

Nitrous Oxide Fluxes in Three Experimental Boreal Forest Reservoirs

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Global atmospheric concentrations of nitrous oxide (N₂O), a powerful greenhouse gas, continue to increase. While many sources and sinks have been identified, there is little known about how existing and newly constructed reservoirs, such as those created for hydroelectric production, impact current atmospheric N₂O concentrations. We hypothesized that N₂O fluxes to the atmosphere would increase because enhanced nutrient availability and increased soil respiration following the flooding of soils during reservoir creation would favor denitrification. Furthermore, we hypothesized that emissions would be linked to the amount of organic carbon contained in the flooded landscape. These hypotheses were tested by creating three experimental reservoirs over boreal upland sub-catchments that ranged in the amount of organic carbon stored in soils and vegetation. Diffusive surface N₂O fluxes within each reservoir were estimated using surface water concentrations of N₂O and the thin boundary layer method. Surface fluxes ranged from -1.0 to $-3.5 \mu\text{g N}_2\text{O m}^{-2} \text{ d}^{-1}$, and water column N₂O concentrations indicated that contrary to expectations, the reservoirs were acting as slight sinks for atmospheric N₂O. This net consumption of N₂O was likely related to an excess of labile carbon and low concentrations of oxygen (O₂) and nitrate (NO₃⁻) in the flooded soils. Therefore, it is postulated that reservoir creation by flooding boreal soils will likely have little or no net effect of adding additional N₂O to the current greenhouse gas (GHG) atmospheric burden, at least over the short term.

Introduction

Fixed nitrogen is returned to the atmospheric nitrogen pool primarily by two microbial processes, either anaerobically by denitrification or aerobically by nitrification. In some instances, such as at the oxic–anoxic sediment water

interface, the two processes can be linked. Nitrous oxide (N₂O) can be found as an intermediate byproduct of both of these processes. Emissions of N₂O to the atmosphere are of concern because of its ability to both deplete stratospheric ozone and to enhance global warming by absorbing infrared radiation. In fact, N₂O is estimated to be 296 times more effective as a greenhouse gas (GHG) than CO₂ on a molecular basis over a 100-year time horizon (1). Currently, global atmospheric N₂O concentrations are at about 314 ppb and are increasing by approximately $0.25 \pm 0.05\% \text{ yr}^{-1}$ (1). Global mass balance discrepancies for this gas have led to continued efforts by researchers to further identify and describe sources and sinks. At present, the sum of photolytic decomposition of N₂O in the stratosphere and the increase in the atmospheric concentration is greater than the identified sources (2). In addition to naturally occurring sources, there are several anthropogenic activities that are adding to the global atmospheric N₂O burden (1).

One region about which very little is known about N₂O exchange with the atmosphere is the northern boreal ecozone. Globally, this ecozone covers 15 million km² or 11% of the earth's terrestrial surface and within Canada amounts to 35% of the total land area or about 3 million km². It is characterized by uplands with thin organic and mineral soils variably covered with mixed deciduous and coniferous trees, interspersed with wetlands (including peatlands) and shallow to deep lakes lying lower on the landscape. To date, there is very little information identifying these various sites as being either potential sources or sinks for N₂O. Boreal agricultural soils (3), various forest soils (4–6), and wetlands (including peatlands) (7–12) are small sources of N₂O to the atmosphere. Similarly, while surface waters of most lakes tend to be supersaturated with N₂O (13–15), eutrophic lakes and anoxic waters in stratified lakes (16, 13) can be sinks for atmospheric N₂O. Reservoirs are another potential source of N₂O and other carbon GHGs to the atmosphere. Extensive reservoirs of varying depths and covering thousands of hectares have been developed over the past 20 years in boreal areas of Canada (17) as well as northern Europe (8, 18) resulting in the release of CO₂ and CH₄ (17, 19, 20), two GHGs known to contribute to climate warming. However, little is known about N₂O emissions from these locations. Older reservoirs in Finland (18, 21) and a more recently constructed one in northern Quebec (22) are only slight sources of N₂O to the atmosphere. Nitrous oxide emissions from these boreal reservoirs were calculated to amount to only 5% of total GHG emissions and were about equal to those of CH₄ (22). With the global demand for electricity increasing by 2–3% annually (23), it is anticipated that hydroelectric development will continue within the northern boreal ecozone leading to further GHG emissions and a further potential for climate warming.

This study was a part of a large whole-ecosystem experiment (the Flooded Upland Dynamics Experiment, FLUDEX) conducted at the Experimental Lakes Area (ELA) in NW Ontario, Canada, that was designed to study the impact of hydroelectric reservoir creation on GHG fluxes to the atmosphere (24). As with the other GHGs CO₂ and CH₄, carbon is necessary for the production of N₂O via the denitrification pathway directly by providing the necessary substrate for growth of the denitrifiers and indirectly through the removal of O₂ by microbial respiration. However, nutrient-poor soils are very low emitters of N₂O because of limited availability of NO₃⁻ (4, 25). The upland soils in the ELA have been characterized as having high C:N ratios (27:1 in forest islands) (26). Therefore, we hypothesized that, unlike the other GHGs

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TABLE 1. Carbon Stores in the FLUDEX Reservoir Sites before Flooding and Physical Characteristics of the Reservoirs after Flooding

	units	high C reservoir site	medium C reservoir site	low C reservoir site
above ground carbon biomass	kgC ha ⁻¹	27 560	27 730	19 762
soil carbon biomass	kgC ha ⁻¹	18 300	7200	11 100
water surface area	m ²	7400	5000	6300
reservoir volume	m ³	6870	4270	7120
mean depth	m	0.9	0.9	1.1
pumping rate	2000 L sec ⁻¹	9.2	7.6	12.0
	2001 L sec ⁻¹	8.0	8.2	12.1
turnover time	2000 d	8.0	6.0	7.0
	2001 d	9.4	6.0	6.7

CO₂ and CH₄, fluxes of N₂O in these reservoirs could in fact be controlled more by nitrogen availability than carbon stores. This research was undertaken as a study to begin to understand the processes controlling spatial and temporal N₂O concentrations and fluxes in three experimental reservoirs following flooding and to determine if these experimental reservoirs would be either a source or a sink of atmospheric N₂O. The magnitude of these apparent fluxes was directly compared to those of CO₂ and CH₄ (also measured as part of this study) to assess the net greenhouse warming potential (GWP) (1) of creating reservoirs by flooding forested boreal uplands.

Methods

Site Description. All experiments and sample collection were performed in experimental reservoirs created by diking and damming three upland subcatchments within the boreal forest at the ELA (Table 1, Figure 1) (24).



FIGURE 1. Aerial photograph of FLUDEX high C, medium C, and low C reservoir sites during the third year of flooding showing the N₂O sampling sites (J. Shearer provided the photographs). Symbols: ○ = vertical profile sampling sites; □ = shallow and deep dissolved sampling sites; A, B, C = temperature, O₂, and NO₃⁻ sampling sites.

Individual subcatchments were characterized by the amount of carbon, mainly in the form of vegetation and organic soils, and by the general moisture condition prior to flooding (27, 28). These variables comprised the nomenclature for each subcatchment/reservoir: high C reservoir, moist forest; medium C reservoir, dry forest; low C reservoir, very dry forest (Table 1) (24).

Each reservoir was kept flooded by pumping water (8–12 L s⁻¹ per reservoir) from a nearby lake (Lake 468) from early June to late September maintaining water renewal times of 6–9 days during 2000 and 2001 (Table 1) (24). Dissolved O₂ profiles, using an YSI 55 Dissolved O₂ Meter (YSI Inc., Yellow Springs, Ohio) and temperature profiles were collected weekly at 0.2-m intervals at the three main sampling platforms A, B, and C (Figure 1) and at several other locations within each reservoir. Additional O₂ profiles were measured at vertical

profile sampling locations (see N₂O profiles) in each reservoir on several occasions during 2000 and 2001. NO₃⁻ was also measured weekly at the sampling platforms and several other locations within each reservoir usually at depths of 0.5, 1.0, and 1.5 m according to standard collection and analytical protocols (29).

Surface N₂O Concentrations. In each reservoir, surface waters (10 cm below the surface) were sampled to determine N₂O concentrations overlying one shallow (<0.5 m) station during 2000 and one deep (>1.0 m) station during 2000 and 2001 (Figure 1). Sampling was done twice daily at 7:00 and 20:00 to determine diel concentration patterns. In both years, nighttime N₂O surface concentrations were assumed to be similar to daytime concentrations as diurnal surface water temperatures only varied by about 1 °C in each reservoir from late June to mid September (Majewski, A., Freshwater Institute, Winnipeg, Manitoba, Canada, 2004, unpublished data). Samples were collected directly into evacuated 160-mL Wheaton glass serum bottles capped with red butyl rubber stoppers with 20 mL of added UHP helium (He) as a headspace and 250 μL of 10 N sodium hydroxide (NaOH) as a preservative. Bottles were filled by inserting an 18-gauge needle through the stopper while holding the bottle below the surface of the water. Atmospheric pressure (mmHg) and surface water temperature (°C) were also recorded at the same time and were used to calculate sample N₂O concentrations (see extraction and analysis of N₂O samples, below). Water samples were stored at 4 °C and processed within 2 weeks of collection. Dissolved N₂O concentrations were stable during storage for at least 4 weeks.

N₂O Profiles. Water column N₂O concentrations were measured in each reservoir (Figure 1) at 20-cm intervals from the sediment–water interface to the surface. Profiles were collected every 2 weeks in 2000 and approximately every 3 weeks in 2001. Profile water samples were collected through a series of fixed sampling ports along a manifold connected to the surface by lengths of Tygon tubing. Maximum dead volume was 16 mL, so tubes were always flushed with 20 mL of reservoir water prior to collecting a sample. Evacuated 160-mL Wheaton glass serum bottles, as described previously, were used to collect water samples.

Extraction and Analysis of N₂O Samples. N₂O was extracted from the water samples into the He headspace by warming the bottles to 30 °C and shaking them on an orbital shaker at 200 rpm for 20 min. Samples were then held at this temperature while 10 mL of the headspace was drawn into a prepared Vacutainer while simultaneously injecting 10 mL of distilled water back into the bottle to replace the displaced volume of gas. Once filled, Vacutainer stoppers were coated with silicone sealant to minimize leakage, and the gas contents were analyzed within 4 weeks. Gas samples were analyzed by electron capture (ECD) gas chromatography. All N₂O gas analyses were performed using either a Varian Star 3600 or 3800 Gas Chromatograph by injecting either 0.5 or 0.25 mL, respectively, onto a Porapak QS 80/100 column. In

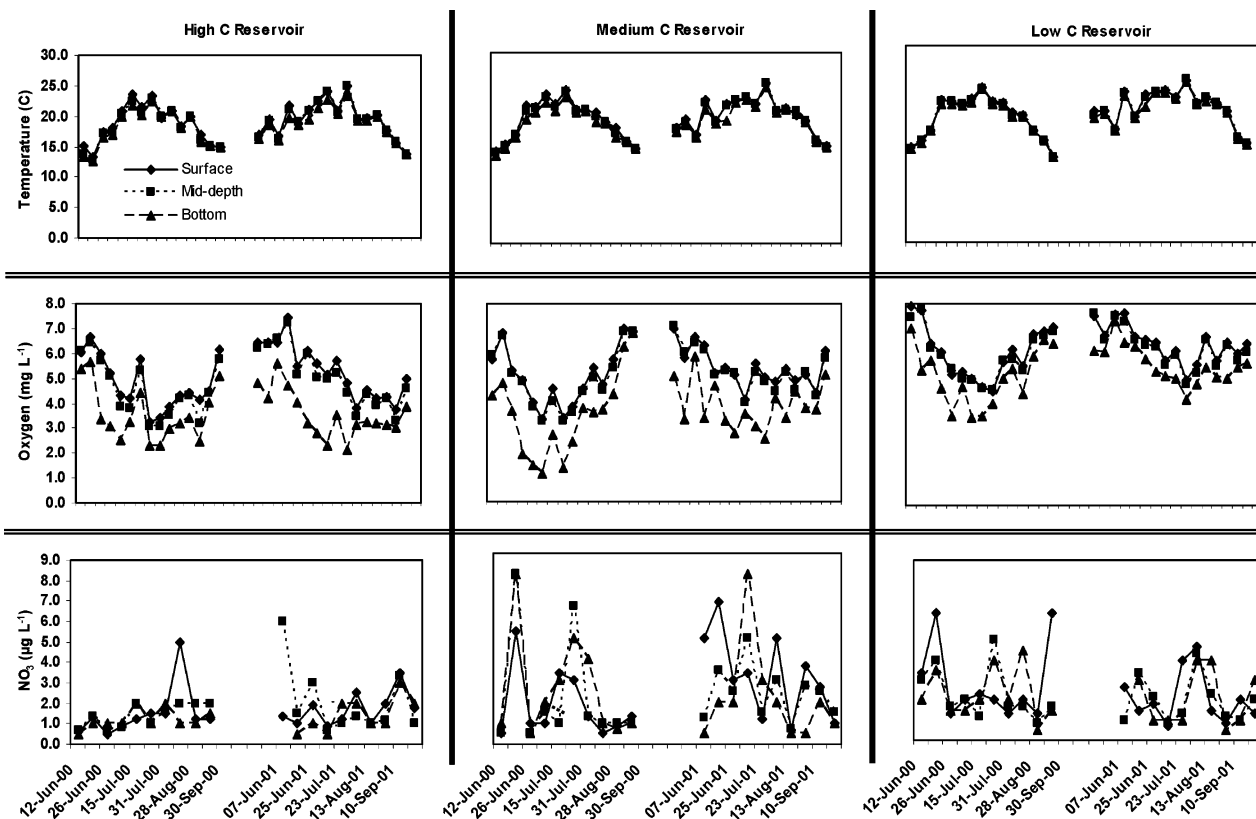


FIGURE 2. Mean surface (0.5 m), mid depth (1.0 m) and bottom (1.5 m) water temperature ($^{\circ}\text{C}$), and concentrations of O_2 (mg L^{-1}) and NO_3^- ($\mu\text{g L}^{-1}$) in the three FLUDEX reservoirs during 2000 and 2001.

each case, the ECD was operated at 300°C with 10%Ar/90% CH_4 carrier gas at a flow rate of 30 mL min^{-1} . The Porapak QS 80/100 precolumn (0.32-cm diameter \times 46-cm length) and analytical columns (0.32-cm diameter \times 183-cm length) were contained in a column oven at 70°C . The precolumn was used in combination with a four-port valve to remove water from the sample. Five replicates of two concentrations of standard gas mixtures were included in each run and were used to construct standard calibration curves. Analytical precision was calculated to be between 2 and 5%. One of the gas standards with a concentration closest to the sample concentrations was collected into Vacutainers at the time of sample headspace extraction and was used to determine and confirm sample integrity at the time of extraction and during storage before analysis.

Diffusive surface N_2O fluxes for the reservoirs (see Supporting Information) were calculated from the analyzed sample concentrations (30, 31, and Vollmer, M. University of California, San Diego, personal communication, 2000) using the volumetric solubility functions [$\text{mol L}^{-1}\text{ atm}^{-1}$] for N_2O of Weiss et al. (30). Specific reservoir gas transfer velocities (k) used in calculating diffusive surface N_2O fluxes were determined from loss estimates of SF_6 from the surface waters of Reservoir 2 during 2000 and 2001 (32).

Results

Reservoir Physical and Chemical Characteristics. Once filling was complete (10, 11, 15 days for high C, medium C, and low C reservoirs, respectively), water temperatures quickly increased from about 15°C to between 21 and 25°C by midsummer, falling back to about 15°C by mid September for both years.

In each reservoir, water temperatures were fairly consistent with depth at any point in time during the flooded period although weekly surface fluctuations could be $2\text{--}3^{\circ}\text{C}$ during the summer (Figure 2). Average nitrate (NO_3^-) and

ammonium (NH_4^+) concentrations in the pumped water over the 2 years were $1.61 \pm 0.28\ \mu\text{g L}^{-1}$ and $13.28 \pm 2.03\ \mu\text{g L}^{-1}$, respectively (seasonal data not shown). Fully filled NO_3^- concentrations during 2000–2001 (Figure 2) were often less than $2.0\ \mu\text{g L}^{-1}$ with many individual sampling sites within each reservoir having concentrations of $1.0\ \mu\text{g L}^{-1}$ or less. NH_4^+ concentrations (seasonal data not shown) were quite variable, ranging between 5 and $89\ \mu\text{g L}^{-1}$ and 5 and $61\ \mu\text{g L}^{-1}$ during those same years. Mean ($\pm\text{SE}$) water column NH_4^+ concentration was $17.8 \pm 0.50\ \mu\text{g L}^{-1}$. Dissolved O_2 concentrations at multiple locations within the three reservoirs ranged between 4 and $8\ \text{mg L}^{-1}$ during the summer with lower concentrations noted in the deeper waters (Figure 2). Bottom concentrations of dissolved O_2 at individual locations during 2000 were often less than $3.0\ \text{mg L}^{-1}$ in all reservoirs and occasionally as low as $0.5\ \text{mg L}^{-1}$ in the high and medium C reservoirs. O_2 concentrations were similar during 2001.

Reservoir Surface Water Concentrations of Dissolved N_2O . Surface N_2O concentrations collected in the morning and late afternoon at both the shallow and deep water column station within each reservoir in the summer of 2000 were very similar (see $\pm 1\text{SE}$, Figure 3) on any sampling date (individual data not shown). Therefore, morning and late afternoon surface concentrations measured at both stations were averaged to produce a surface water concentration that was representative of the entire reservoir and, because diurnal surface temperatures only varied by $1\text{--}2^{\circ}\text{C}$, this mean concentration was extrapolated to a 24-h period. During 2001, only surface concentrations at deep water column stations were measured for each reservoir and morning and late evening samples were similarly averaged to yield a representative 24-h reservoir concentration.

In 2000, there were only slight differences in mean surface N_2O concentrations in the three reservoirs, ranging between 0.29 ± 0.02 and $0.44 \pm 0.01\ \mu\text{g L}^{-1}$ during the flooded season (Figure 3). In 2001, surface N_2O concentrations in the

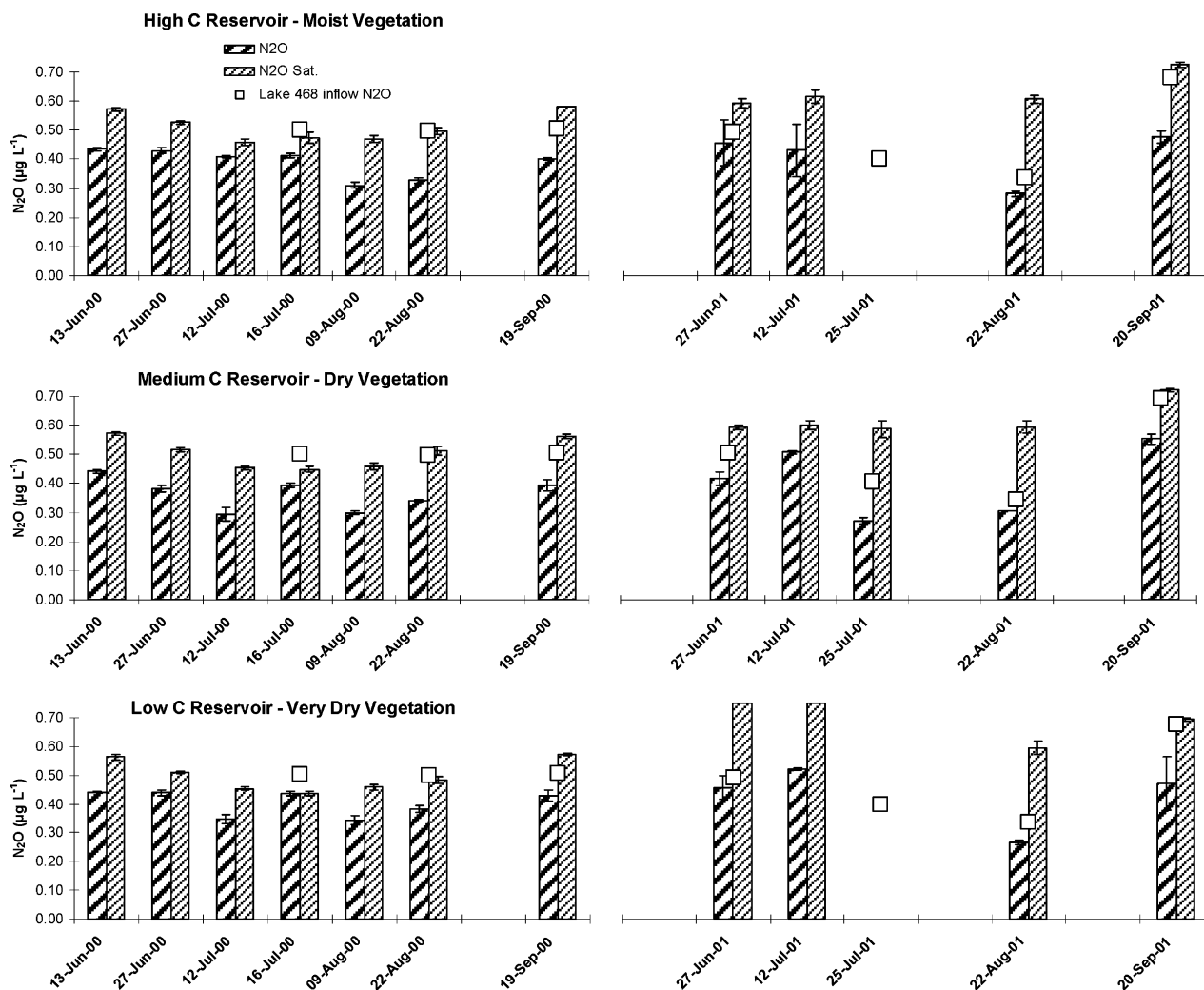


FIGURE 3. Dissolved N_2O concentrations ($\mu\text{g L}^{-1}$) in surface waters along with atmospheric equilibrium and inflow N_2O concentrations for 2000 and 2001 in the three FLUDEX reservoirs. ± 1 SE. N_2O sat. are the theoretical N_2O concentrations if in equilibrium with the atmosphere.

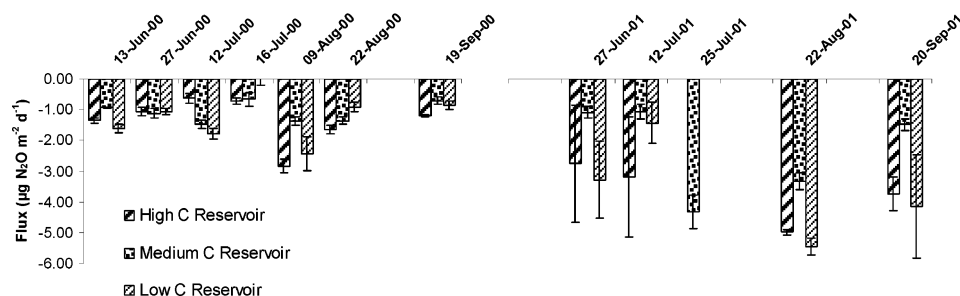


FIGURE 4. Daily diffusive surface water N_2O fluxes ($\mu\text{g N}_2\text{O m}^{-2} \text{d}^{-1}$) for 2000 and 2001 in the three FLUDEX reservoirs. ± 1 SE.

reservoirs ranged from 0.20 ± 0.01 to $0.42 \pm 0.01 \mu\text{g L}^{-1}$ (Figure 3). Surface water N_2O concentrations in all three reservoirs were always lower than theoretical N_2O water concentrations in equilibrium with the atmosphere. As well, N_2O concentrations were always lower than in the inflowing water pumped from Lake 468. There appeared to be a seasonal pattern in reservoir surface water N_2O concentrations, with some of the lowest being measured during July and August.

Diffusive Surface Water N_2O Fluxes. Calculated morning and late evening surface flux rates from a shallow and deep station (only deep stations in 2001) within each reservoir were averaged (see ± 1 SE, Figure 4) to obtain a daily surface flux rate for each reservoir. During both years, each reservoir was acting as a slight sink for atmospheric N_2O with inward flux being higher in 2001 than in 2000 (Figure 4).

In 2000, mean surface diffusive flux rates of N_2O ranged between $0.05 \pm 0.26 \mu\text{g m}^{-2} \text{d}^{-1}$ in the low C reservoir in July and $-2.83 \pm 0.23 \mu\text{g m}^{-2} \text{d}^{-1}$ in the high C reservoir in August (Figure 4). During 2001, diffusive surface fluxes of N_2O in all reservoirs were greater (more negative) and somewhat more variable than in 2000, ranging from $-1.00 \pm 0.22 \mu\text{g m}^{-2} \text{d}^{-1}$ in the medium C reservoir in July and $-5.16 \pm 0.25 \mu\text{g m}^{-2} \text{d}^{-1}$ in the low C reservoir in August (Figure 4).

N_2O Concentrations in the Water Column. N_2O concentrations generally decreased with water column depth in the three reservoirs during the summers of 2000 and 2001 (Figure 5). In the high and low C reservoirs, N_2O concentrations decreased to the greatest extent in the strata of water adjacent to the sediments while in the medium C reservoir

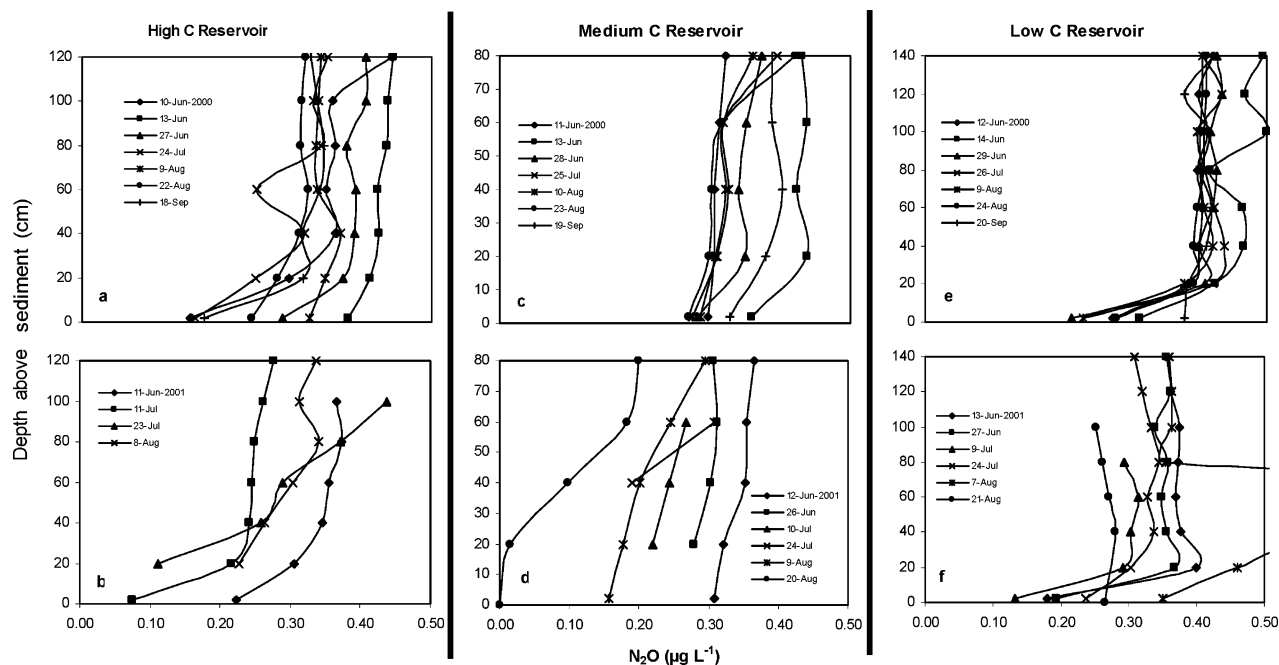


FIGURE 5. Seasonal water column N_2O concentrations ($\mu\text{g L}^{-1}$) for 2000 and 2001, respectively, in (a, b) high C; (c, d) medium C; and (e, f) low C FLUDEX reservoirs.

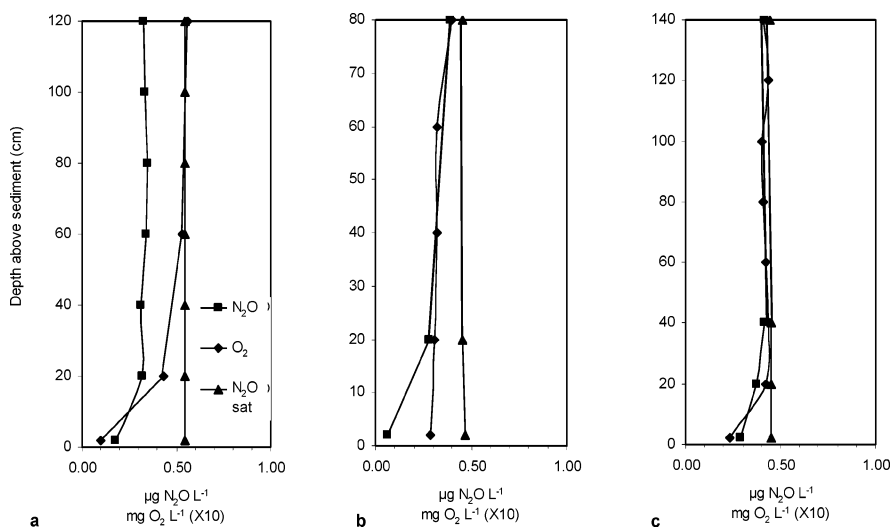


FIGURE 6. N_2O ($\mu\text{g L}^{-1}$), O_2 (mg L^{-1}), and $\text{N}_2\text{O}_{\text{sat}}^*$ ($\mu\text{g L}^{-1}$) concentration profiles in FLUDEX (a) high C reservoir, September 18, 2000; (b) medium C reservoir, July 25, 2000; and (c) low C reservoir, July 26, 2000. * = at equilibrium with the atmosphere.

concentrations decreased more linearly with depth. Surface water N_2O concentrations were similar for the three reservoirs ranging from about 0.20 to 0.42 $\mu\text{g L}^{-1}$ during July and August with somewhat higher values of 0.40–0.50 $\mu\text{g L}^{-1}$ being measured soon after the reservoirs were filled in early June. Concentrations of N_2O in water just above the sediments were always less than those in surface waters in each reservoir, and at times were less than 0.20 $\mu\text{g L}^{-1}$.

On one sampling day (August 7, 2001), nitrification appeared to be occurring within the water column of the low C reservoir (Figure 5f), with a sharp increase in N_2O concentrations midway between the sediments and the reservoir surface. At about this time, O_2 and NH_4^+ (data not shown) concentrations were $>4.0 \text{ mg L}^{-1}$ and $>17 \mu\text{g L}^{-1}$, respectively, throughout the water column and dissolved N_2O increased to 1.41 $\mu\text{g L}^{-1}$ within a layer about 60 cm above the sediments.

On the several occasions when O_2 and N_2O concentrations were measured coincidentally in the three reservoirs, concentrations of O_2 and N_2O both declined with depth.

Representative profiles of O_2 , N_2O , and $\text{N}_2\text{O}_{\text{sat}}^*$ concentrations at equilibrium with the atmosphere ($\text{N}_2\text{O}_{\text{sat}}^*$) (Figure 6) show that oxygen concentrations closely followed those of N_2O while $\text{N}_2\text{O}_{\text{sat}}^*$ remained constant. Measured O_2 concentrations in the bottom strata of water just above the sediments were $<3.0 \text{ mg L}^{-1}$ in the medium and low C reservoirs and $<1.0 \text{ mg L}^{-1}$ in the high C reservoir while N_2O concentrations were $<0.3 \mu\text{g L}^{-1}$.

Discussion

Flooded Boreal Forest Soils. Various forest soils (4–6), wetlands (7–10, 12), and boreal ponds (11) are known sources of N_2O to the atmosphere. However, flooding boreal forest soils with different amounts of stored organic C to create three experimental reservoirs resulted in bodies of water that were small sinks for atmospheric N_2O . The small surface fluxes associated with these reservoirs appear to be linked to the microbial decomposition of the newly flooded vegetation and soils. Surface water concentrations that were below atmospheric equilibrium, and water column profile con-

TABLE 2. Mean FLUDEX Reservoir Net^a Surface Water ($\mu\text{g N}_2\text{O m}^{-2} \text{ d}^{-1}$) N_2O Fluxes. ± 1 SE

	surface water flux $\mu\text{g N}_2\text{O m}^{-2} \text{ d}^{-1}$	
	2000	2001
high C reservoir site	1.349 ± 0.281	-3.469 ± 0.455
medium C reservoir site	1.093 ± 0.126	-2.132 ± 0.628
low C reservoir site	1.230 ± 0.301	-3.383 ± 0.799

^a Dilution from the addition of Lake 468 water.

centrations that decreased with depth, indicated that microbial activity in the surficial sediments or bottom waters of these reservoirs was an important factor in consuming atmospheric N_2O . This was contrary to the original expectation that these experimental reservoirs would be N_2O sources

The consumption of atmospheric N_2O by each of the reservoirs during two consecutive summers of flooding appeared to be caused by the decomposition of vegetation and other newly flooded organic matter. Even though the amount of labile C across the three sites varied between 0.9 and $1.9 \times 10^4 \text{ kg C ha}^{-1}$ (24), the mean daily net flux of atmospheric N_2O into the surface of each reservoir (Table 2) was quite similar for each flooding season. This would suggest that the relative amount of organic carbon was not the factor controlling the flux of N_2O into these reservoirs and was likely in excess to demand by the microbes. Uniform undersaturated surface N_2O concentrations within each reservoir (Figure 3) suggested that the microbial demands for N_2O , as a further reducible N substrate, were consistent through the flooded period. Consumption of atmospheric N_2O by the reservoirs during 2001 was slightly higher than those measured in 2000 (Table 2, Figure 4). While there is no clear reason to explain this increase, it can be speculated that in addition to continuing N demands, persistent nutrient export (Venkiteswaran, J. University of Waterloo, Ontario, Canada, personal communication, 2003), wind speed, water column heating, and quite possibly the quality of the decomposable carbon within each reservoir may all have been variables contributing to these somewhat higher negative N_2O flux rates of 2001. Even though average wind speed in the immediate area was similar for both years, slightly higher air and water temperatures (Beaty, K., Freshwater Institute, Winnipeg, Manitoba, Canada, personal communication, 2003) during 2001 could have resulted in increased gas exchange. Also of importance would be the amount of NO_3^- in the soils available to these systems prior to flooding. While other studies have shown that soil denitrification can be enhanced by elevated soil NO_3^- concentrations at the time of spring thaw (3, 5, 6, 33), no such increase in denitrification was seen in the FLUDEX reservoirs for 2000 and 2001. This would be explained by the general lack of any available NO_3^- in these soils for this location (12, 26). The highest negative N_2O flux rates in all reservoirs (Figure 4) occurred on or near

dates in both years when bottom water temperatures (and microbial activity) were high (Figure 2) and during 2001 when surficial sediment temperatures were reported to be 2–3 °C higher than in previous years (34). In both years, elevated bottom water temperatures coincided with low bottom water O_2 concentrations (Figure 2). Therefore, the slight increase in sediment temperatures for 2001, as well as low sediment O_2 concentrations, likely explains the year-to-year variability of these fluxes and corresponds with an increase in methanogenesis (34) reported during the same time.

Vertical water column profiles of dissolved N_2O (Figure 5) in the three reservoirs from 2000 to 2001 corroborate the observation that the bottom waters and sediments of the reservoirs (Figure 6) were functioning as active sinks of atmospheric N_2O . Surface waters were routinely undersaturated relative to atmospheric concentrations (Figure 3), and in most cases bottom concentrations of dissolved N_2O were lower than the surface water concentrations (Figure 5). Knowles et al. (13) showed that in some Ontario lakes when O_2 and NO_3^- became depleted with depth that N_2O also became depleted and N_2O was seen to diffuse into the surface waters from the atmosphere. Similarly, Lemon and Lemon (14) described how N_2O in the surface waters of Lakes Huron and Erie can at times be undersaturated and therefore sinks for atmospheric N_2O . In contrast to the well-mixed surface waters (this study and 32), bottom N_2O concentrations were often about 50% or less of the concentrations measured in the upper region of the water column. Water column gradients of N_2O differed somewhat between reservoirs possibly reflecting differences in mixing patterns within each reservoir site (Figure 5). While wind speed was not measured within the individual reservoirs, it was generally thought that the more open nature of the low C reservoir and the resultant movement of the numerous tree boles in the medium C reservoir because of wind resulted in more mixing in these reservoirs than in the high C reservoir. Seasonal water column gradients of N_2O (Figure 5) showed that the more densely treed, high C reservoir was less mixed than the more upland and uniformly treed, medium C reservoir which itself was less mixed than the more open low C reservoir.

Flooding natural boreal forest soils to create the FLUDEX reservoirs resulted in the enclosed water being small sinks for N_2O of approximately equal amounts, suggesting that microbial respiration in conditions of low O_2 and NO_3^- was responsible for maintaining this sink effect. Denitrifiers had to selectively utilize N_2O as the next most readily available electron acceptor to facilitate the decomposition of large amounts of labile organic carbon. The importance of this sink effect at the global scale is unclear from these relatively small-scale, short-term experiments; however, some general comparisons to emissions of CO_2 and CH_4 under the same conditions (34) can be made with respect to global warming potential (GWP). The reservoirs were relatively well mixed with short residence times allowing for accurate flux estimates at the reservoir scale.

TABLE 3. Comparison of the Range of Average Areal Diffusive Fluxes of CO_2 ,^a CH_4 ,^a and N_2O ^b from the Three Reservoirs and the Greenhouse Warming Potential (GWP) in CO_2 Equivalents ($\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) for the Summers of 2000 and 2001

	CO_2 $\text{mg CO}_2 \text{ m}^{-2} \text{ d}^{-1}$		CH_4 $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$		N_2O $\mu\text{g N}_2\text{O m}^{-2} \text{ d}^{-1}$	
	2000	2001	2000	2001	2000	2001
areal diffusive flux (average range)	590–970	660–1150	3.4–7.4	5.2–10.6	(–1.09) to (–1.35)	(–2.13) to (–3.47)
greenhouse warming potential ($\text{CO}_2 = 1$)	1		21		296	
CO_2 equivalents ($\text{g m}^{-2} \text{ d}^{-1}$)	0.59–0.97	0.66–1.15	0.07–0.16	0.11–0.22	–0.32 to –0.40 ($\times 10^{-3}$)	–0.63 to –1.03 ($\times 10^{-3}$)

^a From Matthews et al. (34). ^b From Table 2, this paper.

The average diffusive flux of N_2O (with a GWP of 296 times that of CO_2 over a 100 year period) from the atmosphere into the FLUDEX reservoirs during flooding (Table 3) would have little (<1%) or no net effect in offsetting the positive warming potential attributed to the simultaneous release of CO_2 and CH_4 (compared as CO_2 equivalents) out of the reservoirs reported by Matthews et al. (34) (Table 3), even if we assume that the forest soils in our subcatchments were likely sources of N_2O to the atmosphere prior to flooding (4–6, 12).

Over time, the continued removal of the more labile carbon would likely result in a reduction in N_2O consumption and the reservoirs variably becoming either sources or sinks for N_2O if NO_3^- became more available. This would lead to a reduction of the sediment C:N ratio and an increase in the availability of nitrogen to the microorganisms including the denitrifiers. Unlike the ELARP (Experimental Lakes Area Reservoir Project) reservoir which experimentally flooded a wetland with enough decomposable peat stores to fuel GHG production for hundreds of years (20), the FLUDEX reservoirs contain much less carbon (27). This may result in declining GHGs within a relatively short period of time following reservoir creation, similar to what Galy-Lacaux et al. (35) reported for CO_2 and CH_4 from a tropical reservoir thus minimizing the effects of any N_2O emissions to the atmosphere. In the few boreal ecozone hydroelectric reservoirs where diffusive N_2O fluxes have been measured, the reservoirs have acted as small sources of N_2O to the atmosphere and flux rates appear to be declining with reservoir age (21, 36). While N_2O fluxes from older Finnish reservoirs were also reported as low, fluxes of CO_2 and CH_4 could remain high because of efficient internal recycling of carbon (18).

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Supporting Information Available

Diffusive surface water N_2O flux calculations for the FLUDEX reservoirs are detailed. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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