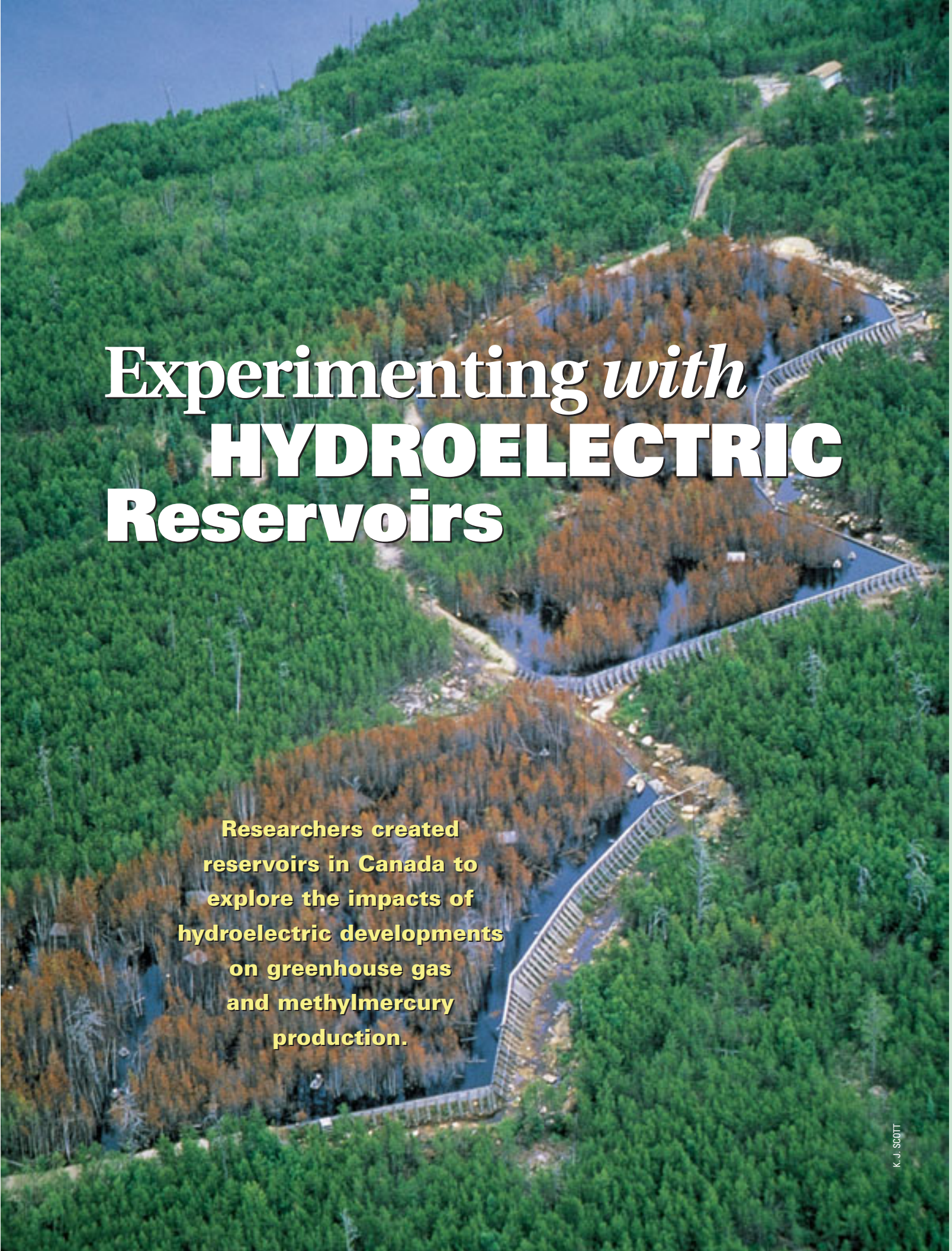

Experimenting *with* HYDROELECTRIC Reservoirs

Researchers created reservoirs in Canada to explore the impacts of hydroelectric developments on greenhouse gas and methylmercury production.

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Conventional hydroelectric power requires reservoirs to store water and provide the necessary head to run turbines. However, flooding landscapes to create these reservoirs has many significant environmental impacts, including releasing carbon-based greenhouse gases (GHGs), carbon dioxide (CO_2), and methane (CH_4) into the air and accelerating production and bioaccumulation of methylmercury (MeHg) (*1*, *2*). These changes are closely related because they each result from the microbial decomposition of flooded terrestrial organic matter. Hydroelectricity continues to be an important source of power in North America; therefore, understanding the environmental effects associated with creating reservoirs is important for current and future energy policy.

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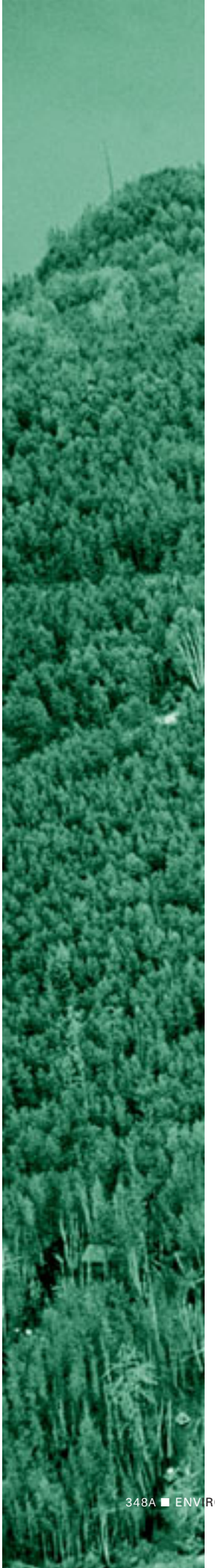

To learn more, researchers created two sets of hectare (ha)-scale experimental reservoirs to investigate the biogeochemical processes involved in the production of GHGs and MeHg in reservoirs (*3*, *4*). Both experiments were carried out at the Experimental Lakes Area, a field facility in northwestern Ontario that is operated by Fisheries and Oceans Canada. These projects were intended to reflect the ecosystems inundated by recent hydroelectric developments in Canada. The first one, the Experimental Lakes Area Reservoir Project (ELARP), was flooded in 1993 and consists of a large flooded boreal wetland complex. In 1999, reseachers established the Flooded Uplands Dynamics Experiment (FLUDEX), a set of three reservoirs that flooded boreal forest uplands. Results from this second project were collected through 2003. In this feature, we will concentrate on results from the first three years of FLUDEX.

The nature of the problem

Researchers created the experimental reservoirs, which, like larger hydroelectric reservoirs, flooded substantial quantities of organic carbon stored in vegetation biomass and soils. This flooding accelerates microbial decomposition of organic carbon and releases GHGs. Recent research has shown that fluxes of CO_2 and especially CH_4 from reservoir surfaces are greater than those from natural lakes and unflooded terrestrial areas (*3*, *5*, *6*). Global fluxes of GHGs from reservoirs were estimated as ~7% of current anthropogenic emissions, on a CO_2 equivalent basis (*6*). However, this estimate did not include nitrous oxide (N_2O) because little research has been conducted on its fluxes into or out of hydroelectric reservoirs. Compared to CO_2, N_2O has 310× more global warming potential per molecule in the atmosphere.

Flooding also causes high rates of microbial methylation of mercury. MeHg is a major contaminant of freshwater fishes throughout North America (*7*, *8*), where concentrations often substantially exceed guidelines for human fish consumption (*9*). In reservoirs, fish tissue concentrations of MeHg increase three- to five-fold after flooding (*10*, *11*). Concentrations typically remain elevated for at least two decades (*10*, *11*) at levels that may be high enough to affect fish reproduction and growth (*12–14*) and the reproduction of piscivorous waterfowl (*15*). Within a few years of flooding, MeHg concentrations in piscivorous species (northern pike and walleye) may reach average values of 2–4 μg/g wet weight and levels of 8 μg/g or higher in individual fish (*10*, *11*), which is much higher than the limits for commercial sale in Canada (0.5 μg/g) and in the United States (0.3 μg/g). Therefore, a person eating fish containing 4 μg/g of MeHg and consuming the upper limit for acceptable human intake of ~50 μg MeHg, proposed by the U.S. EPA and subsequently supported by the National Academy of Sciences (*16*), could only eat a mere 12.5 g of fish per week.

Policy implications

Northern hydropower systems located on the Canadian Shield make up a large part of the potential additional sources of electricity in North America. Projects with a combined annual energy production of 40 TWh, which is equivalent to ~7 GW of capacity, are being considered (*17*). Boreal developments generally involve reservoirs with large surface-area-to-volume ratios that flood substantial quantities of organic biomass, which predisposes these reservoirs to high production rates of GHG and MeHg relative to the amount of power produced (*3*, *5*, *18*). In the case of the La Grande Complex in northern Québec, creating 15,000 MW of hydroelectric capacity involved flooding nearly 13,000 sq km of terrestrial ecosystems, which translates to ~160 sq km/TWh of annual energy.

Present estimates of GHG emissions from boreal and temperate reservoirs are 265±150 g CO_2 equiv/(m^2 • year) (*5*). These emissions equate to 0.02–0.06 Mt CO_2 equiv/TWh of hydroelectric power produced. Corresponding GHG emissions from fossil-fuel-fired power generation are 0.5–1.2 Mt CO_2 equiv/TWh (*5*). Thus, electricity produced using reservoirs appears to have a significant GHG emissions advantage over that produced using coal, but not when considered on a regional basis. Furthermore, GHG emissions per TWh power produced depend strongly on the ratio of flooded area to electrical capacity. At this time, regulatory agencies in the United States and Canada consider hydroelectric production as "GHG-neutral", and neither country includes reservoir emissions in its national inventory.

MeHg contamination of reservoir fish stocks is another factor that must be considered, especially because feasible or economically viable mitigating solutions have been elusive. Right now, the only practical way to reduce MeHg levels in fish is to limit flooding when new power developments are planned. Other strategies include providing information to local fishers and fish consumers about mercury in various species or sizes of fish or supplying local residents with fish that contains lower concentrations of MeHg. However, these approaches do not prevent the cultural and economic disruption that follows MeHg contamination of fisheries.

Hypotheses

Experimental reservoirs are relatively easy to sample, the terrain to be flooded can be selected and well characterized before inundation, and the timing of flooding can be controlled. Because water inputs and outputs are measured and sampled for nutrients, inorganic and organic carbon, and mercury species, researchers can determine mass balances in these smaller reservoirs. Experimental reservoirs also possess a level of realism that cannot be duplicated in laboratory incubation studies.

Data and knowledge derived from experimental flooding projects help researchers to refine dynamic mercury models that will be used to predict the impacts of the toxic metal, evaluate different hydroelectric sites and project configurations, and develop mitigation strategies. Small experimental systems such as the FLUDEX reservoirs differ from operational systems in size and hydrology. The FLUDEX reservoirs mimic the shallow areas of larger reservoirs that exchange water with adjacent open areas, where greenhouse gas and mercury process rates are thought to

be gr eatest. The FL UDEX reservoirs were drawn down in the winter, which is characteristic of the shallow zones of larger boreal reservoirs. Most of the decomposition and mercury methylation activity occurs in the summer, when water and sediment temperatures are highest.

In the ELARP study, 16.8 ha of a boreal wetland complex that included a central pond, *Sphagnum* moss, and black spruce trees was flooded and examined (*3*, *4*; Figure 1). Actual reservoirs inundate landscapes consisting of low-lying wetlands and upland forests. These two areas have different amounts of carbon stored in soils and vegetation; therefore, an experimental flooding project that inundated forested uplands was needed.

Enter the FLUDEX project. Researchers flooded forested boreal uplands with contrasting moisture conditions, plant communities, and quantities of stored organic carbon to create three 0.5–0.7-ha reservoirs. Carbon stores were found to be much lower than those in the ELARP reservoir.

At the start of FLUDEX, we hypothesized that the production of GHGs, such as CO_2 and CH_4, and increases in MeHg production and bioaccumulation would be proportional to the total amount of organic carbon stored in vegetation and soils on the sites before flooding. Thus, we predicted that in the long term, GHG and MeHg production would be significantly lower in the FLUDEX reservoirs than in the ELARP reservoir (*3*, *4*).

TABLE 1

Description of the FLUDEX reservoirs

Carbon stores	Description	Area (ha)	Mean depth (m)	Total carbon (kg C/ha)	Labile carbon[1] (kg C/ha)
High carbon	Moist forest	0.74	0.93	4.6×10^4	1.9×10^4
Medium carbon	Dry forest	0.50	0.85	3.5×10^4	0.9×10^4
Low carbon	Very dry forest	0.63	1.13	3.1×10^4	1.1×10^4

[1] Labile carbon was defined as carbon in tree foliage, shrubs, herbs, mosses, lichens, and in the litter fungal/humic soil layer.

FIGURE 1

Aerial view of the ELARP reservoir

(top) This wetland at the Experimental Lakes Area in Canada (Lake 979) was flooded to become (bottom) an experimental reservoir where the effects of flooding on greenhouse gases and mercury were studied.

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FLUDEX sites

Table 1 lists the different vegetation communities and total amounts of organic carbon in the three FLUDEX sites before flooding. The high-carbon site had two kinds of vegetation communities; approximately half the area was a moist, forested community, with the remainder a drier, treed community. Both communities were dominated by jack pine (*Pinus banksiana*). This site had the highest amount of apparently labile (non-woody) organic carbon. The medium-carbon site had a community dominated by jack pine and birch (*Betula papyrifera*). The low-carbon site's shallow soils had extensive bedrock outcrops. A jack-pine-dominated community covered roughly three-quarters of this site; moss and bedrock covered the remainder of the area. Despite having the lowest stores of total carbon, this site had as much apparently labile organic carbon as the medium-carbon site. All three sites had much smaller amounts of stored organic carbon than the ELARP reservoir, which was created over a wetland that contained ~1.3 $\times$ 10^6 kg C/ha.

Wooden and gravel dikes were constructed around the three sites to create the FLUDEX reservoirs. The reservoirs were first flooded in 1999 to mean depths of ~1 m and maximum depths of ~2 m (Table 1). Researchers flooded the reservoirs annually from early June to early October by pumping water from a nearby oligotrophic lake that had low concentrations of dissolved organic carbon (DOC) and mercury. Water renewal times were approximately 6–9 days.

Initially, organic carbon decomposed rapidly, depleting oxygen and elevating concentrations of total mercury (all forms of mercury), MeHg, CO_2, CH_4, DOC, and other dissolved nutrients. In the first year, the medium-carbon reservoir exported the most decomposition byproducts, but levels dropped in the following years.

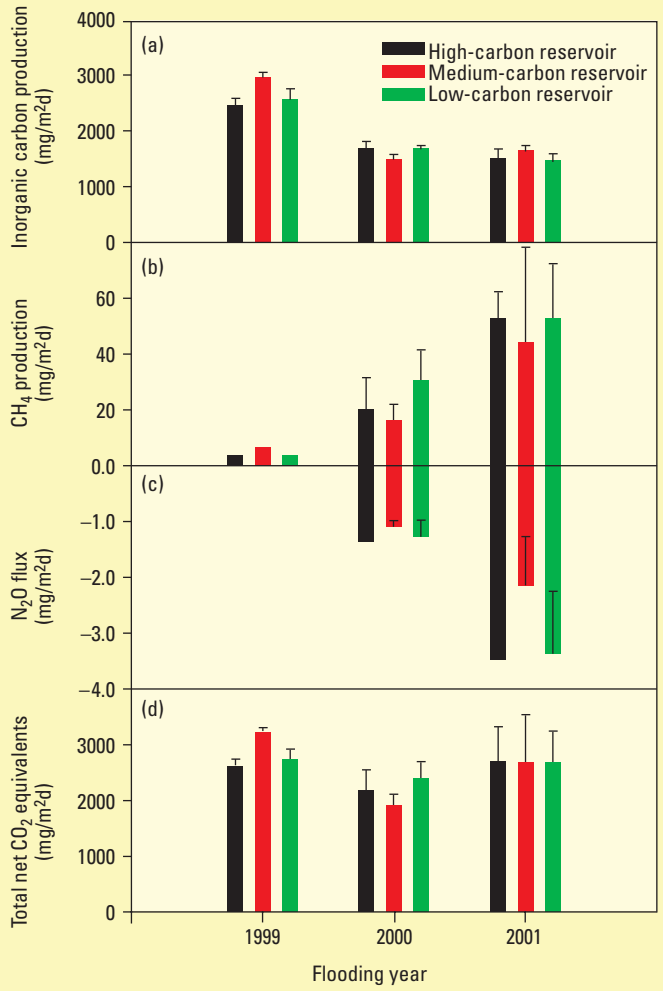
Greenhouse gas impacts

Before flooding, the boreal ecosystems in the FLUDEX project had net atmospheric CO_2 fluxes near zero over the long term (due to cycles of forest growth followed by fires), were considered sinks for atmospheric CH_4 (due to CH_4 oxidation in soils), and emitted variable

FIGURE 2

Net production of inorganic carbon and methane, surface fluxes of nitrous oxide, and total net GHG production in the FLUDEX reservoirs

(a) Net inorganic carbon production is surface fluxes + export out of reservoir outflows – inflows. (b) Net CH_4 production is surface fluxes + export out of reservoir outflows – inflows. (c) N_2O fluxes were not measured in 1999. (d) Total greenhouse gas net production in CO_2 equivalent is net production of inorganic carbon + net production of CH_4 – N_2O surface fluxes. Error bars are one standard error. CO_2 equivalent fluxes were calculated as inorganic C (as CO_2 equivalents) production + 23 (CH_4 net production) – 310 (N_2O flux).



but generally neutral fluxes of N_2O (*19*). After flooding, net CO_2 production was generally similar at all three reservoirs during each of the three flooding seasons (Figure 2a). Thus, community respiration was not related to overall flooded organic carbon stores. However, reservoir net CO_2 production decreased noticeably from the first to the second and third flooding seasons. Studies of stable carbon isotopes enabled researchers to quantify the biological processes of community respiration and primary production. Flooded organic matter was the primary source of community respiration, and primary production played a significant role in reducing the net production of CO_2/dissolved inorganic carbon (*19*, *20*). As labile organic carbon is depleted, inflowing DOC would be expected to become a proportionately larger source of community respiration. Net CO_2 production (~1500–3000 mg/m^{2}d) was similar to levels in other boreal reservoirs and the ELARP reservoir (*5*, *6*).

Net CH_4 production, like net CO_2 production, was similar in all three reservoirs in each flooding season (Figure 2b). However, reservoir CH_4 production consistently increased with each flooding season. Compared to CO_2, anoxic CH_4 production was delayed in all post-flood years; however, the length of this delay shortened in each successive year. Ebullition (bubble) fluxes of CH_4 were negligible during the first flooding season but were 3–5× higher than surface diffusive fluxes by the third flooding season. By comparison, ebullition accounted for <1% of reservoir CO_2 emissions. Total CH_4 fluxes from the FLUDEX reservoirs were similar to those from other boreal reservoirs (*5*, *6*) but generally less than those from the ELARP wetland reservoir (*19*). Thus, flooding causes a net increase in GHG production compared with the original terrestrial areas, because a portion of the carbon originally sequestered as CO_2 in plants is released as CH_4, which has 23× more warming potential than CO_2.

Unlike CO_2 and CH_4 production, which are directly related to organic carbon mineralization, N_2O production is part of the nitrogen cycle. The oxide is produced by denitrification in boreal soils and wetlands, and thus nitrate availability controls the production of N_2O (*21*). Therefore, we predicted that reservoirs could be net sources of N_2O to the atmosphere because nitrate stored in soils along with surplus labile organic carbon would be available for denitrification after flooding. However, after flooding, N_2O concentrations in surface waters were less than atmospheric concentrations and undersaturation increased with depth, which indicated that the reservoirs were acting instead as N_2O sinks (Figure 2c). The decomposition of flooded organic matter in these reservoirs appeared to conserve nitrogen, resulting in the consumption of atmospheric N_2O as carbon was respired away. Rates of N_2O consumption were not related to the relative amount of carbon stored in the reservoir before flooding. On the basis of CO_2 equivalents, N_2O fluxes into the reservoirs were three orders of magnitude lower than the CO_2 and CH_4 outward fluxes. Measurements in other reservoirs have indicated small positive fluxes of N_2O to the atmosphere (*5*, *22*), which contrast our findings.

Mercury impacts

Figure 3 shows that a large amount of MeHg was produced in the flooded soils of the FLUDEX reservoirs and moved to overlying waters (*23*). The high-carbon reservoir had much higher MeHg burdens in its soils before and after flooding (Figure 3a), yet fluxes of MeHg from flooded soils and net export of MeHg from the medium-carbon reservoir were always the greatest (on a per-area basis) of any reservoir; fluxes and exports were always lowest in the low-carbon reservoir (Figure 3b). Annual exports of MeHg from the reservoirs ranged up to 13× pre-flood soil burdens, indicating that the majority of the MeHg was being

produced after flooding (*23*). Exports of MeHg from the reservoirs were noticeably lower in the third year of flooding compared with the first two, although total stores of MeHg were highest in the second year. Water concentrations of MeHg during the first year were highest in the medium-carbon reservoir, lower in the high-carbon reservoir, and lowest in the low-carbon reservoir (*23*). On average, concentrations of MeHg in water in the FLUDEX reservoirs were lower than those in the ELARP flooded wetland during the first three years of inundation (*4*).

MeHg uptake by zooplankton, benthic invertebrates (with emerging insects as indicators), and fish (stocked into the reservoirs) was also measured. MeHg levels in all food chain organisms were much higher than those from natural lakes, but there was little correspondence between MeHg production in the reservoirs and MeHg uptake in the food chain (*25*). Pools of MeHg in the food chain were small compared with the amount of MeHg in flooded soils or exported from the reservoirs. MeHg concentrations in food chain organisms were as high as or higher than those in the ELARP flooded wetland.

One of the objectives of FLUDEX is to investigate possible mitigation measures to reduce MeHg in reservoir and lake fisheries. Currently, we are investigating controlled burns of vegetation and soil before flooding. Burning may reduce MeHg and GHG production but may be impractical because of safety issues and cost. Future research will examine the effects of selenium on MeHg accumulation in the food chain of freshwater systems and the possibility that the metalloid is not toxic to freshwater life at concentrations effective in reducing MeHg bioaccumulation.

Conclusions thus far

Although expensive and logistically challenging, conducting whole-ecosystem manipulations is important. In this project, for example, most of our main conclusions were significantly different from our original hypotheses. After analyzing three years of data, we made four conclusions.

First, rates of carbon decomposition, GHG fluxes, MeHg production, and food chain uptake were not directly related to the total amount of carbon stored on the three sites after initial flooding. Community respiration was similar among the reservoirs, but MeHg fluxes from flooded soils were highest in the medium-carbon reservoir. Thus, carbon quality (lability) may be more important than total carbon stores in determining MeHg production. Compared with the ELARP reservoir, with its much higher stores of organic carbon (*3*, *4*), the FLUDEX reservoirs did have significantly lower rates of decomposition and MeHg production. Reservoirs in northern Québec had concentrations of MeHg in the water column that were generally at the low end of the range observed in the FLUDEX reservoirs (*18*).

Second, the initially high rates of community respiration, net GHG fluxes, and MeHg production in the FLUDEX reservoirs have dropped significantly with time, especially compared with the ELARP reservoir. Fluxes of CO_2 from the FLUDEX reservoirs were much lower than those from the ELARP study. CO_2 concentrations in the ELARP reservoir did not peak until 5–6 years after flooding. The production of CO_2 from temperate reservoirs is related to the age of the reservoir, but the decline is generally not rapid—only about 2-fold over 40 years (*6*). The decline of GHG production in the FLUDEX reservoirs, however, has been relatively rapid, occurring in only three years. There should be a relationship between the duration of decomposition and the quantity of organic carbon flooded.

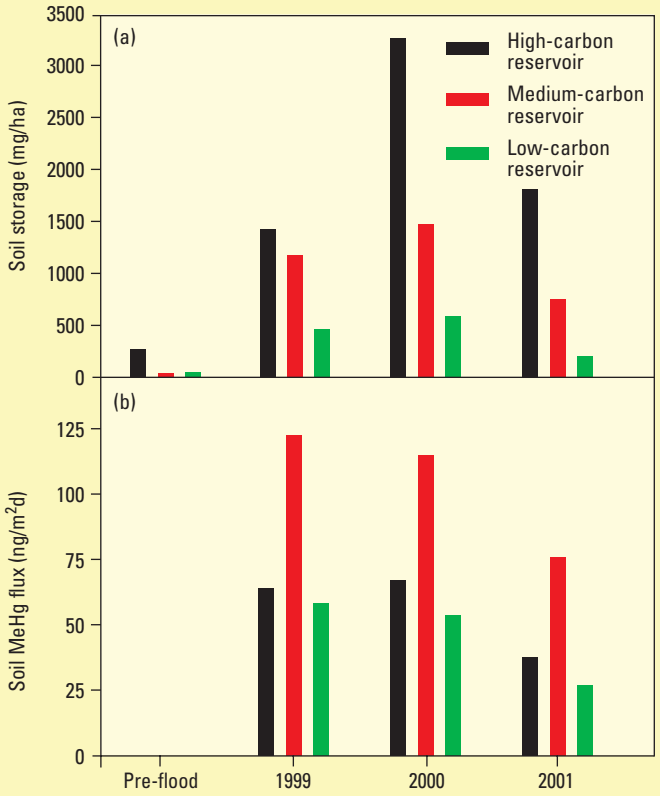
Third, MeHg bioaccumulation in the food chain was generally not closely linked to the rates of MeHg production in the reservoirs. Despite a clear decrease in rates of carbon decomposition and MeHg production over the three years of flooding, uptake of mercury by fish, zooplankton, and emerging insects in the second and third years of flooding was often as high as or higher than that in the first year. Also, although concentrations of MeHg in the water of the FLUDEX upland reservoirs were lower than those in the ELARP wetland reservoir during the first three years, concentrations in zooplankton were as high and concentrations in fish were higher in the FLUDEX reservoirs (*25*, *26*).

Fourth, the FLUDEX reservoirs were small sinks for N_2O. The fact that these reservoirs are not sources of N_2O to the atmosphere is a significant finding.

FIGURE 3

Methylmercury burdens and fluxes

(a) Soil storage in the FLUDEX reservoirs increased dramatically after flooding. (b) Fluxes out of flooded soils, calculated as net MeHg production of each FLUDEX reservoir, were highest in the medium-carbon reservoir.



However, as these reservoirs age, they could become small sources of N_2O to the atmosphere, as seen in other reservoirs.

Flooding associated with hydroelectric developments is only one type of water-level disturbance that may increase the supply of MeHg to aquatic systems. For example, there are notable parallels between the findings of FLUDEX and those of researchers studying mercury cycling in the Florida Everglades. Those studies have shown that periodic wetting and exposure of sediments result in MeHg concentrations >10× higher than the long-term average. Estimates of fluxes of MeHg from an Everglades site ranged from 22 to 192 ng/m^{2}d, similar to fluxes in the FLUDEX reservoirs. Furthermore, there are documented instances of elevated MeHg in small streams where falling leaves in the autumn stimulated methylation (*27*).

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