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

Collaborative team: John Rudd, Carol Kelly, Drew Bodaly, Sherry Schiff, Ken Beaty, Nigel Roulet, Grant Edwards, Cory Matthews, Elizabeth Joyce, Jason Venkiteswaran, Nathalie Boudreau, Kris Rolfus, Jim Hurley, Reed Harris

What got it all started!

Wetland ponds in the Hudson Bay Lowlands were sources of the greenhouse gases CO_2 and CH_4 to the atmosphere.

If you flooded landscapes to create reservoirs for hydroelectricity production, would they also be were sources of CO_2 and CH_4 to the atmosphere.

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Flux to the atmosphere of CH_4 and CO_2 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 CH_4 and CO_2 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 CH_4 and CO_2 to the atmosphere at mean rates of 110 -180 mg CH_4 m^{-2} d^{-1} and 3700-11,000 mg CO_2 m^{-2} d^{-1}. Rates peaked in August and September. For CH_4 the pond fluxes were 3-30 times higher than adjacent vegetated surfaces. For CO_2 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 CH_4 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 N_2 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 (CH_4) and carbon dioxide (CO_2) 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 CO_2 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, CH_4 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 CH_4 to the atmosphere [e.g., *Aselmann and Crutzen*, 1989; *Fung et al.*, 1991]. Flux of CO_2 between the wetlands and the atmosphere is poorly understood. To improve the understanding of CH_4 and CO_2 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 CH_4 and CO_2 from the wetland ponds on the HBL to the atmosphere.

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

While CH_4 flux from the vegetated surfaces of wetlands has been studied quite extensively, there are few reports of CH_4 flux from wetland ponds. Reported CH_4 fluxes for wetland ponds range from 21 to 74 mg CH_4 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, CO_2 fluxes from wetland ponds have been studied only once. *Kling et al.* [1991] reported fluxes for Alaskan tundra ponds ranging from -242 mg CO_2 m^{-2} d^{-1} to 2630 mg CO_2 m^{-2} d^{-1}.

The main objective of this work was to measure the flux of CH_4 and CO_2 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 m^2 to 42,000 m^2 (Table 1) were chosen at three sites on a linear transect of the HBL beginning near the coast of James Bay and ending at Kinosheo 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 CH_4 and CO_2.

We found that the ponds behaved quite differently than the vegetated surfaces. CH_4 fluxes to the atmosphere were generally much higher from the ponds than from the vegetated surfaces. CO_2 fluxes from the ponds were almost always at least 10 times greater than CH_4 fluxes and were almost always to the

Synopsis

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 g CH_4 m^{-2} 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, 450–1800 gCO_2 m^{-2} yr^{-1}, 15–30 gCH_4m^{-2} 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).

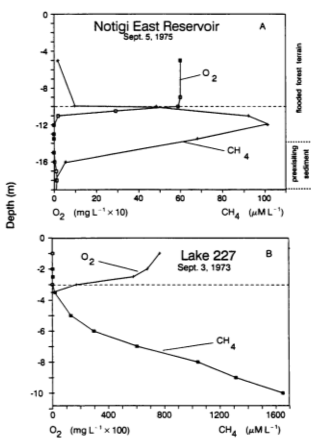
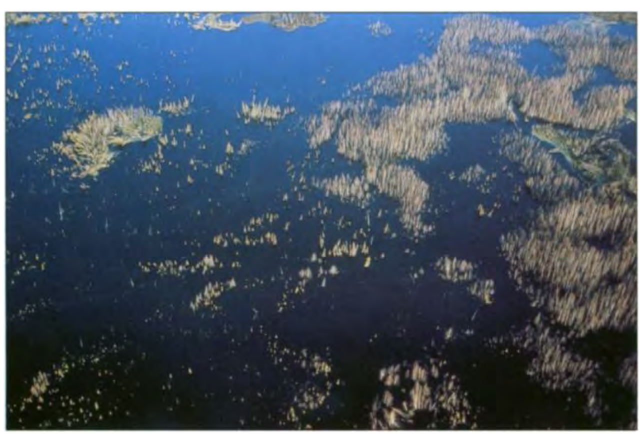


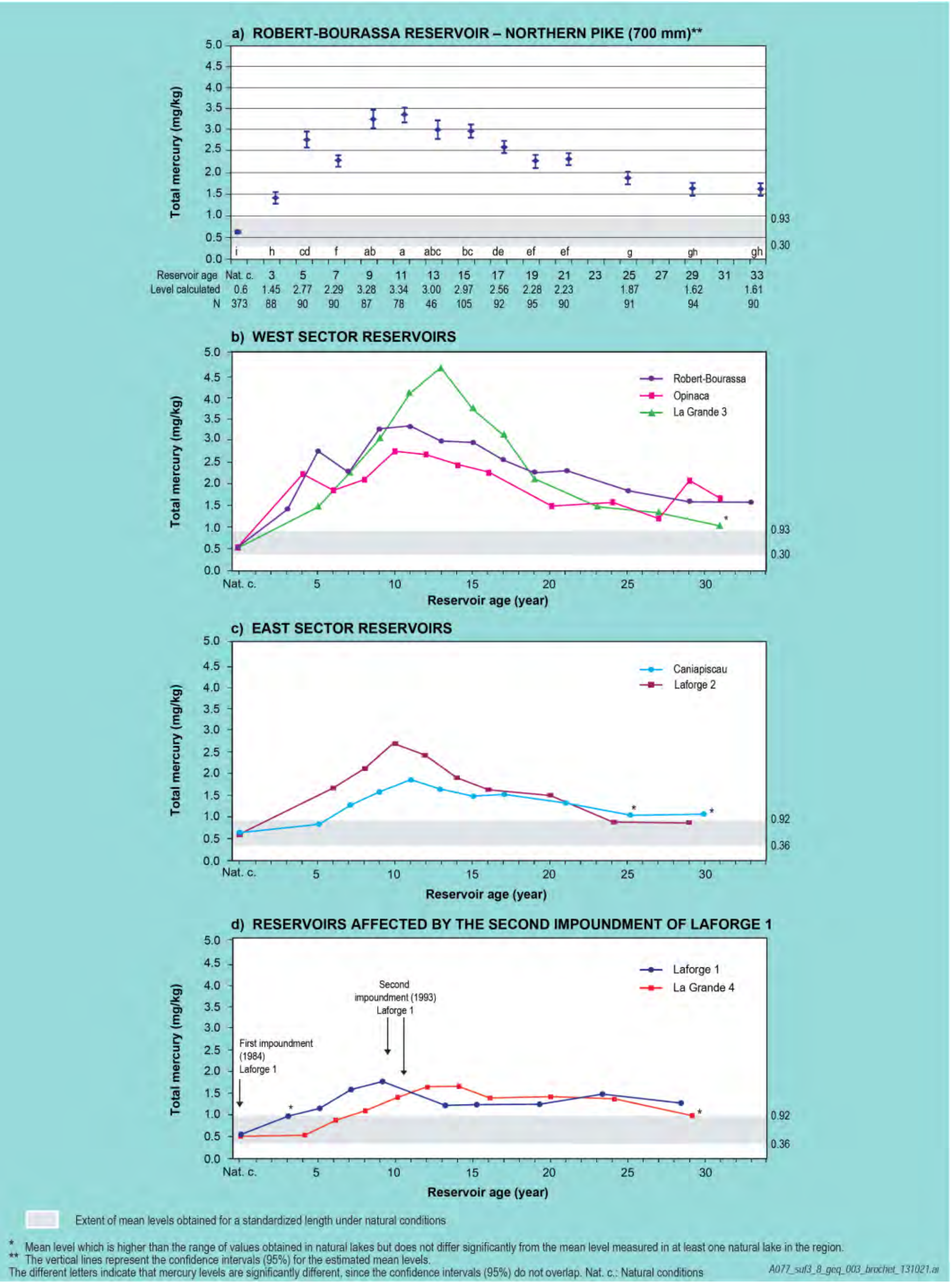
Figure 1. Depth profiles of O_2 and CH_4 concentrations in a) the Notigi Reservoir (northern Manitoba), and in b) Lake 227 at the Experimental Lakes Area, northwestern Ontario. The dashed horizontal lines represent the depth of the mixed layer.



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.

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

Bernhard Lehner[1*], Catherine Reidy Liermann[2], Carmen Revenga[3], Charles Vörösmarty[4], Balazs Fekete[4], Philippe Crouzet[5], Petra Döll[6], Marcel Endejan[7], Karen Frenken[8], Jun Magome[9], Christer Nilsson[10], James C Robertson[3], Raimund Rödel[11], Nikolai Sindorf[12], and Dominik Wisser[13]

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

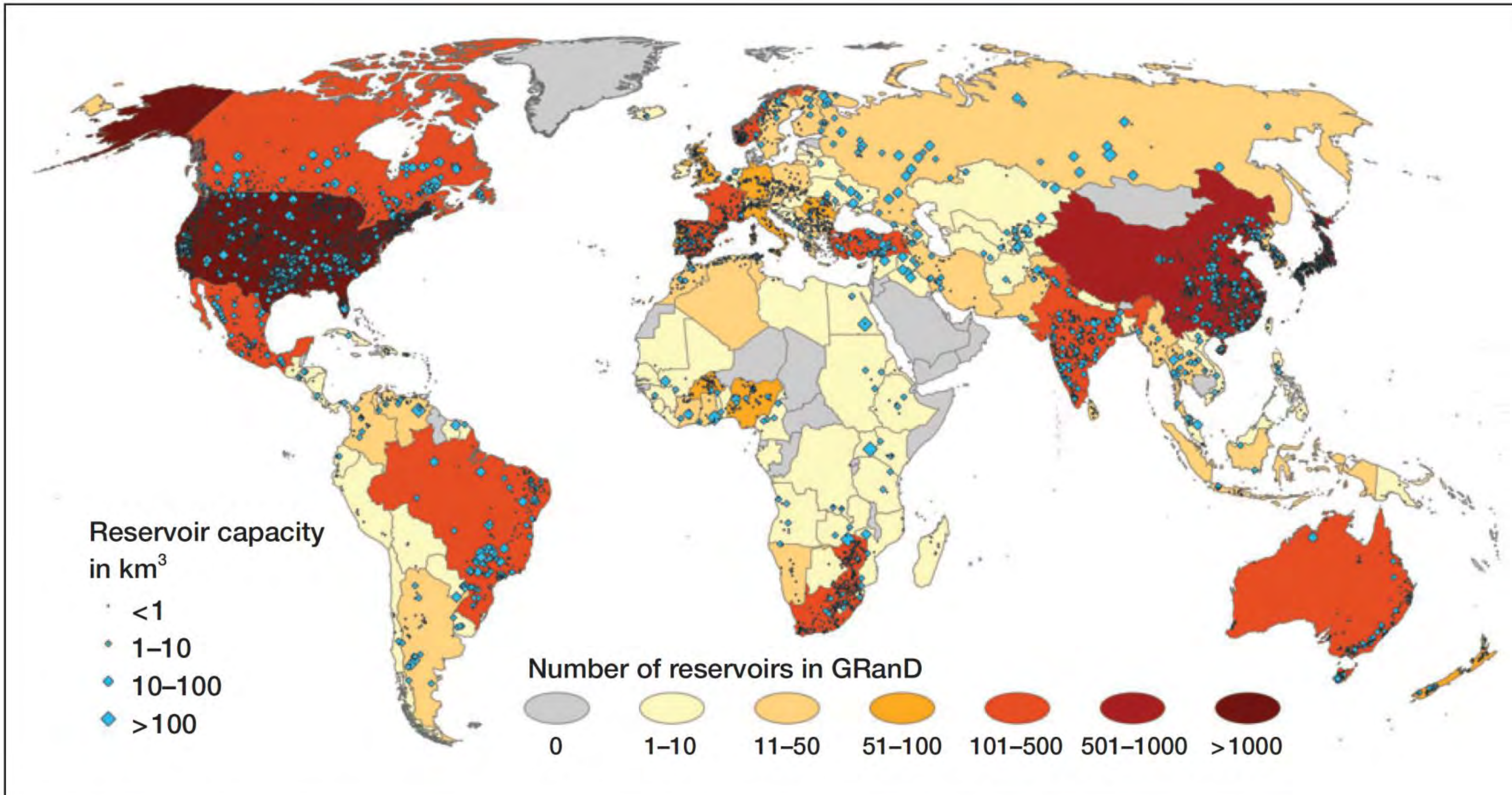
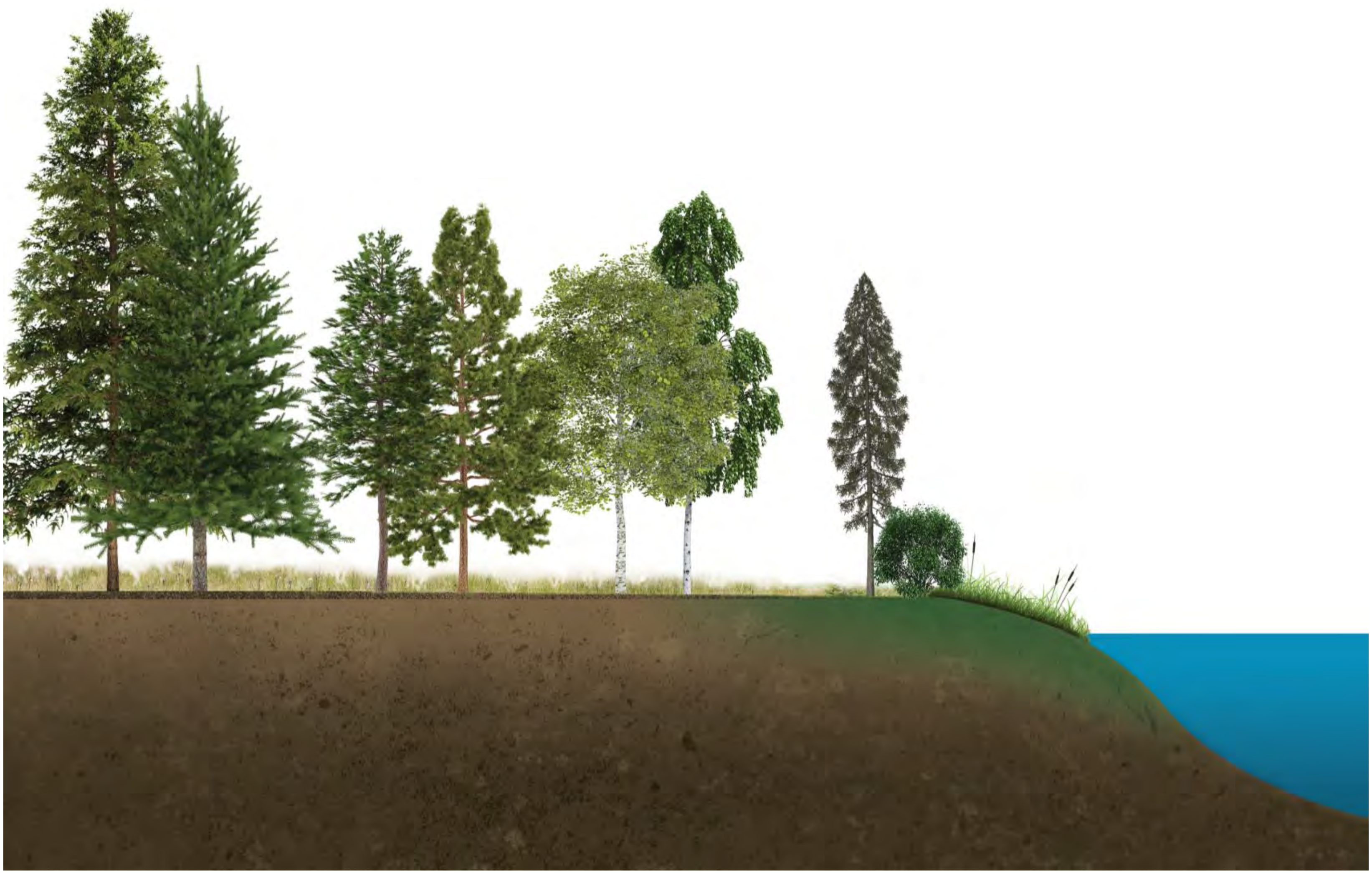


Figure 1. *Global distribution (by country) of large reservoirs included in GRanD.*

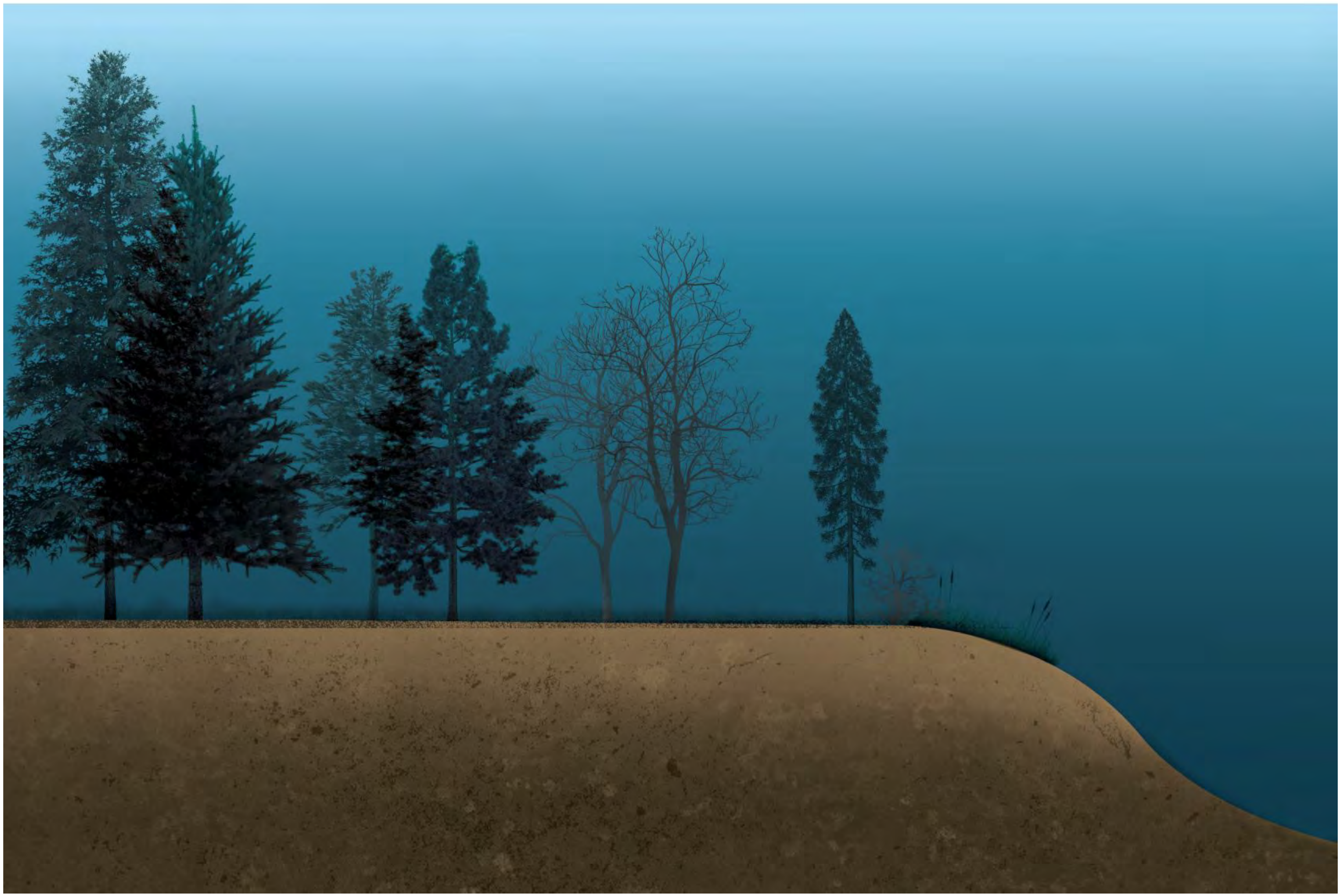
Flooding landscapes changes how they naturally function

ALIVE AND PRODUCTIVE



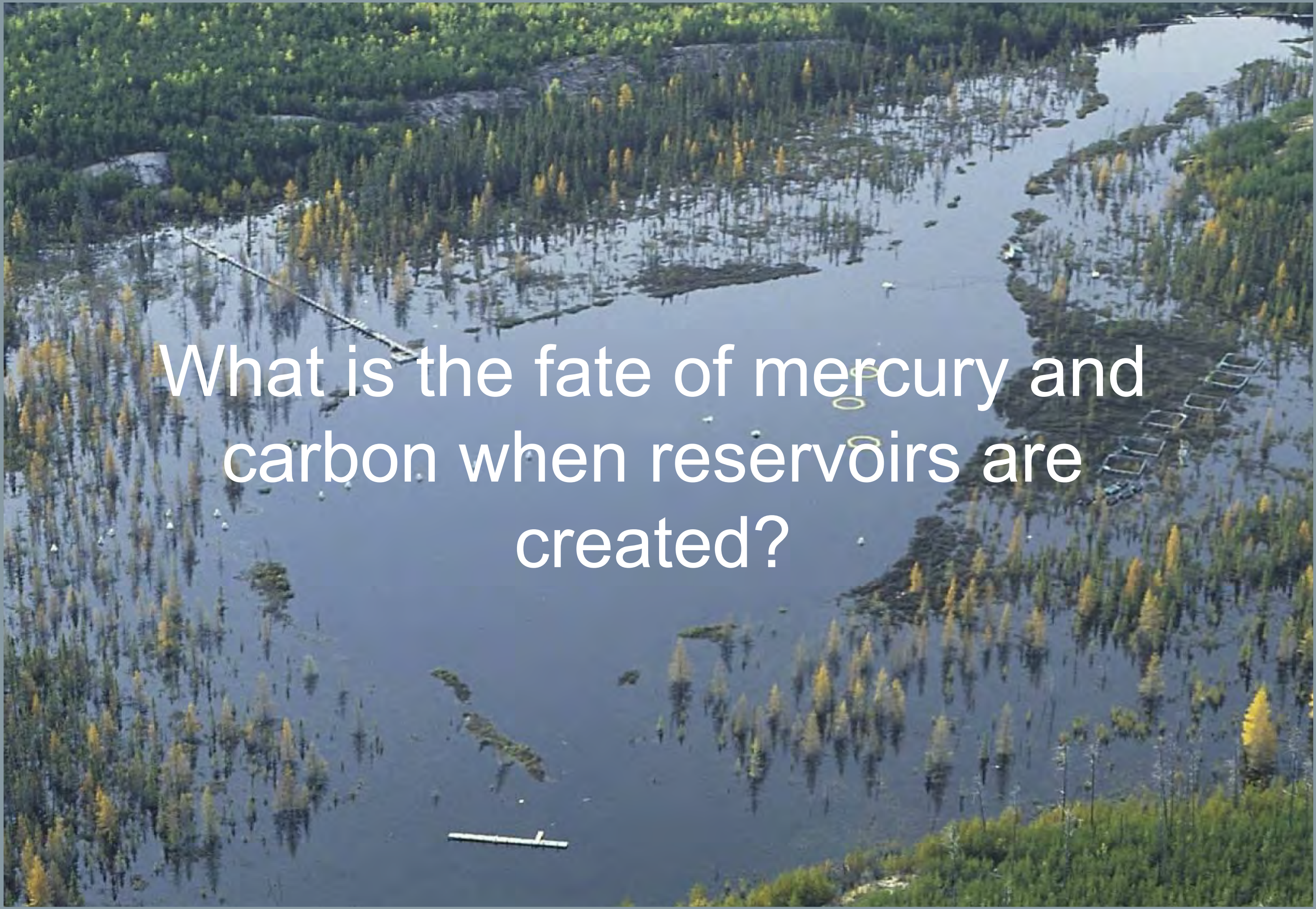
Flooding landscapes changes how they naturally function

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?


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

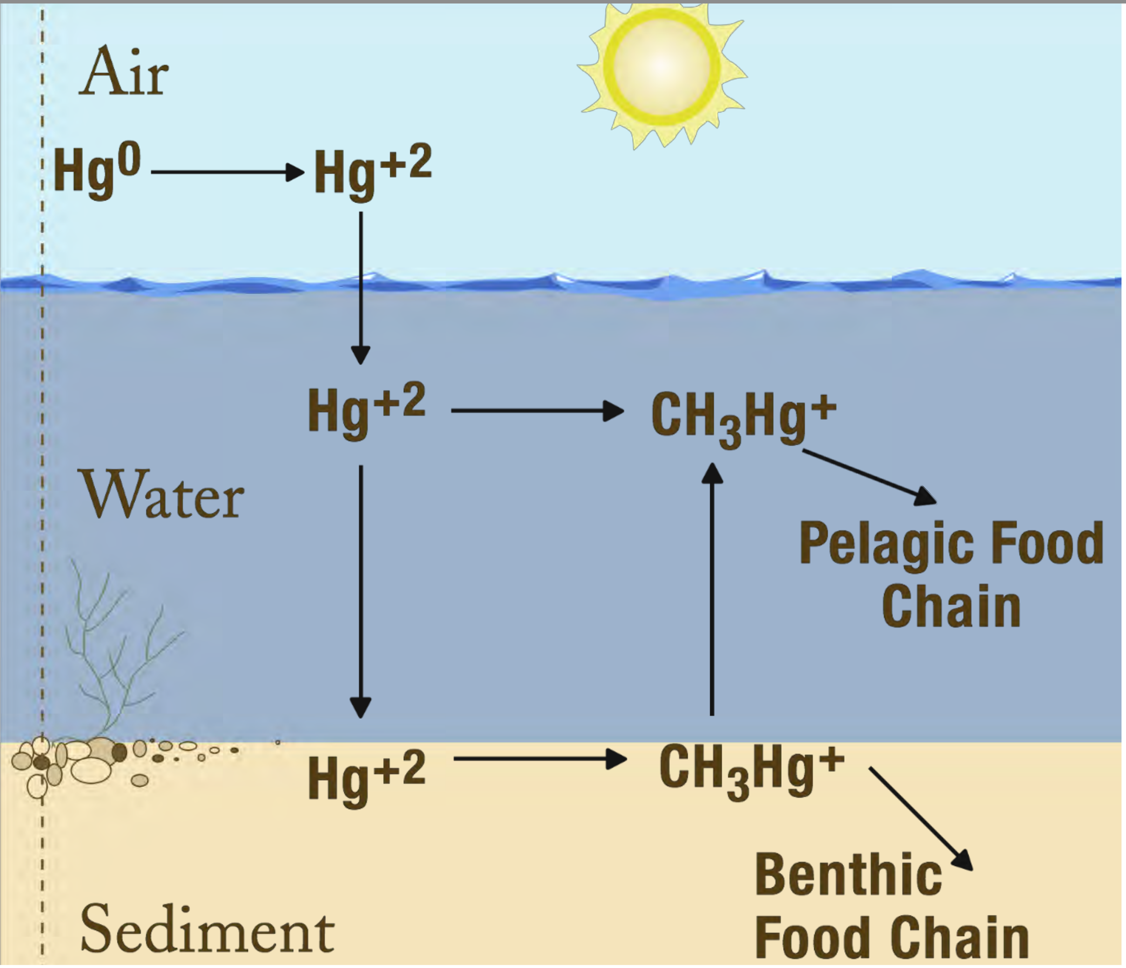
Whole ecosystem manipulations

- 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)

Building the dam at the wetland outflow

Floating peat in the flooded wetland

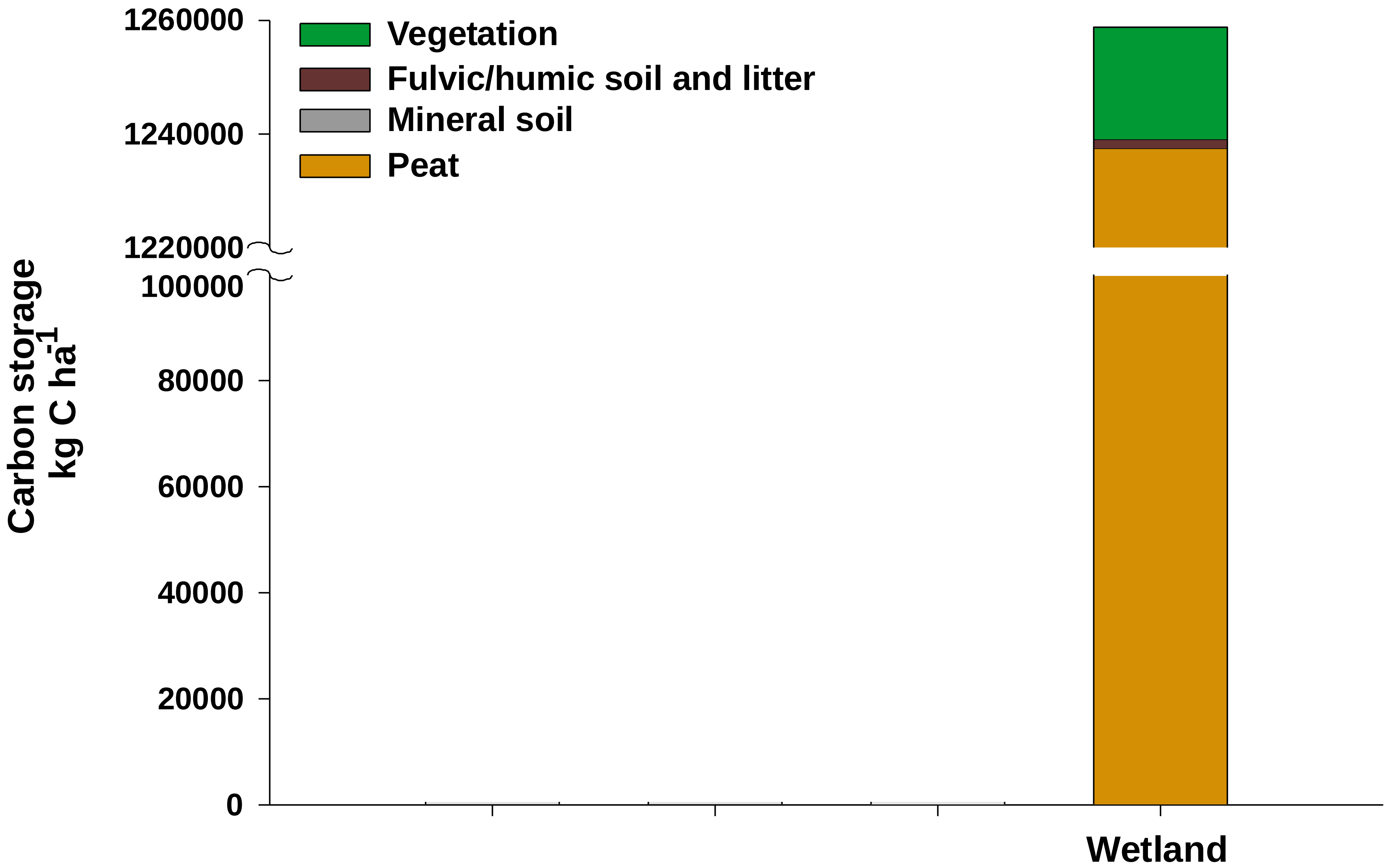

Preflood (1992)


First year of flooding (1993)

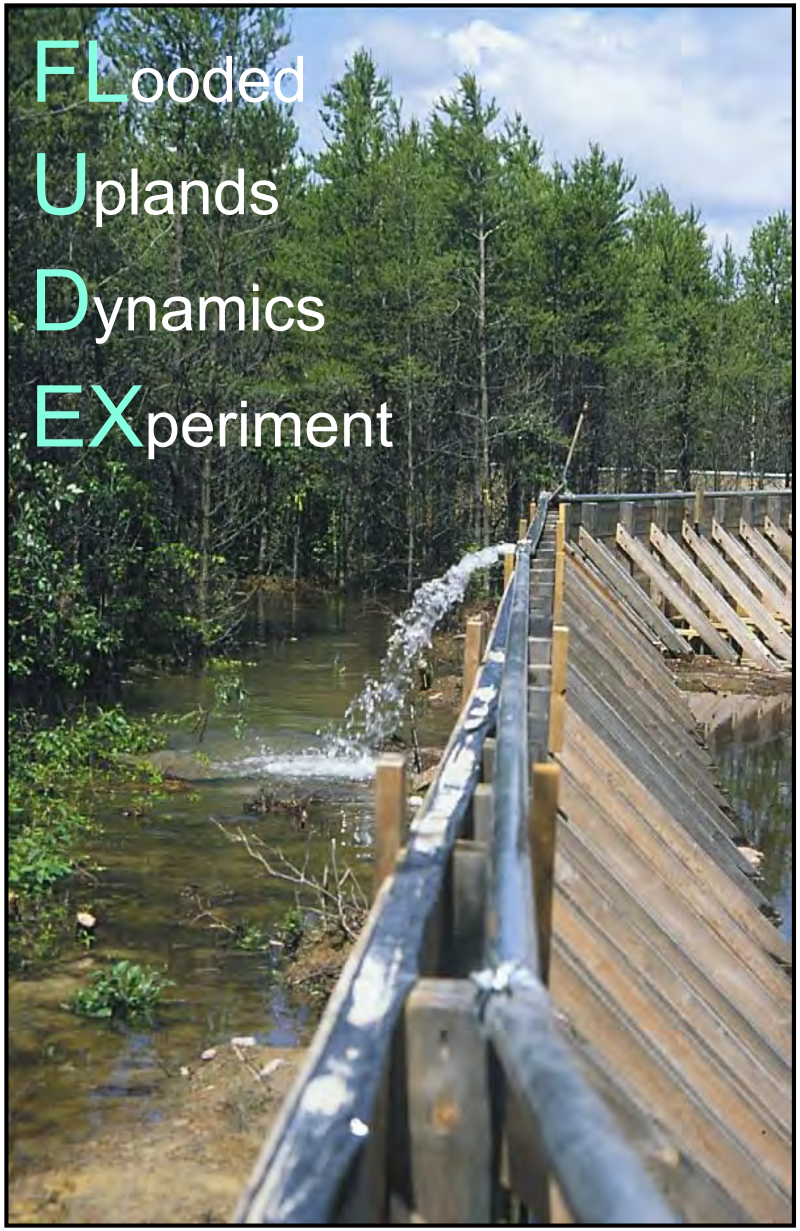

Five years postflood (1997)


Nine years postflood (2001)

Carbon stores in experimental reservoirs

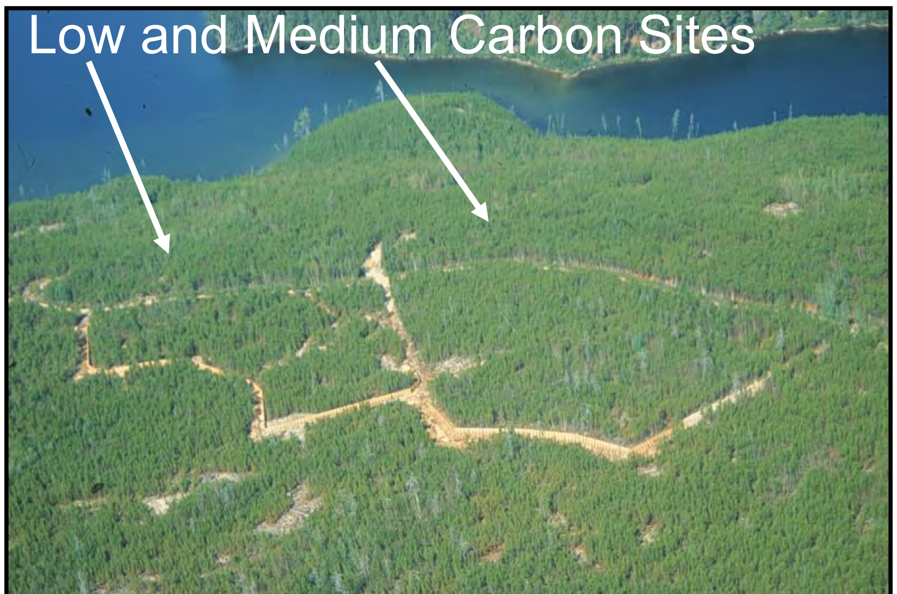


Flooding upland forests



Upland reservoirs

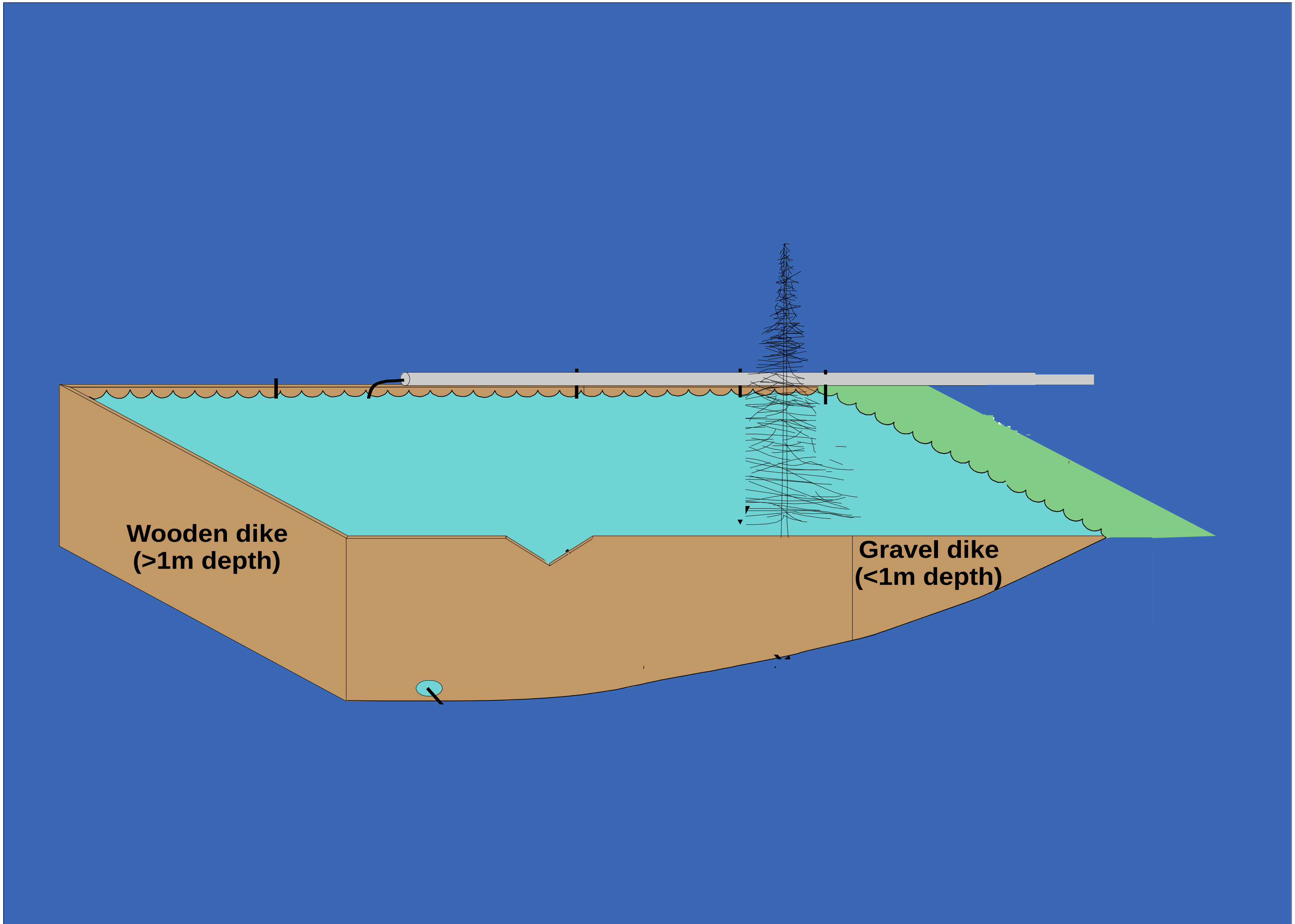
Preflood | **Postflood**



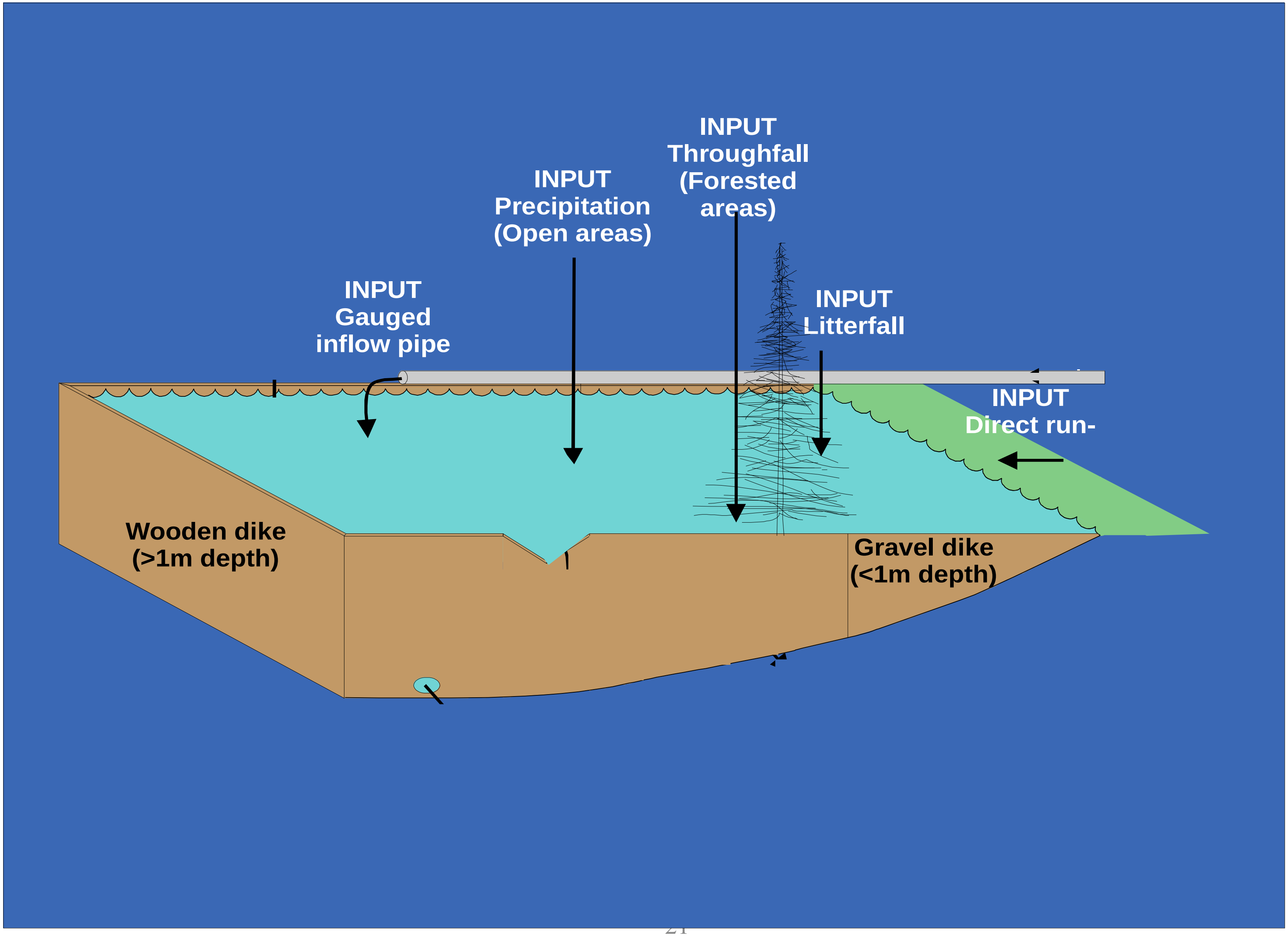
What you need to create a mass budget

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

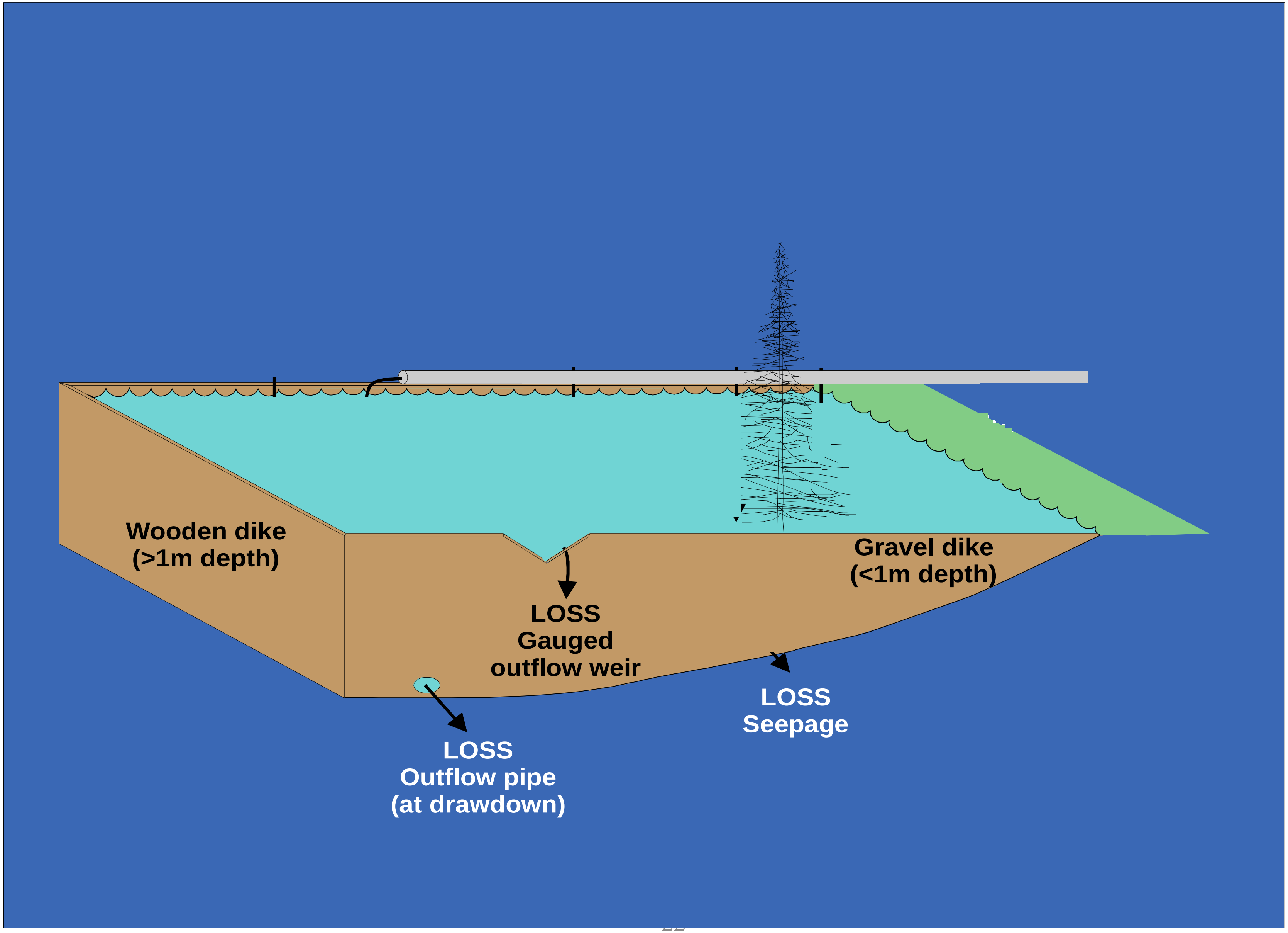
Components of a MeHg budget



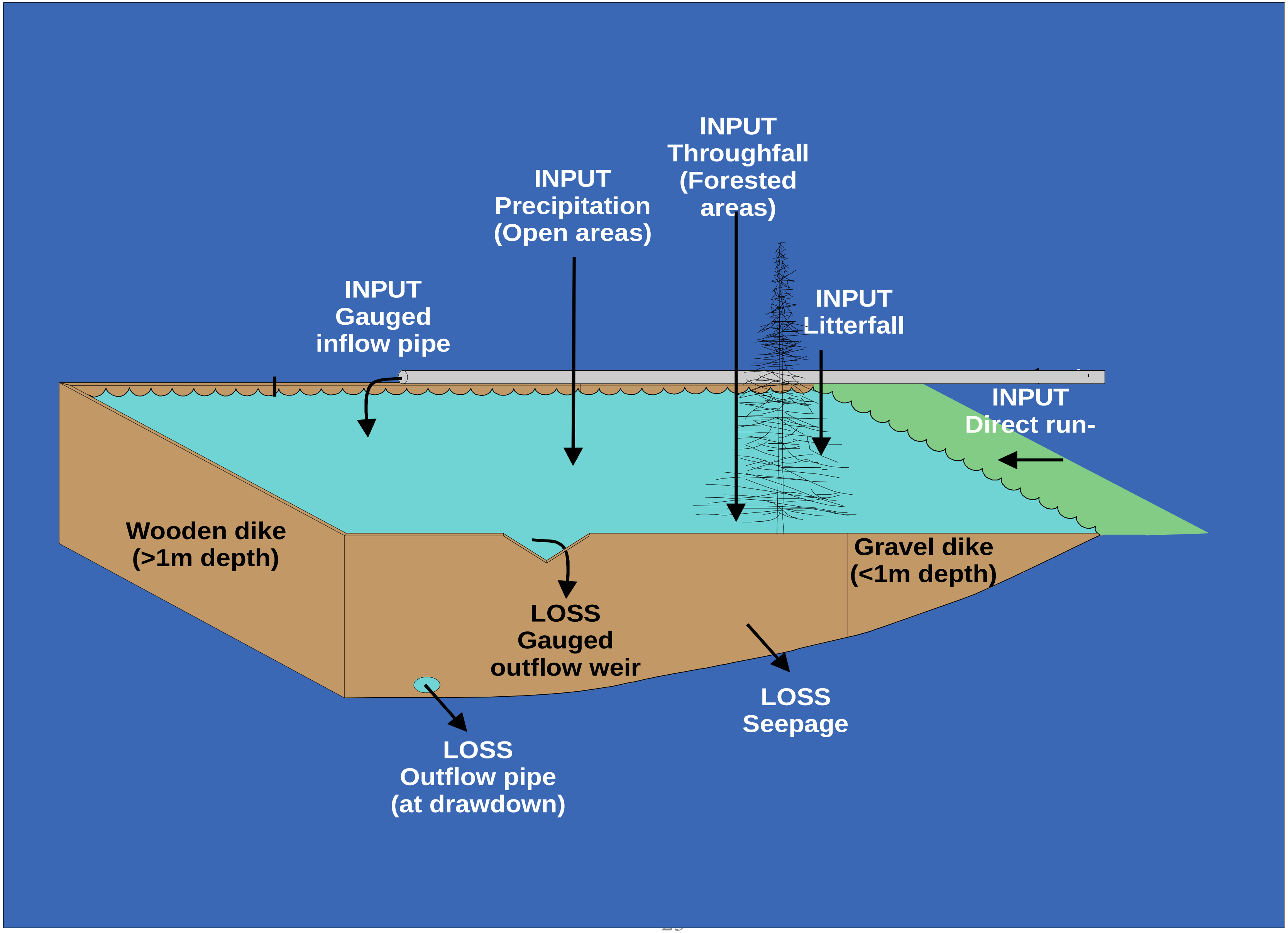
Components of a MeHg budget



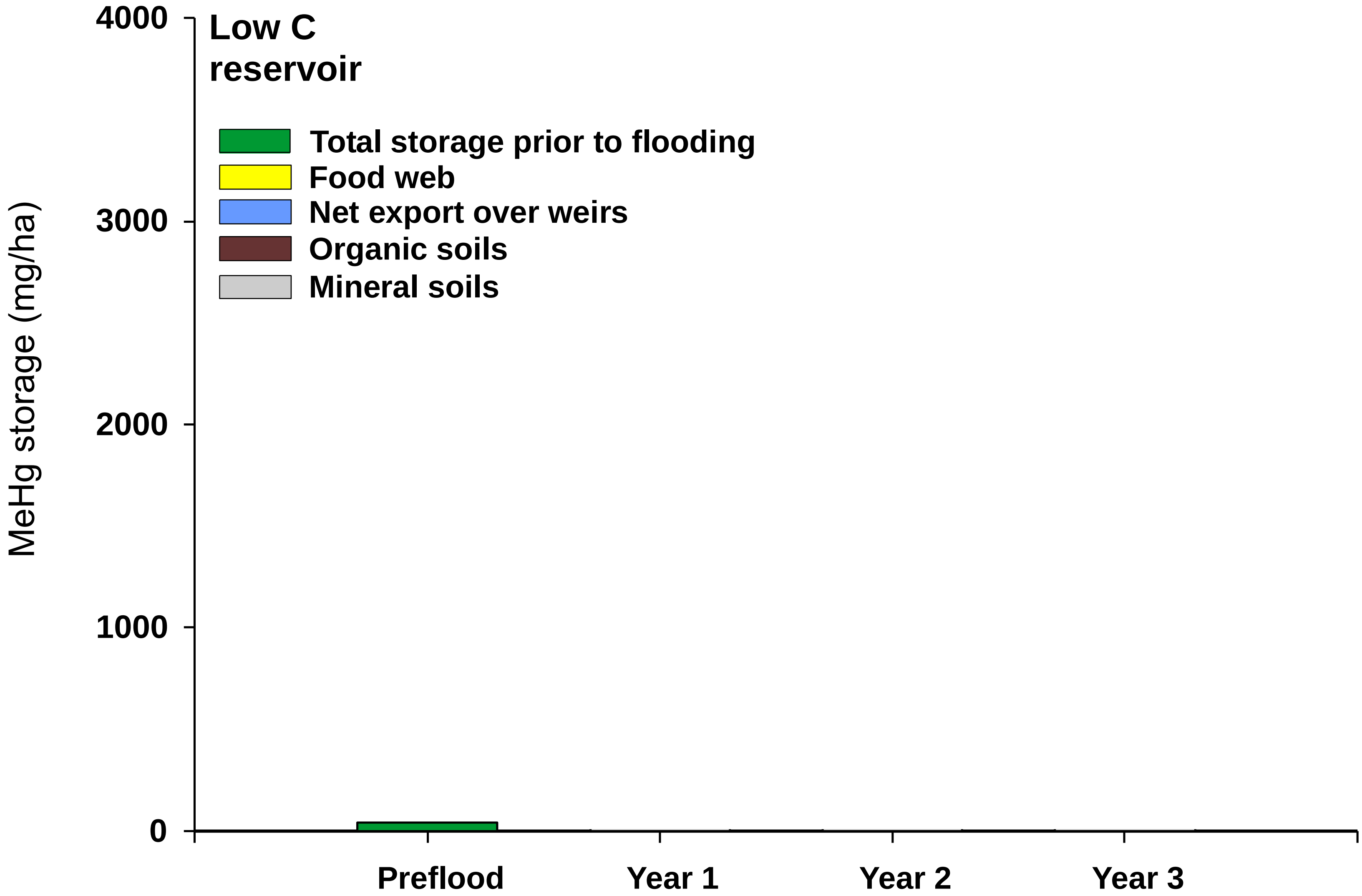
Components of a MeHg budget



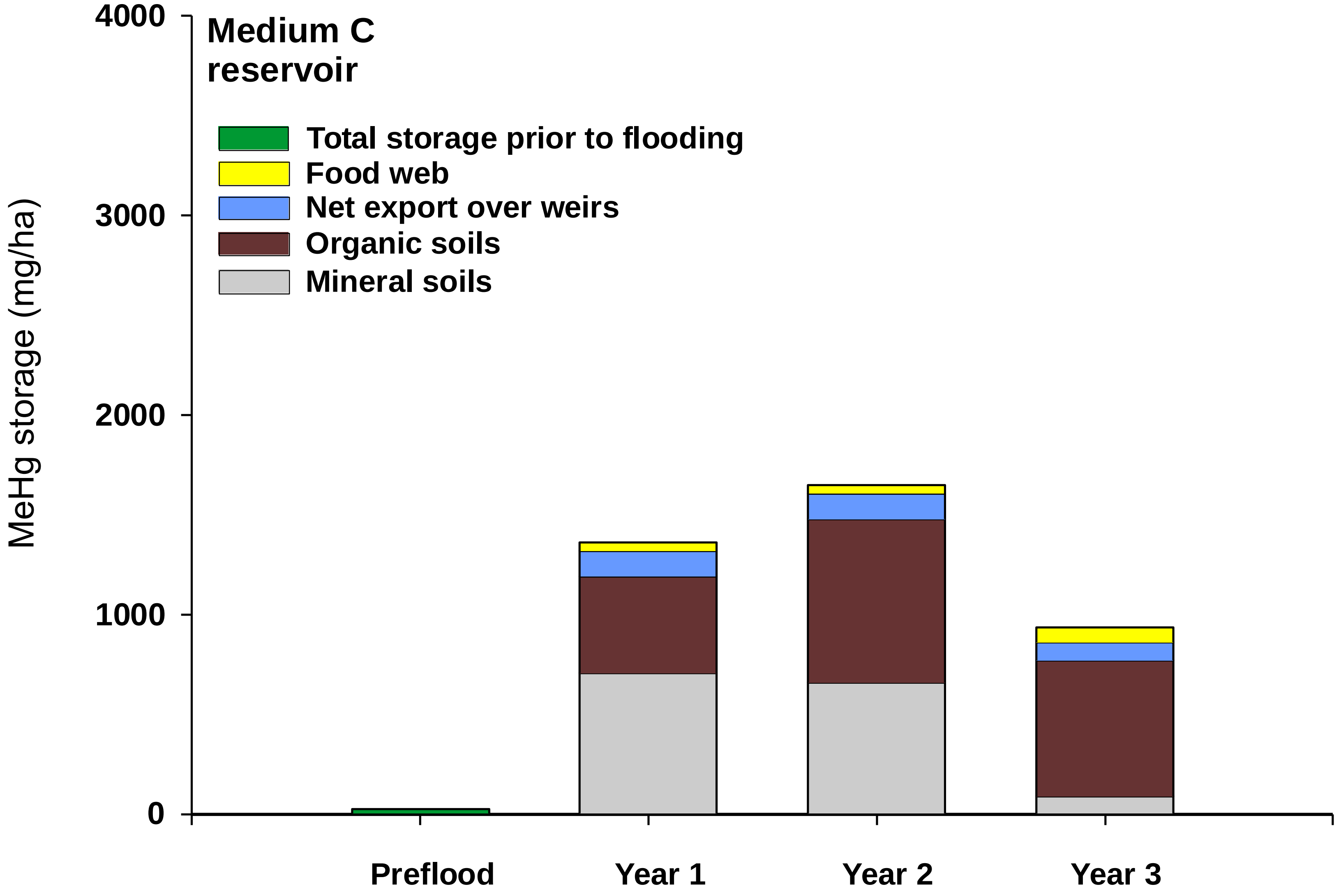
Components of a MeHg budget



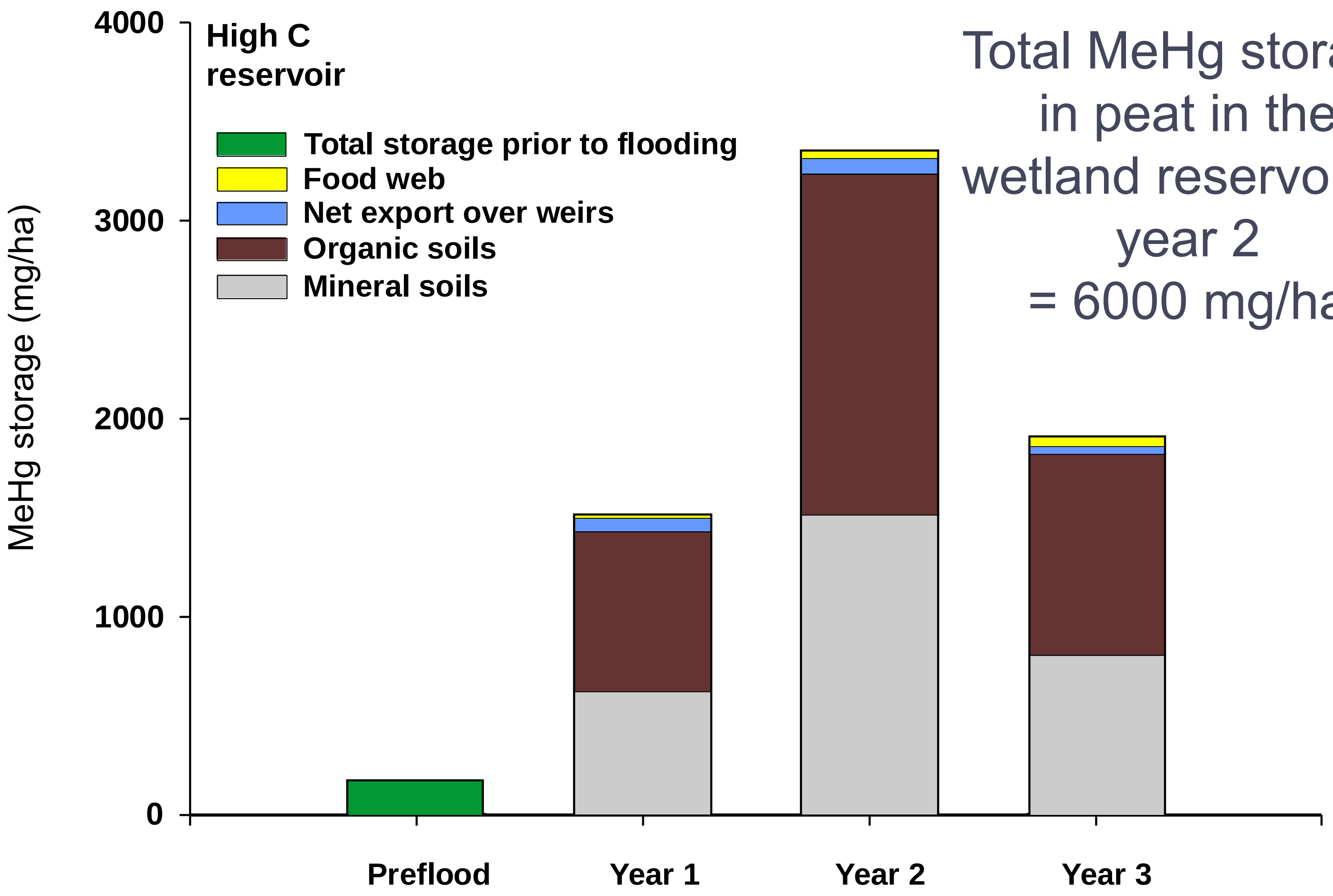
Total MeHg in FLUDEX reservoirs



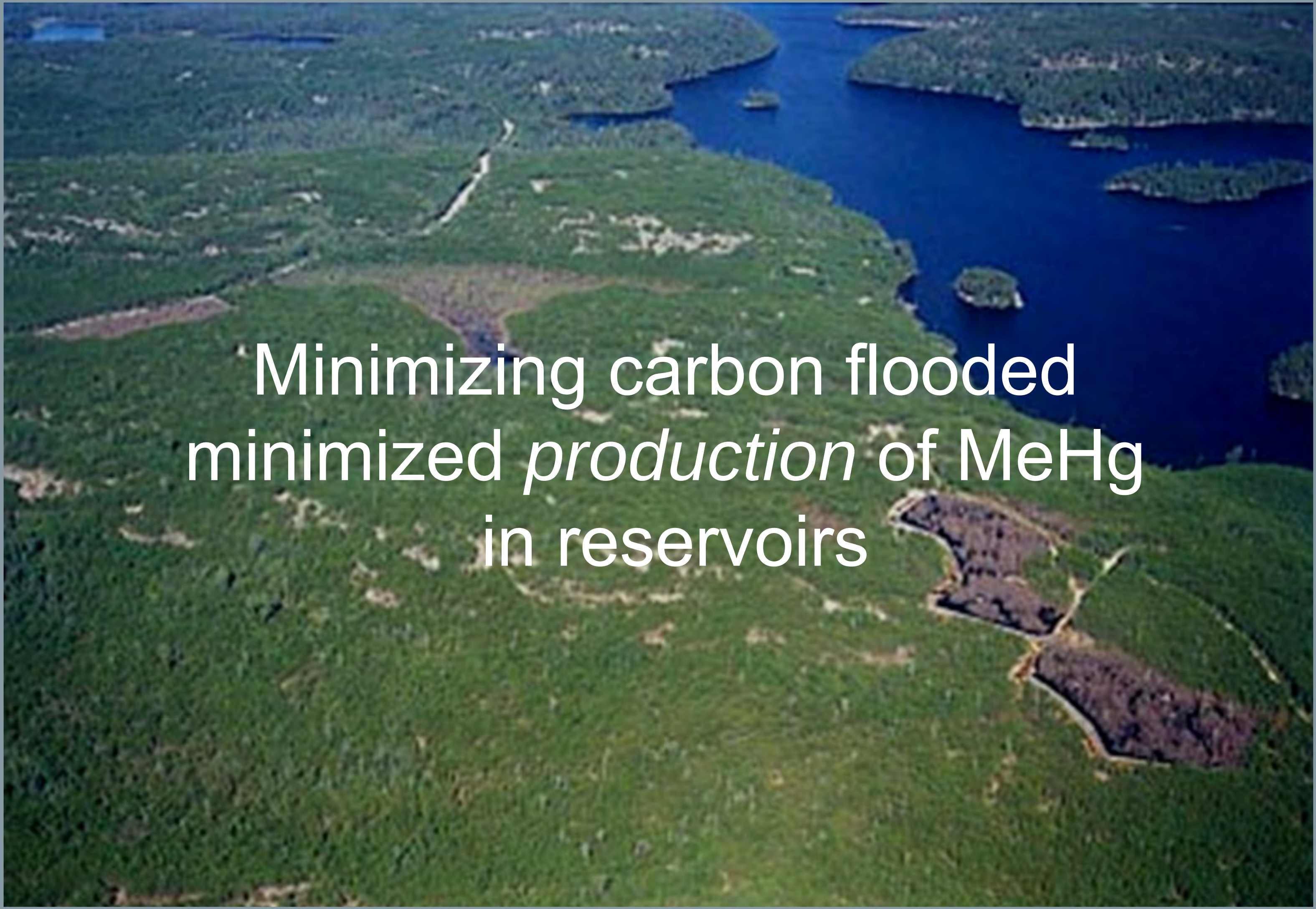
Total MeHg in FLUDEX reservoirs



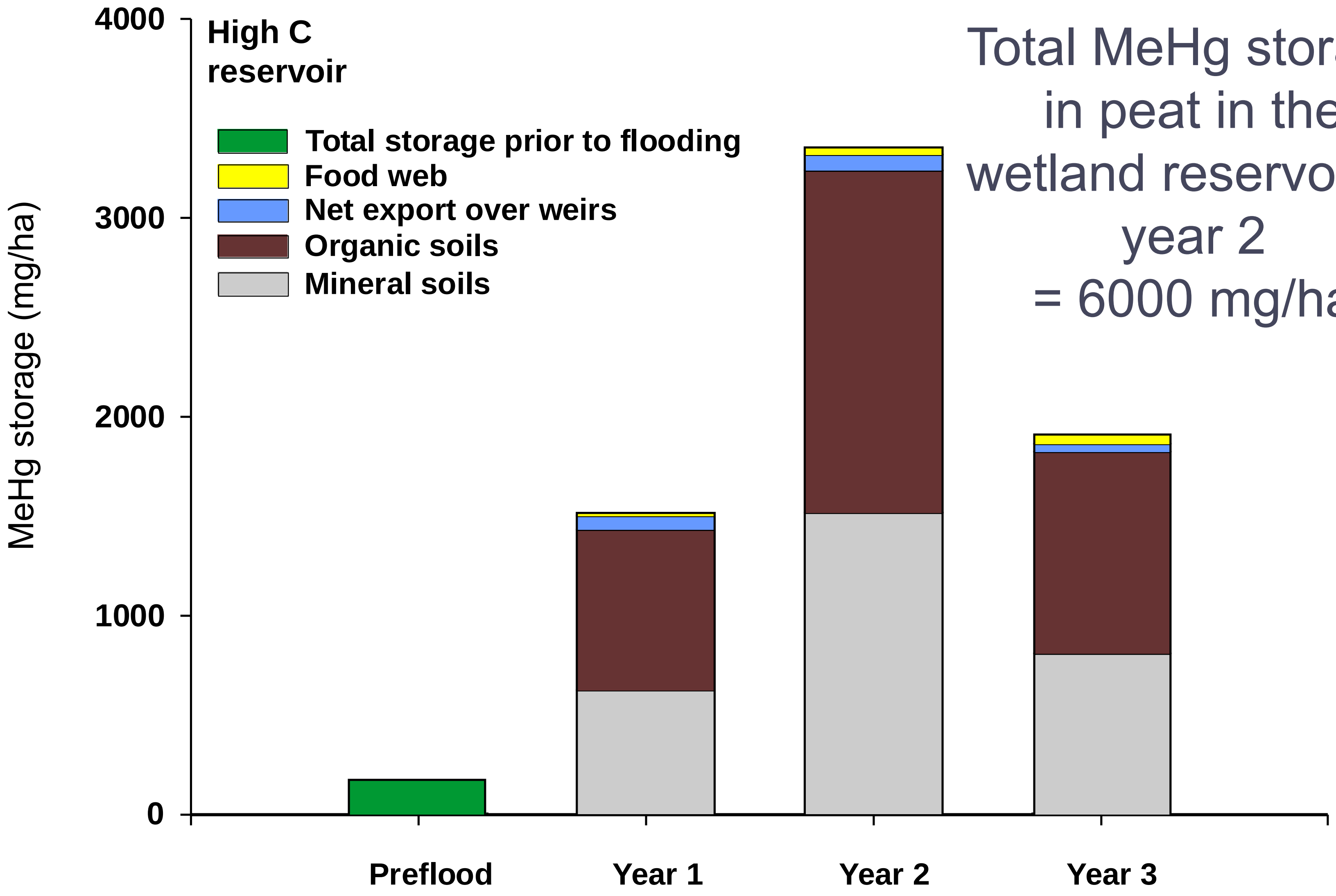
Total MeHg in FLUDEX reservoirs



Total MeHg storage in peat in the wetland reservoir in year 2
= 6000 mg/ha

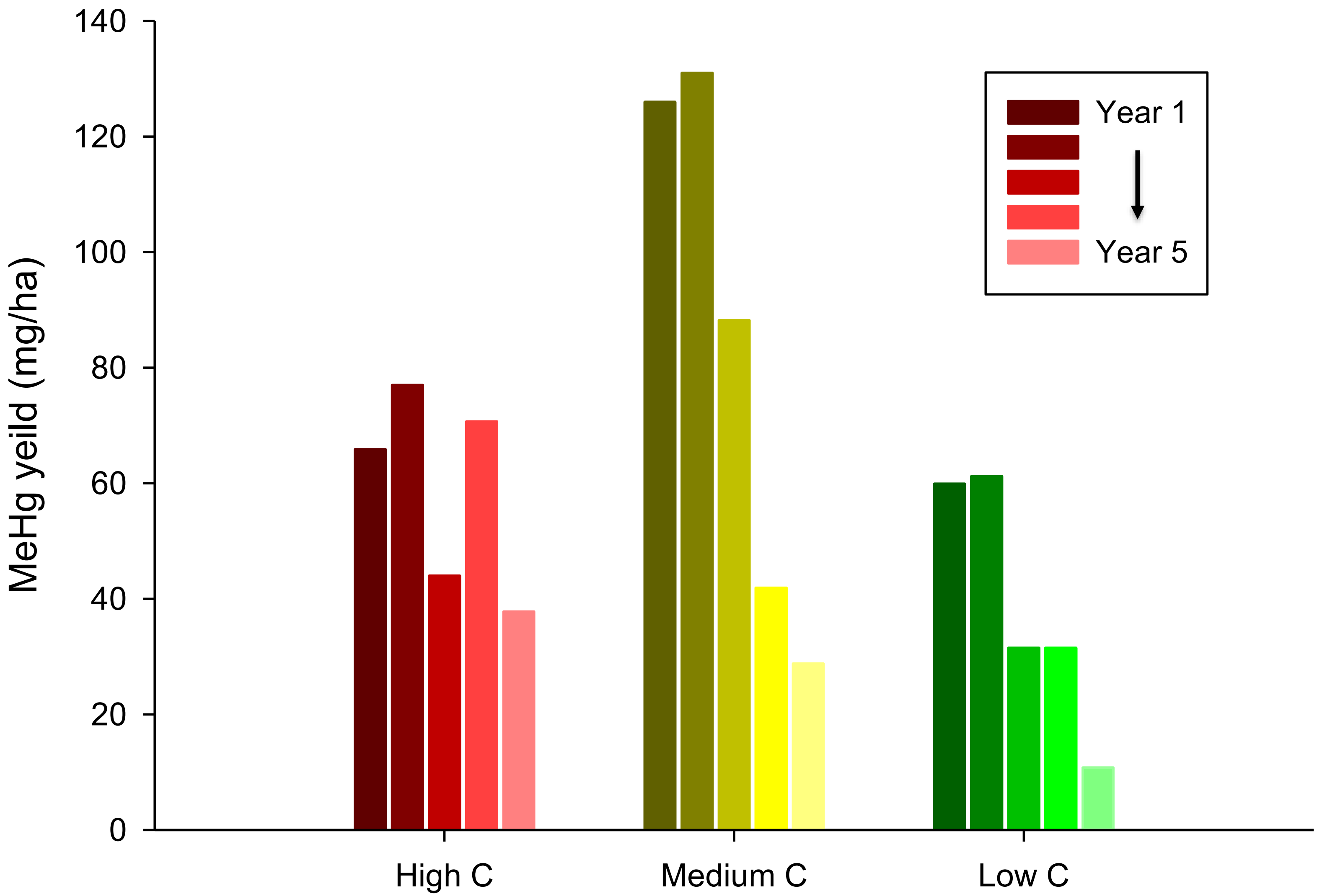

Minimizing carbon flooded
minimized *production* of MeHg
in reservoirs

Total MeHg in FLUDEX reservoirs

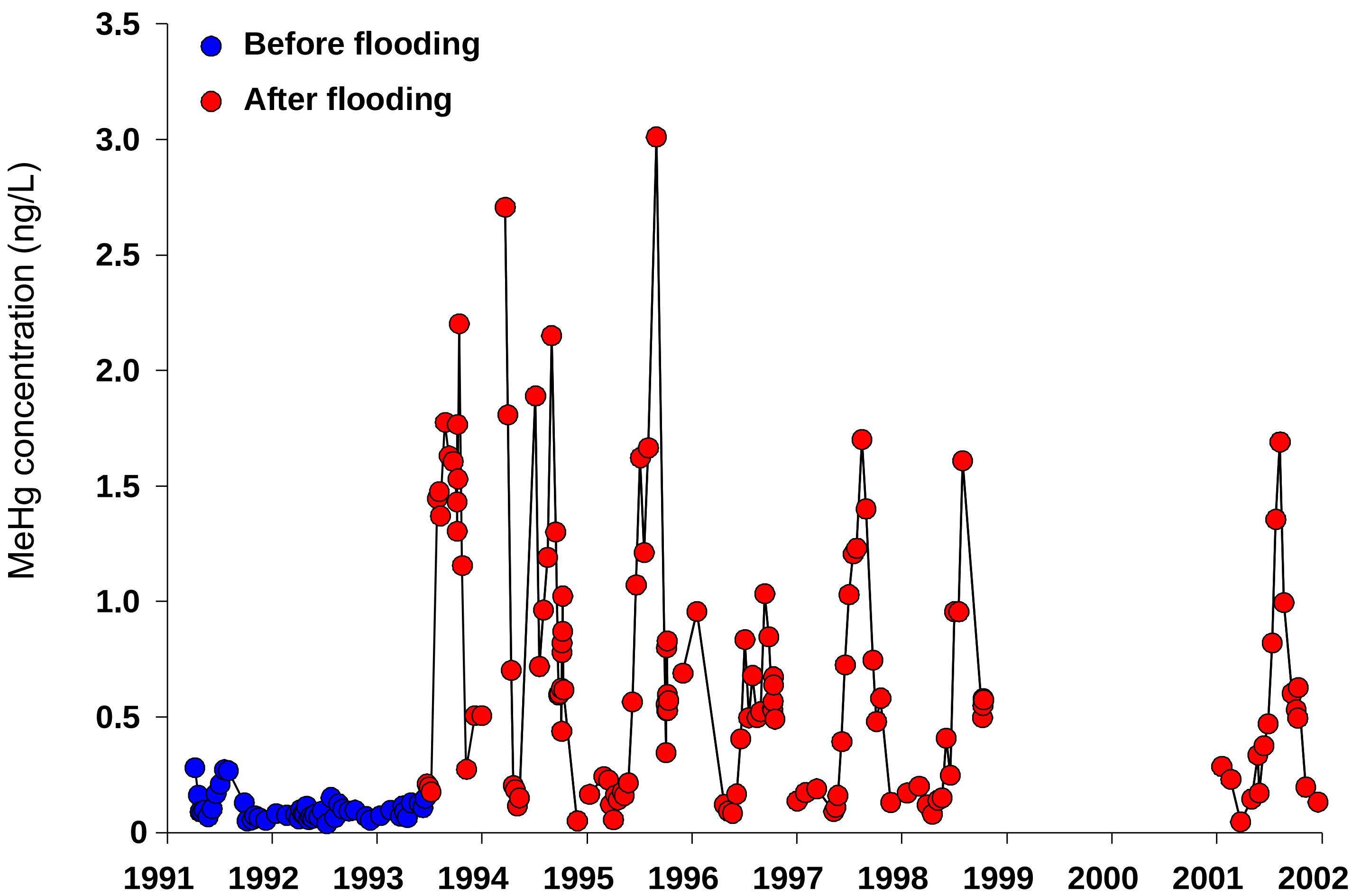


Total MeHg storage in peat in the wetland reservoir in year 2
= 6000 mg/ha

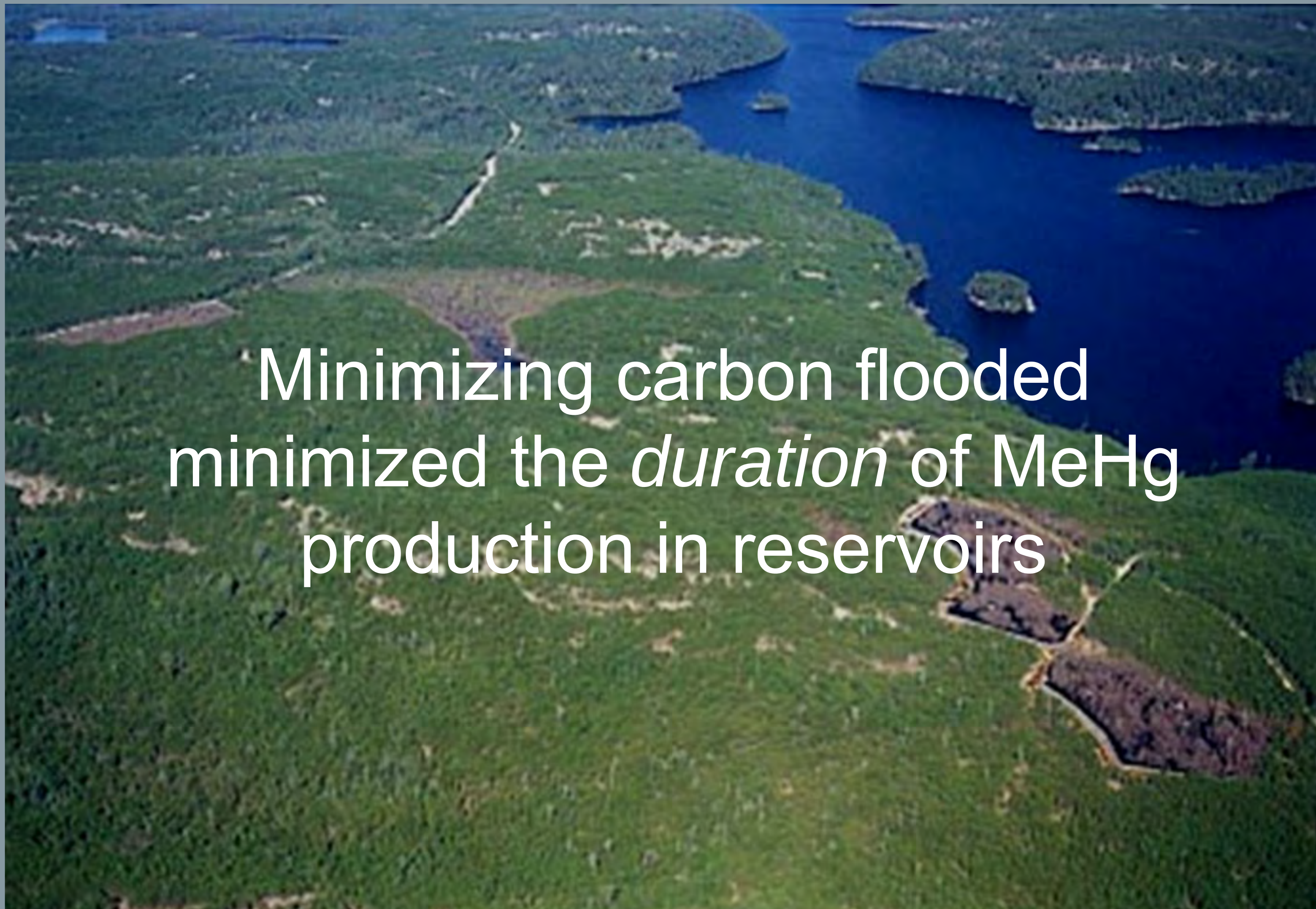
MeHg yield over five years



Results from ELARP



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


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, Ontario[1]

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. Roulet[1]

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. HALL[1], R. A. BODALY[2], R. J. P. FUDGE[2], J. W. M. RUDD[2] and D. M. ROSENBERG[2]

Photodegradation of methylmercury in lakes

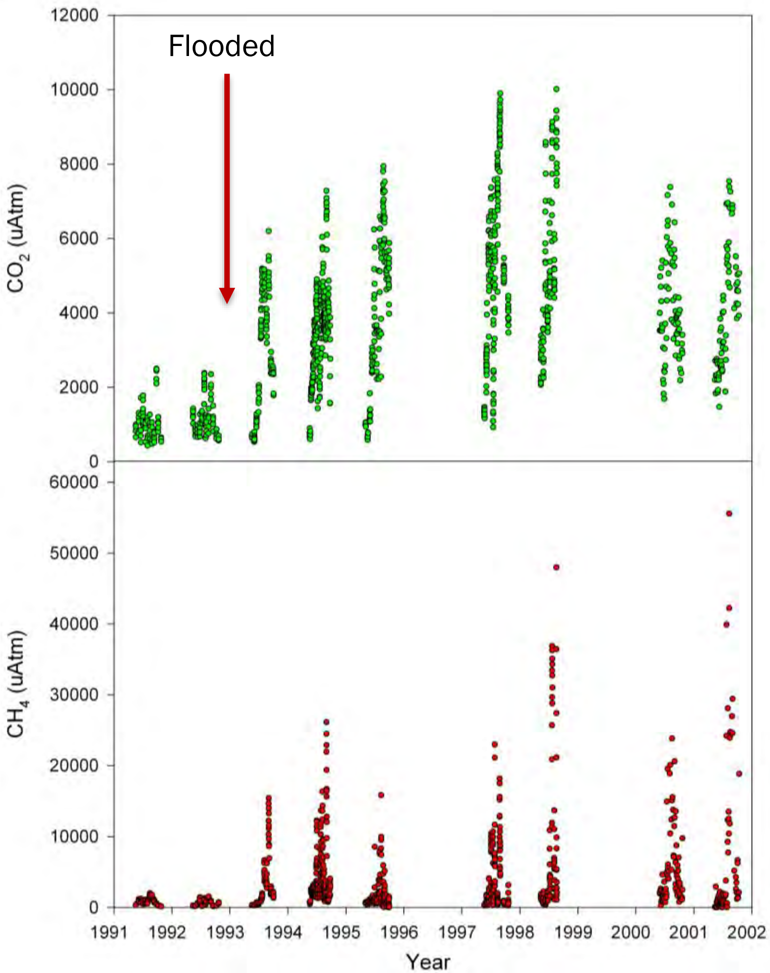
P. Sellers*, C. A. Kelly*, J. W.M. Rudd†, A. R. MacHutchon†

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

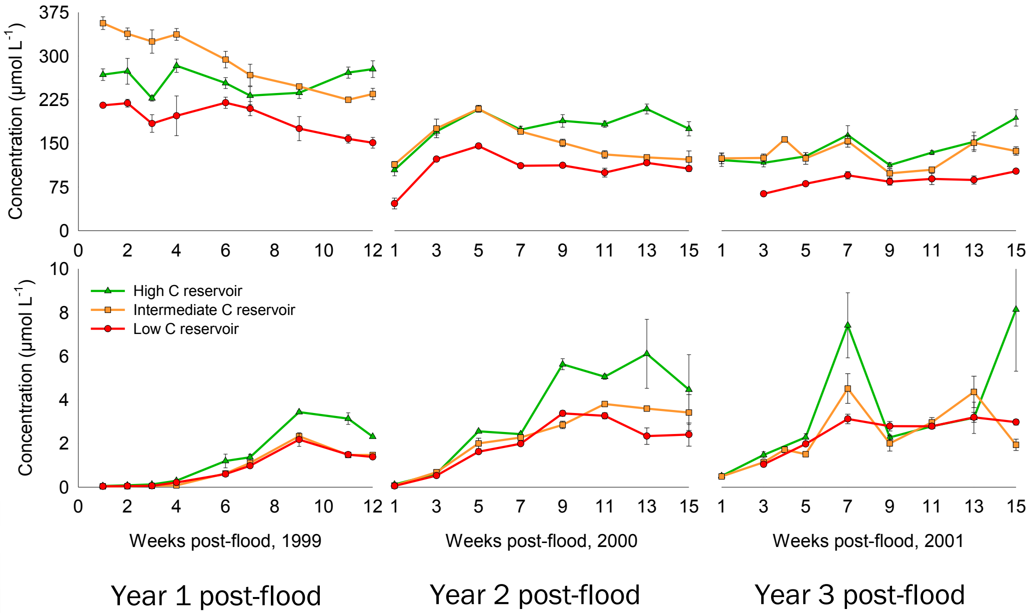
Mariah Mailman [a,*], R.A. (Drew) Bodaly [b]

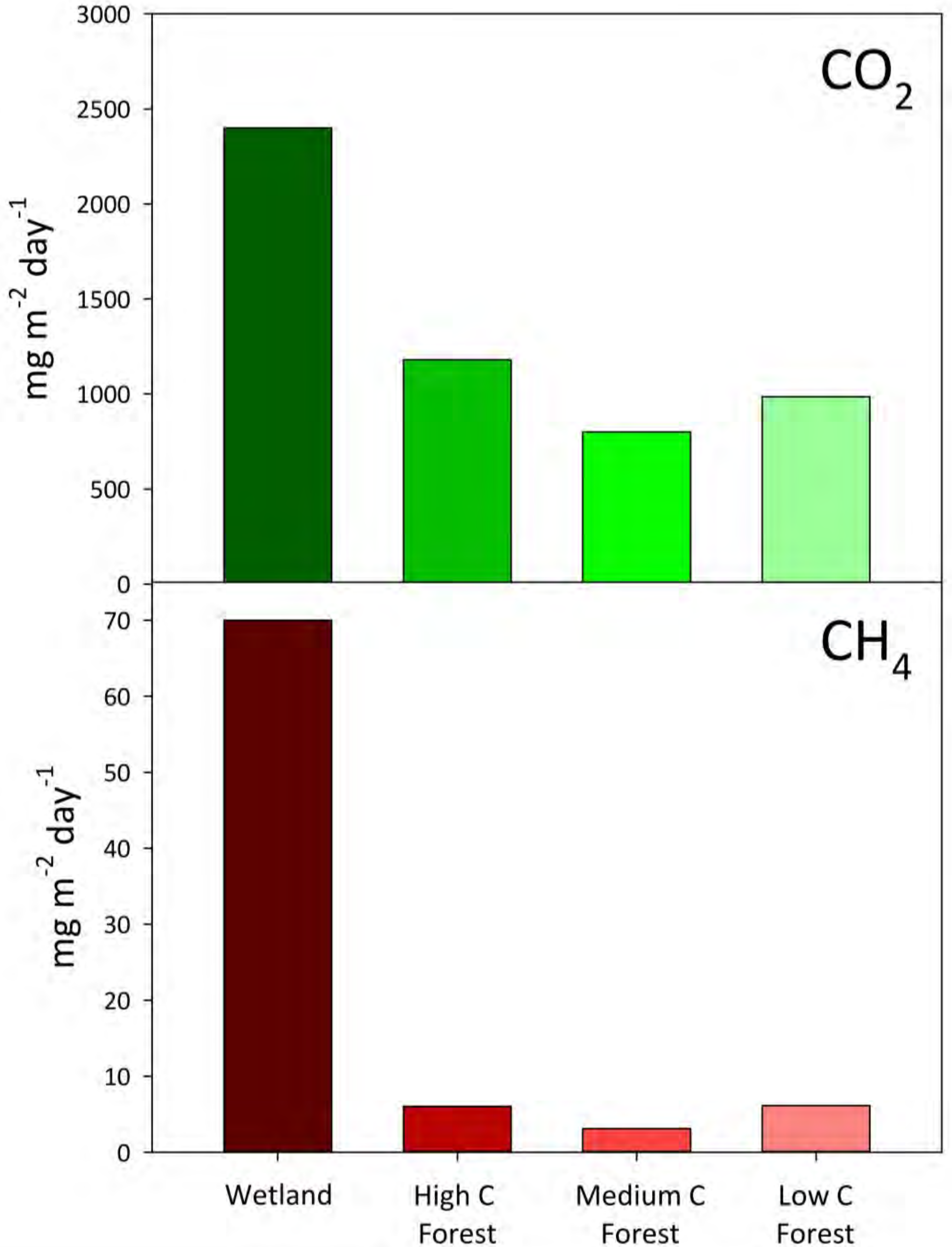
Concentrations of CO_2 and CH_4 in the reservoir water

Experimental Lakes Area Reservoir Project



Flooded Uplands Dynamics Experiment





Average reservoir surface fluxes of CO_2 and CH_4 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 CO_2 and CH_4 emissions from global hydroelectric reservoirs

nature geoscience

LETTERS

PUBLISHED ONLINE: 31 JULY 2011 | DOI: 10.1038/NGEO1211

Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude

Nathan Barros[1], Jonathan J. Cole[2], Lars J. Tranvik[3], Yves T. Prairie[4], David Bastviken[5], Vera L. M. Huszar[6], Paul del Giorgio[4] and Fábio Roland[1]*

Hydroelectric reservoirs cover an area of 3.4×10^5 km^2 and comprise about 20% of all reservoirs. In addition, they contain large stores of formerly terrestrial organic carbon. Significant amounts of greenhouse gases are emitted[2], 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 Tg C as CO_2 and 3 Tg C as CH_4, 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 CO_2 and CH_4 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-CO_2 and C-CH_4, were used to calculate carbon emissions as C-CO_2, C-CH_4, total C and CO_2-equivalent emissions by hydroelectric reservoirs. For comparison, estimates of global emissions from natural lakes were included. The CO_2 equivalent was calculated as the data for CO_2 plus the CH_4 data multiplied by 25 according to IPCC (ref. 18), on the basis of the CH_4 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

ECOSYSTEMS

CrossMark

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

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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; CO_2 and CH_4 emissions; C burial.

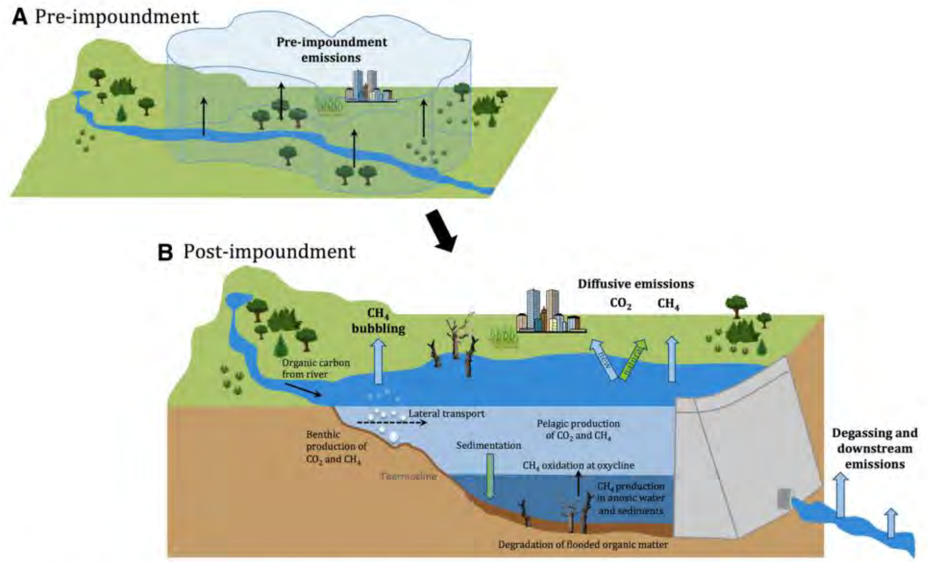

Figure 2. Landscape transformation from a river to a reservoir. **A** Pre-impoundment conditions: the dashed line corresponds to the area of the future reservoir where the GHG balance needs to be accounted for. **B** Post-impoundment conditions and the multiple processes and pathways for CO_2 and CH_4 emissions. Although a large fraction of the diffusive CO_2 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 CH_4 emissions can be considered attributable to the reservoir, except those present in the pre-impoundment conditions. The main CH_4 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).

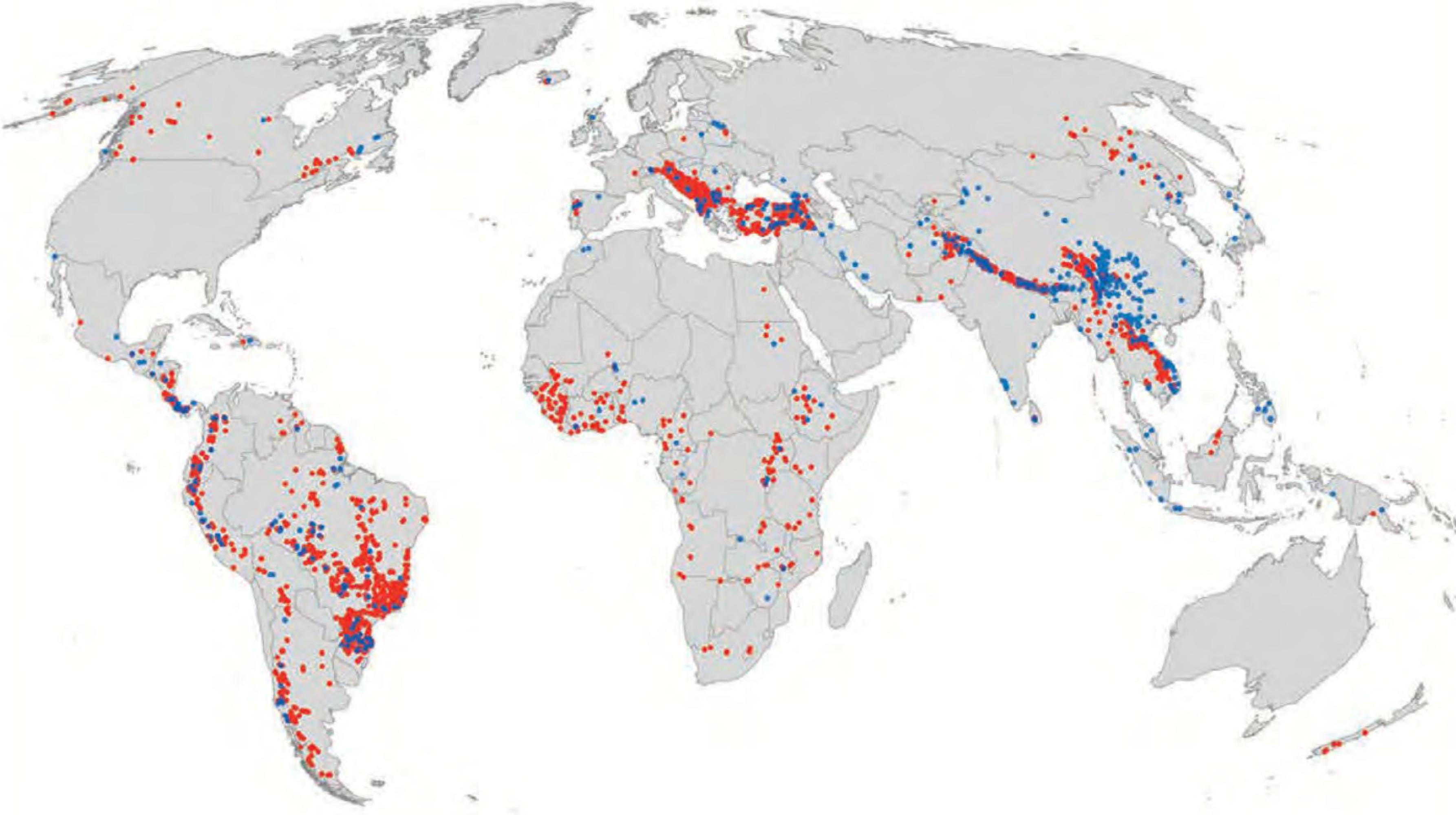

Figure 16: Global distribution of future hydropower dams either planned (red dots, 83 per cent) or under construction (blue dots, 17 per cent) *(Zarfl et al., 2015).*

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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