

Whole ecosystem approach to understanding reservoirs, and the resulting policy impacts

Britt Hall and Vincent St.Louis

Experimental Lakes Area Reservoir Project



Flooded Uplands Dynamics Experiment



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Flux to the atmosphere of CH₄ and CO₂ from wetland ponds on the Hudson Bay lowlands (HBLs)

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Ponds on peatlands of the Hudson Bay lowlands (HBLs) are complex ecosystems in which the fluxes to the atmosphere of CH₄ and CO₂ were controlled by interacting physical and biological factors. This resulted in strong diel variations of both dissolved gas concentrations and gas fluxes to the atmosphere, necessitating frequent sampling on a 24-hour schedule to enable accurate estimates of daily fluxes. Ponds at three sites on the HBL were constant net sources of CH₄ and CO₂ to the atmosphere at mean rates of 110-180 mg CH₄ m⁻² d⁻¹ and 3700-11,000 mg CO₂ m⁻² d⁻¹. Rates peaked in August and September. For CH₄ the pond fluxes were 3-30 times higher than adjacent vegetated surfaces. For CO₂ the net pond fluxes were similar in magnitude to the vegetated fluxes but the direction of the flux was opposite, toward atmosphere. Even though ponds cover only 8-12% of the HBL area, they accounted for 30% of its total CH₄ flux to the atmosphere. There is some circumstantial evidence that the ponds are being formed by decomposition of the underlying peat and that this decomposition is being stimulated by the activity of N₂ fixing cyanobacteria that grow in mats at the peat-water interface. The fact that the gas fluxes from the ponds were so different from the surrounding vegetated surfaces means that any change in the ratio of pond to vegetated area, as may occur in response to climate change, would affect the total HBL fluxes.

INTRODUCTION

Atmospheric concentrations of methane (CH₄) and carbon dioxide (CO₂) have been increasing since the Industrial Revolution [Intergovernmental Panel on Climate Change, (IPCC) 1990]. Methane concentration is increasing at a rate of 0.02 ppm yr⁻¹, or 1% yr⁻¹ while CO₂ concentrations are increasing at a rate of 1.5 ppm yr⁻¹, or 0.4% yr⁻¹. The increasing concentrations of these gases is of growing concern because they both are radiatively-active, "greenhouse" gases. Also, CH₄ participates in a variety of important atmospheric chemical reactions [Cicerone and Oremland, 1988]. For these reasons there is much interest in quantifying the strengths of the natural sources of these gases.

Wetlands are an important source of CH₄ to the atmosphere [e.g., Asefmann and Crutzen, 1989; Fung *et al.*, 1991]. Flux of CO₂ between the wetlands and the atmosphere is poorly understood. To improve the understanding of CH₄ and CO₂ fluxes to the atmosphere from wetlands, the Northern Wetlands Study (NOWES) had the objective of quantifying the fluxes of these gases from the Hudson Bay lowlands. Our particular contribution to the NOWES was to quantify the fluxes of CH₄ and CO₂ from the wetland ponds on the HBL to the atmosphere.

While CH₄ flux from the vegetated surfaces of wetlands has been studied quite extensively, there are few reports of CH₄ flux from wetland ponds. Reported CH₄ fluxes for wetland ponds range from 21 to 74 mg CH₄ m⁻² d⁻¹ [Bartlett *et al.*, 1988; Harriss *et al.*, 1988; Whalen and Reeburgh, 1989; Moore *et al.*, 1990]. None of these efforts were intensive studies of pond fluxes, and only Moore *et al.* [1990] compared pond fluxes to adjacent vegetated surfaces.

To our knowledge, CO₂ fluxes from wetland ponds have been studied only once. Kling *et al.* [1991] reported fluxes for Alaskan tundra ponds ranging from -242 mg CO₂ m⁻² d⁻¹ to 2630 mg CO₂ m⁻² d⁻¹.

The main objective of this work was to measure the flux of CH₄ and CO₂ to the atmosphere from ponds in the HBL in conjunction with flux measurements being made on adjacent vegetative surfaces [Moore *et al.*, this issue; den Hartog *et al.*, this issue]. Ponds ranging in size from about 30 m² to 42,000 m² (Table 1) were chosen at three sites on a linear transect of the HBL beginning near the coast of James Bay and ending at Kinoshoe Bog (see figure in the work of Roulet *et al.* [this issue]).

A secondary objective was to begin to understand the factors controlling microbial decomposition processes in the sediments of these ponds that produce CH₄ and CO₂.

We found that the ponds behaved quite differently than the vegetated surfaces. CH₄ fluxes to the atmosphere were generally much higher from the ponds than from the vegetated surfaces. CO₂ fluxes from the ponds were almost always at least 10 times greater than CH₄ fluxes and were almost always to the

What got it all started!

Wetland ponds in the Hudson Bay Lowlands were sources of the greenhouse gases CO₂ and CH₄ to the atmosphere.

If you flooded landscapes to create reservoirs for hydroelectricity production, would they also be sources of CO₂ and CH₄ to the atmosphere.



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0148-0227/94/93JD-03020\$05.00

Are Hydroelectric Reservoirs Significant Sources of Greenhouse Gases?

Estimates suggest that, per unit of energy produced, greenhouse-gas flux to the atmosphere from some hydroelectric reservoirs may be significant compared to greenhouse-gas emission by fossil-fuelled electricity generation. Greenhouse gases (CO_2 and CH_4) are produced during bacterial decomposition of flooded peat and forest biomass. The amount emitted will be positively related to the area flooded. Early data from hydroelectric reservoirs in northern Canada support this hypothesis.

In Canada, there are about 20 000 km^2 (the size of Lake Ontario) of peatland and upland areas covered by hydroelectric reservoirs (1), with over 11 000 km^2 more planned. In addition to the known mercury contamination of fisheries caused by hydroelectric developments (2–3), we hypothesize that development of hydroelectric reservoirs may increase the flux of CH_4 and CO_2 to the atmosphere. In some cases this increase, per unit of energy produced, may be significant compared to greenhouse gas emitted by fossil-fuelled electricity generation. We are writing to present the basis of our hypothesis because of recent concern that hydroelectric reservoirs may be significant sources of greenhouse gases (4).

Our hypothesis is based primarily on two of our past studies which show that both

upland forests and peatlands are sites of intense microbial decomposition and greenhouse-gas production when they become covered with water.

In the first study, which deals with upland forests, we measured concentrations of CH_4 and O_2 with depth in the Notigi Reservoir (northern Manitoba; Fig. 1a). Two years after flooding, the shape of the CH_4 and O_2 profiles in the water column of the reservoir were very different from CH_4 and O_2 profiles seen in the hypolimnia of natural, productive lakes (Fig. 1b). To interpret these profiles, it is important to understand that during stratification (when these profiles were taken), horizontal rates of transport in the hypolimnia of lakes and reservoirs are orders of magnitude faster than vertical rates of transport. Thus, in hypolimnia, CH_4 and O_2 concentrations at a particular depth largely reflect rates of activity of microbial production and consumption processes in the sediments at that same depth.

Because of the shape of the CH_4 and O_2 profiles, we conclude that in the Notigi Reservoir decomposition rates, and CH_4 production, must have been much faster at the newly flooded depths where the water was covering forested area (above 16 m) than at the depths of preexisting sediments (below 16 m). (Decomposition rates were

probably also high in the flooded epilimnetic sediments, 10 m and above, but this could not be observed because gases released into the epilimnetic water are constantly lost to the atmosphere).

In the hypolimnion of the Notigi reservoir, a methane production rate for the flooded forest area can be determined by summing the total mass of methane that accumulated between 12 and 16 m during the period of stratification plus estimates of vertical transport losses (5). Using this approach we estimated that the CH_4 production rate in the flooded forest area was high, $7.4 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$, even though this area was covered with cold hypolimnetic water. This rate is in the same range as CH_4 production rates in beaver ponds.

In a second recent study, which involves peatlands (6), we found very high seasonal fluxes of CO_2 and CH_4 , $450\text{--}1800 \text{ gCO}_2 \text{ m}^{-2} \text{ yr}^{-1}$, $15\text{--}30 \text{ gCH}_4 \text{ m}^{-2} \text{ yr}^{-1}$, from the surface of ponds that form naturally on peatlands near the west coast of James Bay. ^{14}C dating measurements of CO_2 and CH_4 showed that the gases were being mostly produced by bacterial decomposition of old flooded peat underlying the pools (7). Other related studies showed that where the peat is covered by vegetation, instead of water, the peat was accumulating (8).

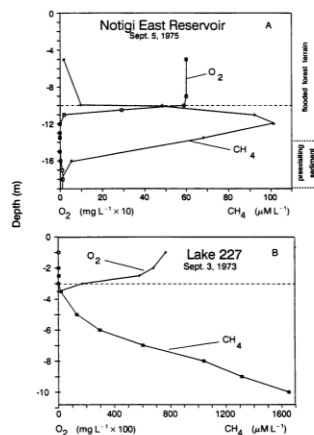


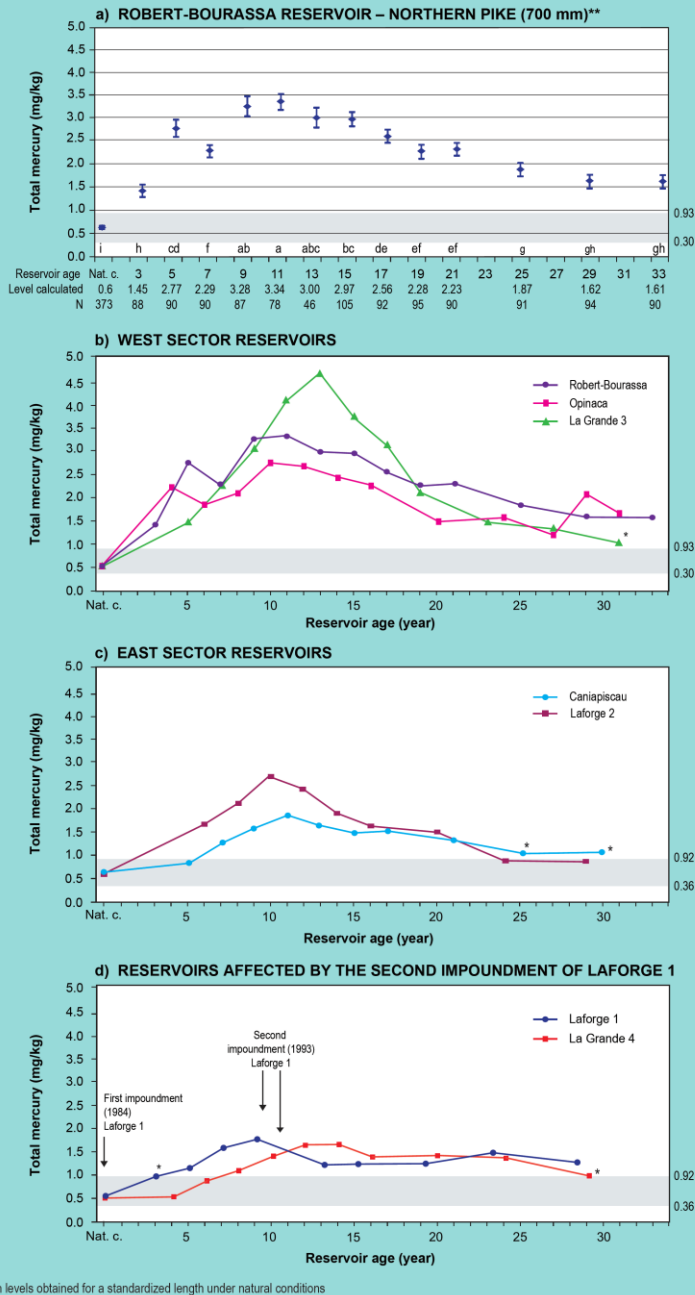
Figure 1. Depth profiles of O_2 and CH_4 concentrations in a) the Notigi Reservoir (northern Manitoba), and in b) Lake 227 at the Experimental Lakes Area, northwestern Ontario. The dashed horizontal lines represent the depth of the mixed layer.



Aerial photograph of the Notigi Reservoir, northern Manitoba, Canada. Trees are usually not removed before flooding. Thus, areas of water where trees are not visible are sites where water depth is greater than forest height. Photo: J.W.M. Rudd.

This is a big question because in the era of adapting to climate change, hydroelectricity was being touted as “carbon-free” source of energy.

Mercury in northern pike in Hydro Quebec reservoirs



Another issue is the production and bioaccumulation of MeHg in reservoirs following flooding.

This creates long-term socio-economic problems for Indigenous peoples and others that rely on healthy freshwater resources and services for their ways of life.

* Mean level which is higher than the range of values obtained in natural lakes but does not differ significantly from the mean level measured in at least one natural lake in the region.

** The vertical lines represent the confidence intervals (95%) for the estimated mean levels.

The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap. Nat. c.: Natural conditions

High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management

Bernhard Lehner^{1*}, Catherine Reidy Liermann², Carmen Revenga³, Charles Vörösmarty⁴, Balazs Fekete⁴, Philippe Crouzet⁵, Petra Döll⁶, Marcel Endejan⁷, Karen Frenken⁸, Jun Magome⁹, Christer Nilsson¹⁰, James C Robertson³, Raimund Rödel¹¹, Nikolai Sindorf¹², and Dominik Wisser¹³

Front Ecol Environ 2011; 9(9): 494–502, doi:10.1890/100125

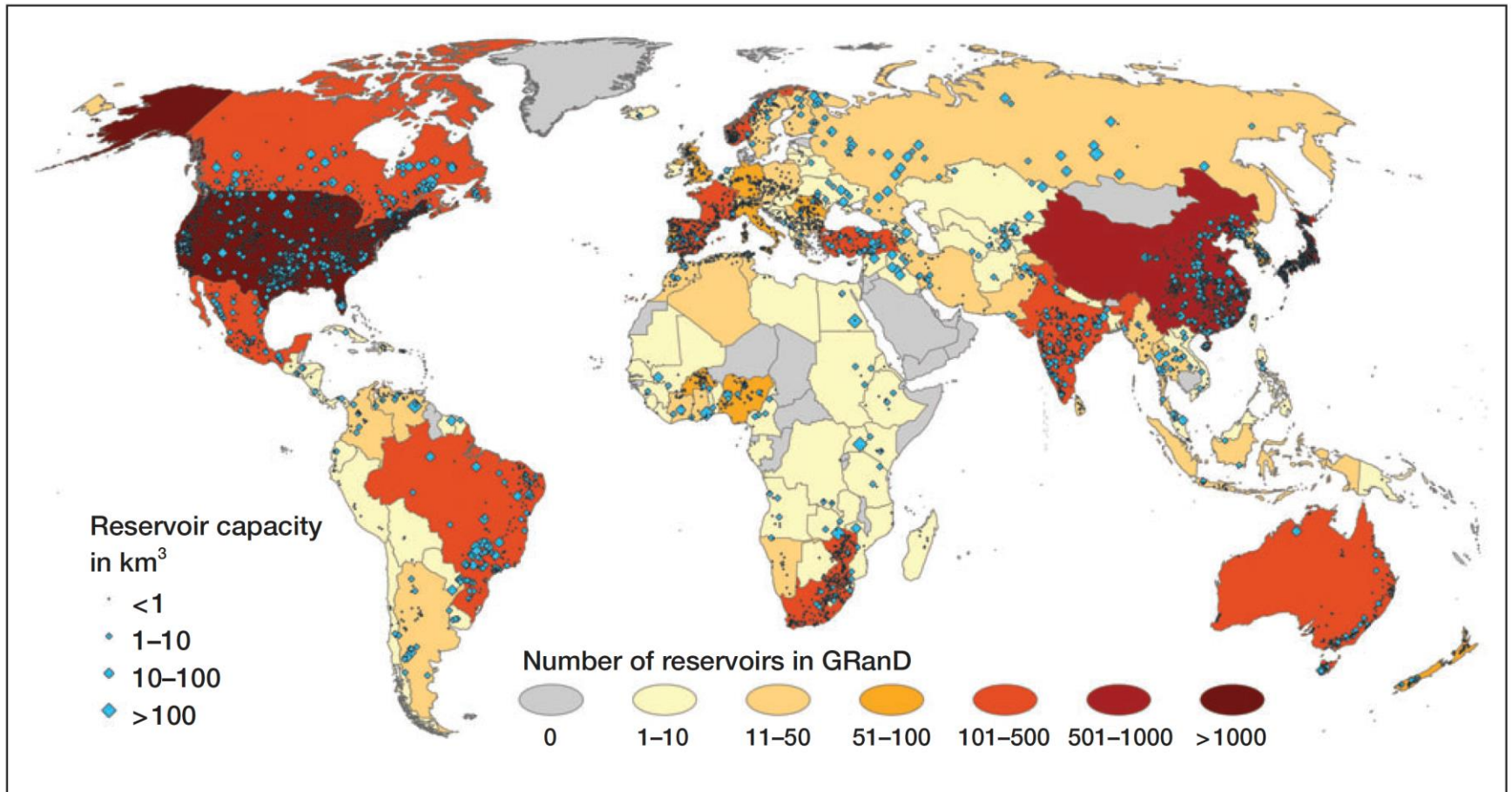
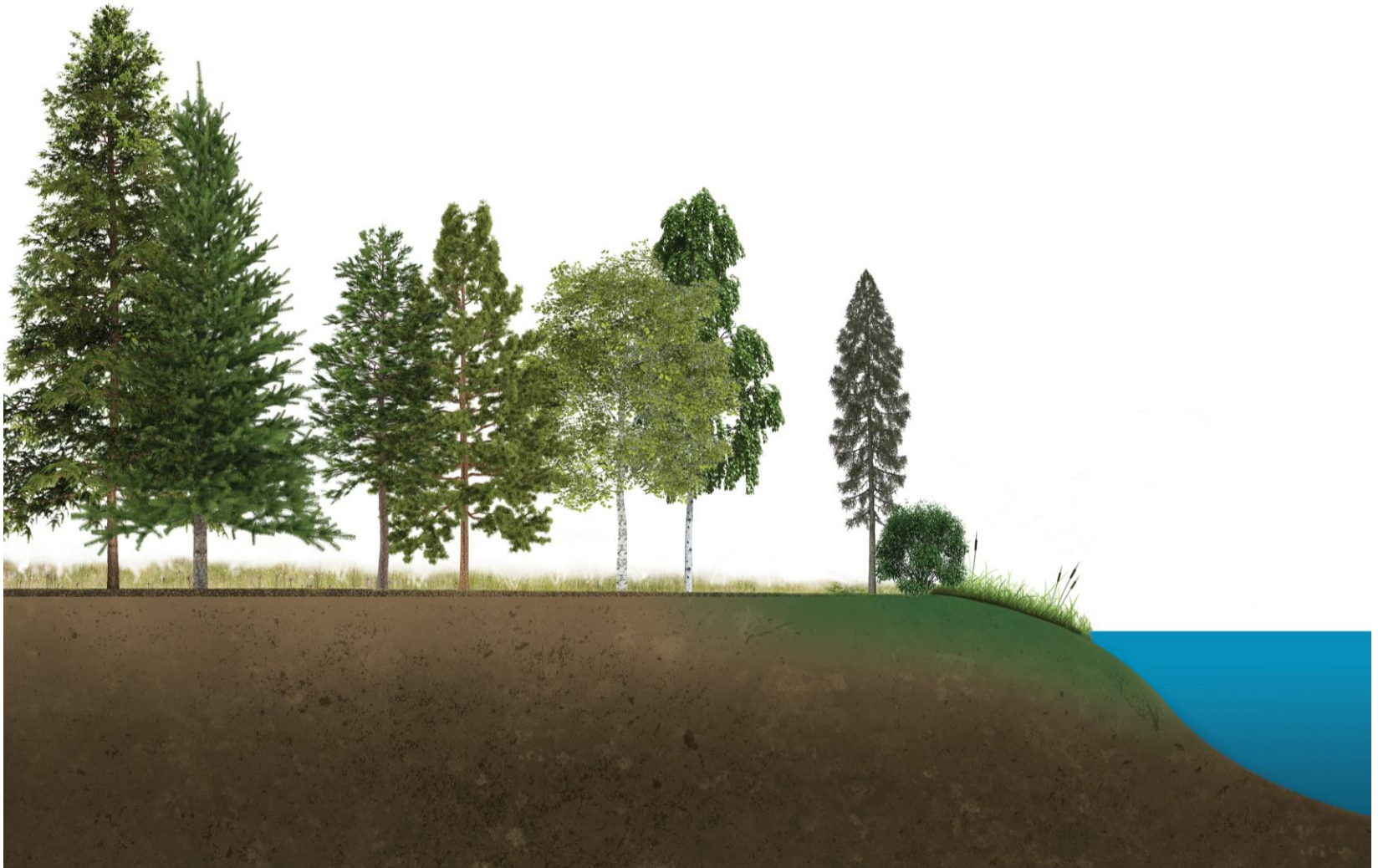


Figure 1. Global distribution (by country) of large reservoirs included in GRanD.

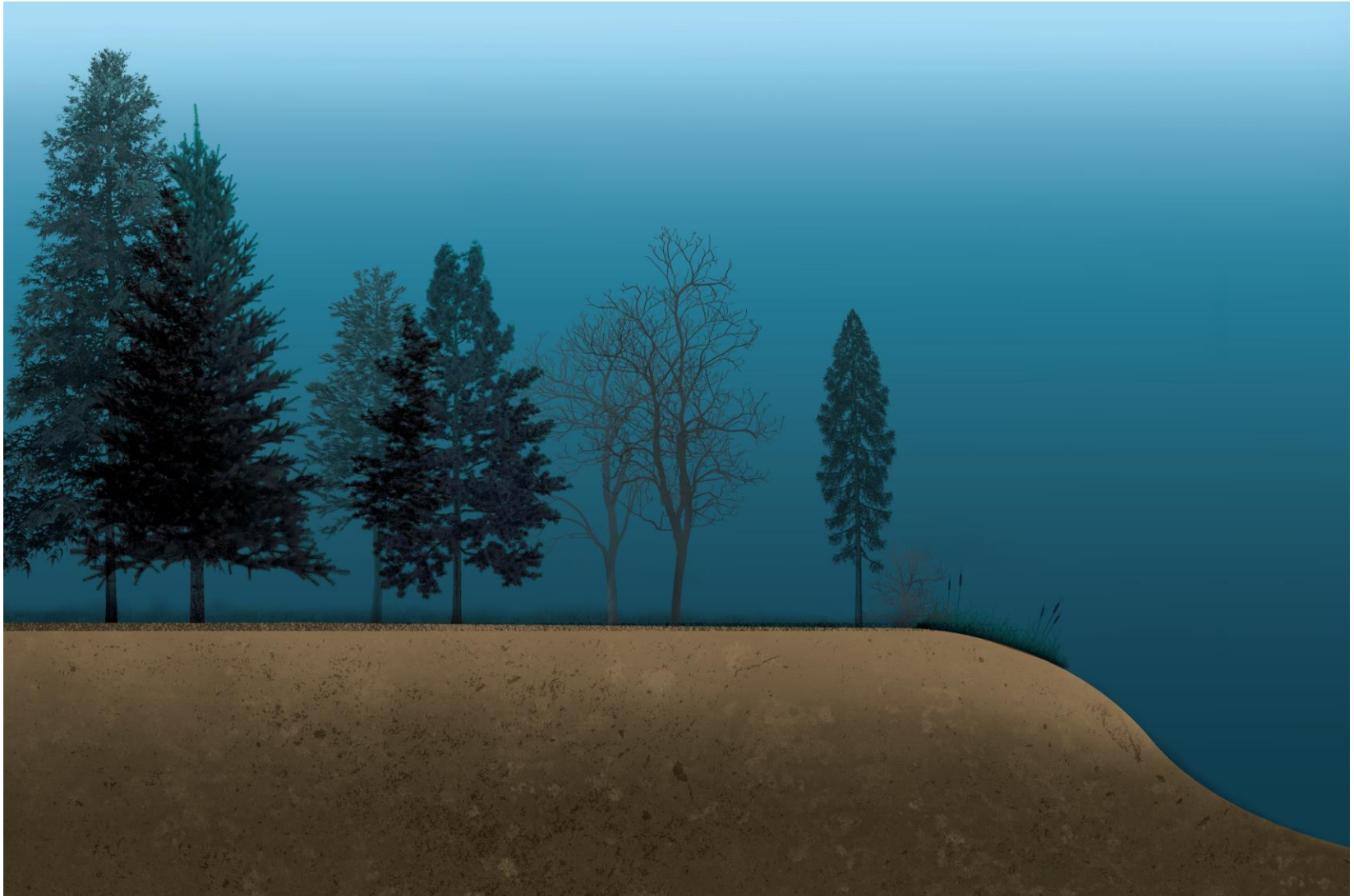
Flooding landscapes changes how they naturally function

ALIVE AND PRODUCTIVE



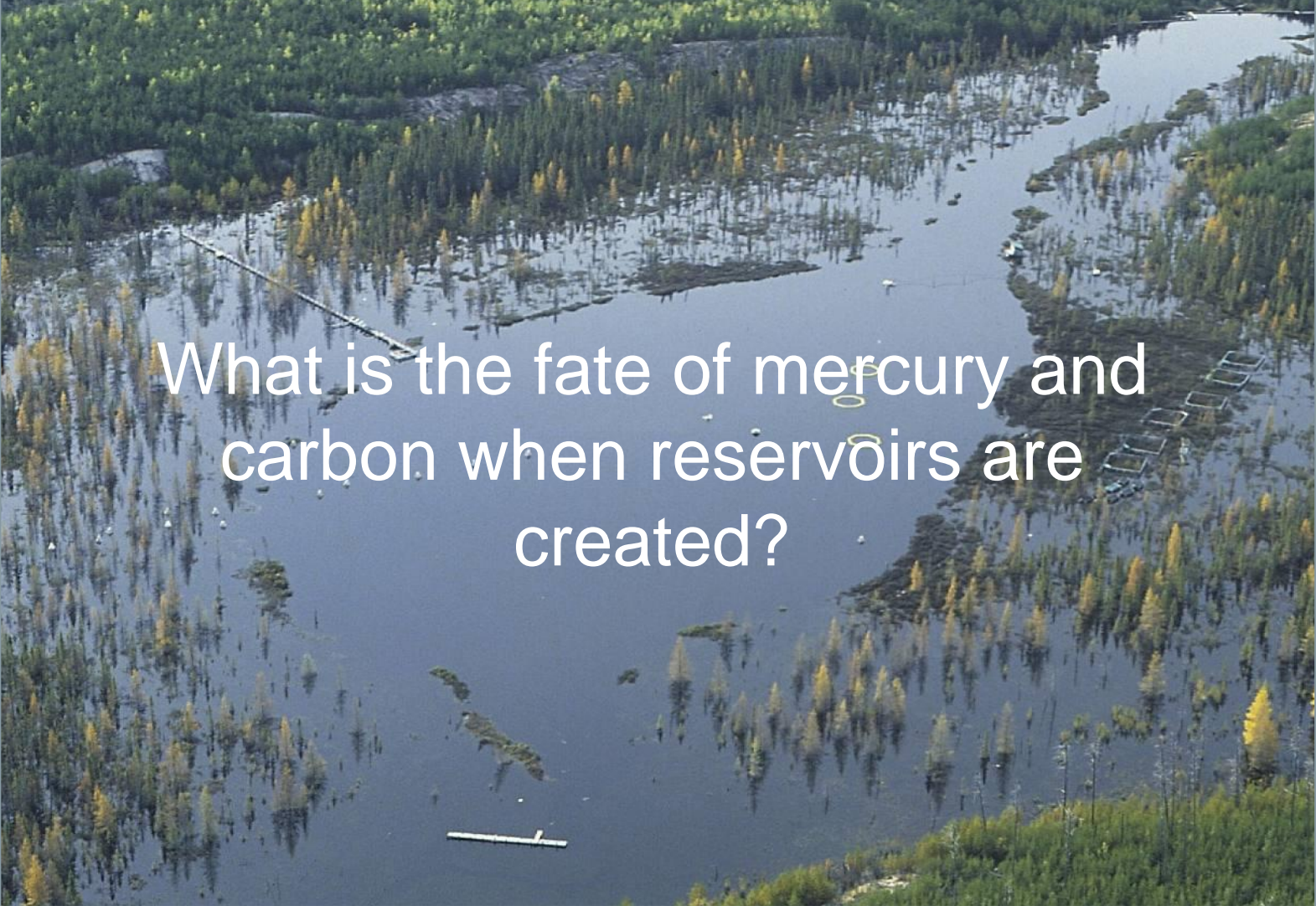
Flooding landscapes changes how they naturally function

DEAD AND DECAYING



Using unique whole-ecosystem experimentation at the Experimental Lakes Area, we were able to ask:

- What is the net impact of flooding landscapes on greenhouse gas (CO_2 and CH_4) emissions and methylmercury production?
- Does flooding different amounts of organic carbon change the intensity of these impacts?
- How long do these impacts last post-flooding?
- Are hydroelectric reservoirs important net sources of greenhouse gases to the atmosphere?

An aerial photograph showing a large reservoir in the foreground, surrounded by a dense forest. The water is dark and reflects the surrounding trees. In the background, a long, narrow dam or barrier spans across the water. The forest is a mix of green and yellow, suggesting autumn. The overall scene is a natural landscape with a significant water body.

What is the fate of mercury and carbon when reservoirs are created?

Whole ecosystem manipulations

- Scientists at ELA use mass balance budgets on impacted and natural lakes to determine the fate of matter in lakes

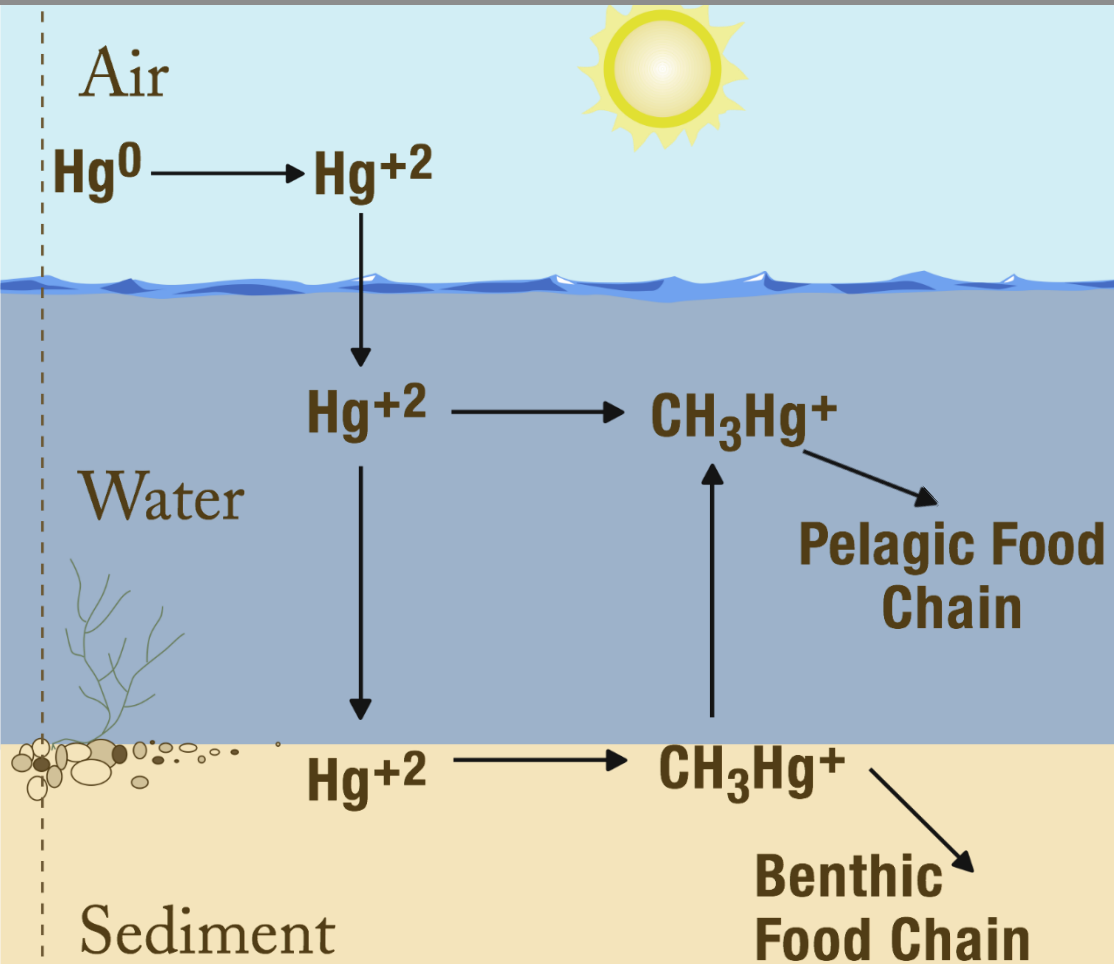


What you need to create a mass budget

- Our “currency” was Mercury (Hg) and Carbon



Mercury transformations in the environment



- Microbial methylation in wetlands and anoxic sediments is the main source of MeHg in aquatic environments
- Many environmental factors affect MeHg production

Because bacteria produce MeHg, our hypothesis was that increased carbon in reservoirs would fuel MeHg production

What you need to create a mass budget

- Our “currency” is Mercury (Hg)

E
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Building the dam at the wetland outflow



Floating peat in the flooded wetland

Preflood (1992)



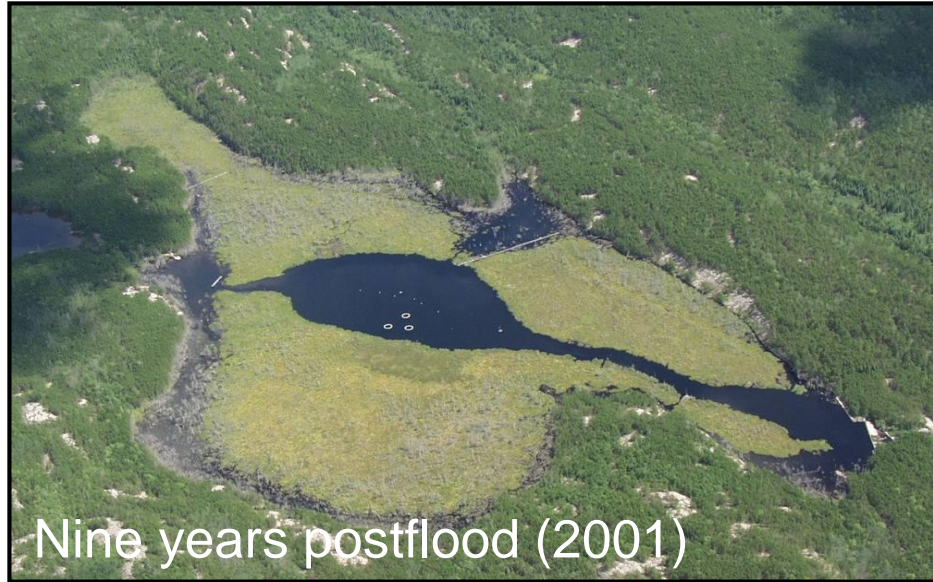
First year of flooding (1993)



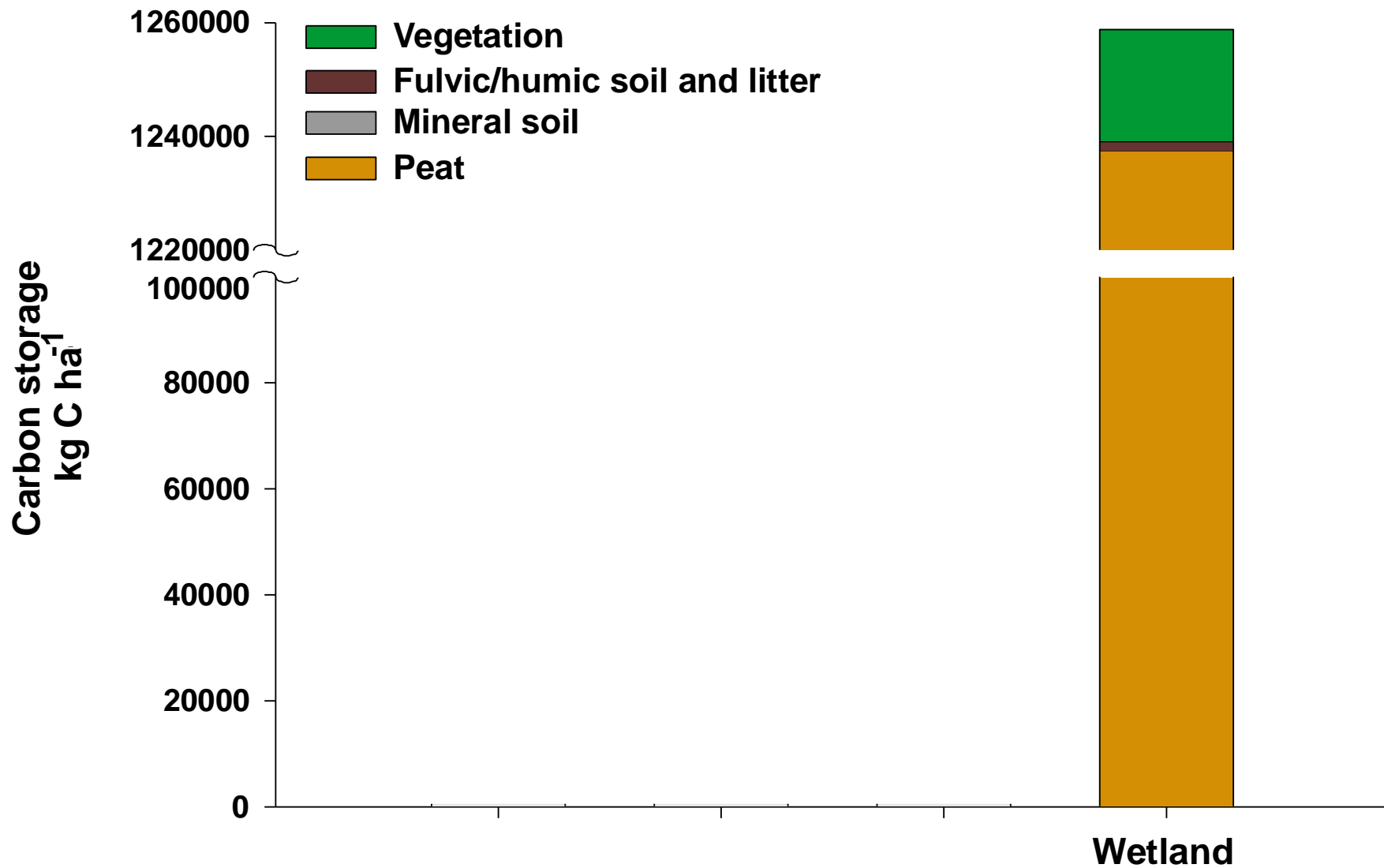
Five years postflood (1997)



Nine years postflood (2001)



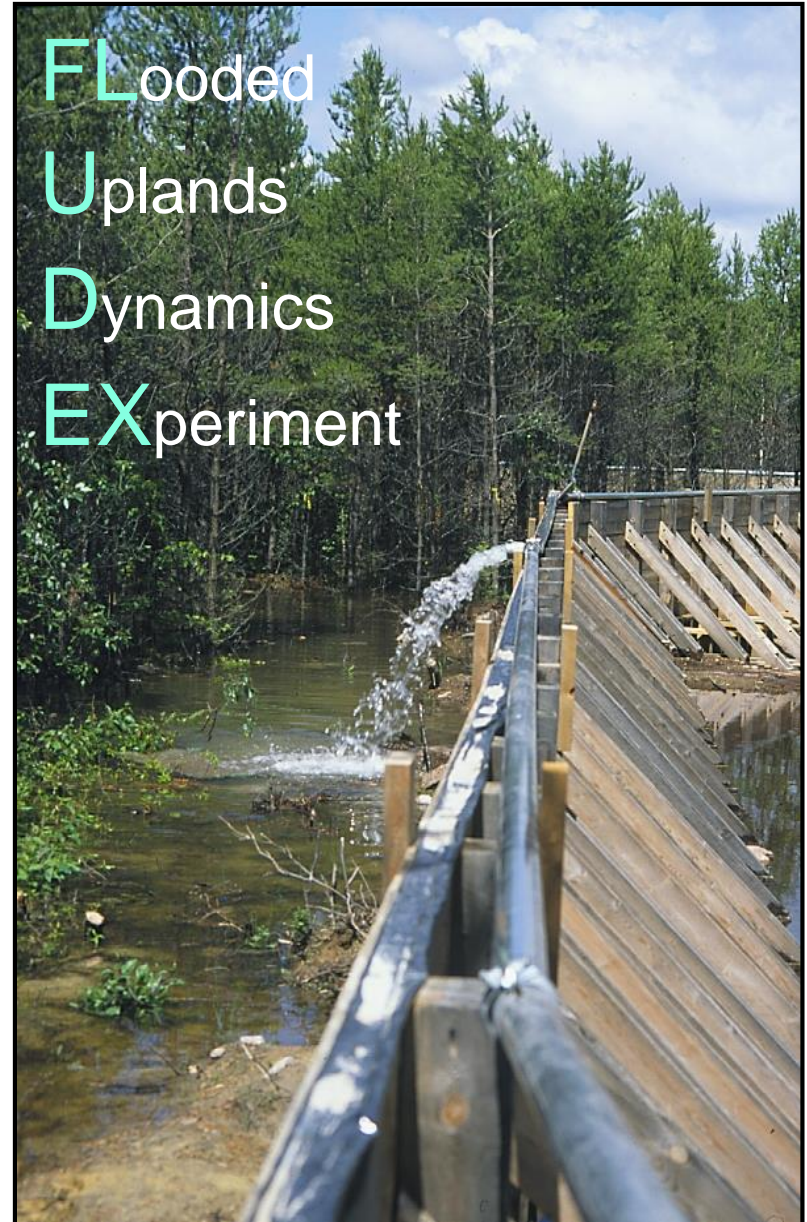
Carbon stores in experimental reservoirs



Flooding upland forests



FLooded
Uplands
Dynamics
EXperiment



Upland reservoirs

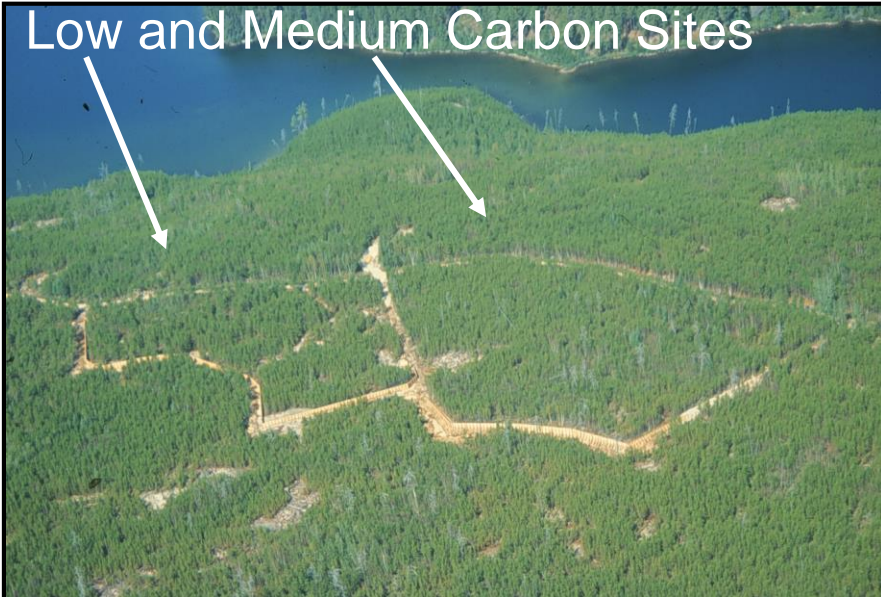
Preflood

Postflood

High Carbon Site



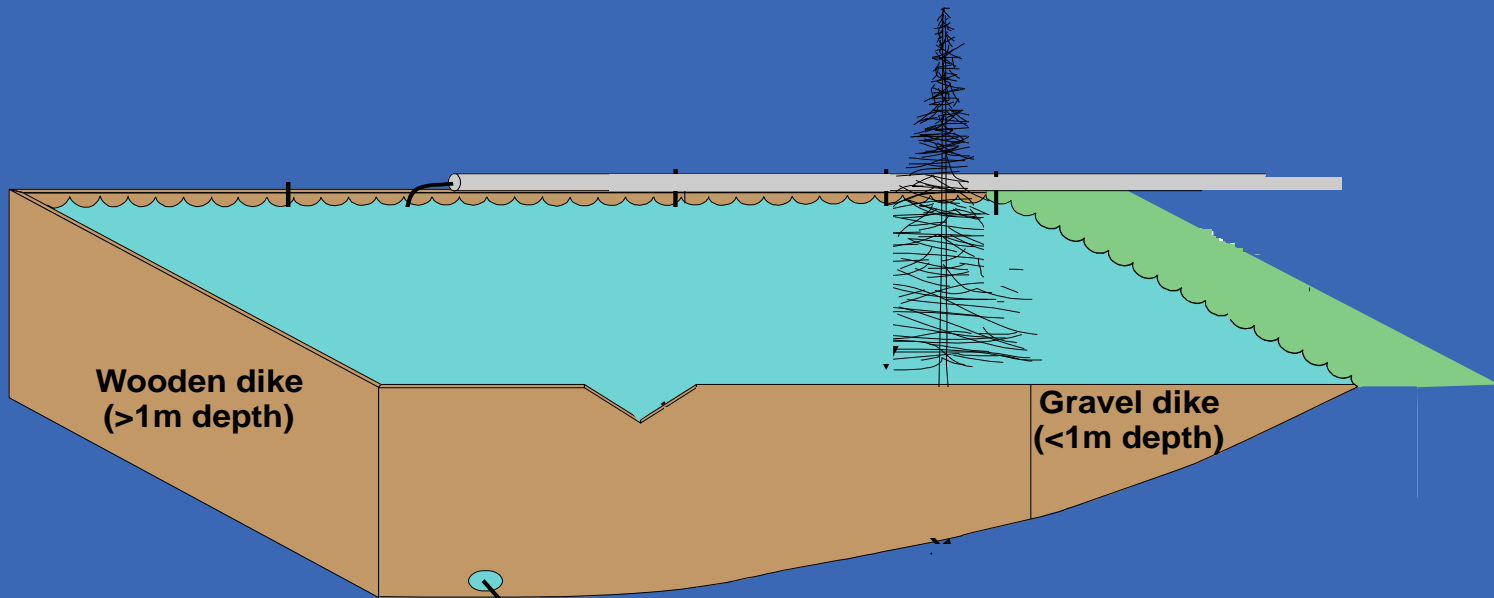
Low and Medium Carbon Sites



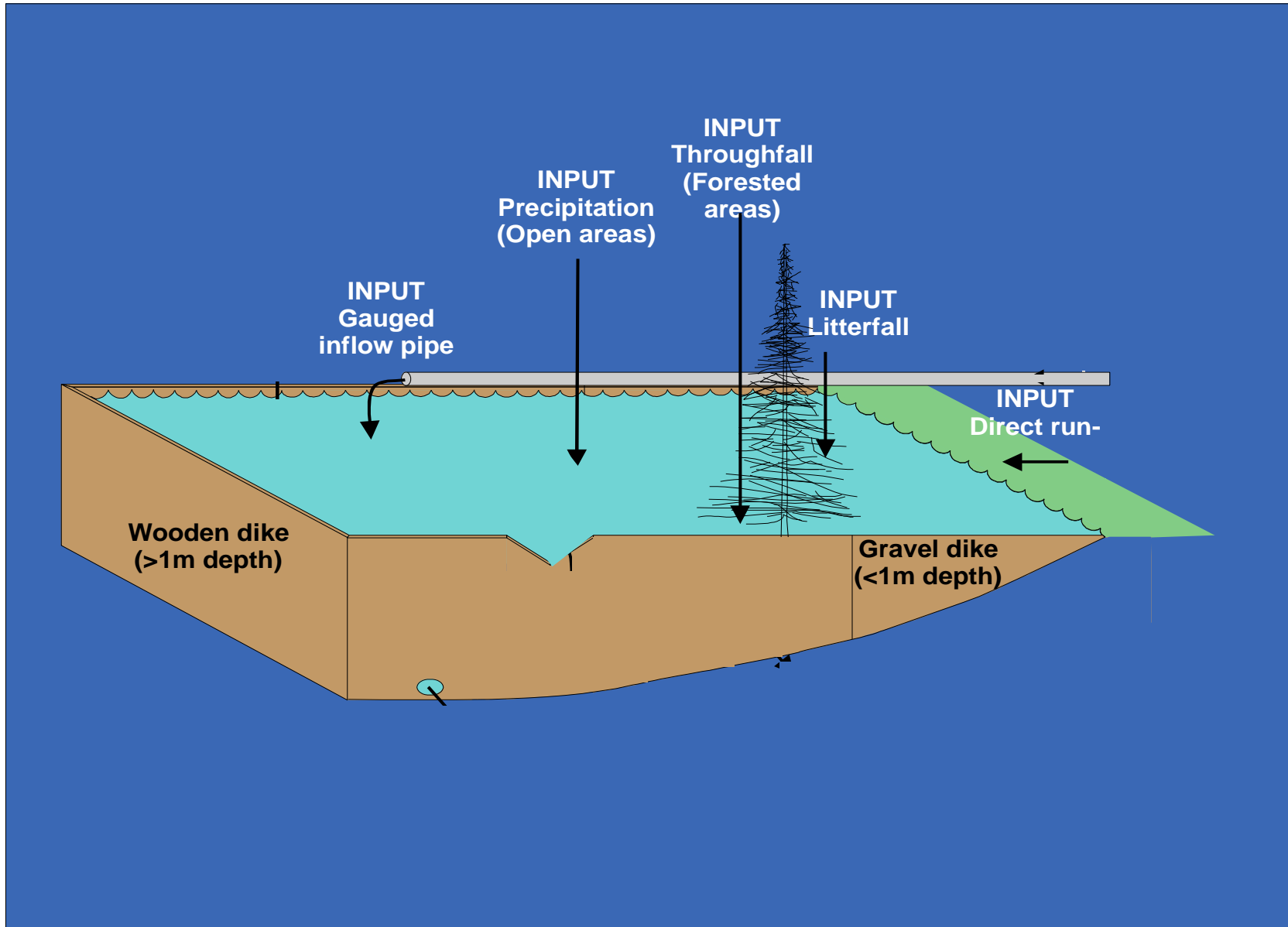
What you need to create a mass budget

- Our “currency” is Mercury (Hg)
- Our “scale” is whole ecosystem and before/after
- Our “transactions” are how MeHg moves and changes

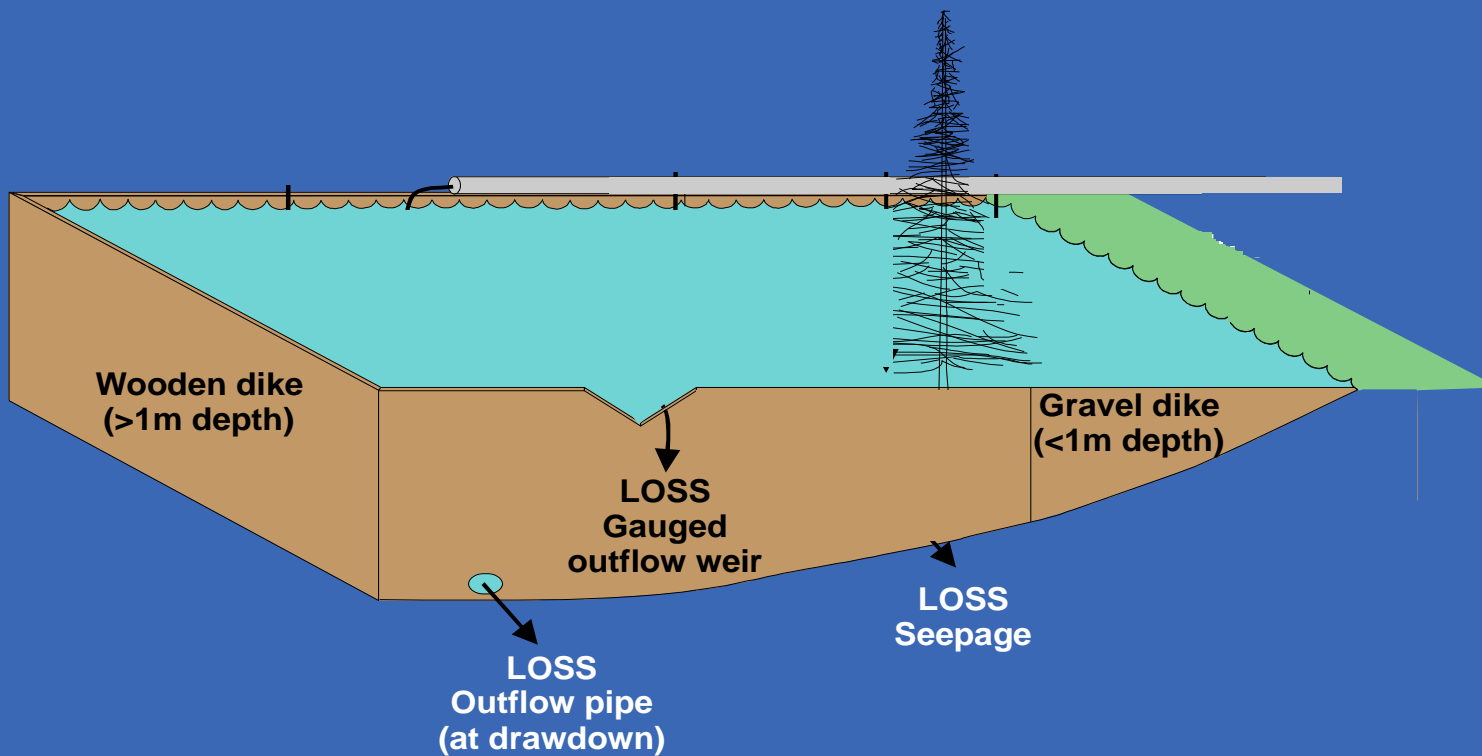
Components of a MeHg budget



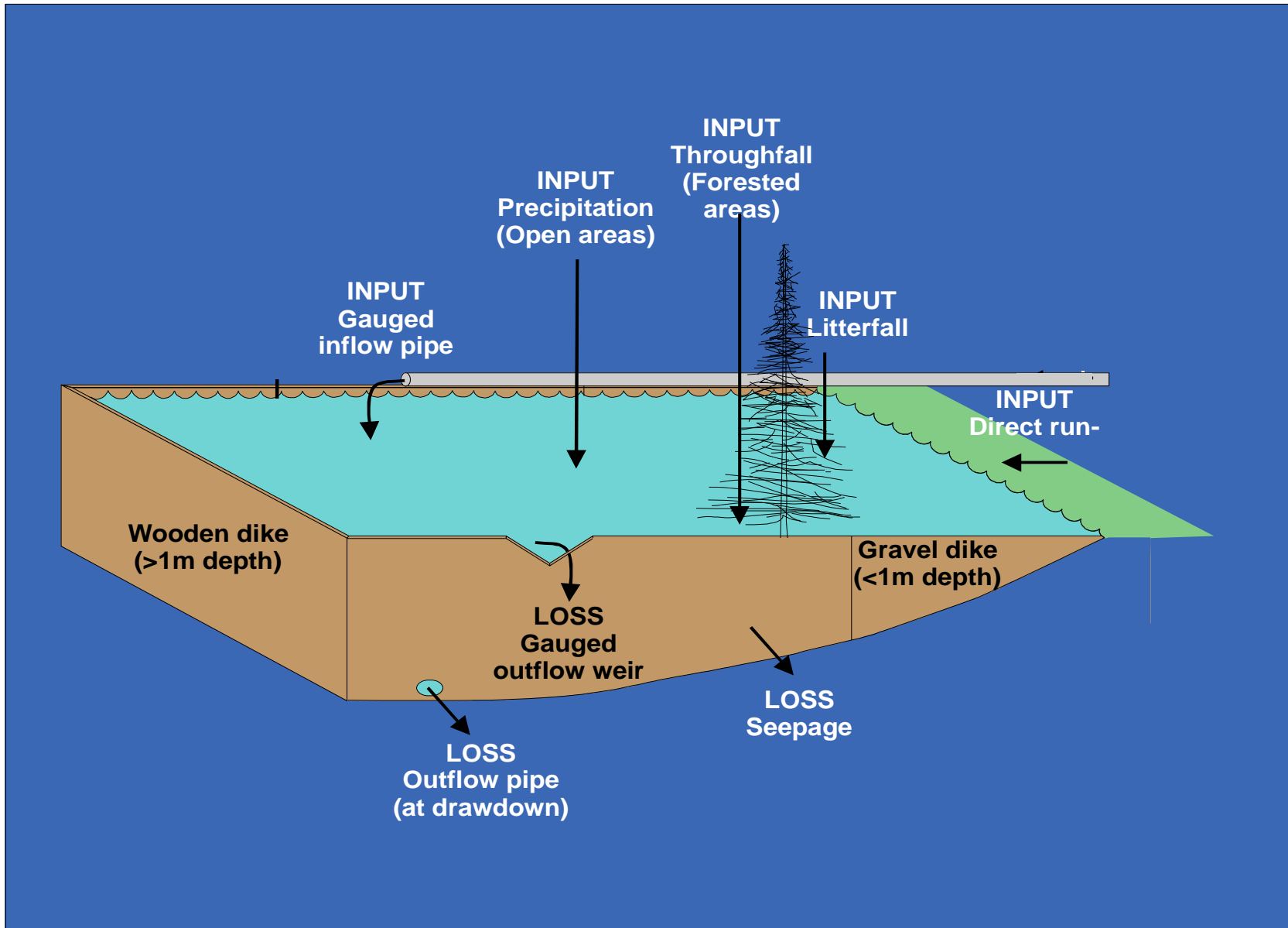
Components of a MeHg budget



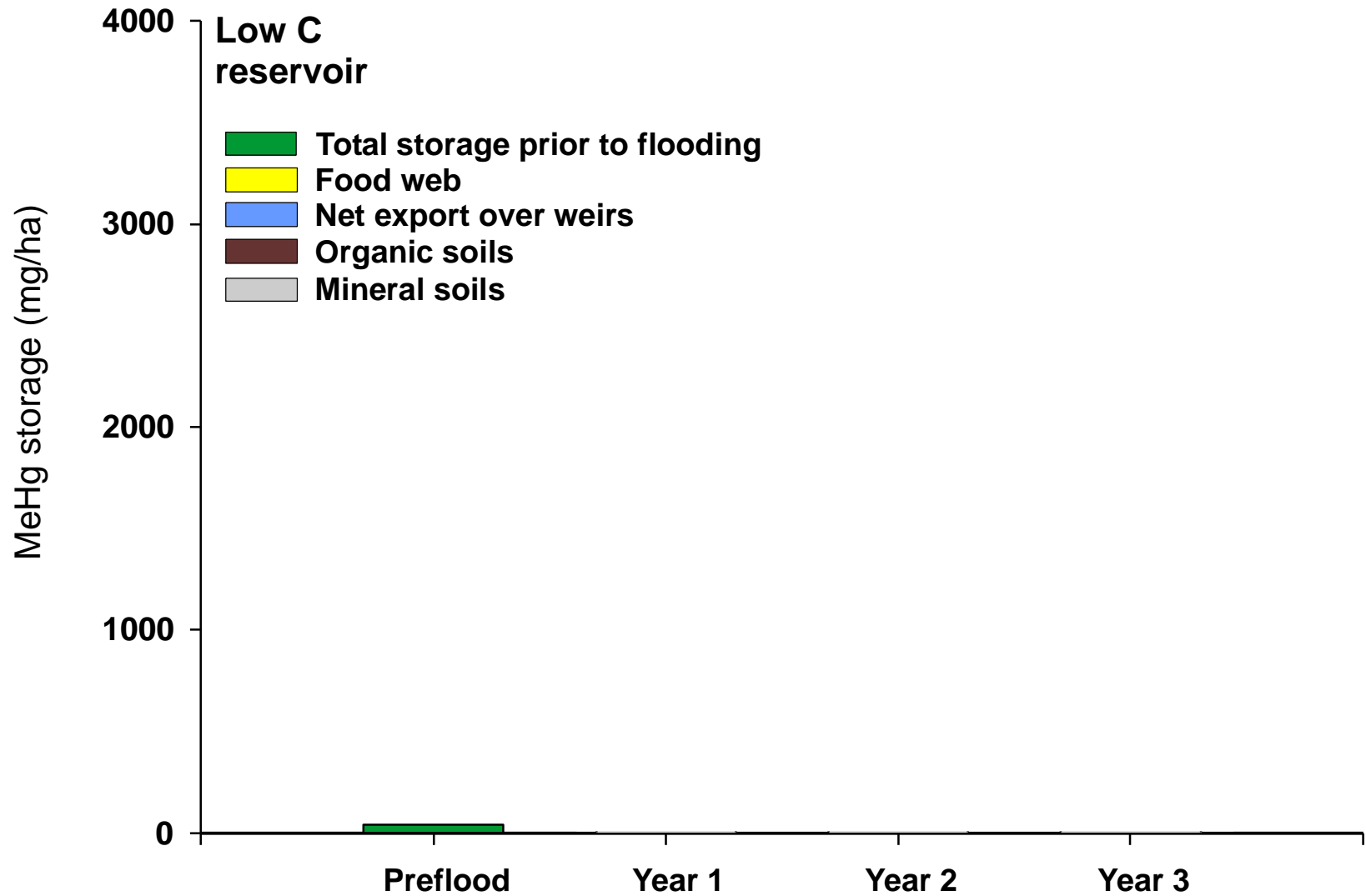
Components of a MeHg budget



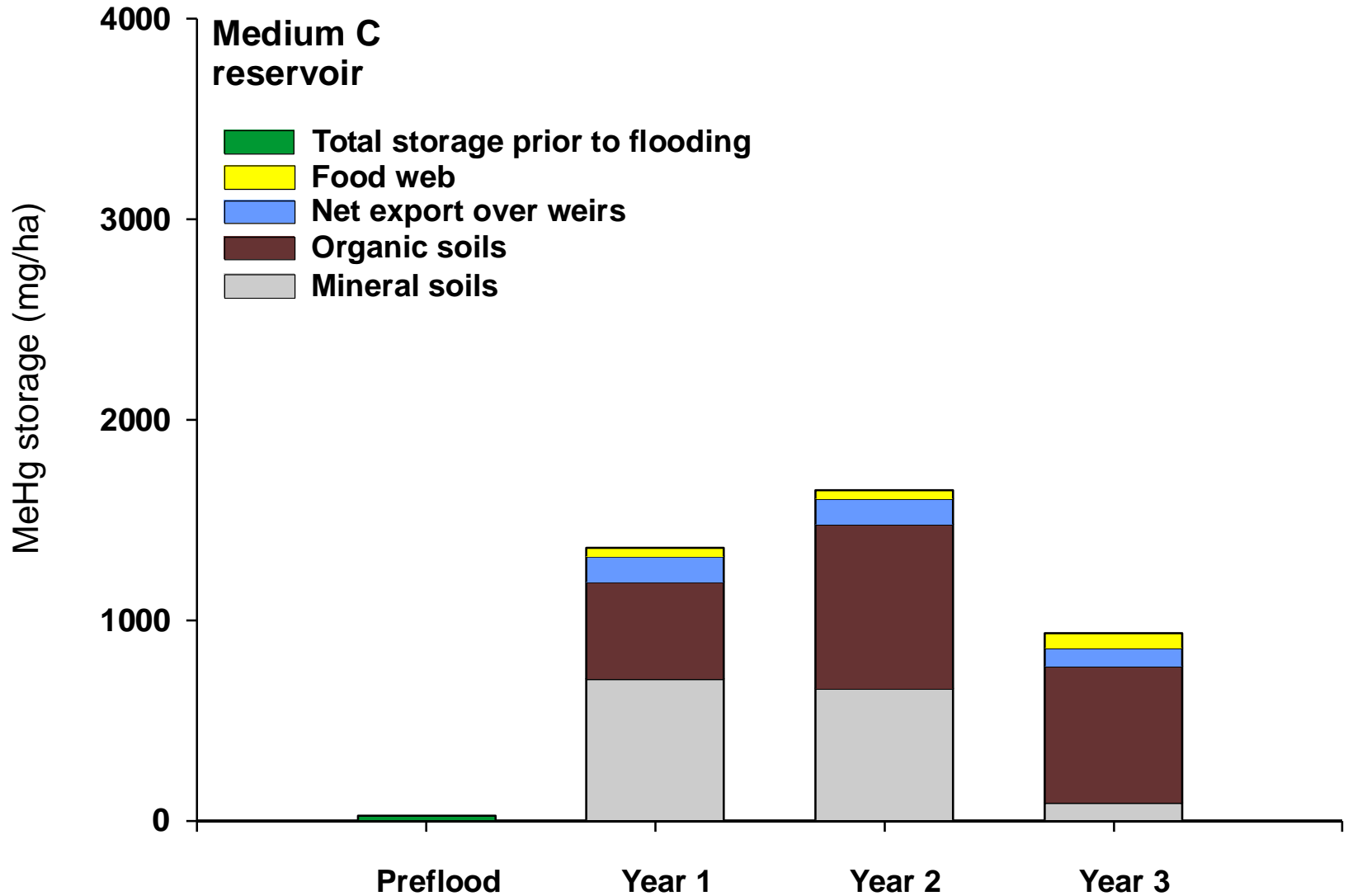
Components of a MeHg budget



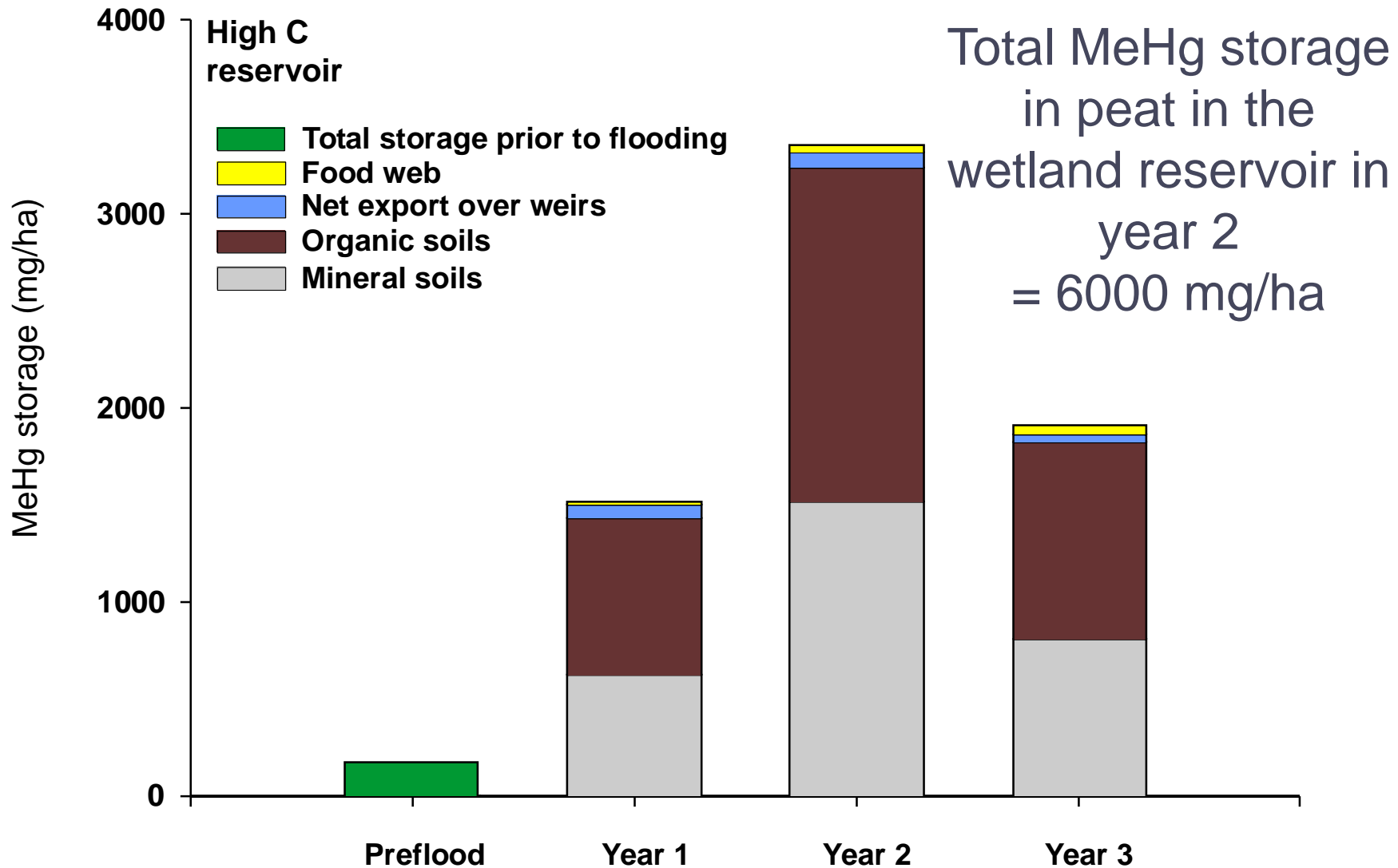
Total MeHg in FLUDEX reservoirs



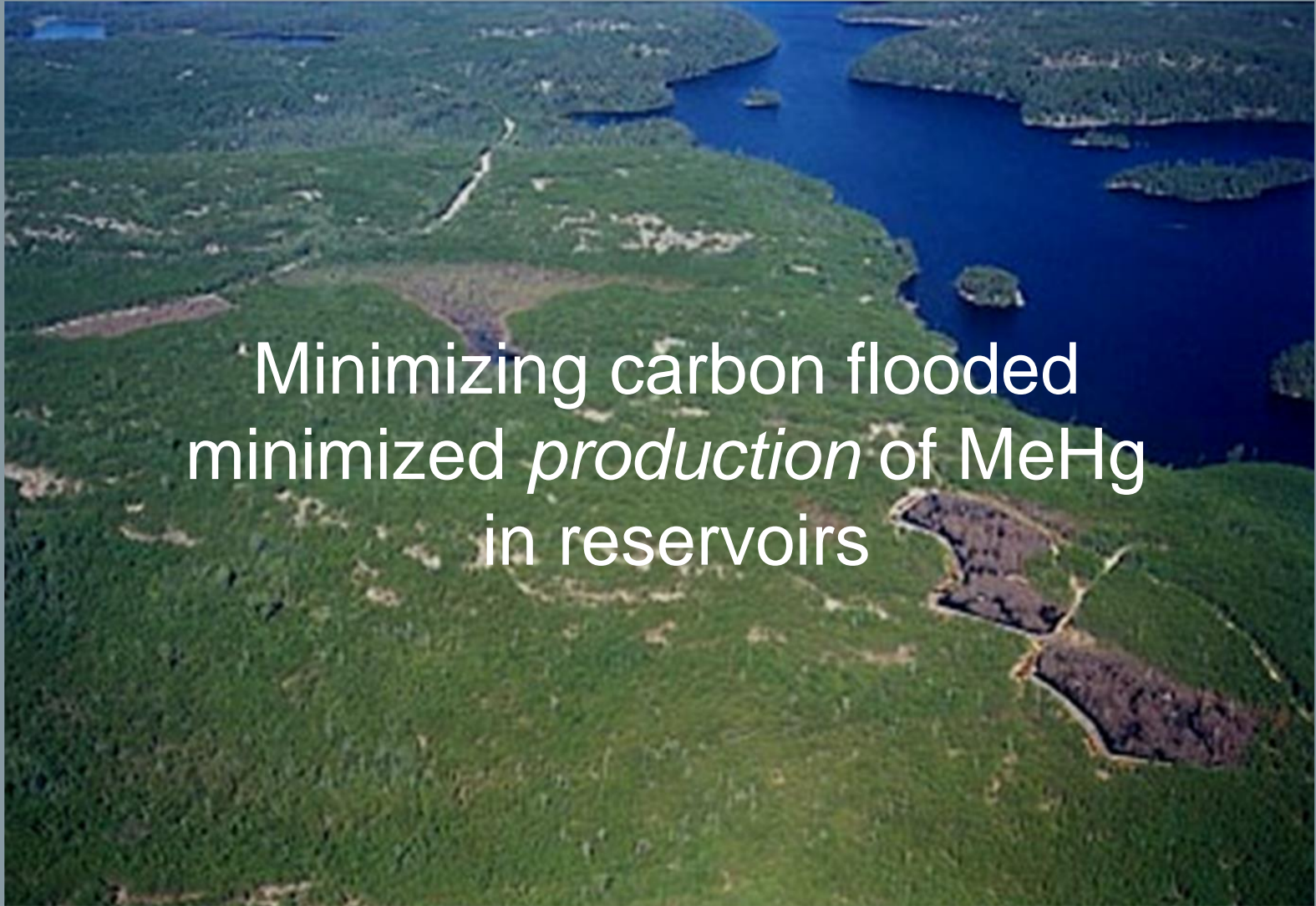
Total MeHg in FLUDEX reservoirs



Total MeHg in FLUDEX reservoirs

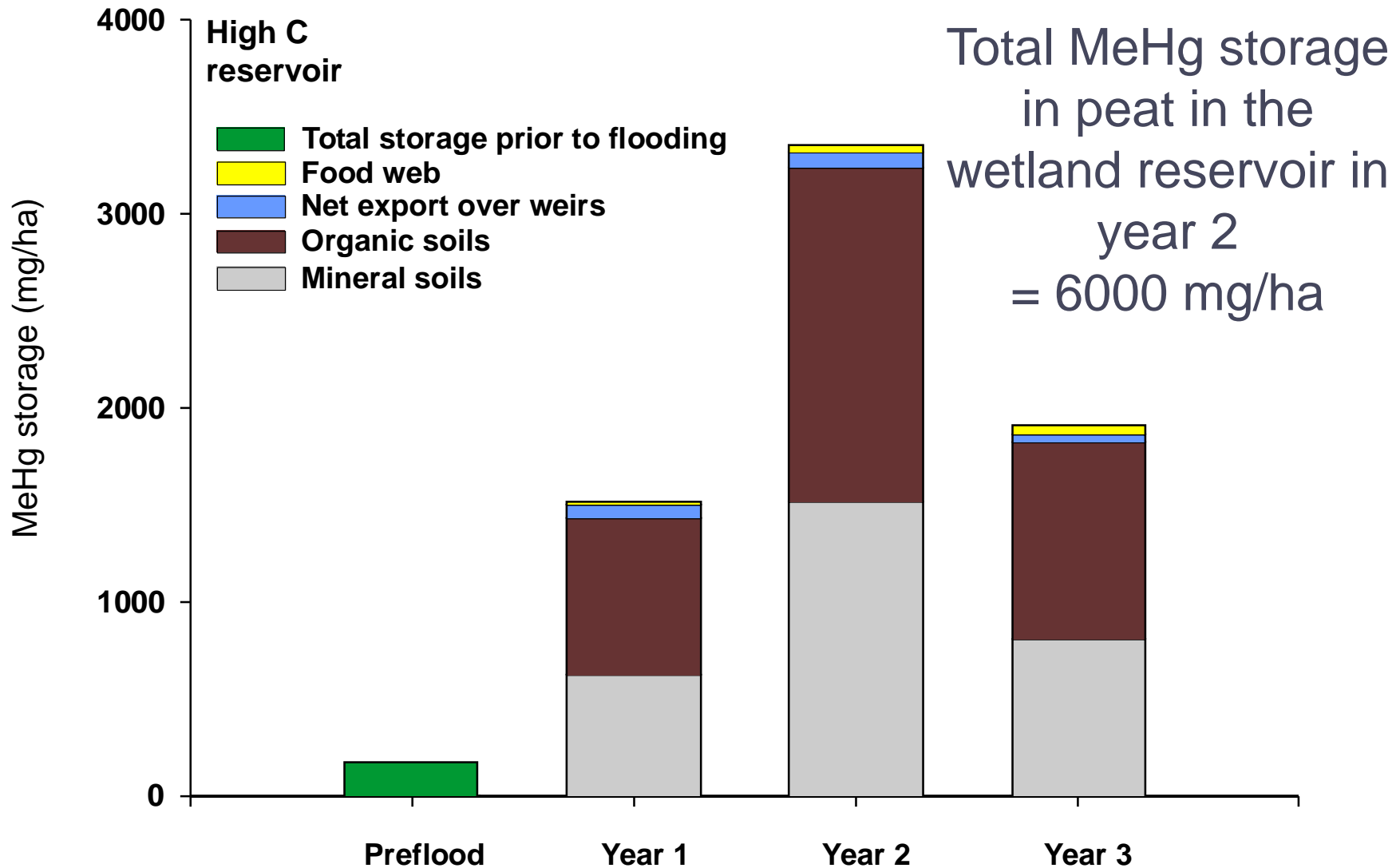


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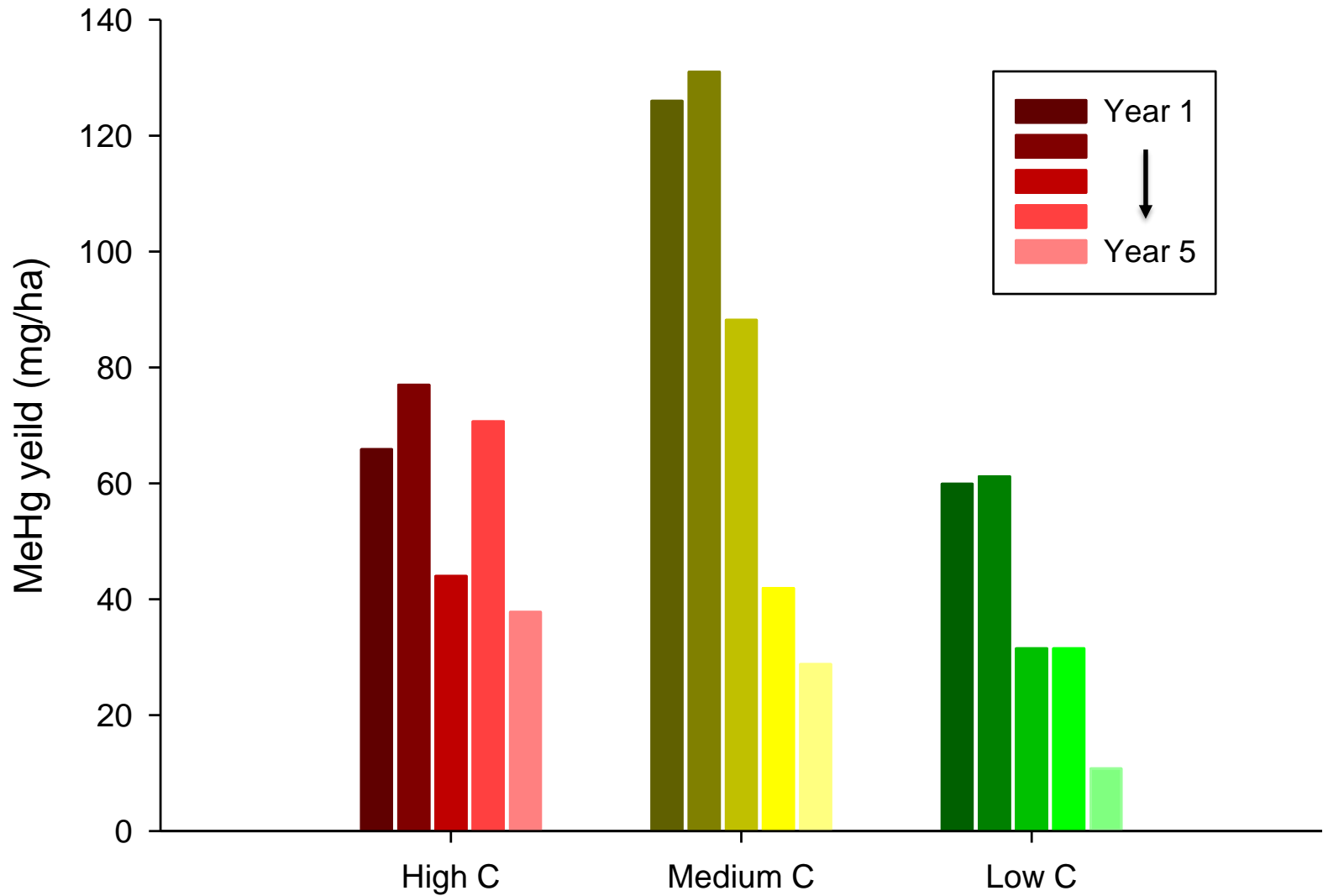


Minimizing carbon flooded
minimized *production* of MeHg
in reservoirs

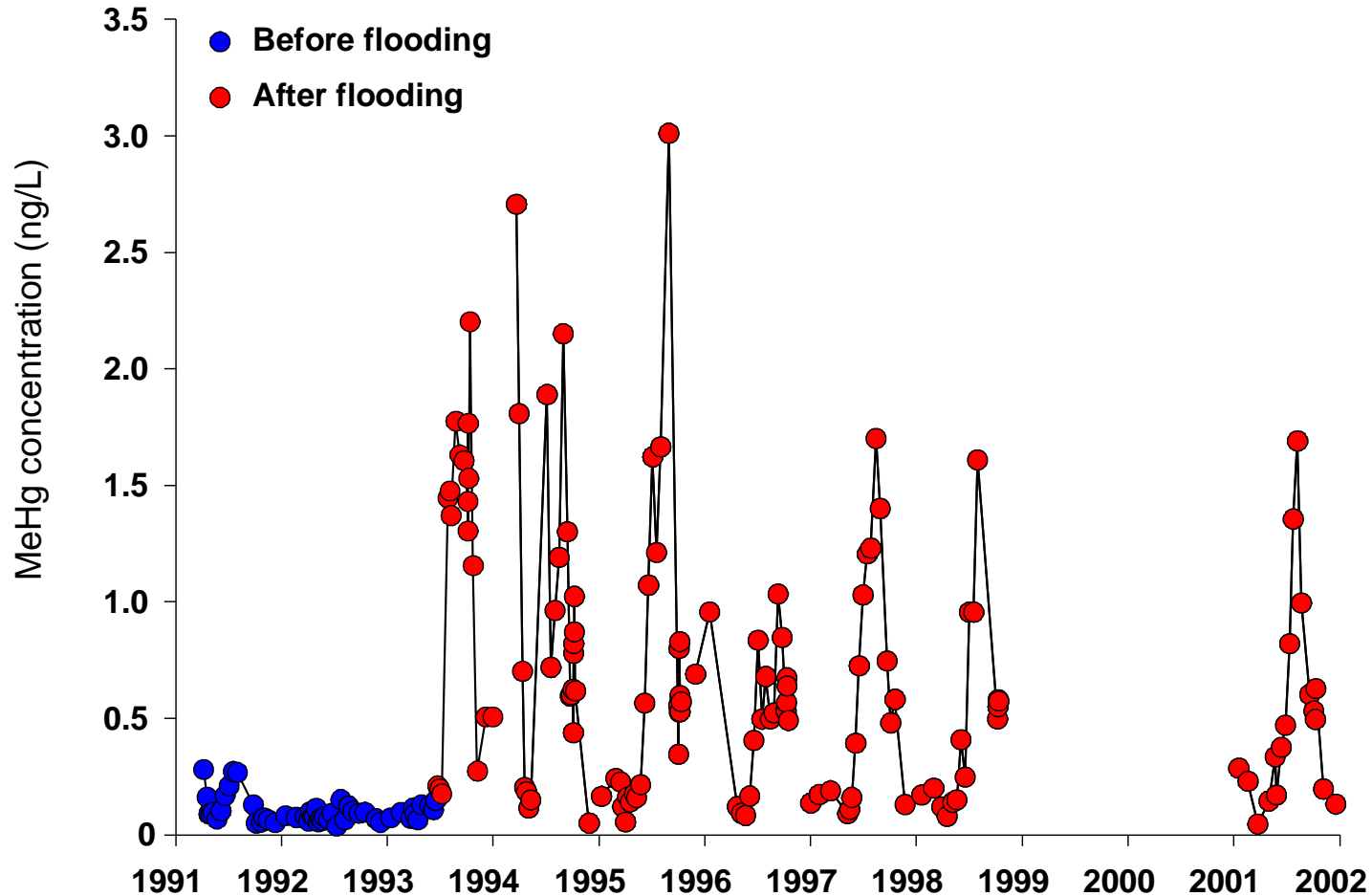
Total MeHg in FLUDEX reservoirs



MeHg yield over five years

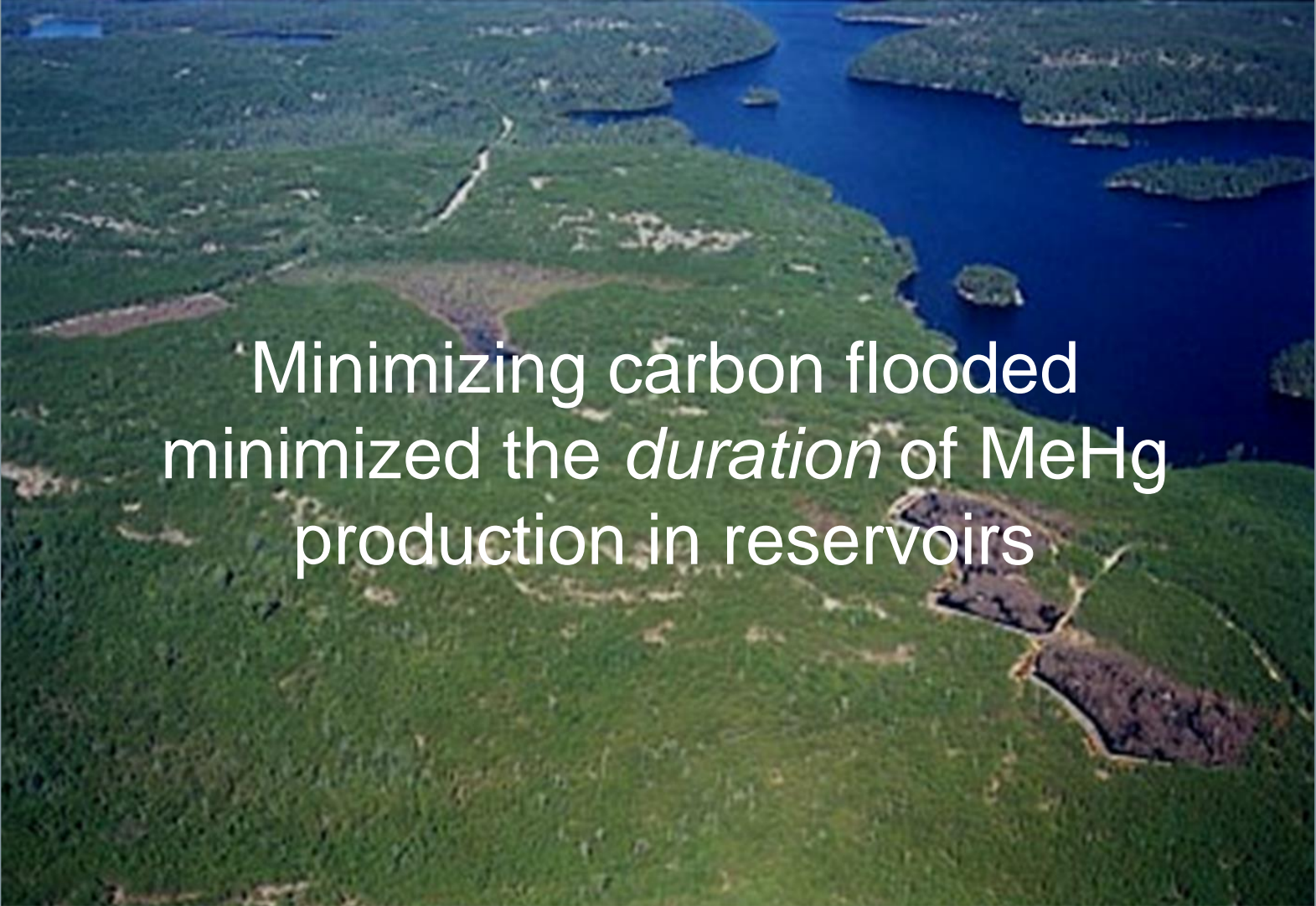


Results from ELARP



Flooding areas with large organic carbon stores results in a worst case scenario for long term MeHg contamination

■

An aerial photograph of a large reservoir with several forested islands and a central landmass. The water is a deep blue, and the surrounding land is covered in dense green forest. A dirt road or path is visible on the central landmass. The text is overlaid on the image in white.

Minimizing carbon flooded
minimized the *duration* of MeHg
production in reservoirs

Contested Muskrat Falls methylmercury recommendation could cost \$742M



Environment minister says government reviewing report from committee established after hunger strikes



Daniel MacEachern · CBC News · Posted: Apr 11, 2018 1:15 PM NT | Last Updated: April 11



Not just mass budgets...

Methyl mercury in pristine and impounded boreal peatlands, Experimental Lakes Area, Ontario¹

A. Heyes, T.R. Moore, J.W.M. Rudd, and J.J. Dugoua

The hydrology and methylmercury dynamics of a Precambrian Shield headwater peatland

Brian A. Branfireun,¹ Andrew Heyes, and Nigel T. Roulet¹

Production and Loss of Methylmercury and Loss of Total Mercury from Boreal Forest Catchments Containing Different Types of Wetlands[†]

VINCENT L. ST. LOUIS,^{*,‡}
JOHN W. M. RUDD,[§]
CAROL A. KELLY,[‡] KEN G. BEATY,[§]
ROBERT J. FLETT,^{||} AND
NIGEL T. ROULET[†]

FOOD AS THE DOMINANT PATHWAY OF METHYLMERCURY UPTAKE BY FISH*

B. D. HALL¹, R. A. BODALY², R. J. P. FUDGE², J. W. M. RUDD² and
D. M. ROSENBERG²

Photodegradation of methylmercury in lakes

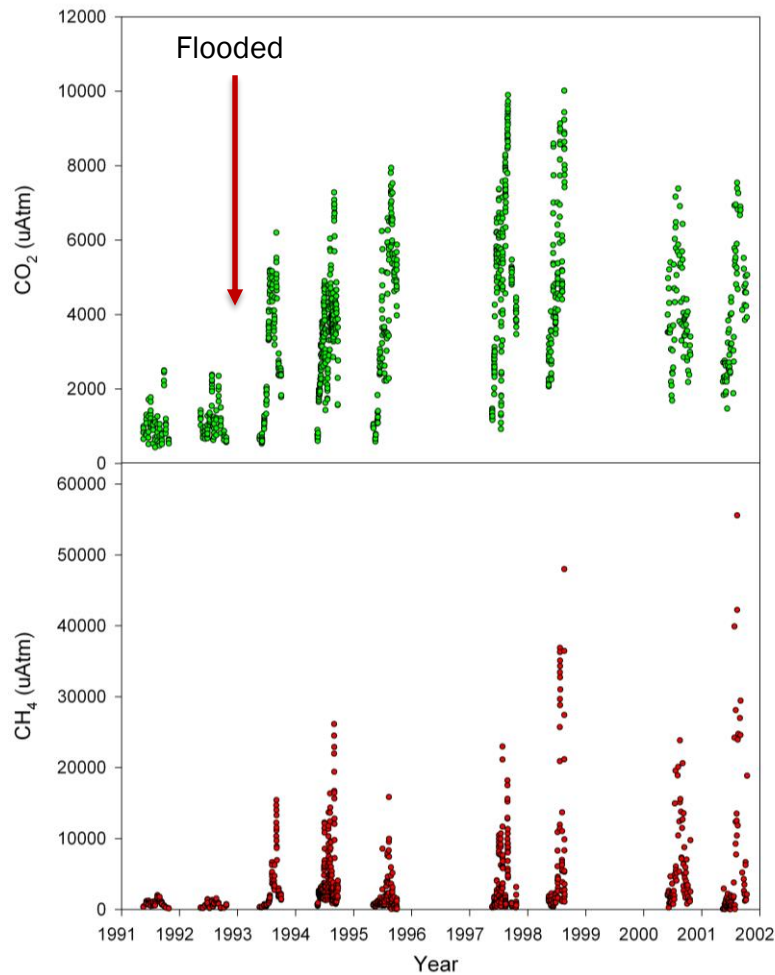
**P. Sellers^{*}, C. A. Kelly^{*}, J. W.M. Rudd[†],
A. R. MacHutchon[†]**

The burning question: Does burning before flooding lower methyl mercury production and bioaccumulation?

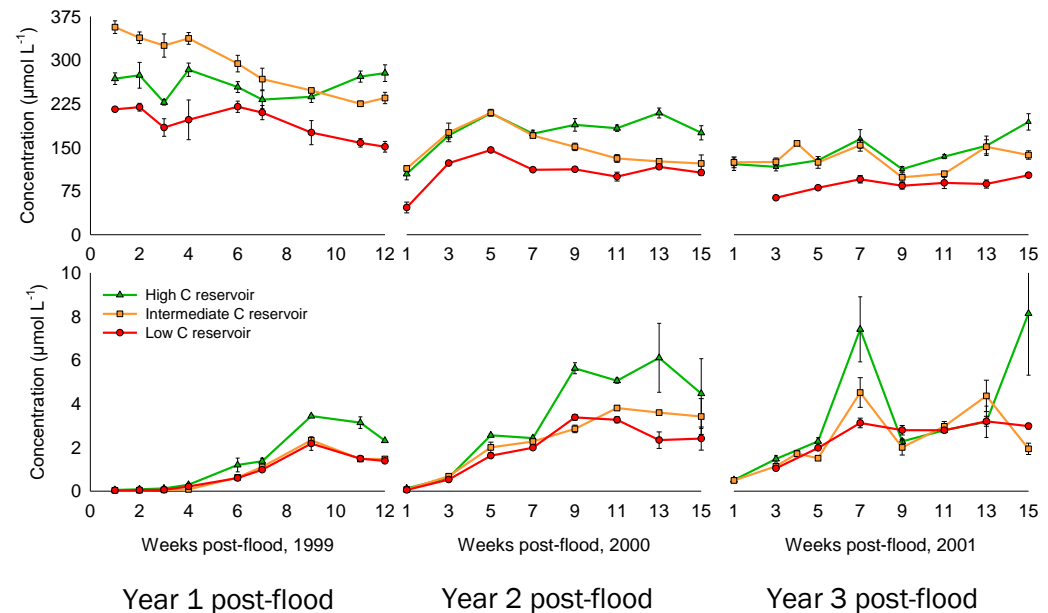
Mariah Mailman^{a,*}, R.A. (Drew) Bodaly^b

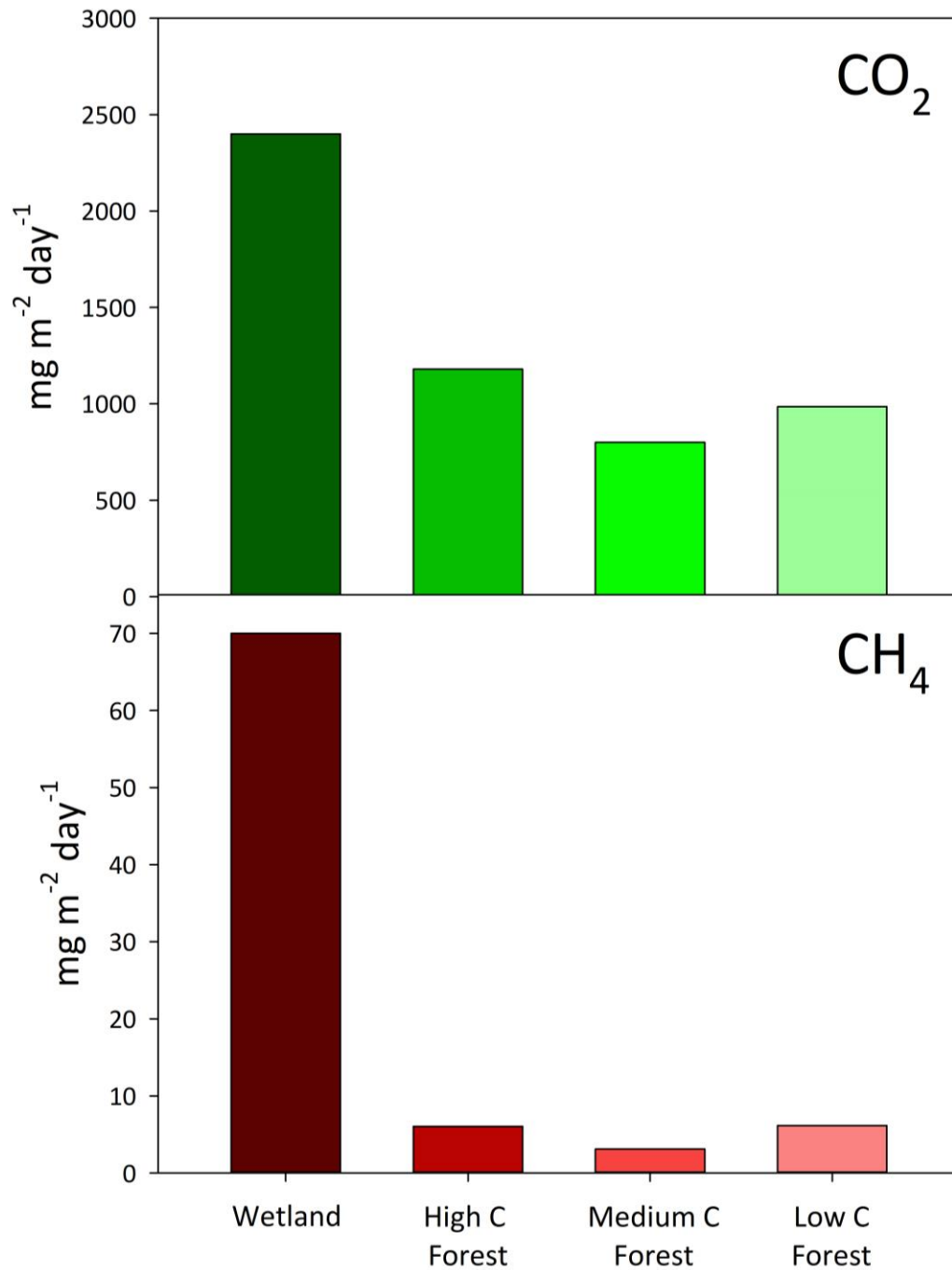
Concentrations of CO₂ and CH₄ in the reservoir water

Experimental Lakes Area Reservoir Project



Flooded Uplands Dynamics Experiment





Average reservoir surface fluxes of CO₂ and CH₄ in first 2-3 years post-flood

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

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



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

Updated estimates of CO₂ and CH₄ emissions from global hydroelectric reservoirs

nature
geoscience

LETTERS

PUBLISHED ONLINE: 31 JULY 2011 | DOI: 10.1038/NGE01211

Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude

Nathan Barros¹, Jonathan J. Cole², Lars J. Tranvik³, Yves T. Prairie⁴, David Bastviken⁵, Vera L. M. Huszar⁶, Paul del Giorgio⁴ and Fábio Roland¹*

Hydroelectric reservoirs cover an area of 3.4×10^5 km² and comprise about 20% of all reservoirs. In addition, they contain large stores of formerly terrestrial organic carbon. Significant amounts of greenhouse gases are emitted², especially in the early years following reservoir creation, but the global extent of these emissions is poorly known. Previous estimates of emissions from all types of reservoir indicate that these human-made systems emit 321 Tg of carbon per year (ref. 4). Here we assess the emissions of carbon dioxide and methane from hydroelectric reservoirs, on the basis of data from 85 globally distributed hydroelectric reservoirs that account for 20% of the global area of these systems. We relate the emissions to reservoir age, location biome, morphometric features and chemical status. We estimate that hydroelectric reservoirs emit about 48 TgC as CO₂ and 3 TgC as CH₄, corresponding to 4% of global carbon emissions from inland waters. Our estimates are smaller than previous estimates on the basis of more limited data. Carbon emissions are correlated to reservoir age and latitude, with the highest emission rates from the tropical Amazon region. We conclude that future emissions will be highly dependent on the geographic location of new hydroelectric reservoirs.

Table 1 | Global estimates of CO₂ and CH₄ emissions from reservoirs and natural lakes.

Systems	Area ($\times 10^5$ km ²)	Carbon emission ($\times 10^{12}$ g yr ⁻¹)			
		C-CO ₂	C-CH ₄	Total C	CO ₂ equivalents
	Age gradient				
Younger than 20 years	0.3	11	0.7	12	62
Older than 20 years	3.1	38	2.9	41	234
	Latitudinal gradient				
Boreal	0.8	6	0.2	7	31
Temperate	1.3	5	0.1	5	24
Tropical	1.2	37	3.0	40	233
Tropical—Amazonian	0.2	8	1.0	9	63
Tropical—non-Amazonian	1.0	25	1.5	27	143
	Global scenario				
Human-made fresh waters*	15	273	48	321	2,600
Hydroelectric reservoirs	3.4	48	3	51	288
Natural lakes	42	530 [†]	54 [‡]	584	3,743
	Hydroelectric reservoir emissions/total human-made freshwater emissions (%)	18	7	16	11
	Hydroelectric reservoir emissions/total natural lake emissions (%)	9	6	9	8

The areas of reservoirs and natural lakes, and the carbon fluxes of both C-CO₂ and C-CH₄, were used to calculate carbon emissions as C-CO₂, C-CH₄, total C and CO₂-equivalent emissions by hydroelectric reservoirs. For comparison, estimates of global emissions from natural lakes were included. The CO₂ equivalent was calculated as the data for CO₂ plus the CH₄ data multiplied by 25 according to IPCC (ref. 18), on the basis of the CH₄ global warming potential (see Methods). All data used to produce these estimates are available in Supplementary Information. *Data from ref. 4 (updated data using the factor of 25 according to IPCC (ref. 18)). [†]Data from ref. 20. [‡]Data from ref. 22.

Greenhouse gas emissions from reservoirs continues to be a hot topic of research!

Ecosystems (2018) 21: 1058–1071
DOI: 10.1007/s10021-017-0198-9



Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See?

Yves T. Prairie,^{1*} Jukka Alm,² Jake Beaulieu,³ Nathan Barros,⁴ Tom Battin,⁵ Jonathan Cole,⁶ Paul del Giorgio,⁷ Tonya DelSontro,⁷ Frédéric Guérin,⁸ Atle Harby,⁹ John Harrison,¹⁰ Sara Mercier-Blais,¹ Dominique Serça,¹¹ Sebastian Sobek,¹² and Dominic Vachon¹³

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ABSTRACT

Freshwater reservoirs are a known source of greenhouse gas (GHG) to the atmosphere, but their quantitative significance is still only loosely constrained. Although part of this uncertainty can be attributed to the difficulties in measuring highly variable fluxes, it is also the result of a lack of a clear accounting methodology, particularly about what constitutes new emissions and potential new sinks. In this paper, we review the main processes involved in the generation of GHG in reservoir systems and propose a simple approach to quantify the reservoir GHG footprint in terms of the net changes in GHG fluxes to the atmosphere induced

by damming, that is, 'what the atmosphere sees.' The approach takes into account the pre-impoundment GHG balance of the landscape, the temporal evolution of reservoir GHG emission profile as well as the natural emissions that are displaced to or away from the reservoir site resulting from hydrological and other changes. It also clarifies the portion of the reservoir carbon burial that can potentially be considered an offset to GHG emissions.

Key words: GHG footprint; reservoirs; CO₂ and CH₄ emissions; C burial.

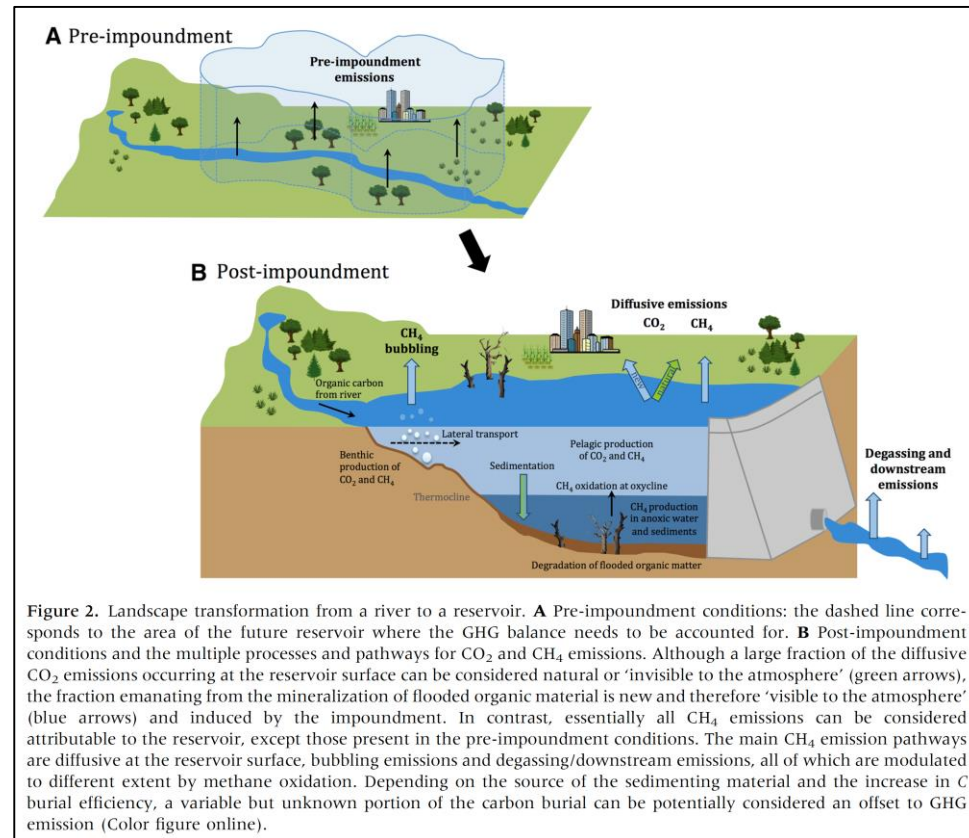


Figure 2. Landscape transformation from a river to a reservoir. **A** Pre-impoundment conditions: the dashed line corresponds to the area of the future reservoir where the GHG balance needs to be accounted for. **B** Post-impoundment conditions and the multiple processes and pathways for CO₂ and CH₄ emissions. Although a large fraction of the diffusive CO₂ emissions occurring at the reservoir surface can be considered natural or 'invisible to the atmosphere' (green arrows), the fraction emanating from the mineralization of flooded organic material is new and therefore 'visible to the atmosphere' (blue arrows) and induced by the impoundment. In contrast, essentially all CH₄ emissions can be considered attributable to the reservoir, except those present in the pre-impoundment conditions. The main CH₄ emission pathways are diffusive at the reservoir surface, bubbling emissions and degassing/downstream emissions, all of which are modulated to different extent by methane oxidation. Depending on the source of the sedimenting material and the increase in C burial efficiency, a variable but unknown portion of the carbon burial can be potentially considered an offset to GHG emission (Color figure online).

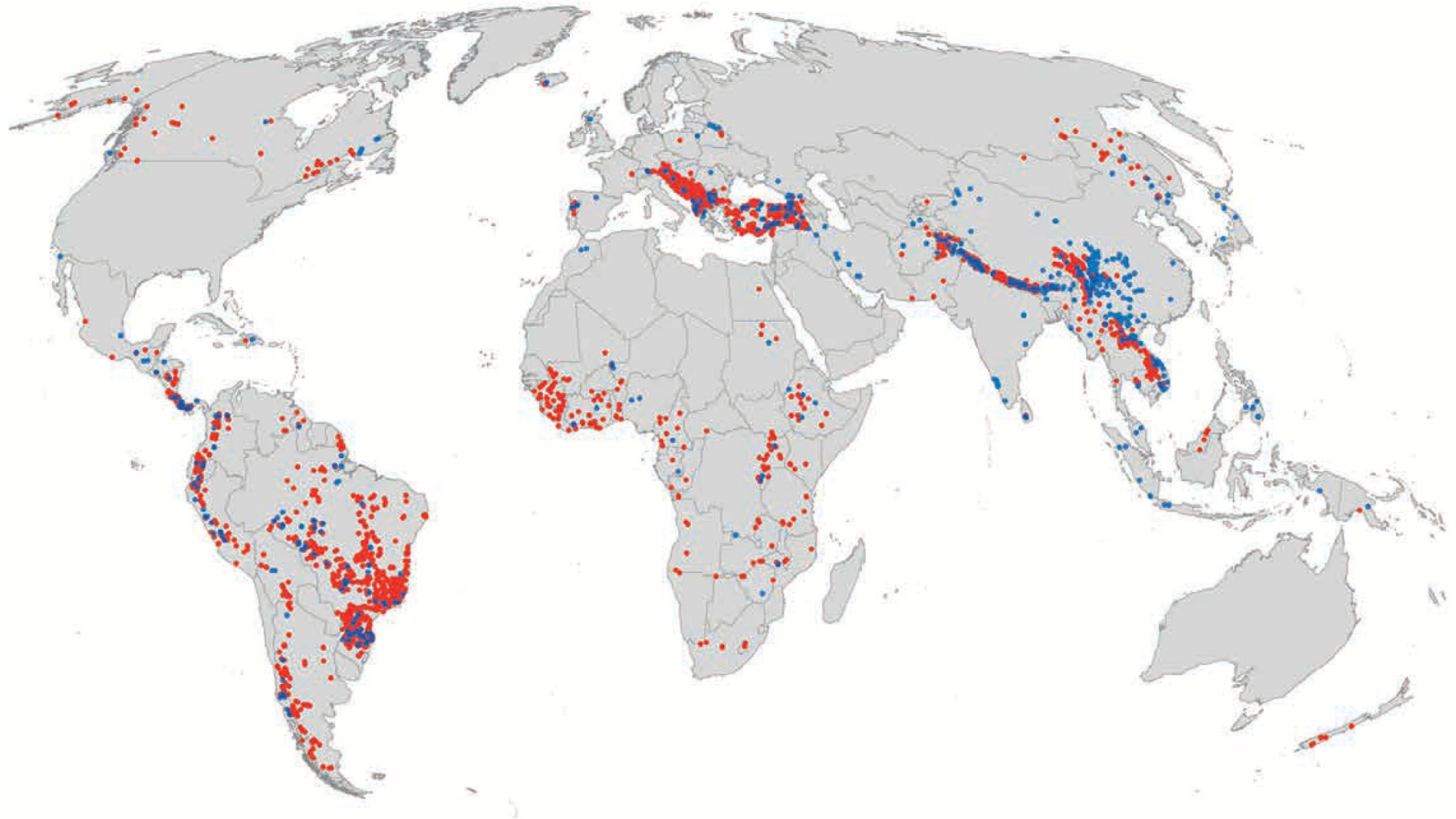


Figure 16: Global distribution of future hydropower dams either planned (red dots, 83 per cent) or under construction (blue dots, 17 per cent) (Zarfl et al., 2015).

Key



Dams under construction



Dams planned

CONCLUSIONS

Using unique whole-ecosystem experimentation at the Experimental Lakes Area, we were able to conclude:

- Flooding landscapes increases net greenhouse gas (CO_2 and CH_4) emissions and methylmercury production
- Flooding less amounts of organic carbon lessens the intensity of these impacts
- The duration of these impacts post-flooding depends on the amount of organic carbon flooded
- Hydroelectric reservoirs are net sources of greenhouse gases to the atmosphere

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