below the dam, we estimate from our N_2O fluxes and the gas transfer velocity [*Guérin et al.*, 2007] that the N_2O concentrations are in the range of 1 to 2 μmol L^{-1}. Assuming a same degassing efficiency as for CO_2 and CH_4, the N_2O concentration of the water passing through the turbines would be in the range of 1.4 to 3.6 μmol L^{-1}. The corresponding concentration gradient between the water and the atmosphere for N_2O would be intermediate between that of CO_2 and that of CH_4 allowing us to give an order of magnitude of the degassing of N_2O. With a total water discharge below the dam of 150 m^3 s^{-1} in May and 70 m^3 s^{-1} in Dec., the estimate of the degassing of N_2O would be in the range of 30 to 120 Gg-CO_{2eq} y^{-1}. If this estimate of the degassing is taken into account, the contribution of N_2O to the total global warming potential of emissions from the PSR is $\sim$ 19–26%, the degassing of N_2O contributing only for 3–12% of the GWP of the total GHG emissions.

[13] In contrast to CH_4, N_2O emissions from tropical reservoirs occur mainly at the reservoir surface. The contribution of N_2O to gross GHG emissions is significant for some tropical reservoirs like the PSR. By contrast, in boreal areas, the flooding of soils resulted in turning the flooded surface from a N_2O source to a sink [*Hendzel et al.*, 2005] or does not have a significant impact on the N_2O emission [*Huttunen et al.*, 2002]. However, for most of the studied tropical reservoirs, the contribution of N_2O to

Table 3. Nitrous Oxide Emissions ($F(N_2O)$ From Natural Tropical Ecosystems[a]

Country	Environment	Season	$F(N_2O)$, μmol m^{-2} d^{-1} Mean	Range	n	Reference[b]
		Tropical Rivers				
French Guiana	Sinnamary[c]	W	100 ± 45	68–131	2	1
	Kourou	W	41 ± 9	32–50	3	1
Panama	Arena	D	35 ± 7	31–40	2	1
	Mellizas	D	<5	<5	2	1
	Bonita	D		<5–10	2	1
Brazil	Amazon mainstream	Y	6			2
	Amazon floodplains	Y	−0.3			2
French Guiana	*Marsh* (Pri Pri Yi-Yi)	W	51 ± 96	−66–145	5	1
		Tropical Soils				
French Guiana	Sinnamary Catch. (RF)	D	63 ± 30	32–100	4	3
	Sinnamary Catch. (RF)	D–W	83 ± 60	40–125	2	1
	Sinnamary Catch. (RF)	W	44 ± 52	−5–142	5	3
Brazil	Moist tropical forest	Y		6–131		4
	Amazon Basin	Y		27–47		4
	Rodônia (RF)	Y	63		52	5
	Mature Amazonian forest	Y	39			4
	Serra de Mesa Catch.	W	−20 ± 70		3	6
	Manso Catch.	W	−8 ± 33		2	6
Costa Rica	La selva (RF)	Y	114 ± 26	9–261		7
	Guacimo (RF)	Y	89 ± 16	48–166		8
Puerto Rico	Tabunoco Forest	Y	1.5			9
Venezuela	Rainforest	Y		16–72		10
	Savannah	Y		−6–13		10
		Y	−12			11
		Y	3.5			12

[a]RF, Rainforest; W, wet season; D, dry season; Y, yearly average; D–W, transition period between dry and wet season.
[b]References: 1, this study; 2, *Richey et al.* [1988]; 3, *Delmas et al.* [2001]; 4, *Davidson et al.* [2001]; 5, *Garcia-Montiel et al.* [2003]; 6, *Sikar et al.* [2005]; 7, *Keller and Reiners* [1994]; 8, *Liu et al.* [2000]; 9, *Keller et al.* [1986]; 10, *Sanhueza et al.* [1994]; 11, *Donoso et al.* [1993]; 12, *Hao et al.* [1988].
[c]Upstream of the PSR.

the global warming potential of emissions was less than 10% (Table 4).

3.4. Net N_2O Emissions From Tropical Reservoirs

[14] To properly take into account the anthropogenic perturbation related with the creation of reservoirs, only net emissions must be accounted for. Net emissions are gross emissions from the reservoir minus emissions from the pristine environment. In tropical areas, $F(N_2O)$ from the forest soils constituted most of the emissions from the watersheds. In Central Amazon, emissions from forest soils are in the range of 27–47 μmol (N_2O) m^{-2} d^{-1} in most of the area of the watershed, whereas emissions from the Amazon River and floodplain are in the range of −0.25–6 μmol (N_2O) m^{-2} d^{-1} on a restricted area (Table 3). On average, before impoundment of the PSR, the forest soils were estimated to emit 63 ± 20 μmol (N_2O) m^{-2} d^{-1} (Table 3). This pre-impoundment emission includes hilltop,

Table 4. CO_2, CH_4 and N_2O Emissions From Tropical Reservoirs[a]

Reservoir	Pathways	CO_2	CH_4	N_2O	$\%N_2O$
Petit Saut	Flux at the lake surface	275[b]	61[b]	140	30
	Degassing at the weir	34[b]	173[b]		
	Flux from the river below the dam[c]	138[b]	52[b]	3	<2
	Total Petit Saut	447	286	143	16
Fortuna	Diffusive flux at the lake surface	4.2[d]	0.6[d]	0.4	7
Manso[d,e]	Diffusive flux at the lake surface	−192	1	0.01	
Serra de Mesa[d,e]	Diffusive flux at the lake surface	419	0.2	0.4	<1
Tucurui	Flux at the lake surface	189460[f]	1315[g]	1715[h]	<1
Samuel	Flux at the lake surface	660[i]	297[j]	438[j]	31
	Flux from the river below the dam	120[k]	9[k]		
	Total Samuel	780	306	438	29

[a]Units are Gg-CO_{2eq} y^{-1}.
[b]*Abril et al.* [2005].
[c]Only the first 40 km below the PSR.
[d]A. Tremblay, unpublished data, 2003.
[e]*Sikar et al*, [2005].
[f]*dos Santos et al.* [2006].
[g]*Lima* [2005] and *dos Santos et al.* [2006], including bubbling.
[h]*Lima et al.* [2002].
[i]*Guérin et al.* [2006] and *dos Santos et al.* [2006].
[j]*Guérin et al.* [2006], *Lima* [2005] and *dos Santos et al.* [2006].
[k]*Guérin et al.* [2006].

hill slope and lowland sites during three distinct seasons. The soils of the tropical rainforest in French Guiana emitted similar amounts of N_2O as soils in the tropical rainforest in Brazil and Costa Rica (Table 3). Pre-dam N_2O emissions were thus 46% of the average N_2O emission from the reservoir surface (97 ± 61 μmol m^{-2} d^{-1}). If the degassing we assumed is taken into account, the impoundment of the PSR increased N_2O emissions from this surface area by 85 to 185%. Although the contribution of degassing of N_2O to the global warming potential of total emissions from the PSR is not significant, these theoretical calculations show that this pathway could potentially contribute to the landscape-scale N_2O exchange following the impoundment of tropical reservoirs. N_2O emission from the FR which floods tropical rainforest was 7 ± 11 μmol m^{-2} d^{-1}, which is 2 to 15 times lower than emissions from these pristine ecosystems in Costa Rica and Venezuela (Table 3). The Tucurui and Samuel Reservoirs also flood tropical rainforest area in the Amazon watershed. The reservoir surfaces of Tucurui and Samuel Reservoirs emitted on average 127 ± 93 and 218 ± 148 μmol m^{-2} d^{-1}, respectively (Table 2). Based on the values of N_2O fluxes from Brazilian and Costa Rican rainforests, the impact of flooding on N_2O emissions for these two reservoirs ranged from no change to an increase of the fluxes by 140%, the median value being 80% (Table 3). This last value should be taken with caution since N_2O fluxes from rainforest soils are highly variable and measurements for these soils are not available. The Manso and Serra de Mesa Reservoirs flood tropical savanna. A few data gathered in their watershed shows that the soil in these areas acted as N_2O sinks (Table 3), as also shown by *Donoso et al.* [1993] in Venezuelan savannas (Table 3). Nevertheless, the fluxes measured at the reservoir surfaces are still very close to emissions commonly found in tropical savannas (Table 3).

[15] There is a clear evidence of an increase of N_2O emissions by $\sim$50 to up to 185% after flooding the PSR. On the other hand, the flooding of the FR, Serra de Mesa and Manso Reservoirs had no significant effect on the net $F(N_2O)$. These results show that the maximum net contribution of N_2O emissions after flooding a tropical reservoir is $\sim$50–70% of gross N_2O emissions. Consequently, the maximum contribution of net N_2O emissions to the total GHG emissions from tropical reservoirs was less than 10% (Table 4). Of course, the contribution of net N_2O emissions must be compared to net GHG emissions from these man-made ecosystems. Unfortunately, it is currently not possible to estimate net CO_2 and CH_4 emissions from tropical reservoirs. Freshwater reservoirs inundate large amounts of OM from soils and plant biomass. In the pristine environment, plants sequester atmospheric CO_2 in photosynthesis and parts of the OM can be preserved in terrestrial ecosystems for decades to millennia before a fraction is respired and degassed as CO_2 in the aquatic ecosystems [*Cole and Caraco*, 2001]. The lag between the CO_2 pumping and degassing in the pristine environment compared to the large burst of CO_2 after flooding of the reservoirs make difficult the assessment of net CO_2 emissions from reservoirs. For CH_4, soils in tropical humid forest are net sinks [*Potter et al.*, 1996]. Terrestrial plants could produce CH_4 but the existence of this source is currently under debate [*Keppler et al.*, 2006; *Dueck et al.*, 2007]. Therefore, more studies dedicated to the determination of net GHG emissions from tropical reservoirs are needed to definitely assess the impact of damming on GHG emissions. Particularly, pre-dam emissions must be determined in the watershed where the dam will be or is built since, as shown with the example of N_2O emissions from soils, emissions vary significantly from one site to another for a given type of ecosystem (Table 3).

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