The Power of the Past:

Using lake sediments to study long-term environmental changes in lake ecosystems

John P. Smol

Paleoecological Environmental Assessment and Research Laboratory (PEARL)

Dept. Biology, Queen's University,

Kingston, Ontario, Canada

SmolJ@QueensU.Ca

Important management questions

What were pre-disturbance conditions?

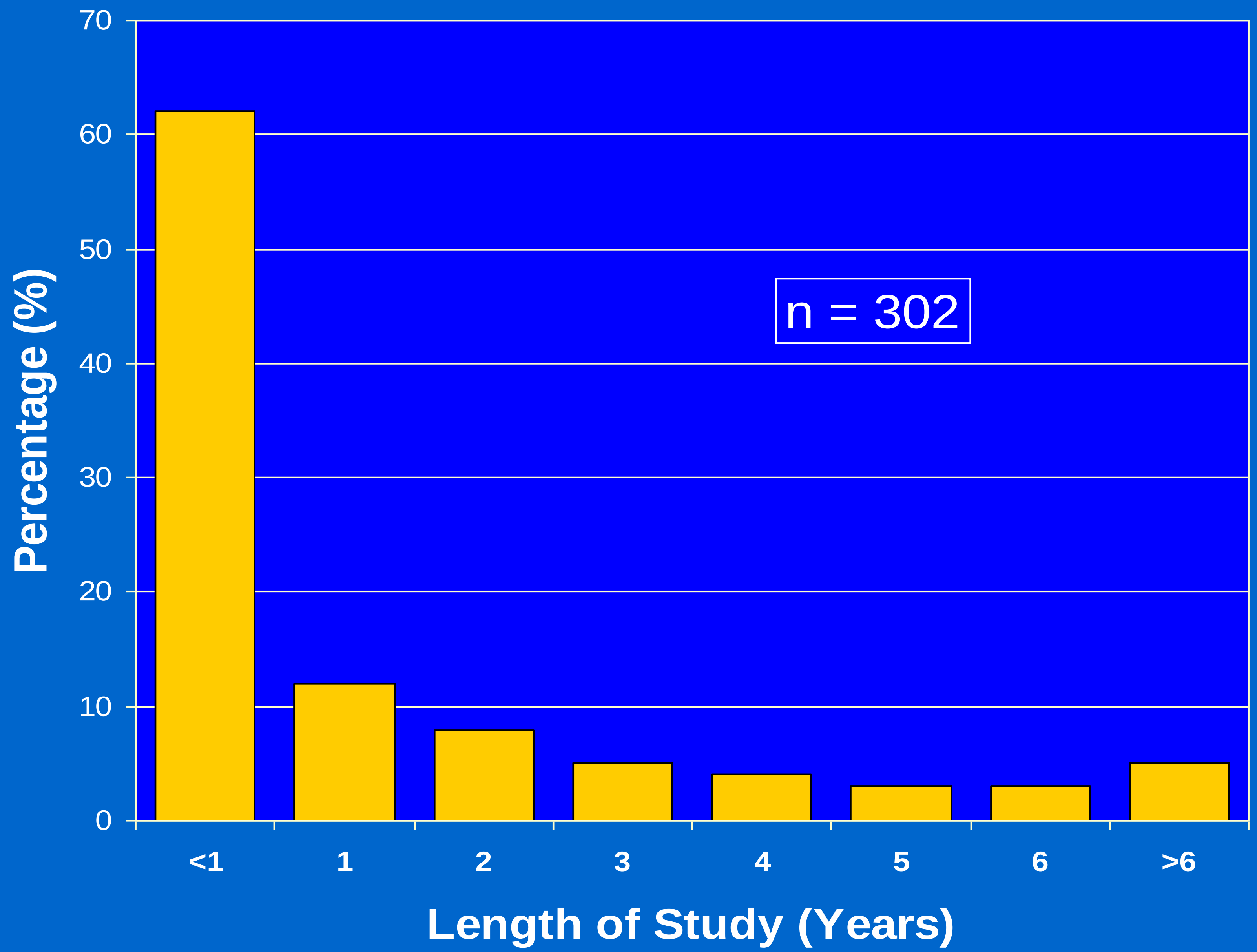
What is the range of natural variability?

Have conditions changed? How? How much?
How fast? When? Why?

Can evidence of human activity be detected?

How much improvement can be expected?

Environmental Monitoring and Assessment - 1981-1993



Smol (2008) *Pollution of lakes and rivers: A paleoenvironmental perspective*. 2nd ed.

Techniques to Assess Past Environmental Change

historical records

model hindcasts

natural archives

Paleolimnology: reconstructing lake and river histories using the physical, chemical, and biological information stored in sediments

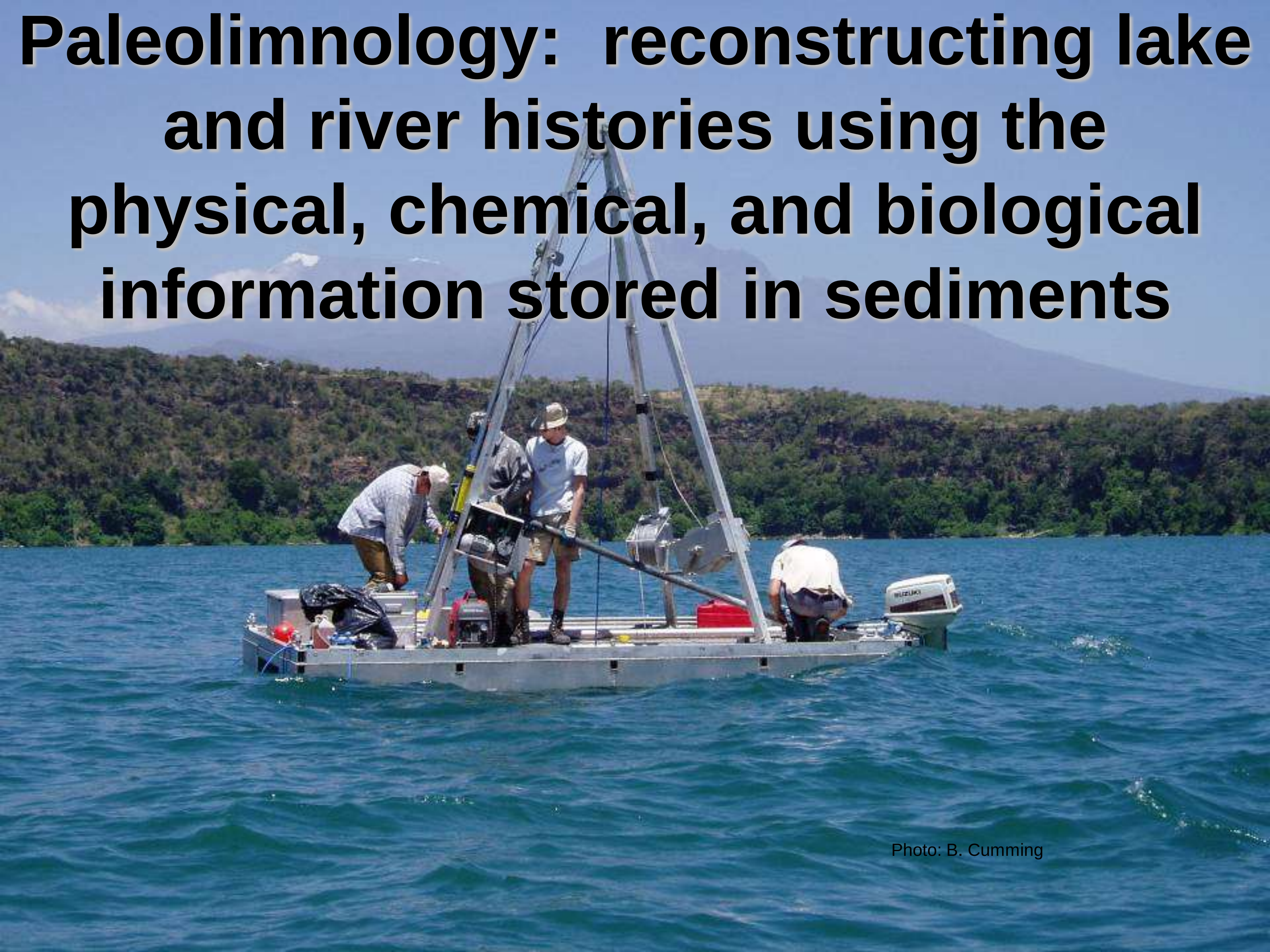
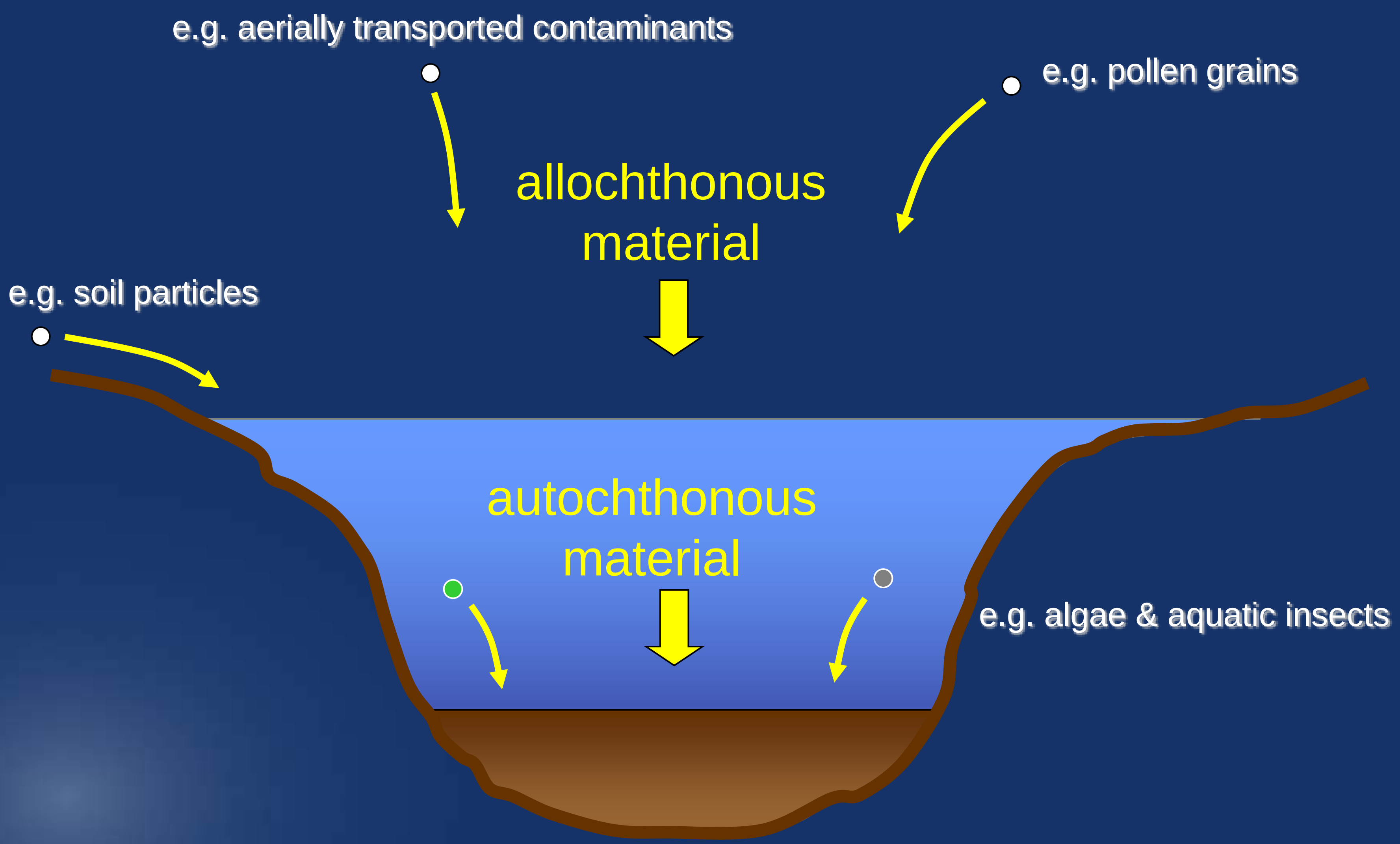


Photo: B. Cumming

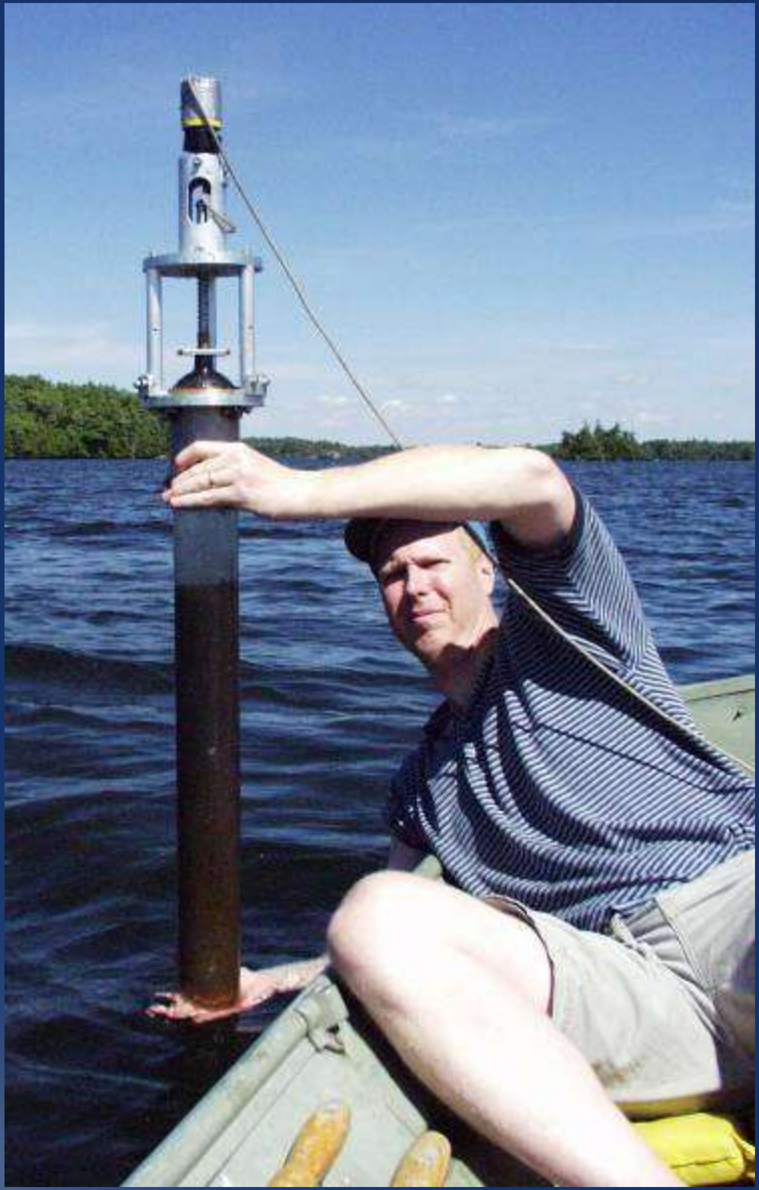
Sediments: environmental archives



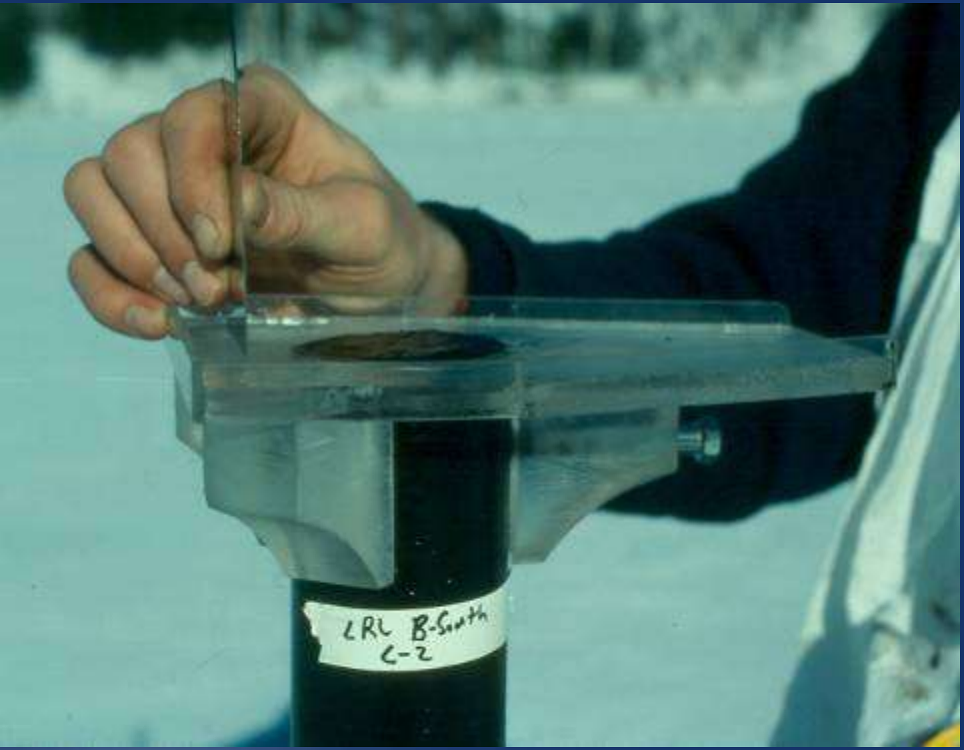
Continuing Advances

- technology and methodology
- amount of information
- interpretation

Surface sediment gravity coring

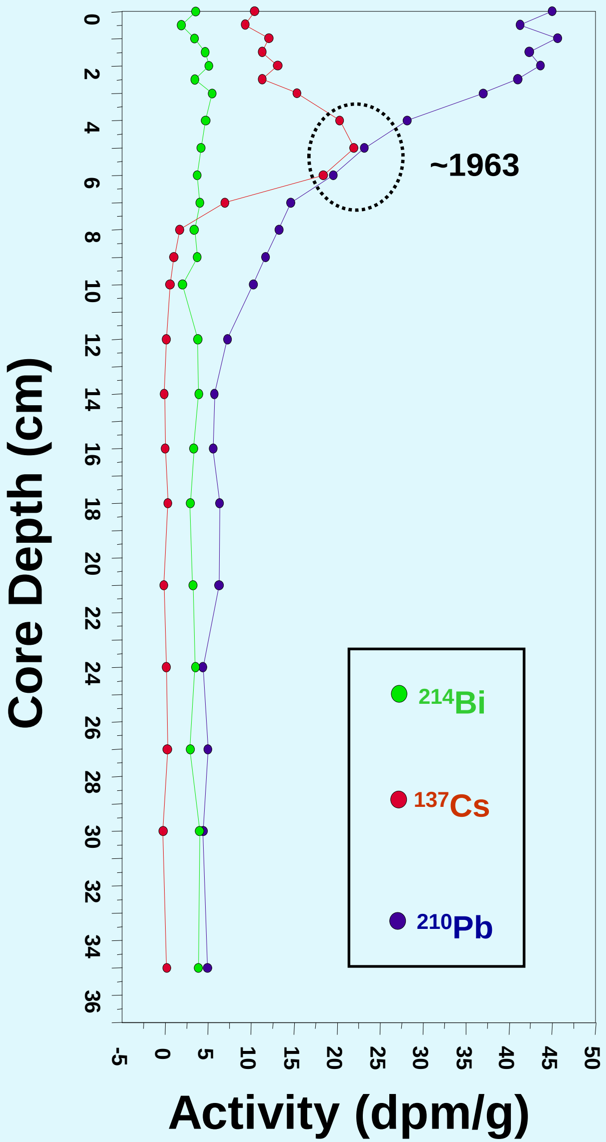


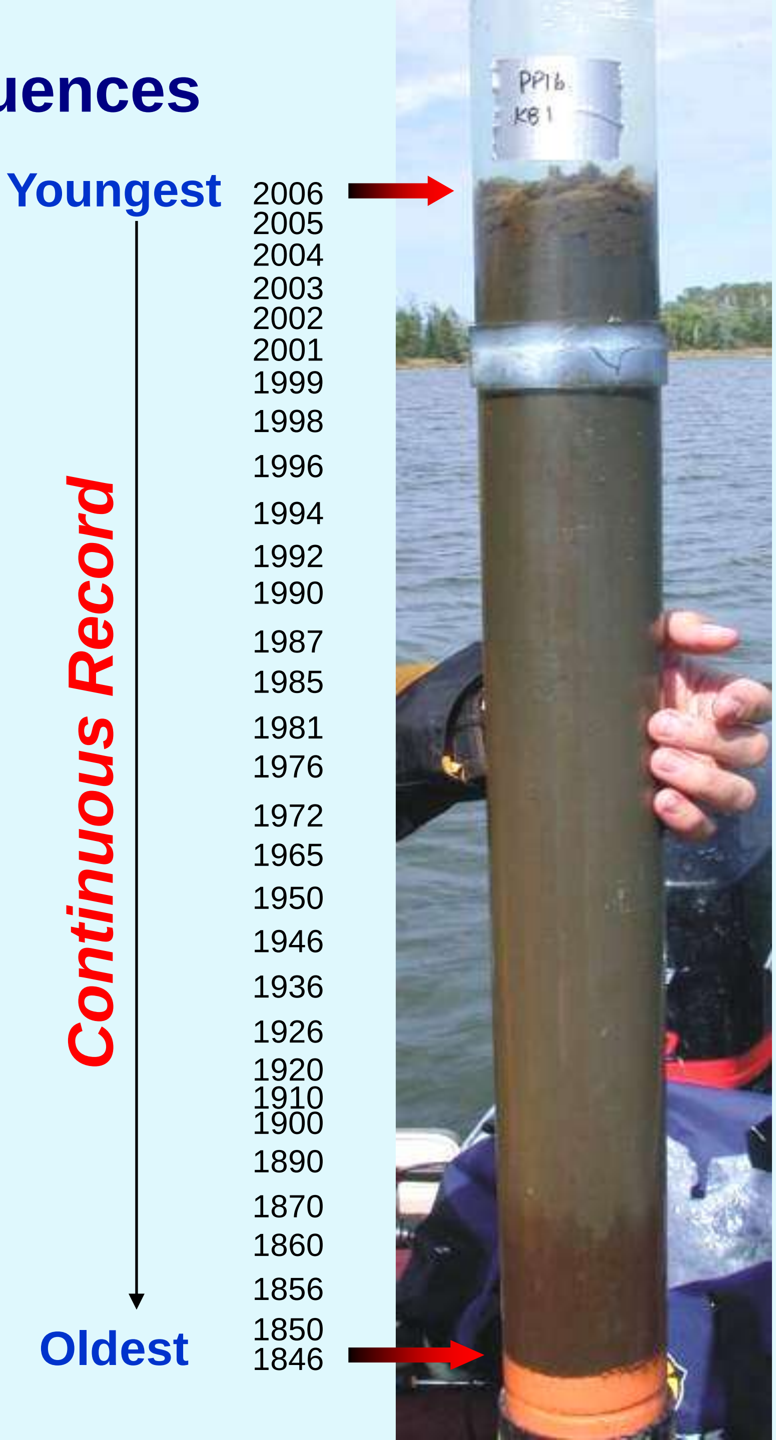
Close-interval sectioning



Dating the sedimentary sequences

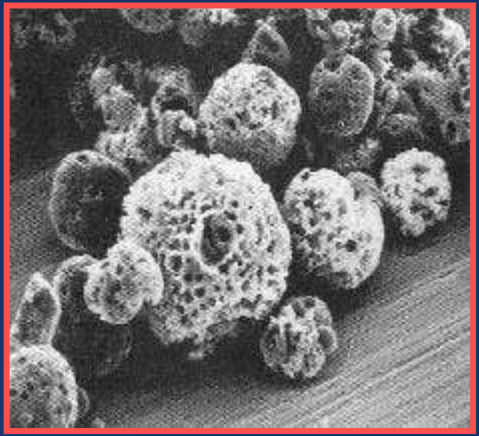
● ^{210}Pb & ● ^{137}Cs (radioisotopes)



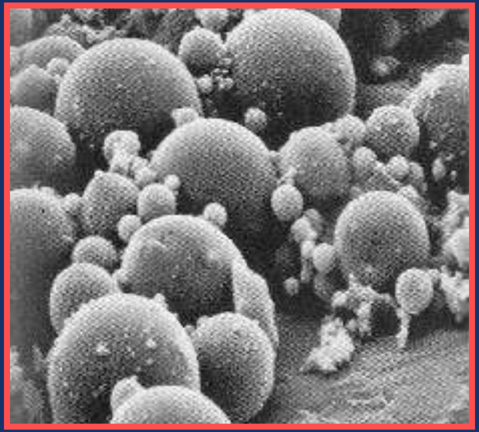


From the Atmosphere

carbon particles from carbon combustion



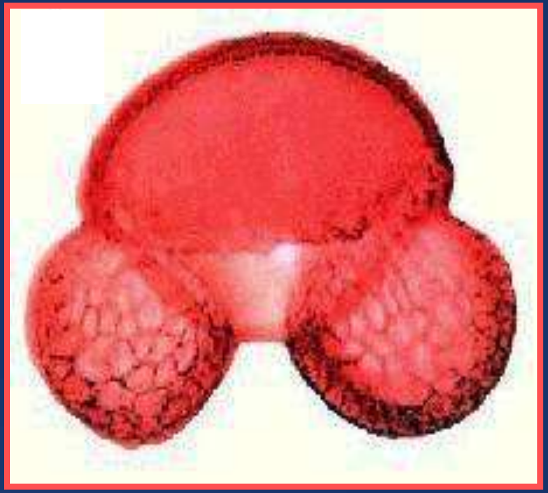
fly ash from coal combustion



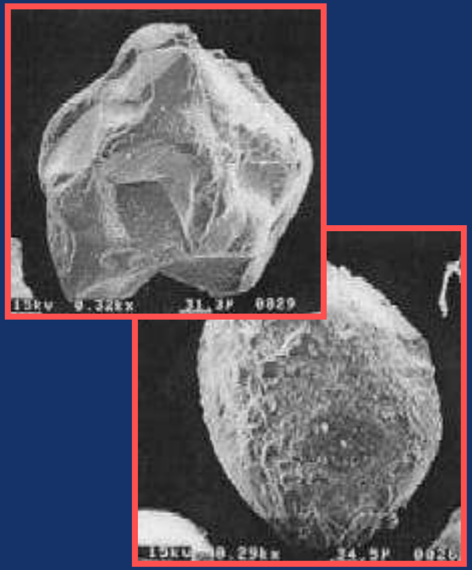
metals and other pollutants from industry

From the Catchment

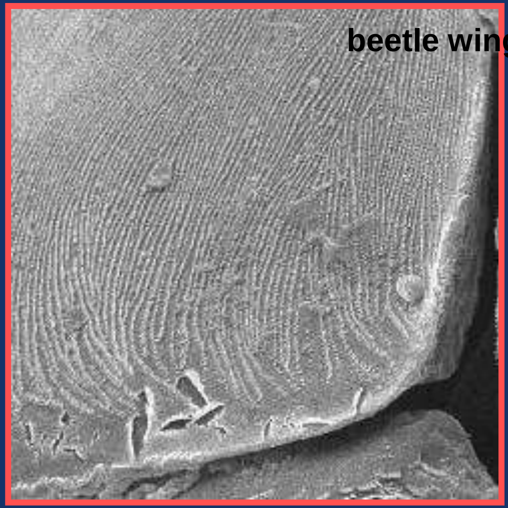
pollen



mineral particles

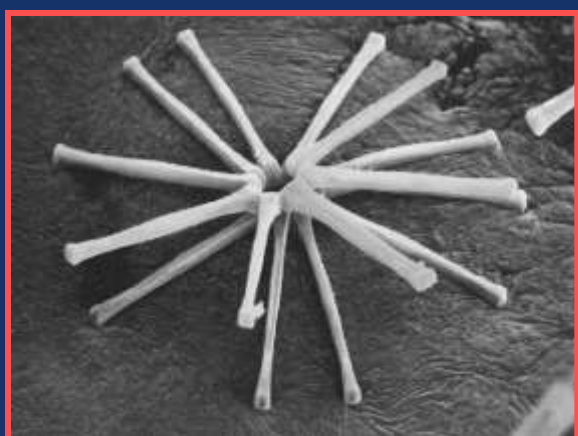


insect remains

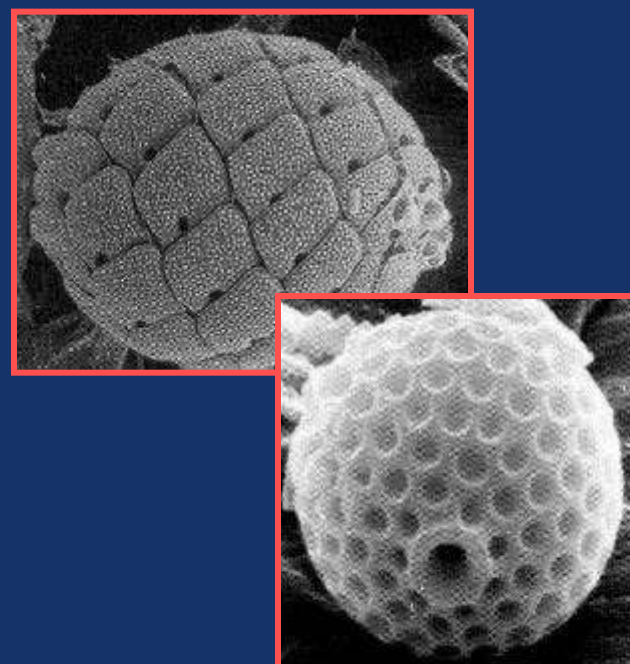


From the Aquatic System

diatoms



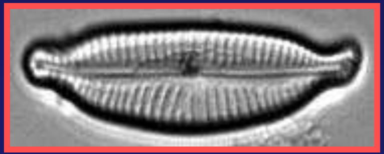
chrysophytes



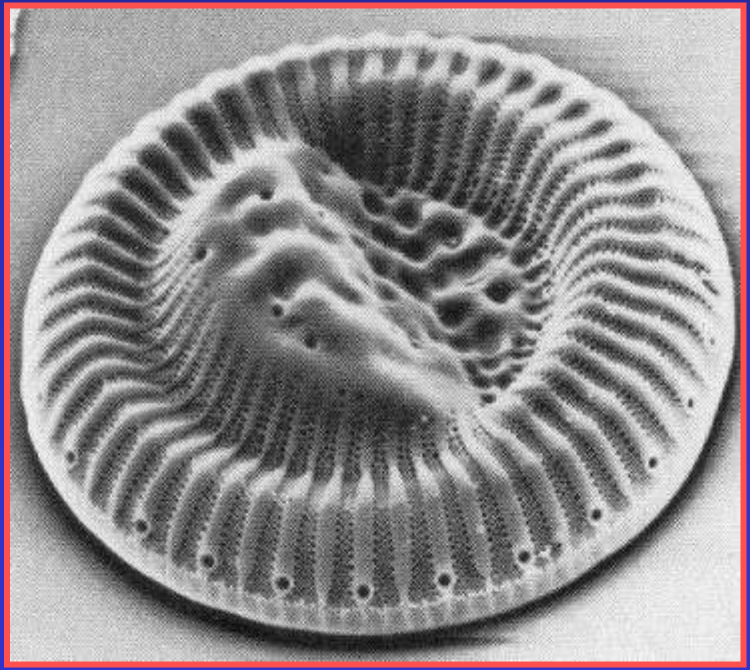
chironomids

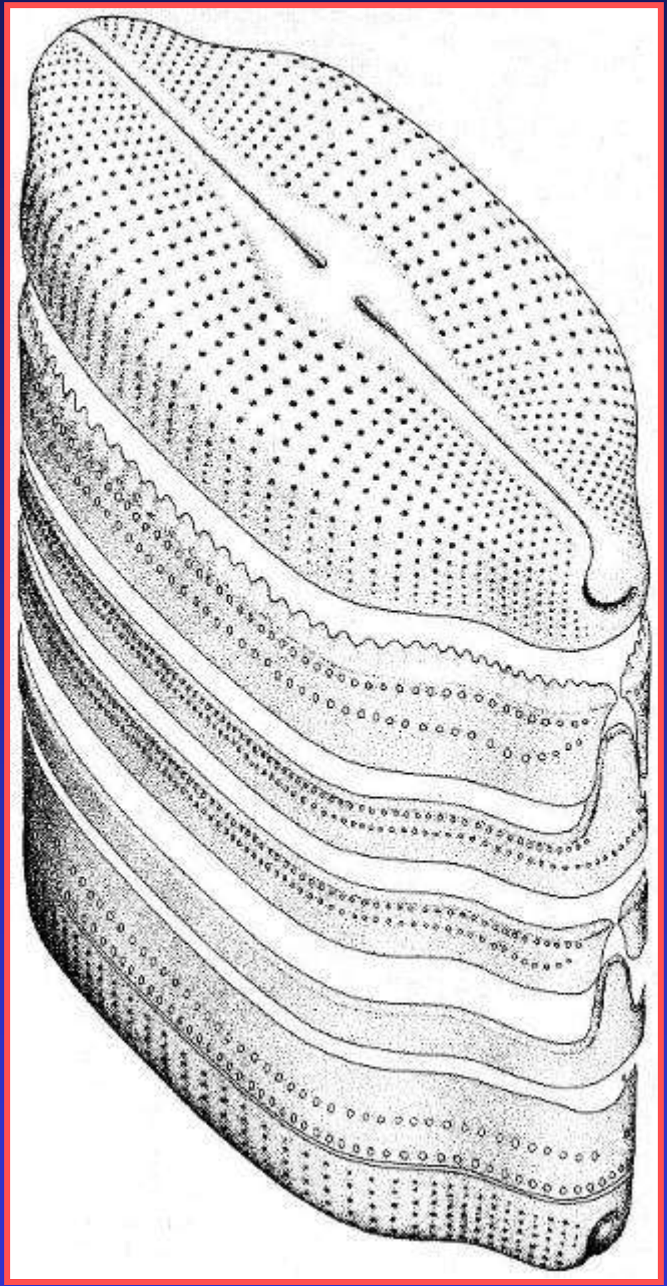
Photo: I Walker

Diatoms

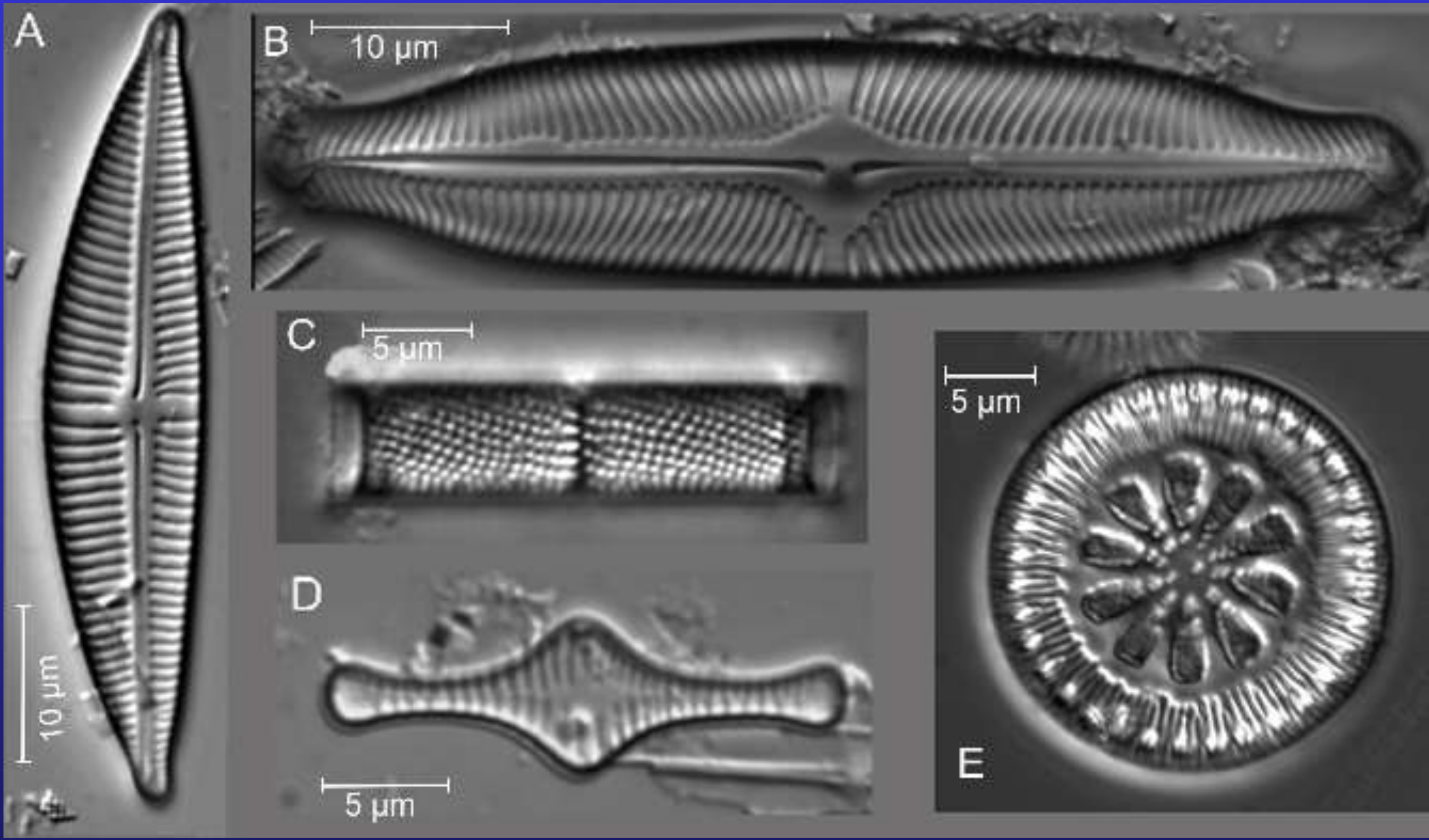


- Bacillariophyta
- abundant and diverse
- excellent environmental indicators
- siliceous cell walls (frustules)





Freshwater diatoms



Photos: K. Laird and B. Cumming;
in Smol (2008) *Pollution of lakes and rivers: A paleoenvironmental perspective*.
2nd ed. Blackwell Publ., Oxford.

The Paleolimnological Approach

Select Study Lake

Select Coring Site & Retrieve Sediment Core

^{210}Pb

^{14}C

^{137}Cs

Section & Date Sediment Core

Sub-sample Sediments & Isolate Indicator of Interest

Collect Indicator Data

Analyze Data

Photos courtesy of B. Cumming, I. Walker, Dell & Leica

- Targets
- Trajectories

Users of Water

“The Real” Users of Water

What factors can be addressed using paleolimnology?

eutrophication
anoxia and fish habitat
climate change
groundwater quality
river paleoecology
acidification
fire history
species invasion
speciation / evolution, etc.

Three lake characteristics we typically wish to track

1) Lakewater nutrient levels

2) Deepwater oxygen levels

3) Algal and cyanobacterial blooms

1) Trends in lakewater nutrients

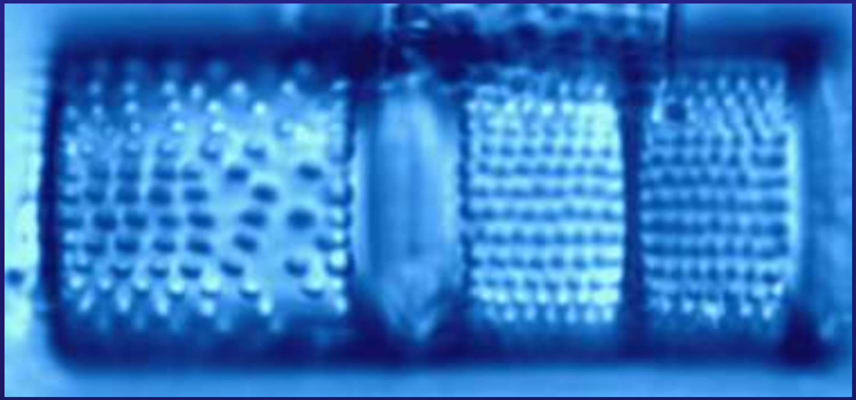
Why not just measure total P in the sediments?

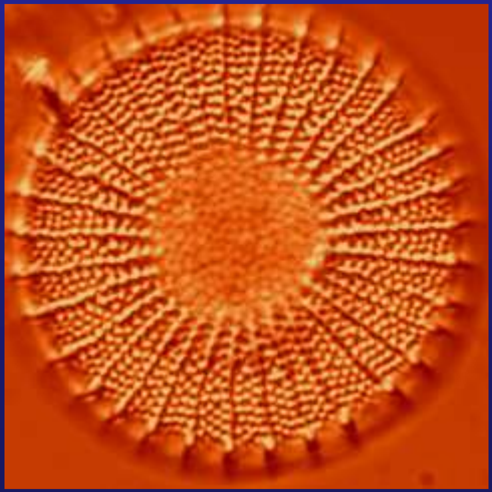
Many pitfalls and largely abandoned ~30 years ago

(this is not to say that sedimentary P has no value in other applications – very important in mass balance studies and determining processes, etc.)

So we have to use indirect proxy methods that are related to lakewater total phosphorus (TP)

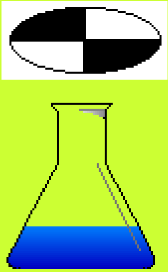
Research ongoing for over 30 years,
but especially last 20 years





Construction of a Transfer Function

lake surface sediment samples

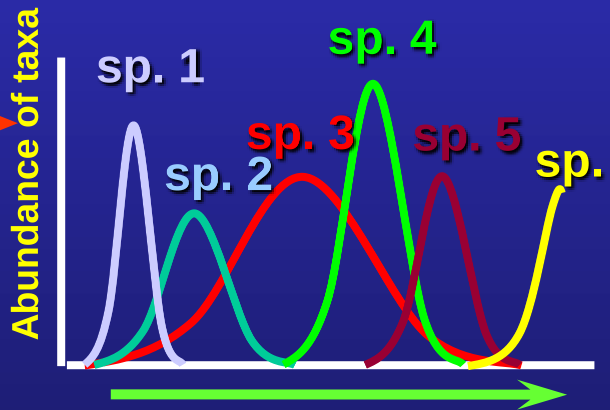


Surface area
Depth
Development
Total phosphorus
Total nitrogen
Chlorophyll *a*

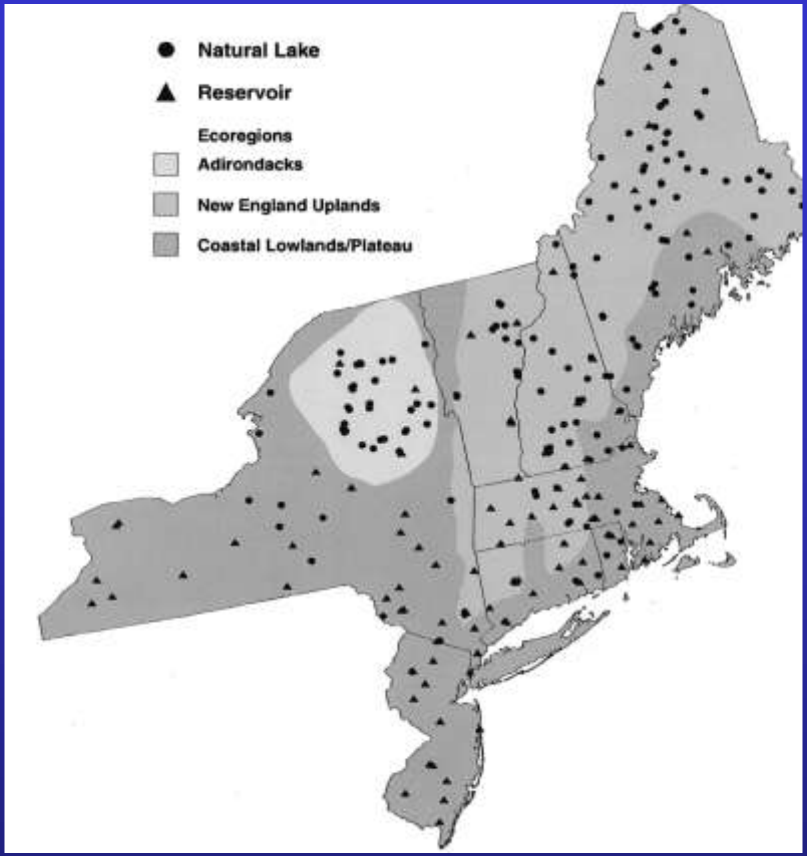
pH
Secchi depth
Temperature
Conductivity
Oxygen
Alkalinity
Ammonium

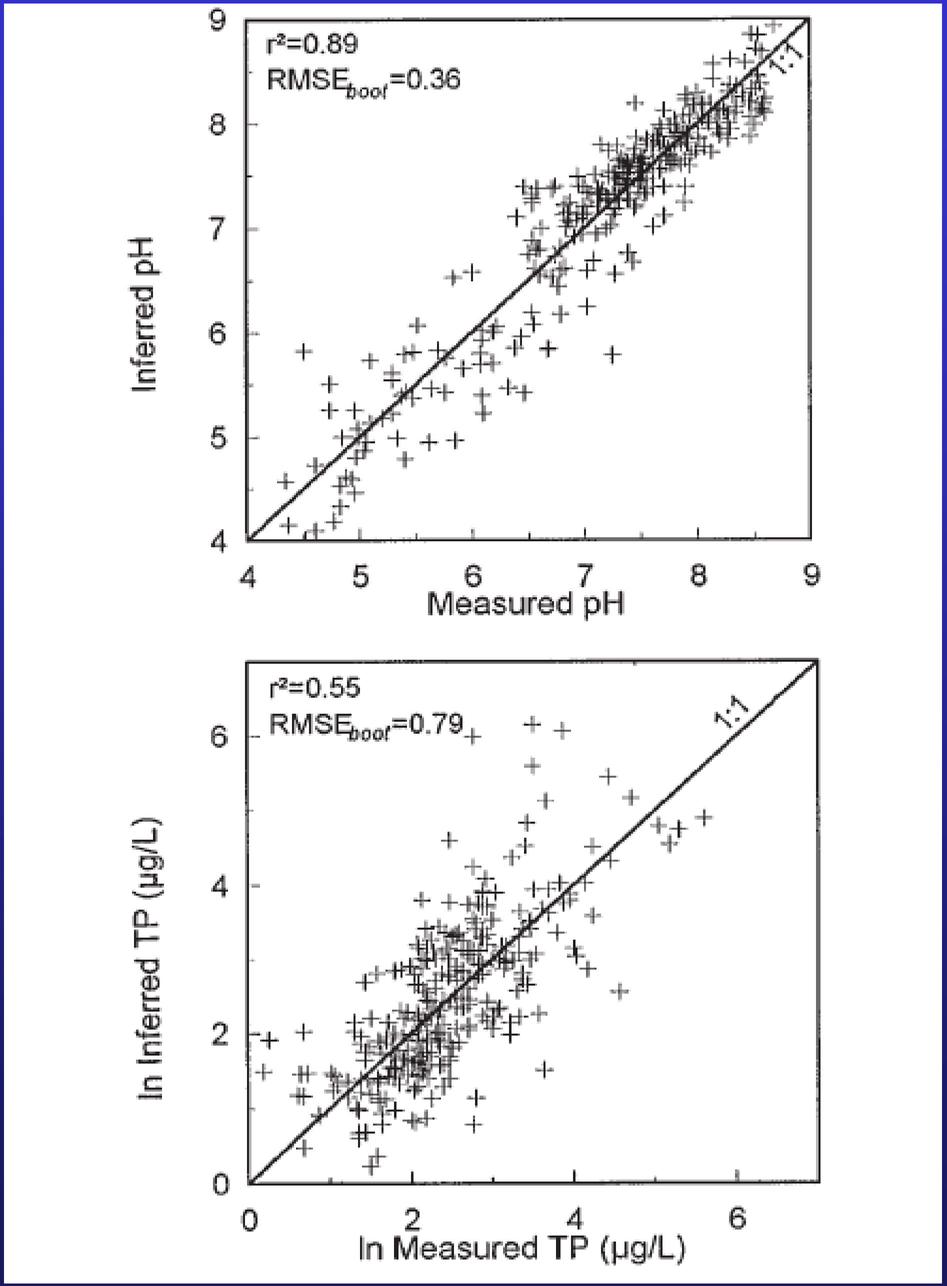
environmental data

species response curves



Regional Scale Diatom Calibration Set





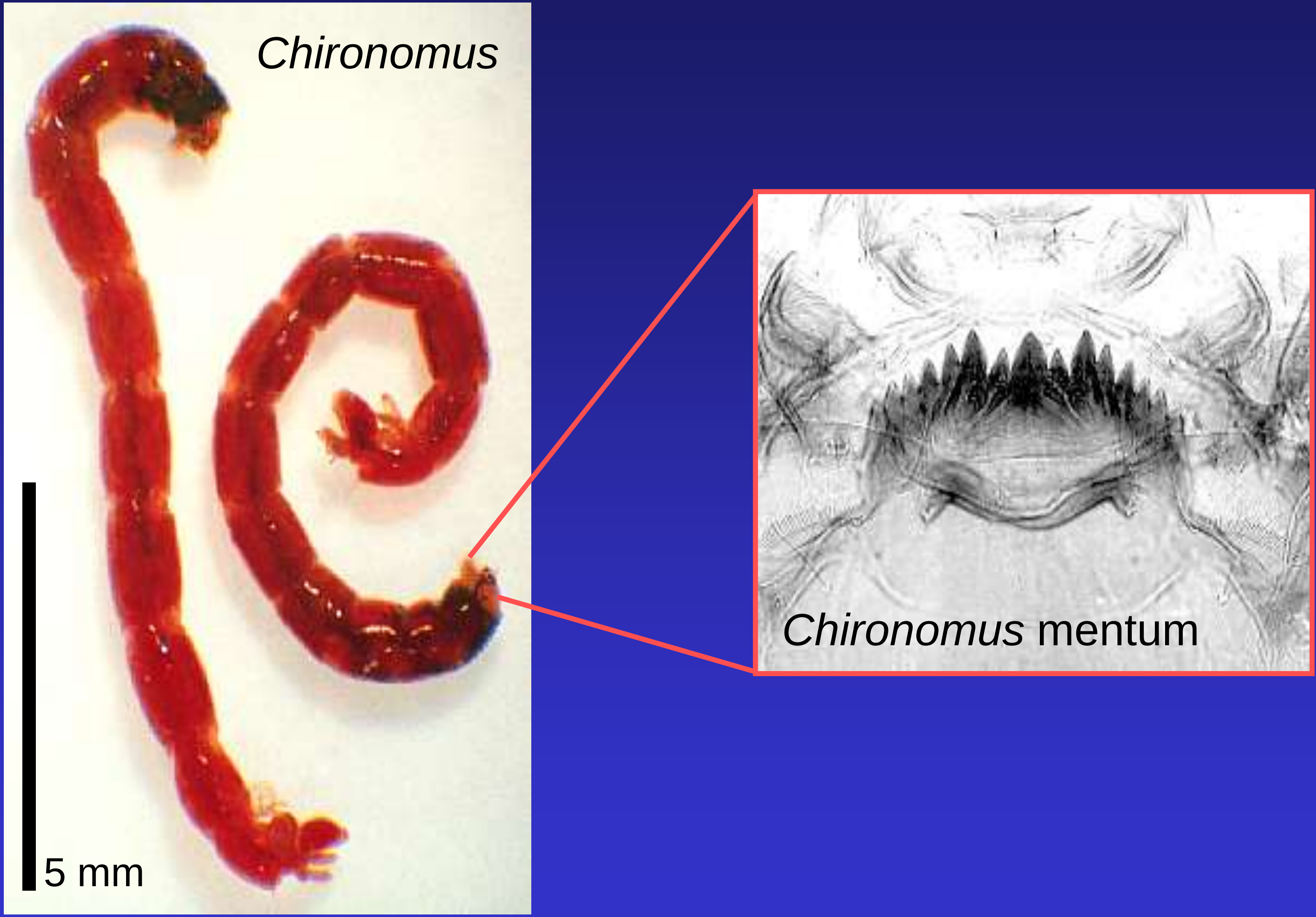
Dixit, S.S., Smol, J.P., et al. 1999. Assessing water quality changes in the lakes of the Northeastern United States using sediment diatoms. *Can. J. Fish. Aq. Sci.* 56: 131-152.

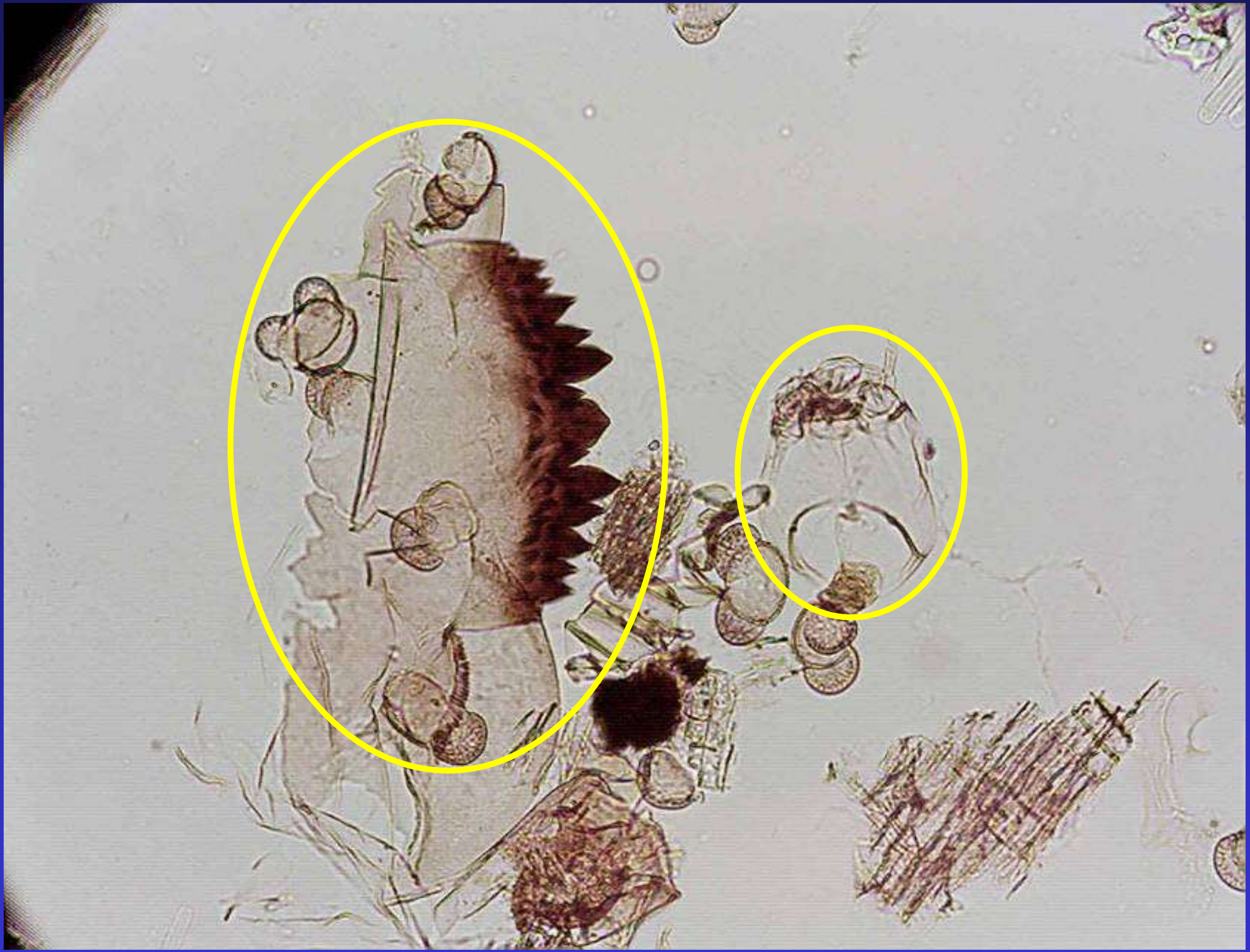
2) Deepwater oxygen levels?

Use organisms that need oxygen, and live in the deep waters

http://www.nzfreshwater.org/food.html

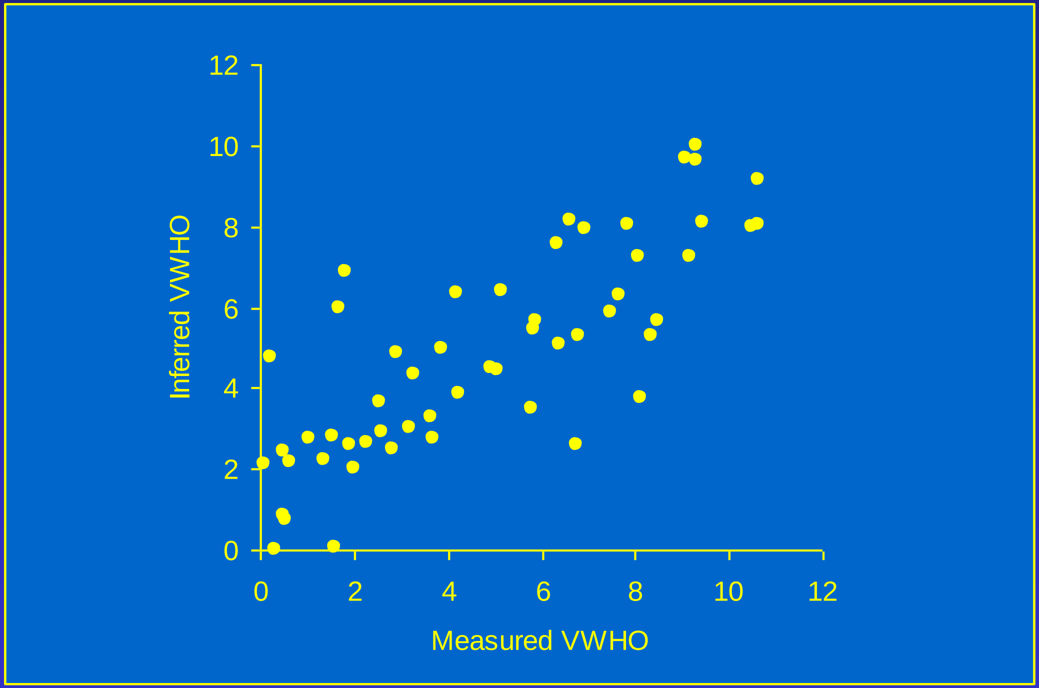
Chironomid head capsules as indicators





(Photo: D. Bos)

Predictive O_2 Model Based on Aquatic Communities

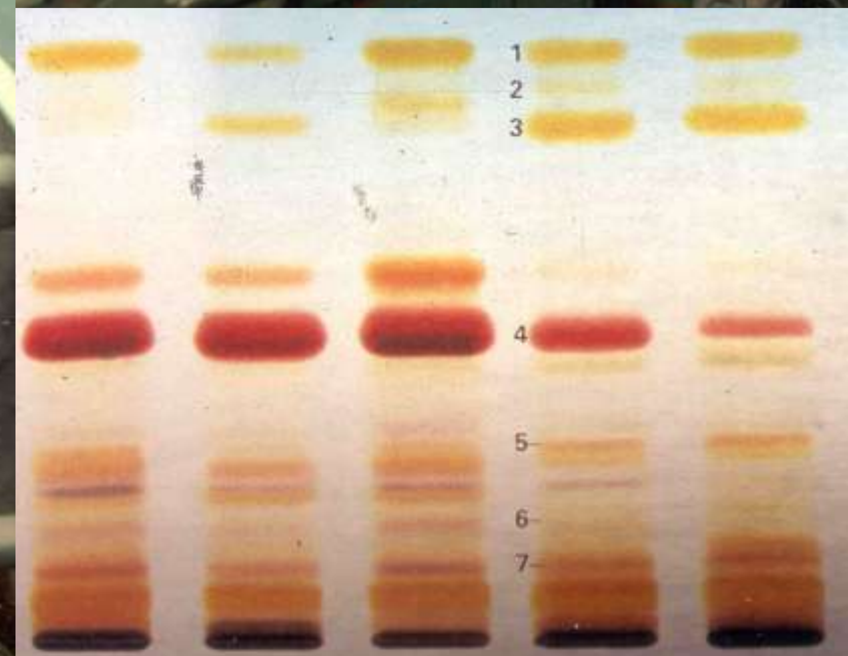


(from Ontario lakes)

(modified from Quinlan & Smol 2001)

3) Algal and cyanobacterial blooms

Photo Todd Sellers



Fossil Pigments

Example #1: The effects of urbanization and shoreline development on water quality

Peninsula Lake and the Deerhurst Resort

Clerk, S., Hall, R., Quinlan, R., and Smol, J.P. 2000. Quantitative inferences of past hypolimnetic anoxia and nutrient levels from a Canadian Precambrian Shield lake. *J. Paleolimnology* 23: 319-336.

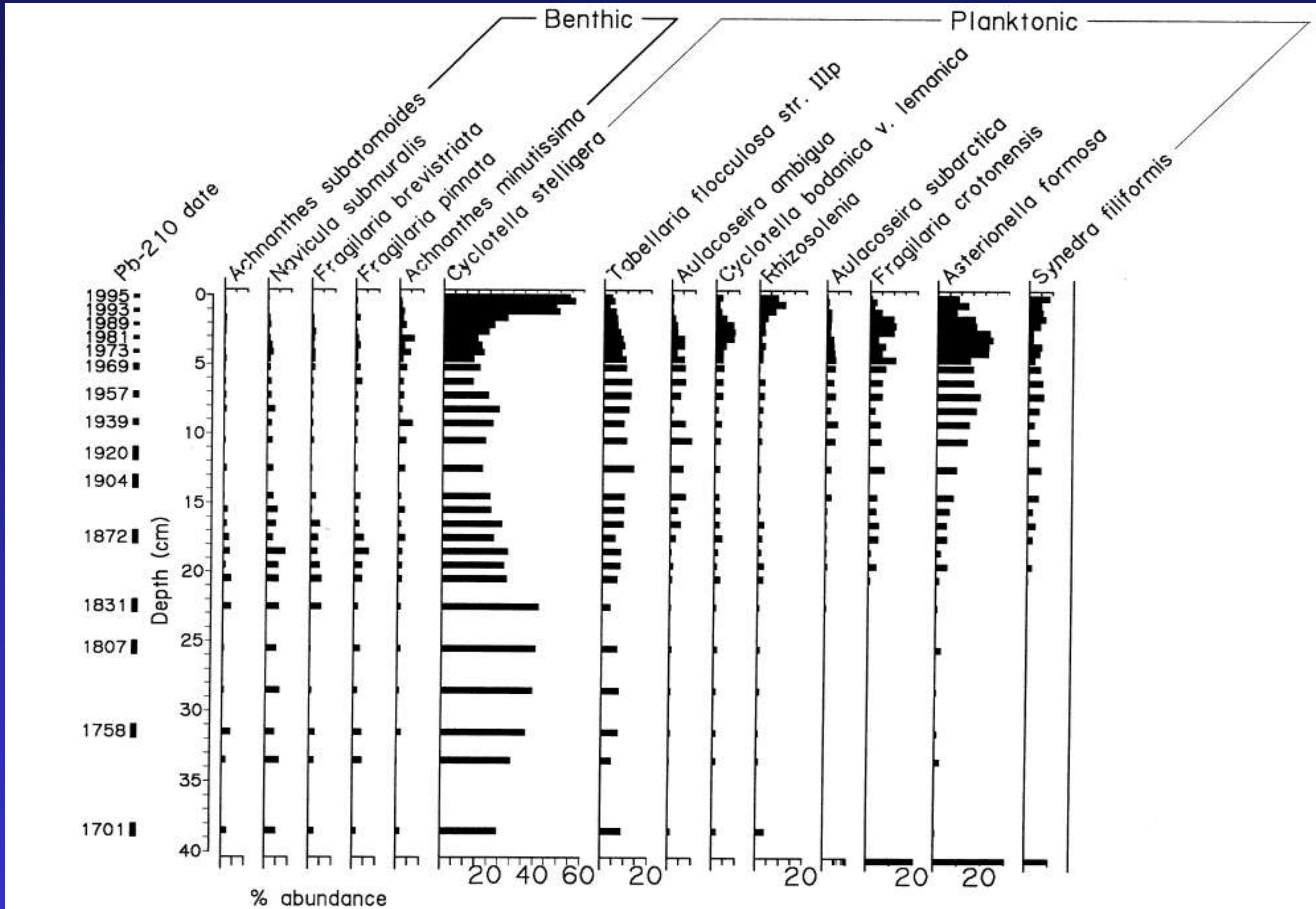
Peninsula Lake, Huntsville, Ont

1867	First pioneers
1885	Railway to area
1870-90	Development of local industries
1895	Deerhurst Resort
Late-1800s – early-1900s	Significant logging
1972	Sewage Treatment

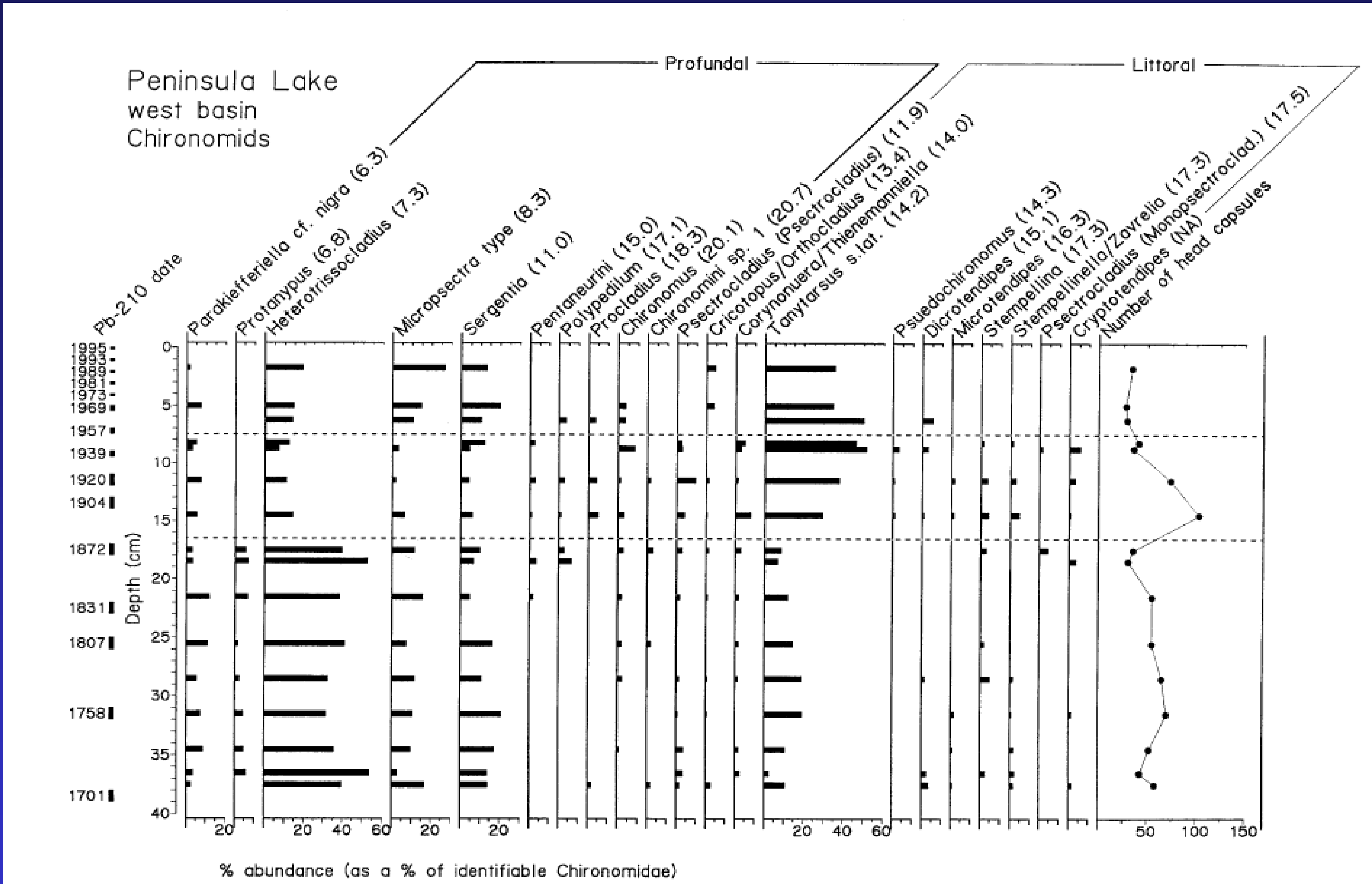
Lake area = 822.9 ha

Mean depth = 9.9 m

Maximum depth = 34.1 m



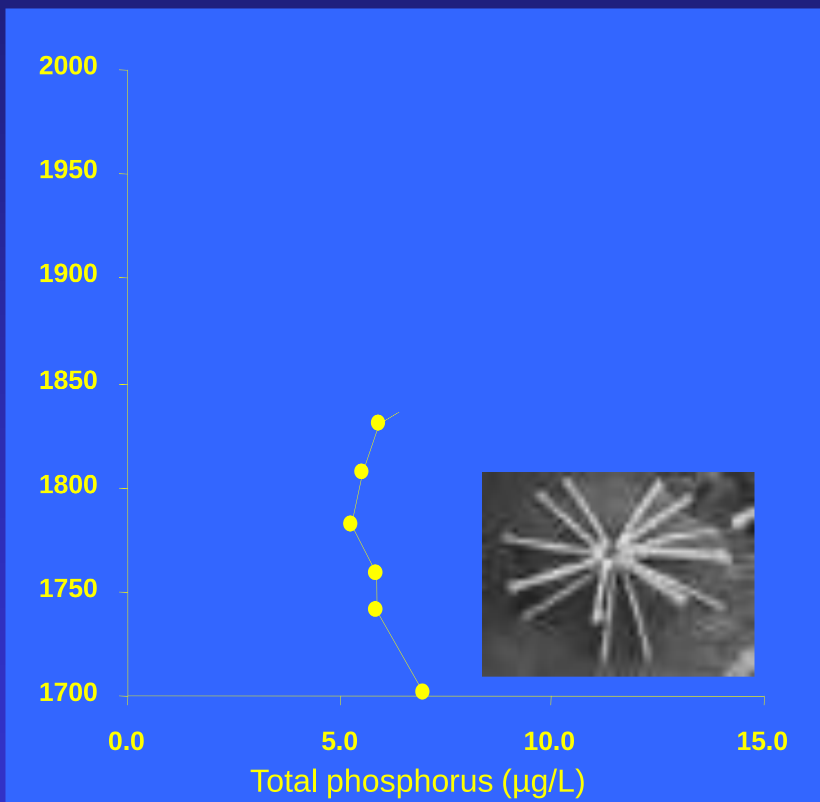
Diatoms indicate striking eutrophication and recovery



Similarly chironomids indicate marked changes
in deepwater oxygen levels

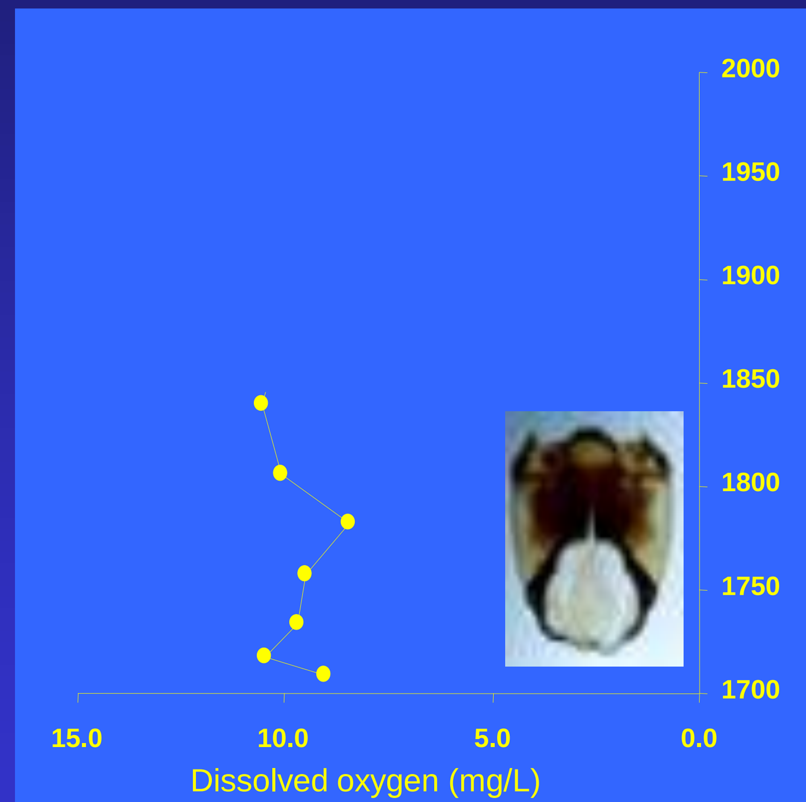
‘Natural’ conditions:
Before European settlement in the region

Phosphorus



low → high

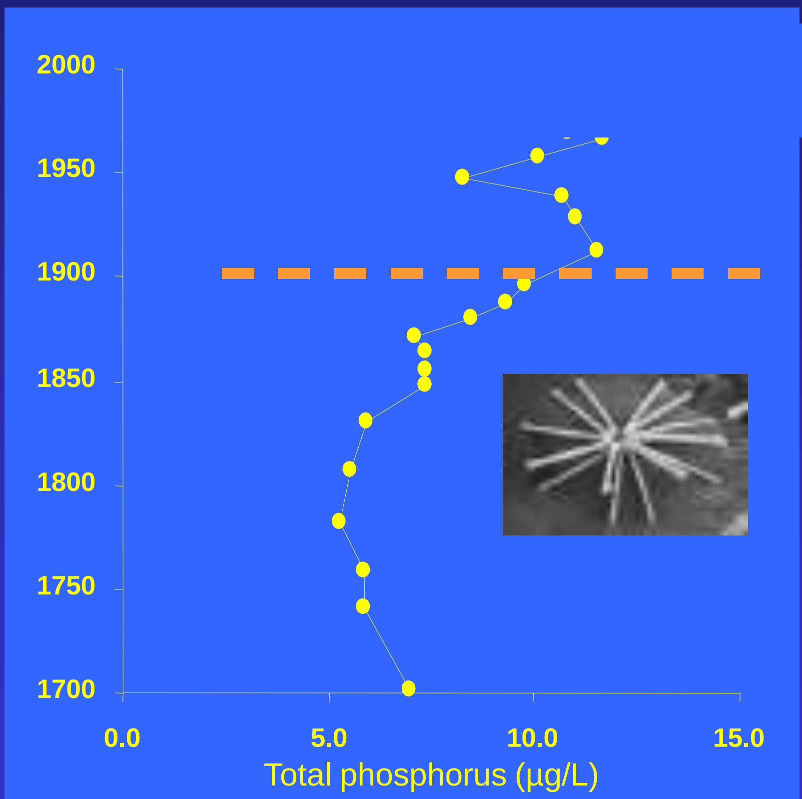
Deep-water oxygen



high → low

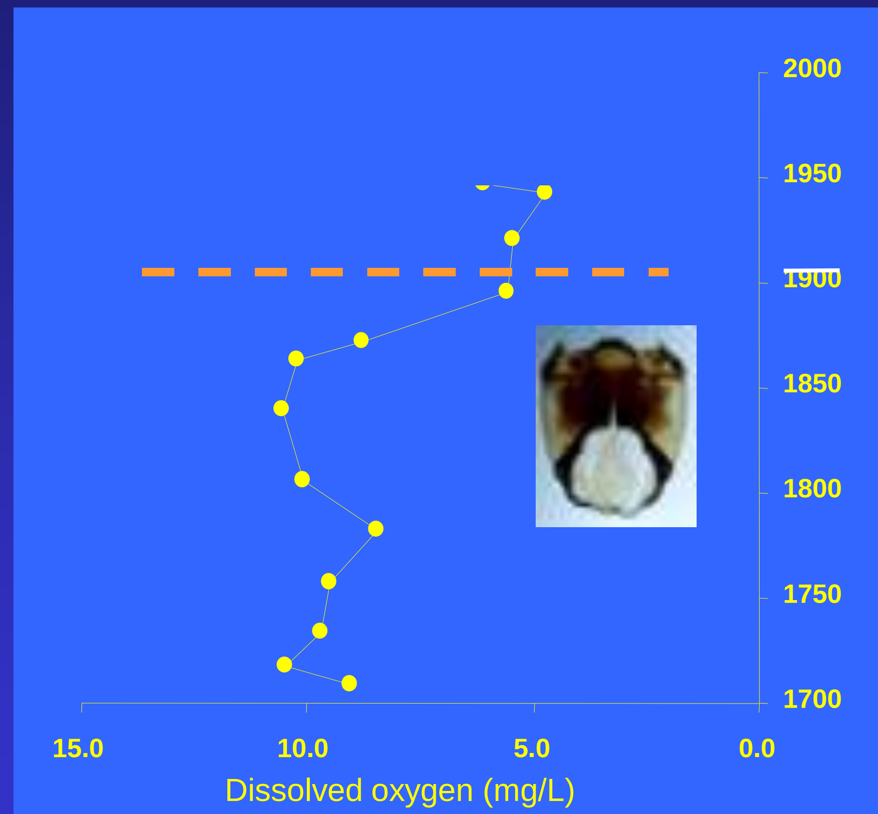
A decline in water quality

Phosphorus



low → high

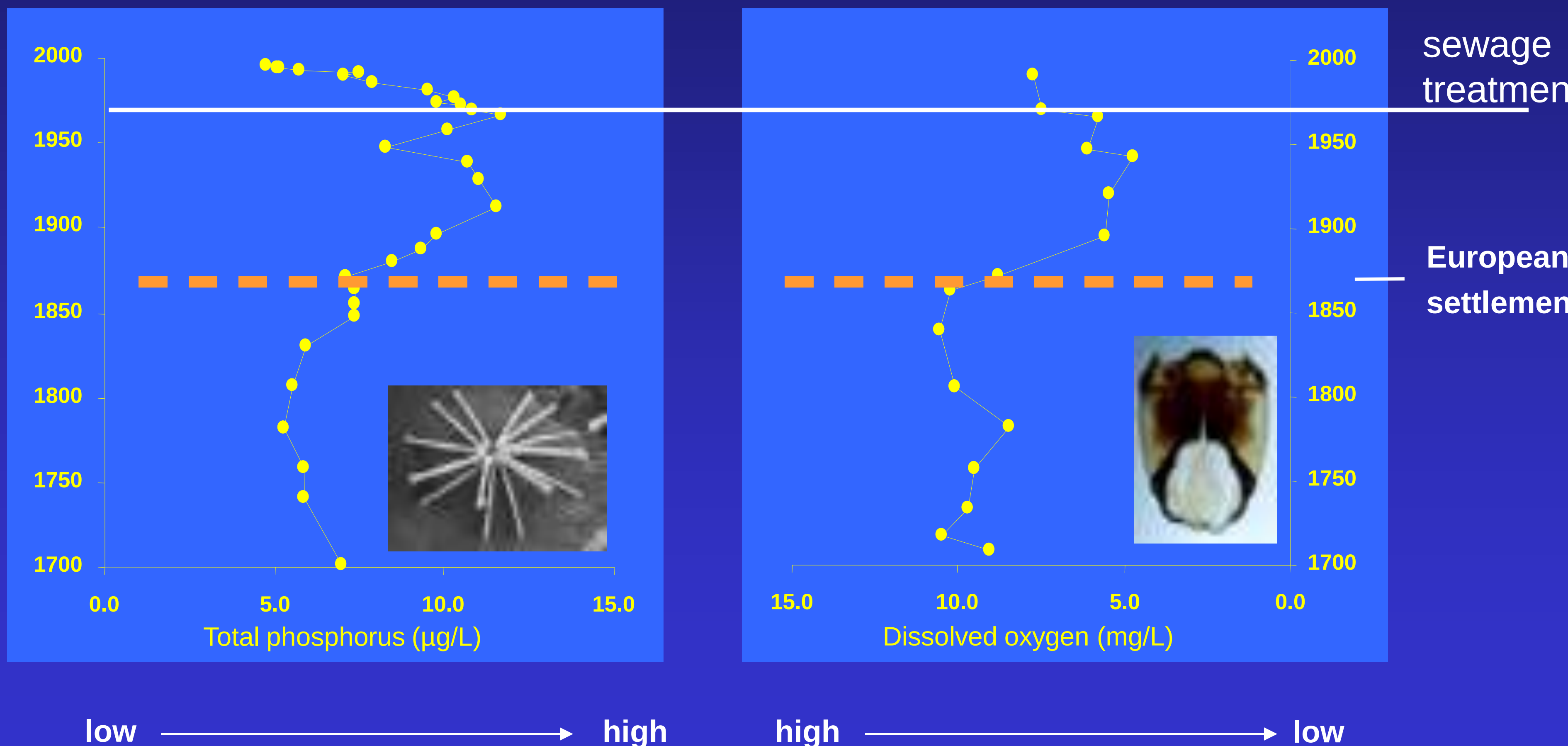
Deep-water oxygen



high → low

Turning the corner

Phosphorus **Deep-water oxygen**

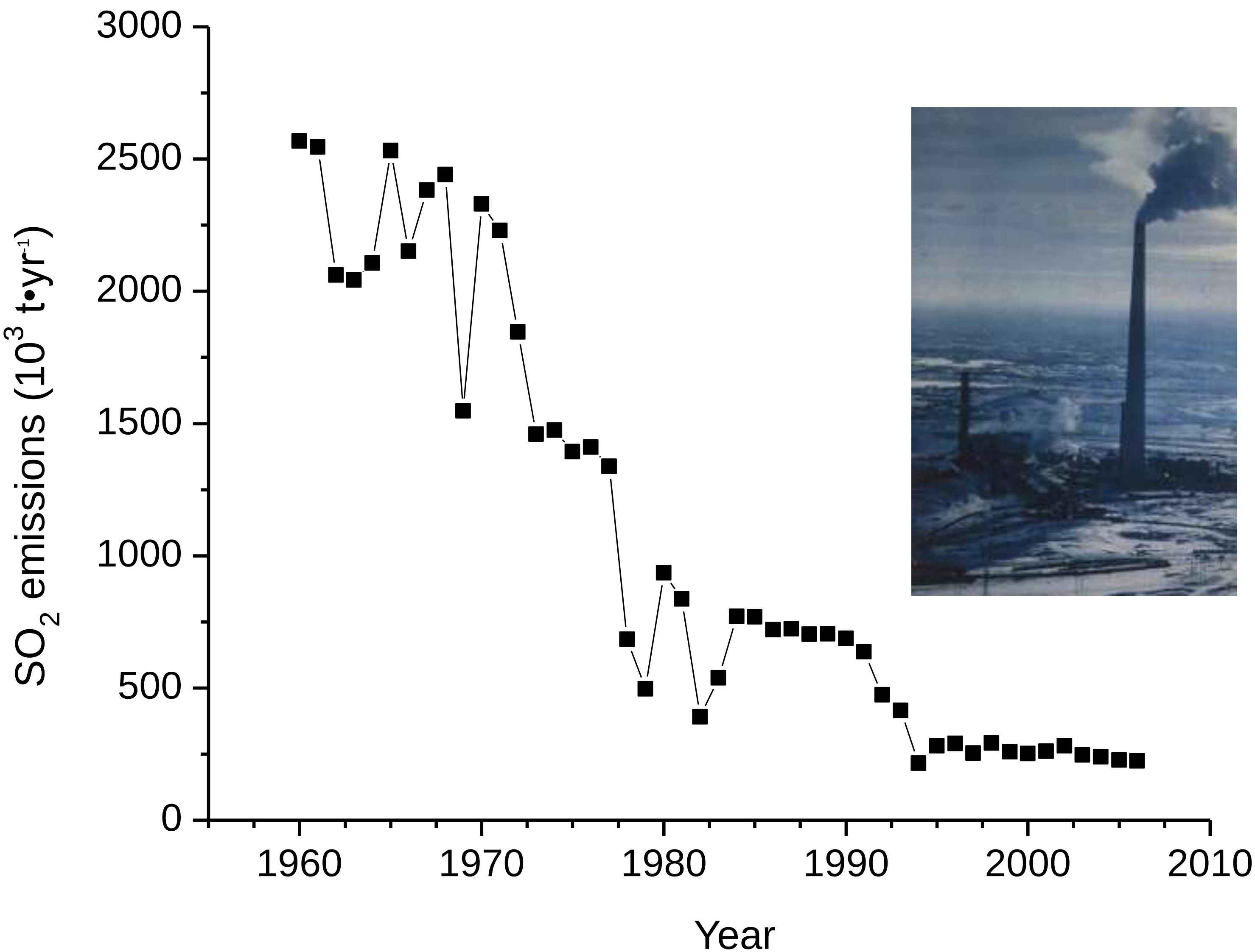


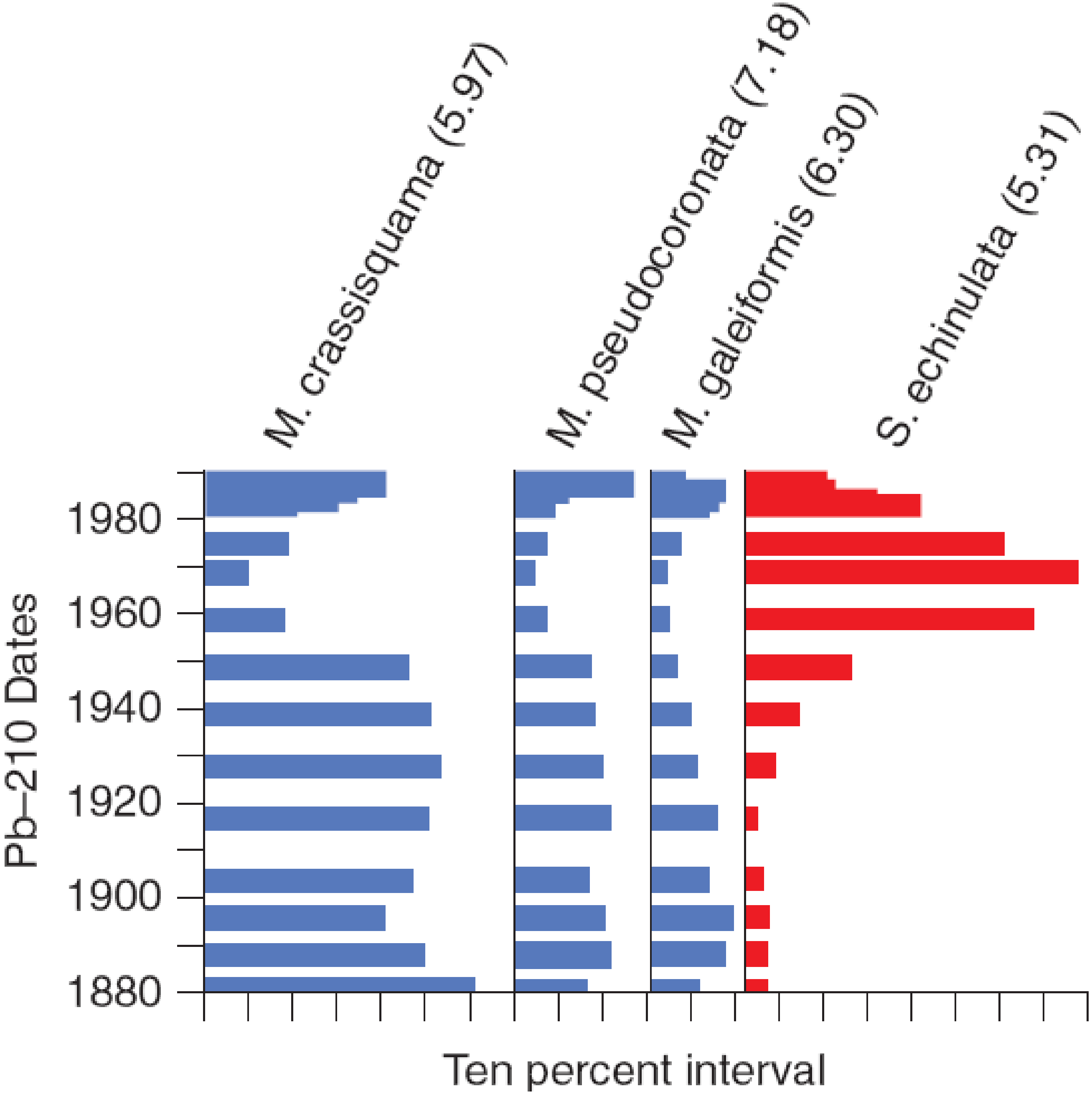
What factors can be addressed using paleolimnology?

eutrophication
anoxia and fish habitat
climate change
groundwater quality
river paleoecology
→ acidification
fire history
species invasion
speciation / evolution, etc.

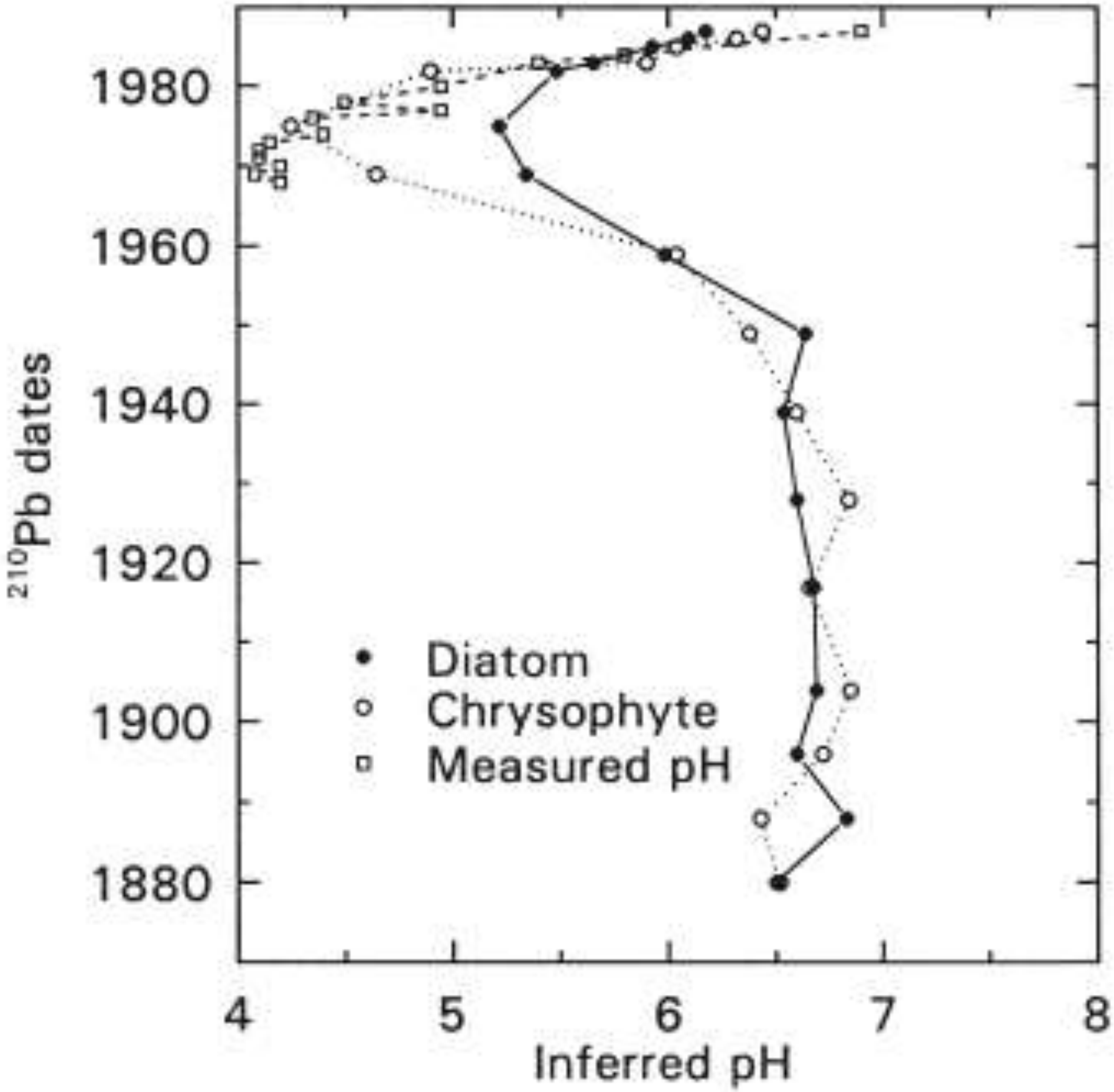
SO_2 emissions have been reduced by 55% from 1980 levels in Canada, and by 40% in the USA

Emissions from Sudbury smelters





Baby Lake, Sudbury. Fossil chrysophyte scales From Dixit *et al.* (1992, *WASP*)



Baby Lake, Sudbury. Inferred pH

From Dixit *et al.* (1992, *WASP*)

What can we learn from these Ontario studies?

1) Lake ecosystems can respond quickly (in both directions)

2) Paleolimnology can be used to identify problems, suggest solutions and to monitor improvements

Many paleolimnological studies were completed around the world, showing eutrophication and acidification were detrimentally affecting lake ecosystems.

However, nothing ever seems to be as simple as it first appears to be.

Be prepared for surprises

The threat of “multiple-stressors”

Lake [Ca] Decline

"Aquatic Osteoporosis": The widespread threat of calcium decline in fresh waters

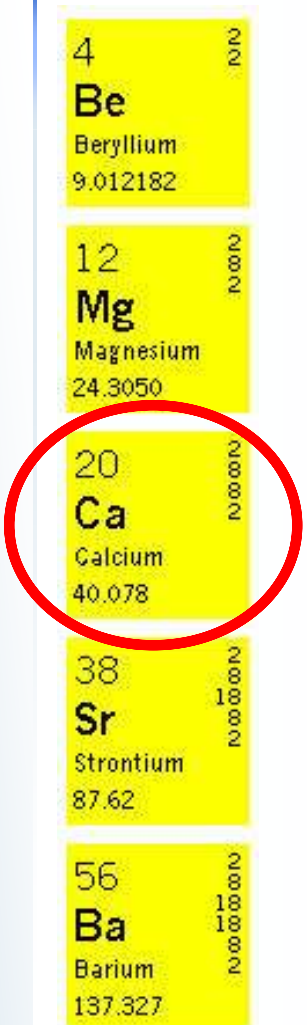
Adam Jeziorski, N. D. Yan, A.M. Paterson, and John P. Smol

M. A. Turner, D. S. Jeffries, W. Keller, R. C. Weeber, D. K. McNicol, M. E. Palmer, K. McIver, K. Arseneau, B. K. Ginn, and B. F. Cumming

Jeziorski et al. (2008) *Science* 322: 1374-1377

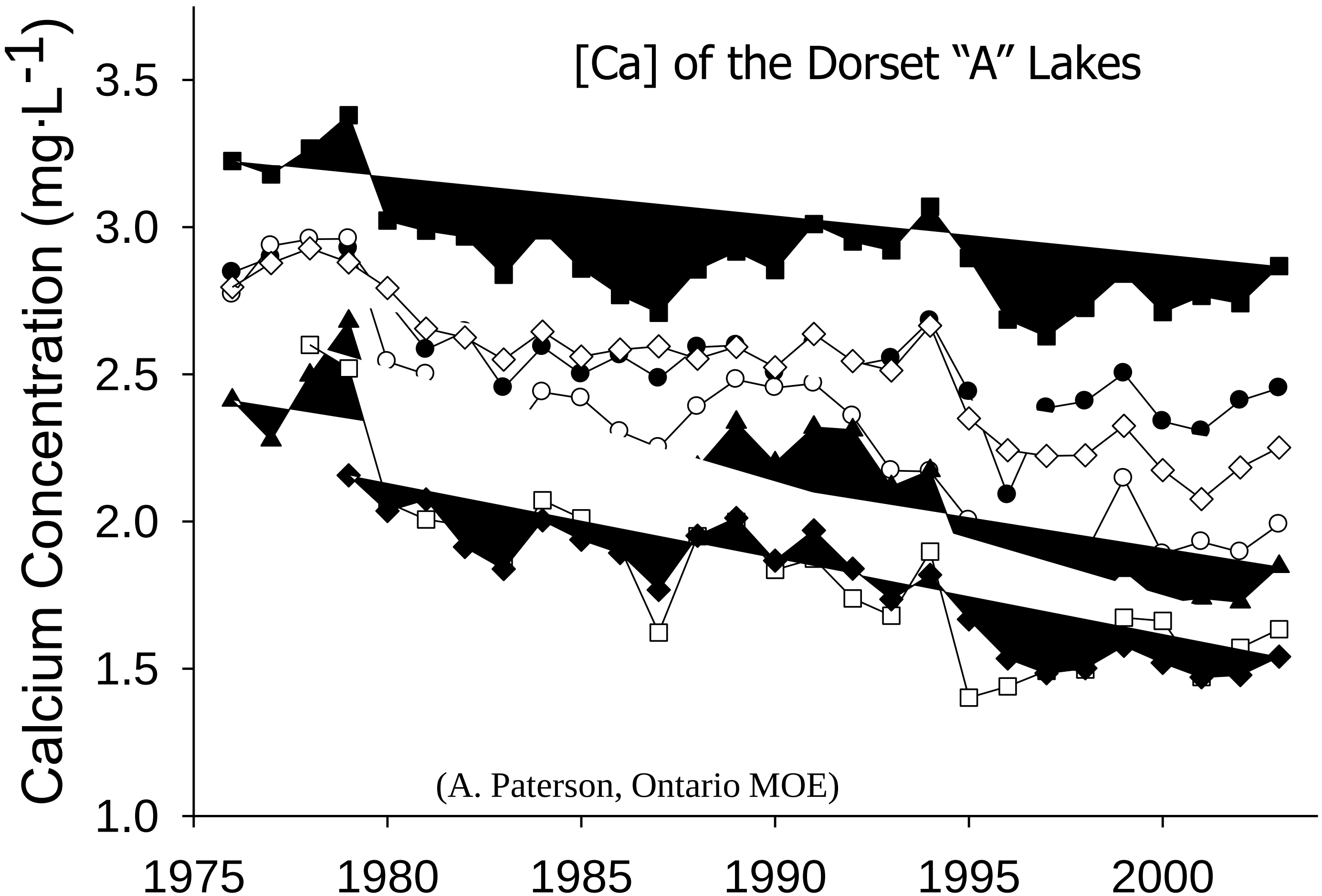
Queen's UNIVERSITY

Calcium – why do we care?



- Alkaline earth metal
- Essential nutrient, critical to the survival, development and biogeographic distribution of biota
- Ca concentrations are currently falling in many softwater regions of North America and Europe

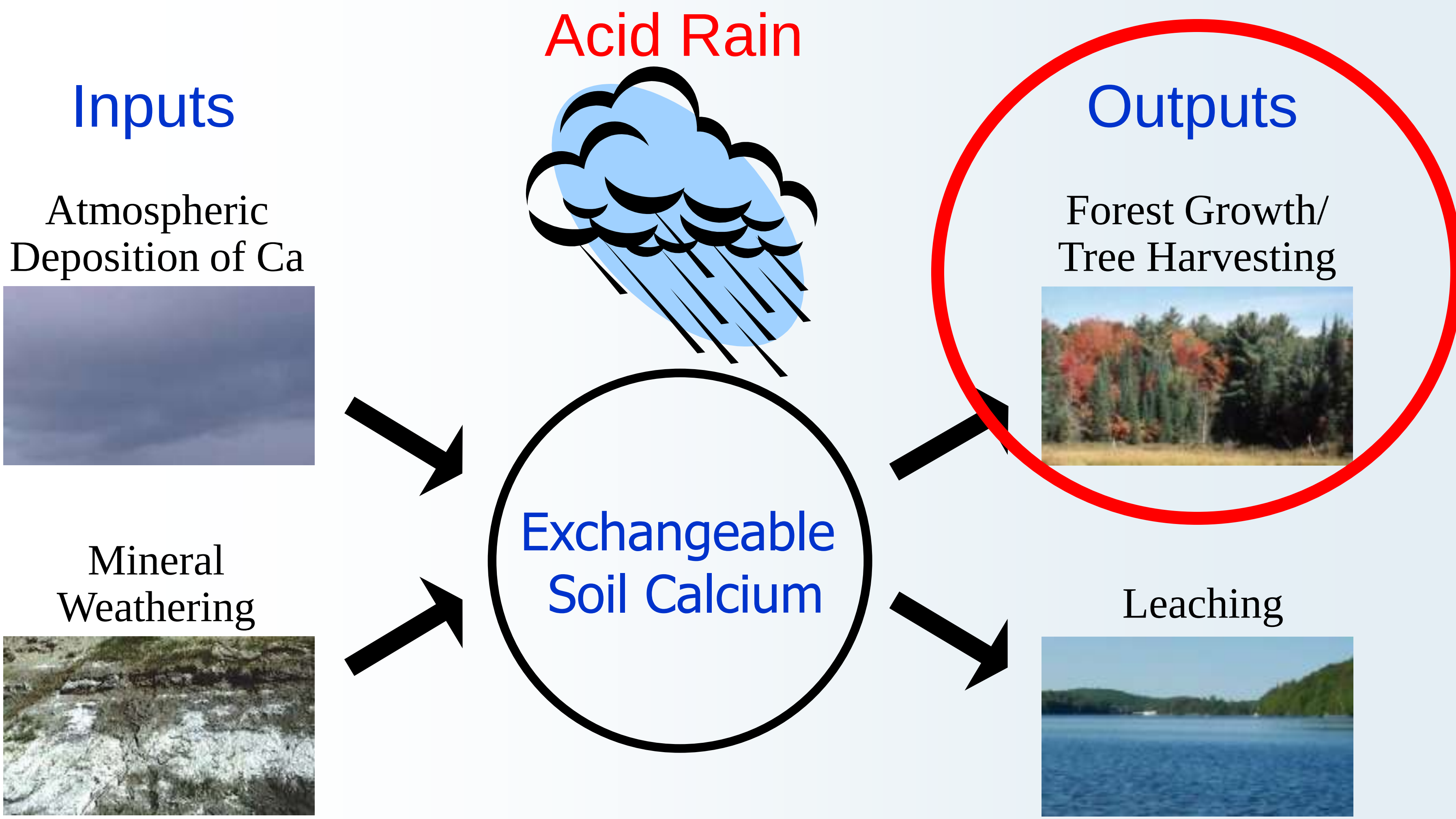
Lake [Ca] Decline



Ca Decline/ "Aquatic Osteoporosis"

- Declines in lakewater calcium (Ca) concentrations have been observed in many regions of Eastern N.A. and Europe
- Due to a lack of baseline data, some of the questions currently being raised are only answerable using paleolimnological techniques

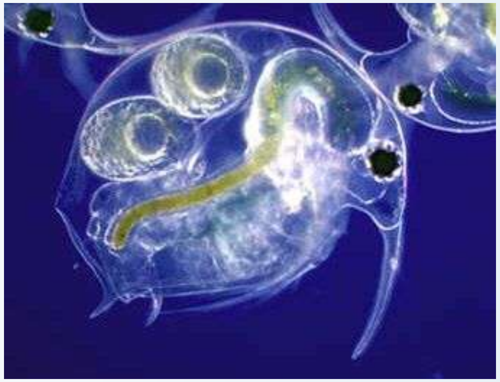
Mechanism of Ca Decline

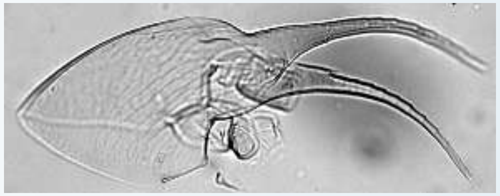


Identifying an Indicator for Calcium Thresholds

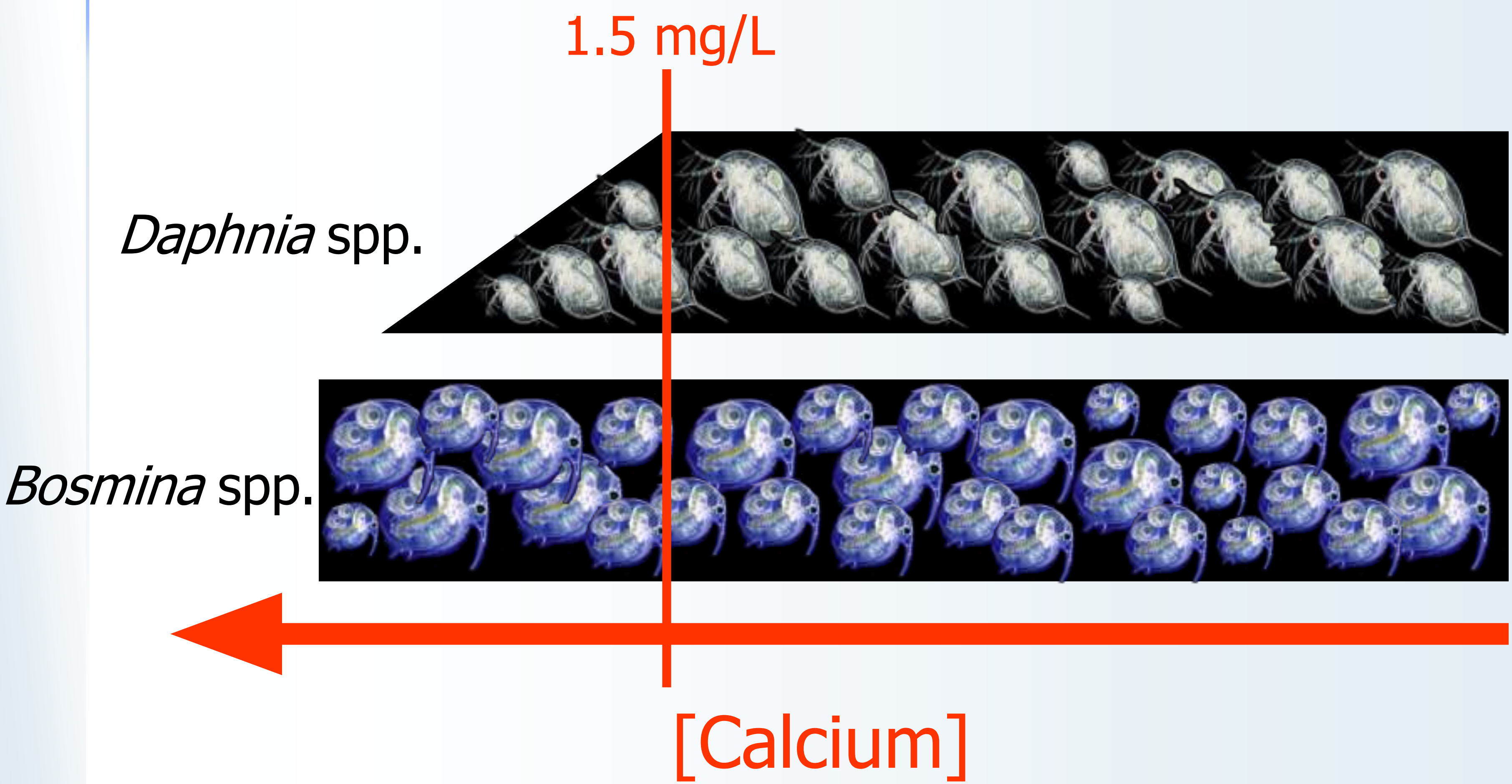
Crustacean Zooplankton

- Crustacean zooplankton have a direct dependence upon Ca (used as a structural material in the carapace)
- Species-specific [Ca] differences (and by extension Ca requirements)
- Leave identifiable remains that preserve well in sediments (head-shields, carapaces, ephippia)



Daphnia – the Miner's Canary ?



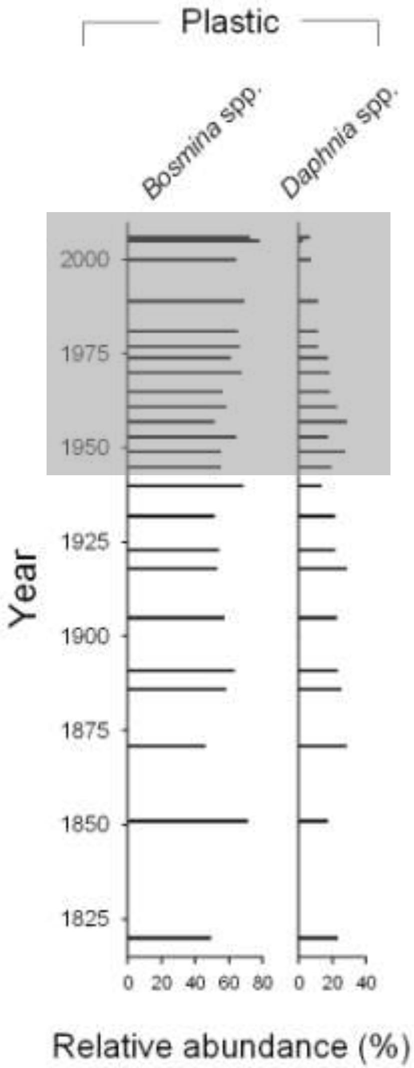
3 Paleolimnological Case Studies

- Plastic Lake (Ontario) - Received little acid deposition and the lake did not acidify;
  [Ca] = 1.4 mg/L

- Little Wiles Lake (NS) - Naturally acidic;
  [Ca] = 1.0 mg/L

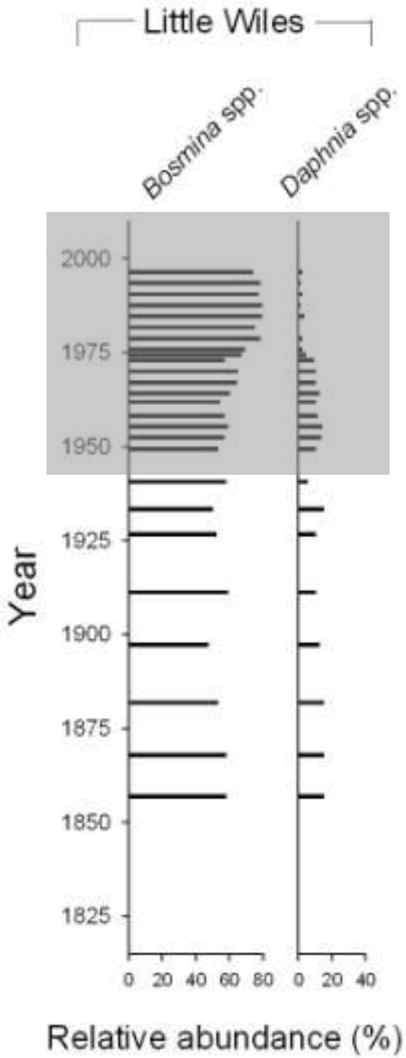
- Big Moose Lake (NY) - Experienced a steady pH decline throughout the 1950s (peak acidification) to 4.5 and has subsequently recovered to >5.5;
  [Ca] = 1.5 mg/L

Plastic Lake (ON, Canada)



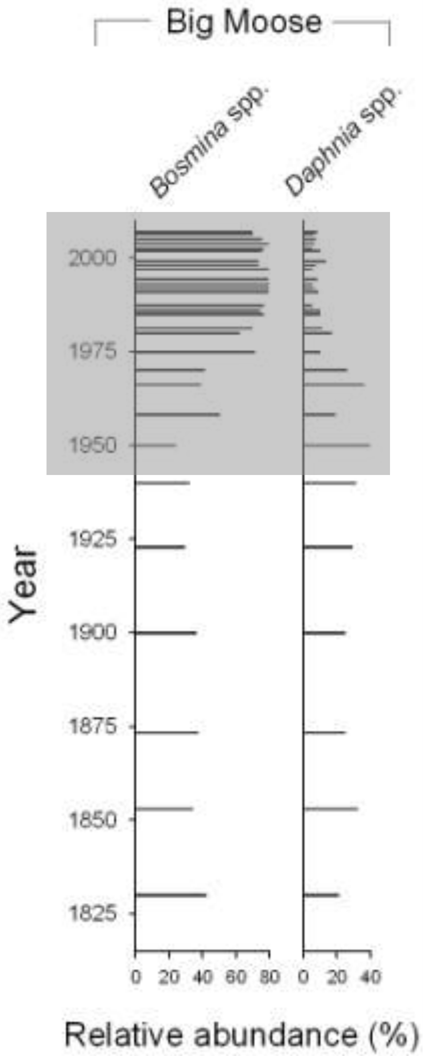
- Located on the Canadian Shield
- Received little acid deposition and the lake did not acidify
- 2006 [Ca] = 1.4 mg/L

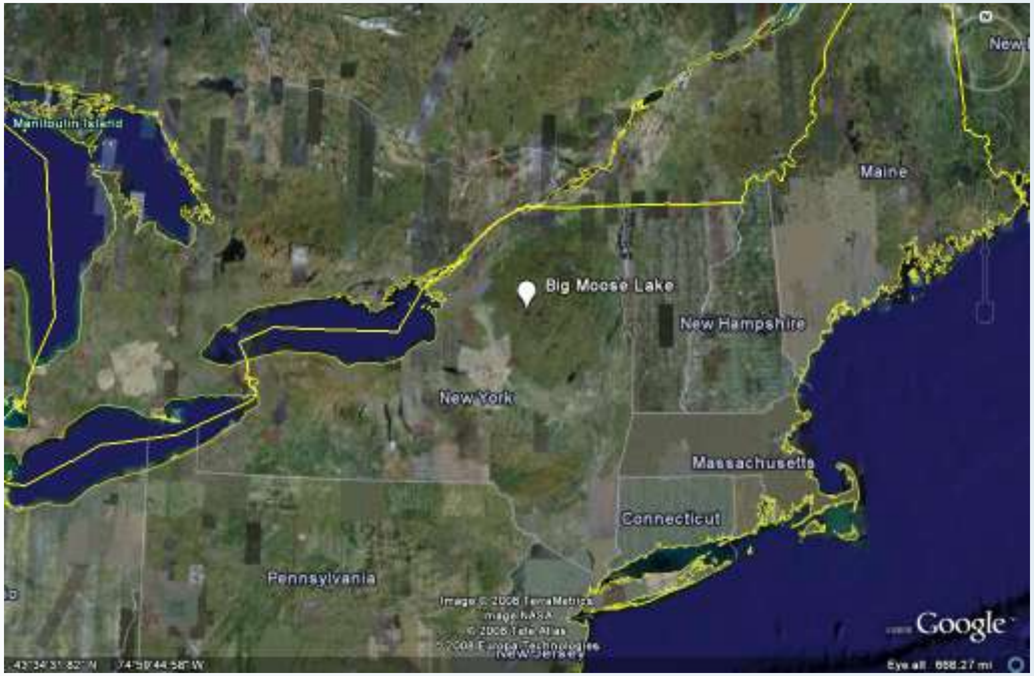
Little Wiles Lake (NS, Canada)



- Located off the Canadian Shield
- Naturally acidic
- 2006 [Ca] = 1.0 mg/L

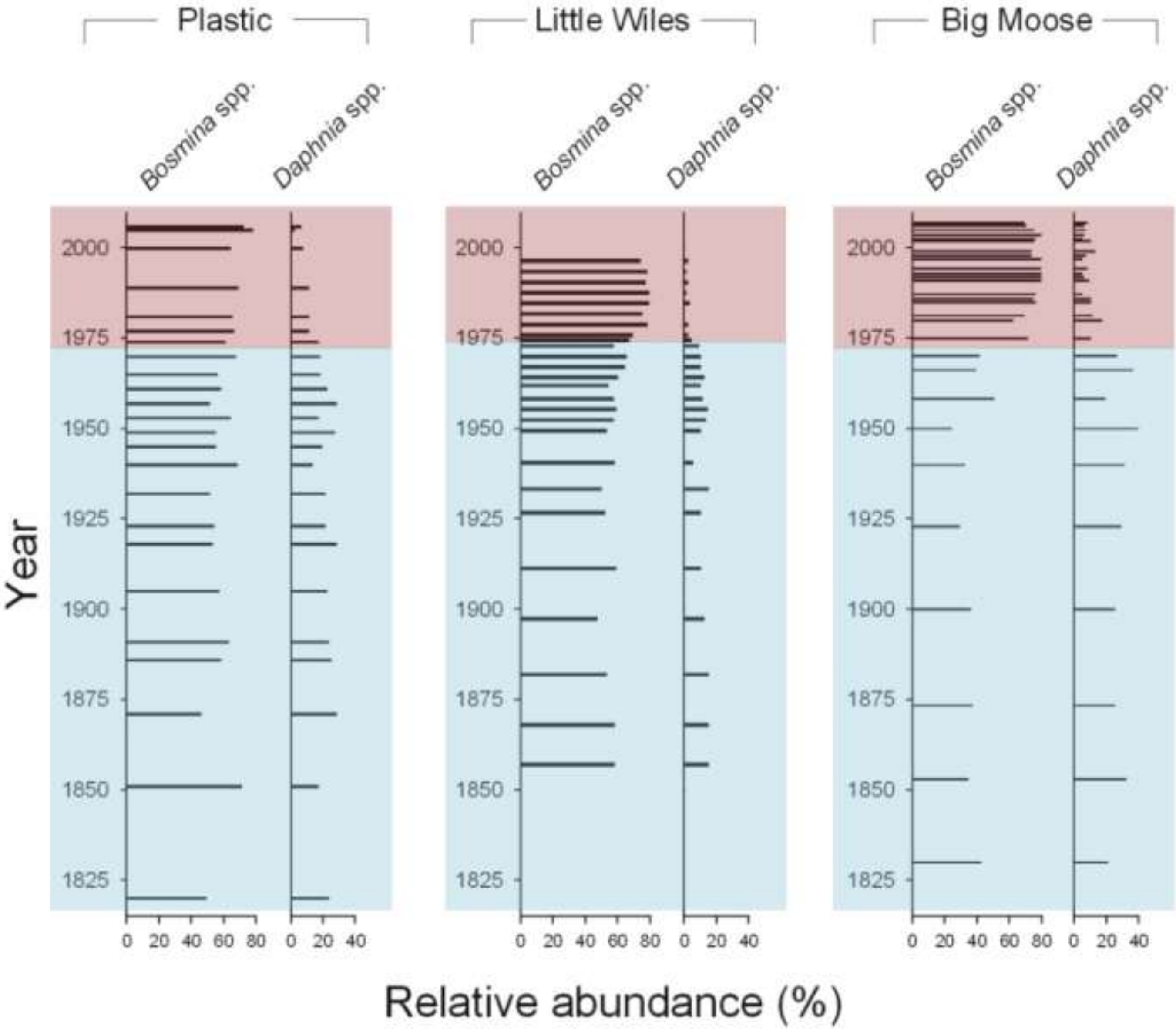
Big Moose Lake (NY, USA)



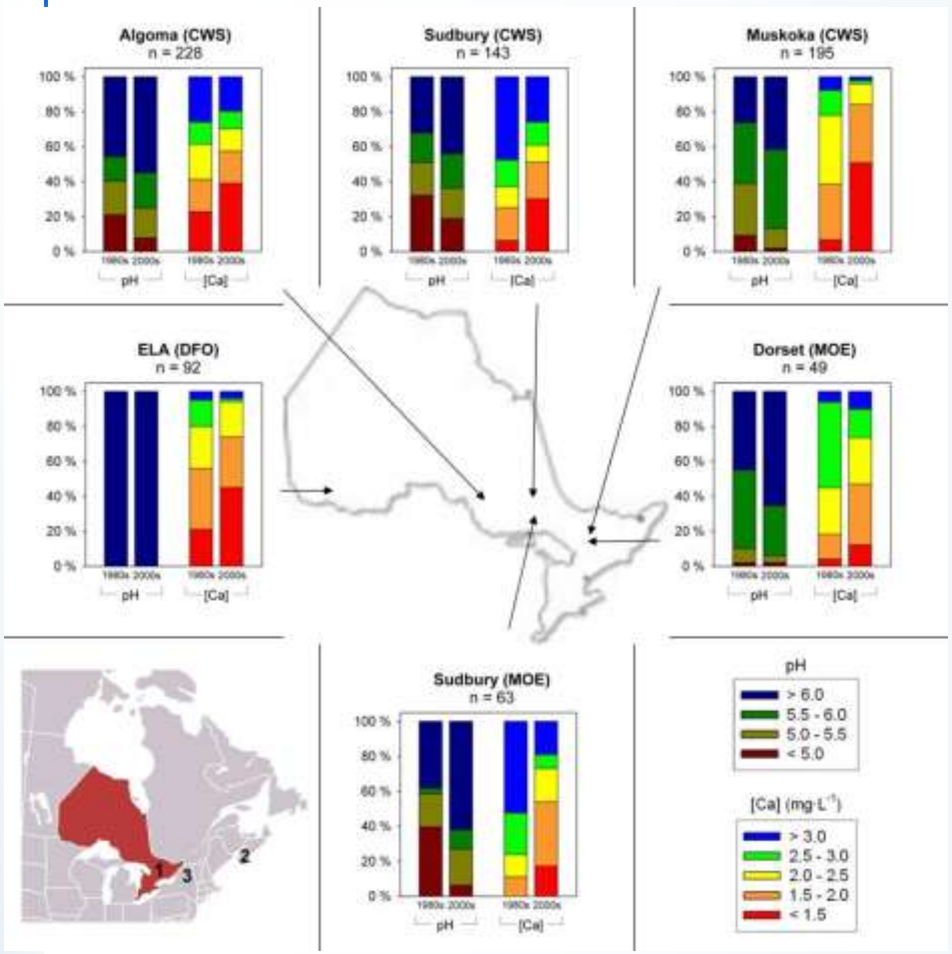


- Located on the Pre-Cambrian Shield in Adirondack Park of NY
- Experienced a steady pH decline throughout the 1950s (peak acidification) to 4.5 and has subsequently recovered to >5.5
- 2006 [Ca] = 1.5 mg/L

3 acidification scenarios, similar *Daphnia* responses



Low calcium levels are now widespread on Shield lakes

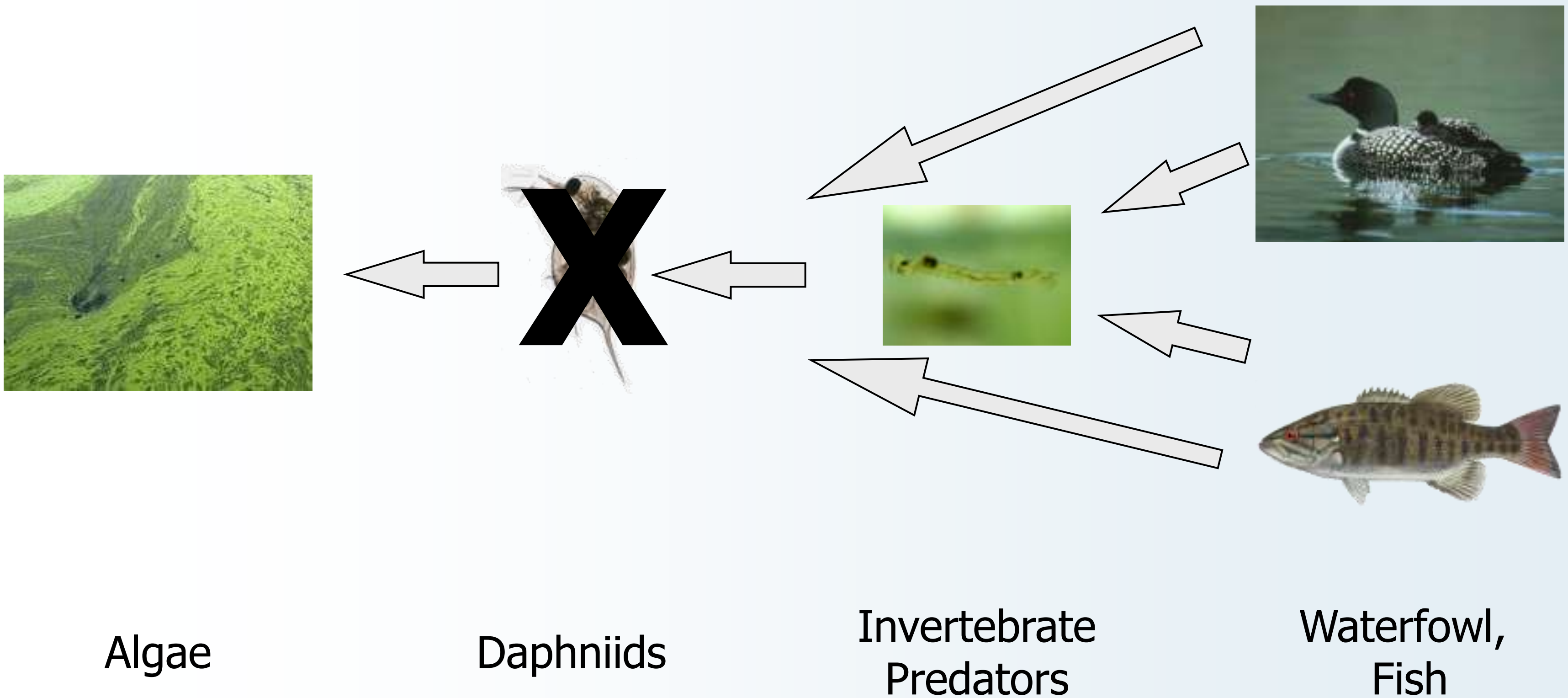


- About 1/3 of shield lakes surveyed have declined in Ca levels to below the 1.5 mg/L level
- About 2/3 are now below the 2.0 mg/L level

n = 770

(Jeziorski et al., 2008)

Ecosystem Implications: Daphniid Cascade



Ecosystem Implications: Other Biota

Potentially sensitive biota include:

- Mussels (shell)
- Gastropods (shell)
- Crayfish (exoskeleton)
- Macrophytes
- Waterfowl (dietary, egg shells)

Also indirect effects such as:

- pH resilience
- Metal toxicity

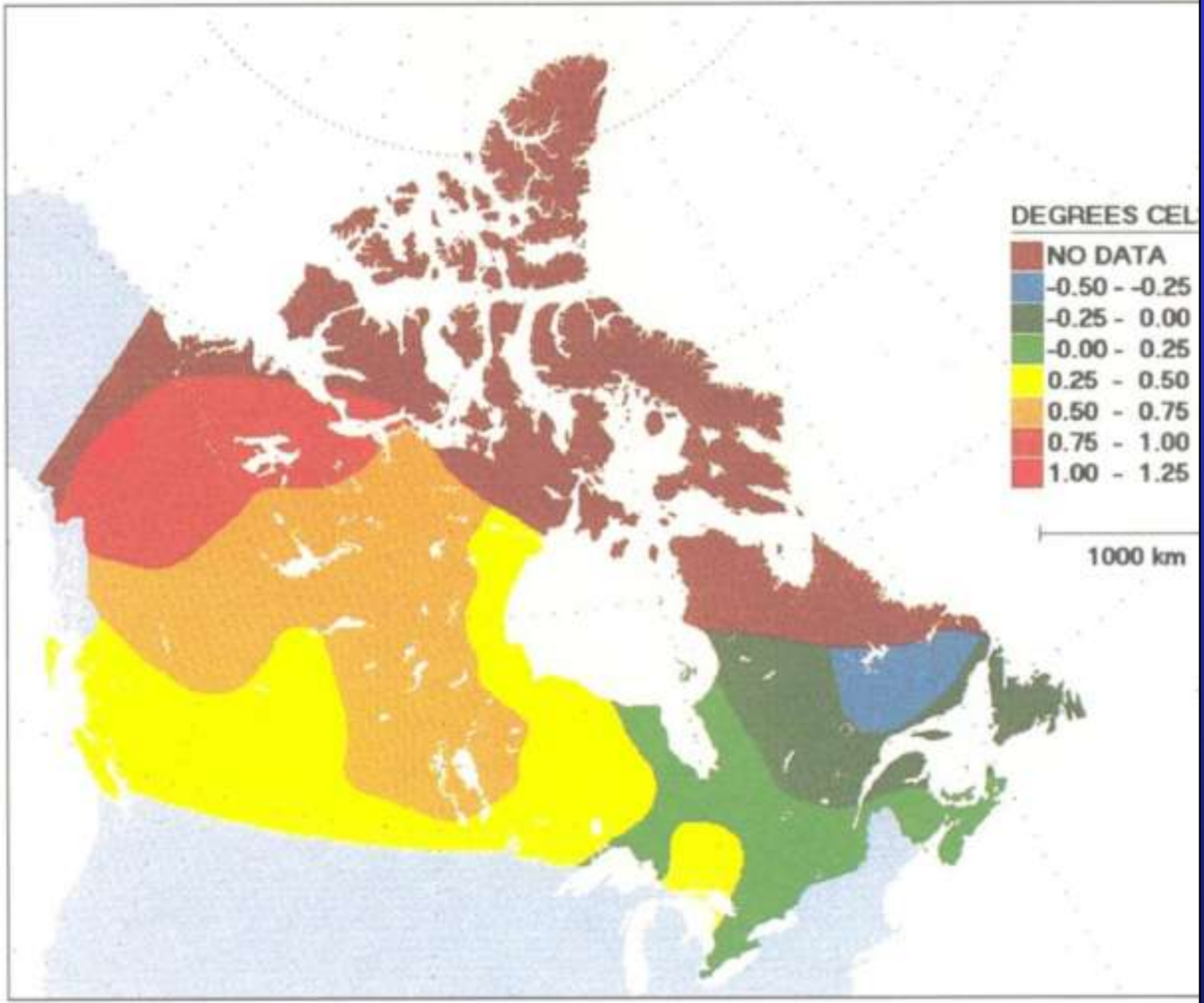
The Limnologist's Canary?

Climate change:

The new “threat multiplier”

www.ccepr.org/liu/researchCC_en.html

Figure 21
Average Annual Temperature Departures From 1951-80
Average For 1940 to 1949



SOURCE: Environment Canada.

Environment Canada, SOE Report No. 92-2

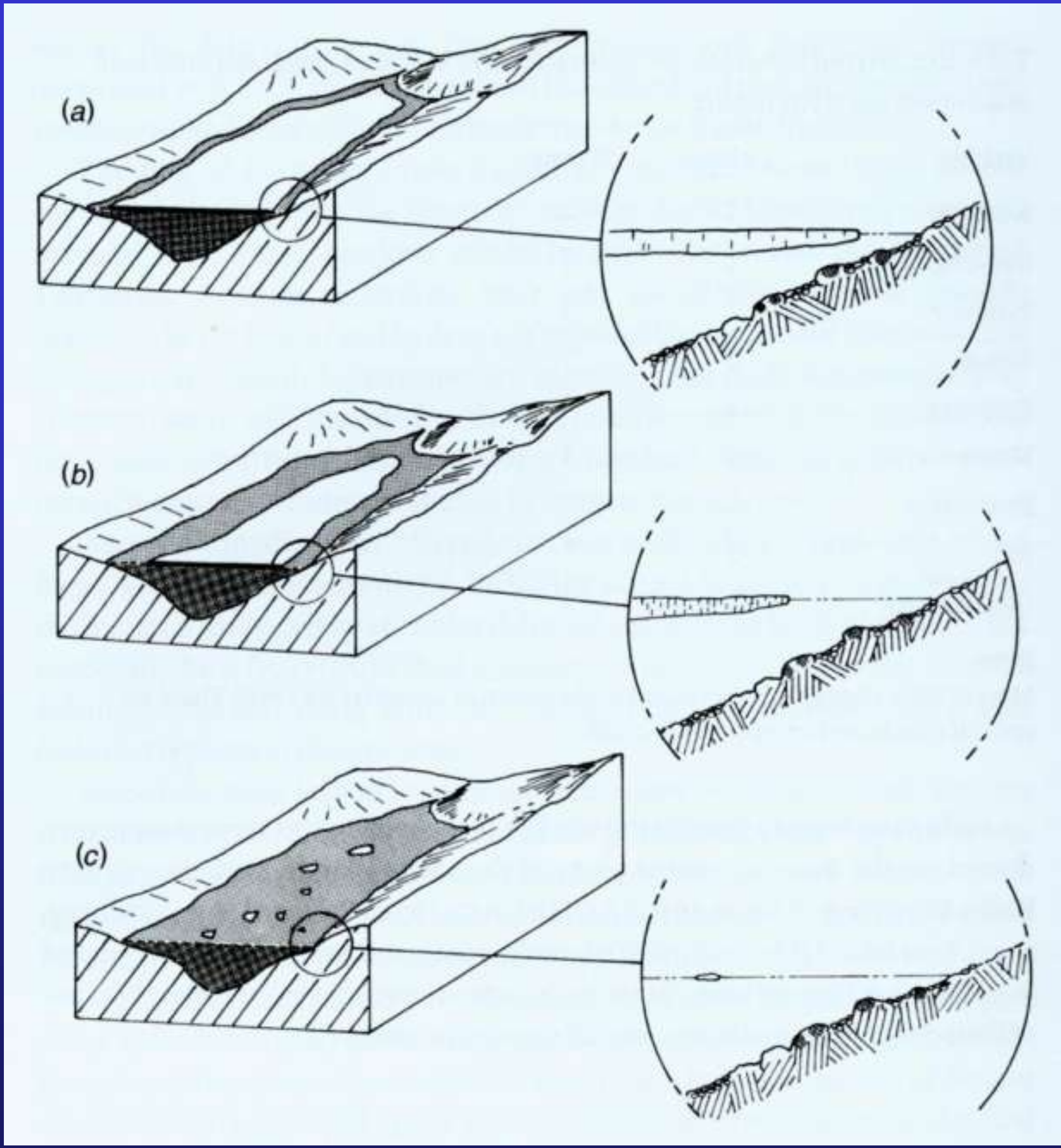

RUSSIA
ARCTIC OCEAN
Norwegian Sea
Chukchi Sea
Arctic Circle
Beaufort Sea
GREENLAND
ICELAND
Reykjavik
Baffin Bay
Yukon
Anchorage
Godthab
Gulf of Alaska
Whitehorse
Mackenzie
Great Bear Lake
Juneau
Yellowknife
Great Slave Lake
CANADA
Prince Rupert
Hudson Bay
St. John's
PACIFIC OCEAN
Edmonton
Lake Winnipeg
Calgary
Victoria
Vancouver
Regina
Charlottetown
Seattle
Spokane
Winnipeg
Fredericton
Vancouver
Portland
Helena
Lake Superior
Montreal
Halifax
Augusta
Concord
Boston
ATLANTIC OCEAN
Boise
Bismarck
Missouri
St. Paul
Minneapolis
Lake Huron
Lake Michigan
Lake Ontario
Lake Erie
Toronto
Hartford
Providence
Milwaukee
Buffalo
New York
Salt Lake City
Cheyenne
Chicago
Detroit
Cleveland
Philadelphia
Omaha
Pittsburgh
Baltimore
San Francisco
Denver
U. S. A.
Indianapolis
Washington D. C.

Cape Herschel, Ellesmere Island

Cape Herschel Field Station; July 9, 2007

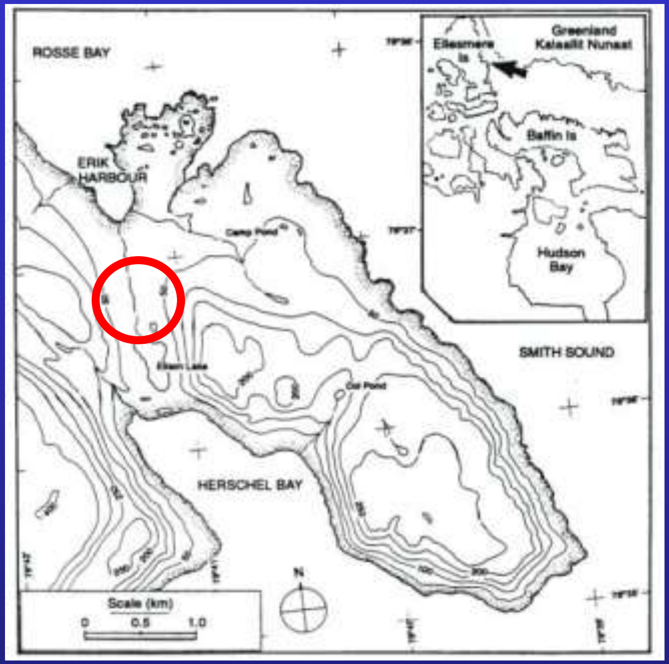
Cooler temperatures

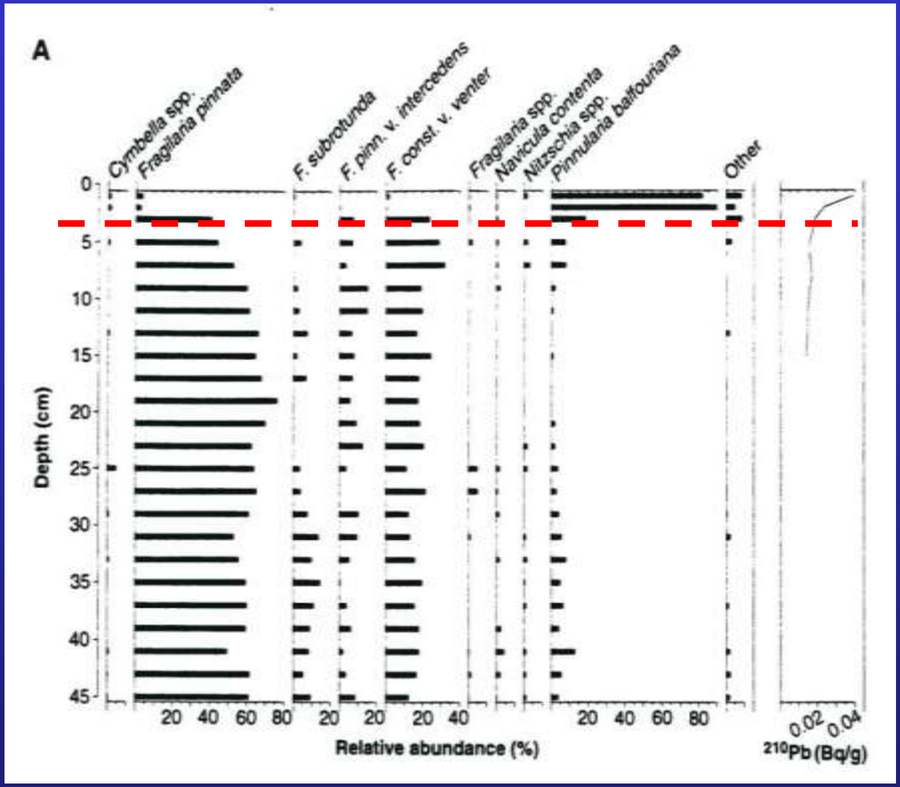
Warmer Temperatures



(Smol 1983, 1988)

Cape Herschel, Ellesmere I., Elison Lake

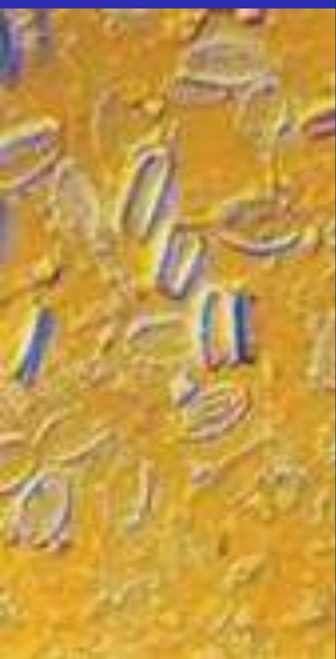


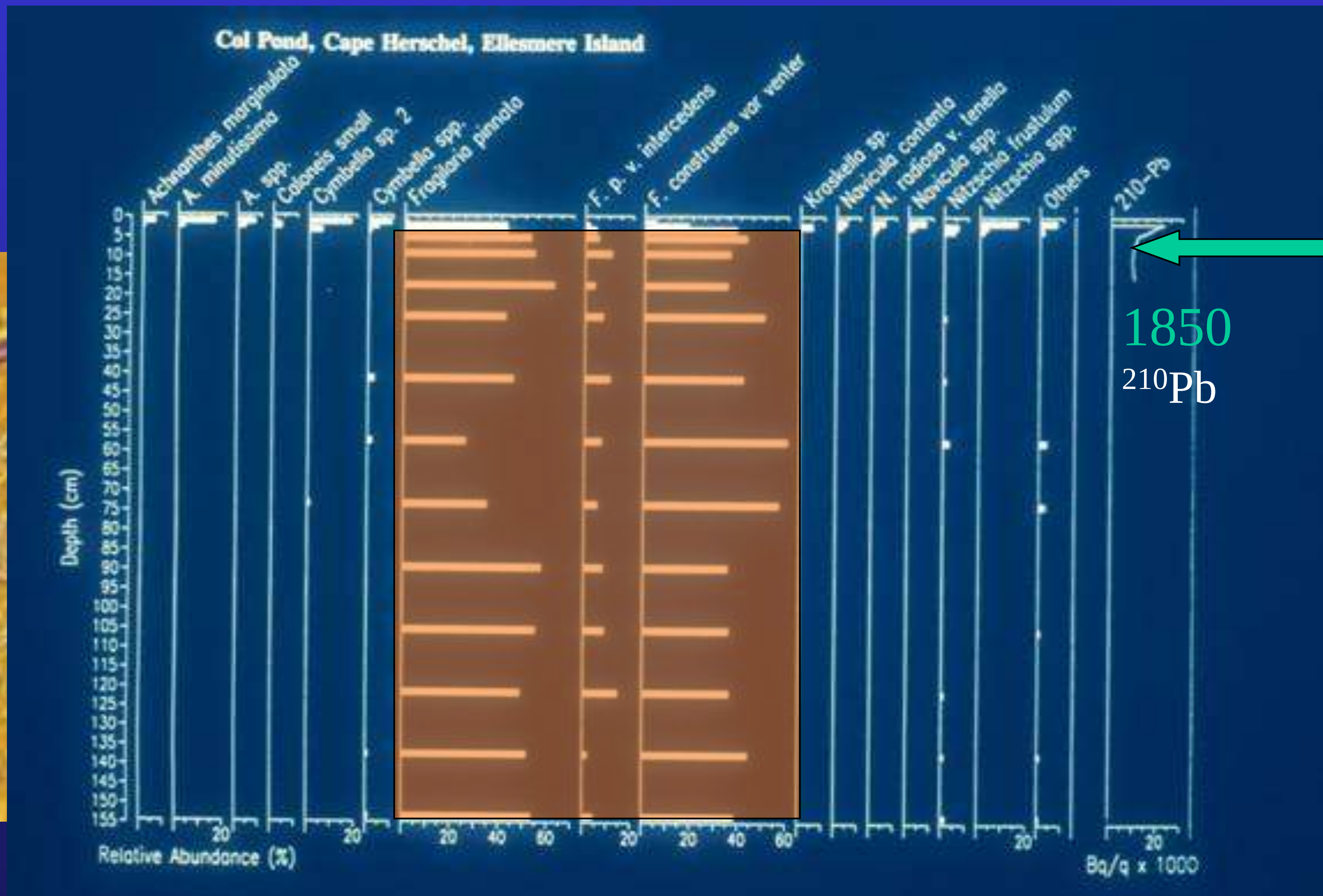


Douglas *et al.*, 1994, *Science*

- unprecedented ecosystem change in ~4 k yr

Cape Herschel, Ellesmere I., Col Pond





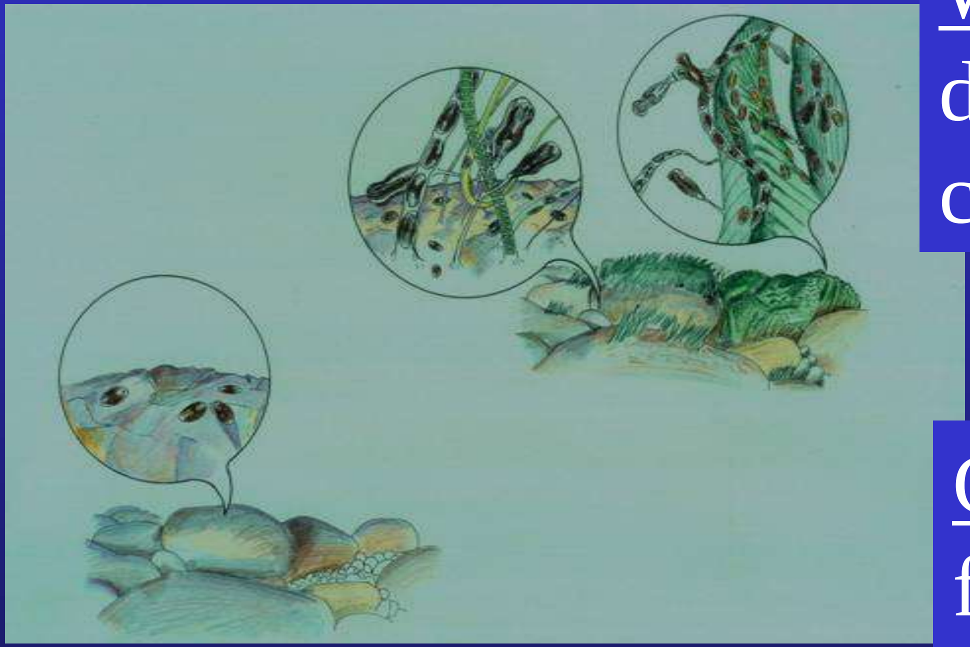
(Douglas, Smol & Blake; *Science* 1994)

Predicted Responses to Climate Change

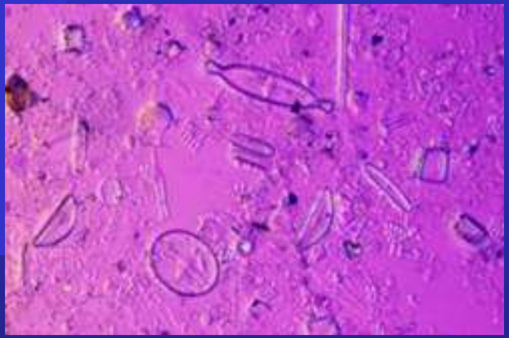
Douglas and Smol, 1999

VARIABLE	COLDER	WARMER
Ice Cover	↑	↓
Growing Season	↓	↑
Plankton	↓	↑
Mosses	↓	↑
Diversity	↓	↑
Nutrients	↓	↑
Production	↓	↑
pH	↓	↑
Conductivity	↓	↑

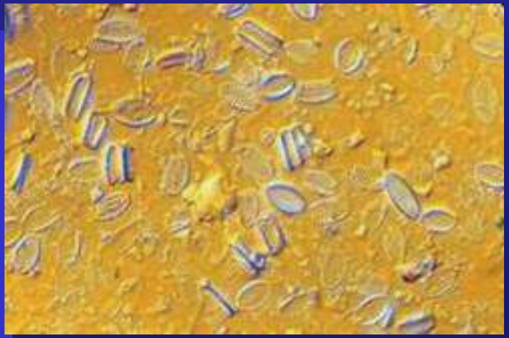
Interpretation of data: warming scenario



Warmer: diverse, complex



Cooler: few taxa, simple



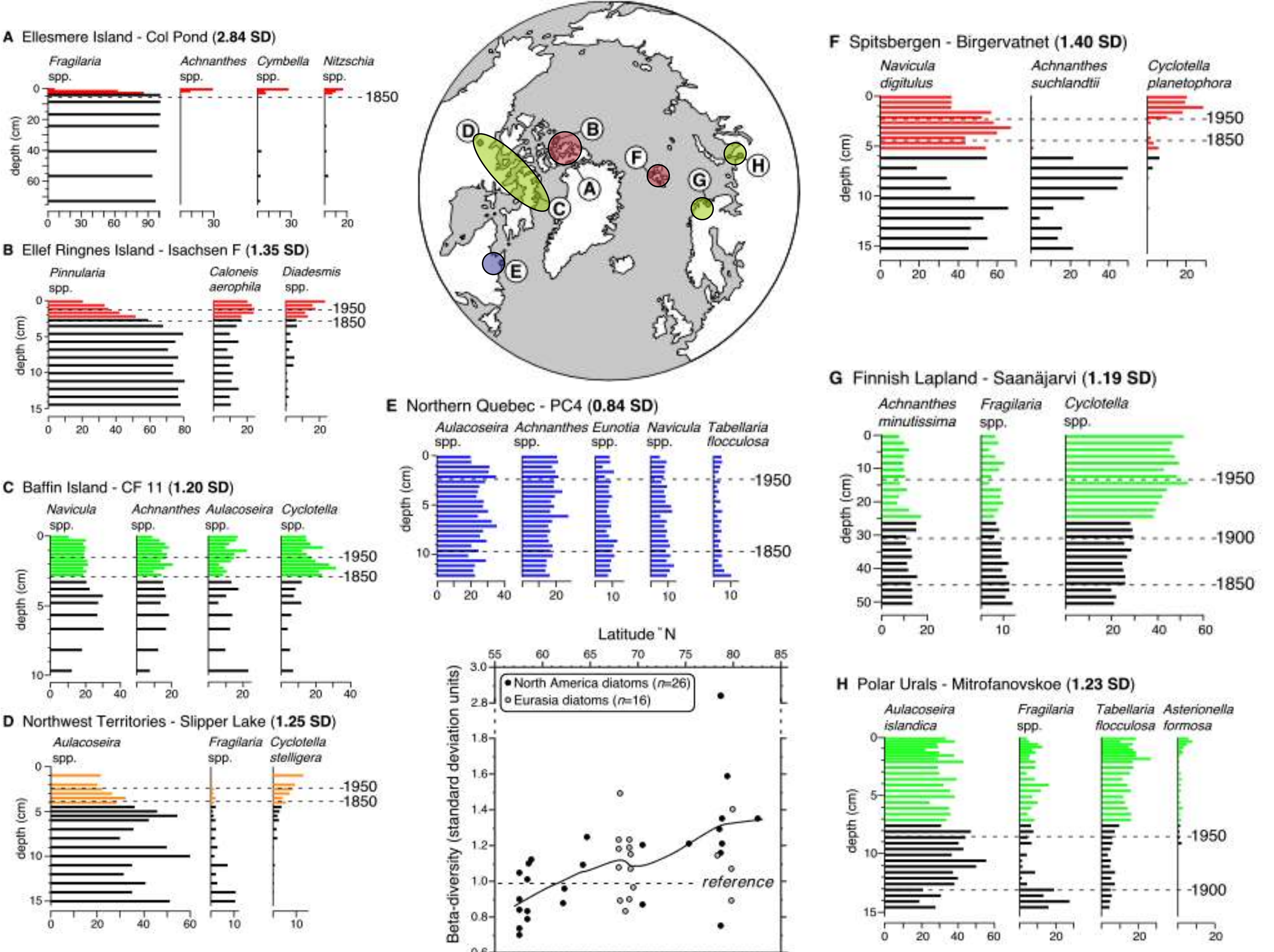
Douglas and Smol, 1999

Douglas, M.S.V., Smol, J.P., and Blake, W., Jr. 1994. Marked post-18th century environmental change in high Arctic ecosystems. *Science* 266: 416-419.

Climate-driven regime shifts in the biological communities of arctic lakes.

Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J, Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M-A., Hughes, M., Keatley, B.E., Laing, T.E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A.M., Perren, B., Quinlan, R., Rautio, M., Saulnier-Talbot, É, Siitonen, S., Solovieva, N., and Weckström, J.

(2005) Proc. Nat. Acad. Sci. 102: 4397- 4402.



(From Smol, Wolfe *et al*. 2005, *PNAS*)

Climate-Related Ecological Thresholds in High Arctic Lakes and Ponds

Ice and snow cover

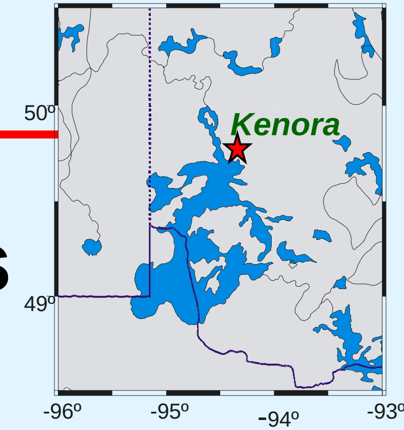
Substrates, such as mosses

Thermal stratification

Water chemistry, such as nutrients

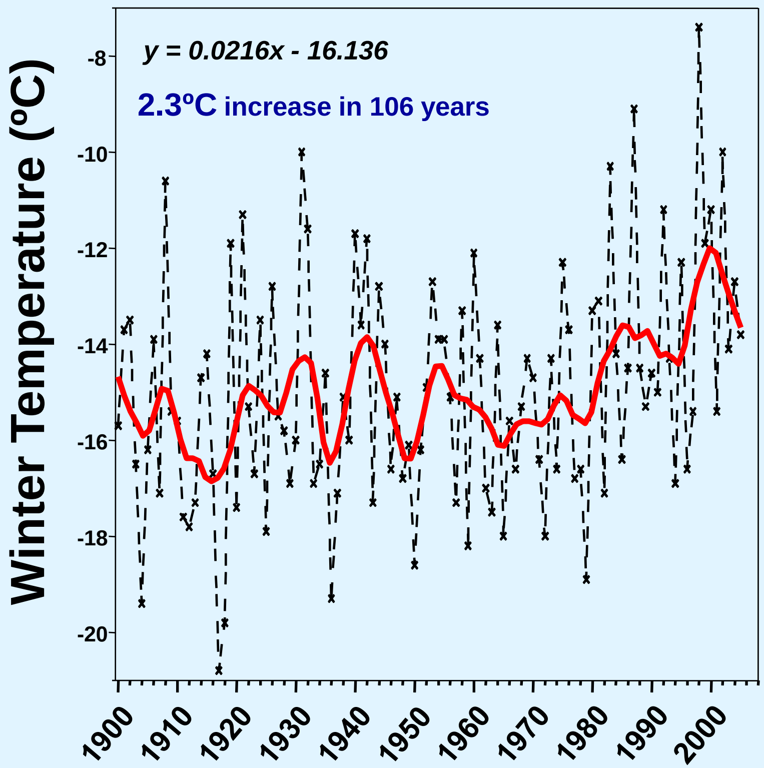
Are similar patterns occurring in temperate lakes?

Kenora 100-year Temperature Record

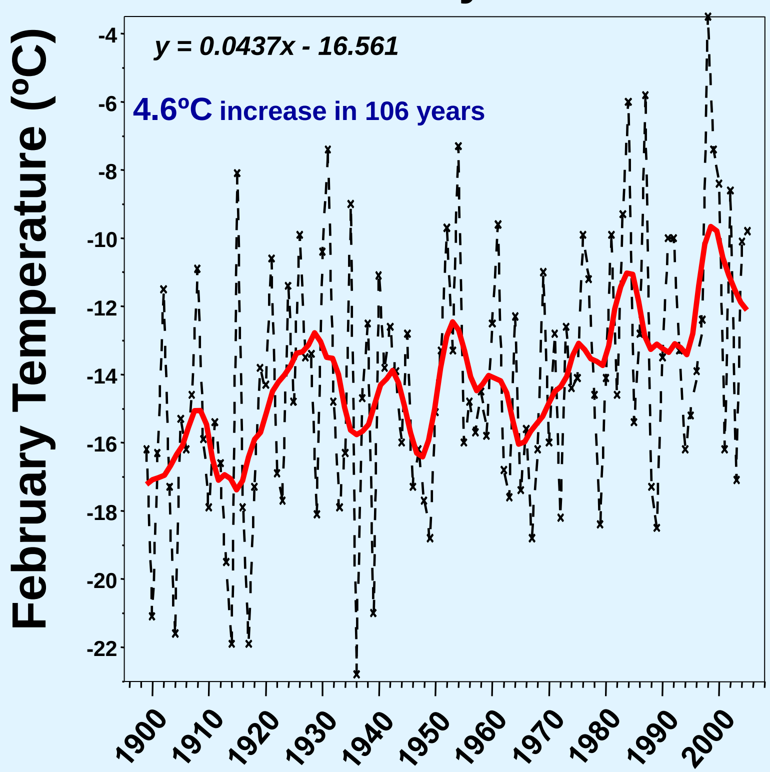


Lake of the Woods

Winter



February



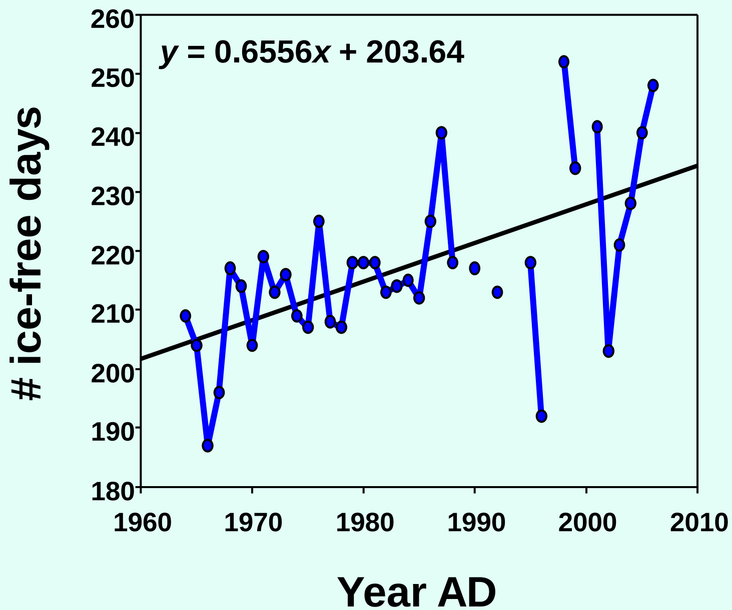
Rühland et al submitted

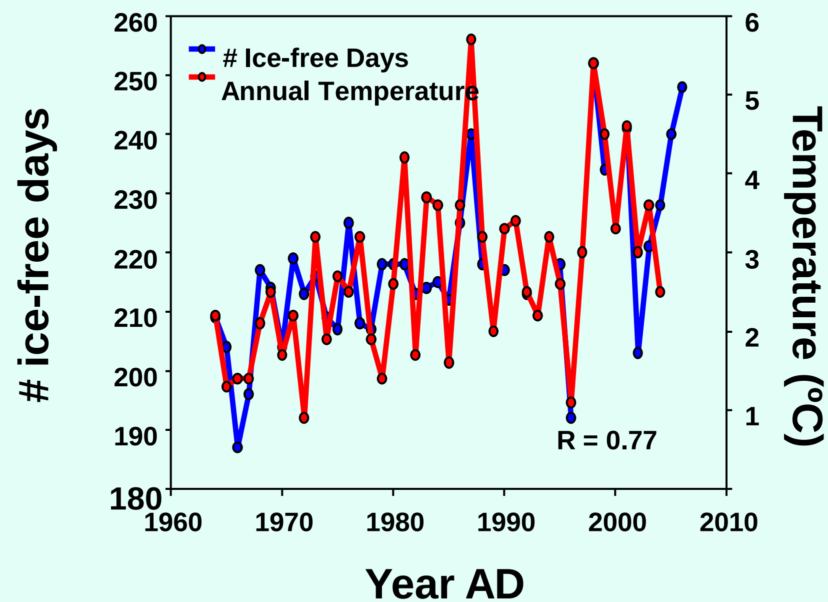
Environment Canada data
(http://www.cccma.ec.gc.ca/hccd/)

Whitefish Bay Ice Cover Record

“The longer & colder a winter is, the earlier lakes freeze & the later they thaw.”

D. M. Livingstone (2005)





- Ice-free period increased by **27.7** days since 1964
- Corresponds to increased temperatures

Data from Ministry of Natural Resources, Kenora, Ontario, Canada

Rühland, Paterson & Smol 2008: Global Change Biology

Taxon-specific shifts: *Cyclotella-Aulacoseira-Fragilaria*

Lake water properties & warming

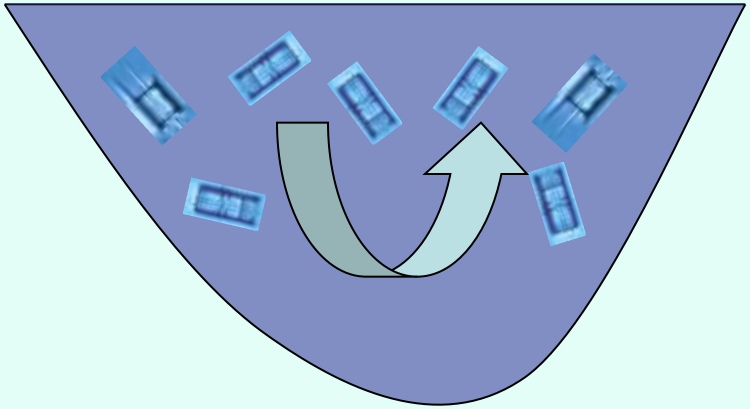
Length of ice-free season- timing of ice-off & ice-on

Timing, duration, strength of the spring freshet & spring overturn

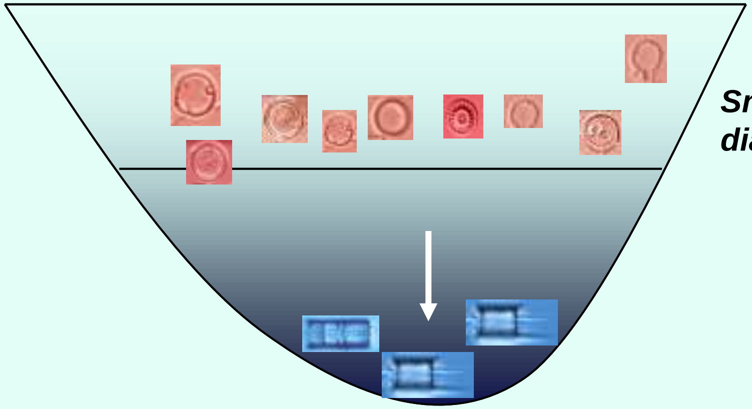
Timing, duration, strength of thermal stratification – depth of mixed epilimnion

Warming & related factors favour small, planktonic *Cyclotella* taxa

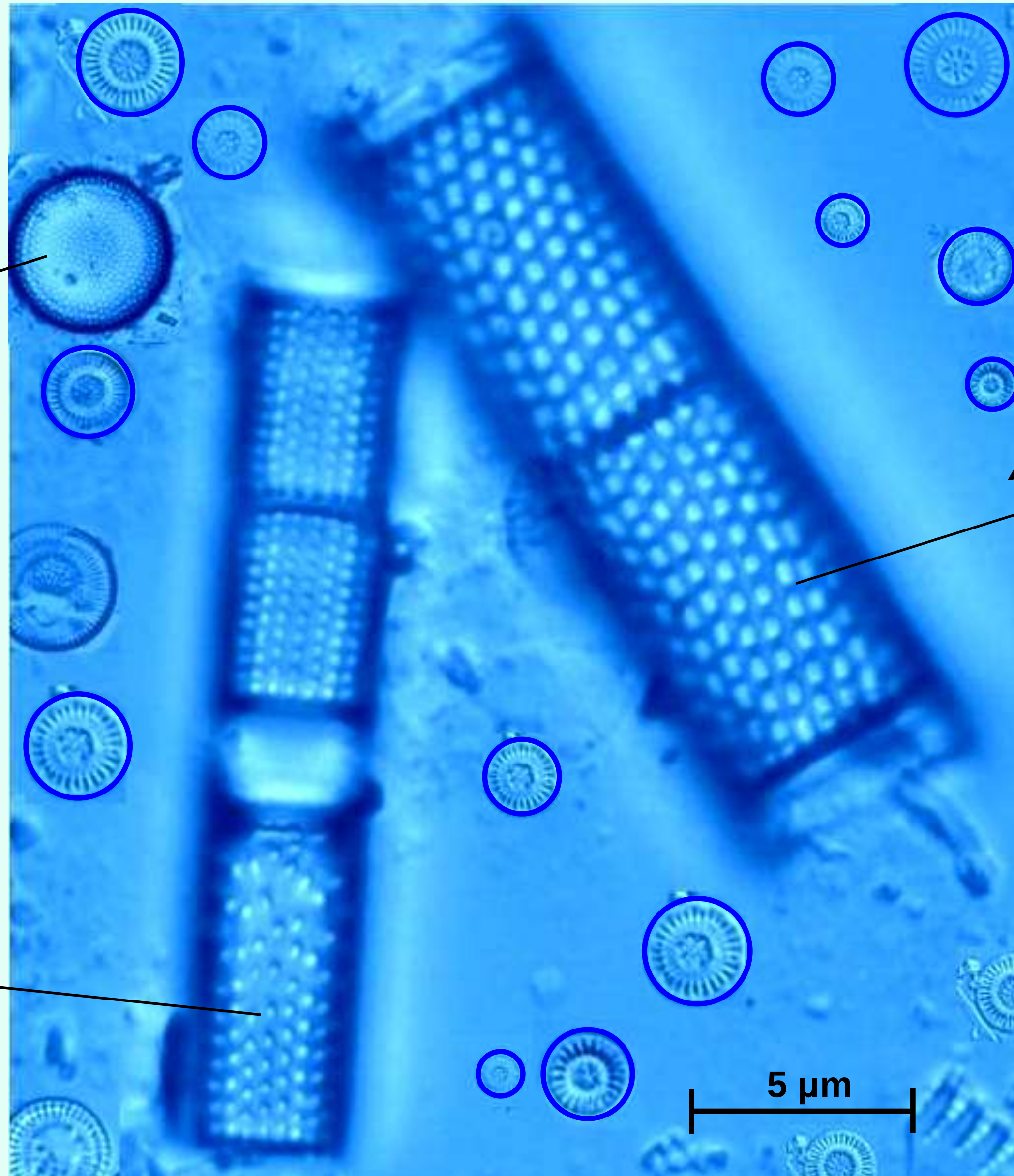
Mixed water column



Stratified water column



Taxon-specific shift: *Cyclotella-Aulacoseira*



Aulacoseira islandica

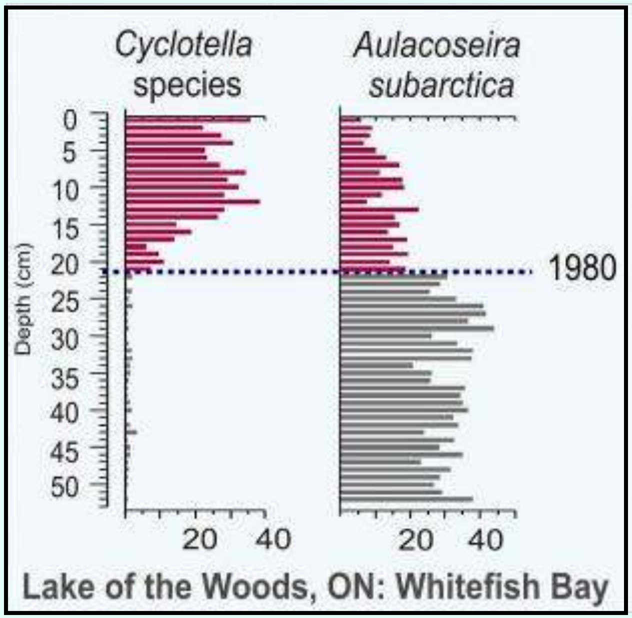
Aulacoseira granulata

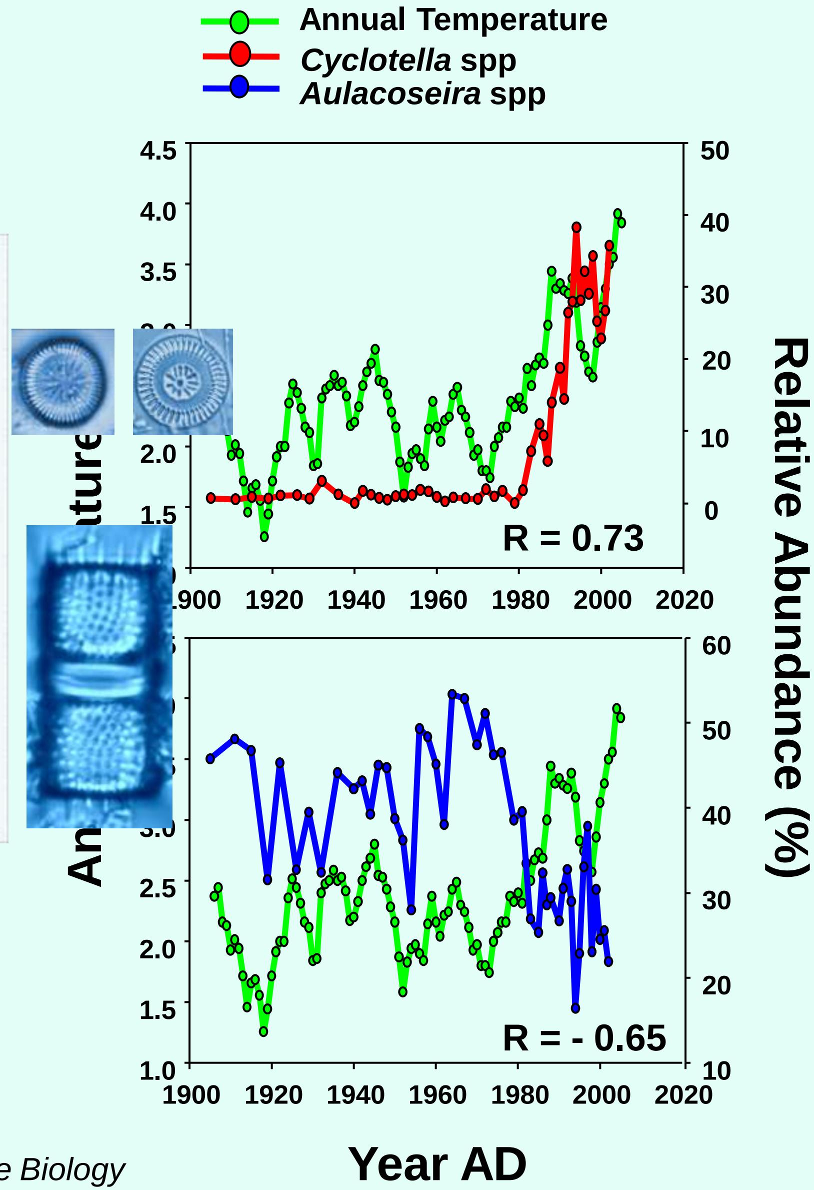
Aulacoseira islandica

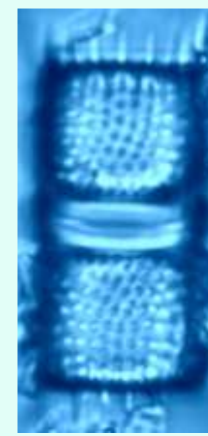
Taxon-specific Relationships

Kenora Temperature Record

Whitefish Bay – Reference site



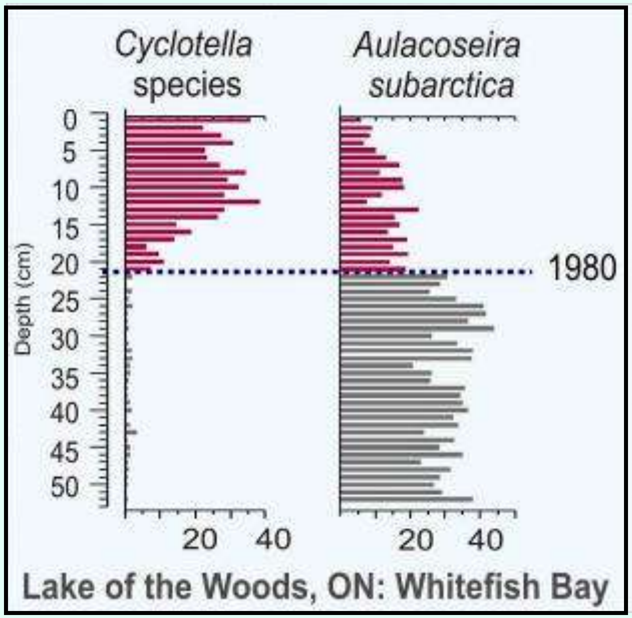


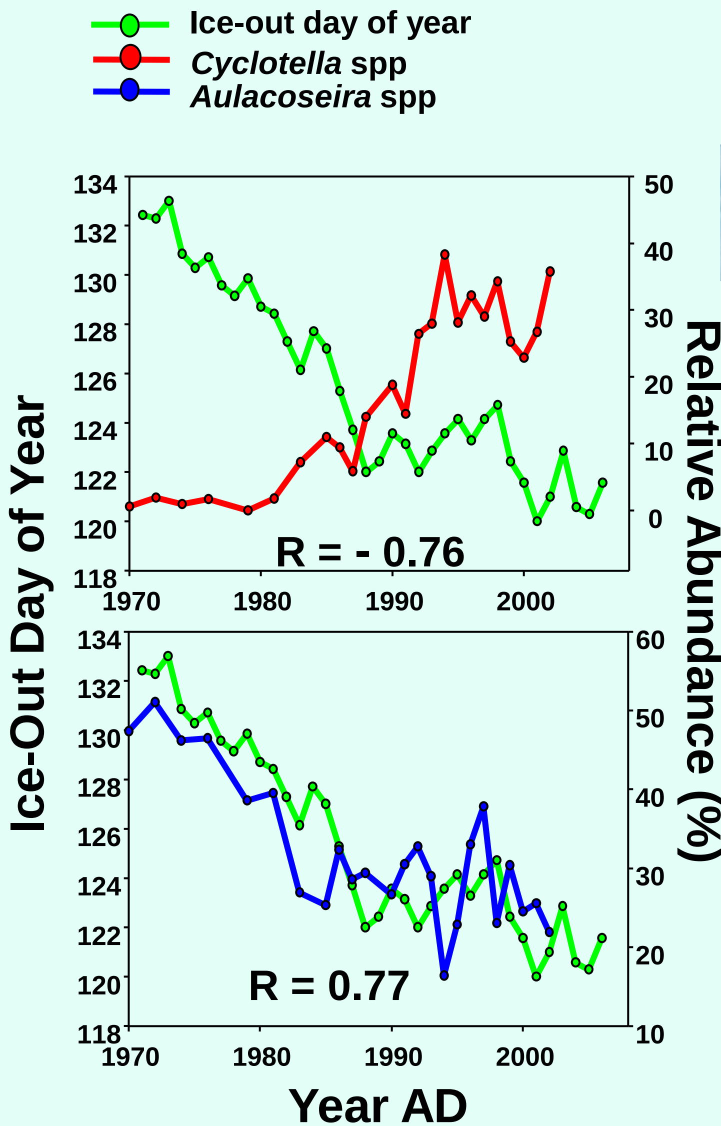


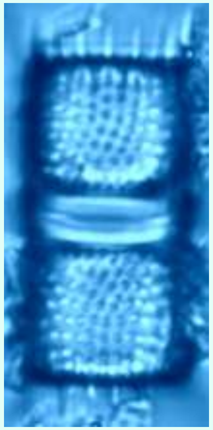
Rühland, Paterson, Smol 2008: Global Change Biology

Taxon-specific Relationships: *Ice-out record*

Whitefish Bay – Reference site

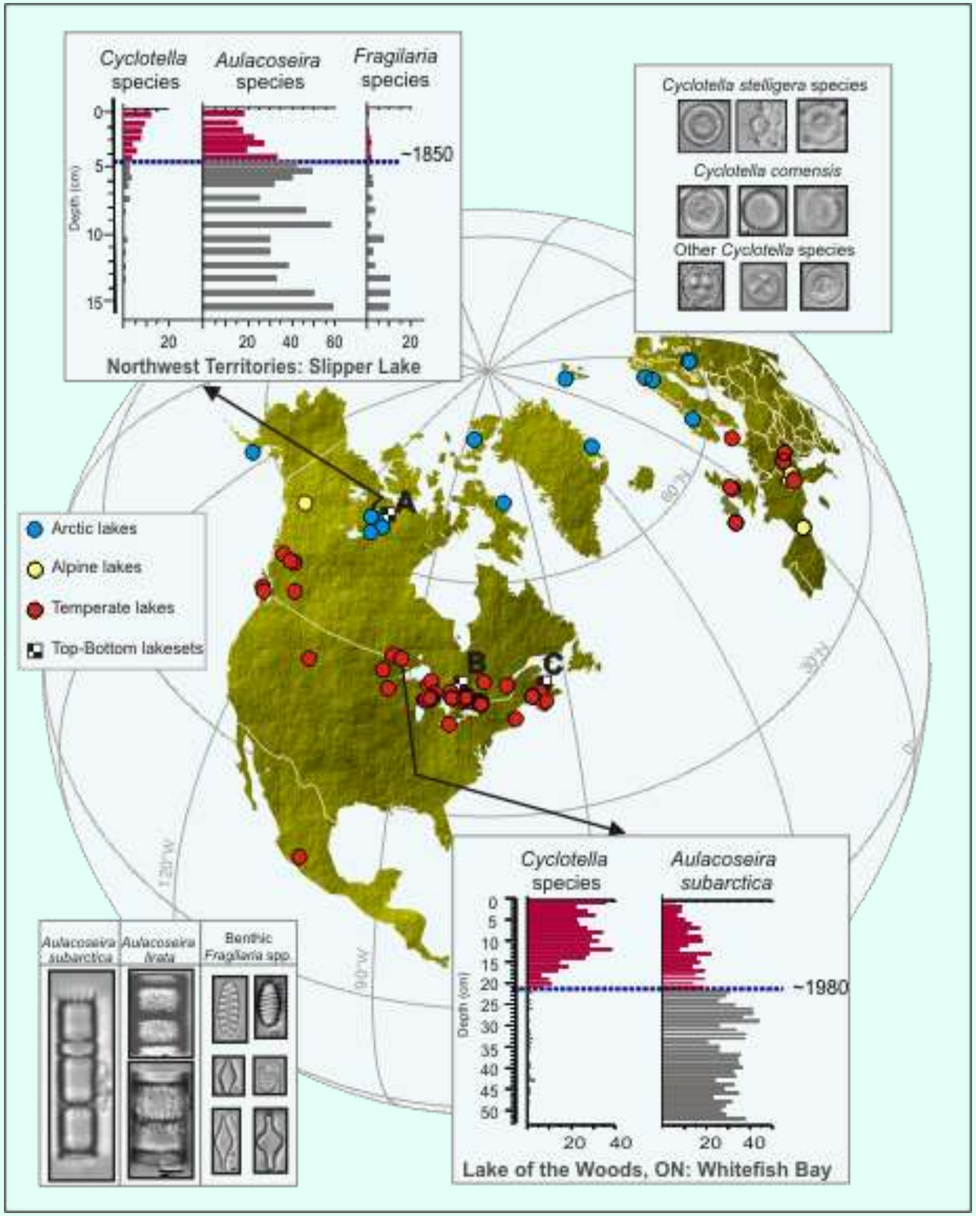






Rühland, Paterson, Smol 2008: Global Change Biology

Warming & Hemispheric –scale shifts in *Cyclotella* Species



Rühland, Paterson, Smol 2008: Global Change Biology

Conclusions

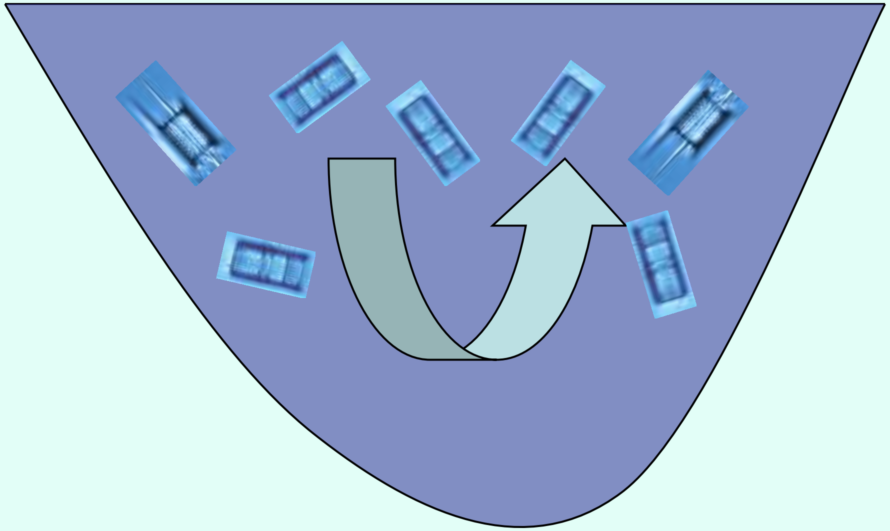
- Climate-driven, taxon-specific diatom changes throughout the N Hemisphere, consistent with decreased ice cover and/or stronger thermal stratification

- Likely only the beginning of what is to come

How will this affect other algae and cyanobacteria?

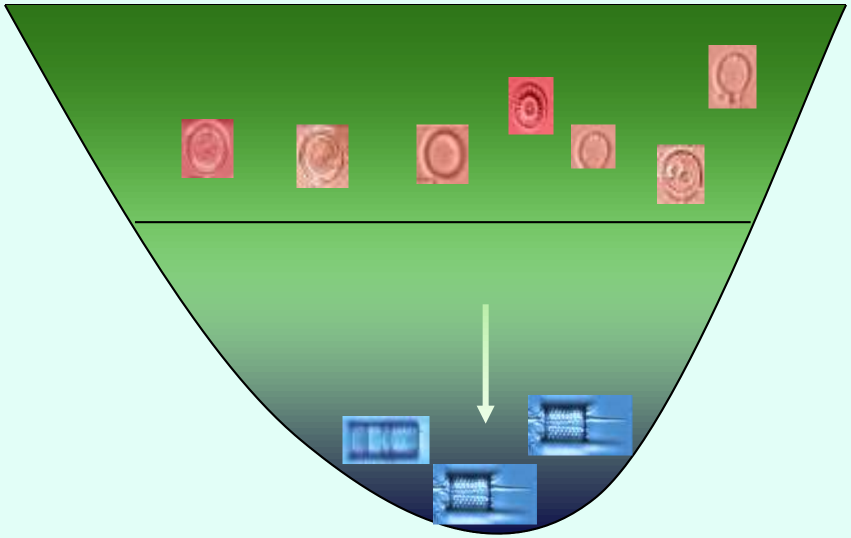
Blue-greens like it hot!

Mixed water column



Stratified and/or less ice:

Exacerbates blooms



If we are seeing these changes in deep lakes, what is happening to the very shallow lakes?

Large → Small

Let’s return to the Cape Herschel High Arctic Ponds

Based on our paleoenvironmental data, the Cape Herschel High Arctic ponds have been permanent water bodies for thousands of years.

But they have started to change profoundly over the last century or so, consistent with climate warming.

What has happened to these ponds over the last few years? (The warmest years on record in this part of the Arctic.)

The final ecological threshold?

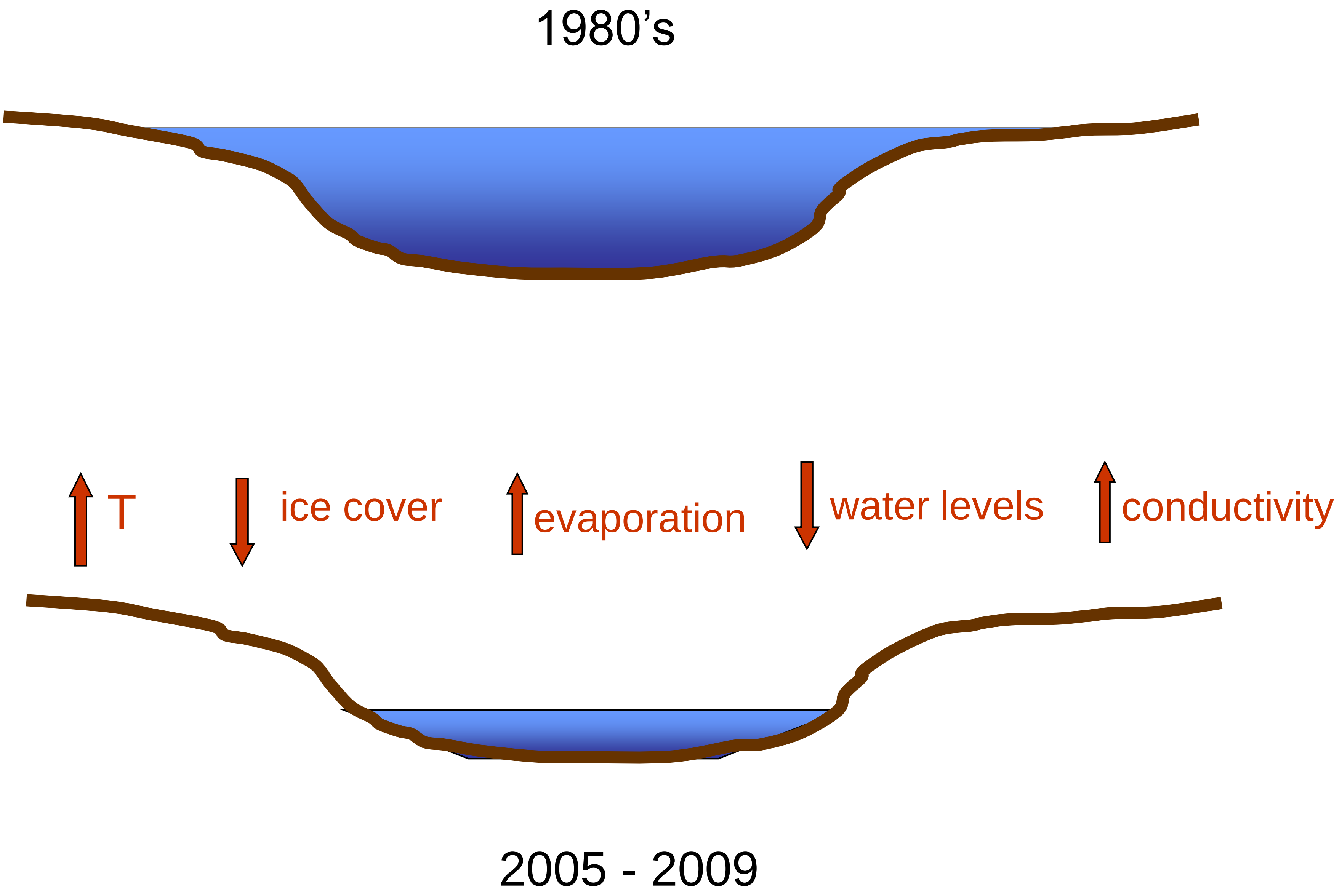
July 16, 2007; Cape Herschel

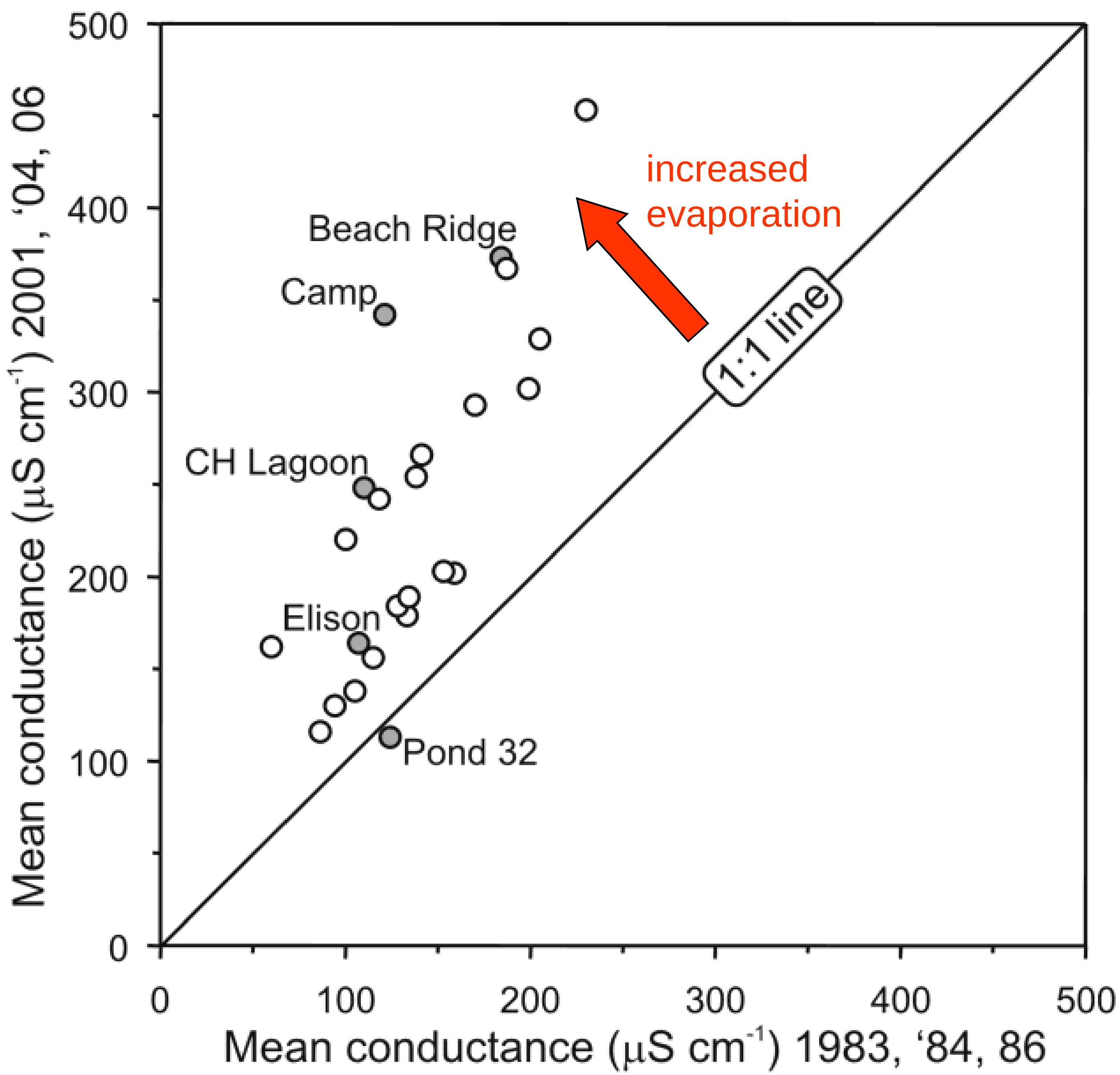
Smol, J.P. and Douglas, M.S.V. 2007. Crossing the final ecological threshold in high Arctic ponds. *Proceedings of the National Academy of Sciences* 104: 12395-12397.

Smol & Douglas (2007) *PNAS* 104: 12395-7.

Smol & Douglas (2007) *PNAS* 104: 12395-7.

Smol & Douglas (2007) *PNAS* 104: 12395-7.


1980’s
T
ice cover
evaporation
water levels
conductivity
2005 - 2009



Smol & Douglas (2007) *PNAS* 104: 12395-7.

Exposed shoreline and dried up moss bank
Horseshoe Pond 16 July, 2007

Greenhouse Gas Sink → Source?

Smol & Douglas (2007) *PNAS* 104: 12395-7.

Crossing Ecological Thresholds

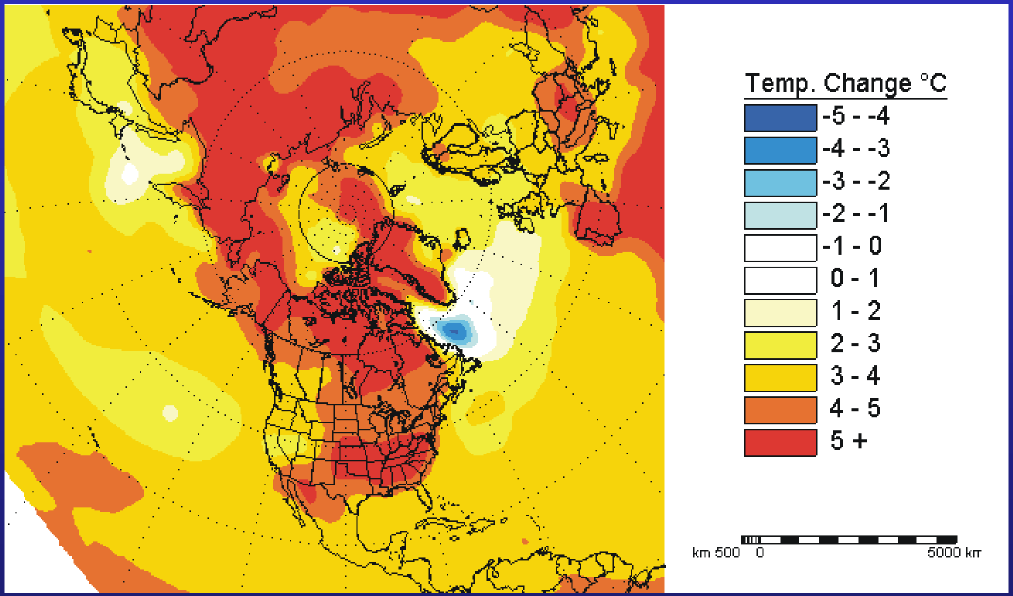
ephemeral ponds → dry land

permanent ponds → ephemeral ponds

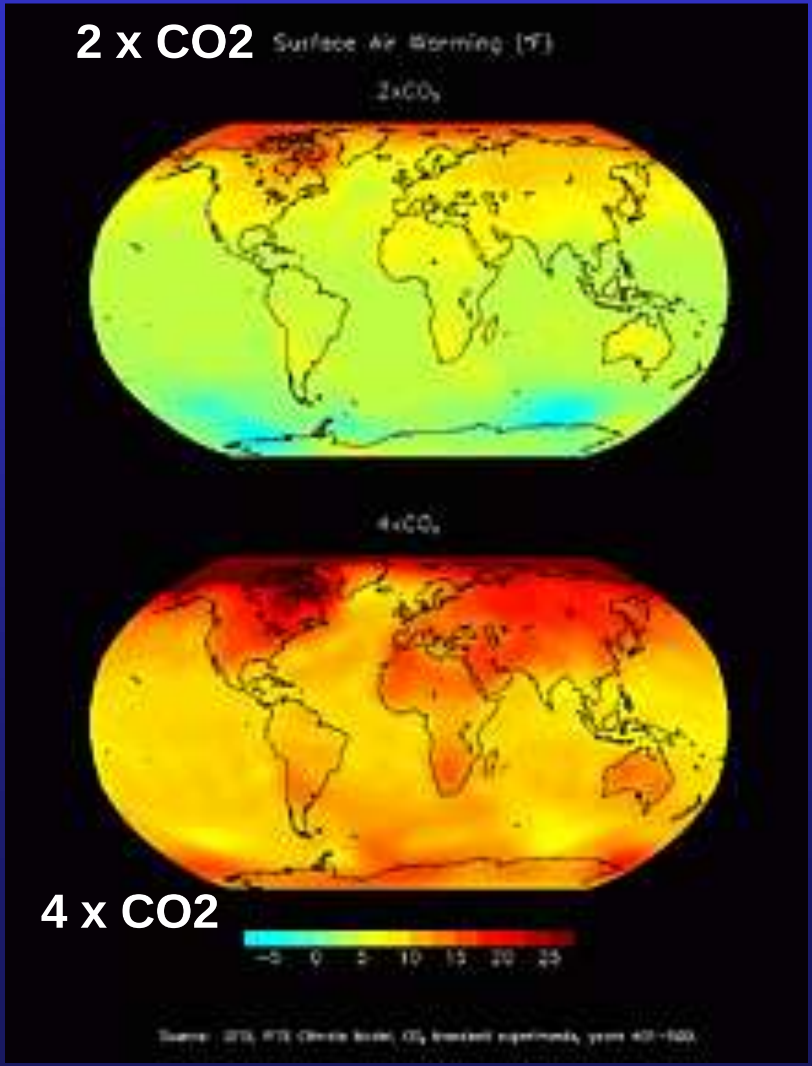
larger, deeper ponds → shallower, exposed shorelines

(and of course other marked changes in the physical, chemical and biological characteristics of the sites)

The Arctic in a “Greenhouse Dominated” World?



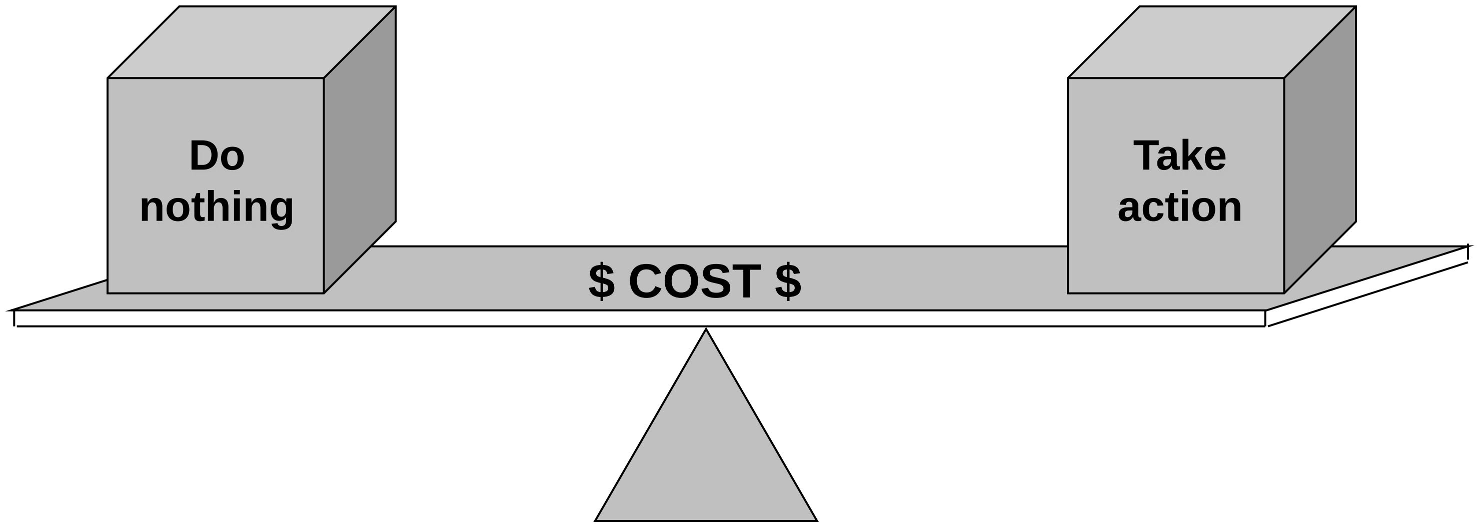
Estimated summer temperatures by *ca* 2090



“Yes, but you scientists don’t understand economics. Trying to fix ‘all this’ is going to cost way too much”.

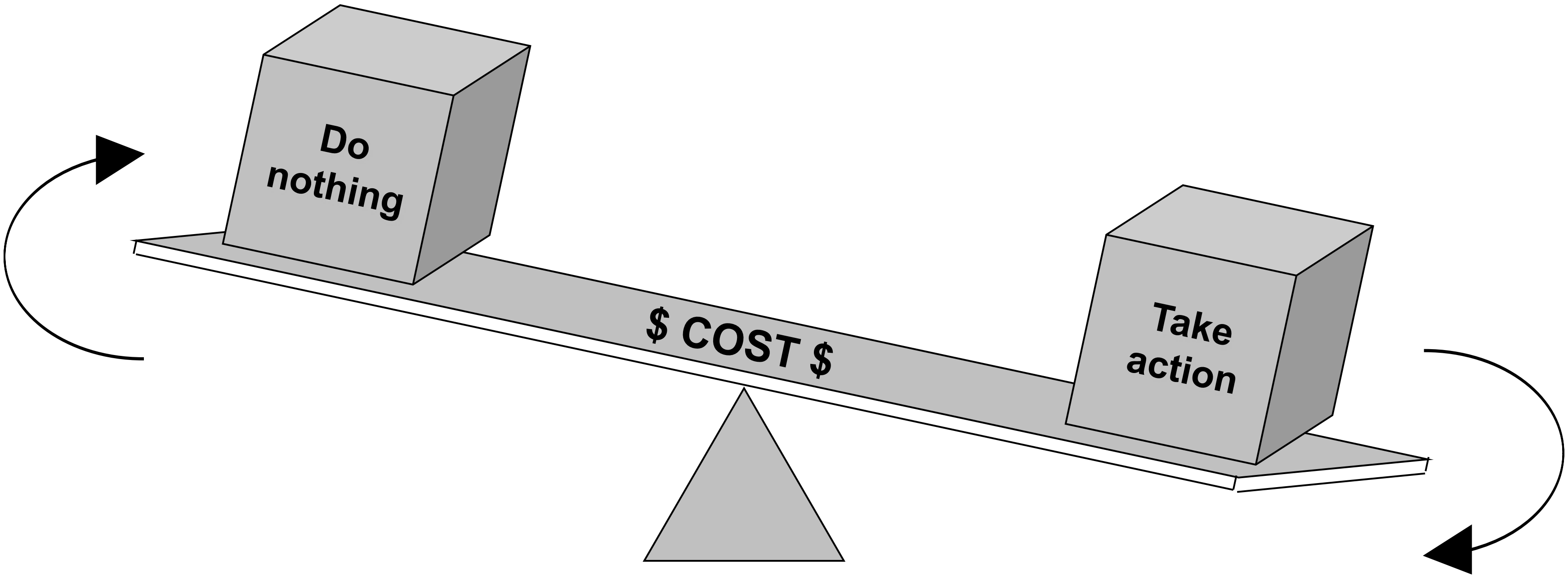
(almost any politician or industry spokesperson)

e.g. Costs and Benefits: US Acid Rain Program



What is the cost of taking action on environmental issues?

SHORT-TERM COSTS

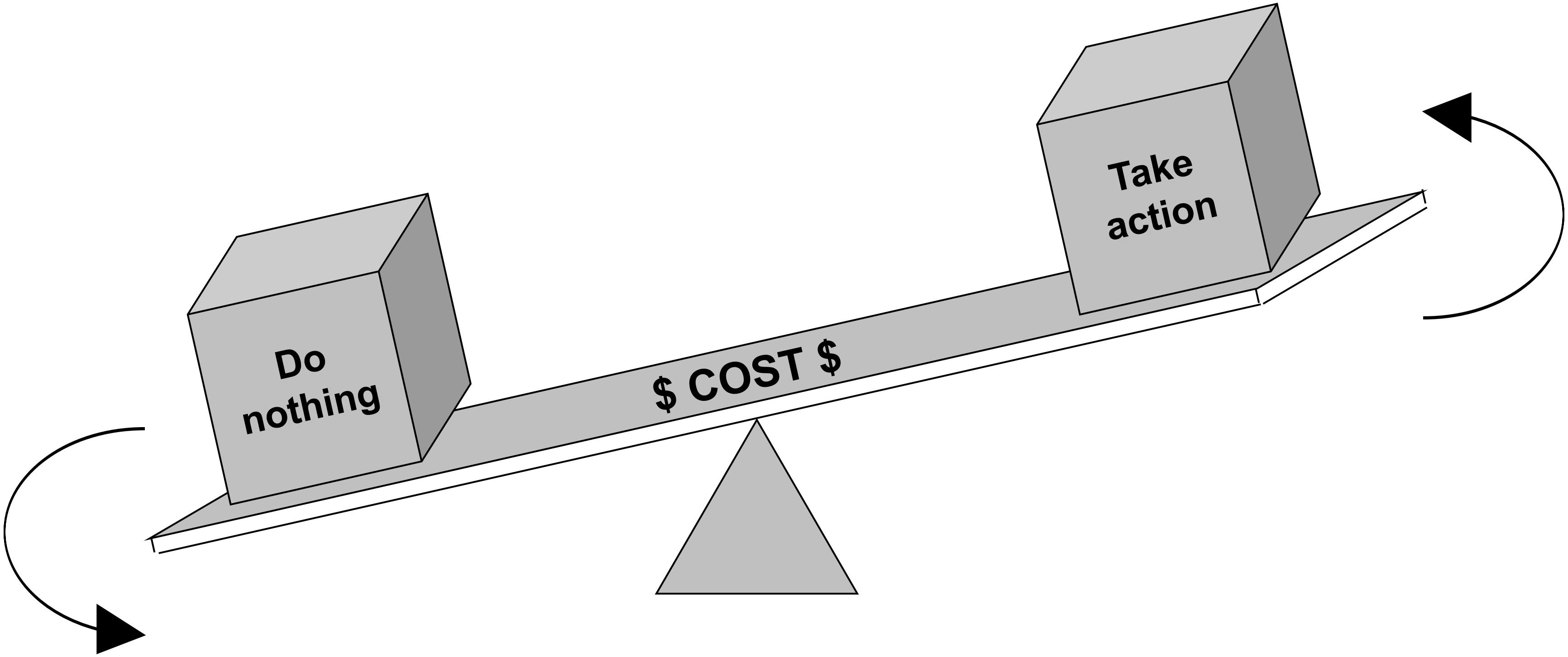


- compliance costs (industry)
- monitoring and research (government)

$ 3.1 billion / year[1]

[1]Chestnut and Mills. 2005. A fresh look at the benefits and costs of the US acid rain program. J. Env. Mgt. 77: 252-266.

LONG-TERM COSTS



• health costs

• ecosystem damage

• monitoring and research (government)

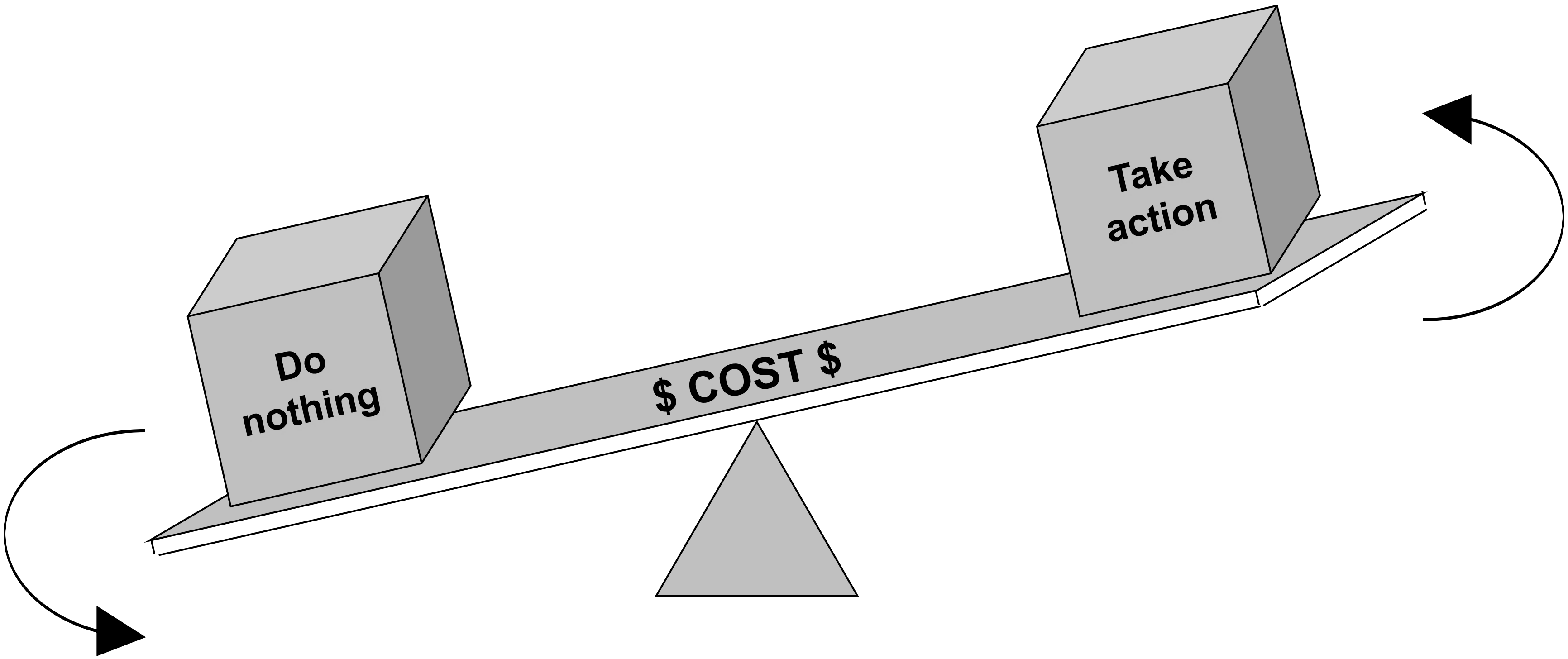
• compliance costs (industry)

$ 122 billion / year[1]

$ 3.1 billion / year[1]

[1]Chestnut and Mills. 2005. A fresh look at the benefits and costs of the US acid rain program. J. Env. Mgt. 77: 252-266.

LONG-TERM COSTS



- **Cost of monitoring is ~0.4 % of compliance costs, and < 0.01% of estimated health and ecosystem benefits**

[1]Chestnut and Mills. 2005. A fresh look at the benefits and costs of the US acid rain program. J. Env. Mgt. 77: 252-266.

Not really an option

http://www.natural-health-information-centre.com/image-files/head-in-sand.jpg

Lessons from the Past

1) The recurring patterns of "unintended consequences"

2) We tend to be overly optimistic – things are generally worse and more complicated than we initially imagined.

Limnological Sampling

neolimnology

a continuum of time scales

paleolimnology

Paleolimnology: extending the sampling window back in time

From : Smol (2008) *Pollution of lakes and rivers: A paleoenvironmental perspective*. 2nd ed. Blackwell Publ., Oxford