

Carbon Dioxide and Methane Production in Small Reservoirs Flooding Upland Boreal Forest

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ABSTRACT

The Flooded Uplands Dynamics Experiment (FLUDEX) was designed to assess the impact of reservoir creation on carbon cycling in boreal forests by (a) determining whether production of the greenhouse gases (GHG) carbon dioxide (CO₂) and methane (CH₄) in reservoirs is related to the amount of organic carbon (OC) stored in the flooded landscape, (b) examining temporal trends in GHG production during initial stages of flooding, and (c) considering the net difference between GHG fluxes before and after flooding to estimate the true effect of reservoir creation on atmospheric GHG levels. Three forested sites that varied in the amount of OC stored in soils and vegetation (30,870–45,860 kg C ha⁻¹) were experimentally flooded from June to September in 1999–2001. Throughout the study, net CO₂ and CH₄ production in all three reservoirs was not related to overall

site OC storage. During the 1st flooding season, net CO₂ production in the three reservoirs was 703–797 kg C ha⁻¹, but it decreased during the 2nd and 3rd flooding seasons to between 408 and 479 kg C ha⁻¹. However, CH₄ production increased in all reservoirs with each flooding season, from about 3.2–4.6 kg C ha⁻¹ in 1999 to 12.8–24.9 kg C ha⁻¹ in 2000 and 29.7–35.2 kg C ha⁻¹ in 2001. Over the long term, effects of boreal reservoir creation on atmospheric GHG levels may be largely due to net changes in CH₄ cycling between the undisturbed and flooded ecosystems.

Key words: greenhouse gases; carbon dioxide; methane; reservoirs; decomposition; landscape organic carbon storage; Flooded Uplands Dynamics Experiment (FLUDEX); Ontario, Canada.

INTRODUCTION

In addition to the many environmental and socio-economic consequences of reservoir development, reservoirs have most recently been identified as sources of the greenhouse gases (GHG) carbon dioxide (CO₂) and methane (CH₄) to the atmo-

sphere, resulting from the decomposition of flooded vegetation and soils (Duchemin and others 1995, 2000; Galy-Lacaux and others 1997, 1999; Kelly and others 1997; Campo and Sancholuz 1998; Rosenberg and others 1997). In a recent review of the global contribution of reservoirs to atmospheric pools of CO₂ and CH₄, St. Louis and others (2000) estimated that GHG emissions from reservoirs may be equivalent to as much as 7% of the total global warming potential (GWP) of other anthropogenic carbon (C) emissions.

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Although concern about CO₂ and CH₄ emissions from reservoirs has led to emissions monitoring in existing reservoirs, to understand the overall net effect of reservoir creation on GHG flux to the atmosphere, C fluxes must be measured in both the undisturbed, natural ecosystem prior to flooding and the flooded landscape (St. Louis and others 2000; Kelly and others 1997). The Experimental Lakes Area Reservoir Project (ELARP) (Kelly and others 1997) experimentally flooded a boreal wetland after two years of pre-flood measurements of C exchange between the wetland and the atmosphere. Prior to flooding, the wetland was a natural C sink of approximately 7 g C m⁻² y⁻¹. After flooding, it became a relatively large source of C to the atmosphere (130 g C m⁻² y⁻¹). This change was attributed to the loss of the photosynthetic CO₂ sink due to the death of the flooded vegetation, as well as the microbial production of CO₂ and CH₄ from the decomposition of large organic C (OC) stores contained in peat and plant tissues.

A companion experiment to the ELARP, the FLOoded Uplands Dynamics EXperiment (FLUDEX), was designed to address the hypothesis that minimizing the amount of OC available for decomposition in the flooded landscape should, in the long term, reduce GHG emissions from reservoirs. The FLUDEX consisted of three experimental reservoirs flooding upland boreal forest sites that varied in OC stores in soils and vegetation. The three main objectives of the FLUDEX were (a) to understand the relationship between landscape OC storage and subsequent reservoir CO₂ and CH₄ production; (b) to examine temporal trends in CO₂ and CH₄ production in newly flooded upland forests, and (c) to assess the net effect (pre- versus postflood) of reservoir creation on GHG fluxes in the boreal ecosystem.

METHODS

Site Description

The FLUDEX was conducted at the Experimental Lakes Area (ELA), which is situated on the Precambrian shield in northwestern Ontario, Canada. Three boreal forest sites characterized by an 18-year-old fire regenerating jack pine (*Pinus banksiana*) and birch (*Betula papyrifera*) forest and differing in amounts of OC stored in vegetation and soils were chosen for flooding. Stores of OC were determined from estimates of aboveground vegetation and soil biomass prior to flooding. Biomass of low shrubs, herbs, mosses, and lichens was estimated by harvesting and weighing material from 5–10

quadrats (0.5 × 0.5 m) in each site (D. Heubert unpublished). Woody tissue in tall shrubs and trees was estimated from trunk diameter measurements using standard regression equations (Dyck and Shay 1999). Biomass stored in the forest canopy was estimated from monthly collections of litterfall from three locations within each reservoir. Sub-samples of oven-dried biomass of each species were analyzed for C content as in Dyck and Shay (1999). Soil cores were collected from six or seven locations within each site and divided into different horizons (litter, fungal humic, charcoal, and mineral soil), which were measured and analyzed for percent C (Boudreau 2000). Soil C content in each horizon was multiplied by average bulk density of each horizon to estimate total soil OC storage.

The high-C site (0.74 ha) was characterized by two forest communities of similar area: a moist jack pine forest, with an understory of Labrador tea (*Ledum groenlandicum*), *Sphagnum* spp., and leatherleaf (*Chamaedaphne calyculata*) and a drier upland area dominated by jack pine and *Polytrichum* spp. mosses (D. Heubert unpublished). The average soil depth was 41 cm (Boudreau 2000), and small pools of standing water were occasionally present. The high-C site had the largest OC stores of the three sites (45,860 kg C ha⁻¹), with about 60% in aboveground vegetation and 40% in soils (Table 1).

The medium-C site (0.50 ha) consisted of dense jack pine forest with a sparse understory of birch, alder (*Alnus* spp.) and blueberry shrub (*Vaccinium* spp.), and an extensive groundcover of various mosses and herbs (D. Heubert unpublished). The soil was well drained and had an average depth of 39 cm (Boudreau 2000). The medium-C site had medium levels of stored OC (34,930 kg C ha⁻¹), with most of it in aboveground vegetation (79%). The remaining 21% was stored in soils (Table 1).

The low-C site (0.63 ha) included three vegetation communities. Jack pine forest with stands of birch and a blueberry shrub understory comprised 73% of the area, lichen and moss communities on exposed bedrock made up 22% of the area, and the remaining 5% consisted of an organic pillow community comprised of lichens, mosses, and grasses (D. Heubert unpublished). The average soil depth was 15 cm (Boudreau 2000) and was very dry. This site contained the least amount of stored OC (30 870 kg C ha⁻¹), with 64% stored in aboveground vegetation and 36% in soils (Table 1).

Reservoir Construction

Wooden reservoir walls were constructed along the lowest topographic contours of each site where the

Table 1. Summary of Carbon (C) Stores in the FLUDEX Sites Prior to Flooding

	High-C Site		Medium-C Site		Low-C Site	
	<i>Pinus/Ledum/Sphagnum</i> (53%) <i>Pinus/Polytrichum</i> (47%)	%Overall	<i>Pinus/Betula</i> (100%)	%Overall	<i>Pinus/Vaccinium</i> (73%) <i>Polytrichum/Cladina</i> (22%) Organic Pillows (5%)	%Overall
Dominant vegetation (percent coverage) ^a						
Range of soil depth (cm) ^b	6.3–105.0		15.6–90.6		0–69.0	
Range of forest floor (litter and fungal/humic layers) depth (cm) ^b	1.0–37		3.5–13.0		2.0–7.5	
	kg C ha ⁻¹	%Overall	kg C ha ⁻¹	%Overall	kg C ha ⁻¹	%Overall
C in trees ^a	26,210	57.2	27,600	79.0	19,570	63.4
C in foliage	1,970	4.3	2,730	7.8	1,770	5.7
C in bark	2,440	5.3	3,760	10.8	1,970	6.4
C in wood	21,800	47.5	21,110	60.4	15,830	51.3
C in shrubs ^a	1,350	3.0	130	0.4	200	0.6
C in litter and fungal/humic layer ^b	15,400	33.6	5,700	16.3	8,700	28.2
C in mineral layer ^b	2,900	6.3	1,500	4.3	2,400	7.8
Total soil C (including litter) ^b	18,300	39.9	7,200	20.6	11,100	36.0
Total C in aboveground vegetation ^a	27,560	60.1	27,730	79.4	19,770	64.0
Total C	45,860		34,930		30,870	

^aData from D. Heubert (unpublished)^bData from Boudreau (2000)

Table 2. Summary of the Physical Characteristics of the FLUDEX Reservoirs

	High-C Reservoir	Medium-C Reservoir	Low-C Reservoir
Water surface area (m ²)	7,400	5,000	6,300
Catchment area (m ²)	47,800	7,300	900
Total site area (m ²)	55,200	12,300	7,200
Reservoir volume (m ³)	6,870	4,270	7,120
Mean depth (m)	0.9	0.9	1.1
Length of wood dike (m)	132	92	237
Length of gravel dike (m)	102	41	94

C, carbon

Table 3. FLUDEX Reservoir Water Inputs and Outputs (10³ m³) During the 1999, 2000, and 2001 Flooding Seasons

	High-C Reservoir			Medium-C Reservoir			Low-C Reservoir		
	1999	2000	2001	1999	2000	2001	1999	2000	2001
Inputs									
Inflow	78.6	93.3	84.8	76.7	69.6	74.7	96.9	108.6	106.9
Precipitation	1.9	2.8	2.6	1.3	1.9	1.8	1.7	2.5	2.3
Catchment input	4.7	12.2	5.0	0.7	1.9	0.8	0.1	0.2	0.1
<i>Total water input</i>	<i>85.2</i>	<i>108.3</i>	<i>92.4</i>	<i>78.7</i>	<i>73.4</i>	<i>77.3</i>	<i>98.7</i>	<i>111.3</i>	<i>109.3</i>
Outputs									
Weir	60.2	80.2	64.0	60.8	57.2	63.7	33.5	42.5	51.5
Seepage	16.0	15.9	13.0	15.4	13.9	14.5	23.1	19.1	12.2
Bedrock fracture	0	0	0	0	0	0	36.9	43.4	40.8
Drawdown	6.9	6.9	6.9	4.3	4.3	4.3	7.1	7.1	7.1
Evaporation	1.6	1.8	1.9	1.4	1.3	1.4	1.4	1.7	1.6
Canopy interception	0.8	1.3	0.4	0.6	0.9	0.3	0.7	1.0	0.3
<i>Total water output</i>	<i>85.5</i>	<i>106.1</i>	<i>86.2</i>	<i>82.5</i>	<i>77.6</i>	<i>84.2</i>	<i>102.7</i>	<i>114.8</i>	<i>113.5</i>
% water yield	100.4	97.9	93.3	104.7	105.7	108.8	104.1	103.2	103.9
Residence time (d)	8.5	7.5	9.4	5.3	5.5	5.7	10.1	7.0	7.1
# of water exchanges ^a	12.4	14.0	11.2	19.8	18.7	18.3	10.4	14.9	14.7

^aTotal water output during the flooding season (around 100 days) divided by the reservoir volume
C, carbon

flooded water depth was projected to be greater than 1 m. Gravel dikes lined with polyethylene sheeting were built where the flood depth was less than 1 m. No dikes were built where natural contours of the sites were greater than the maximum height of the water, creating regions open to catchment input.

The sites were studied in their natural state in 1998 and then flooded in 1999, 2000 and 2001. During the flooding season (June to September), surface water from a nearby oligotrophic lake (Roddy Lake) was pumped continuously to the sites via aluminium irrigation pipes ending in three inlets at the top of the reservoir walls, flooding the sites to

average depths of 0.9–1.1 m (Table 2). Reservoir volumes ranged from 4,270 to 7,120 m³ (Table 2). During the flooding season, water inputs (inflow, precipitation, and catchment input), storage in soils, and outputs (outflow, dike seepage, and evaporation) were monitored using standard procedures and equipment (V-notch weirs, calibrated flow meters) to calculate a detailed water budget for each flooding season (Table 3). Annual drainage of the FLUDEX reservoirs from October until May mimicked seasonal fluctuations in water levels at the shallow margins of large northern hydroelectric reservoirs, when turbine flow is increased to meet heightened electrical demands in winter.

Net Reservoir Greenhouse Gas Production—Inorganic Carbon and Methane Mass Budgets

Carbon dioxide and CH₄ produced via microbial decomposition of flooded soils and vegetation either dissolved into the reservoir water column (forming dissolved inorganic carbon [DIC] and dissolved CH₄) or formed bubbles and was emitted directly to the atmosphere as CO₂ and CH₄. Net reservoir CO₂ and CH₄ production was determined from inorganic C and CH₄ mass budgets that included total reservoir inorganic C and CH₄ inputs (DIC and CH₄ added via pumped inflow water, precipitation, and catchment input) and total reservoir inorganic C and CH₄ outputs (DIC and CH₄ removed via outflow water, dike seepage, fracture flow, and drawdown; diffusive surface CO₂ and CH₄ fluxes; and ebullition CO₂ and CH₄ fluxes) over the flooding season. Inorganic C and CH₄ inputs and outputs were determined by multiplying DIC and dissolved CH₄ concentrations (measured frequently throughout the flooding season) in each of the budget components by water volumes entering and exiting the reservoirs (monitored throughout the flooding season using flow meters and V-notch weirs). Carbon dioxide and CH₄ outputs via diffusive gas exchange were estimated using sulphur hexafluoride (SF₆)-derived gas transfer velocities and dissolved surface water CO₂ and CH₄ concentrations, and CO₂ and CH₄ outputs via ebullition were measured directly. Total seasonal inorganic C and CH₄ inputs were subtracted from total seasonal inorganic C and CH₄ outputs to determine net reservoir CO₂ and CH₄ production during each flooding season.

Inorganic Carbon and Methane Inputs (Inflow, Precipitation, and Catchment Input)

Inflow water was sampled for DIC and CH₄ content at only one site (entering the low-C reservoir) because DIC and CH₄ concentrations in water supplying each of the three reservoirs was the same (data not shown). Water was collected at 13:00 for three consecutive days biweekly using evacuated 60-ml Wheaton bottles. Immediately after collection, inflow samples were acidified using 0.5 ml 85% phosphoric acid (H₃PO₄) to convert all DIC to CO₂. Samples were then analyzed for CO₂ and CH₄ content using a Varian 3800 gas chromatograph (GC) equipped with a flame ionization detector (FID) at 250°C. Samples were placed on a wrist-action shaker for 10 min to

equilibrate gases between the liquid phase and nitrogen headspace. Headspace (0.2 ml) was injected through an injection port using a pressure lock gastight syringe. Carbon dioxide and CH₄ were separated using UHP hydrogen as a carrier gas through a hayesep D column at 80°C. A ruthenium methanizer converted CO₂ to CH₄. Six to seven standards (supplied by Praxair and Linde-Union Carbide) ranging from 75 to 1,000 ppm for CO₂ and 1.6 to 75 ppm for CH₄ were used to calibrate the GC. Standard calibration curves with an r^2 greater than 0.99 were accepted for analyses, and a standard was analyzed after every 10 samples to check the GC calibration. A Varian Star Workstation program integrated peak areas and duplicate injections were performed on approximately 10% of samples to ensure reproducibility of results. Gas concentrations were corrected for temperature and barometric pressure differences between sample collection and gas analyses. Dissolved inorganic C and CH₄ inputs via inflow were determined by multiplying average biweekly inflow DIC and CH₄ concentrations by inflow water volume over the 2-week period (quantified using an in-line flow meter attached to inflow pipes). Biweekly inputs were summed to obtain seasonal inputs.

Dissolved inorganic C inputs via precipitation were estimated by multiplying total precipitation volume over the flooding season (Table 3) by average precipitation DIC and CH₄ concentrations (precipitation data were collected at the ELA meteorological station less than 1 km from the reservoirs). Seasonal watershed DIC and CH₄ inputs were estimated by multiplying DIC and CH₄ concentrations in catchment flow from a nearby upland catchment (ELA Lake 114 [L114]) by total catchment input water volumes (estimated by adjusting flow volume data collected at a nearby terrestrial flow monitoring site so that it was proportionate to reservoir catchment area) over the flooding season. Seasonal average DIC and CH₄ concentrations in inflow, precipitation, and catchment flow were used in the calculations because frequent measurements throughout the season showed them to be constant.

Inorganic Carbon and Methane Outputs (Diffusive Surface Flux, Outflow Water, and Ebullition)

Diffusive Surface Carbon Dioxide and Methane fluxes. Sulfur hexafluoride gas was used to determine gas transfer coefficients (k) at the surface of each reservoir. The k values were then used with

dissolved surface CO₂ and CH₄ concentrations to estimate diffusive fluxes of these gases to the atmosphere. For theory behind the SF₆ method and details on SF₆ addition, sample collection, and analysis, refer to Matthews and others (2003). Briefly, SF₆ was added to each reservoir every two weeks approximately 4–5 days before sampling for dissolved surface CO₂ and CH₄ began. After SF₆ concentrations were uniform throughout the reservoir, surface water was collected daily to determine SF₆ concentrations at 10 locations in each reservoir. Samples were analyzed within 2–4 hours after collection using a GC.

Dissolved surface water CO₂ and CH₄ concentrations were measured to estimate diffusive gas flux from the reservoir surfaces. Surface water samples were collected for three consecutive days every two weeks (in conjunction with inflow and outflow water sampling), resulting in eight sampling sets throughout each flooding season. Samples were collected about 10 cm below the surface at four locations with the following characteristics: (a) treed and deep water, (b) open and deep water, (c) treed and shallow water, and (d) open and shallow water. These locations were chosen to examine differences in surface concentrations in open versus sheltered areas of the reservoir and in surface waters close to (less than 0.5 m) and far from (more than 1 m) sediments. During flooding in 2000, sampling was done three times daily at 7:00, 13:00, and 20:00 to determine if there were diel patterns in concentrations. Samples were analyzed for dissolved CO₂ and CH₄ content on a GC following the same procedure as inflow water samples, except that the samples were not acidified prior to analysis. There were no consistent differences or noticeable spatial patterns in either CO₂ or CH₄ concentrations between deep/shallow or sheltered/open areas, but there were diel differences in CO₂ concentrations, with morning concentrations higher than evening concentrations. Midday concentrations equaled the average of morning and evening concentrations (data not shown); therefore, the midday sampling run was omitted in 2001. Morning and evening concentrations from the four locations were averaged to obtain a concentration representative of the entire reservoir over a 24-h period.

Outflow Water (Weir Outflow, Dike Seepage, Fracture Flow, Drawdown). Water was collected at the outflow weir of each reservoir to determine the amount of DIC and CH₄ exiting each reservoir; sample collection and analysis procedures were the same as for inflow procedures. Dissolved inorganic C and CH₄ outputs via weir outflow

were determined by multiplying average biweekly outflow DIC and CH₄ concentrations by weir outflow water volume during the 2-week period (calculated using continuous stage level recorders located at the outflow weir of each reservoir). Seasonal outputs were determined by summing biweekly outputs.

Dike seepage and bedrock fracture flow (low-C reservoir, Table 3) volumes were determined by channeling water flowing beneath the dikes along the reservoir perimeter into a gauged weir. Volumes were then multiplied by weir outflow DIC and CH₄ concentrations to estimate seasonal DIC and CH₄ losses. Estimates of DIC and CH₄ lost via seepage and fracture flow are conservative because weir outflow DIC and CH₄ concentrations were lower than DIC and CH₄ concentrations in bottom and pore waters that also contributed to seepage and fracture flow.

Dissolved inorganic C and CH₄ outputs during reservoir drawdown at the end of the flooding season were estimated by multiplying water column DIC and CH₄ concentrations at 120, 100, 80, 60, 40, 20, and 2 cm above the soil/water interface 2–4 days before drawdown began by volumes corresponding to each of those depth profiles (determined from reservoir storage–discharge curves). Dissolved inorganic C and CH₄ storage in each depth profile was then summed to obtain the total amount of DIC and CH₄ in the reservoirs at the time of drawdown.

Ebullition. Five inverted 30-cm-diameter plastic funnels were deployed at the water surface in each reservoir to trap bubbles originating from flooded soils. Bubble traps were deployed continuously and checked weekly to biweekly for bubble accumulation. Bubble volume was measured by removing the accumulated gas via a rubber septum using a needle and syringe. Fresh bubbles were collected into another bubble trap for concentration analysis by probing the flooded soils with a pole. Carbon dioxide and CH₄ concentrations in fresh bubbles were determined using a GC (see above). Bubble CO₂ and CH₄ concentrations were multiplied by bubble volume collected over the weeklong period to determine CO₂ and CH₄ ebullition fluxes.

Error Associated with Inorganic Carbon and Methane Mass Budgets

Error associated with the various terms in the budget would arise from (a) analytical precision of GC measurement; (b) temporal/spatial variation in DIC and CH₄ concentrations averaged for calcula-

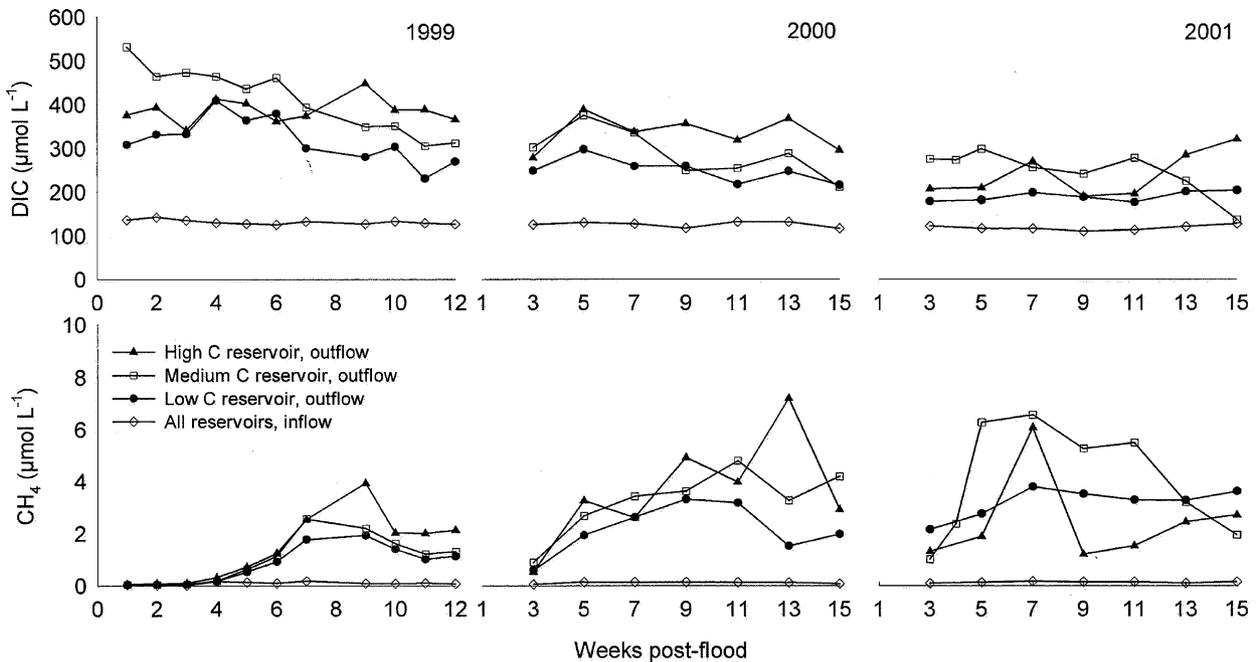


Figure 1. Dissolved inorganic carbon (DIC) (*top*) and methane (CH_4) (*bottom*) concentrations in reservoir inflow and outflow water during 1999, 2000, and 2001.

tion purposes; and (c) errors in our estimates of water volumes used in our calculations.

Analytical precision was $\pm 10\%$ for both CO_2 and CH_4 . Duplicate injections of gas samples showed results to be reproducible within less than $\pm 5\%$. Variation in DIC and CH_4 concentrations in inflow, outflow, and precipitation over the entire season was very low. Dissolved CO_2 and CH_4 concentrations in reservoir surface waters and bubbles varied both spatially and temporally throughout the flooding seasons. Therefore, seasonal CO_2 and CH_4 outputs via diffusive surface fluxes and ebullition have been bracketed by high and low estimates based on the standard deviation (SD) around mean concentrations used in the calculations, providing a range in the net production estimates. Estimation of catchment DIC and CH_4 inputs constitutes the largest uncertainty in the inorganic C and CH_4 mass budgets because the ephemeral nature of L114 catchment flow allowed for only several concentration measurements to be made. However, for the most part, catchment input is an unimportant term in the inorganic C and CH_4 mass budgets (except for DIC in the high-C reservoir), so uncertainty in this term does not likely affect overall production estimates to a large degree.

The largest components of reservoir water budgets were inflow, outflow, dike seepage, and bedrock fracture flow (Table 3). These volumes were measured using V-notch weirs and cali-

brated flow meters, for which the generally accepted errors are $\pm 5\%$ (Winter 1981). Errors associated with other components of reservoir water budgets are $\pm 5\%$ for precipitation, $\pm 15\%$ for evaporation, and $\pm 18\%$ when applying gauged catchment flow to similar ungauged areas (Winter 1981).

RESULTS AND DISCUSSION

Inorganic Carbon and Methane Mass Budgets and Net Reservoir Carbon Dioxide and Methane Production

Inorganic Carbon and Methane Inputs (Inflow, Precipitation, and Catchment Input)

Dissolved inorganic C and CH_4 concentrations in inflow water were similar during all 3 flooding seasons (Figure 1). Inflow DIC concentrations in 1999, 2000, and 2001 were 130 ± 3 , 126 ± 6 , and $120 \pm 6 \mu\text{mol L}^{-1}$, respectively. Inflow CH_4 concentrations in 1999, 2000, and 2001 were 0.11 ± 0.04 , 0.11 ± 0.03 , and $0.13 \pm 0.03 \mu\text{mol L}^{-1}$, respectively. Average DIC concentration in precipitation over 1999 to 2001 was $40 \pm 20 \mu\text{mol L}^{-1}$; CH_4 in precipitation was below our detection limit of $0.01 \mu\text{mol L}^{-1}$. Average catchment flow DIC and CH_4 concentrations varied over 1999 to 2001, mostly due

Table 4. Inorganic carbon (C) Mass Budget of Total Seasonal Inorganic C Inputs and Outputs into the FLUDEX Reservoirs in 1999, 2000, and 2001

	High-C Reservoir Mass (kg C ha ⁻¹)			Medium-C Reservoir Mass (kg C ha ⁻¹)			Low-C Reservoir Mass (kg C ha ⁻¹)		
	1999	2000	2001	1999	2000	2001	1999	2000	2001
Inputs									
Inflow	169	194	167	248	217	222	248	268	251
Precipitation	0	1	0	0	1	0	0	1	0
Catchment	41	128	56	8	29	13	0	2	1
<i>Total inputs</i>	<i>210</i>	<i>323</i>	<i>223</i>	<i>256</i>	<i>247</i>	<i>235</i>	<i>248</i>	<i>271</i>	<i>252</i>
Outputs									
Diffusive flux (range)	389 (370–407)	278 (263–293)	324 (301–346)	263 (252–273)	162 (153–171)	337 (174–200)	337 (316–359)	216 (210–222)	210 (194–226)
Weir outflow	378	407	249	602	369	406	194	196	185
Wall seepage	101	84	58	155	101	88	147	88	51
Fracture flow	0	0	0	0	0	0	233	199	172
Drawdown	45	33	35	33	23	30	41	41	47
Ebullition (range)	0 (0–0)	0 (0–1)	2 (1–3)	0 (0–0)	0 (0–1)	1 (1–2)	0 (0–0)	1 (1–1)	1 (1–2)
<i>Total outputs (range)</i>	<i>913 (894–931)</i>	<i>802 (787–818)</i>	<i>668 (664–691)</i>	<i>1053 (1042–1063)</i>	<i>655 (646–665)</i>	<i>713 (699–726)</i>	<i>952 (931–974)</i>	<i>741 (735–747)</i>	<i>666 (650–683)</i>
Net CO₂ production (range)	703 (684–721)	479 (464–495)	445 (421–468)	797 (786–807)	408 (399–418)	478 (464–491)	704 (683–726)	470 (464–476)	414 (398–431)

to the infrequent sampling regime dictated by rain-fall amounts sufficient to collect catchment flow from the L114 reference catchment. Over 3 years, average DIC concentrations were $690 \pm 140 \pm \mu\text{mol L}^{-1}$ and average CH₄ concentrations were $0.07 \pm 0.1 \mu\text{mol L}^{-1}$.

Pumped inflow water was the major water input into all three reservoirs (at least 90% of total inputs) and represented a higher proportion of total water inputs in the medium- and low-C reservoirs (96%–98%) than in the high-C reservoir (around 90%) (Table 3). Precipitation water inputs were minimal compared to the overall input water volume (less than 2%) (Table 3), and DIC and CH₄ inputs via precipitation were low for all reservoirs in all flooding seasons (Tables 4 and 5). Only the high-C reservoir, which had a larger watershed area than the other two reservoirs (Table 2), had important catchment water input (Table 3). During all three flooding seasons, high-C reservoir catchment DIC inputs were approximately five to 30 times greater than similar inputs into the medium- and low-C reservoirs and represented 20%–40% of inorganic C inputs to the high-C reservoir (Table 4). Negligible concentrations of CH₄ in inflow water, precipitation, and catchment input made them unimportant sources of CH₄ to the reservoirs (Table 5).

Inorganic Carbon and Methane Outputs (Diffusive Surface Flux, Outflow Water, and Ebullition)

Diffusive Surface Carbon Dioxide and Methane Fluxes. Gas transfer coefficients (k) measured using SF₆ were lower than those obtained on larger, open water bodies (k_{600} ranged from 0.2 to 1.5 cm h⁻¹) (Matthews and others 2003). The low-C reservoir consistently had the highest k values; a sparse tree canopy, as well as its location on a ridge top, exposed the reservoir surface to relatively greater winds than the other two reservoirs. The k values were higher in 2001 than in 2000 (Matthews and others 2003), likely because needle and leaf loss from dead trees exposed reservoir surfaces to wind and precipitation effects, enhancing gas exchange (Ho and others 2000; Banks and others 1984; Cole and Caraco 1998; Wanninkhof 1992). We did not determine k values in 1999, so biweekly k values calculated for each reservoir in 2000 were averaged and applied to 1999 surface CO₂ and CH₄ concentrations to estimate diffusive surface fluxes (k values determined in 2001 were not used because canopy cover was much less than in 1999, when the reservoirs were relatively more sheltered).

Table 5. Methane (CH₄) Mass Budget of Total Seasonal CH₄ Inputs and Outputs into the FLUDEX Reservoirs in 1999, 2000, and 2001

	High-C Reservoir Mass (kg C ha ⁻¹)			Medium-C Reservoir Mass (kg C ha ⁻¹)			High-C Reservoir Mass (kg C ha ⁻¹)		
	1999	2000	2001	1999	2000	2001	1999	2000	2001
Inputs									
Inflow	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Precipitation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Catchment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Total inputs</i>	<i>0.1</i>	<i>0.1</i>	<i>0.2</i>	<i>0.2</i>	<i>0.2</i>	<i>0.2</i>	<i>0.2</i>	<i>0.2</i>	<i>0.2</i>
Outputs									
Diffusive flux (range)	2.7 (2.5–2.9)	5.7 (5.2–6.2)	7.3 (6.0–8.5)	1.0 (1.0–1.0)	2.7 (2.4–3.0)	4.0 (3.5–4.6)	1.9 (1.7–2.2)	4.2 (4.1–4.4)	7.1 (6.6–7.5)
Weir outflow	1.4	4.3	2.8	1.7	4.6	6.0	0.6	1.8	3.1
Wall seepage	0.3	0.9	0.9	0.4	0.9	1.2	0.4	1.0	0.7
Fracture flow	0.0	0.0	0.0	0.0	0.0	0.0	0.6	2.3	2.4
Drawdown	0.3	0.4	0.6	0.2	0.4	0.6	0.2	1.1	2.2
Ebullition (range)	0.0 (0.0–0.0)	5.6 (2.5–8.7)	19.1 (11.5–26.7)	0.1 (0.1–0.1)	4.4 (2.5–6.2)	18.1 (8.2–27.8)	0.0 (0.0–0.0)	14.7 (11.0–18.4)	19.9 (13.5–25.9)
<i>Total outputs (range)</i>	<i>4.7 (4.5–4.9)</i>	<i>16.9 (13.3–20.5)</i>	<i>30.7 (21.8–39.5)</i>	<i>3.4 (3.4–3.4)</i>	<i>13.0 (10.8–15.1)</i>	<i>29.9 (19.5–40.2)</i>	<i>3.7 (3.5–4.0)</i>	<i>25.1 (21.3–29.0)</i>	<i>35.4 (28.5–41.8)</i>
Net CH₄ production (range)	4.6 (4.4–4.8)	16.8 (13.2–20.4)	30.5 (21.6–39.3)	3.2 (3.2–3.2)	12.8 (10.6–14.9)	29.7 (19.3–40.0)	3.5 (3.3–3.8)	24.9 (21.1–28.8)	35.2 (28.3–41.6)

C, carbon

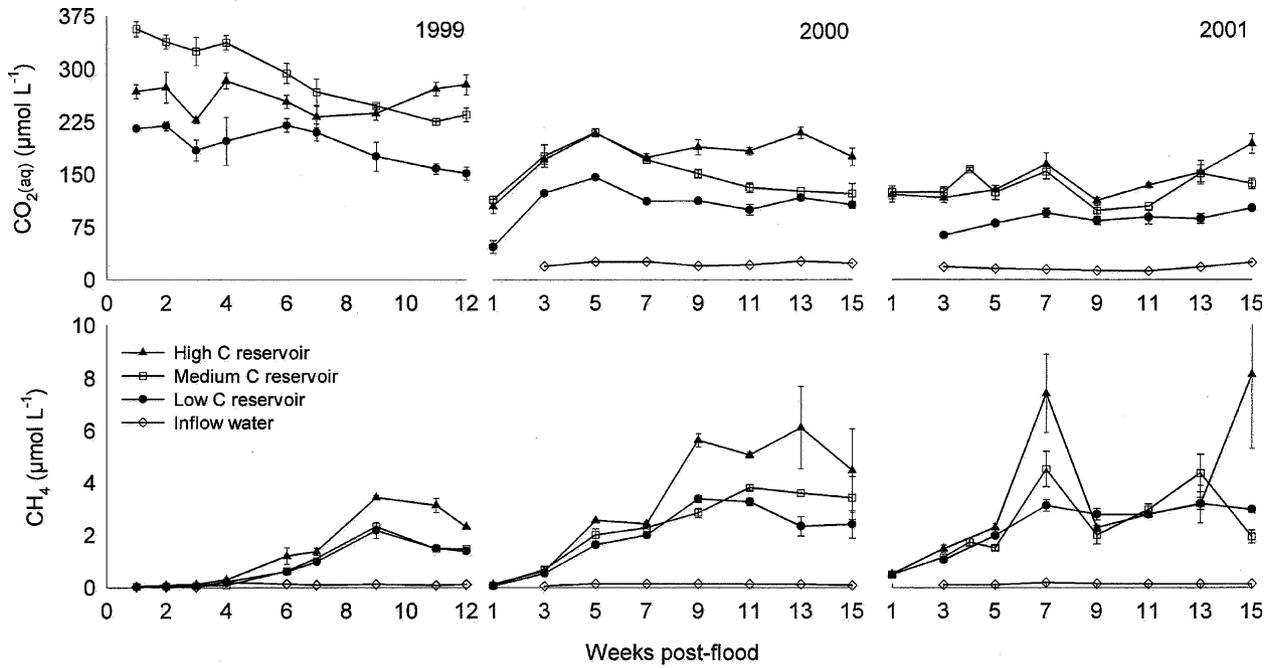


Figure 2. Dissolved surface concentrations of carbon dioxide (CO₂) (top) and methane (CH₄) (bottom) in the three FLUDEX reservoirs during 1999, 2000, and 2001. Dissolved CO₂ concentrations in inflow water were not measured in 1999.

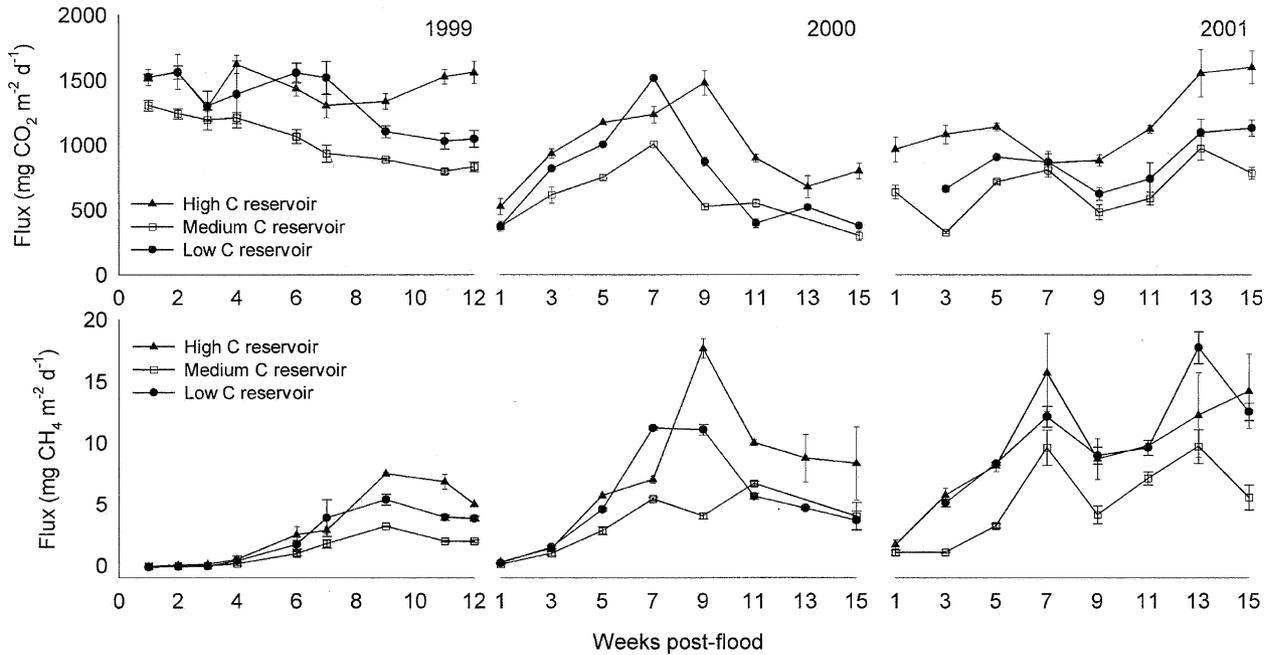


Figure 3. Diffusive surface fluxes of carbon dioxide (CO₂) (top) and methane (CH₄) (bottom) from the three FLUDEX reservoirs during 1999, 2000, 2001. 1999 fluxes were estimated from 1999 surface concentration data and gas transfer coefficients (*k*) determined during the 2000 flooding season.

Surface water CO₂ concentrations remained fairly constant from the beginning to the end of each flooding season (Figure 2). In 1999, mean surface water CO₂ concentrations in the high-,

medium-, and low-C reservoirs were 260 ± 10, 290 ± 10, and 190 ± 10 μmol L⁻¹, respectively. In 2000, mean CO₂ concentrations in the high-, medium-, and low-C reservoirs were 180 ± 30,

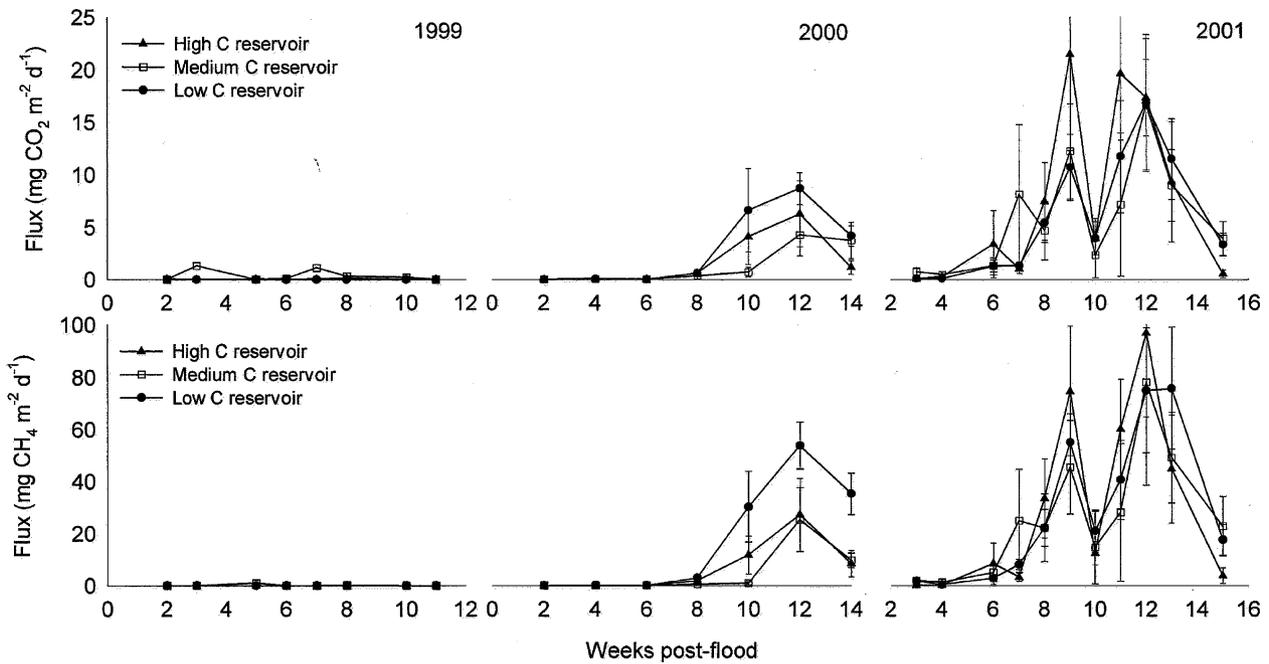


Figure 4. Ebullition fluxes of carbon dioxide (CO_2) (top) and methane (CH_4) (bottom) from the three FLUDEX reservoirs during 1999, 2000, and 2001.

150 ± 40 , and $110 \pm 30 \mu\text{mol L}^{-1}$, respectively. Mean CO_2 concentrations in 2001 were 140 ± 30 , 130 ± 20 , and $85 \pm 10 \mu\text{mol L}^{-1}$ in the high-, medium-, and low-C reservoirs, respectively (Figure 2). Diffusive surface CO_2 fluxes were highest during the 1st year of flooding (Figure 3), with mean CO_2 fluxes ranging from 1,050 to 1,460 $\text{mg CO}_2 \text{m}^{-2} \text{d}^{-1}$. In 2000, mean CO_2 fluxes ranged from 590 to 970 $\text{mg CO}_2 \text{m}^{-2} \text{d}^{-1}$. Mean fluxes remained at about the same level in 2001, ranging from 660 to 1,150 $\text{mg CO}_2 \text{m}^{-2} \text{d}^{-1}$ (Figure 3).

In contrast to CO_2 , surface water CH_4 concentrations generally increased from the beginning to end of each flooding season (Figure 2). In 1999, mean surface water CH_4 concentrations in the high-, medium-, and low-C reservoirs were 1.4 ± 0.1 , 0.8 ± 0.03 , and $0.7 \pm 0.04 \mu\text{mol L}^{-1}$, respectively. In 2000, mean CH_4 concentrations in the high-, medium-, and low-C reservoirs were 3.3 ± 2.4 , 2.2 ± 1.4 , and $1.9 \pm 1.2 \mu\text{mol L}^{-1}$, respectively. In 2001, mean dissolved CH_4 concentrations were 3.6 ± 3.2 , 2.5 ± 1.7 , and $2.5 \pm 0.8 \mu\text{mol L}^{-1}$, respectively in the high-, medium-, and low-C reservoirs (Figure 2). Diffusive surface CH_4 fluxes increased with each year of flooding (Figure 3). Mean CH_4 fluxes in 1999 ranged from 1.1 to 2.8 $\text{mg CH}_4 \text{m}^{-2} \text{d}^{-1}$. In 2000, mean CH_4 fluxes ranged from 3.4 to 7.4 $\text{mg CH}_4 \text{m}^{-2} \text{d}^{-1}$. Mean CH_4 fluxes in 2001 ranged from 5.2 to 10.6 $\text{mg CH}_4 \text{m}^{-2} \text{d}^{-1}$ (Figure 3).

Outflow Water (Weir Outflow, Dike Seepage, Fracture Flow, Drawdown). Dissolved inorganic C and CH_4 weir outflow concentrations varied with each season (Figure 1). Average outflow DIC concentrations in 1999 were 380 ± 40 , 430 ± 75 , and $320 \pm 50 \mu\text{mol L}^{-1}$ in the high-, medium-, and low-C reservoirs, respectively. In 2000, average outflow DIC concentrations were 340 ± 40 , 290 ± 60 , and $250 \pm 30 \mu\text{mol L}^{-1}$, respectively, in the high-, medium-, and low-C reservoirs. In 2001, concentrations were 240 ± 50 , 260 ± 25 , and $190 \pm 10 \mu\text{mol L}^{-1}$ in the high-, medium-, and low-C reservoirs, respectively. Average outflow CH_4 concentrations in 1999 were 1.1 ± 1.2 , 0.9 ± 0.9 , and $0.7 \pm 0.7 \mu\text{mol L}^{-1}$ in the high-, medium-, and low-C reservoirs, respectively. In 2000, average outflow CH_4 concentrations were 3.6 ± 2.1 , 3.3 ± 1.3 , and $2.2 \pm 1.0 \mu\text{mol L}^{-1}$ in the high-, medium-, and low-C reservoirs, respectively. In 2001, concentrations were 2.5 ± 1.7 , 4.3 ± 2.1 , and $3.2 \pm 0.6 \mu\text{mol L}^{-1}$ in the high-, medium-, and low-C reservoirs, respectively.

Water losses via weir outflow, dike seepage, fracture flow, and drawdown represented 97%–98% of total water losses in all three reservoirs (Table 3). Given the short water residence times in the reservoirs, combined outflow DIC and CH_4 losses were important terms in the inorganic C and CH_4 budgets (Tables 4 and 5). Together, total outflow DIC outputs were one to three times greater than diffusive surface CO_2 flux outputs, and total

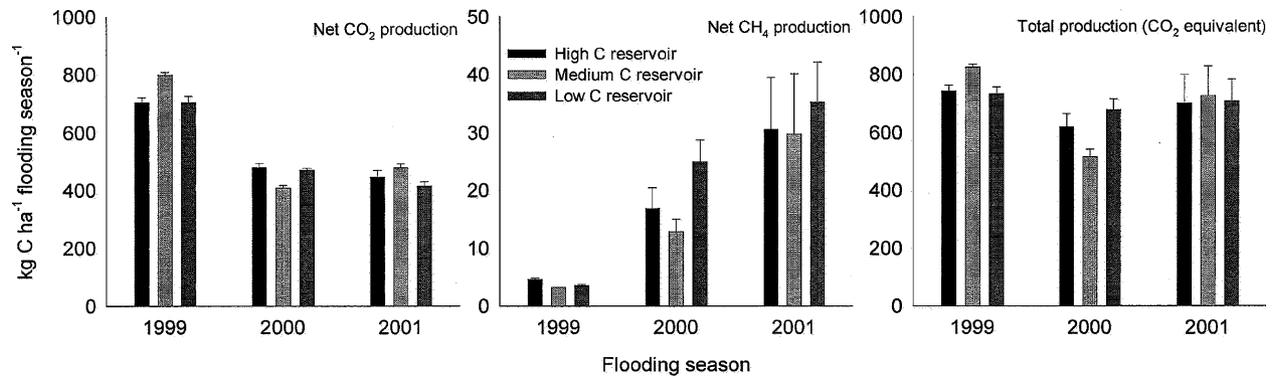


Figure 5. Net carbon dioxide (CO₂) and methane (CH₄) production in the three FLUDEX reservoirs during each of the three flooding seasons (each flooding season lasted around 100 days). The total greenhouse gas (GHG) production as CO₂ equivalents was determined by adding CO₂ production to CH₄ production in CO₂ equivalents (calculated by multiplying CH₄ production by a global warming potential of 23 [Dentener and others 2001]).

outflow CH₄ outputs were one to two times greater than diffusive CH₄ flux outputs. In actual reservoirs, water residence times are usually longer than in the FLUDEX reservoirs and GHG loss via outflow and dam seepage likely represents a smaller percentage of diffusive surface GHG fluxes. However, CH₄ losses via water flow through turbines and the spillway of a hydroelectric dam in Brazil were 14 times greater than ebullition and diffusive CH₄ fluxes (Fearnside 2002).

Ebullition. In 1999 and during the first nine weeks of flooding in 2000, ebullition in all three reservoirs was negligible (Figure 4). From weeks 10 to 14 postflood in 2000, ebullition suddenly increased (Figure 4). In 2001, ebullition rates were low during the first six weeks of flooding but increased sharply at around week 8. Except for a sudden drop at around week 10, ebullition rates were high during the remainder of the season until the final week prior to drawdown (Figure 4). Ebullition fluxes in 2001 were one and a half to four times greater than in 2000 (Figure 4).

Ebullition CO₂ fluxes were equivalent to less than 1 % of the combined diffusive surface and outflow inorganic C outputs during periods of maximum ebullition (Table 4). Other studies have also found ebullition to be insignificant in overall reservoir CO₂ emissions (less than 1 % diffusive CO₂ fluxes) (Duchemin and others 2000; Kelly and others 1997). However, during periods of high ebullition, CH₄ emitted to the atmosphere via ebullition was greater than diffusive surface and outflow CH₄ outputs combined (Table 5). During the 3rd flooding season, ebullition CH₄ fluxes were nearly double combined diffusive surface and outflow CH₄ outputs (Table 5).

Mean CH₄ ebullition fluxes in 2000 and 2001 (5–30 mg CH₄ m⁻² d⁻¹) were comparable to CH₄ ebul-

lition fluxes from the ELARP reservoir, which flooded a boreal peatland (around 20 mg CH₄ m⁻² d⁻¹) (Kelly and others 1997); a reservoir that flooded tropical forests (up to 65 mg CH₄ m⁻² d⁻¹) (Duchemin and others 2000); and a beaver pond flooding boreal forest (23 mg CH₄ m⁻² d⁻¹) (Weyhenmeyer 1999). In fact, ebullition rates midseason in 2001 were higher than the ELARP reservoir and beaver pond and more closely approximated ebullition fluxes from tropical reservoirs, which typically have much higher mean ebullition rates than temperate reservoirs (St. Louis and others 2000). For example, in a 3-year-old tropical reservoir, Galy-Lacaux and others (1997) report CH₄ ebullition fluxes of 164 mg CH₄ m⁻² d⁻¹ in 0–3 m of water.

Ebullition of CH₄ was most likely driven by low oxygen concentrations and warm soil temperatures in the shallow reservoirs (data not shown). Wehenmeyer (1999) attributed high ebullition in a boreal beaver pond to increased methanogen activity and decreased CH₄ solubility at high temperatures. Duchemin and others (2000) found a strong correlation between ebullition and water level fluctuation and attributed the correlation to increasing pressure from increasing water column depth. Because the FLUDEX reservoirs were shallow compared to most large, deep reservoirs, the water column exerted relatively little pressure on the flooded soils.

Inorganic Carbon and Methane Budgets and Net Carbon Dioxide and Methane Production

Total inorganic C and CH₄ outputs (diffusive surface flux, weir outflow, dike seepage, bedrock fracture flow, drawdown, and ebullition fluxes)

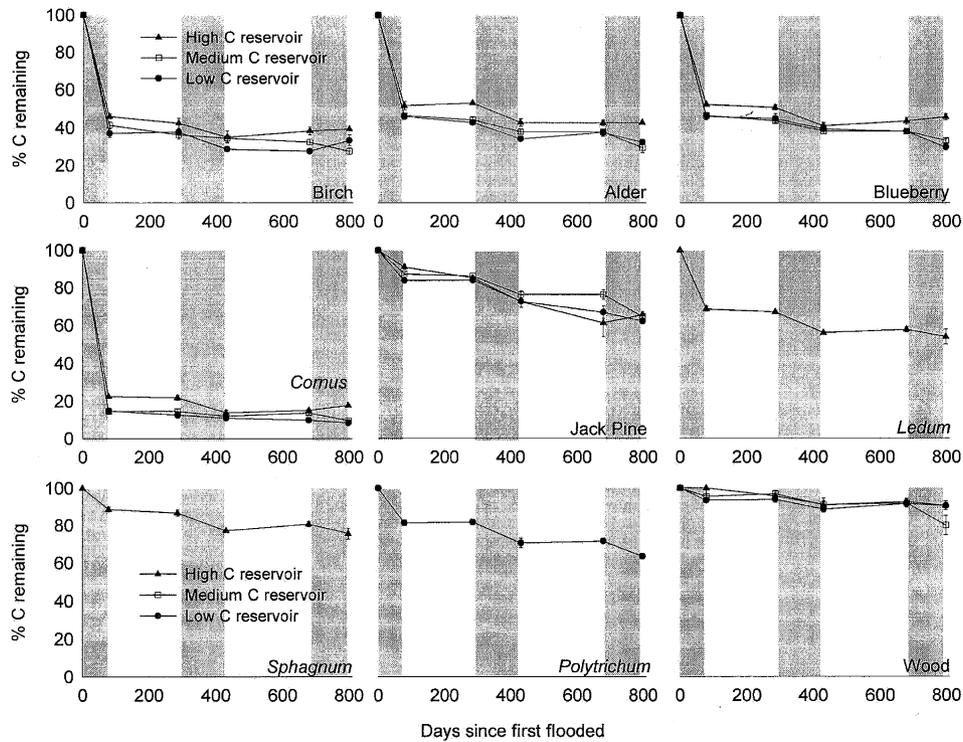


Figure 6. The proportion of carbon (C) remaining in 12 plant tissues enclosed in litterbags (10 × 10 cm; made of 400- μ m Nitex mesh) placed in each reservoir. Litterbags contained about 5 g of dried plant tissue. “Wood” litterbags were assembled with approximately 13 g wooden blocks cut from a single piece of fir lumber, avoiding sapwood and branch knots. Fifteen litterbags of each plant tissue type were placed on top of existing litter in each reservoir. Triplicate litterbags of each plant type

were retrieved after autumn drawdown in the first 3 years of the study (1999, 2000, and 2001) and prior to spring flooding in the 2nd and 3rd years of the study (2000 and 2001) and analyzed for C content using an Exeter Analytical Model 440 Elemental Analyzer at the University of Alberta Limnology Laboratory (Edmonton, Alberta). Shaded areas indicate flooding periods, when litterbags were submerged.

were always greater than total inorganic C and CH₄ inputs (inflow, precipitation, and catchment input) (Tables 4 and 5). Although all three FLUDEX reservoirs were net CO₂ and CH₄ producers during the flooding seasons, production was not related to landscape OC storage during any of the three flooding seasons (Tables 4 and 5). Carbon dioxide production declined with each successive flooding season (Figure 5), decreasing from 703 kg C ha⁻¹ (1999) to 445 kg C ha⁻¹ (2001) in the high-C reservoir; from 797 kg C ha⁻¹ (1999) to 478 kg C ha⁻¹ (2001) in the medium-C reservoir; and from 704 kg C ha⁻¹ (1999) to 414 kg C ha⁻¹ (2001) in the low-C reservoir (Table 4). Methane production, on the other hand, increased with each flooding season (Figure 5), rising from 4.6 kg C ha⁻¹ (1999) to 30.5 kg C ha⁻¹ (2001) in the high-C reservoir, from 3.2 kg C ha⁻¹ (1999) to 29.7 kg C ha⁻¹ (2001) in the medium-C reservoir, and from 3.5 kg C ha⁻¹ (1999) to 35.2 kg C ha⁻¹ (2001) in the low-C reservoir

(Table 5). Methane production would likely have been greater had the reservoirs not been seasonally emptied because exposed soils were oxidized during drawdown periods.

Diffusive DIC and CH₄ fluxes from flooded soils measured over the three flooding seasons using submerged chambers (approximately 13-L transparent chambers placed directly onto grooved plastic collars embedded into the soil) confirm trends in GHG production observed with the inorganic C and CH₄ mass budgets (data not shown). Specifically, submerged chamber flux measurements at five individual sites within each reservoir (representing around 0.04% of the reservoir bottom) also showed a decrease in DIC production in the 2nd and 3rd seasons relative to the 1st season and a general increase in CH₄ production with each season.

Sources of Reservoir Carbon Dioxide and Methane Production. Reservoir CO₂ and CH₄ production could result from the decomposition of (a) OC

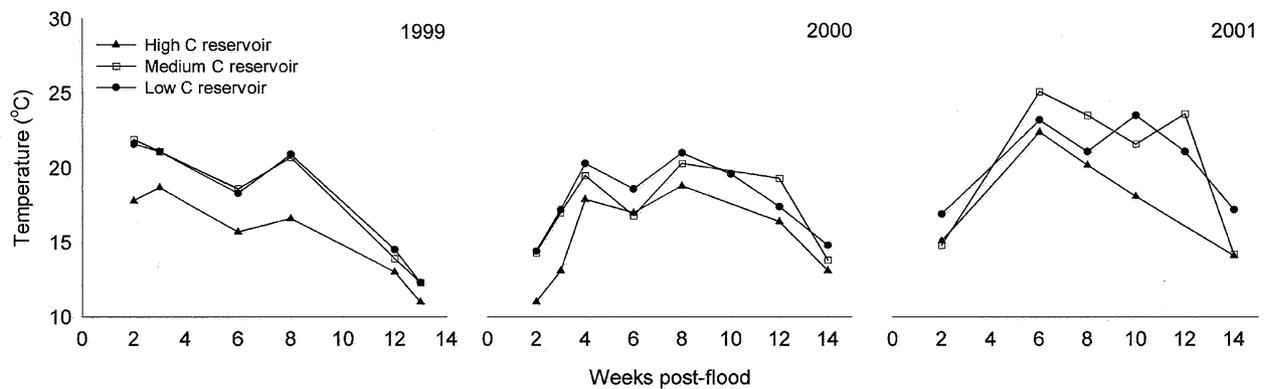


Figure 7. Temperatures at the soil/water interface in each reservoir during the 3 flooding seasons. Temperatures were measured at two locations within each reservoir using a Campbell Scientific CR10X data logger attached to copper-constantan thermocouple rods permanently installed in the soil. Each point is an average of temperatures logged at 30-s intervals for 3 min (error bars are not visible).

stored in soils and vegetation and (b) DOC entering the reservoirs via inflow water and watershed input. However, decomposition of inflow DOC likely contributed very little to net CO_2 and CH_4 production in the FLUDEX reservoirs. Flooded soil DIC and CH_4 fluxes determined using submerged chambers were more than sufficient to support the observed net CO_2 and CH_4 production (data not shown), and stable C isotope analysis show that lake DOC degradation is not the main source of reservoir DIC, which had a different ^{13}C signature than that of lake DOC (J. J. Venkiteswaran and others forthcoming). Dissolved organic C pumped into the FLUDEX reservoirs had been processed in Roddy Lake for approximately 15 years (water residence time of the lake) and was therefore quite recalcitrant and unlikely to have suddenly degraded in the approximately 5–9 days it was in the FLUDEX reservoirs. Moreover, FLUDEX reservoir waters were more deeply colored than Roddy Lake waters, which would have prevented further DOC photodegradation. Finally, reservoir DOC mass budgets show net DOC production in the FLUDEX reservoirs during all three flooding seasons (that is, DOC outputs via outflow water were greater than DOC inputs via inflow water and catchment flow) (data not shown). Dissolved Organic C produced within the reservoir therefore replaced any inflow water DOC that degraded within the reservoir.

Photosynthesis and Methane Oxidation in the Reservoirs. Net reservoir CO_2 and CH_4 production is essentially an estimate of (a) diffusive soil DIC and dissolved CH_4 fluxes minus water column consumption of DIC via photosynthesis and dissolved CH_4 via oxidation, and (b) ebullition CO_2 and CH_4 fluxes from the soil directly to the atmosphere.

Photosynthesis and CH_4 oxidation reduced reservoir DIC and CH_4 concentrations, thereby reducing net reservoir CO_2 and CH_4 production (J. J. Venkiteswaran and others forthcoming).

Algal assemblages on submerged tree surfaces (periphyton) were the dominant photoautotrophs in the reservoirs. Photosynthetic CO_2 uptake by periphyton was equivalent to 148, 172, and 145 kg C ha^{-1} , respectively, in the high-, medium-, and low-C reservoirs in 1999; 182, 225, and 211 kg C ha^{-1} respectively, in the high-, medium-, and low-C reservoirs in 2000; and 77, 180, and 273 kg C ha^{-1} , respectively, in the high-, medium-, and low-C reservoirs in 2001 (J. J. Venkiteswaran and others forthcoming). Photosynthetic uptake rates were therefore important compared to net reservoir CO_2 production rates (Table 4). The considerable quantities of CO_2 produced in the reservoirs and eventually sequestered in algal material was likely emitted to the atmosphere upon decomposition of the algae after reservoir drawdown, thereby representing a GHG source not accounted for in the net CO_2 production estimates.

Water column CH_4 oxidation was negligible in 1999; however, in 2000 approximately 50% of the CH_4 produced in all reservoirs was oxidized, and in 2001, 70% to 88% of the CH_4 produced was oxidized (J. J. Venkiteswaran and others forthcoming). Methane oxidation was therefore important in lowering the overall GHG impact of the FLUDEX reservoirs through conversion of CH_4 to CO_2 (including direct and indirect effects, CH_4 is 23 times more effective as a GHG than CO_2 over a 100-year period [Dentener and others 2001]).

Net Reservoir Organic Carbon Production. Inorganic C and CH_4 mass budgets do not incorporate reservoir DOC production. Reservoir DOC mass

budgets show the FLUDEX reservoirs were net DOC producers during all 3 flooding seasons. Dissolved Organic C produced in the reservoirs likely decomposed downstream after leaving the reservoir, providing a GHG source to the atmosphere not incorporated in net reservoir CO₂ and CH₄ production estimates.

Net Carbon Dioxide and Methane Production: The Influences of Organic Carbon Storage and Time

Organic Carbon Storage and Decomposition Rates

Although reservoir CO₂ and CH₄ production resulted from decomposition of flooded OC and not decomposition of OC entering the reservoirs in inflow water or catchment flow, GHG production was not related to the overall amount of OC stored in the FLUDEX sites. Decomposition rates determined from litterbags containing vegetation characteristic of the sites showed four of five vegetation types (birch, alder, blueberry, and *Cornus*) decomposed more rapidly in the medium and low-C reservoirs than in the high-C reservoir (Figure 6). Slower decomposition rates in the high-C reservoir may have been related to the consistently lower temperatures at the bottom of the reservoir (in each of the three flooding seasons, temperatures at the soil/water interface in the high-C reservoir were as much as 4–5°C lower than in both the medium and low-C reservoirs) (Figure 7). The observed similarity in net CO₂ and CH₄ production in the three reservoirs may also in part reflect the influence of substrate quality on decomposition rates. Decomposition of leaf litter characteristic of the medium and low-C reservoirs (birch, alder, and blueberry) was greater than decomposition of leaf litter and ground vegetation characteristic of the high-C reservoir (*Ledum*, *Sphagnum* spp., *Polytrichum* spp.) (Figure 6). Therefore, although the high-C reservoir had the highest amount of stored OC, litter characteristic of the medium and low-C reservoirs decomposed more rapidly. Jack pine needles, which were an important litter component in all three reservoirs, decomposed at similar rates in all of them (Figure 6).

The decrease in production from the 1st to 2nd flooding season was greater than that from the 2nd to 3rd flooding season (Figure 5). Decomposition of all vegetation types was greatest during the 1st flooding season in all three reservoirs (Figure 6); high decomposition of labile C during the 1st

flooding season may have left more recalcitrant C to be slowly broken down in subsequent flooding seasons. Reservoir CO₂ production was similar in the 2nd and 3rd years of flooding, possibly due to decomposition of litterfall entering the reservoirs as the trees died. During the 1st flooding season, litterfall into the reservoirs ranged between 270 to 570 kg ha⁻¹, rates similar to those measured previously in upland forests at the ELA (St. Louis and others 2001). However, flooded jack pine trees lost almost all their needles near the end of the 2nd flooding season, when litterfall rates were approximately five times greater than during the 1st year (2,180–2,500 kg ha⁻¹). This large source of decomposable OC likely helped sustain reservoir GHG production rates during the 3rd flooding season. Flooded soil temperatures were also about 3°C warmer during the 3rd flooding season than during the 2nd flooding season (Figure 7), perhaps increasing microbial activity in the decomposition zone.

Time Scale of Reservoir Greenhouse Gas Emissions Studies

To best understand the relationship between OC storage and GHG fluxes from flooded landscapes, C cycling in reservoirs needs to be studied over the long term. Greenhouse gas emissions from reservoirs are assumed to decrease with time as decomposition depletes OC stores. St. Louis and others (2000) found a significant negative exponential decline in CO₂ fluxes with age from 21 temperate reservoirs. However, few studies have monitored emissions from one reservoir over a period of time. Galy-Lacaux and others (1997, 1999) showed dissolved CO₂ and CH₄ concentrations in surface waters and CH₄ fluxes (both diffusive and ebullition) from the Petit Saut reservoir in French Guyana to reach maximum levels 1 year after impoundment, but to rapidly decrease by the 3rd year of flooding. Fearnside (1995, 1997) calculated C emissions from Brazilian reservoirs and predicted CO₂ emissions to be concentrated in a tremendous pulse in the first 10 years of flooding. Carbon dioxide and CH₄ surface concentrations in the experimental ELARP reservoir have been monitored since impoundment in 1993, and concentrations were as high 10 years after impoundment as they were during the first few flooding seasons (St Louis and others 2004). Kelly and others (1997) calculated complete decomposition of peat in the ELARP reservoir could sustain post-flood GHG emissions at present rates for approximately 2000 years.

For comparison, the FLUDEX reservoirs have OC stores (in soils, litter, and vegetation) to support current decomposition rates (around 500 kg C ha⁻¹) for 70–100 years (assuming complete decomposition of all OC stores). However, decomposition of wood is minimal in northern reservoirs, especially if they are in cold or anoxic waters (Smith 1991). Litterbag results showed slow decomposition of wood over the first 3 years of flooding in the FLUDEX reservoirs (Figure 6). With 50%–60% of the total OC flooded by the FLUDEX reservoirs contained in wood (Table 1), the extent of wood decomposition in the FLUDEX reservoirs will influence long-term reservoir GHG emissions. Furthermore, long-term flux patterns in these reservoirs may differ from those observed in the first 3 years of flooding as decomposition rates in each reservoir reflect the relative amounts of labile versus recalcitrant OC remaining for decomposition. For example, some of the OC available for decomposition in the high-C reservoir is present in slowly degraded plant material like *Sphagnum* spp. (Figure 6) (Heyes and others 1998).

An important consideration in evaluating reservoir GHG emissions is how CO₂ and CH₄ production changes with reservoir age (Kelly and others 1994; Fearnside 1995, 1997; Rosa and others 1996; Galy-Lacaux and others 1999; St. Louis and others 2000). After three years of flooding the FLUDEX reservoirs, two temporal GHG production trends became apparent: (a) total net CO₂ production decreased with each flooding season, while (b) net CH₄ production increased with each flooding season (Figure 5). Temporal changes in GHG emissions are important to consider in an overall evaluation of the effects of reservoir GHG emissions to the atmosphere. For example, the relative year-to-year increase in CH₄ emissions in the FLUDEX reservoirs is important because the GWP of CH₄ is 23 times greater than that of CO₂ (Dentener and others 2001). Therefore, over three seasons in the FLUDEX reservoirs, relatively small increases in CH₄ production offset larger decreases in CO₂ production from a GWP perspective (Figure 5).

The Net Effect of Reservoir Creation on Atmospheric Greenhouse Gas Levels

Concern about GHG emissions from reservoirs has led to monitoring of the CO₂ and CH₄ fluxes from the surfaces of existing reservoirs. However, the true effect of reservoir creation on atmospheric GHG levels is the net difference between GHG fluxes before and after flooding. For example, although reservoirs tend to be a source of both CO₂

and CH₄ to the atmosphere, forested upland regions tend to be net sinks of these GHGs via photosynthesis and CH₄ oxidation in soils. Therefore, net ecosystem exchange (NEE) of both CO₂ and CH₄ in the undisturbed landscape prior to flooding needs to be considered in addition to reservoir GHG emissions after flooding (St. Louis and others 2000; Kelly and others 1997).

Net Greenhouse Gas Effect over the First three Flooding Seasons

Although NEE of CO₂ (total ecosystem photosynthesis minus total ecosystem respiration) in the FLUDEX sites was not quantified prior to flooding, all sites were fire-regenerating forests assumed to be assimilating C at high rates through the accumulation of plant biomass and organic soils. The NEE of CO₂ in a similar boreal forest site (around 30-year-old boreal jack pine forest) was determined to be around -1900 mg C m⁻² d⁻¹ (integrated over a 24-h period during the growing season [May to September] [McCaughy and others 1997]). The average total CO₂ production by the FLUDEX reservoirs over the first three flooding seasons was approximately 550 mg C m⁻² d⁻¹. If CO₂ uptake by the FLUDEX sites prior to flooding was similar to published rates in similar forest, the net change in CO₂ flux between the undisturbed sites and the flooded reservoirs would have been around 2,450 mg C m⁻² d⁻¹. Over the three flooding seasons (approximately 315 days), the net effect of reservoir creation on CO₂ cycling in the FLUDEX sites would have been about 260 g C m⁻² season⁻¹ emitted to the atmosphere.

Dark static chambers were used to measure soil CH₄ oxidation rates (that is, NEE of CH₄) in the FLUDEX sites prior to flooding. Soils in all FLUDEX sites consumed CH₄ at rates of -1.1 to -0.7 mg CH₄-C m⁻² d⁻¹ (data not shown), similar to rates measured in other boreal and temperate forest sites (Savage and others 1997; Crill 1991; Castro and others 1995). After flooding, all soils changed from being CH₄ sinks to CH₄ sources. Total average CH₄ production over the first three flooding seasons was about 19 mg C m⁻² d⁻¹, representing a net change of about 20 mg C m⁻² d⁻¹. Over the first three flooding seasons, the net effect of reservoir creation on CH₄ emissions from the FLUDEX sites was about 2.1 g C m⁻² season⁻¹ emitted to the atmosphere. Factoring in the GWP of CH₄, net CH₄ emissions were equivalent to about 18 g C m⁻² season⁻¹ emitted in CO₂ equivalents. Clearly, in flooding a landscape that was sequestering C at high rates through postfire reforestation, the overall net effect

of reservoir creation on GHG exchange with the atmosphere is due largely to the change between pre- and postflood CO_2 fluxes, not changes in CH_4 fluxes.

Net Greenhouse Gas Effect over the Long Term. To understand the long-term effect of reservoir creation on atmospheric GHG levels, upland boreal forest C cycling in response to fire disturbance must be considered. Frequent fires in the boreal ecoregion release much of the C stored in vegetation and soils to the atmosphere primarily as CO_2 every 50–100 years. Upon forest regeneration, CO_2 is sequestered from the atmosphere through the accumulation of plant biomass and soils. Therefore, boreal uplands are essentially neutral with respect to atmospheric CO_2 levels over the long-term, except for a small C accumulation in unburned soils of about $1\text{--}12 \text{ g C m}^{-2} \text{ y}^{-1}$, or $3\text{--}33 \text{ mg C m}^{-2} \text{ d}^{-1}$ (Schlesinger 1990).

Unlike forest fires, reservoirs release to the atmosphere a high proportion of landscape C as CH_4 , not as CO_2 . Therefore, in the long-term, reservoirs represent a net GHG emission to the atmosphere because terrestrial C originally sequestered as CO_2 is released as CH_4 , a more powerful GHG than CO_2 . Adding to the long-term net effect of reservoir creation on GHG levels in the atmosphere is the loss of the CH_4 sink via soil oxidation in the unflooded ecosystem throughout the lifespan of the reservoir.

Long-term effects of reservoir creation on atmospheric GHG levels therefore depend mostly on changes between terrestrial and reservoir C cycling with respect to CH_4 production/oxidation. Future trends in reservoir CH_4 emissions cannot be estimated from this short-term study. However, although long-term CH_4 fluxes from reservoirs may decrease over time because decomposition should slow with depletion of OC stores, CH_4 production in the FLUDEX reservoirs has increased substantially during the first three flooding seasons. Methane emissions from the ELARP reservoir have remained high over 10 years of flooding (V. L. St Louis and others 2004) and Fearnside (1995, 1997) projected CH_4 emissions from Brazilian reservoirs would remain constant over a 50–100-year period, fueled in part by anaerobic decomposition of allochthonous OC entering the deep zones of reservoirs in river flow. On the other hand, Galy-Lacaux and others (1999) projected CH_4 emissions from a reservoir in French Guyana to decrease to negligible levels within 20 years after flooding. Nevertheless, even if reservoir CH_4 emissions declined to extremely low levels over time, high initial CH_4 pro-

duction would represent a permanent net atmospheric GHG gain. Furthermore, the loss of the CH_4 sink (soil oxidation) in the unflooded ecosystem would always cause the reservoir to act as a net source of CH_4 to the atmosphere.

CONCLUSIONS

After three flooding seasons, CO_2 and CH_4 production in the FLUDEX reservoirs was not related to OC stored in site soils and vegetation. Inorganic C and CH_4 mass budgets showed all reservoirs to produce similar amounts of both CO_2 and CH_4 . A vegetation decomposition study using litterbags showed vegetation in both the medium- and low-C reservoirs to decompose faster than in the high-C reservoir. These results suggest that in the early stages of flooding, factors other than landscape OC storage amounts (such as lability of C-containing compounds and flooded soil temperatures) are important in determining overall GHG production in flooded upland forests. Organic C stores in landscapes may not be a good indication of subsequent GHG production reservoir creation, at least over the short-term.

Carbon dioxide production declined with each flooding season; however, CH_4 production increased with each season. The overall GHG effect of the FLUDEX reservoirs remained relatively constant because increased production of CH_4 , a stronger GHG than CO_2 , offset decreases in CO_2 production. This has important implications for long-term emissions scenarios from reservoirs and in evaluating the atmospheric effects of reservoir GHG production. At this point, it is not known whether CH_4 production will continue to increase, stabilize, or decrease as OC stores continue to be depleted. The FLUDEX is one of the few studies to have monitored GHG production in reservoirs over a period of time, and initial findings indicate that GHG dynamics in newly flooded landscapes change dramatically during the first few years following impoundment.

The net impact (pre- versus postflood) of reservoir creation on GHG fluxes in terrestrial landscapes was estimated by comparing GHG dynamics in the undisturbed ecosystem to the postflood condition. The FLUDEX sites, characterized by an 18-year-old fire regenerating forest, were estimated to be assimilating CO_2 at rates similar to published values for other boreal forest sites and were shown to be sinks for atmospheric CH_4 in their undisturbed state. Although all reservoirs were sources of both gases to the atmosphere, changes in CH_4 dynamics between the pre-flood and postflood bor-

al ecosystem are responsible for long-term GHG implications of reservoir creation.

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