

Greenhouse gas emissions from reservoirs of the western United States

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[1] Six reservoirs located in the Western United States (F. D. Roosevelt, Dworshak, Wallula, Shasta, Oroville, and New Melones) were sampled in order to estimate their greenhouse gas (GHG) emissions. Two types of fluxes were assessed: (1) diffusive fluxes of methane (CH_4) and carbon dioxide (CO_2) at the air/water interface and (2) degassing fluxes of CH_4 and CO_2 from water passing through the turbine spillways. Diffusive flux measurements indicated that the surface of the reservoirs were a source of CH_4 during the sampling period (from +3.2 to +9.5 $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$). Oroville (+1026 $\text{mg CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) and Shasta (+1247 $\text{mg CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) surfaces were also sources of CO_2 . In contrast, the surface of all the other reservoirs constituted sinks for CO_2 (from -349 to -1195 $\text{mg CO}_2 \text{ m}^{-2} \text{ d}^{-1}$). Degassing fluxes ranged from +0.003 to +0.815 $\text{t CH}_4 \text{ d}^{-1}$, and from +16 to +324 $\text{t CO}_2 \text{ d}^{-1}$. Daily GHG budgets ranged from +0.146 to +2.228 $\text{t CH}_4 \text{ d}^{-1}$, and from -15 to +224 $\text{t CO}_2 \text{ d}^{-1}$. Degassing fluxes represented an important term of these budgets. A significant correlation was observed between the magnitude of CO_2 diffusive fluxes and the water pH ($R^2 = 0.81$; $p < 0.0001$). All other correlations between GHG diffusive fluxes and independent variables tested were weak and/or not significant. Finally, while attempting to resolve the spatial variability in diffusive fluxes, we were able to cluster reservoirs neither according to geological nor ecological criteria. *INDEX TERMS*: 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1857 Hydrology: Reservoirs (surface); 4820 Oceanography: Biological and Chemical: Gases; *KEYWORDS*: reservoirs, carbon dioxide, methane, diffusive fluxes, degassing fluxes, western United States, spatial variability

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1. Introduction

[2] Over the last decade, several field studies conducted worldwide have shown that reservoirs constitute sources of greenhouse gases (GHG) for the atmosphere [e.g., Rosenberg *et al.*, 1997; St. Louis *et al.*, 2000; Duchemin *et al.*, 2002]. However, so far, two important gaps still hamper the integration of these emissions into national anthropogenic GHG inventories. On the one hand, there is an obvious lack of data on emission patterns for reservoirs in several regions of the world. On the other hand, there is a high variability in the emission rates of reservoirs [Rosa and dos Santos, 2000; World Commission on Dams (WCD), 2000a], thus leading to

huge uncertainties when attempting to compute regional emission estimates for these perturbed environments.

[3] When addressing the issue of reservoir emissions in the context of the Americas, one must recall that data from the literature belong to the Canadian northern latitudes [Kelly *et al.*, 1994; Duchemin *et al.*, 1995; Kelly *et al.*, 1997; Schellhase *et al.*, 1997; Duchemin, 2000] and tropical latitudes (Brazil [Rosa and Schaeffer, 1994; Duchemin *et al.*, 2000; Matvienko *et al.*, 2000; Tavares de Lima *et al.*, 2000]; French Guyana [Galy-Lacaux *et al.*, 1997, 1999; Delmas *et al.*, 2001]; and Panama [Keller and Stallard, 1994]. Since the magnitude of GHG emissions from reservoirs is known to be partly governed by regional features such as geology, climate, and type of flooded soils and vegetation [WCD, 2000a], these previous studies may not properly depict the case of reservoirs located in temperate countries such as the

United States. This situation is of first concern, since the United States occupies the second rank worldwide in terms of the number of hydropower projects in operation, sheltering ~14% of the world's large dams [International Commission on Large Dams, 1998; WCD, 2000b].

[4] The primary objective of this paper is to increase the spatial coverage of GHG emissions from hydropower generation by supplying the first estimate for six reservoirs located in the western United States. First, we assess two types of fluxes: (1) diffusive fluxes of methane (CH_4) and carbon dioxide (CO_2) at the air/water interface and (2) degassing fluxes of CH_4 and CO_2 from water passing through the turbine spillways when electricity is produced. The latter fluxes are considered to be an important source of GHG for some hydroelectric dams [WCD, 2000a], and have been neglected in many previous studies. Second, we attempt to correlate the diffusive fluxes with some parameters outlined by the literature (for example, wind speed, dissolved organic carbon (DOC) content, water pH), in order to define which of these would influence the emissions of reservoirs. As a secondary objective, we address the issue of spatial variability of diffusive fluxes. We therefore attempt to cluster available data for the Americas in order to find a valid criterion for regional estimates of GHG fluxes from reservoir surfaces.

2. Study Zones and Selected Reservoirs

[5] The sampling campaign was held during September of 2001 in the Columbia River basin and in the Sierra Nevada region (Figure 1, <http://fermi.jhuapl.edu/states>; licensed by North Star Science and Technology). Both zones encompass several hydropower projects [Thornton, 1990; WCD, 2000a]. The former zone extends onto the states of Washington, Idaho, and Oregon. Its summertime climate is warm and dry, and key features of its vegetation are coniferous forests, grasslands, and xeric shrublands. The Sierra Nevada region is located along the eastern part of California. It has a semi-arid climate, and is characterized by oak savannas and chaparral.

[6] Three reservoirs were selected in each study zone. As shown in Table 1, these reservoirs differ in many of their features such as their location (geographical regions, geological provinces, and ecoregions), age, surface area, volume, and outflow. According to data obtained from the owning authorities, most reservoirs under study were almost at their lowest water level during the sampling period. Exceptions are F. D. Roosevelt and Wallula, which were near their highest water level. Both are supplied by the Columbia River, which is characterized by heavy and sustained water flows during late spring and early summer months.

3. Material and Methods

[7] Direct measurements of CH_4 and CO_2 diffusive fluxes at the air/water interface were carried out with static chambers [Duchemin et al., 1995]. The accuracy of this method was previously assessed in a valida-

tion experiment, which has shown that measurements obtained with our static chambers are good estimates of GHG diffusive fluxes under wind speeds ranging from 0 to 3 m s^{-1} . The static chamber is a rectangular prism opened at the lower end. Walls of the chamber are covered with a Mylar[®] sheeting to avoid any warming effect inside the chamber. A buoyancy collar is fitted around the chamber to ensure an air headspace of 35 L above the water surface. The lower end of the chamber is immersed about 25 cm below the surface and acts as a skirt to reduce the perturbation of the air/water interface.

[8] Four sampling sites were selected on each reservoir, both in littoral and pelagic zones. All works on a given site were conducted on the same day during the photoperiod, and the sampling of each reservoir was achieved within 2 days. To assess diffusive fluxes, two consecutive 1-hour measurement series were performed. During each series, four chambers were simultaneously deployed from the anchored boat. Using polypropylene syringes, 30-mL gas samples were collected from the chamber headspace every 20 min over the 1-hour period. Concurrent sampling of dissolved CH_4 and CO_2 along the water column were performed with a modified 3-L Kemmerer bottle. Duplicated 30-mL samples were drawn from the bottle through a gas-tight spigot with syringes. In addition, depth measurements, water temperature, oxygen (O_2), and pH profiles were taken with a YSI-6600 probe. Water samples were collected 15 cm below the surface for quantitative DOC analyses (Shimadzu TOC-5000A). Integrated wind speed and CH_4/CO_2 atmospheric concentrations were also measured.

[9] Upon return to the mobile laboratory, analyses of GHG were carried out within 12 hours. The gas chromatograph (Varian Star-3400) was equipped with a 1-mL sampling loop, a steel packed Haysep-Q column (203 mm-long, 3 mm in diameter, 80/100 mesh, isothermic oven at 50°C , He as carrier gas at 30 mL min^{-1}), a flame ionization detector (CH_4), and a thermal conductivity detector (CO_2). Detection limits relative to concentration changes inside the chambers (the smallest fluxes measurable) were $\pm 0.1 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ and $\pm 100 \text{ mg CO}_2 \text{ m}^{-2} \text{ d}^{-1}$. Aqueous samples (gas profiles) were allowed to reach the ambient temperature prior to analysis. While still in syringes, they were equilibrated with an equal volume of nitrogen by vigorous shaking, following the headspace technique described by McAuliffe [1971]. Water was then gently discarded and the gaseous phase was finally injected into the GC.

[10] Diffusive fluxes were calculated using linear regressions based on the concentration change of a given gaseous species over the 1-hour sampling period. Acceptance of the results was based upon three criteria: (1) initial gas concentrations inside the chamber had to be $\pm 10\%$ of those measured in the atmosphere; (2) correlation coefficients (R^2) had to be $>90\%$ for CH_4 and $>80\%$ for CO_2 ; and (3) regression slopes had to be significantly different from zero. Dissolved gas concentrations were calculated according to their solubility coefficients as a function of the temperature [Wilhelm

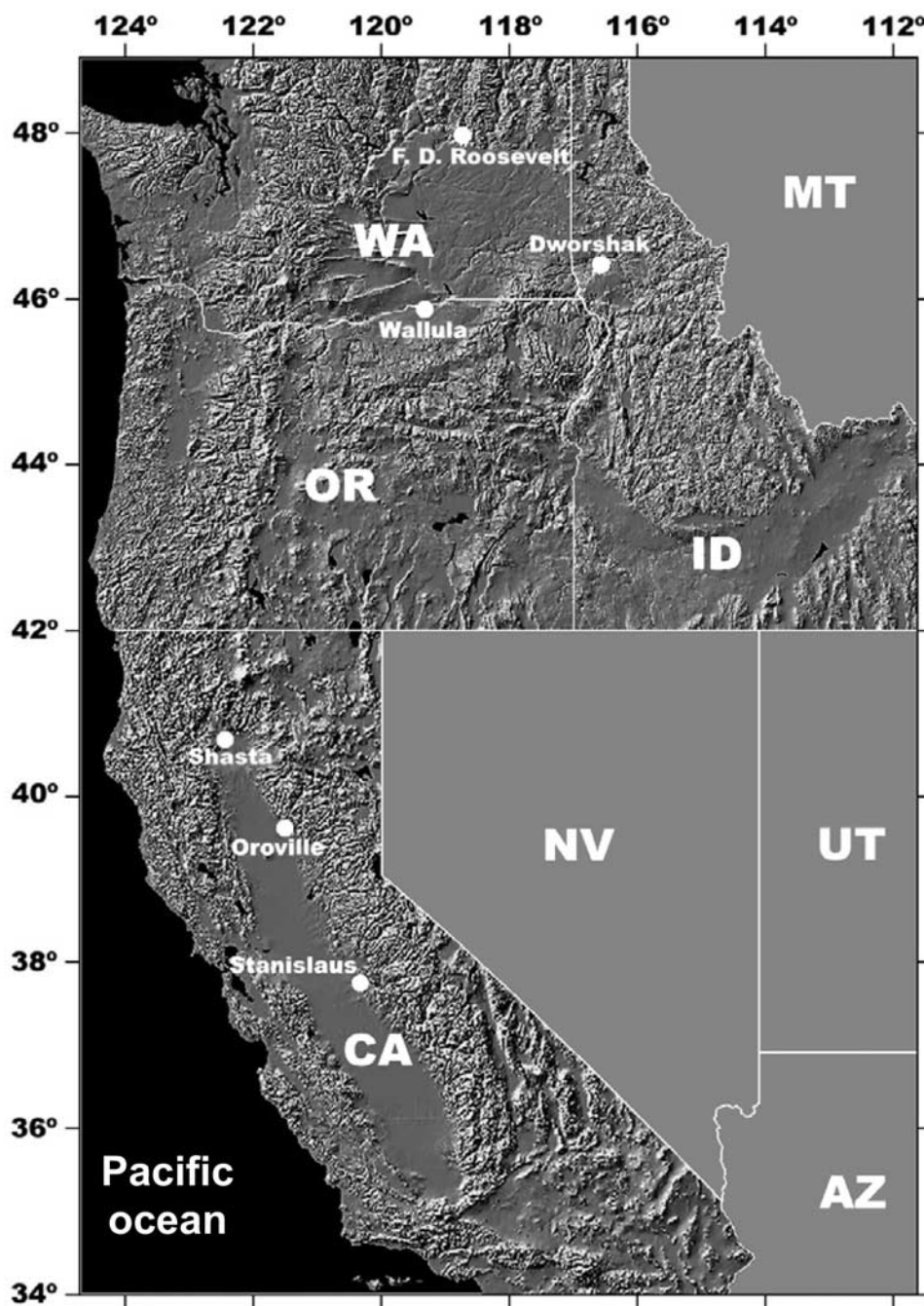


Figure 1. Location of the sampled reservoirs on the western United States map (modified from Ray Sterner, John Hopkins University Applied Physics Laboratory: <http://fermi.jhuapl.edu/states>; licensed by North Star Science and Technology).

et al., 1977]. To calculate the degassing fluxes from water passing through the turbine spillways, we used a method inspired by *Galy-Lacaux et al.* [1997]. For each reservoir, we first calculated integrated dissolved hypolimnetic CH_4 and CO_2 concentrations from gas profiles of all sampling sites. These figures are considered to reflect the CH_4 and CO_2 “upstream concentrations.” Following Henry’s law, we then computed hypothetical dissolved “downstream concentrations” in equilibrium

with the atmosphere, according to the water temperature and atmospheric concentrations of CH_4 and CO_2 . Using the equation below, we finally calculated the degassing fluxes using actual daily water outflows provided by authorities:

$$F = \frac{U - D}{O},$$

Table 1. Features of the Reservoirs Under Study^a

	F. D. Roosevelt	Dworshak	Wallula	Shasta	Oroville	New Melones
Dam	Coulee Dam	Dworshak	McNary	Shasta	Thermalito	New Melones
Location (dam)	47°57'18"N 118°59'00"W	46°31'00"N 116°18'W	45°56'14"N 119°15'12"W	40°43'12"N 122°25'12"W	39°33'20"N 121°28'00"W	37°57'10"N 120°31'00"W
State	Washington	Idaho	Oregon	California	California	California
Geographical region	Columbia basin	Columbia basin	Columbia basin	Sierra Nevada	Sierra Nevada	Sierra Nevada
Geological province	Columbia Plateau	Columbia Plateau	Columbia Plateau	Cascade Ranges	Sierra Nevada	Great Valley
Ecoregion (key number) ^b	NA0522	NA0518	NA1309	NA1202	NA1202	NA1202
Main tributary	Columbia	N. F. Clearwater	Columbia	Sacramento	Feather	Stanislaus
Priming date	1942	1973	1954	1944	1968	1979
Surface area, km ²	306 ^c	37 ^d	157 ^e	77 ^e	34 ^e	38 ^e
Maximum volume, m ³	1.16×10^{10}	4.3×10^9	0.23×10^9	5.8×10^9	4.4×10^9	3.8×10^9
Fluctuation, m	20	24	2	25	14	20
Daily outflow, m ³	1.52×10^8	3.54×10^6	1.97×10^8	1.56×10^7	3.29×10^6	4.79×10^6
Drainage basin, km ²	190,700	6250	548,000	17,065	9342	2315
Power capacity (MW)	6809	400	1120	629	939	300

^aData from U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and California Department of Water Resources.

^bNA0522, Okanagan dry forests; NA0518, North Central Rockies forests; NA1309, Snake-Columbia shrub steppe; NA1202, California interior chaparral and woodlands. Ecoregion names and key numbers according to World Wildlife Fund.

^cActual surface area when the reservoir was sampled.

^dSurface area at inferior limit of normal operating pool (actual surface area not available).

^eIndicates the annual water level fluctuation, i.e., the difference between the lowest and highest water levels registered during the year 2001.

^fDaily average for September 2001.

where F is daily degassing flux, U is upstream concentration, D is downstream concentration, and O is daily water outflow.

4. Results

4.1. Physico-Chemical Parameters of Reservoirs

[11] As indicated in Table 2, all reservoirs under study had slightly basic waters (pH: 7.51–8.71), as well as low surface DOC concentrations (1.061 – 2.783 mg C L⁻¹). The higher DOC content of the third sampling site on Shasta (6.607 mg C L⁻¹) may be attributed to its location near to the shore, where decaying vegetation was present. Most of the reservoirs were also thermally stratified. A thermocline was found 10 m below the surface at Dworshak, Shasta, Oroville, and New Melones. A thermocline at a depth of 20 m was found at F. D. Roosevelt reservoir, while no stratification was observed at Wallula.

4.2. Diffusive Flux Measurements at the Air/Water Interface of Reservoirs

[12] Through acceptance criteria stated earlier, 13% (CH₄) and 9% (CO₂) of diffusive flux measurements were rejected. According to Table 3, the air/water interface of all reservoirs acted as a source of CH₄ for the atmosphere. Mean effluxes were fairly similar between reservoirs, ranging from $+3.2$ to $+9.5$ mg CH₄ m⁻² d⁻¹. However, CO₂ fluxes were much more variable. Four out of the six reservoir surfaces constituted sinks for CO₂ during the daytime, with mean influxes ranging from -349 to -1195 mg CO₂ m⁻² d⁻¹. In contrast, Shasta and Oroville were a source of CO₂ for the atmosphere, with mean effluxes of $+1247$ and $+1026$ mg CO₂ m⁻² d⁻¹, respectively.

[13] We stress the fact that diffusive fluxes were not normally distributed in most cases, and this situation was much more frequent for CH₄ than for CO₂ (Table 3). Furthermore, paired Student's t tests pointed out significant differences in diffusive fluxes between the sampling sites of

a given reservoir (intra-reservoir variability). F. D. Roosevelt exhibited the lowest variability between sampling sites, both for CH₄ and CO₂. The greatest variability for CH₄ was found at Shasta, while the greatest variability for CO₂ was observed at Wallula. The inter-reservoir variability was also significant, as paired Student's t tests indicated the existence of three statistically distinct groups among studied reservoirs, both for CH₄ and CO₂ (Table 3).

4.3. Surface Flux Extrapolations, Degassing Fluxes, and Daily GHG Budgets

[14] Mean CH₄ and CO₂ diffusive fluxes of Table 3 were extrapolated to the whole surface area of each reservoir (Table 4). Although aware that the intra-reservoir variability may reduce the representativeness of such extrapolations, we nevertheless proceeded to calculate them in order to enable comparisons with degassing fluxes as well as to compute daily GHG budgets of reservoirs. So, when the whole reservoir surface is considered, Oroville was the smallest source of CH₄ for the atmosphere ($+0.143$ t CH₄ d⁻¹), while Wallula was the greatest one ($+1.413$ t CH₄ d⁻¹). Surfaces of Dworshak (-44 t CO₂ d⁻¹) and F. D. Roosevelt (-141 t CO₂ d⁻¹) were, respectively, the smallest and the greatest sinks for atmospheric CO₂. Surfaces of Oroville and Shasta, both sources of CO₂ for the atmosphere, emitted $+35$ and $+96$ t CO₂ d⁻¹, respectively. Figures for Dworshak underestimate fluxes of CH₄ and CO₂. As the actual surface area of Dworshak was not available, we performed the extrapolation according to its surface area at the inferior level of the normal operating pool, this reference level being slightly below the actual one.

[15] Integrated hypolimnetic GHG concentrations ranged from 0.05 (Oroville) to 0.26 (Wallula) μmol CH₄ L⁻¹ and from 41 (Wallula) to 200 (Shasta) μmol CO₂ L⁻¹ among reservoirs. The portion of CH₄ profiles considered while computing upstream concentrations were generally con-

Table 2. Physico-Chemical Characteristics of Sampling Sites (Daytime, September of 2001)^a

Site	Location	Depth, m	Thermocline, m	Temperature, ^b °C	pH ^b	[DOC], ^b mg C L ⁻¹	Wind Speed, ^c m s ⁻¹
<i>Roosevelt</i>							
1	47°54'N; 118°46'W	45	22	21.74	NA	2.690	2.90
2	47°56'N; 118°49'W	7	unstratified	22.26	8.36	2.549	1.40
3	47°56'N; 118°58'W	106	20	21.43	8.46	1.330	1.70
4	47°57'N; 118°55'W	17	unstratified	21.36	8.49	2.783	3.75
<i>Dworshak</i>							
1	46°34'N; 116°15'W	56	10	22.22	8.50	1.766	2.65
2	46°32'N; 116°17'W	166	10	22.36	8.61	1.678	2.95
3	46°38'N; 116°14'W	20	10	21.66	8.71	1.678	0.60
4	46°37'N; 116°08'W	18	9	21.46	NA	1.511	4.00
<i>Wallula</i>							
1	45°55'N; 119°10'W	17	unstratified	19.88	8.11	1.491	0.55
2	45°56'N; 119°04'W	15	unstratified	19.69	7.95	0.912	2.05
3	45°56'N; 119°13'W	15	unstratified	21.88	8.24	1.170	1.35
4	45°56'N; 119°15'W	25	unstratified	20.16	8.44	1.439	1.40
<i>Shasta</i>							
1	40°51'N; 122°23'W	21	11	23.54	7.51	1.925	2.05
2	40°50'N; 122°25'W	37	12	23.73	7.63	2.136	1.55
3	40°49'N; 122°23'W	53	10	23.57	7.77	6.607	0.45
4	40°44'N; 122°20'W	32	10	23.40	7.91	1.749	1.50
<i>Oroville</i>							
1	39°33'N; 121°26'W	72	10	23.80	7.82	0.937	0.45
2	39°33'N; 121°25'W	120	10	23.83	7.70	1.521	4.00
3	39°34'N; 121°28'W	152	14	24.48	7.81	1.162	2.60
4	39°33'N; 121°27'W	85	10	23.67	7.77	2.554	0.70
<i>New Melones</i>							
1	37°59'N; 120°31'W	46	10	23.80	8.22	1.431	1.00
2	37°57'N; 120°30'W	66	10	24.45	8.39	1.061	0.80
3	37°59'N; 120°32'W	8	unstratified	25.24	8.23	NA	2.90
4	37°56'N; 120°29'W	55	12	24.46	8.42	1.439	2.80

^aNA: data not available.^bMeasurements taken 15 cm below the air/water interface.^cIntegrated value over the sampling period. Measurements taken 1 m above the air/water interface.

stant, but sometimes showed sharp variations (Wallula and Shasta). Also, CO₂ profiles generally showed steep gradients with increasing depth. Downstream GHG concentrations at equilibrium were similar from one reservoir to another and were much lower than upstream concentrations, reaching ~0.03 μmol CH₄ L⁻¹ and ~14 μmol CO₂ L⁻¹. Consequently, degassing fluxes from water passing through the turbine spillways always constituted sources of GHG for the atmosphere, with emissions ranging from +0.003 to +0.815 t CH₄ d⁻¹ and from +16 to +324 t CO₂ d⁻¹ (Table 4).

[16] According to daily GHG budgets, all reservoirs were sources of CH₄ (from +0.146 t CH₄ d⁻¹ at Oroville to +2.228 t CH₄ d⁻¹ at Wallula) when both surface and degassing fluxes were considered (Table 4). In general, these reservoirs were also sources of CO₂ (from +53 t CO₂ d⁻¹ at Oroville to +224 t CO₂ d⁻¹ at Shasta), with the exception of New Melones and Dworshak, which both constituted small sinks for CO₂ (−15 and −25 t CO₂ d⁻¹, respectively). Generally speaking, GHG degassing fluxes were high enough to have a noticeable impact on the daily GHG budget of the reservoirs studied. This is particularly obvious in the case of F. D. Roosevelt and Wallula, where CO₂ degassing effluxes overwhelmed CO₂ influxes at the

air/water interface and consequently turned a sink into a source of CO₂.

5. Discussion

5.1. Limits and Validity of GHG Flux Measurements From This Study

[17] The previous validation experiment has shown that our static chambers allow for a good estimate of GHG transfers across the air/water interface. Also, wind conditions were appropriate (i.e., <3 m s⁻¹) for chamber deployment on most occasions (Table 2). Accordingly, we are confident that measurements made during this study are accurate. We presented our data on a daily basis instead of on a yearly one since biological, hydrologic, and physico-chemical conditions may fluctuate during the course of a year, hence drastically modifying the emission pattern of reservoirs. Such seasonal fluctuations in CH₄ and CO₂ partial pressures and fluxes have already been observed for natural lakes located in northern Minnesota and Wisconsin [Michmerhuizen *et al.*, 1996; Riera *et al.*, 1999]. Consequently, flux figures depicted in this paper only apply to the time of the year (September) covered by this study. Diel fluctuations in gas exchange patterns may be also

Table 3. Diffusive Fluxes of CH₄ and CO₂ From Reservoirs Under Study (Daytime, September of 2001)

Reservoir	Number of Observations	Range, ^a mg m ⁻² d ⁻¹	Median, ^a mg m ⁻² d ⁻¹	Mean, ^a mg m ⁻² d ⁻¹	Std Dev., ± mg m ⁻² d ⁻¹	Normality ^b (Prob > W)	Group ^c
<i>CH₄ Diffusive Fluxes</i>							
F. D. Roosevelt	27	+1.6 to +8.2	+2.3	+3.2	1.6	no (0.0010)	A
Dworshak	21	+0.6 to +14.8	+3.4	+4.4	3.2	no (0.0040)	A
Wallula	31	+3.5 to +17.0	+8.5	+9.0	3.5	yes (0.1874)	B/C
Shasta	28	-1.5 to +29.2	+11.1	+9.5	8.6	no (0.0037)	B
Oroville	25	+1.1 to +10.5	+3.6	+4.2	2.7	no (0.0119)	A
New Melones	31	+2.7 to +20.4	+6.4	+7.1	4.3	no (0.0001)	C
<i>CO₂ Diffusive Fluxes</i>							
F. D. Roosevelt	25	-852 to +251	-435	-462	260	yes (0.2052)	A
Dworshak	26	-2278 to -720	-1030	-1195	445	no (0.0015)	B
Wallula	28	-1629 to +1060	-417	-349	566	yes (0.2954)	A
Shasta	31	+351 to +2150	+1365	+1247	417	yes (0.9445)	C
Oroville	29	+266 to +2430	+634	+1026	652	no (0.0017)	C
New Melones	31	-3415 to -275	-1042	-1186	665	no (0.0025)	B

^aPositive sign indicates an efflux (reservoir is a source); negative sign indicates an influx (reservoir is a sink).

^bAccording to Shapiro-Wilk tests for normality. Test must show no difference (i.e., $p > 0.05$) to assume a normal distribution.

^cAccording to Student's paired t tests. Reservoirs from the same group have diffusive fluxes that are not statistically different.

suspected [Hamilton *et al.*, 1994; Hanson *et al.*, 2003]. It is possible that observed diurnal CO₂ influxes in several reservoirs are due to photosynthesis and thus these reservoirs would eventually turn into smaller sinks or even sources during the night. Although phytoplankton activity has not been assessed in this study, diffusive flux measurements performed on Dworshak at dusk (data not included in calculations) suggest such a diel cycle. Indeed, mean CO₂ flux at this moment (-455 ± 12 mg CO₂ m⁻² d⁻¹) was 2–3 times lower than those measured during the daytime.

[18] The reliability of the approach used to estimate degassing fluxes hinges on assumptions that deserve some comments. First, we assumed that the integrated hypolimnetic CH₄ and CO₂ concentrations we computed would reflect upstream GHG concentrations. However, along the portion of the gas profile that was considered for calculations, CH₄ concentrations varied up to two-fold, while CO₂ ones varied up to 2.5-fold. It is also possible that contrary to what our approach supposed, water outlets on the dams were actually located above the hypolimnion. We thus consider that the variations in gas profiles as well as the depth of outlets are two critical issues which may affect the representativeness of the upstream computed data. Second, by using downstream GHG concentrations in equilibrium with the atmosphere, we assumed that most of the GHG coming from the reservoirs would eventually escape toward the atmosphere

along the rivers downstream of the dams. This hypothesis is supported by Galy-Lacaux *et al.* [1997], who showed that concentrations of dissolved gases tended to zero several kilometers downstream of the dam. Such an approach also avoided important sampling problems such as unmixed water zones and in-stream production of GHG. However, we may have overestimated degassing fluxes since, as direct measurements have shown, rivers downstream of reservoirs were oversaturated (up to 0.10 μmol CH₄ L⁻¹ and 83 μmol CO₂ L⁻¹) a few meters past the dams.

5.2. Correlating GHG Diffusive Fluxes With Environmental Parameters

[19] Regression analyses indicated a good ($R^2 = 0.81$) and very highly significant ($p < 0.001$) correlation between CO₂ diffusive fluxes and the surface pH (Table 5). According to the regression equation, the pH value 8.10 may be seen as a “boundary” dividing our data set into influxes and effluxes (Figure 2). The total inorganic carbon (ΣCO₂) concentration in fresh water depends on the pH. The latter is largely governed by the buffering reactions of carbonic acid and the amount of bicarbonate and carbonate derived from the weathering of surrounding rocks [Lampert and Sommer, 1997; Wetzel, 2001]. As a matter of fact, pH measurements were generally in good agreement with the geological features of watersheds. Now, in buffered, carbonate-rich hard waters of the mid-

Table 4. Daily GHG Budgets of Reservoirs Under Study (Daytime, September of 2001)

Reservoir	Extrapolated Surface Fluxes, ^a t d ⁻¹		Degassing Fluxes, ^a t d ⁻¹		Total Fluxes, ^a t d ⁻¹	
	CH ₄	CO ₂	CH ₄	CO ₂	CH ₄	CO ₂
F.D. Roosevelt	+0.979 ± 0.490	-141 ± 80	+0.176 ± 0.071	+324 ± 95	+1.155 ± 0.495	+183 ± 124
Dworshak	+0.163 ± 0.118	-44 ± 16	+0.006 ± 0.002	+16 ± 4	+0.150 ± 0.118	-25 ± 17
Wallula	+1.413 ± 0.550	-55 ± 89	+0.815 ± 0.276	+224 ± 56	+2.228 ± 0.615	+169 ± 105
Shasta	+0.732 ± 0.662	+96 ± 32	+0.067 ± 0.019	+128 ± 30	+0.799 ± 0.662	+224 ± 44
Oroville	+0.143 ± 0.092	+35 ± 22	+0.003 ± 0.001	+18 ± 5	+0.146 ± 0.092	+53 ± 23
New Melones	+0.270 ± 0.163	-45 ± 25	+0.004 ± 0.002	+30 ± 9	+0.274 ± 0.163	-15 ± 27

^aPositive sign indicates an efflux (reservoir is a source); negative sign indicates an influx (reservoir is a sink). Indicated errors are standard deviations.

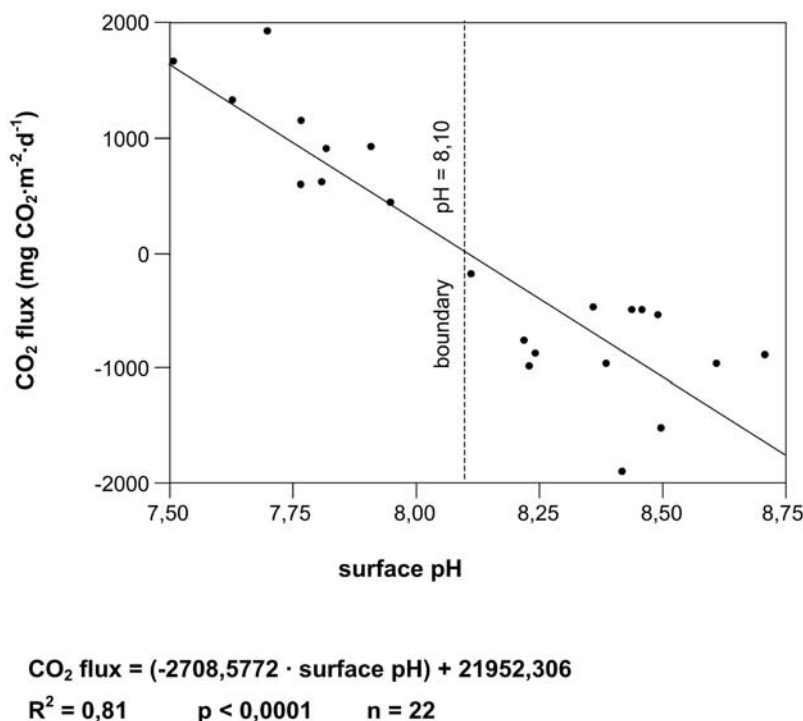


Figure 2. Relationship between CO_2 diffusive fluxes and surface pH. The dashed line indicates the “boundary” (pH = 8.10) between influxes and effluxes.

western United States, the dissolved CO_2 is independent of pH and its concentration is strongly influenced by photosynthesis and respiration processes [Wetzel, 2001]. Although neither biological activity nor trophic state of reservoirs were assessed during the course of this study, we hypothesize that differences in CO_2 fluxes among reservoirs are due to their metabolic balance. As we previously supposed in the case of Dworshak, photosynthesis seemed to play an important role in the withdrawal of dissolved CO_2 .

[20] All the other correlations tested in Table 5 remained weak and/or not significant. However, the relation between CH_4 diffusive fluxes and the depth, although weak ($R^2 = 0.15$), was nevertheless almost significant ($p = 0.0594$). CH_4 is exclusively formed in anaerobic environments [Daniels *et al.*, 1984; Utsumi *et al.*, 1998], and therefore it is mostly produced in anoxic sediments. This gas is then partially mineralized into CO_2 through aerobic oxidation by methanotrophic bacteria in the oxic layer of sediments or in the water column, and only the unoxidized fraction escapes to the atmosphere as CH_4 [Frenzel *et al.*, 1990; King *et al.*, 1990; Scranton *et al.*, 1993]. Oxygen profiles performed during this study (data not shown) indicated that reservoirs generally had well-oxygenated water columns, with relative O_2 concentrations ranging from 66 to 146% at the surface and from 45 to 118% at the bottom. This suggests that CH_4 oxidation occurred in the sediments of most reservoirs under study. CH_4 was further oxidized along the water column and, as indicated by the equation in Table 5, CH_4 diffusive fluxes decreased with increasing depth as it

allows for a longer vertical distance over which CH_4 can be mineralized [Fearnside, 2002]. Since depth accounted for only 15% of the CH_4 flux variation, differences between reservoirs seem to be principally due to methanogenic and methanotrophic activities occurring in sediments, rather than to CH_4 oxidation processes along the water column.

[21] The fact that we did not observe any significant correlation between GHG diffusive fluxes and most of the parameters tested in this study may seem paradoxical since many have already been identified as influential on GHG emissions [WCD, 2000a]. In some cases, we even observed opposite tendencies when compared to other studies. This is the case with the age of reservoirs, for which we observed an increase in both CH_4 and CO_2 fluxes as the reservoirs get older, which contradicts the finding that GHG fluxes, especially CO_2 , decrease with the age of reservoirs [St. Louis *et al.*, 2000; Duchemin *et al.*, 2002]. Contradictions with the literature were also found in the case of CO_2 fluxes versus wind speed, for which we observed a decrease in fluxes as the wind became stronger. Although gas exchanges across the air/water interface seem to be independent of wind at low wind speeds [Cole and Caraco, 1998; Crusius and Wanninkhof, 2003], some studies suggest a positive link between CO_2 fluxes and wind speed [e.g., Duchemin *et al.*, 1999, 2000]. Such discrepancies regarding influential parameters from one study to another are difficult to explain. However, we suggest that the parameter range may play an important role in determining if a specific parameter has any effect on GHG diffusive fluxes. For

Table 5. Results of Linear Regressions Attempting to Correlate GHG Diffusive Fluxes With Selected Parameters

Parameter (x)	Regression Equation (y = CH ₄ or CO ₂ Flux)	Number of Observations	R ²	Prob > F
<i>CH₄ Diffusive Fluxes</i>				
Age of reservoir ^a	$y = (0.0313223x) + 4.9177961$	6	0.03	0.7298
Reservoir surface area ^a	$\log_{10}(y) = (-0.0006154x) + 0.825749$	6	0.12	0.5105
Drainage basin surface area ^a	$y = (0.0000041x) + 5.7090508$	6	0.11	0.5214
DB/R surface area ratio ^{a,b}	$y = (0.0008697x) + 5.5317615$	6	0.19	0.3923
Sampling site depth	$\log_{10}(y) = (-0.0029388x) + 0.8274957$	24	0.15	0.0594
Surface water temperature	$\log_{10}(y) = (-1.119674 \times \log_{10}(x)) + 2.1904882$	24	0.01	0.6416
Surface water pH	$y = (-4.4758135x) + 42.731564$	22	0.11	0.1307
Surface [DOC] ^c	$\log_{10}(y) = (-0.089158x) + 0.8292649$	22	0.02	0.5134
Integrated wind speed	$\log_{10}(y) = (0.2375156 \times \log_{10}(x)) + 0.6276823$	24	0.05	0.3163
<i>CO₂ Diffusive Fluxes</i>				
Age of reservoir ^a	$\log_{10}(y + 1920) = (5.1993104 \times \log_{10}(x)) - 5.903661$	6	0.57	0.0808
Reservoir surface area ^a	$\log_{10}(y + 1920) = (1.3332936 \times \log_{10}(x)) - 0.102846$	6	0.20	0.3719
Drainage basin surface area ^a	$\log_{10}(y + 1920) = (0.6816005 \times \log_{10}(x)) - 0.600469$	6	0.29	0.2739
DB/R surface area ratio ^{a,b}	$\log_{10}(y + 1920) = (1.031337 \times \log_{10}(x)) - 0.204927$	6	0.28	0.2829
Sampling site depth	$y = (538.72624 \times \log_{10}(x)) - 985.0241$	24	0.04	0.3514
Surface water temperature	$y = (130.49741x) - 3100.405$	24	0.04	0.3651
Surface water pH	$y = (-2708.5772x) + 21,952.306$	22	0.81	<0.001
Surface [DOC] ^c	$y = (354.98829 \times \log_{10}(x)) - 232.2801$	22	<0.01	0.8319
Integrated wind speed	$y = (-132.59481x) + 112.60919$	24	0.02	0.5020

^aThese linear regressions were conducted with mean fluxes for each reservoir.

^bDrainage basin/reservoir surface area ratio.

^cSampling site 3 at Shasta ([DOC] = 6.607 mg C L⁻¹) was rejected.

instance, *Hope et al.* [1996], who worked on Wisconsin lakes spanning over a broad range of DOC concentrations (from 1.8 to 19.2 mg C L⁻¹), found a fair and very highly significant correlation ($R^2 = 0.52$; $p < 0.001$) with $p\text{CO}_2$ which can be linked to CO₂ diffusive fluxes, whereas in the present study, where reservoirs spanned over a much more narrow DOC range, no correlation was found between this parameter and CO₂ diffusive fluxes.

5.3. Comparison and Regional Clustering of Reservoirs

[22] Over the last years, studies conducted on reservoirs of the Americas enabled us to gain insights into the differences in their emission patterns, and if we compare the latter on a geographical basis (Figure 3), some observations can be drawn. First, the several geographical groups for which data are available generally differ in their CH₄ and CO₂ flux ranges, although some overlapping is observed. For instance, CH₄ emissions of the “Eastern Canada” group overlap with the upper part of the “Western US” range and the lower part of the “Central/South America” range. Overlapping in CO₂ flux ranges is also found between the “Western Canada,” “Eastern Canada,” and Central/South America groups. Second, it appears that the “Western US” group has the lowest CH₄ and CO₂ emissions, with mean fluxes of 6.2 mg CH₄ m⁻² d⁻¹ and -153 mg CO₂ m⁻² d⁻¹. In comparison to the Eastern Canadian reservoirs, these temperate reservoirs are generally older and located in regions where terrestrial vegetation is scarce, with very little or no peat accumulation. They are also located in valleys surrounded by hilly reliefs, and therefore relatively small areas of land were inundated. Such characteristics suggest small amounts of decomposable soils, slight allochthonous inputs, and subsequently low decomposition rates by heterotrophic organisms leading to relatively weak

emissions, or even invasion, of CO₂. Moreover, the high O₂ contents along their water columns and in the upper layer of sediments seem to enable methanotrophy to a large extent. In contrast, the “Central/South America” group is associated with the highest emissions, both for CH₄ (126.6 mg m⁻² d⁻¹) and CO₂ (3133 mg m⁻² d⁻¹). These tropical reservoirs are known for their high decomposition rates and their oxygen deficit which lead to high CH₄ emissions [*Fornarolli-Andrade et al.*, 1997; *Galey-Lacaux et al.*, 1997, 1999].

[23] Figure 3 only presents a gross overview of the regional tendencies. Indeed, it must not be overlooked that the several studies consulted were performed at different times of the year with reservoirs that probably differ in many of their features. Moreover, it must not be overlooked that different methods have been used to assess diffusive fluxes from reservoirs. Some studies have already shown that important discrepancies may exist between results obtained using these methods [*Duchemin et al.*, 1999; *Matthews et al.*, 2003]. Nevertheless, Figure 3 underlines regional differences in the flux ranges of the reservoirs, which are probably caused by the distinct biological, climatic, and geological conditions inside a given geographical group. For this reason, we hereafter attempt to validate geological or ecological criteria in order to cluster reservoirs and develop acceptable regional estimates of GHG emissions from reservoirs. The six reservoirs under study are distributed in distinct geological provinces and ecoregions (Table 1). According to Table 3, there are two statistically distinct groups for CH₄ and CO₂ fluxes among reservoirs of the Columbia Plateau province (F. D. Roosevelt, Dworshak, and Wallula), the presence of which indicates differences when geological clustering is attempted. Furthermore, the presence of two (CO₂) or even three (CH₄) statistical groups among reservoirs

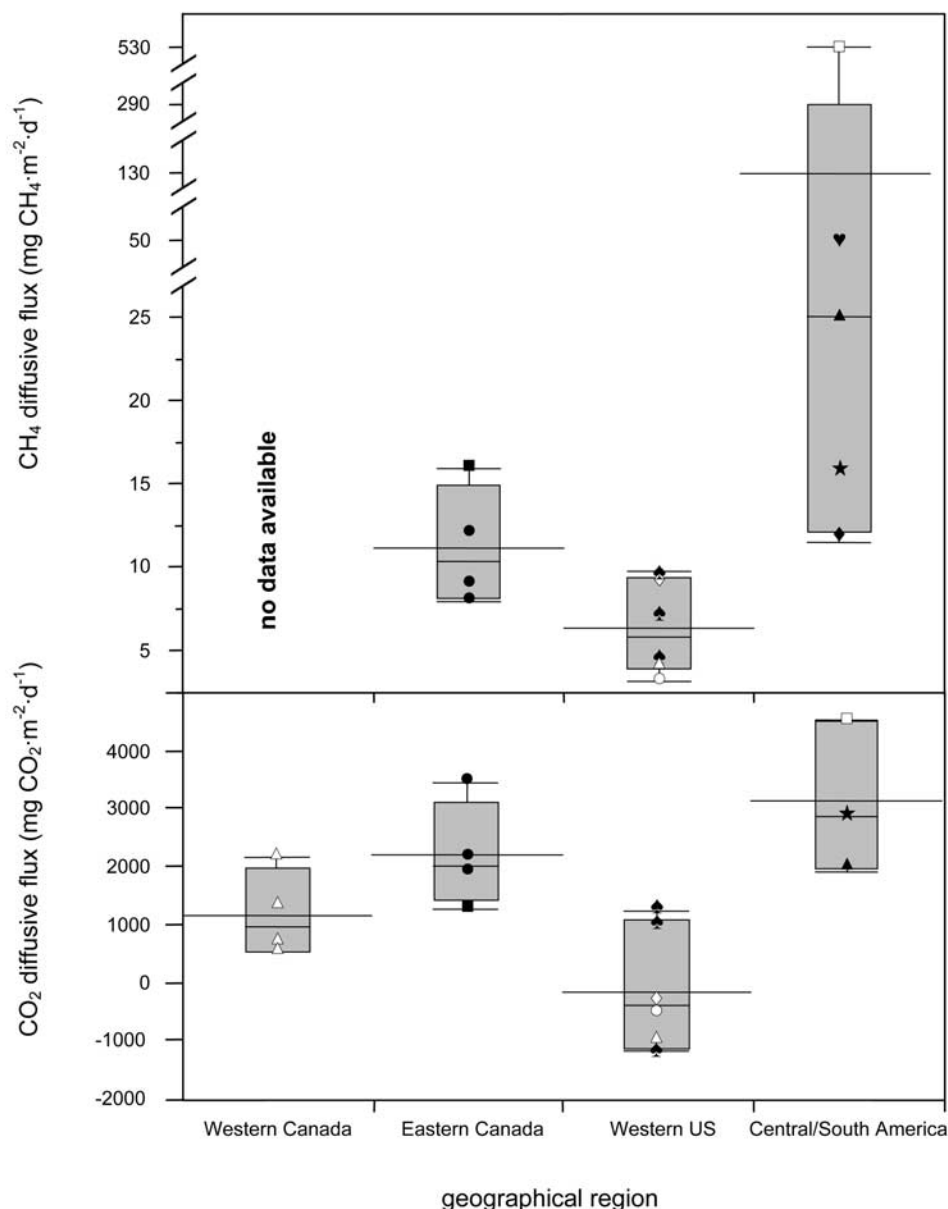


Figure 3. Comparison of CH_4 and CO_2 diffusive fluxes of reservoirs from different geographical regions of the Americas. Each geographical region encompasses several ecoregions: solid squares, eastern forest-boreal transition; solid circles, Eastern Canadian Shield taiga; open triangles, North Central Rockies forests; solid spades California interior chaparral and woodlands; open diamonds, Snake-Columbia shrub steppe; open circles, Okanagan dry forests; open squares, Guianan moist forests; solid hearts, Xingu-Tocantins-Araguaia moist forests; solid triangles Cerrado; solid stars, Tapajós-Xingu moist forests; solid diamonds, Isthmian-Atlantic moist forests (ecoregion names according to World Wildlife Fund). Emission figures are from Keller and Stallard [1994]; Kelly *et al.* [1994]; Galy-Lacaux *et al.* [1997]; Schellhase *et al.* [1997]; Duchemin [2000]; Duchemin *et al.* [2000]; Novo, from Duchemin *et al.* [2000].

of the “California interior chaparral and woodlands” ecoregion (Shasta, Oroville, and New Melones) also highlights distinct emission patterns among an ecological clustering of reservoirs. The same conclusions can be drawn from the emission figures of reservoirs obtained from previous studies conducted in the Americas, where

a huge variability remains among a given ecoregion (Figure 3). Such is the case for the “North Central Rockies forests” (for CO_2) or “Eastern Canadian Shield taiga” (both for CH_4 and CO_2) ecoregions. Consequently, we cannot validate the use of geological nor ecological criteria in order to cluster reservoirs.

6. Conclusions

[24] The present study has shown that reservoirs generally constitute an appreciable source of both CH₄ and CO₂ for the atmosphere when considering their total GHG budgets (diffusive and degassing fluxes). For this reason, reservoirs must be included in national anthropogenic GHG inventories. Our data also indicate that the GHG degassing fluxes from water passing through the turbine spillway were important enough to influence the total GHG budget of reservoirs. This type of flux should therefore be taken into account in future studies attempting to estimate the GHG emissions from reservoirs. However, in order to refine degassing flux estimates, special attention must be paid to the accuracy of information concerning the depth of the water outlets on the dams and the particular hydrodynamics of water masses, as well as upstream and downstream dissolved GHG concentrations.

[25] This study has also shown that reservoir surfaces can sometimes act as a sink for atmospheric CO₂, as was the case for F. D. Roosevelt, Dworshak, Wallula, and New Melones. However, since this study is confined to the month of September of a single year, it would be a difficult task to extrapolate emission patterns of the studied reservoirs over the course of a year or their whole lifetime. When compared to other regions of the Americas, it appears that reservoirs of the Western United States have the smallest GHG emissions at their air/water interface, both for CH₄ and CO₂. These reservoirs might be low GHG emitters because of their age, their low amount of flooded organic matter and allochthonous inputs, their highly oxidic conditions which lead to an important consumption of CH₄, and a suspected great role for photosynthesis in the withdrawal of CO₂. The latter remarks about emission rates are however limited in space by the fact that this study applies to only two geographical regions of the western United States.

[26] Finally, emission patterns from the reservoirs of the Americas seem to be distinct from one geographical region to another. Nevertheless, each region encompasses large variabilities, thereby complicating estimates at a regional level. While trying to cluster reservoirs in order to reduce spatial variability and obtain reasonable regional estimates, our work failed to validate either geological or ecological criteria. Furthermore, this shortcoming seems to apply to other regional groups of reservoirs assessed in previous studies. On the basis of this result, it appears that besides influences arising from the watershed (macroscale level), reservoir GHG emission patterns are probably strongly driven by their internal biological and physico-chemical characteristics at a mesoscale or microscale level [Thornton, 1990].

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