

The Past Matters: Using lake sediments to study the environmental effects of multiple stressors



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Important management questions

What were pre-disturbance conditions?

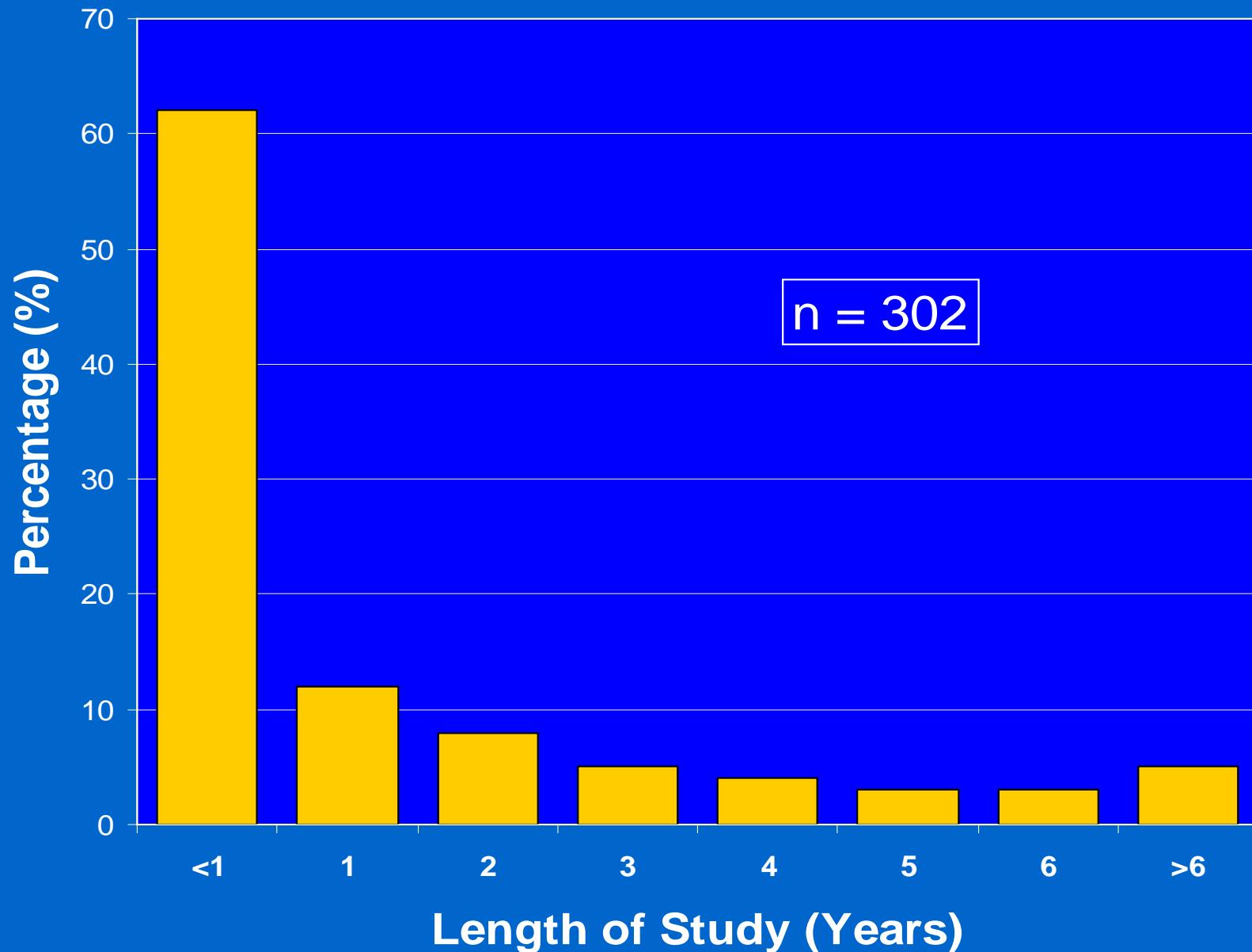
What is the range of natural variability?

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

Can evidence of human activity be detected?

How much improvement can be expected?

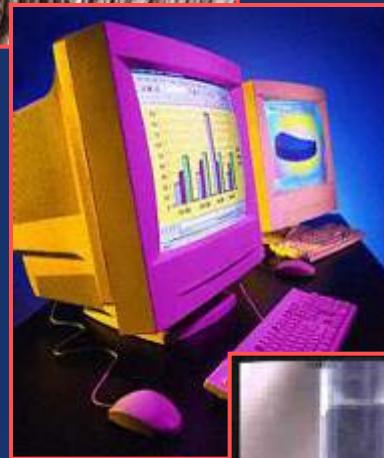
Environmental Monitoring and Assessment - 1981-1993



Techniques to Assess Past Environmental Change



historical records



model hindcasts



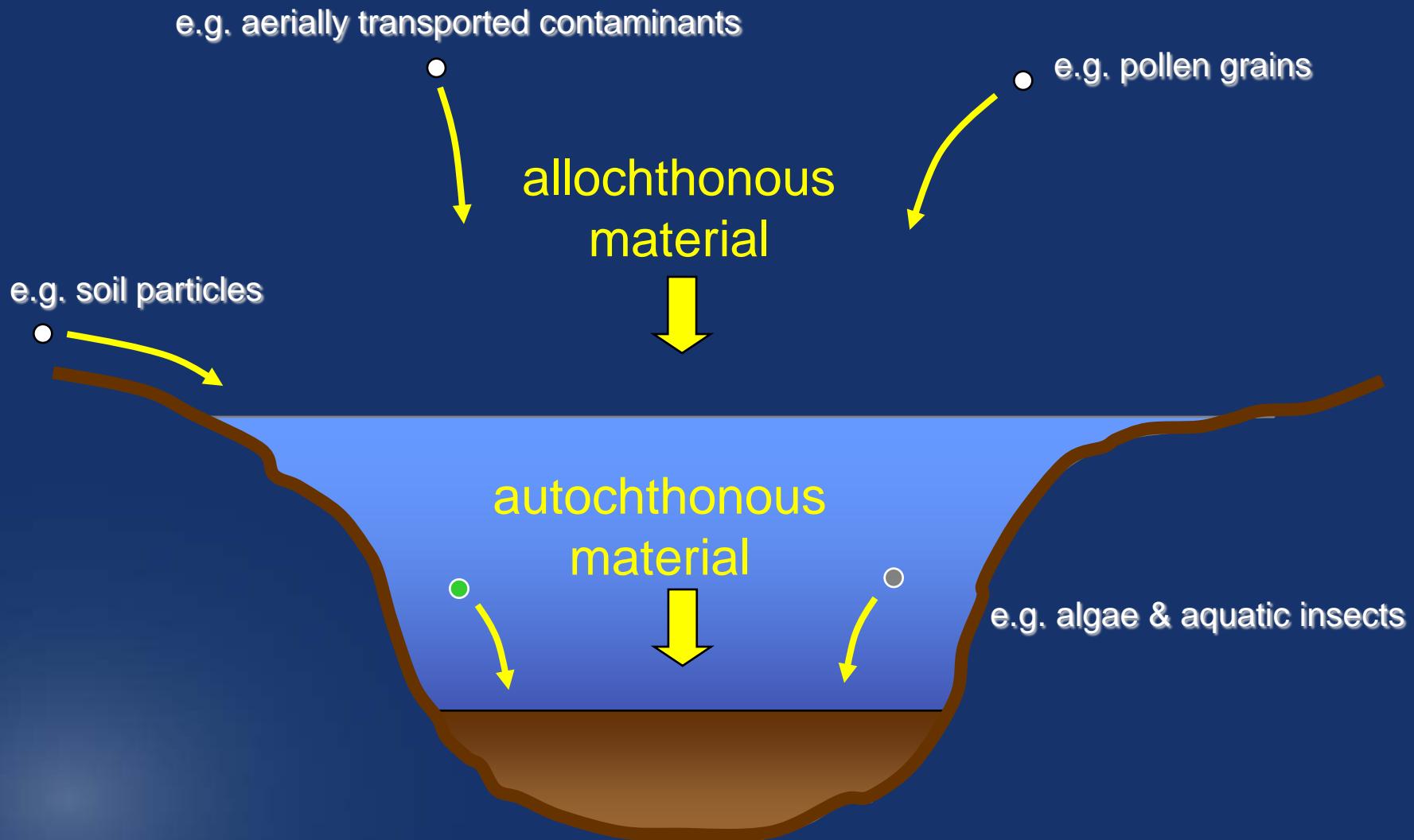
natural archives

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

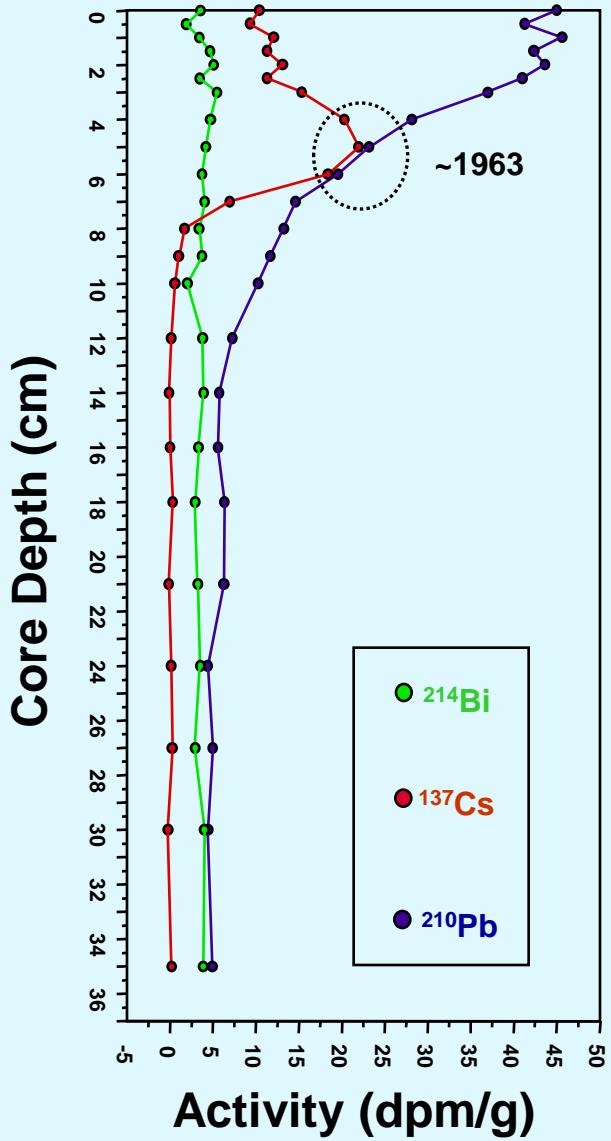


Close-interval sectioning



Dating the sedimentary sequences

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



Youngest

Continuous Record

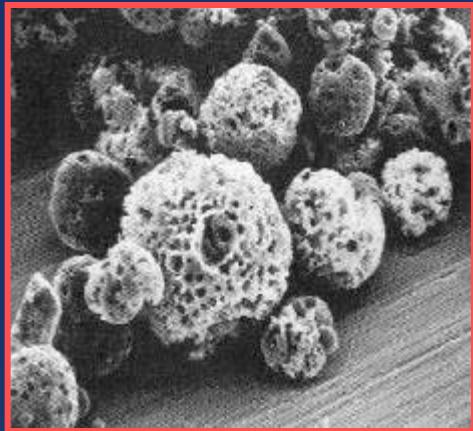
Oldest

2006
2005
2004
2003
2002
2001
1999
1998
1996
1994
1992
1990
1987
1985
1981
1976
1972
1965
1950
1946
1936
1926
1920
1910
1900
1890
1870
1860
1856
1850
1846

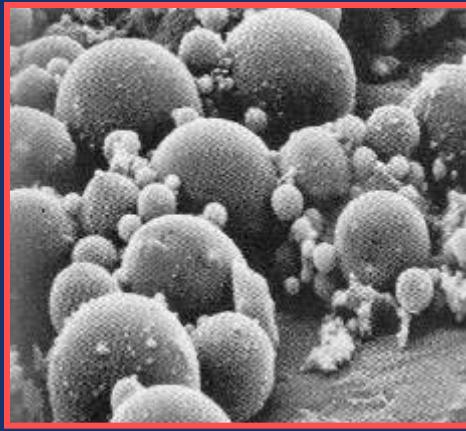


From the Atmosphere

carbon particles
from carbon
combustion



fly ash from coal
combustion

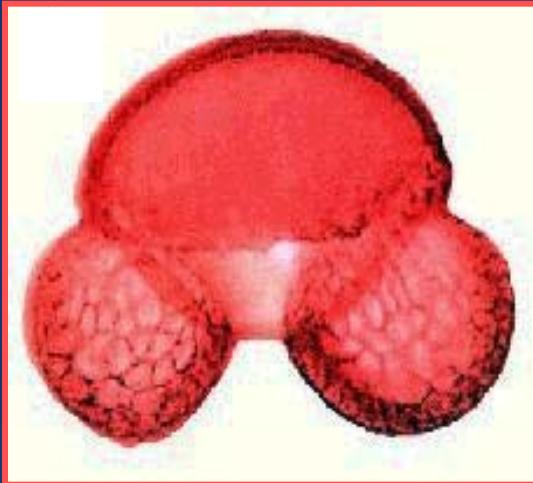


metals and other
pollutants from
industry



From the Catchment

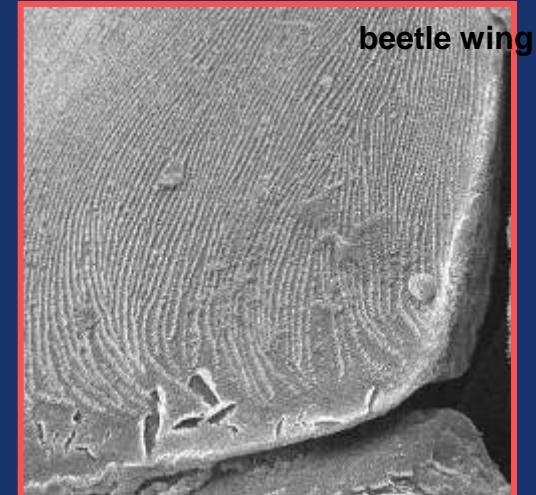
pollen



mineral
particles

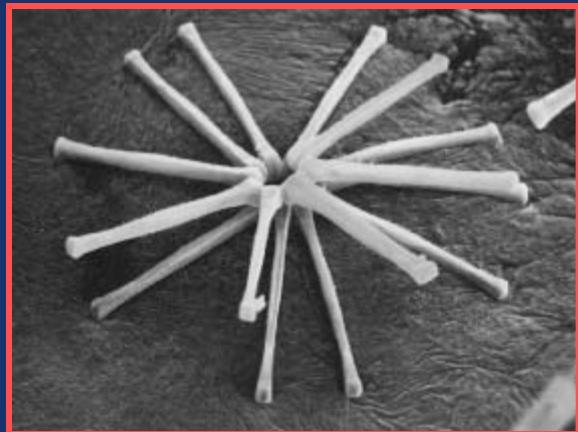


insect
remains

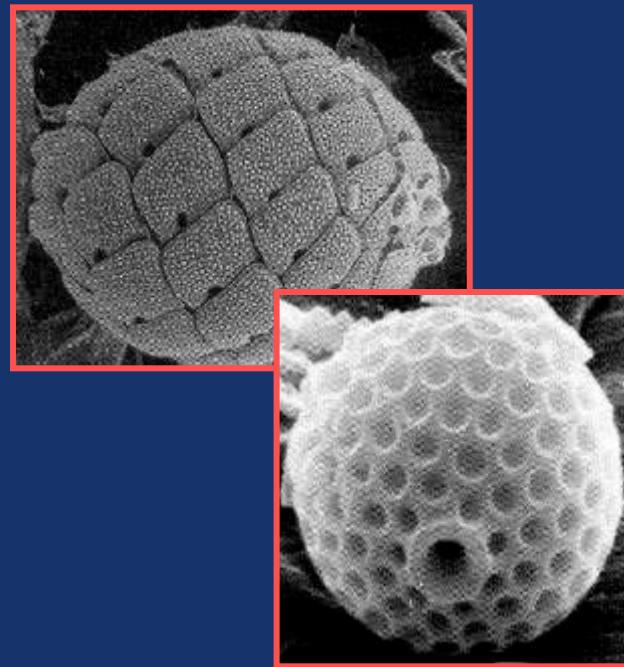


From the Aquatic System

diatoms



chrysophytes

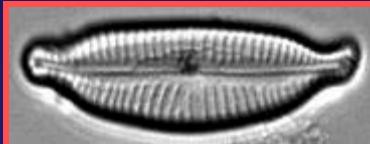


chironomids

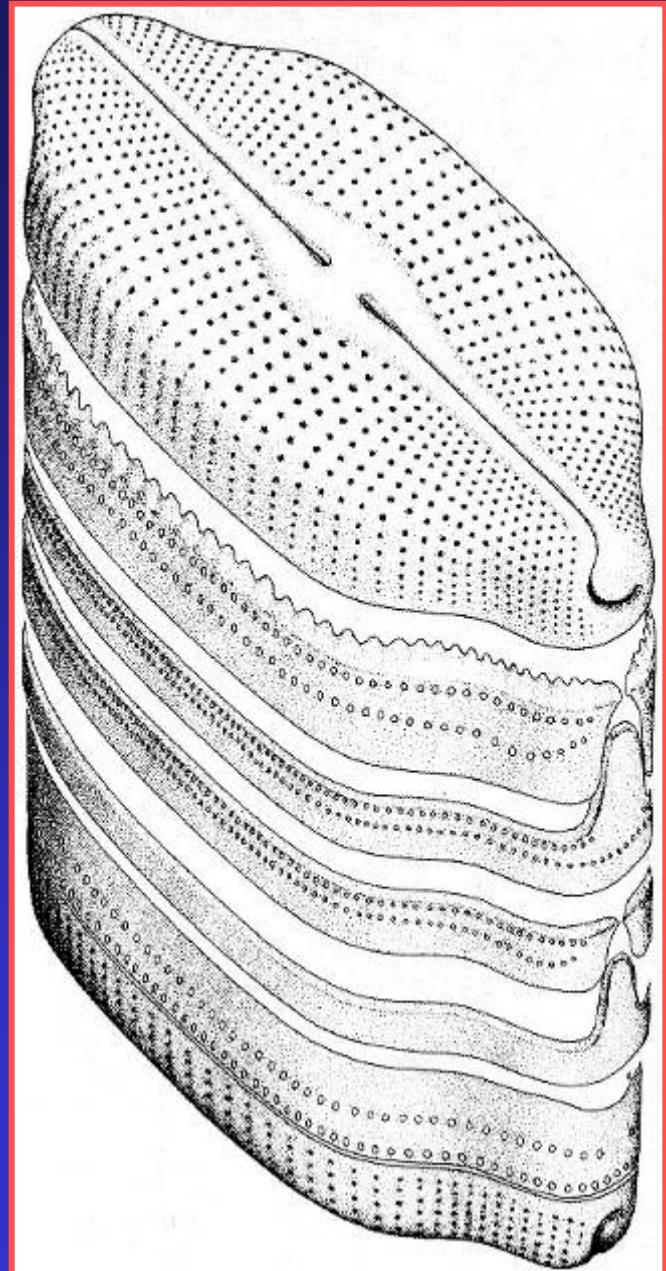
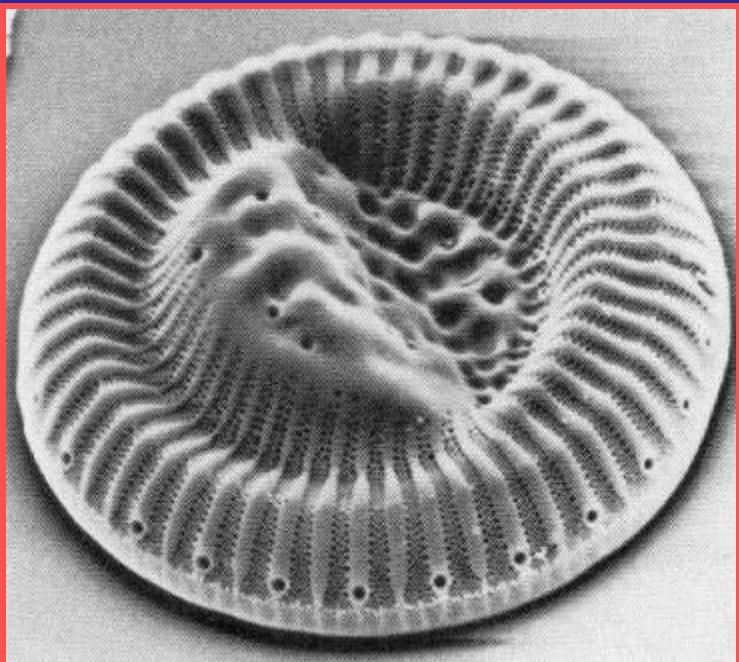


Photo: I Walker

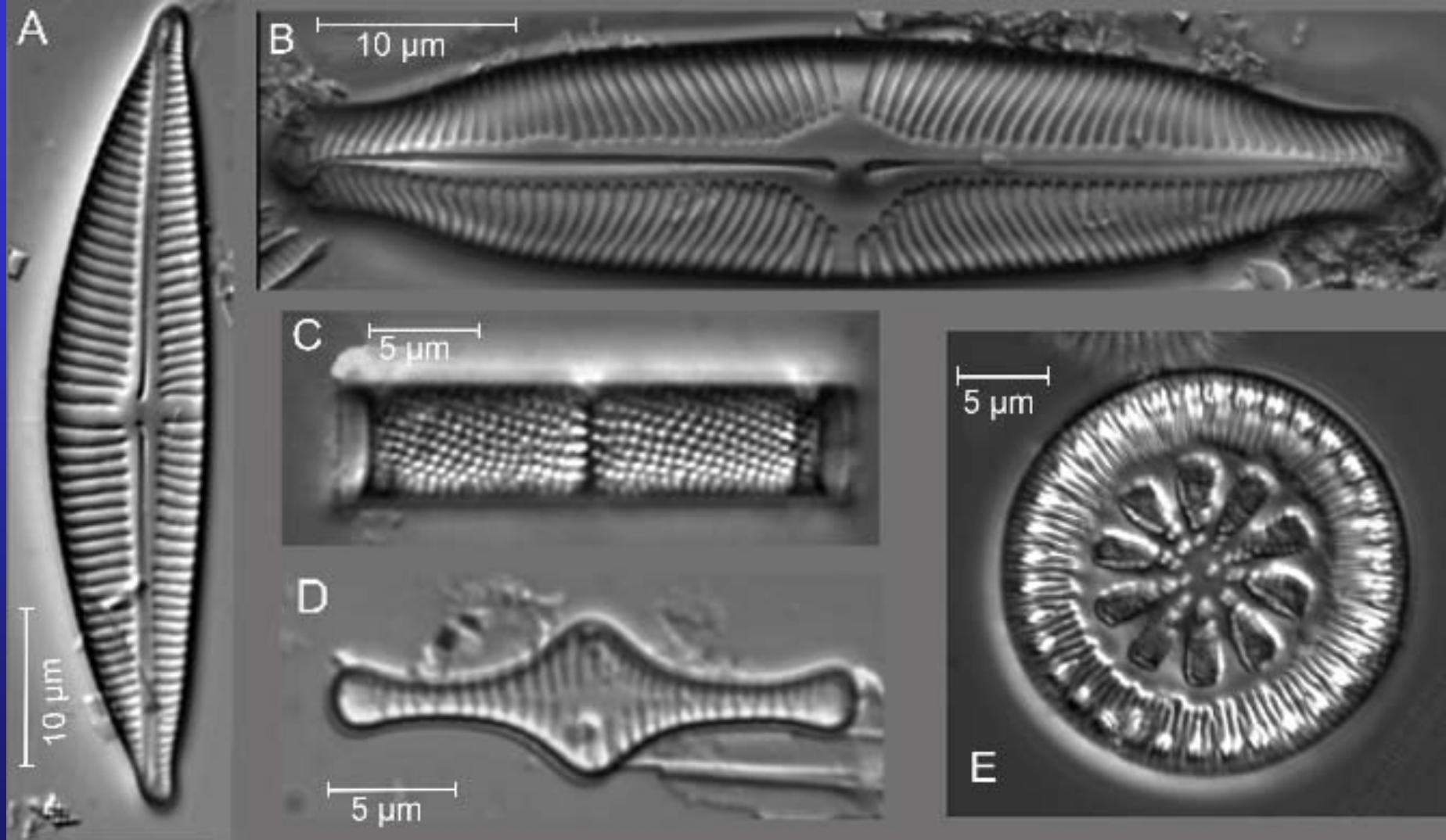
Diatoms



- 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



Section & Date Sediment Core

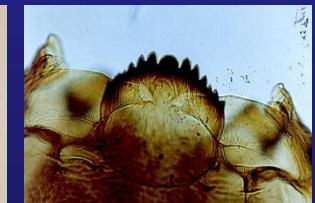
^{210}Pb
 ^{14}C
 ^{137}Cs



Analyze Data



Collect Indicator Data



Sub-sample Sediments &
Isolate Indicator of Interest

- Targets
- Trajectories

Users of Water



“The Real” Users of Water

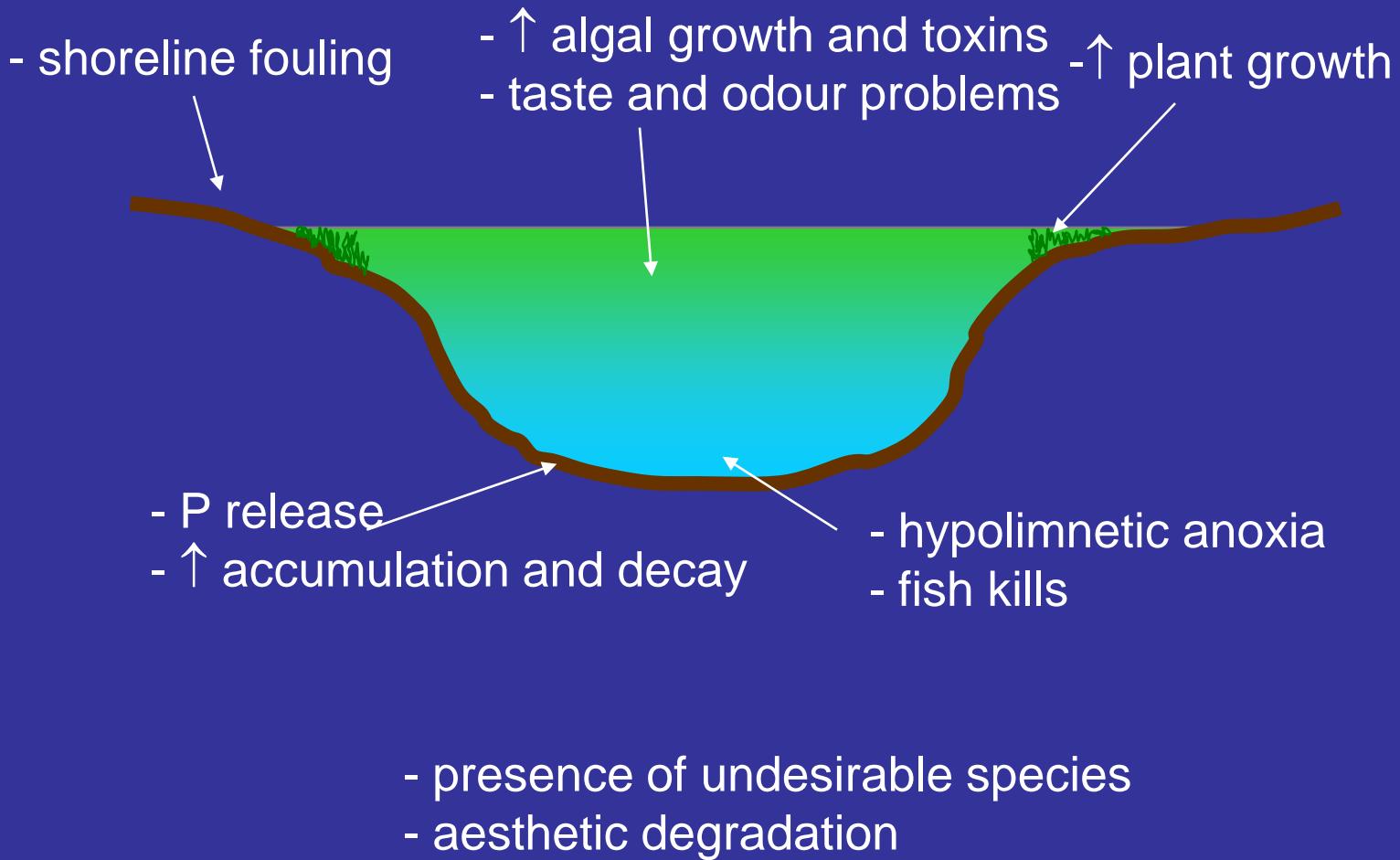


What factors can be addressed using paleolimnology?



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

Impacts of Cultural Eutrophication



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

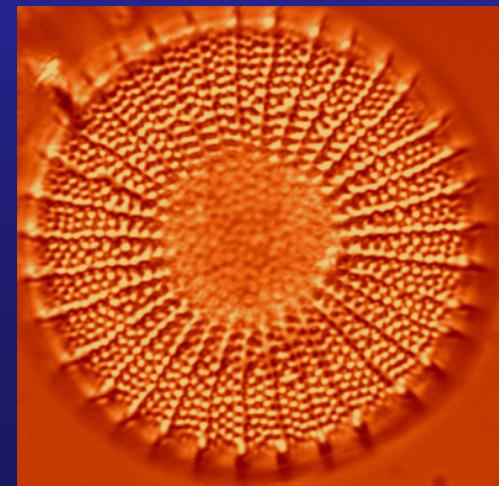
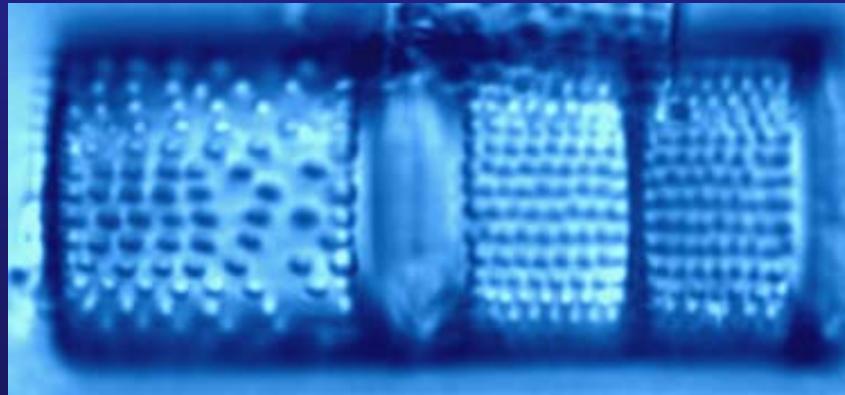
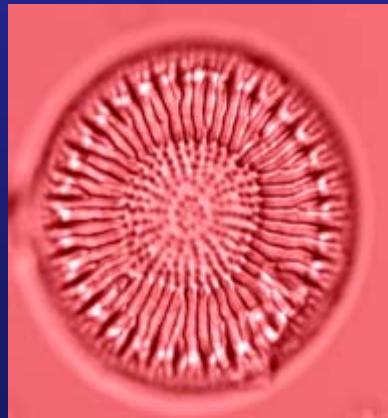
Why not just measure total P in
the sediments?

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.)

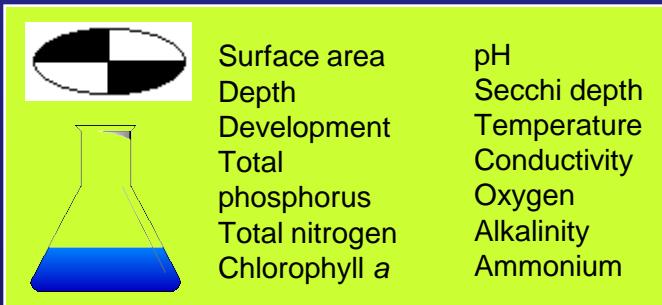
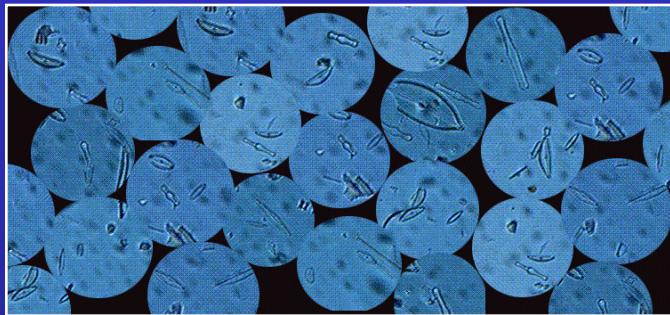
So we have to use indirect proxy methods that are related to lakewater total phosphorus (TP)

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



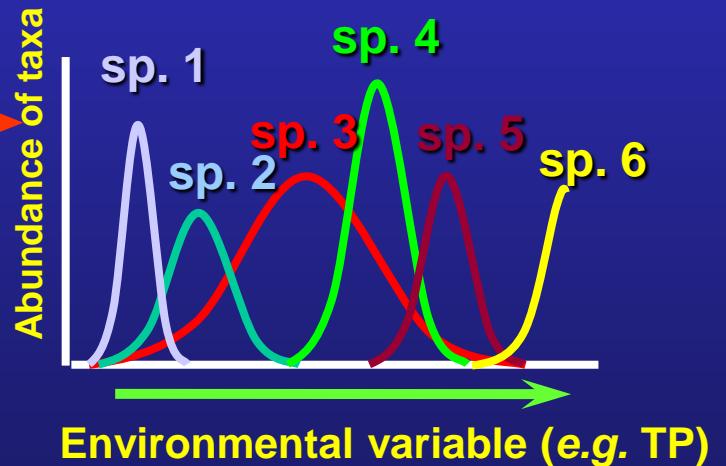
Construction of a Transfer Function

lake surface sediment samples

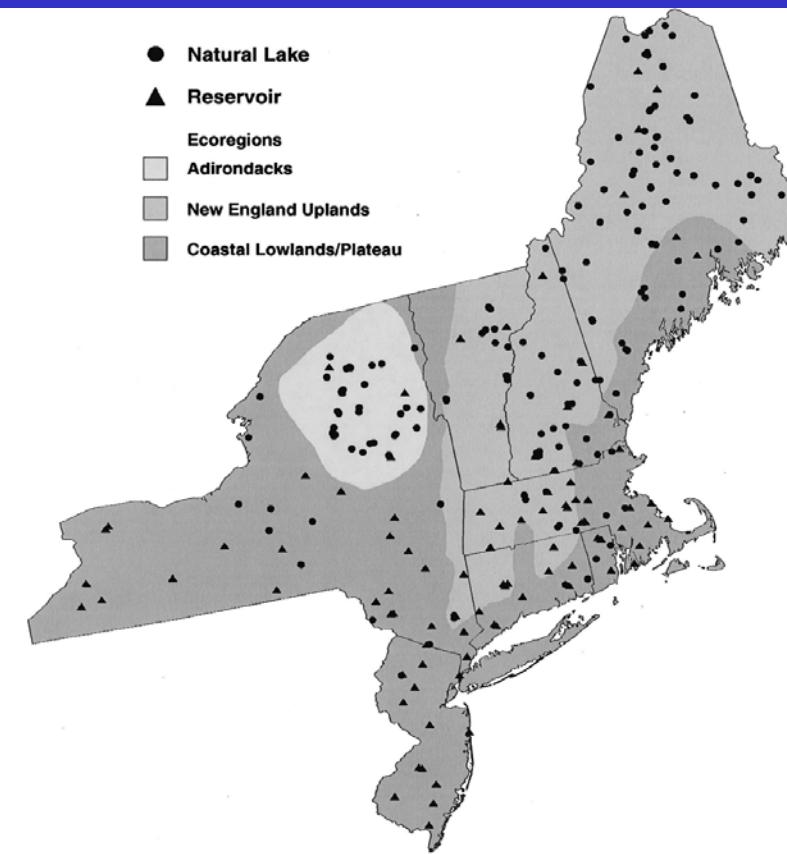


environmental data

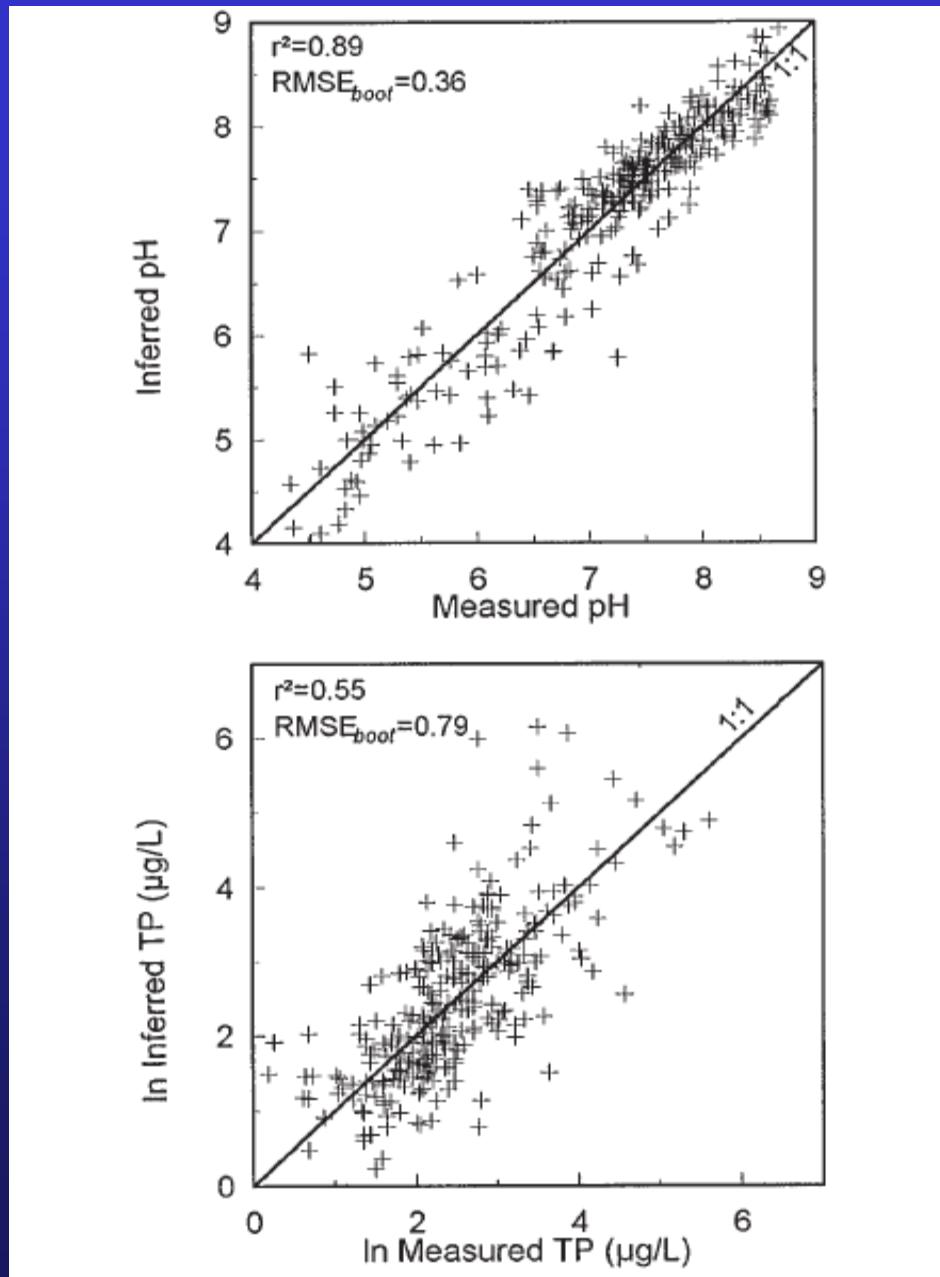
species response curves



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.

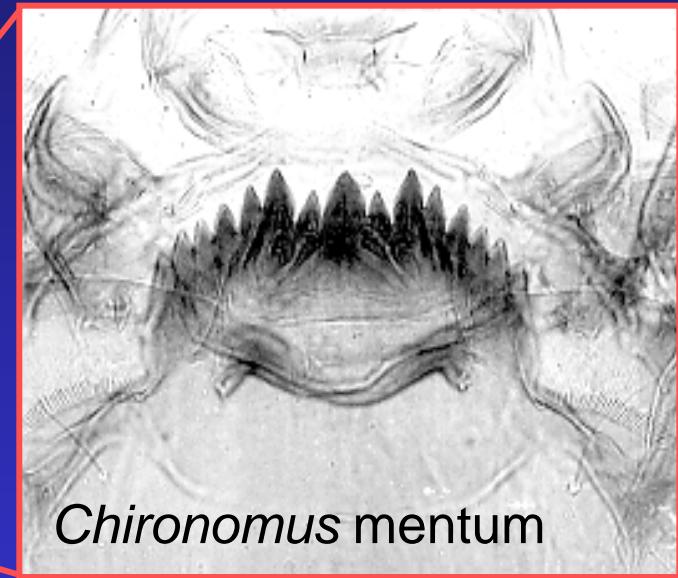


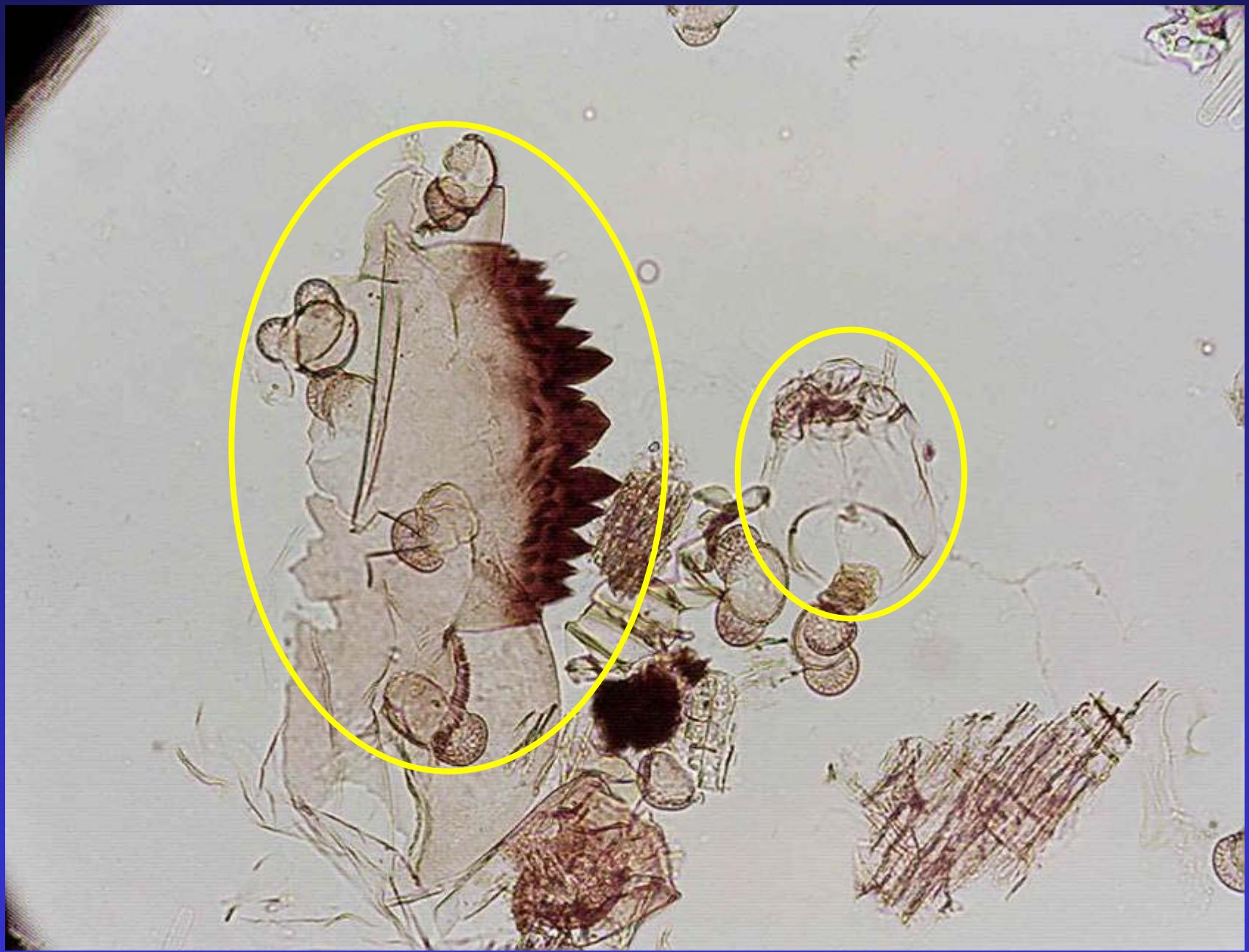
2) Deepwater oxygen levels?

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



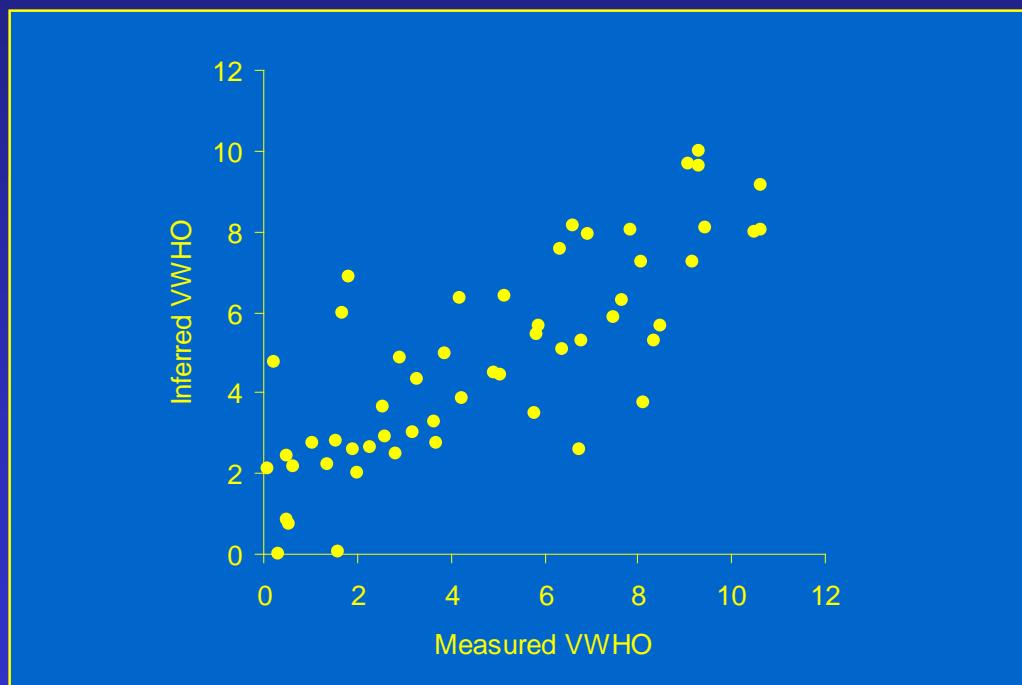
Chironomid head capsules as indicators





(Photo: D. Bos)

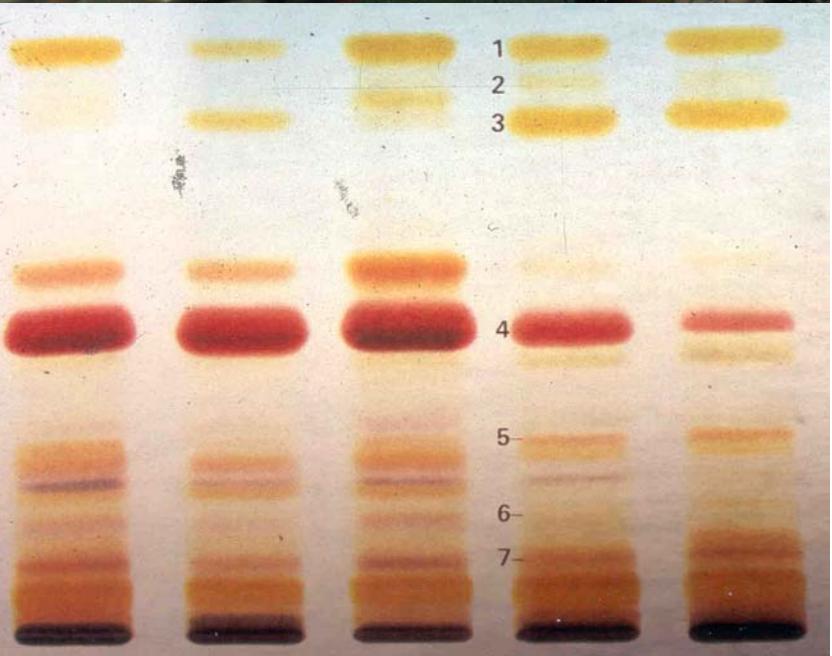
Predictive O₂ Model Based on Aquatic Communities



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



Lake area = 822.9 ha

Mean depth = 9.9 m

Maximum depth = 34.1 m

1867

First pioneers

1885

Railway to area

1870-90

Development of local industries

1895

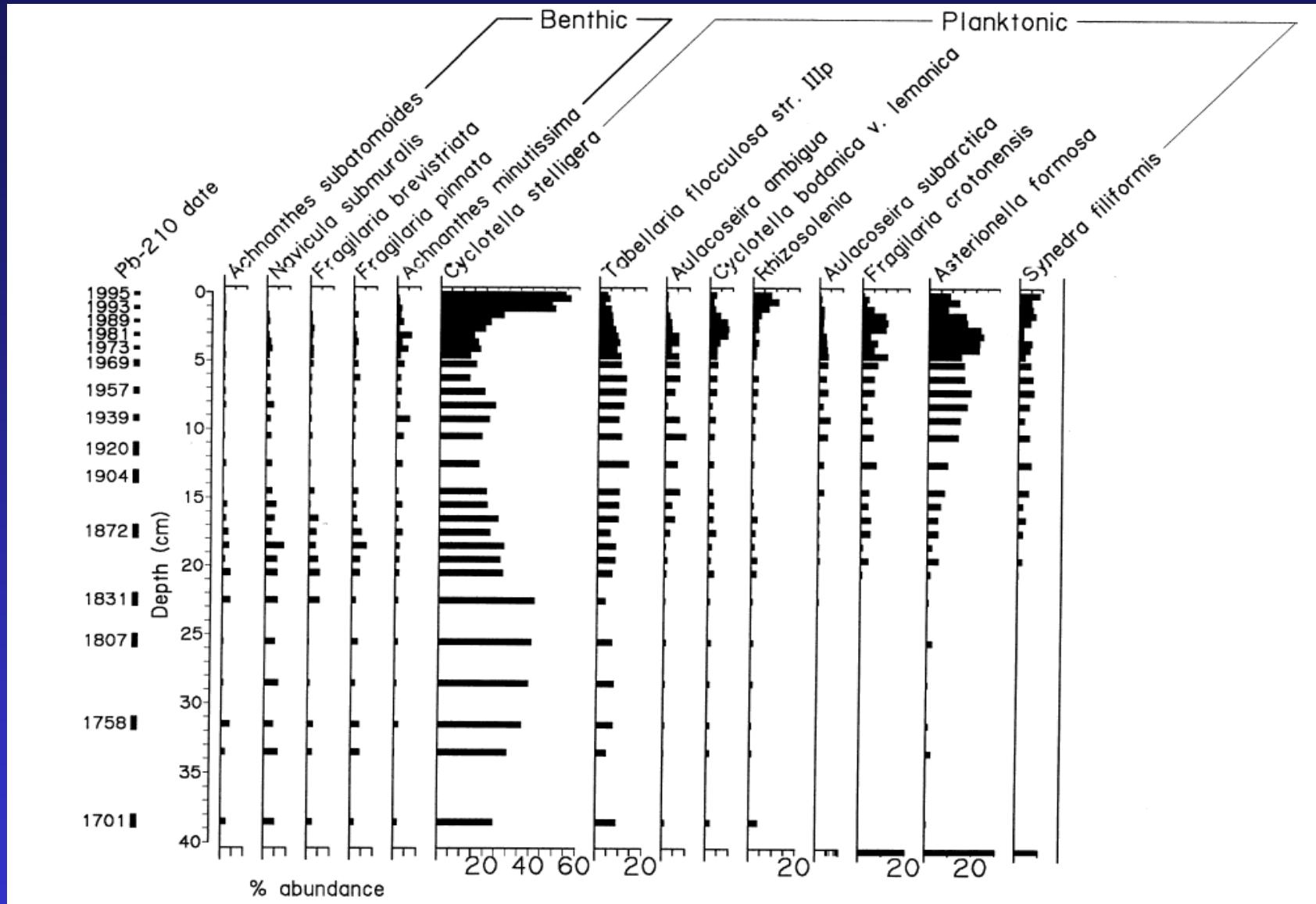
Deerhurst Resort

Late-1800s – early-1900s

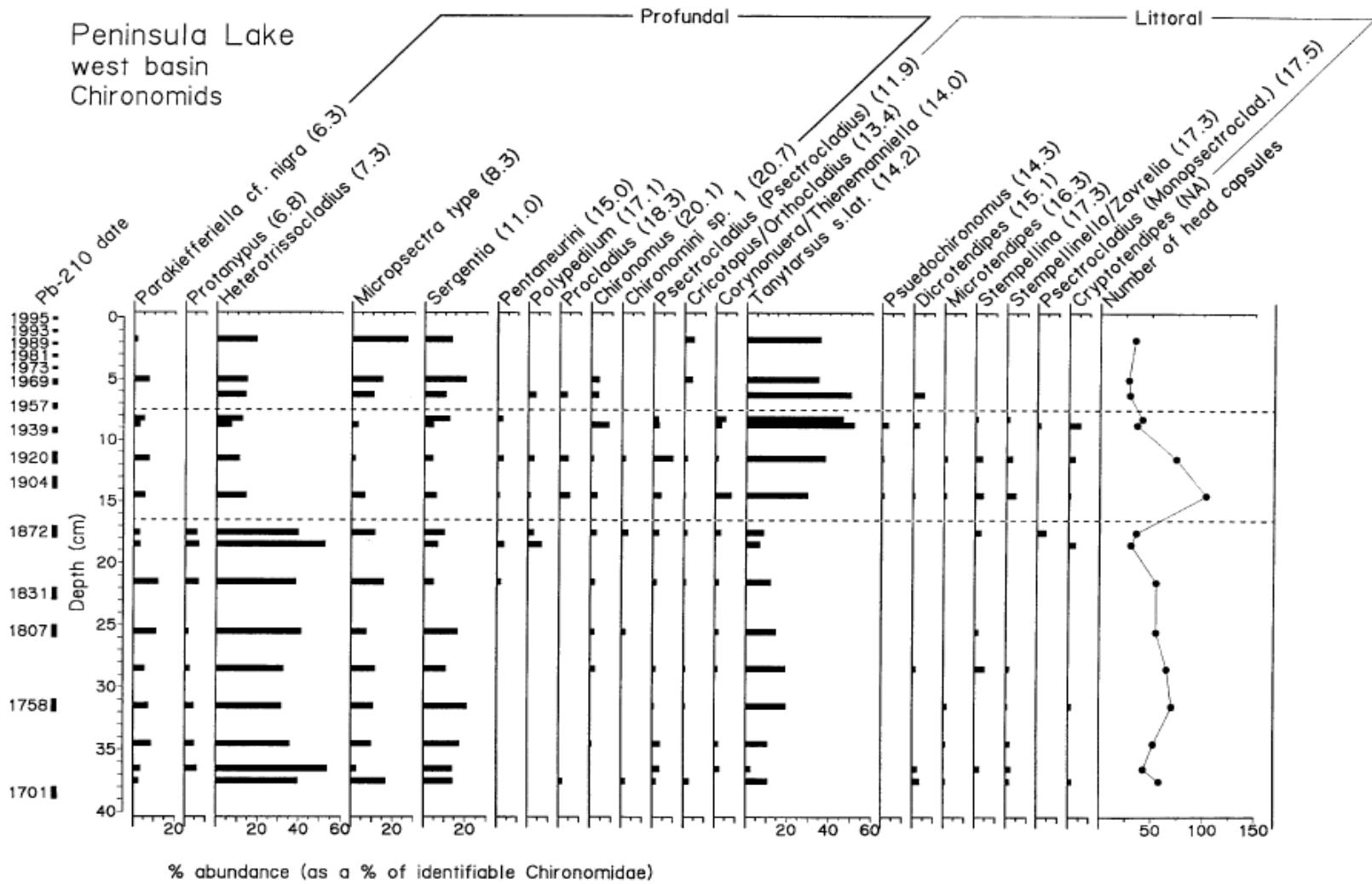
Significant logging

1972

Sewage Treatment



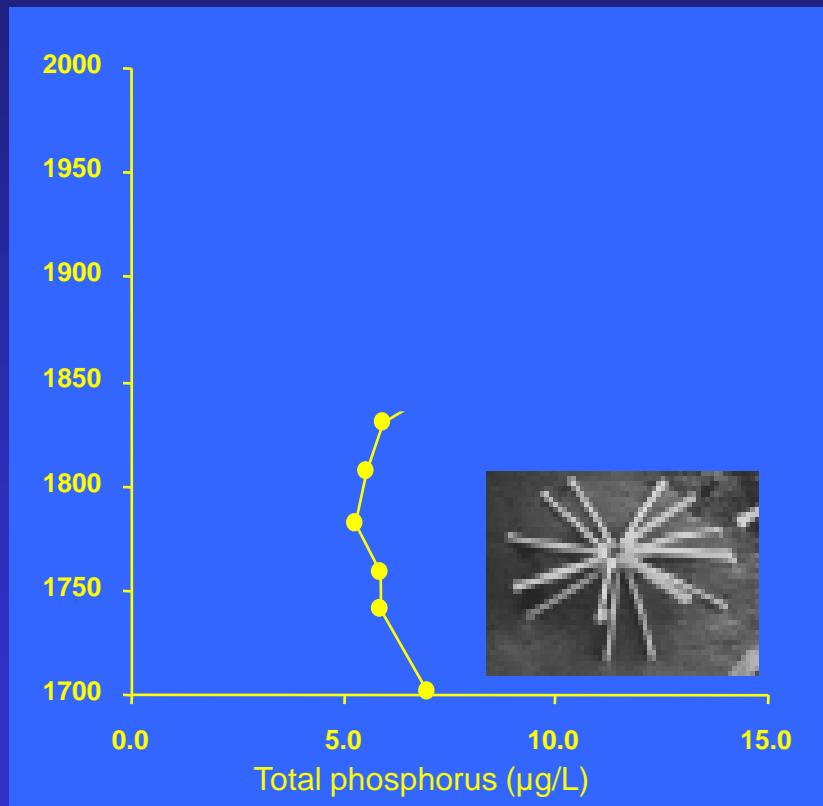
Diatoms indicate striking eutrophication and recovery



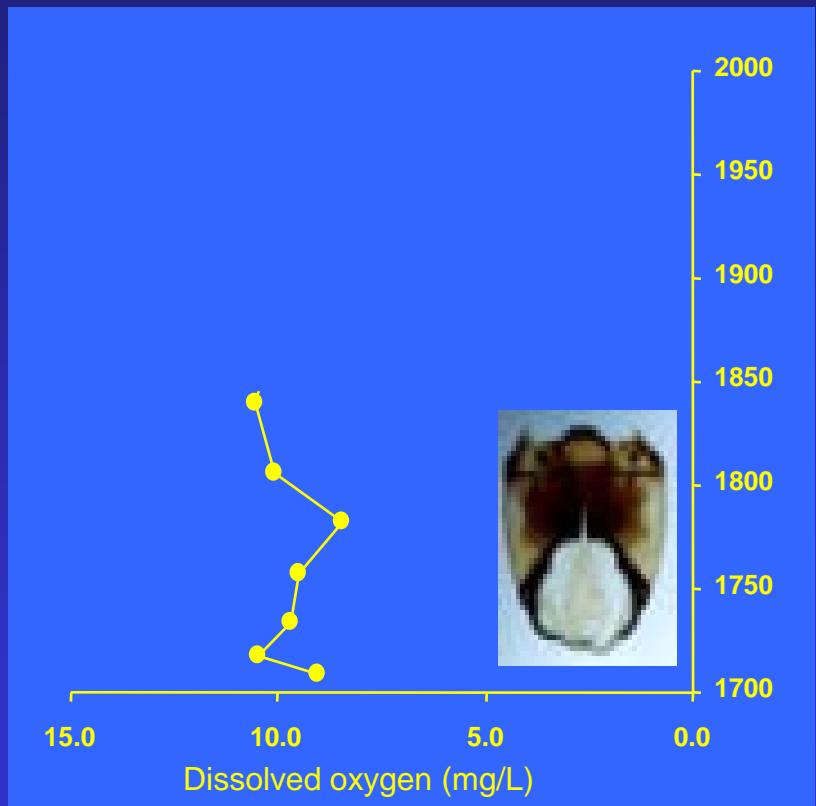
Similarly chironomids indicate marked changes
in deepwater oxygen levels

‘Natural’ conditions: Before European settlement in the region

Phosphorus



Deep-water oxygen

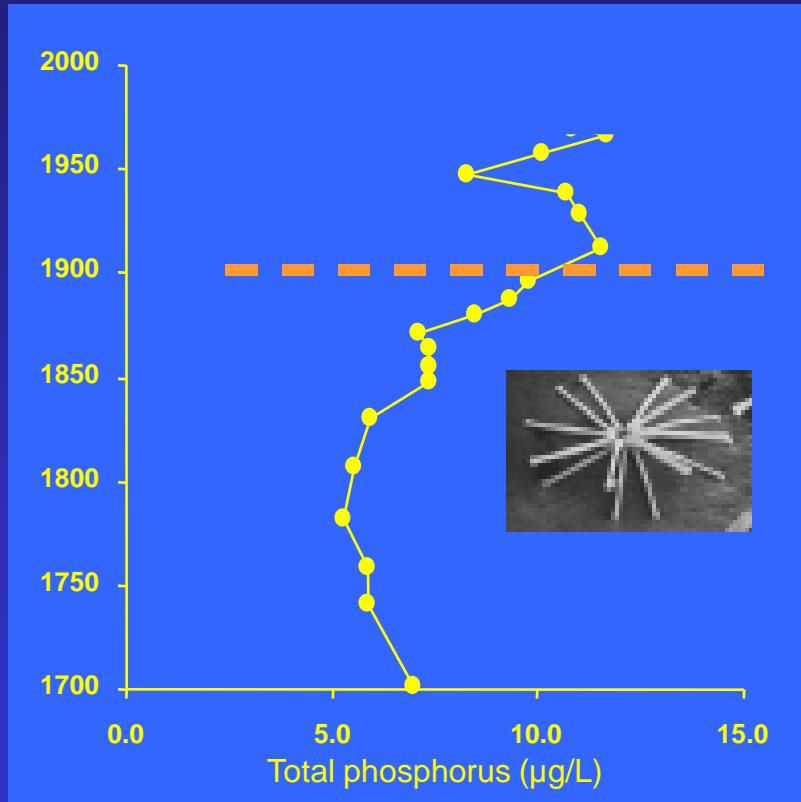


low —————→ high

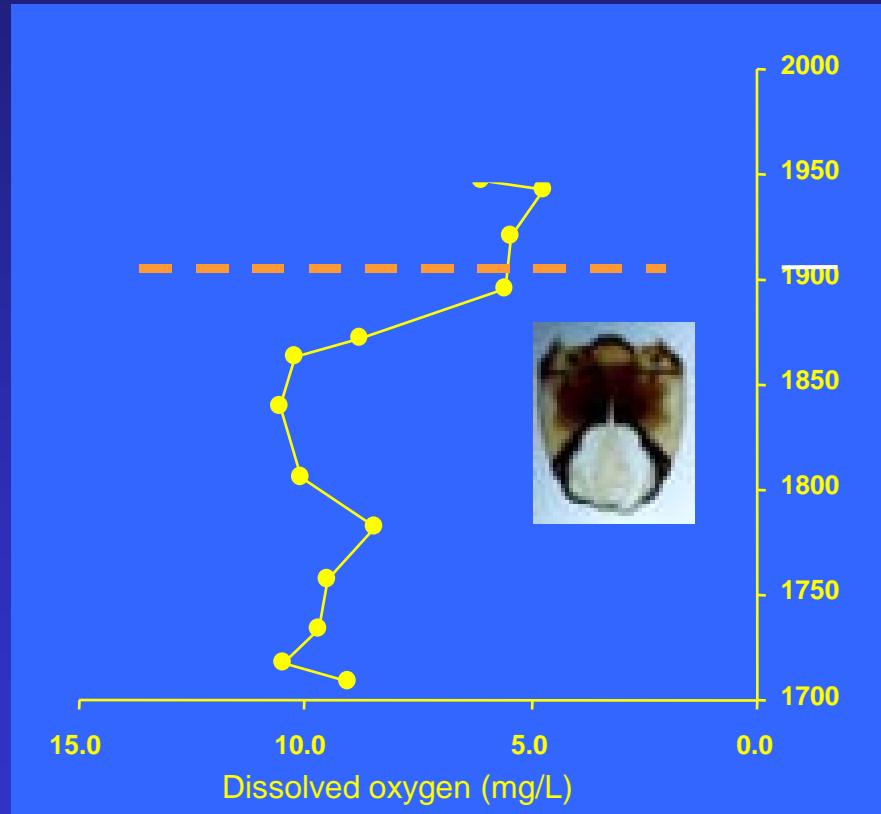
high —————→ low

A decline in water quality

Phosphorus



Deep-water oxygen

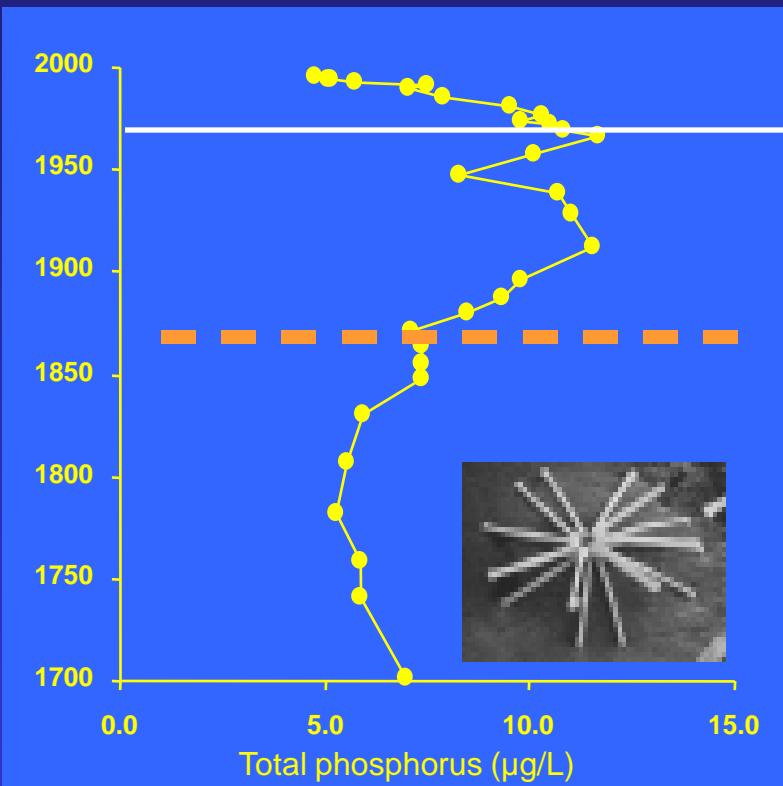


low → high

high → low

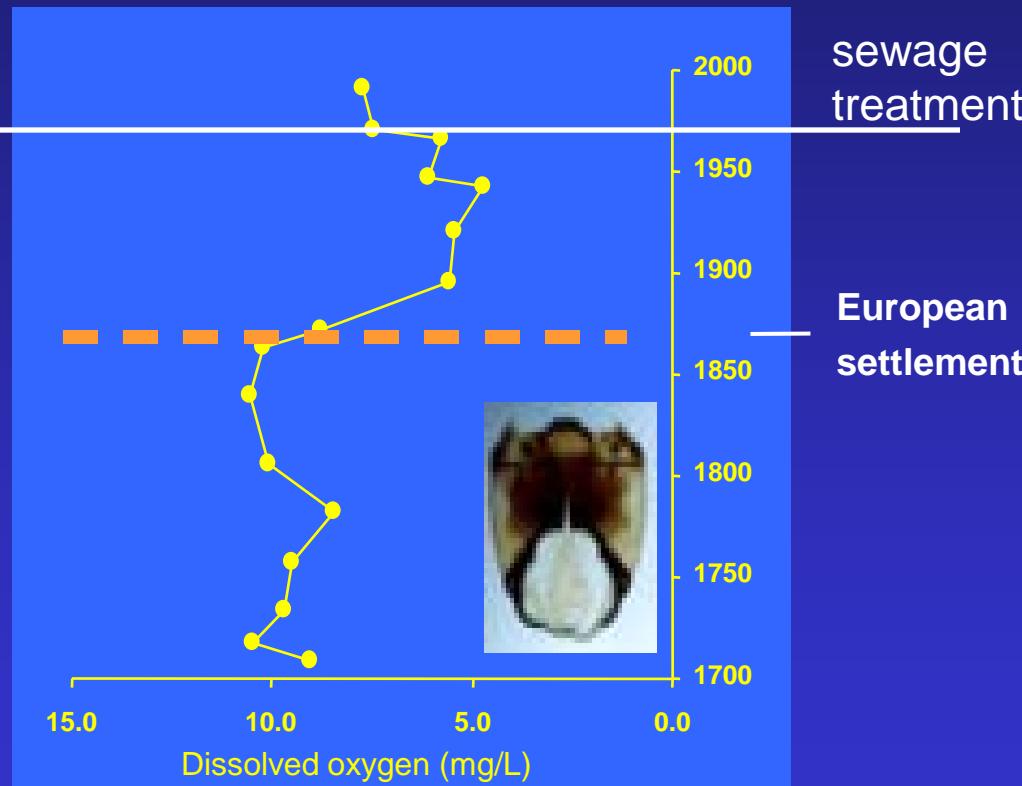
Turning the corner

Phosphorus



low —————→ **high**

Deep-water oxygen



high —————→ **low**

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.

Acidification: Timing of changes

- Study changes at decadal scale

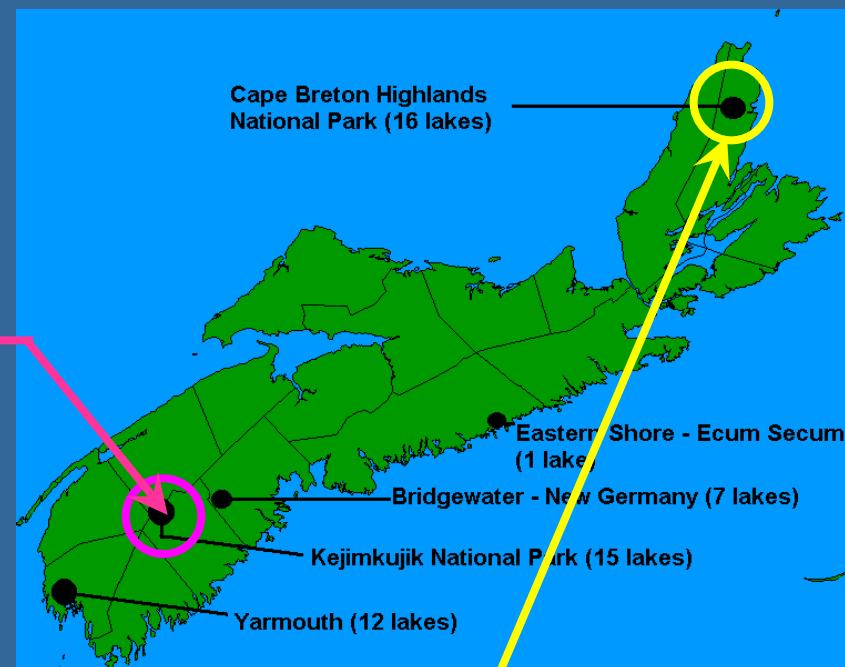
- timing of acidification

- Kejimkujik National Park:

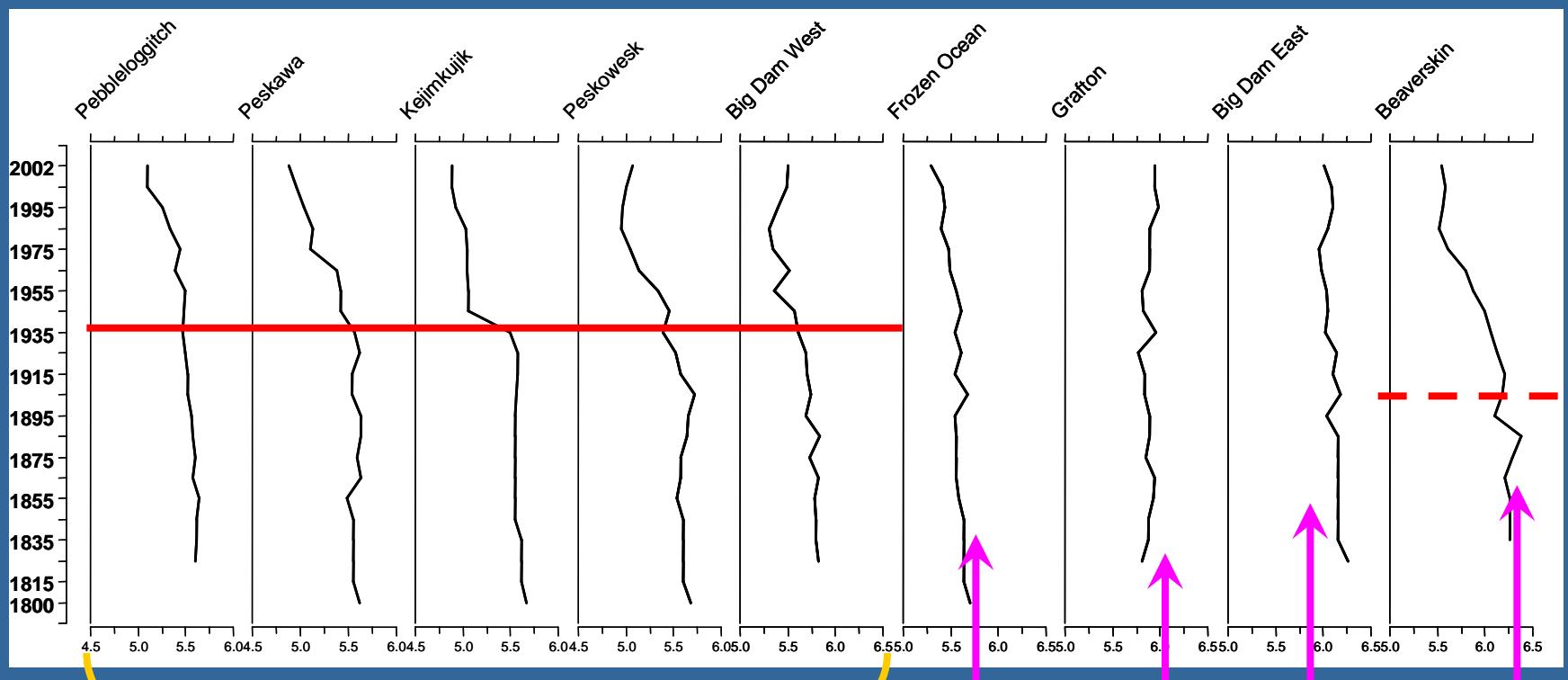
- "high" SO_4^{2-} deposition
 - 8 lakes

- Cape Breton Highlands National Park:

- "low" SO_4^{2-} deposition
 - 6 lakes



Acidification: Timing (Kejimkujik)



Acidification ~ 1940

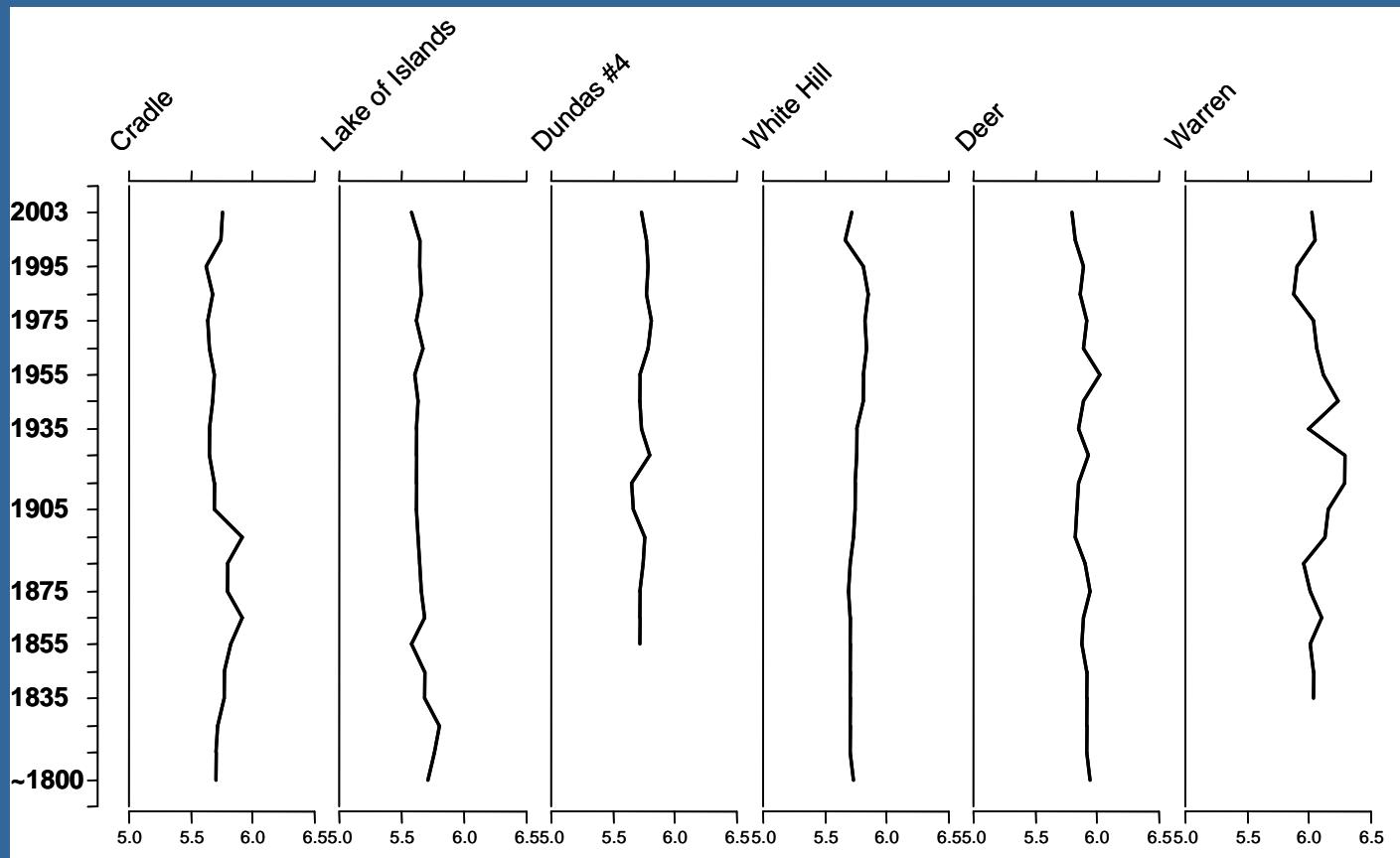
Forest
Fire?
~1878

Logging?

CO_3^{2-}

Acidified
~1925

Acidification: Timing (Cape Breton)



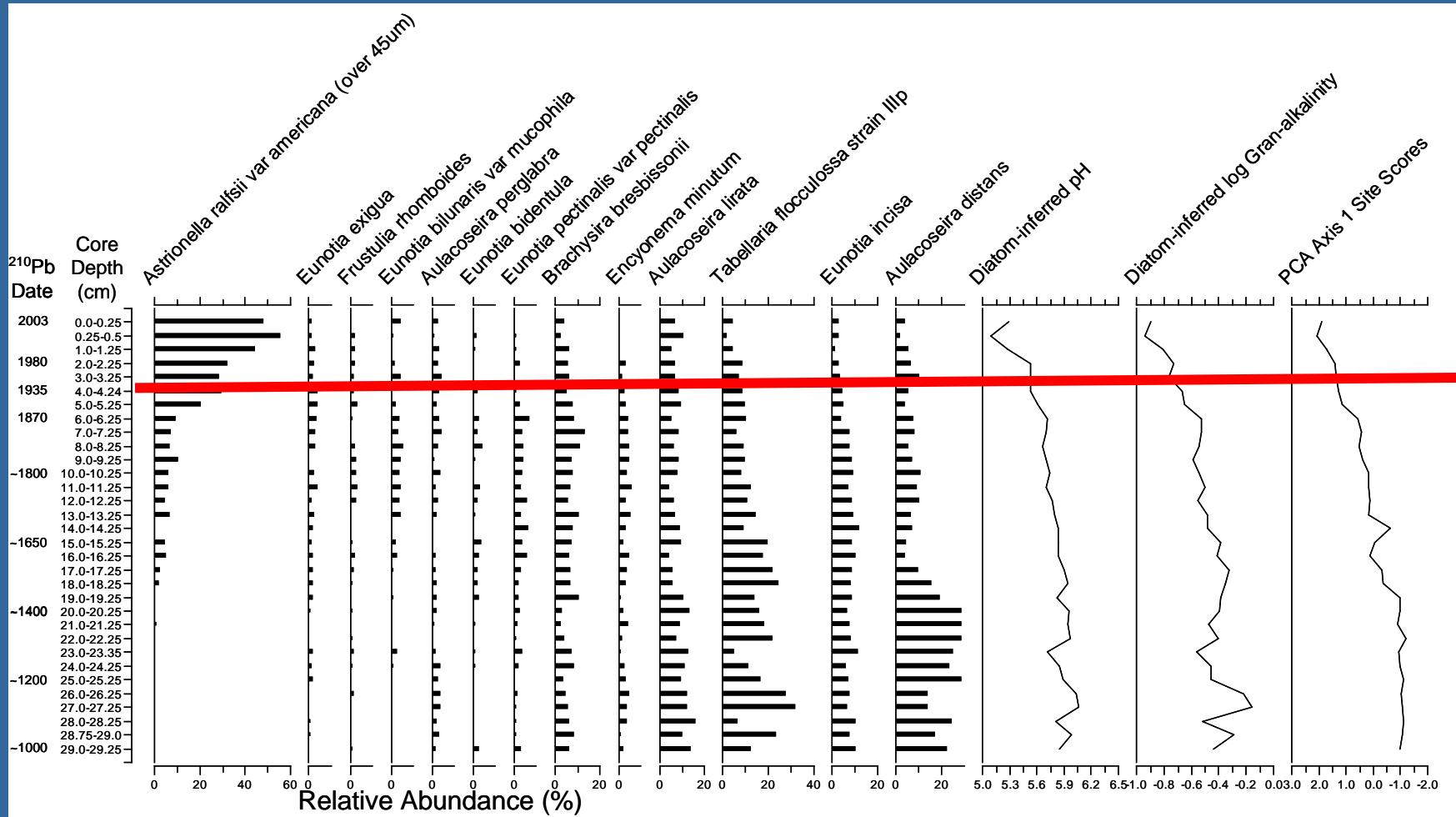
- No acidification trends in 15 of 16 lakes.
- Diatom changes from climatic causes?

Acidification: Cape Breton's Glasgow Lake?



Glasgow Lake:
Rogue signal?
or
Sentinel of acidification?

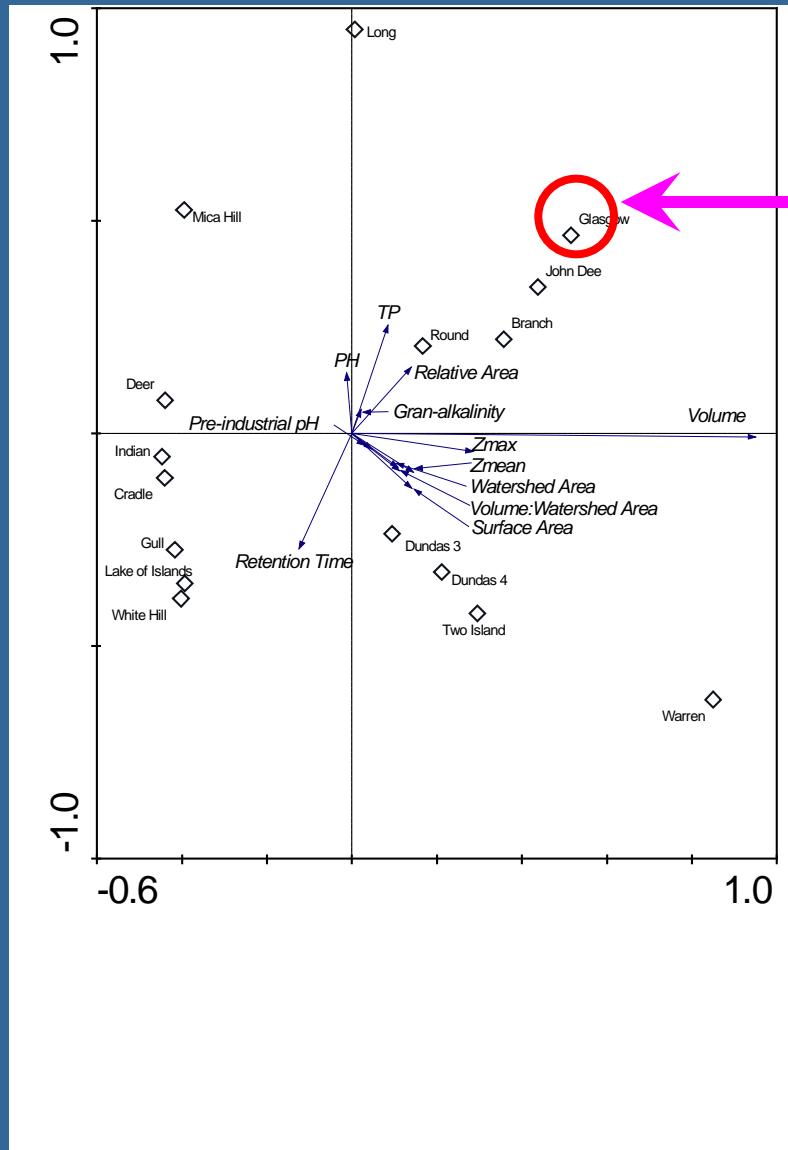
Acidification: Cape Breton's Glasgow Lake



Acidified ~1925 – but why only this lake?

Gerber et al., 2008, Hydrobiologia

Acidification: Cape Breton's Glasgow Lake?



High volume, slow flushing,
very low alkalinity

Critical sulphate load = 0 kg/ha
Sentinel of acidification in Cape
Breton

What can we learn from these 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



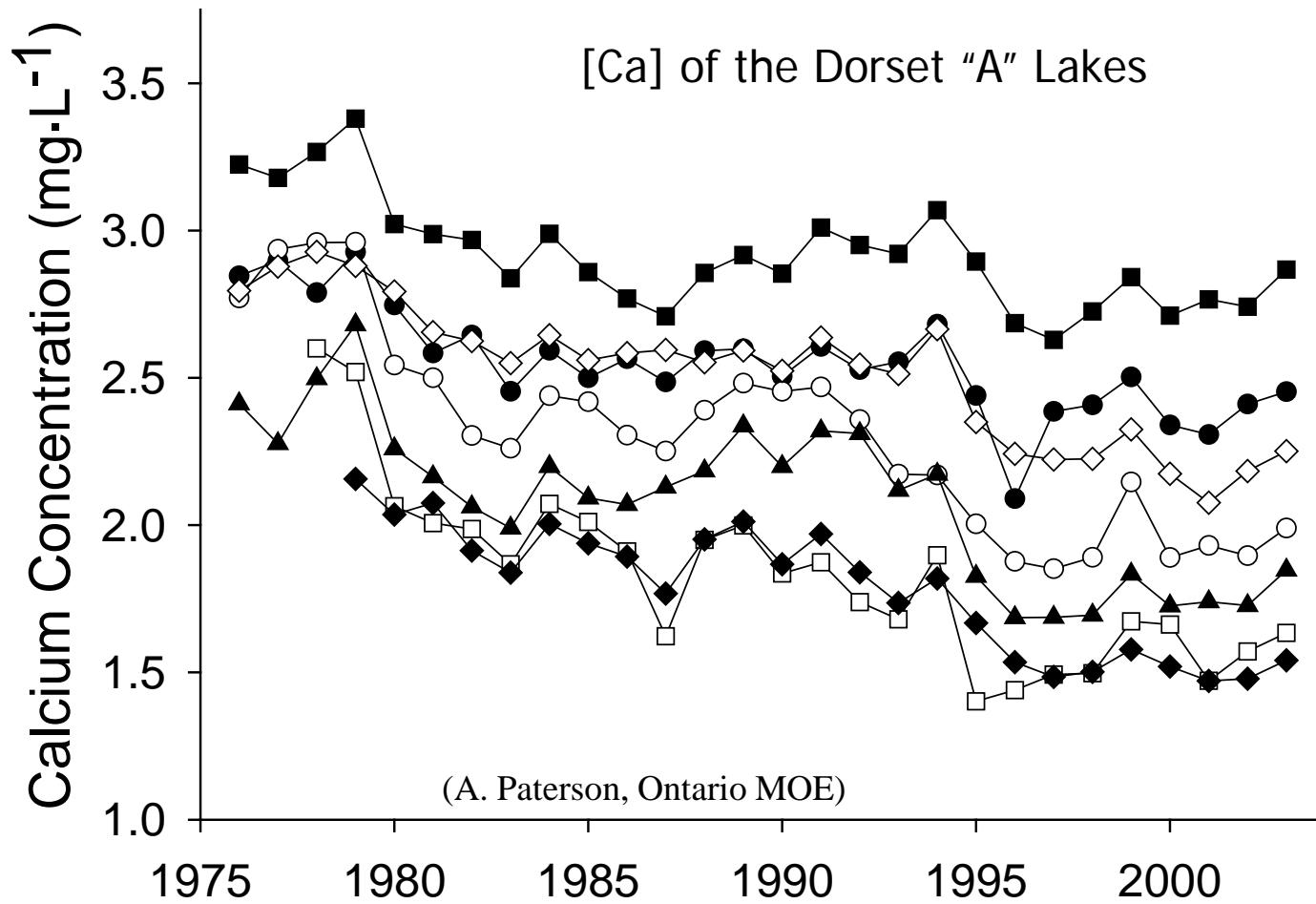
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Calcium – why do we care?

4	Be	2	2
	Beryllium		
	9.012182		
12	Mg	2	8
	Magnesium		2
	24.3050		
20	Ca	2	8
	Calcium		8
	40.078		2
38	Sr	2	8
	Strontium		8
	87.62		2
56	Ba	2	8
	Barium		8
	137.327		2

- 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

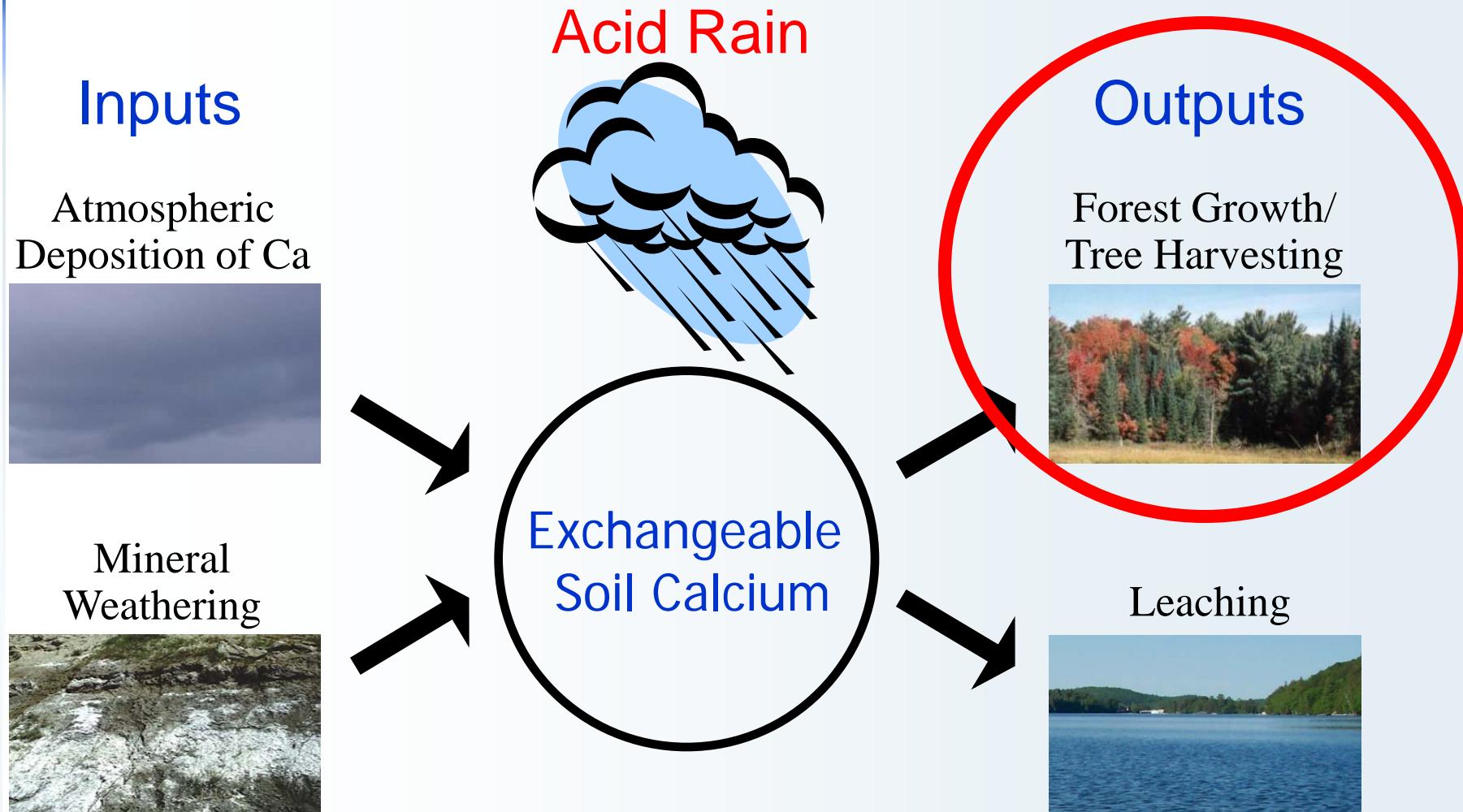
Lake [Ca] Decline



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

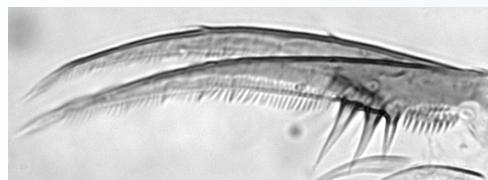


Identifying an Indicator for Calcium Thresholds



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 ?

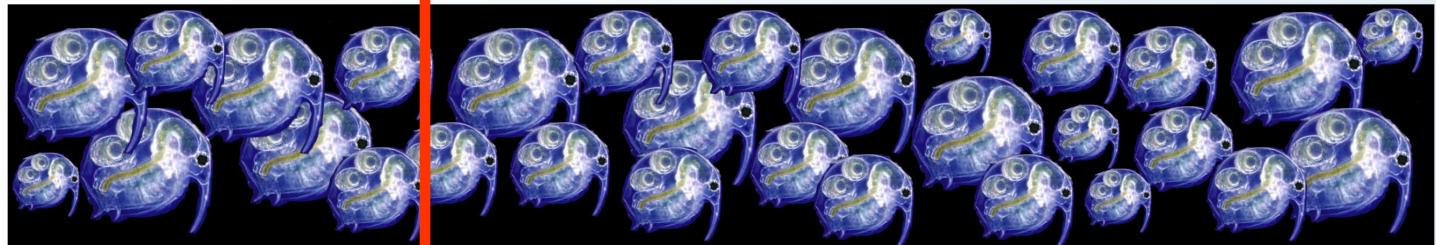
Daphnia spp.

1.5 mg/L



Bosmina spp.

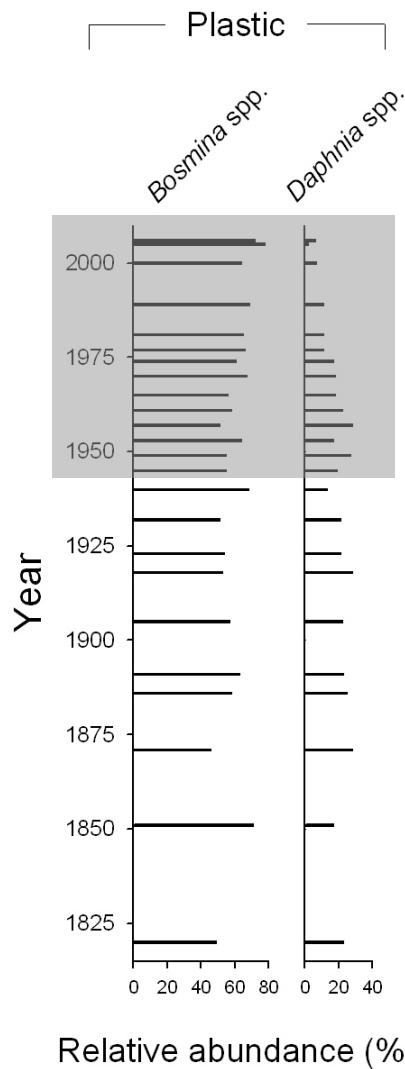
[Calcium]



3 Paleolimnological Case Studies

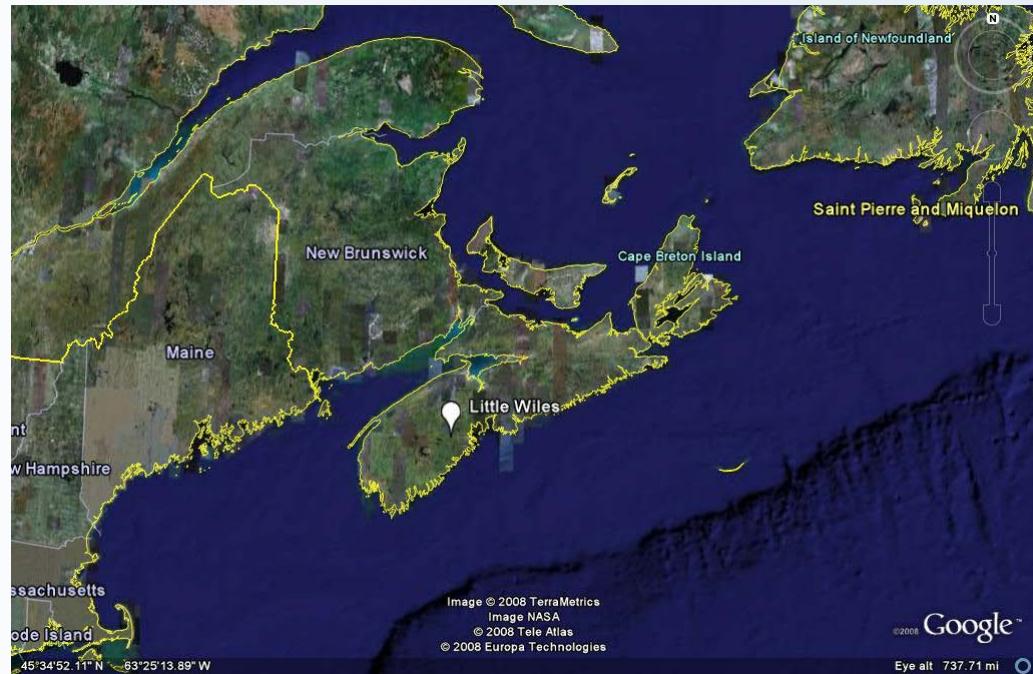
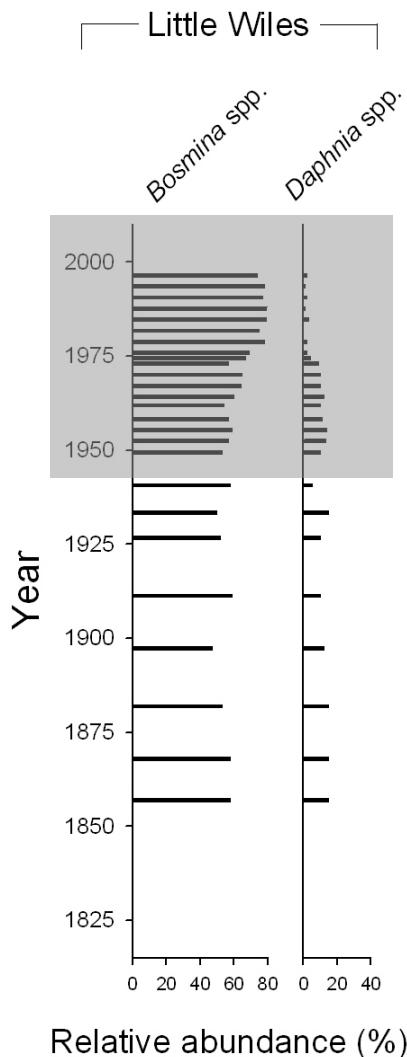
- Plastic Lake (Ontario) - Received little acid deposition and the lake did not acidify;
[Ca] = 1.4 mg/L
- Little Wiles Lake (NS) - Naturally acidic;
[Ca] = 1.0 mg/L
- Big Moose Lake (NY) - Experienced a steady pH decline throughout the 1950s (peak acidification) to 4.5 and has subsequently recovered to >5.5;
[Ca] = 1.5 mg/L

Plastic Lake (ON, Canada)



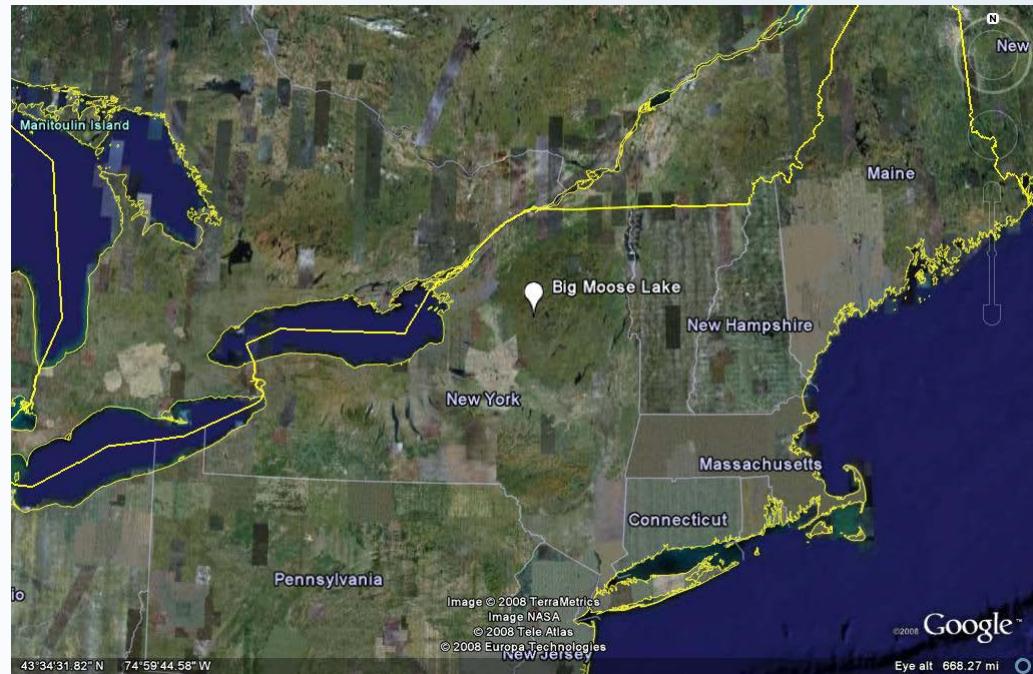
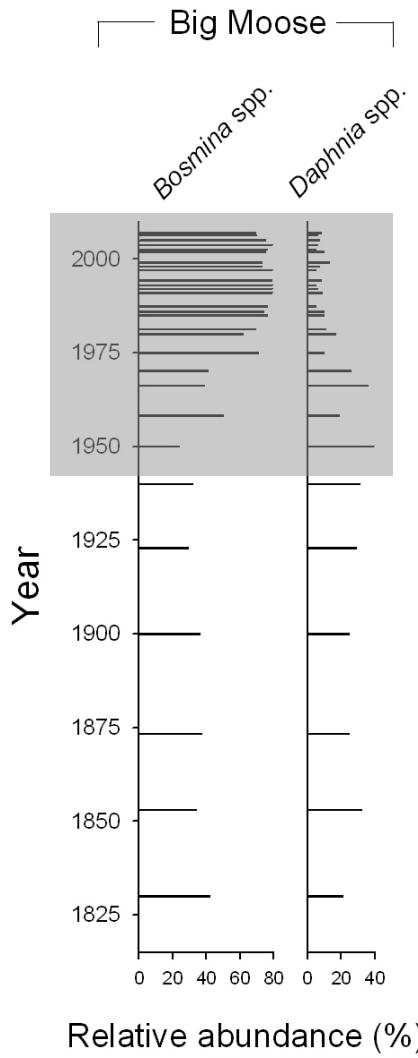
- Located on the Canadian Shield
- Received little acid deposition and the lake did not acidify
- 2006 $[Ca] = 1.4 \text{ mg/L}$

Little Wiles Lake (NS, Canada)



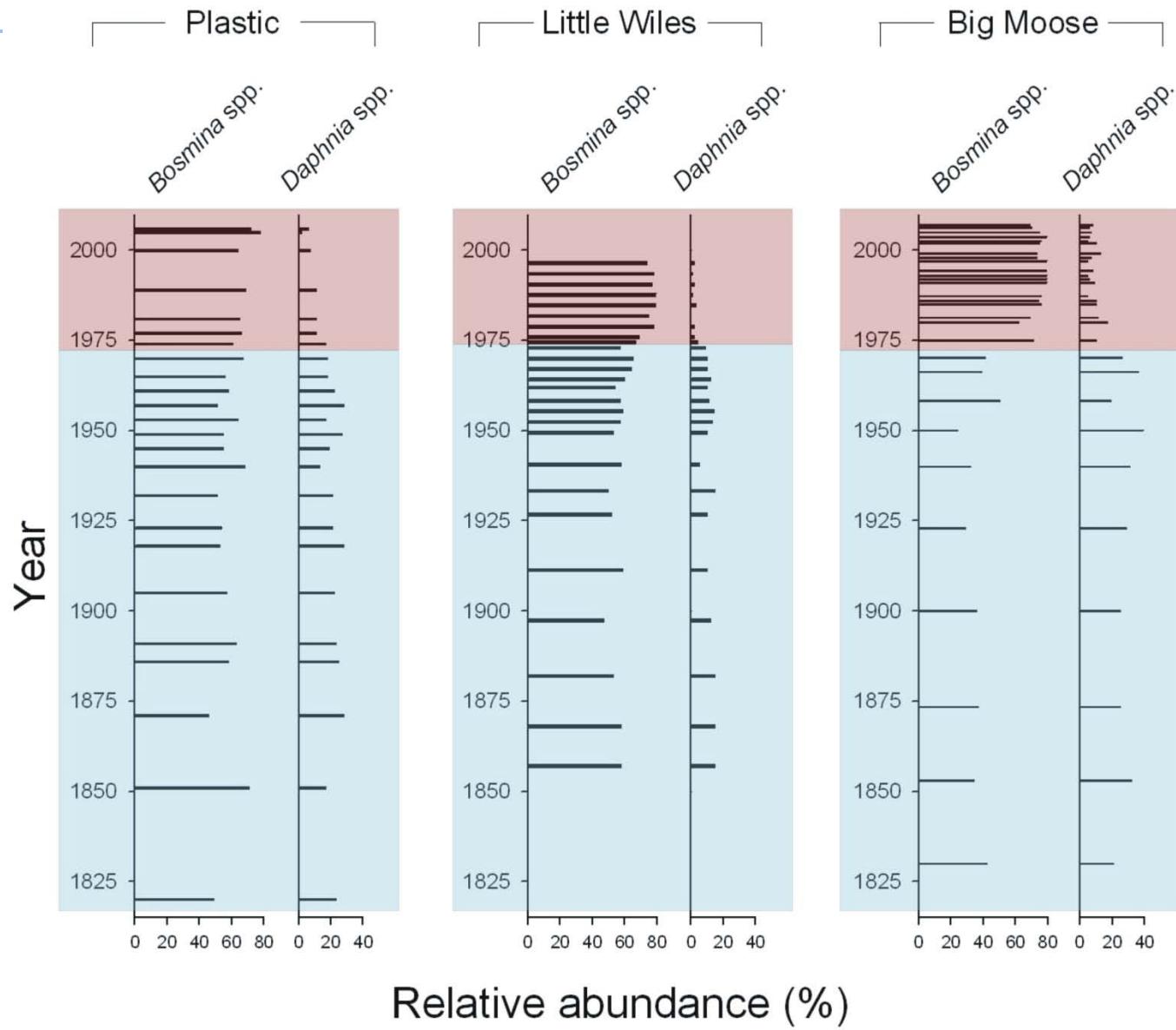
- Located off the Canadian Shield
- Naturally acidic
- 2006 [Ca] = 1.0 mg/L

Big Moose Lake (NY, USA)

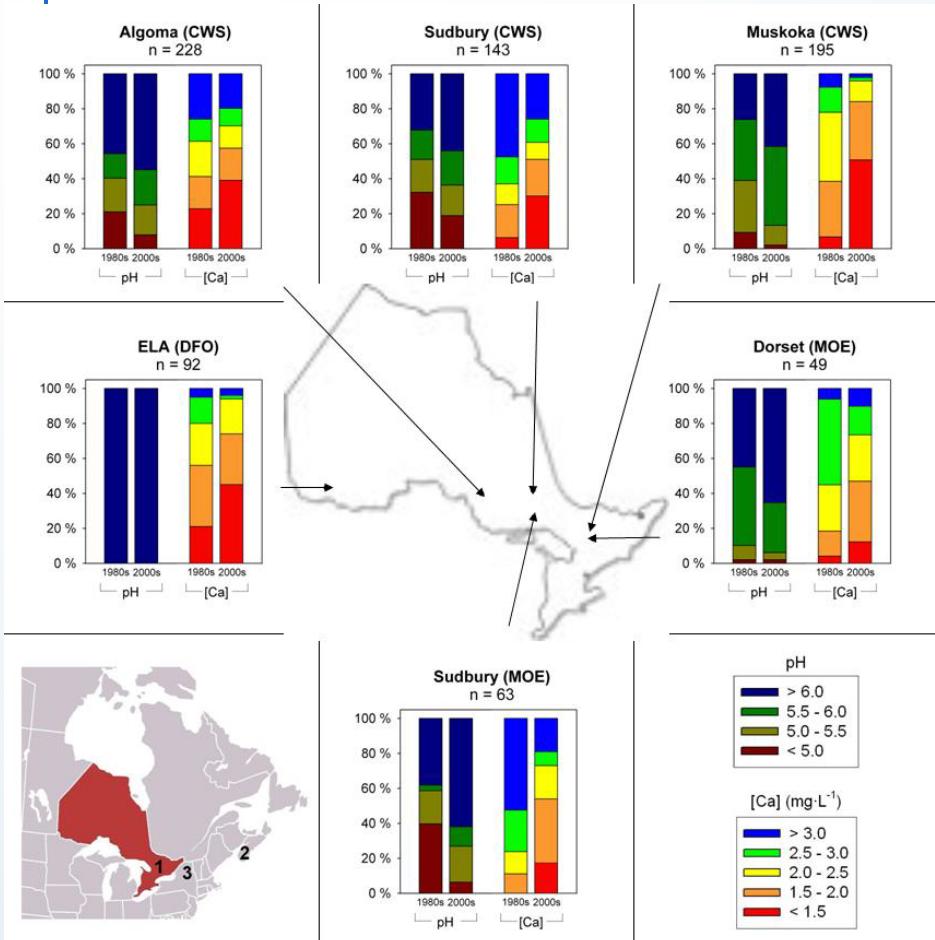


- Located on the Pre-Cambrian Shield in Adirondack Park of NY
- Experienced a steady pH decline throughout the 1950s (peak acidification) to 4.5 and has subsequently recovered to >5.5
- 2006 [Ca] = 1.5 mg/L

3 acidification scenarios, similar *Daphnia* responses

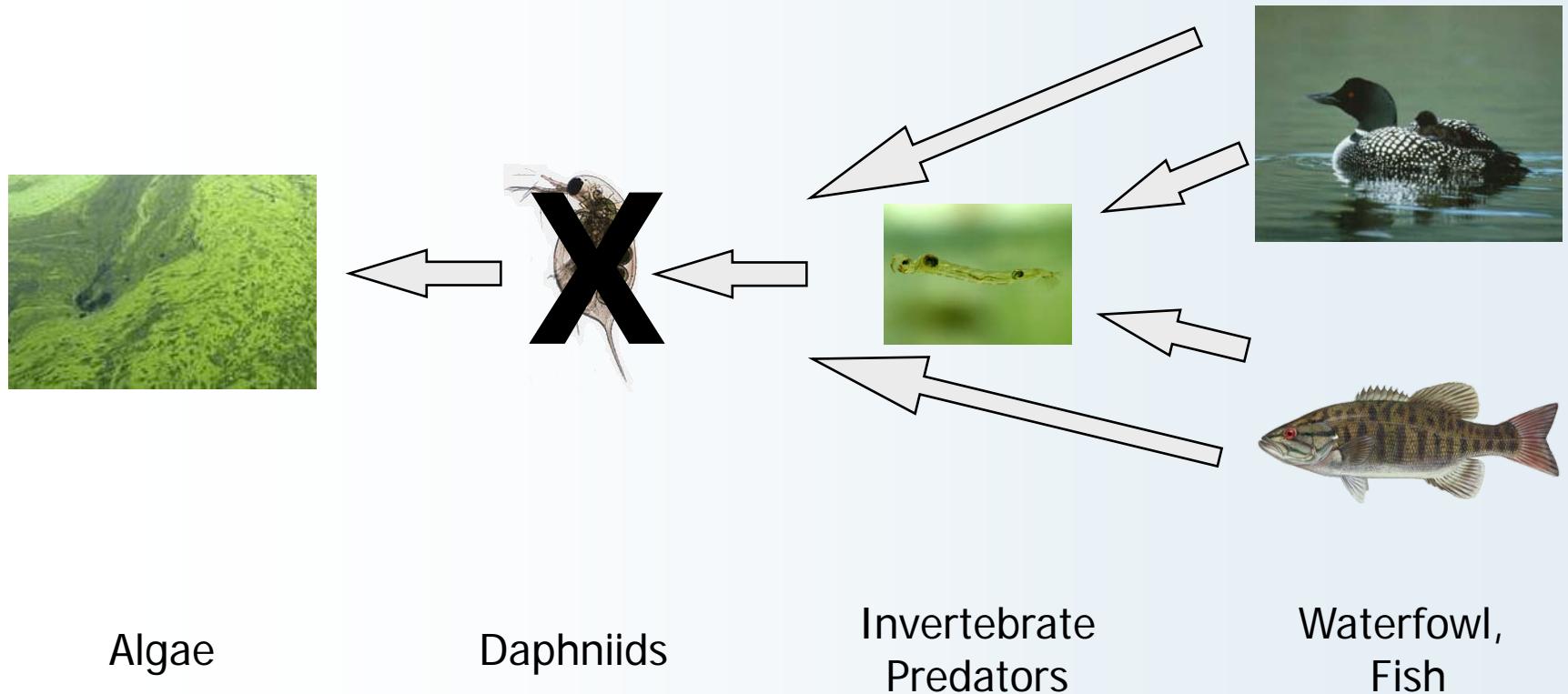


Low calcium levels are now widespread on Shield lakes



- 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

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

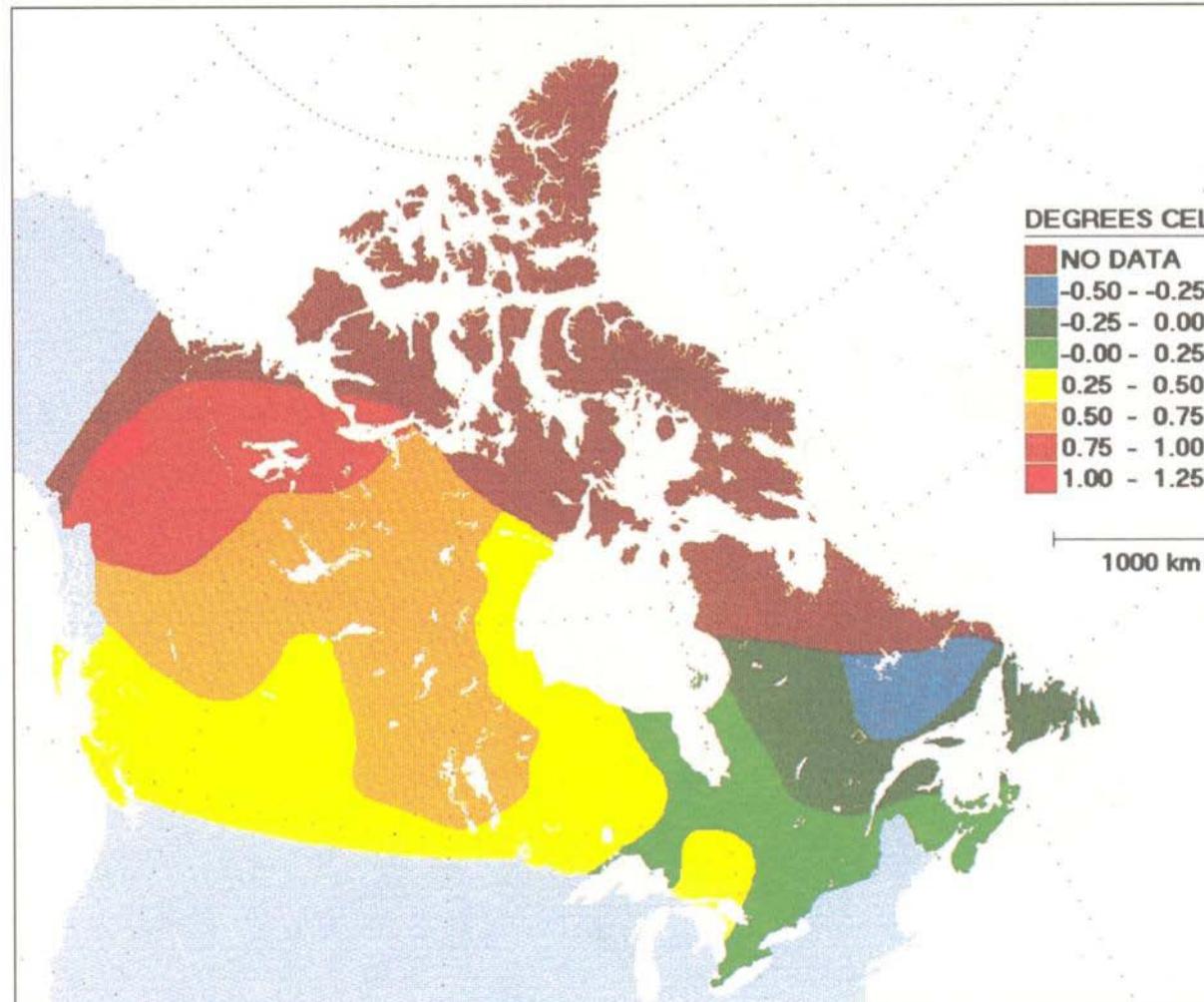
The Limnologist's Canary?



Climate change: The new “threat multiplier”



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



SOURCE: Environment Canada.



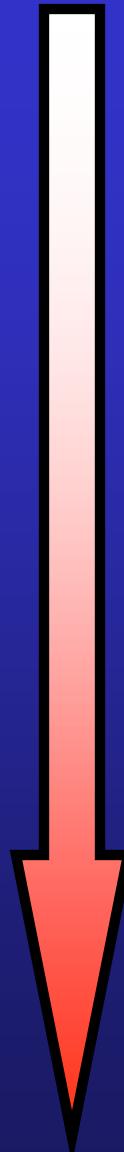


Cape Herschel, Ellesmere Island

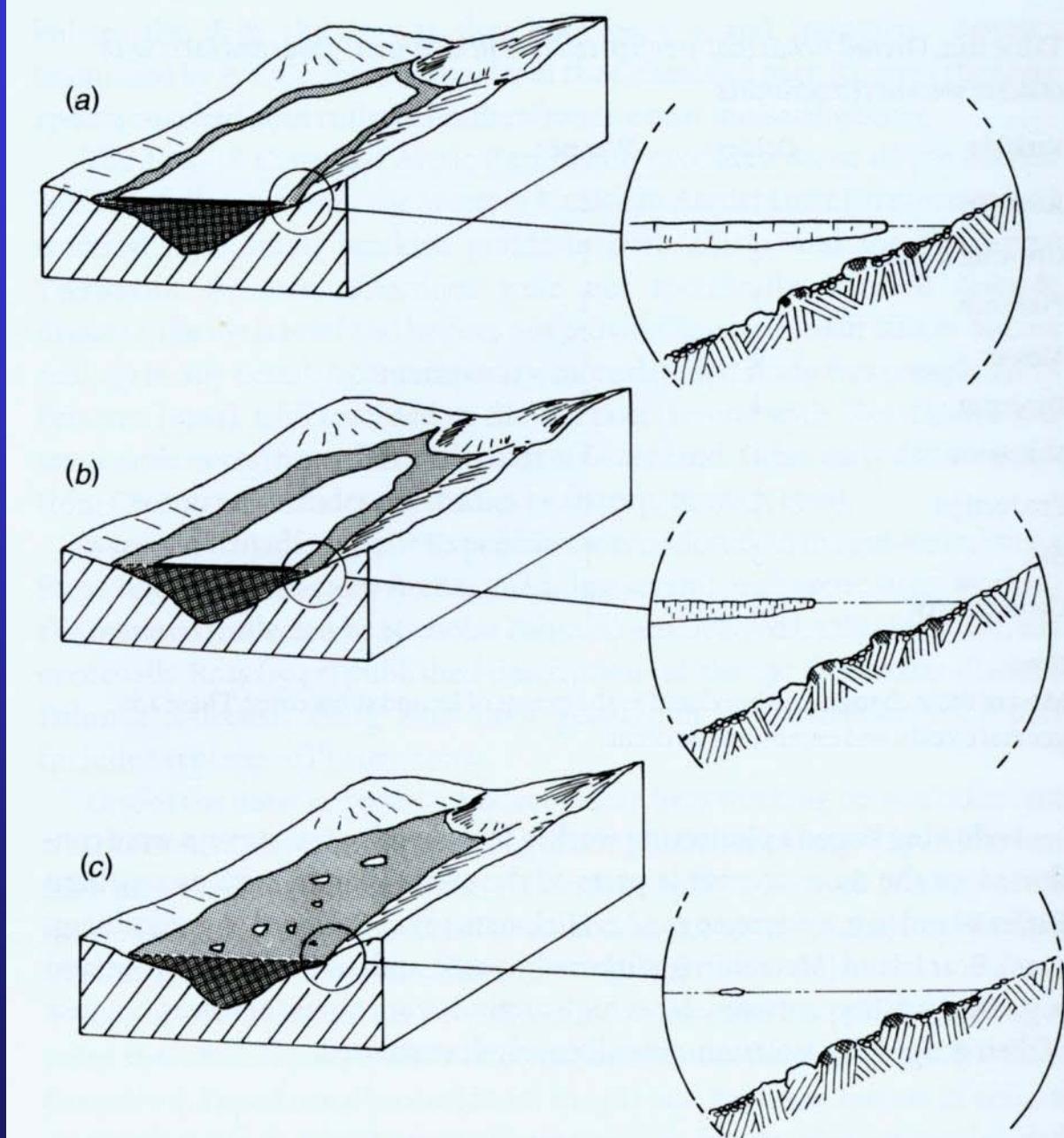


Cape Herschel Field Station; July 9, 2007

Cooler temperatures



Warmer Temperatures

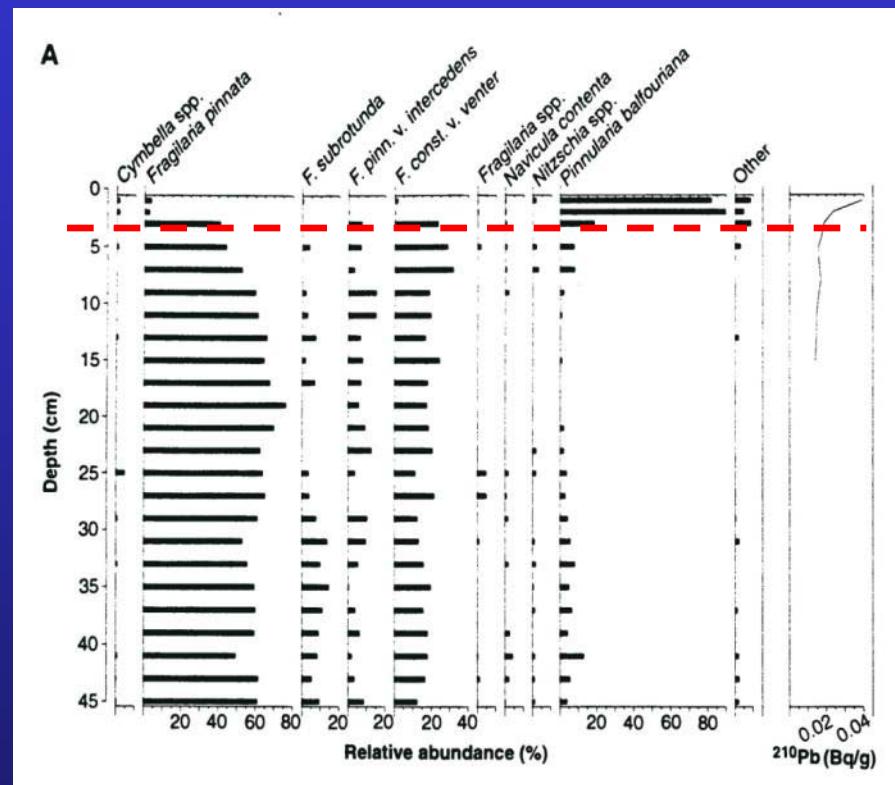
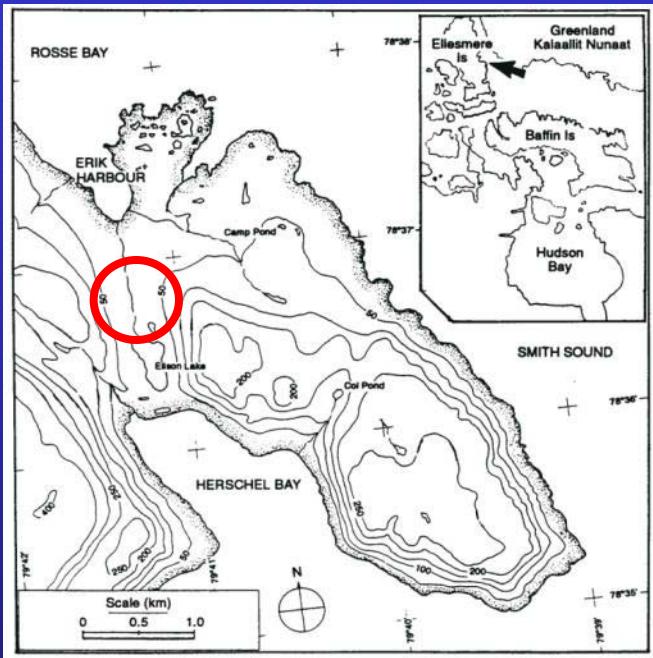


(Smol 1983, 1988)

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.

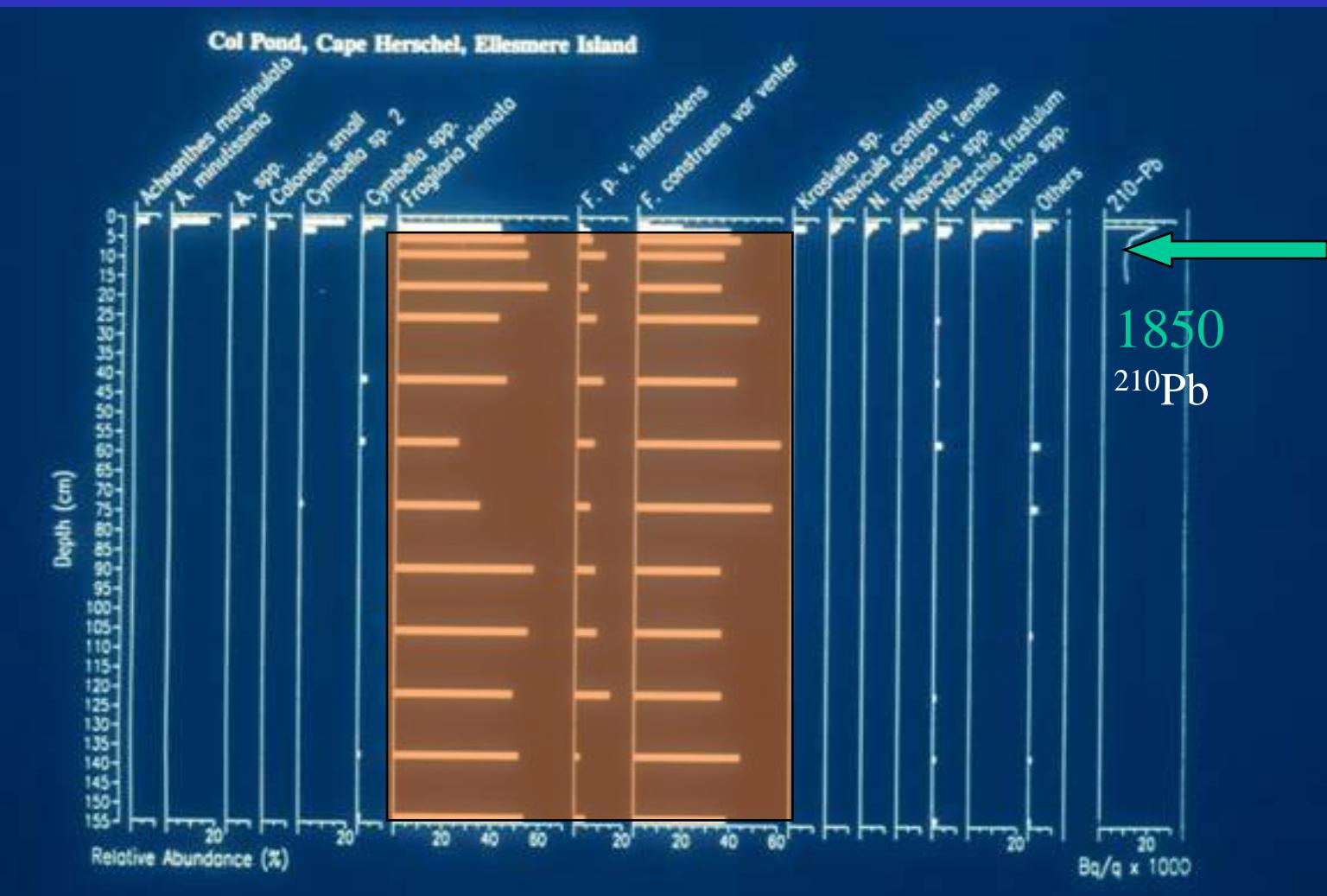
Cape Herschel, Ellesmere I., Elison Lake



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

- unprecedented ecosystem change in ~ 4 k yr

Cape Herschel, Ellesmere I., Col Pond



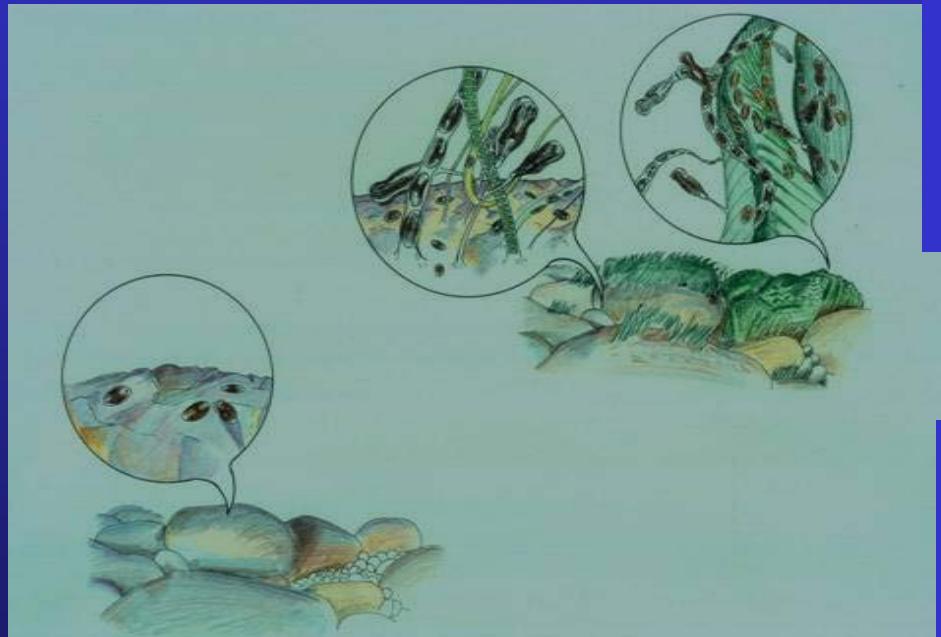
(Douglas, Smol & Blake; *Science* 1994)

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



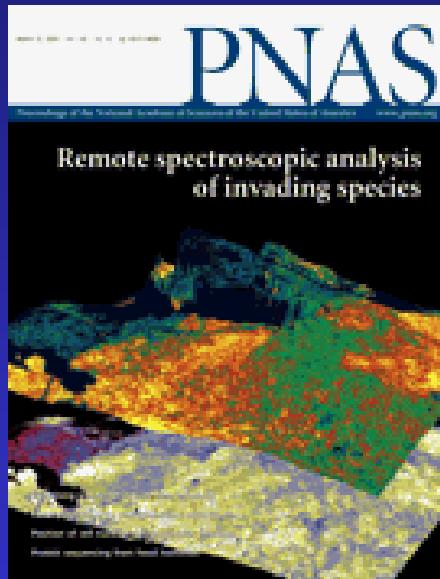
Warmer:
diverse,
complex



Cooler:
few taxa,
simple

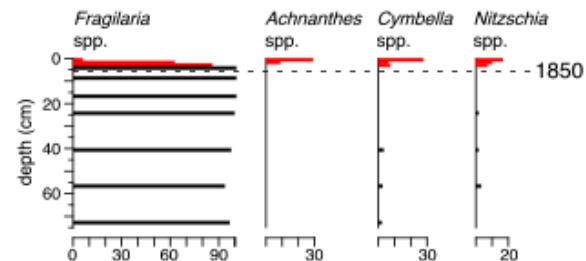
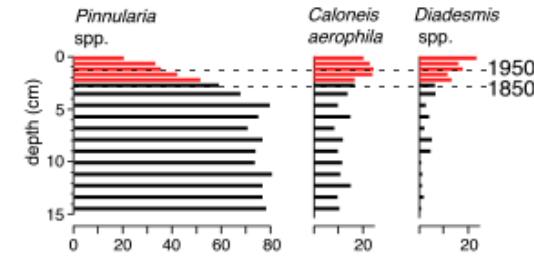
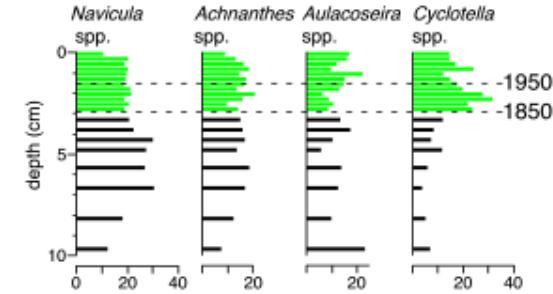
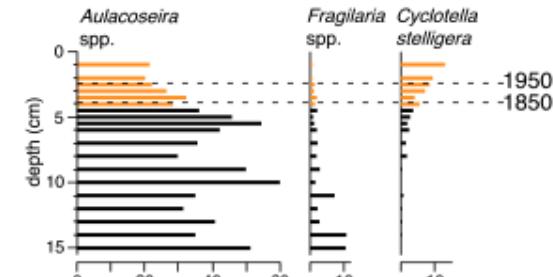
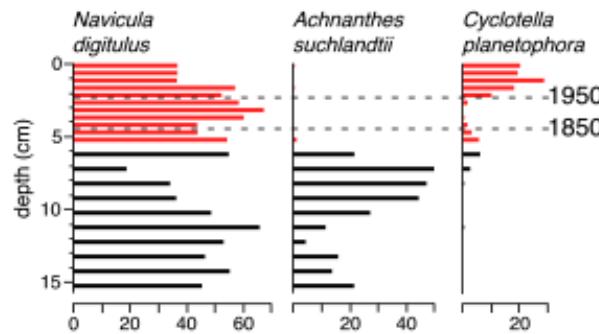
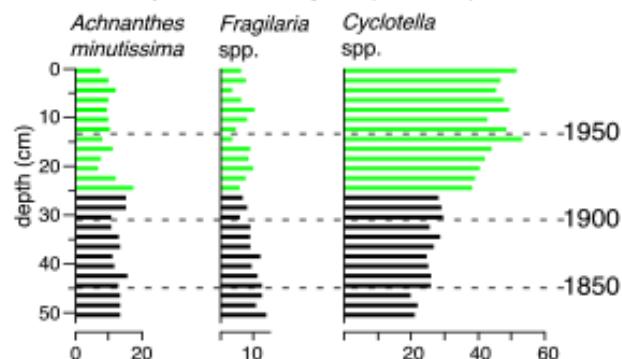
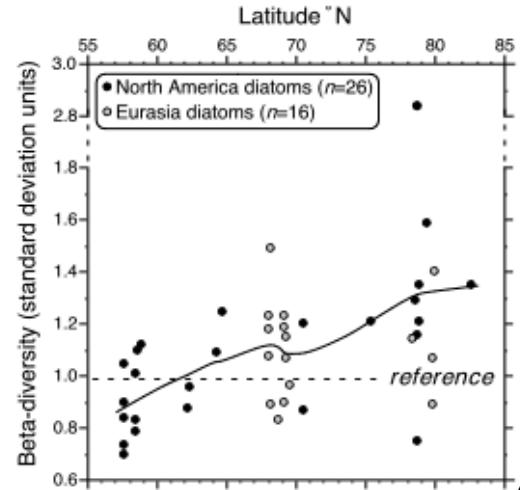
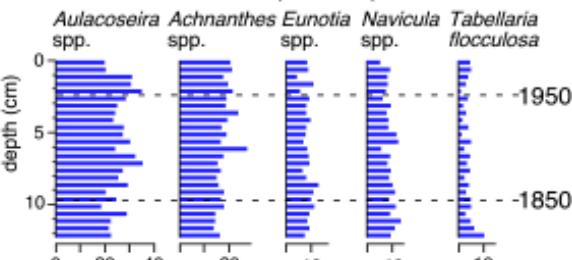
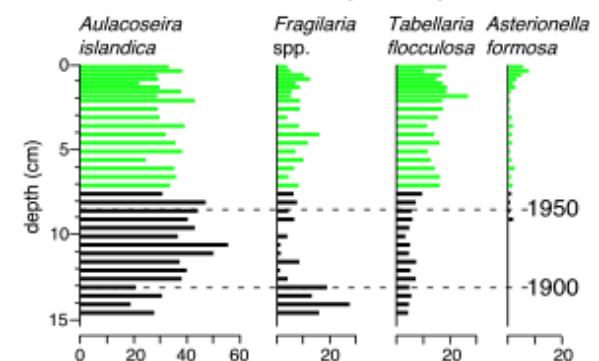


Climate-driven regime shifts in the biological communities of arctic lakes.



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., Siitonens, S.,
Solovieva, N., and Weckström, J.

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

A Ellesmere Island - Col Pond (2.84 SD)**B Ellef Ringnes Island - Isachsen F (1.35 SD)****C Baffin Island - CF 11 (1.20 SD)****D Northwest Territories - Slipper Lake (1.25 SD)****F Spitsbergen - Birgervatnet (1.40 SD)****G Finnish Lapland - Saanäjarvi (1.19 SD)****E Northern Quebec - PC4 (0.84 SD)****H Polar Urals - Mitrofanovskoe (1.23 SD)**

(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

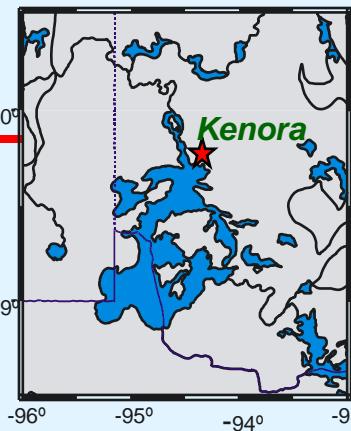
Thermal stratification

Water chemistry, such as nutrients



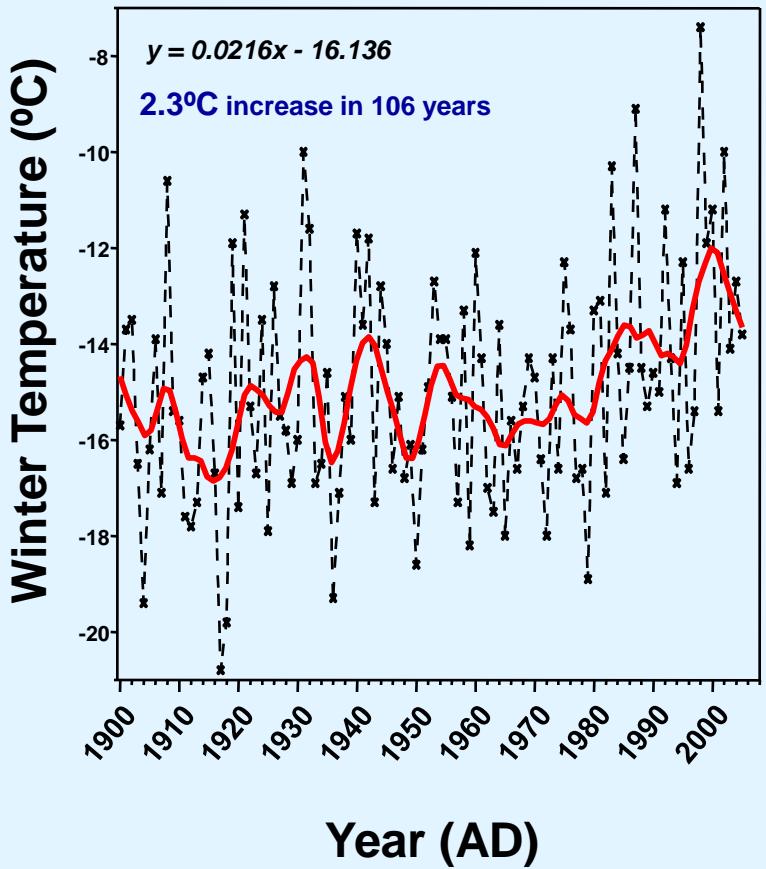
Are similar patterns
occurring in temperate
lakes?

Kenora 100-year Temperature Record

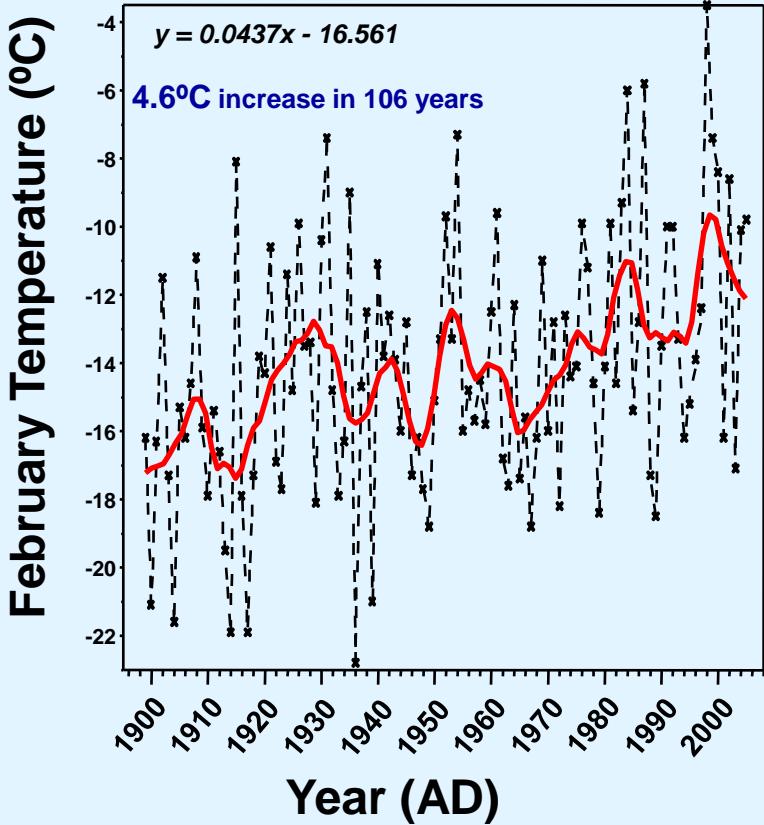


Lake of the Woods

Winter



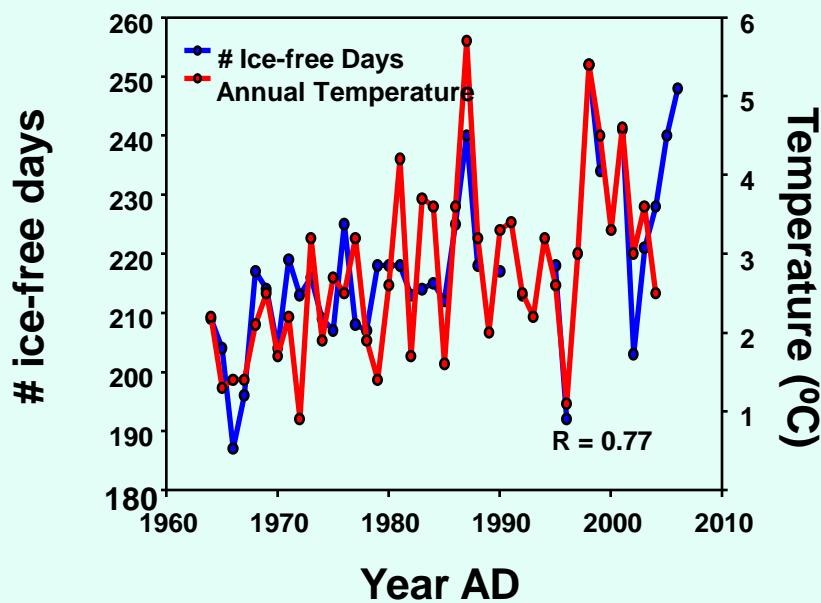
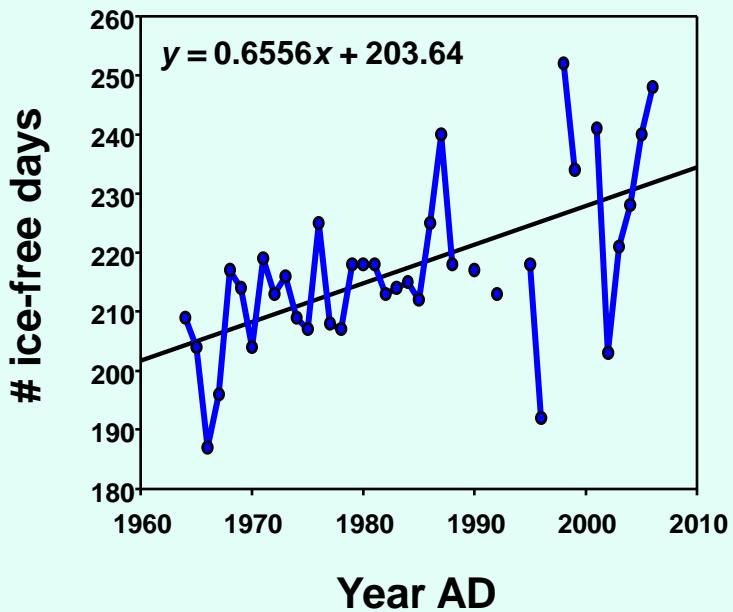
February



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

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

Lake water properties & warming

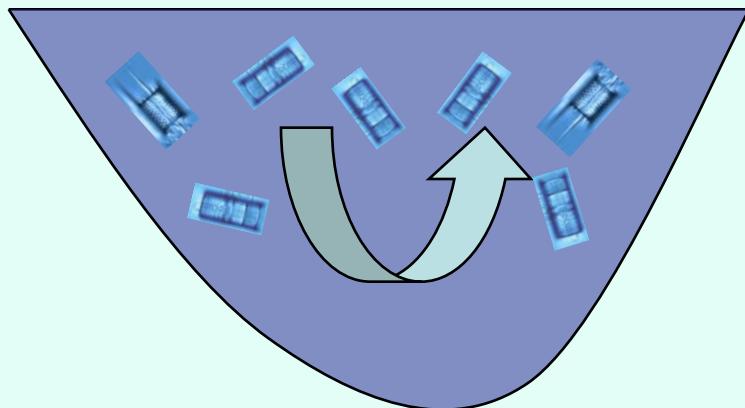
Length of ice-free season- timing of ice-off & ice-on

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

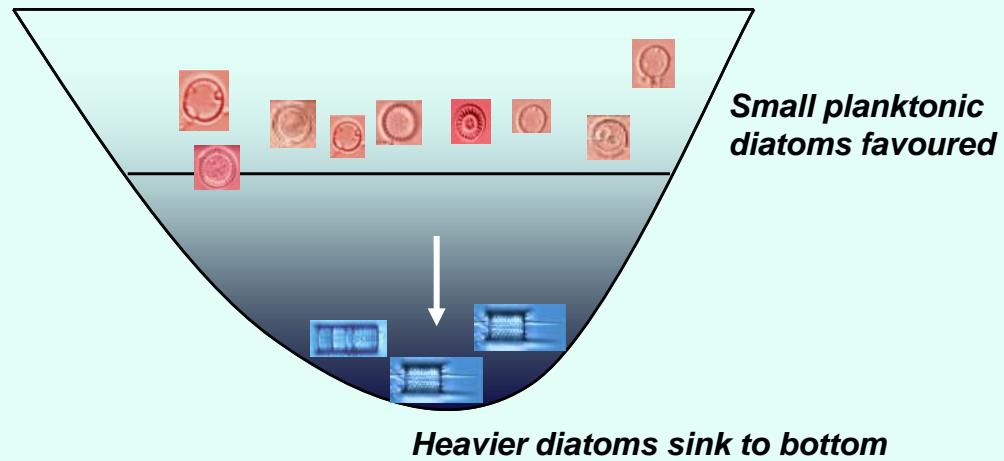
Timing, duration, strength of thermal stratification – depth of mixed epilimnion

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

Mixed water column



Stratified water column

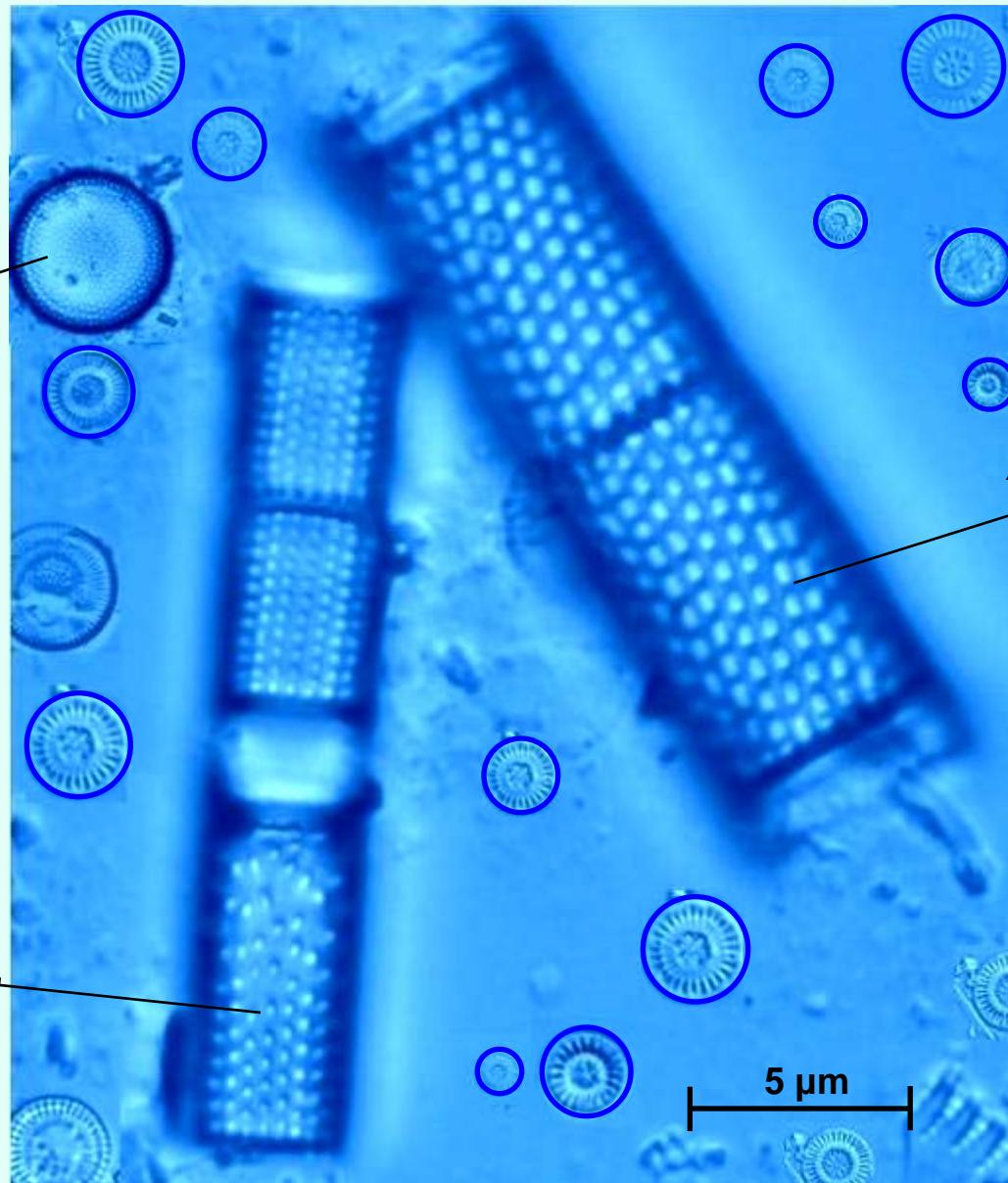


Taxon-specific shift: *Cyclotella-Aulacoseira*

Aulacoseira islandica

Aulacoseira granulata

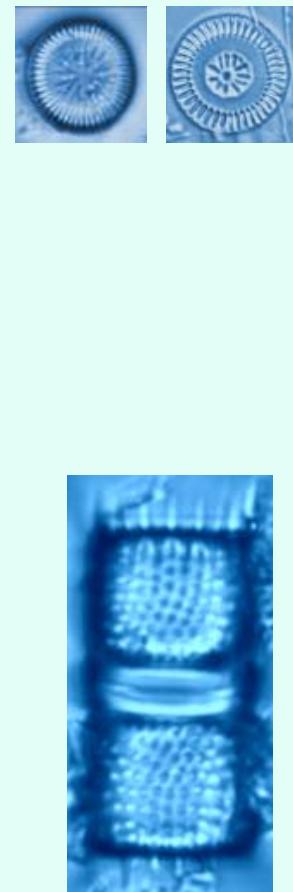
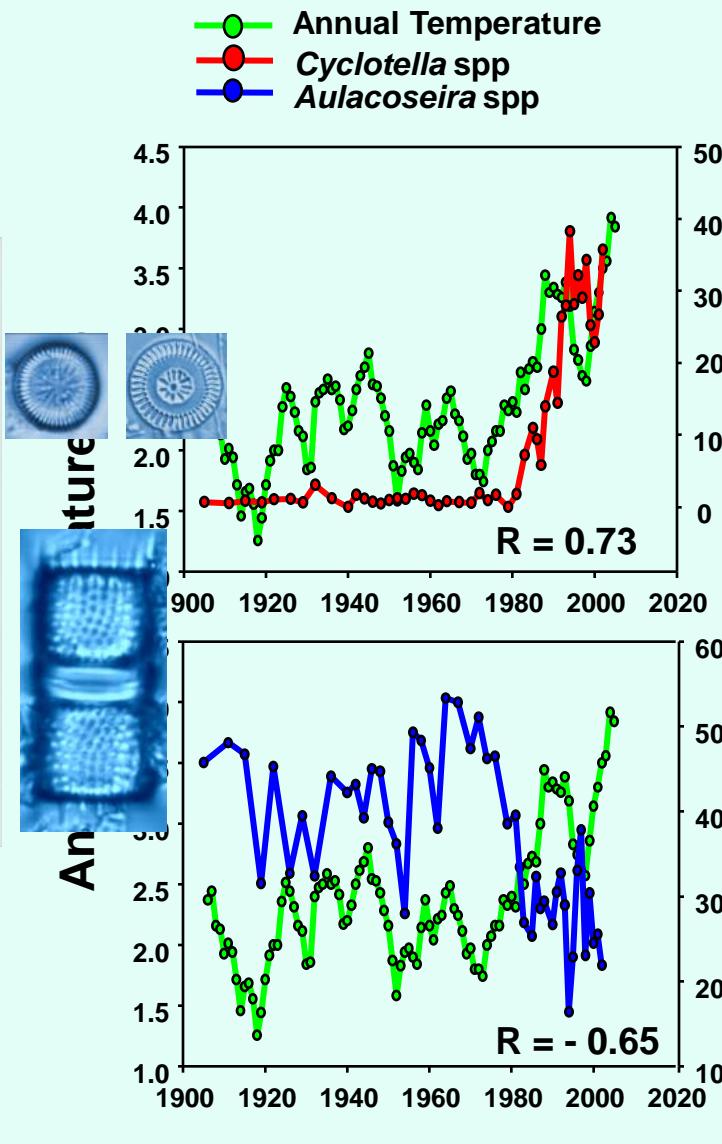
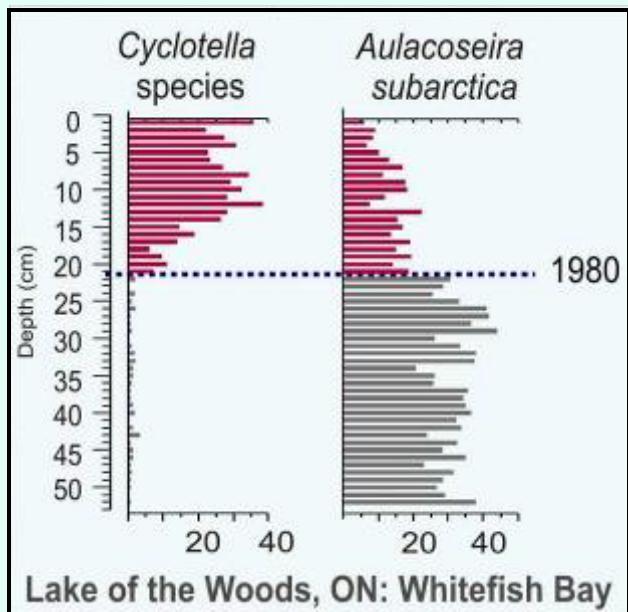
Aulacoseira islandica



Taxon-specific Relationships

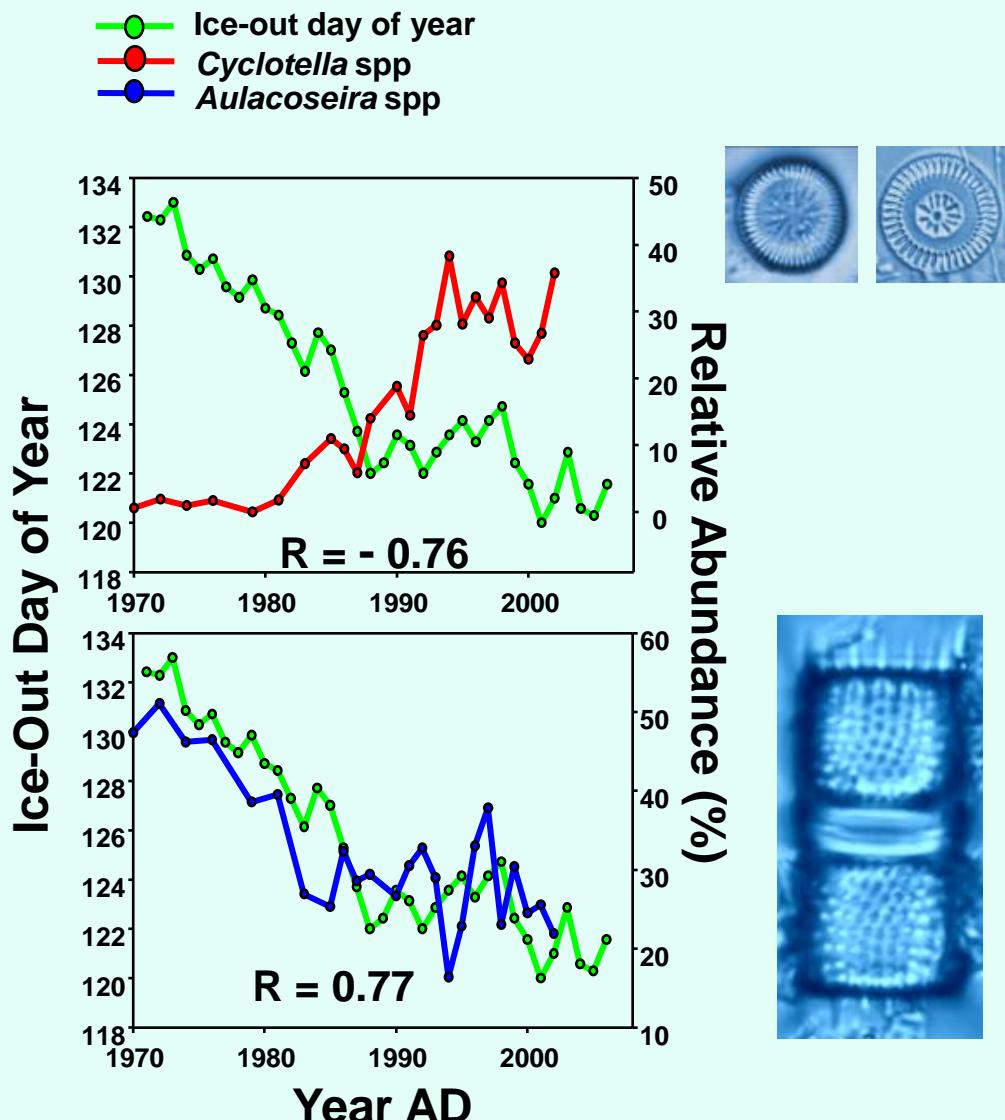
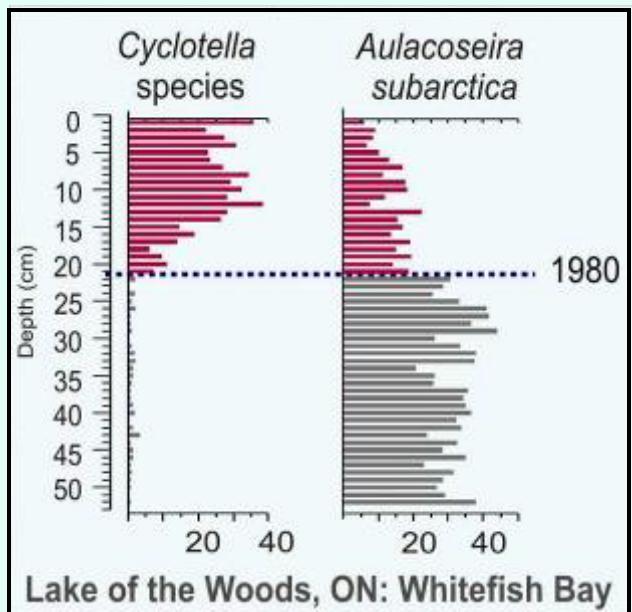
Kenora Temperature Record

Whitefish Bay – Reference site



Taxon-specific Relationships: Ice-out record

Whitefish Bay – Reference site

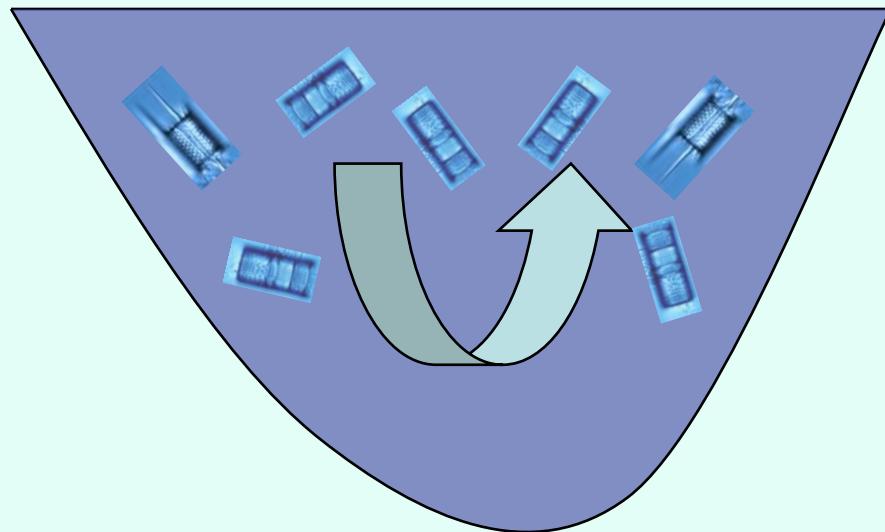


How will this affect other algae
and cyanobacteria?

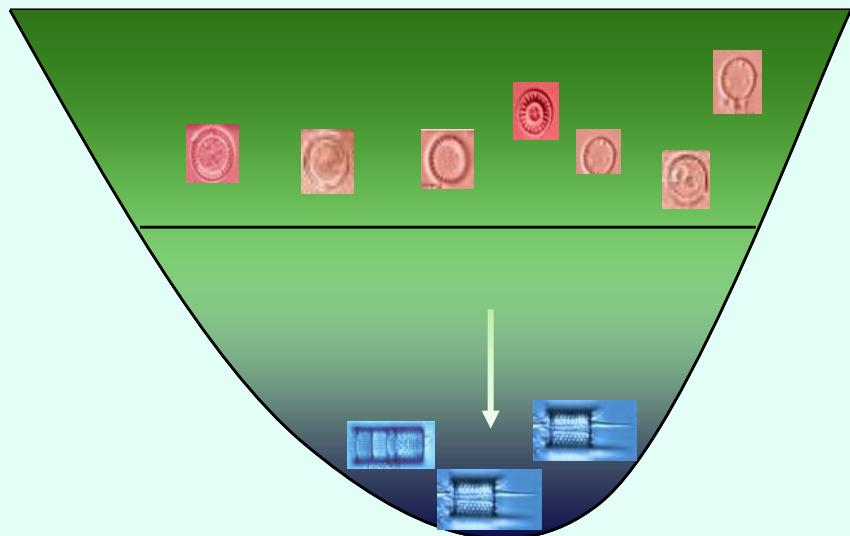
Blue-greens like it hot!



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.



Camp Pond, 14 Jul 1979



Camp Pond, 24 Aug 1987

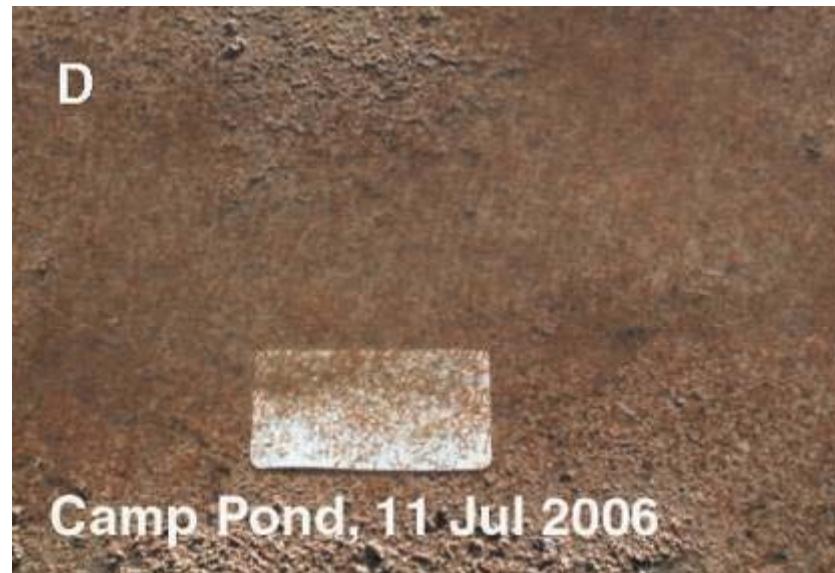


Camp Pond, 12 Jul 2006

Camp Pond, 16 July 2007



D



Camp Pond, 11 Jul 2006

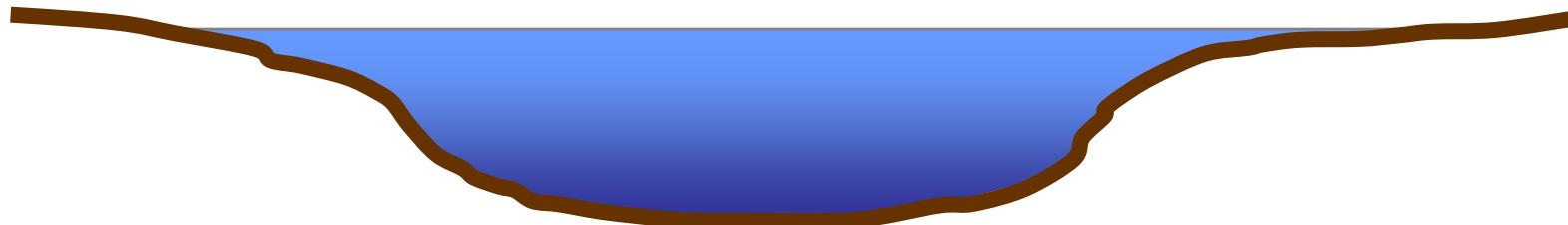


July 12, 2007



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

1980's



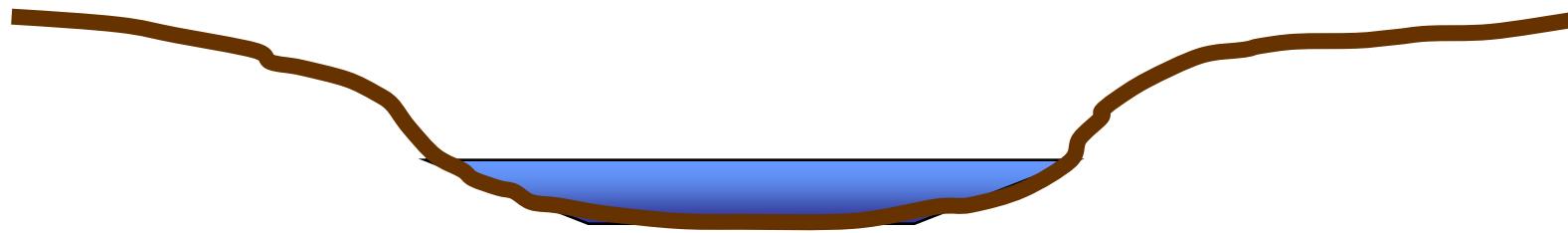
↑ T

↓ ice cover

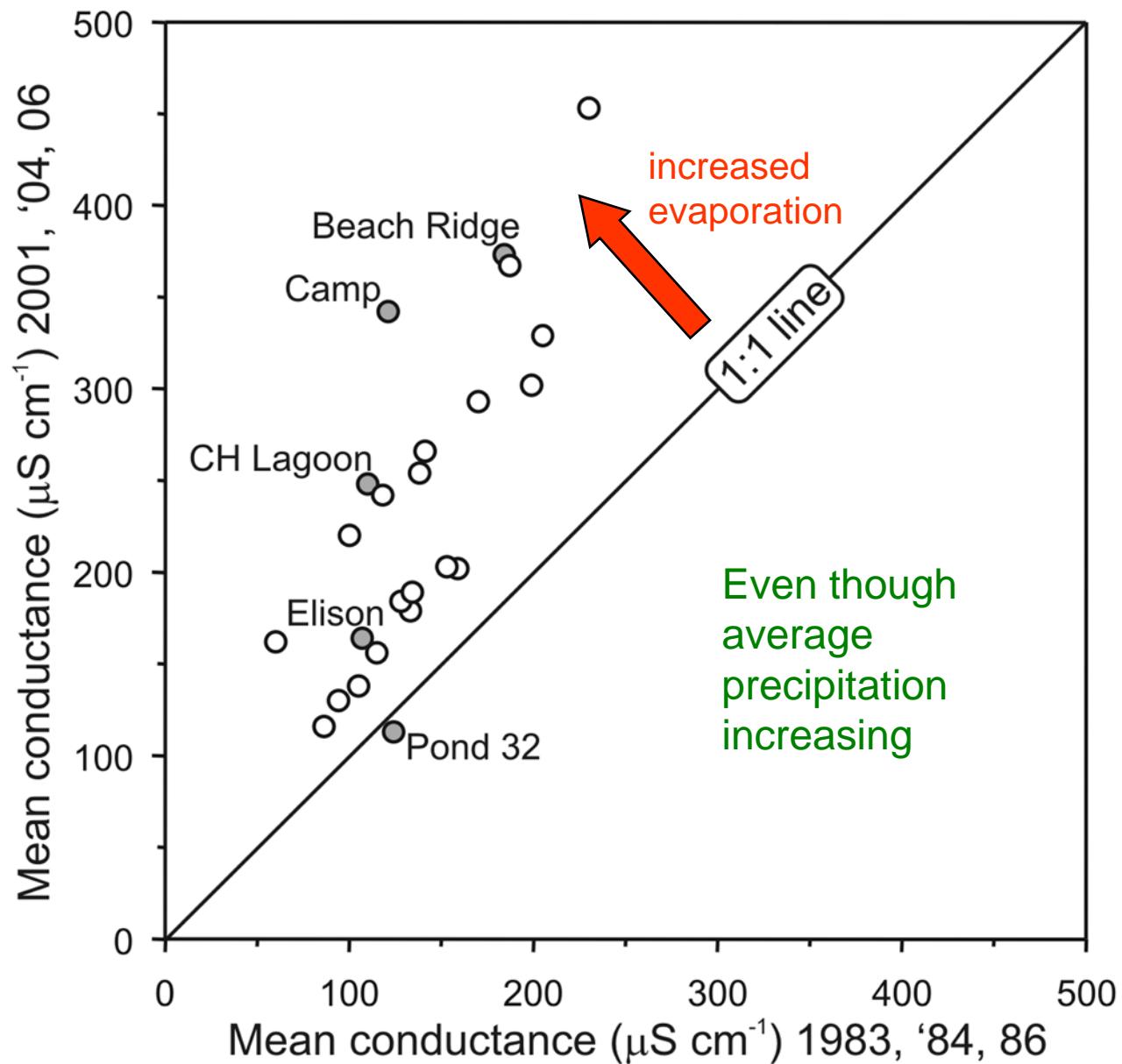
↑ evaporation

↓ water levels

↑ conductivity



2005 - 2009





Willow Pond, 21 Aug 1987



Willow Pond area, 18 Jul 2006

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

Crossing Ecological Thresholds

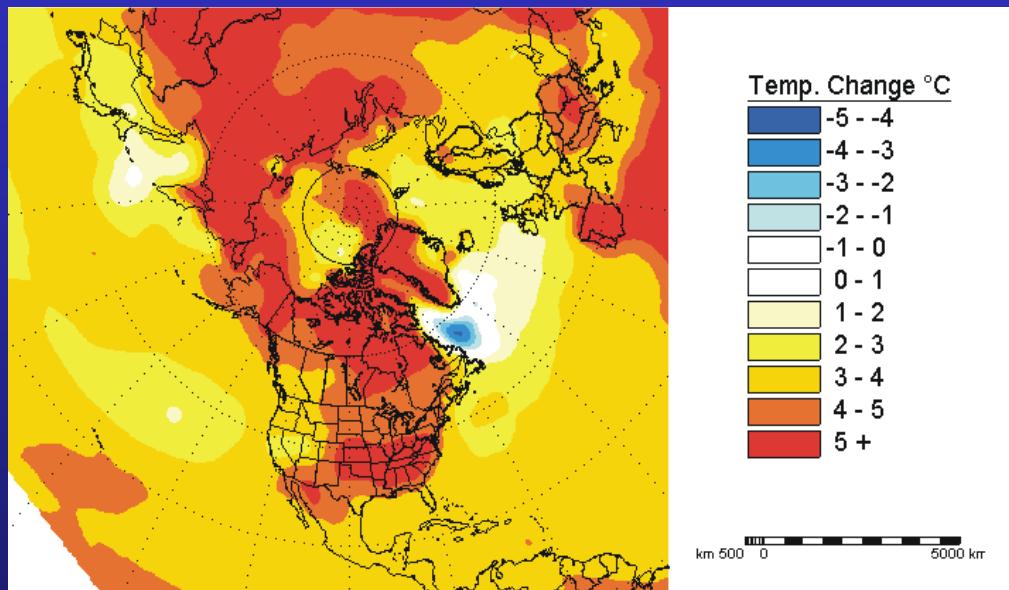
ephemeral ponds → dry land

permanent ponds → ephemeral ponds

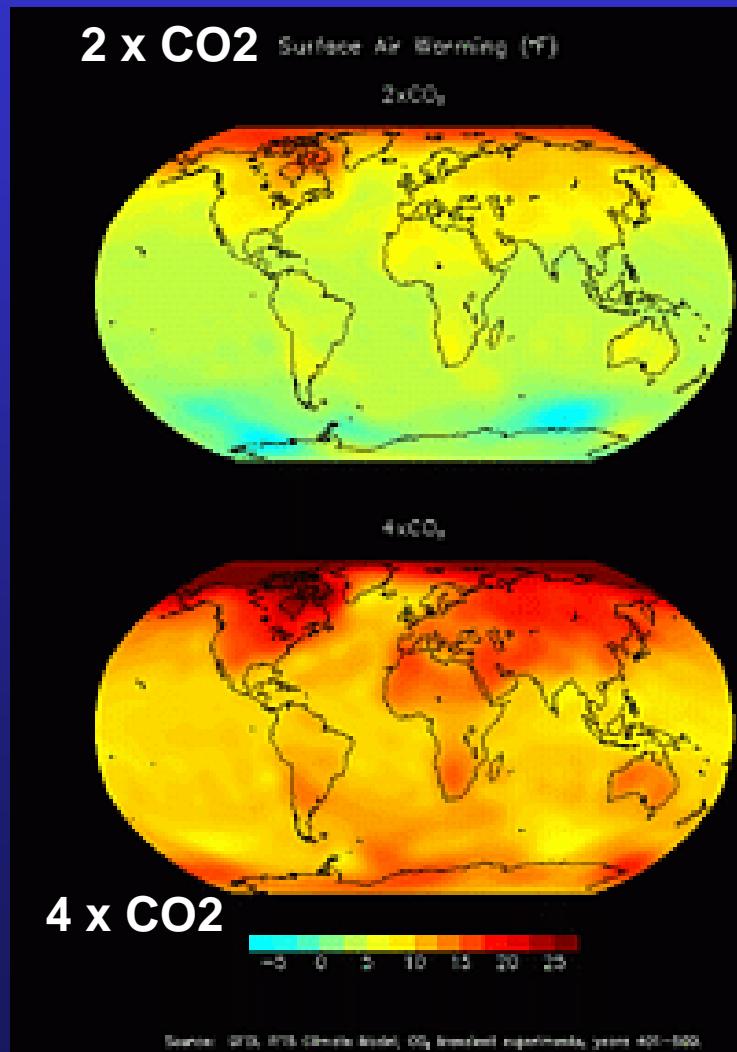
larger, deeper ponds → shallower,
exposed shorelines

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

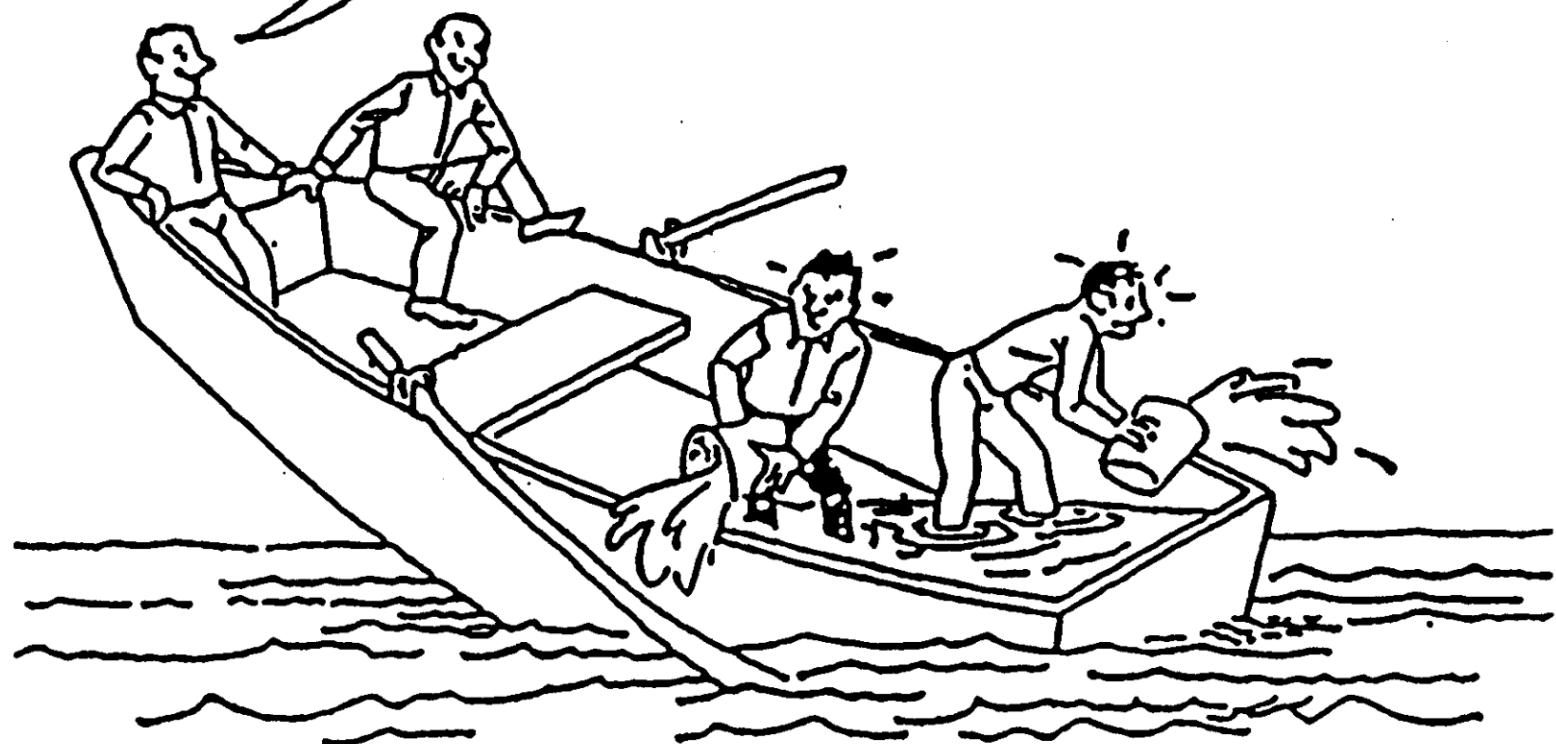
The Arctic in a “Greenhouse Dominated” World?



Estimated summer temperatures by ca 2090



*I'm sure glad the
hole isn't in our end . . .*



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.

Multiple stressors



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