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Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: A Global Estimate

VINCENT L. ST. LOUIS, CAROL A. KELLY, ÉRIC DUCHEMIN, JOHN W. M. RUDD, AND DAVID M. ROSENBERG

Following flooding of landscapes to create any kind of reservoir, terrestrial plants die and no longer assimilate carbon dioxide (CO_2) by photosynthesis (Figure 1), resulting in the loss of a sink for atmospheric CO_2. In addition, bacteria decompose the organic carbon that was stored in plants and soils, converting it to CO_2 and methane (CH_4), which are then released to the atmosphere. All of the reservoirs examined to date emit CO_2 and CH_4 to the atmosphere (Table 1), but different landscapes contain different amounts of stored organic carbon in soils and vegetation (Schlesinger 1997), and so the potential for gas production and loss varies from site to site. For example, in the boreal region of Canada, a worst-case scenario is flooded peatlands because they possess a large store of organic carbon held in peat, which can decompose and be returned to the atmosphere as greenhouse gases over a long period (Kelly et al. 1997). Reservoirs that flood peatlands probably emit more greenhouse gases in the long term than reservoirs created over upland boreal forests, which have thin soil layers and no peat deposits.

The first studies of greenhouse gas fluxes from reservoirs focused on hydroelectric generation (Rudd et al. 1993, Kelly et al. 1994, Duchemin et al. 1995) because it was, and still is, widely viewed as a carbon-free source of energy (Hoffert et al. 1998, Victor 1998). This view likely originated because before 1994, there were no data available on CO_2 and CH_4 emissions from reservoirs, even though it was well known that oxygen depletion resulting from active decomposition of flooded organic matter was common in waters of newly constructed reservoirs (Baxter and Glaude 1980). The first discussion of greenhouse gas emissions from reservoirs (Rudd et al. 1993) pointed out that greenhouse gas production per unit of power generated (e.g., in kWh) is not zero and should depend on the amount of organic carbon flooded to create the electricity. For example, reservoirs that flood large areas to produce few kWh, such as those built in areas with low topographical relief, would produce more greenhouse gases per kWh than reservoirs built in canyons where little area is flooded and large amounts of electricity are produced.

RESERVOIRS ARE SOURCES OF GREENHOUSE GASES TO THE ATMOSPHERE, AND THEIR SURFACE AREAS HAVE INCREASED TO THE POINT WHERE THEY SHOULD BE INCLUDED IN GLOBAL INVENTORIES OF ANTHROPOGENIC EMISSIONS OF GREENHOUSE GASES

A more recent concern is the global impact of reservoir construction on greenhouse gas emissions. Most reservoirs are developed not for hydroelectric production but rather for other purposes, including flood control, water supply, irrigation, navigation, recreation, and aquaculture

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(ICOLD 1998). The determination of the global effect of all types of reservoirs on the atmosphere requires two general pieces of information: flux measurements from reservoirs that vary in amount of organic carbon flooded, age, and global distribution; and the surface area of all reservoirs around the world. In this article, we examine the range of greenhouse gas fluxes available to date from both temperate and tropical reservoirs and assess the quantity and quality of data available for the global surface area of reservoirs. Although there are uncertainties in both flux and surface area information, it is important to ask the question: Could these emissions be significant on a global basis, and should we be improving our knowledge of this aspect of reservoir development? Initial calculations indicate that, globally, these emissions may be equivalent to 7% of the global warming potential of other documented anthropogenic emissions of these gases. This percentage is similar to contributions from other currently inventoried sources. As a result, we argue that these fluxes should be included in greenhouse gas inventories by country and in models of global carbon cycling.

Measuring fluxes of greenhouse gases from reservoir surfaces

Fluxes of greenhouse gases from water surfaces can be quantified using a number of techniques (Kelly et al. 1997, Cole and Caraco 1998, Duchemin et al. 1999). For example, floating static chambers have been used to estimate the diffusive flux of CO_2 and CH_4 from the surface of reservoirs by calculating the linear rate of gas accumulation in the chambers over time (Figure 2). Diffusive flux of CO_2 and CH_4 from reservoir surfaces has also been estimated using the thin boundary layer method (Liss and Slater 1974). This calculated flux requires knowledge of the concentration gradient between the water and the air of either CO_2 or CH_4 and the gas exchange coefficient for the given gas at a given temperature. The concentration gradient is expressed as the difference between the measured partial pressure of dissolved gas in the water and the calculated partial pressure of the gas in the water if it were in equilibrium with the atmosphere. The gas exchange coefficient can simply be derived as a function of wind speed or of the rate of removal of gases from just above the water surface. Gases formed in decomposing organic matter at the bottom of reservoirs that ebullate directly to the reservoir surface in bubbles are measured using inverted funnel traps.

Several studies have compared the chamber and thin boundary layer techniques (Kelly et al. 1997, Cole and Caraco 1998, Duchemin et al. 1999). For the wind speeds and conditions used to calculate fluxes from the surface of an experimentally created reservoir at the Experimental Lakes Area (ELA) in Ontario, Canada, agreement between the chamber and thin boundary layer techniques was very good (Kelly et al. 1997) and fluxes measured also agreed with a third micrometeorological flux-gradient technique

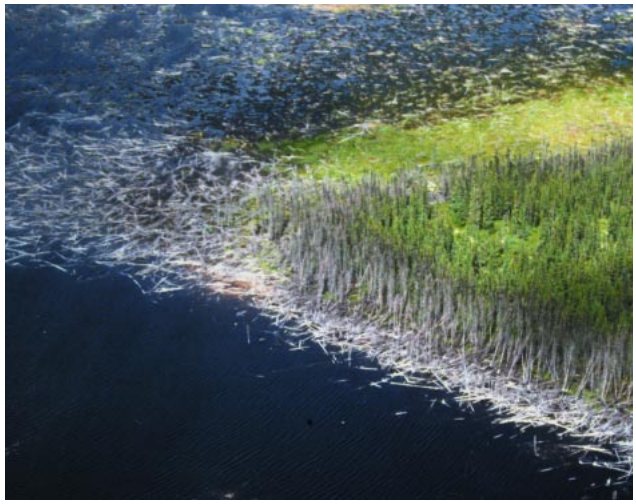

Figure 1. Dead trees and snags along the shore of a northern Canadian reservoir. Foliage from these trees, and labile soil carbon such as that found in leaf litter, decomposes initially and rapidly after flooding. Trunks of trees decompose little over time at the bottom of reservoirs. Photo courtesy of V. L. St. Louis.

(e.g., Chan et al. 1998). However, other studies found that the thin boundary layer method underestimated the flux measured by chambers (Duchemin et al. 1999) and sulfur hexaflouride (SF_6) loss, especially at low wind speeds (less than 2 m/sec; Cole and Caraco 1998). In practice, the methods chosen to determine fluxes from reservoirs to the atmosphere are dictated by local conditions at the sampling site. For example, flooded tree snags or backwater bays are sheltered conditions, favoring the use of chambers because of their low and variable wind speeds. Conversely, chambers are often difficult to deploy in open stretches of

Figure 2. A static floating chamber deployed in the backwaters of the Experimental Lakes Area Reservoir Project reservoir. Fluxes of CO_2 and CH_4 from the surface of the reservoir are calculated by measuring the rate of buildup of these gases over time inside the chamber. Photo courtesy of V. L. St. Louis.

Table 1. Fluxes of CO_2 and CH_4 from the surface of temperate and tropical reservoirs of different sizes and ages.

Location	Reservoir	Area (km^2)	Age (yr)	Type of flux[a]	Number of measurements[a]	Areal flux[b] ($mg \cdot m^2 \cdot d$)		References
						CO_2	CH_4	
Temperate								
Canada								
Quebec	Laforge-1	1000	1–5	D & B	182D/37B	2300 (200–8500)	13 (1–130)	Duchemin et al. 1995, Duchemin 2000
Quebec	Robert-Bourassa	2500	12–19	D & B	106D/14B	1500 (160–12,000)	13 (1–100)	Kelly et al. 1994, Duchemin et al. 1995, Duchemin 2000
Quebec	Eastmain-Opinica	1000	12–13	D	4	3450 (2200–4300)	8 (4–15)	Kelly et al. 1994
Quebec	Cabonga	400	68–70	D & B	104D/37B	1400 (320–4800)	18 (2–260)	Duchemin et al. 1995, Duchemin 2000
British Columbia	Revelstoke	120	8	D	11	2200 (1560–3000)	nm[d]	Schellhase et al. 1997
British Columbia	Kinsbasket	430	19	D	6	530 (460–600)	nm	Schellhase et al. 1997
British Columbia	Arrow	520	22	D	16	1300 (570–1770)	nm	Schellhase et al. 1997
British Columbia	Whatshan	15	40	D	8	670 (540–790)	nm	Schellhase et al. 1997
Ontario	ELARP[e,f]	0.2	1–2	D & B	hundreds	2000 (1100–3700)	54 (50–90)	Kelly et al. 1997
United States								
Colorado	Dillon Lake	13	26–27	D	14	nm	21 (12–60)	Smith and Lewis 1992
Wisconsin[c]	Day Lake	2	29	D	570	700 (600–800)	7 (6–8)	Carol A. Kelly and John W. M. Rudd, unpublished data
Wisconsin[c]	Tigercat Lake	3	60	D	570	220 (180–250)	11 (9–12)	Carol A. Kelly and John W. M. Rudd, unpublished data
Wisconsin[c]	Nelson Lake	25	61	D	570	710 (620–800)	6 (5–6)	Carol A. Kelly and John W. M. Rudd, unpublished data
Wisconsin[c]	Chippewa Lake	61	73	D	570	390 (340–450)	7 (6–8)	Carol A. Kelly and John W. M. Rudd, unpublished data
Wisconsin[c]	Moose Lake	7	73	D	570	1300 (1100–1400)	3	Carol A. Kelly and John W. M. Rudd, unpublished data
Finland	Lokka[f]	417	28	D & B	approx 75	2000 (770–3400)	79 (11–250)	Hellsten et al. 1996
Finland	Porttipahta[f]	214	25	D & B	approx 75	2100 (1360–3300)	13 (12–15)	Hellsten et al. 1996
Average fluxes						*1400 (750–3100)*	*20 (10–80)*	
Tropical								
Central/South America								
Panama	Gatun Lake	430	78	D & B	hundreds	nm	537 (59–1310)	Keller and Stallard 1994
Brazil	Curua-Una	72	21–22	D & B	27D/94B	2900 (330–10,000)	65 (2–680)	Duchemin et al. in press
Brazil	Serra da Mesa	1784	1	D & B	not given	4000	80	Matavienko et al. in press
Brazil	Tucurui	2800	13	D & B	14	nm	75 (20–140)	Tavares et al. in press
French Guyana	Petit Saut	300	1–2	D & B	10 (CO_2); 40 (CH_4)	4460 (580–10,500)	1140 (5–3800)	Galy-Lacaux et al. 1997
Average fluxes						*3500 (450–10,200)*[g]	*300 (20–1500)*[g]	

[a]D, diffusive (thin boundary layer method, static chambers); B, bubble; D & B, combined flux.
[b]Areal fluxes are best estimates from a number of studies or average flux given in reference cited. Range of fluxes measured (low–high), when available from the references, are presented in parentheses. Average fluxes from temperate reservoir surfaces are from the ice-free season only.
[c]All Wisconsin reservoir fluxes were calculated from average partial pressures of dissolved CO2 and CH4 measured monthly during the ice-free season in 1995 and assuming a wind speed of 2.5–3 m/s.
[d]nm, not measured.
[e]ELARP (Experimental Lakes Area Reservoir Project) is a reservoir experimenally created over a peatland (Kelly et al. 1997).
[f]Proportion of peatland flooded in the Experimental, Lokka, and Porttipahta rservoirs was 100%, 80%, and 50% respectively.
[g]We first averaged the 1 to 2-year-old reservoirs before taking an overall average

windy, wavy water, and so the thin boundary layer method is appropriate. Therefore, flux measurements from reservoirs have relied on a combination of both techniques.

The flux data summarized in this article (Table 1) were obtained primarily with floating chambers and/or the thin boundary layer method. Most of the reservoirs were of such a size that low wind speeds, such as in the Cole and Caraco (1998) study, were unusual, and so inclusion of data produced by both methods is reasonable. Fluxes calculated using the thin boundary layer techniques make our global greenhouse gas flux estimates somewhat conservative because bubble ebullition is often not measured in addition to diffusive fluxes (Table 1). Lack of bubble data affects estimates of CH_4 flux the most because bubbles are

Table 2. Average fluxes of CO_2 and CH_4 from the surfaces of different ecosystems.

Ecosystem	Areal flux (mg · m² · d)[a]		References
	CO_2	CH_4	
Temperate reservoirs	*1500*↑	*20*↑	*Table 1*
Tropical reservoirs	*3000*↑	*100*↑	*Table 1*
Boreal/temperate forests	2100↓	1.0↓	Crill 1991, Savage et al. 1997, Fan et al. 1998
Tropical forests	710↓	0.2↓	Keller et al. 1986, Phillips et al. 1998
Northern peatlands	230↓	51↑	Gorham 1991
Lakes (worldwide)	700↑	9↑[b]	Cole et al. 1994, Schlesinger 1997

[a]Downward arrows indicate net consumption by ecosystem. Upward arrows indicate net flux to the atmosphere.
[b]Averaged over 365 days assuming 1.5 million km² of lake surface area globally.

usually composed mainly of CH_4. Measurement of bubble ebullition is less likely to lead to an underestimation of overall CO_2 flux because bubble fluxes of CO_2 are relatively small compared with diffusive fluxes (Kelly et al. 1997, Duchemin 2000).

An experimental study of greenhouse gas emissions from reservoirs

In direct response to Rudd et al's (1993) hypothesis that greenhouse gas production in reservoirs is not zero and may depend on the amount of organic carbon flooded to create the reservoir, a unique whole-ecosystem experiment—the Experimental Lakes Area Reservoir Project (ELARP)—was initiated at the ELA. The primary goals of the ELARP were to experimentally create a reservoir to quantify in a controlled manner the net change in greenhouse gas fluxes to the atmosphere as a result of flooding and to understand the mechanisms causing these changes. The ELARP experimentally flooded a wetland, which hypothetically provided a worst-case scenario for long-term decomposition and greenhouse gas production because of the large stores of organic carbon held in peat deposits (Figure 3). Before flooding, the ELARP site consisted of both a pond surface and a peatland surface, each with its own natural characteristic greenhouse gas flux. A mixture of water and terrestrial surfaces is common in sites before reservoir construction. The pond surface emitted both CO_2 and CH_4 to the atmosphere, whereas the peatland surface took up CO_2 and emitted a small amount of CH_4. In general, lakes tend to emit both CO_2 and CH_4, whereas forests tend to take up both CH_4 and CO_2 (Table 2).

The whole-ecosystem flooding experiment resulted in conversion of the wetland from a small greenhouse gas sink to a relatively large source of greenhouse gases to the atmosphere. Before flooding, the wetland was on average a carbon sink of 6.6 g · m² · yr of carbon. After flooding, it was a large carbon source (130 g · m² · yr of carbon) in the form of CO_2 (120 g · m² · yr of carbon) and CH_4 (9 g · m² · yr of carbon; Kelly et al. 1997).

Litterbags containing leaves from different trees, shrubs, and herbaceous plants, which were placed in the experimental reservoir before flooding, showed that most of this vegetation decomposed in the first 3 years of flooding (Tim R. Moore, McGill University, Montréal, Québec, personal communication). However, 7 years after flooding, gas fluxes from the flooded pond were the highest recorded over the entire course of the experiment (Carol A. Kelly and Vincent L. St. Louis, unpublished data), demonstrating that peat decomposition continued. The peat deposits before flooding contained 1×10^5 g/m² of carbon, so if present rates of decomposition continue, there is enough organic carbon to support the current greenhouse gas flux for 2000 years (Kelly et al. 1997).

The formation of floating peat islands resulting from gas buildup in the decomposing peat is another consequence of flooding peatlands (Figure 3). These floating peat islands have especially high rates of CH_4 emissions, primarily because of low rates of CH_4 oxidation (Scott et al. 1999). On a mass basis, CH_4 has a much larger global warming potential than CO_2 (21-fold over a 100 year time horizon; Houghton et al. 1996).

Studies of fluxes of greenhouse gases from existing reservoir surfaces

In the past 7 years, studies of 21 existing reservoir sites worldwide have shown that emission of CO_2 and CH_4 from the flooded surfaces occurred in every case (Table 1). Thus, we conclude that in general reservoirs are sources of greenhouse gases to the atmosphere. A more difficult question to answer is the relative importance of reservoir fluxes on a global basis.

Estimates are difficult for several reasons. For example, in the ELARP study described above, greenhouse gas flux was measured both before and after flooding to give an accurate overall estimate of the net change of greenhouse gas flux caused by flooding, but in all other studies greenhouse gas flux was measured only after flooding (Table 1). Thus, the loss of the carbon sink is not included, and the reported fluxes underestimate the actual effect on the atmosphere of reservoir creation.

Most flux estimates have been made on reservoirs located in temperate regions (Canada, United States, and Finland) that ranged widely in size (0.2–2500 km²) and age

Figure 3. The Experimental Lakes Area Reservoir Project reservoir 4 years after experimentally flooding a wetland by raising the water level 1.2 m. The wetland before flooding consisted of a 2.3-ha central pond surrounded by a 14-ha peatland. Note that most of the inundated peat is now floating. Photo courtesy of V. L. St. Louis.

(1–73 years; Table 1). For these temperate reservoirs, we calculated average fluxes of 1400 mg · m^2 · d of CO_2 and 20 mg · m^2 · d of CH_4 (Table 1). Fewer data are available for reservoirs in tropical regions (Table 1). However, there appears to be an obvious difference between temperate and tropical reservoirs. CH_4 fluxes seem to be much higher relative to CO_2 fluxes in tropical reservoirs than they are in temperate ones.

Because the newly flooded tropical reservoirs (Serra da Mesa and Petit Saut) appeared to have much higher fluxes than reservoirs flooded on the longer term, and because there are not enough data for a good age distribution, we first averaged the 1–2 year old reservoirs before taking an overall average. Our rough estimates of average flux for tropical reservoirs are 3500 mg · m^2 · d of CO_2 and 300 mg · m^2 · d of CH_4 (Table 1).

Factors affecting greenhouse gas fluxes from existing reservoirs

The quite wide range of average fluxes from reservoirs around the world (220–4460 mg · m^2 · d of CO_2 and 3–1140 mg · m^2 · d of CH_4; Table 1) was expected because fluxes of CO_2 and CH_4 depend on a number of factors, including the amount of organic carbon flooded, age of the reservoir, and mean annual temperature.

Organic carbon. The flux per unit area of greenhouse gases from reservoir surfaces should be proportional to the amount of decomposable organic carbon that is flooded to create the reservoir. The largest amounts of organic carbon per unit area are found in peatlands. CH_4 fluxes in temperate regions were highest in reservoirs that flooded at least 80% peatlands (the ELARP and Finnish reservoirs; Table 1). Fluxes of gases from reservoirs that flood low-carbon areas, such as the desert areas in the US Southwest, are needed to complete the picture. Unfortunately, information on the type and amount of carbon flooded is generally not known.

After inundation, some of the flooded organic carbon is not readily decomposable. Much of the aboveground organic carbon of forests is located in tree boles, which are quite resistant to decomposition after being submerged. Decomposition of submerged wood is very slow because lignin decomposition by fungal organisms, which is rapid in the terrestrial environment, is inhibited under water. Thus, when attempts are made to estimate flux of greenhouse gases from reservoirs using estimates of the mass of flooded organic carbon in forests, the mass of tree boles should be subtracted from the total biomass (Rudd et al. 1993).

Age. The age of reservoirs should also affect greenhouse gas fluxes because newly flooded labile carbon, such as that found in leaves and litter, should decompose rapidly, followed by slow decomposition of older, more recalcitrant organic carbon such as soil carbon and peat (Kelly et al. 1997). Fluxes from reservoirs are therefore expected to slow over time. When we examined fluxes from all the reservoirs in our data set (Table 1), there was a negative exponential decline in fluxes of CO_2 from temperate reservoirs with age (Figure 4). However, emissions of CO_2 remained high, at approximately 1000 mg · m^2 · d of CO_2, 80 years after flooding of the oldest reservoir. A similar decline for CH_4 was not observed, possibly because many studies did not include bubble ebullition, and bubbles contribute a much larger portion of fluxes of CH_4 than of CO_2 (Duchemin 2000).

However, the use of data from a number of reservoirs to determine the flux–age relationship is problematic if reservoirs flood different types of ecosystems. Other factors, such as the quantity of biomass flooded in different types of ecosystems, confound possible flux–age relationships. Ideally, the same set of reservoirs should be followed over time because factors other than age might influence the gas flux.

We attempted to address this flux–age question using a set of reservoirs located in Wisconsin, ranging in age from 29 years to 73 years (Table 1). These reservoirs were created for recreational purposes and flooded peatlands to varying degrees. Thus, we were able to compare their fluxes to the ELARP site, which was only 2 years old (Table 1), to complete the set. All of the older sites had lower green-

house gas fluxes than the newly flooded ELARP site, but age was obviously not the sole controlling factor because one of the Wisconsin reservoirs, which was the oldest, also had the highest flux measured in that state (Table 1).

Furthermore, the Wisconsin reservoirs still had much higher greenhouse gas emissions than natural lakes in the same geographic area (Wisconsin reservoirs in Table 1 compared with Round Lake in Wisconsin: 139 mg · m^2 · d of CO_2 and 2.8 mg · m^2 · d of CH_4) or terrestrial surfaces before flooding (Table 2), demonstrating that fluxes of greenhouse gases from reservoirs do not become similar to nearby lakes even after eight decades of flooding.

Water temperature. Rates of decomposition in tropical reservoirs were probably high because annual water temperatures are much higher in tropical reservoirs than they are in temperate environments. Tropical reservoirs had higher rates of CO_2 flux than temperate reservoirs and much higher rates of CH_4 flux, mainly because of bubble ebullition (Table 1). Bubble formation is expected in sediments with high CH_4 production rates because the CH_4 accumulation rate will exceed the rate of vertical diffusion toward the sediment-water interface, which gives rise to supersaturation and bubble formation. Bubbles contribute significantly to greenhouse gas fluxes because they are a direct conduit of CH_4 from sediments to the atmosphere, escaping microbial oxidation. Sites with bubbles emit a high proportion of gas as CH_4, with the correspondingly higher global warming potential (e.g., Galy-Lacaux et al. 1997).

Other factors. Other factors also affect greenhouse gas fluxes from reservoir surfaces. For example, some of the terrestrially derived allochthonous carbon that is deposited in reservoirs from watershed runoff will decompose to CO_2 and CH_4, and the amount of allochthonous input will vary from one reservoir to another.

High primary productivity in reservoirs may reduce greenhouse gas emissions to the atmosphere through algal

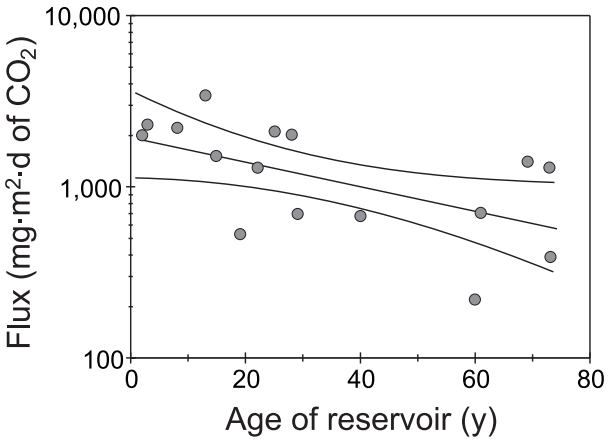

Figure 4. Negative relationship between the age of temperate reservoirs and the average areal flux of CO_2 (regression analysis: log (flux) = 3.26 – 0.0071(age of reservoir); R^2 = 0.35, d.f. = 15, p < 0.025, confidence interval of 95%). Data are from Table 1.

CO_2 fixation during the summer, but most of this carbon is later decomposed and returned to the atmosphere. In eutrophic reservoirs with anoxic hypolimnia, a relatively large amount of decomposed organic carbon fixed by photosynthesis is recycled as CH_4. Large amounts of CH_4 can be released at reservoir turnover time (Rudd et al. 1978). Because of the higher global warming potential of CH_4 as compared to CO_2, this return of CH_4 to the atmosphere could more than offset any favorable effect of algal fixation.

The frequency and extent of reservoir drawdown can also affect rates of bubbling due to pressure changes brought about by fluctuating water level (Keller and Stallard 1994, Duchemin et al. in press).

Table 3. Estimated fluxes of CO_2, CH_4, and total C from the surface of reservoirs globally.

	Global surface area of reservoirs ($\times 10^6$ km^2)	Areal fluxes (mg · m^2 · d)		Global reservoir fluxes ($\times 10^{14}$ g/yr)			
		CO_2	CH_4	CO_2	CH_4	Total C	CO_2 Equivalents[a]
Temperate reservoirs	0.9	*1400*	*20*	3[b]	0.04[b]	0.7	3
Tropical reservoirs	0.6	*3500*	*300*	7	0.6	2	20
All reservoirs combined	1.5			10	0.7	3	23
Other anthropogenic emissions				260[c]	3.8[d]	74	339
% of anthropogenic emissions				**4**	**18**	**4**	**7**

[a]A conversion factor of 21 was used for the global warming potential (global warming potential on a mass basis; direct and indirect effects) of CH_4 as CO_2 for a 100-year period, the approximate life of a reservoir.

[b]Temperate reservoirs were assumed to be ice-free for on average 200 days.

[c]Average annual CO_2 emissions (1980–1989) include those from fossil fuel and cement production (5.5 Gt/yr of carbon) and changes in tropical land use (1.6 Gt/yr of carbon). Carbon emissions have been converted to CO_2 for comparison (Houghton et al. 1996).

[d]Estimated anthropogenic sources include emissions from fossil fuel combustion (100 Tg/yr of CH_4), waste management (90 Tg/yr of CH_4), enteric fermentation (85 Tg/yr of CH_4), biomass burning (40 Tg/yr of CH_4), and rice paddies (60 Tg/yr of CH_4; Houghton et al. 1996).

Global surface area of reservoirs

The global surface area of reservoirs to which average flux estimates should be applied is not as well known as might be expected. The most complete inventory of reservoir surface area (behind 25,410 dams from 110 countries) totals 394,213 km^2 (ICOLD 1998). However, the International Commission on Large Dams (ICOLD) database is incomplete, and thus is only a starting point for estimating the true global area inundated by reservoir construction. First, not all large reservoirs are listed. For example, Japan and China only registered dams more than 30 m high. Russia only reported 91 dams built for hydroelectricity production, leaving more than 3000 dams unlisted (ICOLD 1988). Second, surface area is reported for only 71% of the reservoirs that are listed, and 14 countries do not list reservoir surface areas at all. These 14 countries include Canada, for which independent data show that in four of 10 provinces there are approximately 73,000 km^2 of surface area in reservoirs that have been developed primarily for hydroelectric generation. The addition of data from Canada alone brings the world total reservoir surface area to almost 500,000 km^2. Third, there are very few data on how much of the reservoir surface area was previously terrestrial and how much was natural lake or river. This is a limitation in estimating the change in flux (i.e., increased flux from water surface plus loss of terrestrial sink), as opposed to simply looking at current fluxes.

Reservoirs with dams less than 15 m high are not usually listed in the *World Register of Dams* (ICOLD 1998). However, the surface area of reservoirs behind small dams is considerable. For example, the US Army Corps of Engineers' National Inventory of Dams (1996), which lists all dams in the United States whose failure would result in loss of human life or significant property damage, reports a fourfold larger surface area (259,495 km^2) than does the *World Register of Dams* listing of large dams for the United States (60,545 km^2; ICOLD 1998). This size ratio might not be precisely applicable to a global area estimate, but the best-documented data on global reservoir area (ICOLD 1998) are certainly an underestimate.

Considering both the incomplete listing of large dams in many countries and the overall lack of data on small reservoirs, we estimate that the global surface area of all reservoirs today is approximately 1.5 million km^2, or approximately three times the documented area behind large dams. This area is equivalent to the estimated global surface area of natural lakes (Shiklomanov 1993).

Estimate of global flux of greenhouse gases from reservoirs

Approximately 40% of the surface area of all reservoirs listed in ICOLD (1998) is located in countries found between 30° N and 30° S latitudes and considered to have tropical climates. We therefore estimate that the surface area of reservoirs is approximately 600,000 km^2 in the tropics and 900,000 km^2 in temperate regions.

Combining the average areal fluxes (Table 1) with the estimated surface area of reservoirs in temperate and tropical regions yields annual global fluxes of 10×10^{14} g/yr of CO_2 and 0.7×10^{14} g/yr of CH_4 (Table 3). We estimate that a total of approximately 70% and 90% of global reservoir fluxes of CO_2 and CH_4, respectively, occurred from tropical reservoirs even though these reservoirs only accounted for approximately 40% of the global surface area. On a global basis, the CO_2 flux from reservoirs was only equivalent to 4% of other anthropogenic emissions of CO_2, but the CH_4 flux was equal to approximately 20% of other anthropogenic CH_4 emissions. These large estimated CH_4 fluxes from reservoirs exceed estimated fluxes from rice paddies or biomass burning worldwide (Table 3).

It is difficult to assign variation to these fluxes because of the way in which averages were calculated for each reservoir (see footnote b in Table 1). However, we can assign a range of between 1% and 10% for other anthropogenic CO_2 emissions, and between 2% and 85% for other anthropogenic CH_4 emissions, using the average range of fluxes (low and high) from temperate and tropical reservoirs (Table 1). Thus, rather than emphasizing a single value for the estimate of the current greenhouse gas flux from reservoirs globally, we want to make the point that the range of possible fluxes is such that further study and quantification is needed to understand the relative importance of reservoir development to greenhouse gas production, compared to other sources of greenhouse gases. This is especially true with respect to CH_4.

When CO_2 and CH_4 fluxes are combined and converted to a flux of total carbon to the atmosphere, the fluxes from reservoir surfaces are equal to 0.3 Gt/yr of carbon, or 4% of other documented anthropogenic fluxes of carbon as CO_2 and CH_4. On a mass basis, the global warming potential of CH_4 relative to CO_2 is 21 over a 100-year period (Houghton et al. 1996), the average life span of reservoirs. With this global warming potential of CH_4 factored in, greenhouse gas emissions from reservoirs were equivalent to an average of 7% of the global warming potential of other emissions for the same period (Table 3). A global warming potential of 21 (for a 100 year time horizon) is commonly used when comparing CH_4 emissions to CO_2 emissions from other anthropogenic sources of greenhouse gases. However, because reservoirs may not emit CO_2 and CH_4 at a constant rate over time (i.e., they may produce higher fluxes at first and lower later), the application of a single, 100-year global warming potential may lead to an underestimation of the short-term contribution to global warming, and alternative approaches may be necessary, especially when considering single sites (e.g., see Fearnside 1997).

Interpretation of the estimate of global flux of greenhouse gases from reservoirs

A number of factors affect the interpretation of how the current estimated global flux of greenhouse gases from the

surface of reservoirs relates to global change. These factors include the incorporation of greenhouse gas fluxes from landscapes before flooding and the burial of organic carbon in the sediments of reservoirs.

Current fluxes versus net change in greenhouse gas flux due to flooding. The fluxes presented in Tables 1 and 3 are from reservoir surfaces after flooding has occurred, a measurement that is necessary to describe the characteristics of these surfaces as they exist today. However, it is also important to ask how these current fluxes are different from those that existed before flooding, because the true effect of reservoir creation on the atmosphere is the *net* difference between fluxes of greenhouse gases before flooding and after flooding. For example, if the entire reservoir area was previously a net sink for both CO_2 and CH_4, as forests are (Table 2), then the loss of these sinks should be added to the current reservoir fluxes. However, part of the preflood landscape is often already water covered, and was likely emitting some CO_2 derived from decomposition of watershed-derived allochthonous organic carbon. Some natural water surfaces take up CO_2, if net primary production is greater than allochthonous organic carbon degradation, but this is apparently less common in lakes than net release of CO_2 (Table 2; Cole et al. 1994). All aquatic surfaces emit some CH_4 (Table 2). Any aquatic emissions existing before flooding should be subtracted from the current fluxes. Thus:

Net change due to reservoir creation = current flux from reservoir surface + previous CO_2 and CH_4 uptake from terrestrial regions – previous CO_2 and CH_4 emissions from aquatic regions in watershed

Knowledge of all the parameters in the above equation is ideal. However, only the ELARP study included preflood measurements of greenhouse gas fluxes in both the terrestrial and aquatic regions of the watershed that was later flooded. Estimates for preflood fluxes of other reservoirs could be done, using generic flux data on forest, peatland, and aquatic systems (Table 2), if knowledge of the preflood areas of terrestrial and aquatic surfaces were available. Unfortunately, measurements of preflood areas are often not available.

Given these limitations, can we make some general estimates of preflood greenhouse gas fluxes from reservoir areas that are useful in interpreting current reservoir fluxes? One approach is to estimate the loss of the carbon sink as if all the area flooded had originally been terrestrial (the greatest number that could be added onto the current fluxes to obtain the net change in the above equation) and then to estimate the maximum flux in current reservoirs that might be due to decomposition of allochthonous organic carbon derived from the watershed remaining after flooding (the greatest number that could be subtracted in the above equation).

Published data for areal fluxes of greenhouse gases from boreal/temperate and tropical forests (Table 2), and calculations similar to those presented in Table 3 for the distribution of existing reservoirs, were used to make the first estimate. If all the currently flooded area had originally been forest, we would need to add approximately 5×10^{14} g/yr of CO_2 to the current emission rates to correct for the loss of this carbon sink. Similarly, if all the currently flooded area had previously been natural lake area, emitting an average flux of 700 mg $\cdot$ m^2 $\cdot$ d of CO_2 (Table 2), then we would subtract approximately 3×10^{14} g/yr of CO_2 from the current fluxes to obtain the net change in the above equation.

Thus, the maximum corrections are an addition of 5×10^{14} g/yr of CO_2 and a subtraction of 3×10^{14} g/yr of CO_2 to the global estimate of approximately 10×10^{14} g/yr of CO_2 from reservoir surfaces listed in Table 3. Equivalent corrections for CH_4 are an addition of 2×10^{11} g/yr of CH_4 and a subtraction of 4×10^{12} g/yr of CH_4 to the global estimate of approximately 7×10^{13} g/yr of CH_4 from reservoir surfaces. Some portion of each of these maxima is obviously required, and so the actual correction will lie somewhere in between. Therefore, an important aid in determining the net change in greenhouse gas flux due to reservoir creation is to know the average proportion of land to water in reservoir areas before flooding. However, because the information required is currently not available on a global basis, we have not adjusted the estimates that appear in Table 3.

Organic carbon burial in reservoirs. Because reservoir creation slows water flow to oceans, there is increased sedimentation of organic carbon behind dams at an estimated rate of approximately 400 g $\cdot$ m^2 $\cdot$ yr of carbon, even though the percentage of organic carbon in reservoir sediments is less than in most lake sediments (Mulholland and Elwood 1982, Dean and Gorham 1998). Is this type of carbon burial a carbon sink with respect to the atmosphere? It could be if the allochthonous organic carbon particles that are trapped behind dams decompose to a lesser degree than they would have if they had traveled freely to the oceans. However, there have been no studies done to determine if this is true, and surface gas fluxes provide no information on this. Reservoir construction could simply mean that the final resting place for some organic carbon particles is in reservoir sediments rather than ocean sediments.

Conclusions and future research needs

Reservoir creation is not greenhouse gas neutral with respect to production of electricity by hydroelectric generation, as has recently been suggested (Hoffert et al. 1998, Victor 1998). Although there is uncertainty in our estimates, they show that reservoir fluxes are of a similar magnitude to other fluxes already included in efforts to understand anthropogenic changes taking place in the global

carbon cycle (e.g., CH_4 from biomass burning; Table 3). Also, researchers have been unable to balance the global carbon budget because more CO_2 is being emitted from anthropogenic sources than can be accounted for by either the well-documented rise in CO_2 concentrations in the atmosphere or uptake by oceans, resulting in a missing "sink" for CO_2. Our estimate increases this unknown sink of CO_2 by approximately 20%, from 1.3 Gt/yr of carbon (Houghton et al. 1996) to 1.6 Gt/yr of carbon (0.3 Gt/yr of carbon as C–CO_2; Table 3), by effectively increasing the anthropogenic CO_2 emissions to the atmosphere.

We anticipate that fluxes of greenhouse gases to the atmosphere from all reservoirs will increase in the future because they are needed as a relatively clean alternative to energy produced by fossil fuel combustion and because of needs for water and food as well as the industrial and recreational demands of a growing global population. The global terrestrial area flooded by reservoirs will increase in the future because only 17% of potential hydroelectric sites have been developed (Pircher 1993). It is possible that greenhouse gas fluxes from hydroelectric reservoirs could reach approximately 15% of the global warming potential of all other current anthropogenic emissions and the surface area of hydroelectric reservoirs only comprise 25% of all reservoir types (ICOLD 1998).

To more accurately determine the relative importance of reservoir fluxes as compared to other greenhouse gas sources, more CO_2 and CH_4 flux measurements are required from reservoirs in all global regions, with an emphasis on tropical reservoirs. Also, an improved database is needed on areas of existing and planned reservoirs, and relative extents of terrestrial and aquatic areas flooded in each reservoir, so that the *net* change in greenhouse gas flux due to flooding can be calculated. It is essential for greenhouse gas studies on reservoirs to continue, given the magnitude of our estimate for the collective flux resulting from reservoir construction, and the magnitude of increase in the unknown sink for CO_2 in the biosphere. Only then will we be able to determine the true impact of reservoir creation on the global carbon cycle and climate change.

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