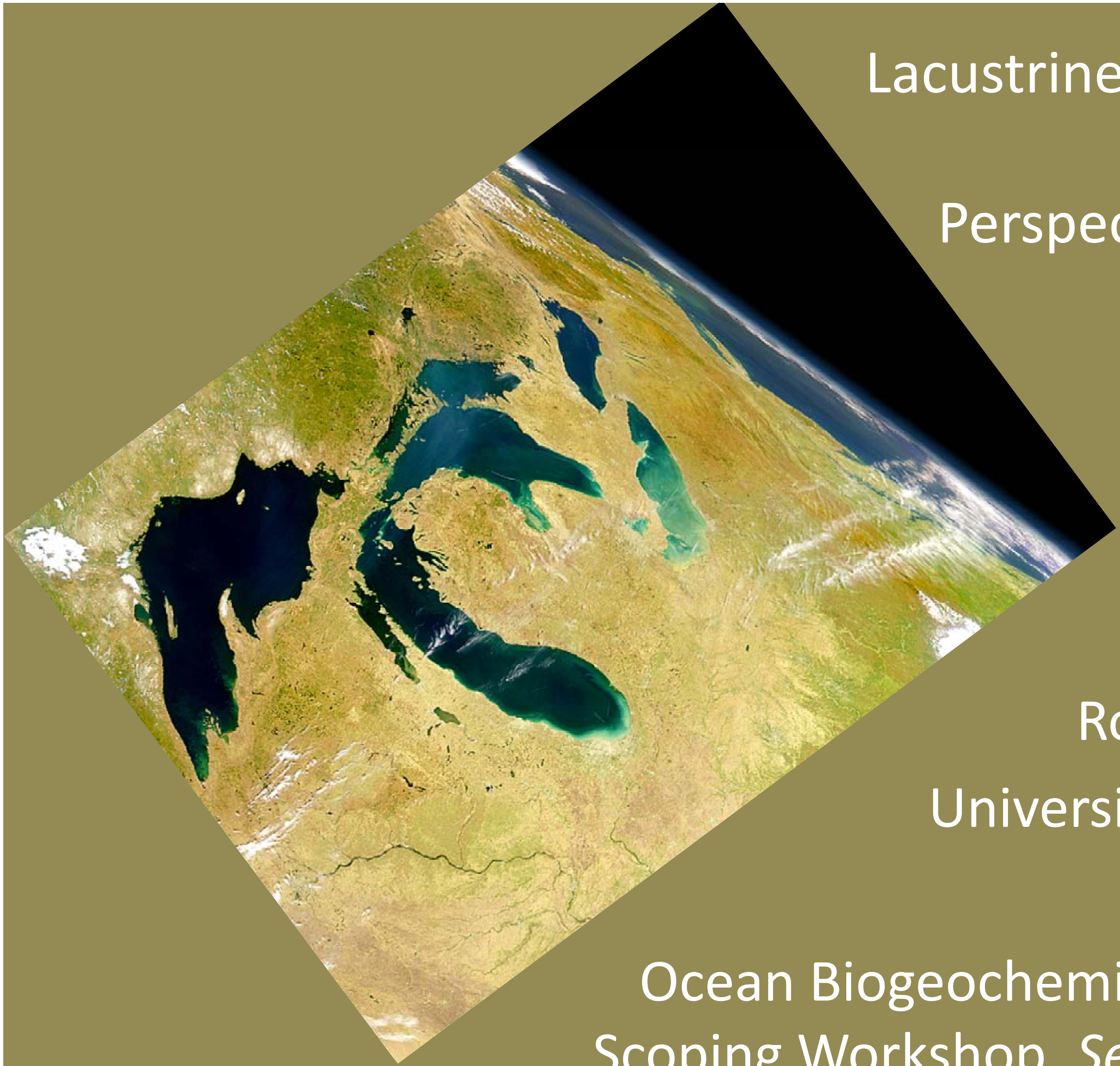


# Lacustrine Time Series and Cross-Ecosystem Perspectives on Aquatic Biogeochemistry

Robert W. Sterner

University of Minnesota

Ocean Biogeochemistry Time-series Scoping Workshop, *Sea Change*, Sept, 2010, Honolulu

# Three iconic limnological time series

# Lake Washington

**Effects of nutrient loading and grazing on lake ecosystems.**

**Involving the public.**

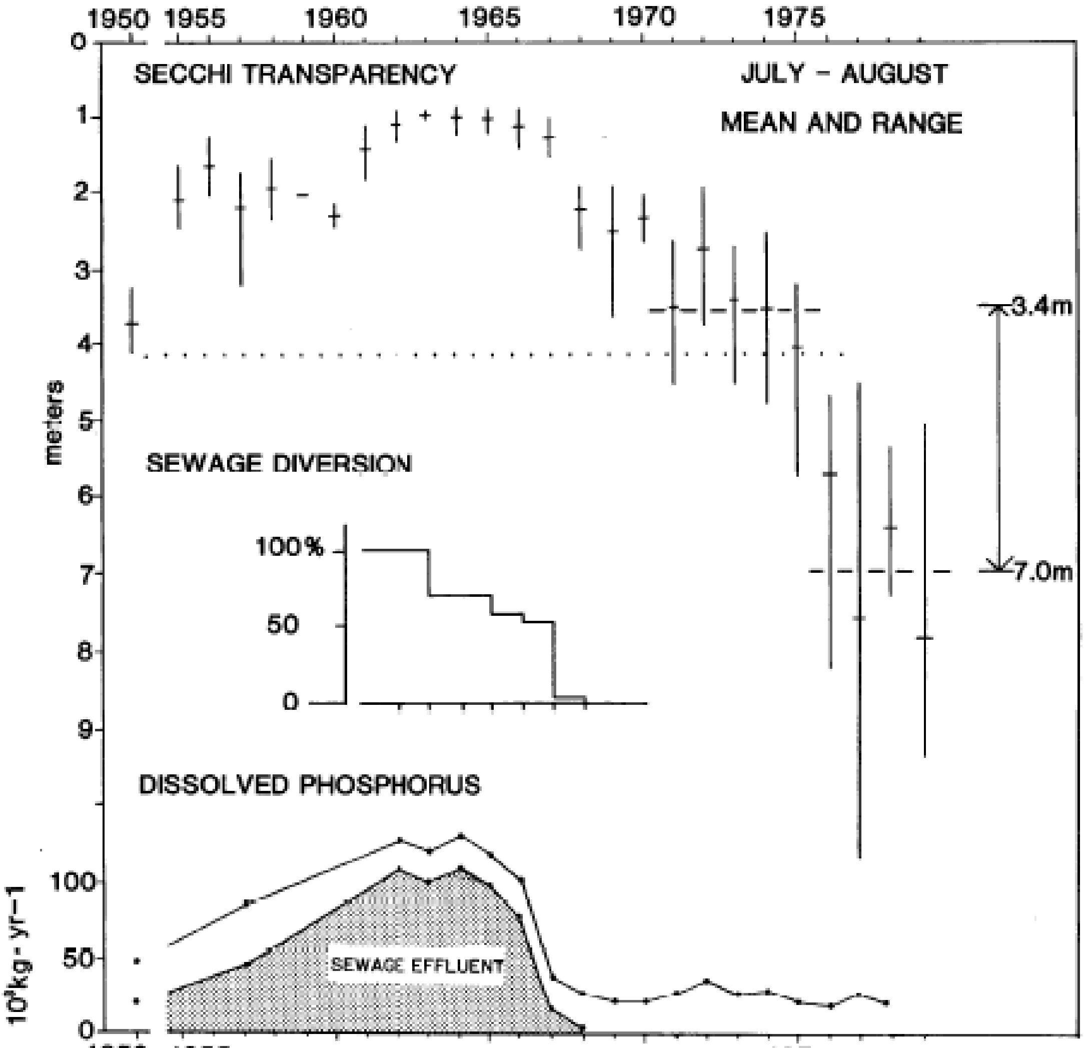
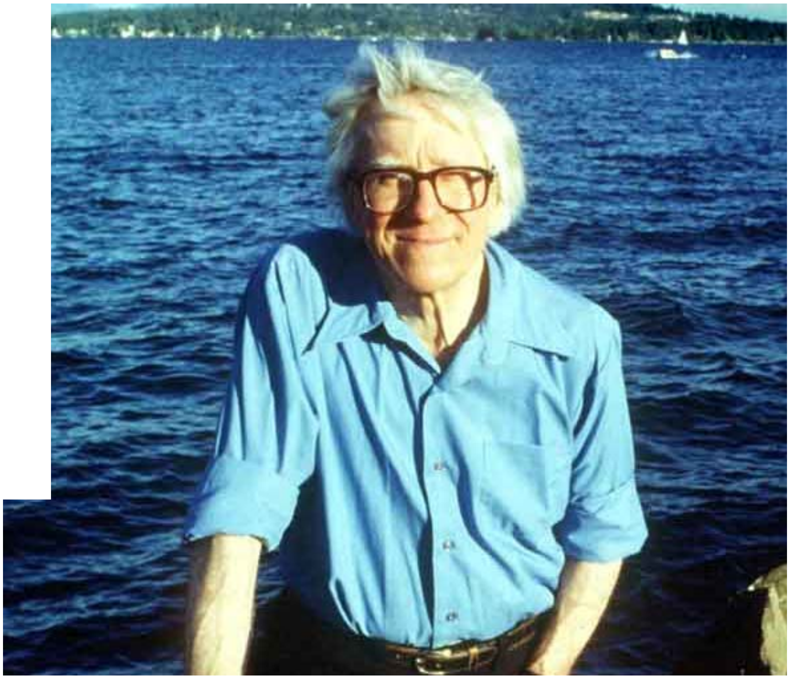


Fig. 1. Above—mean and range of summer Secchi disk transparency for each year (means for 1971–1975 and 1976–1979 are shown). Middle—schedule of diversion of sewage effluent; Line shows relative input of effluent; 100% is approximately 75,700 $m^3 \cdot d^{-1}$. Bottom—loading rate of dissolved phosphorus; amount contained in sewage effluent indicated by shading.



# Lake Tahoe

**Long term eutrophication**

**Later: climate couplings**

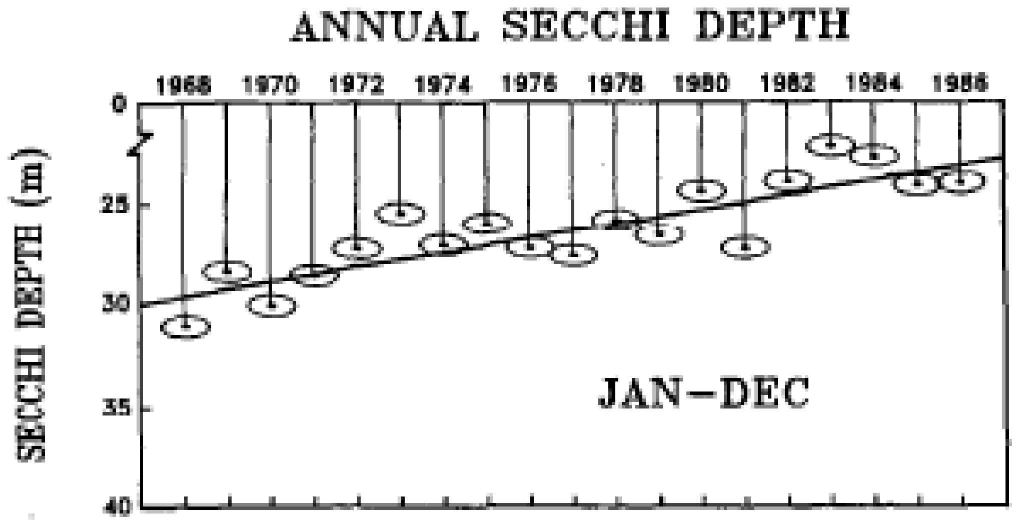
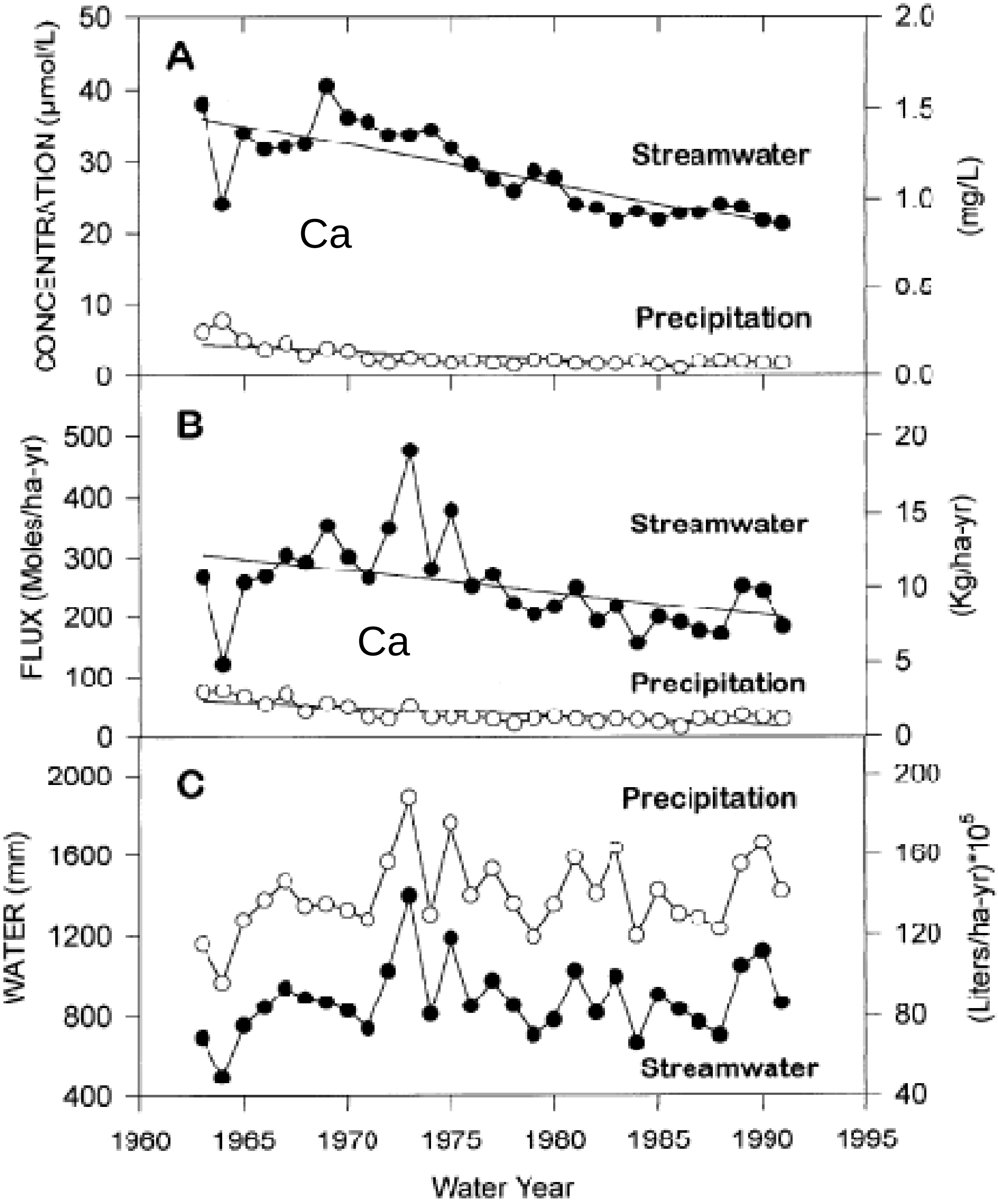


Fig. 10. Annual average transparency measured with a 20-cm white Secchi disk. Each point represents about 35 individual measurements. Dates where stormy, poor light conditions occurred have been eliminated from each year's average.

# Hubbard Brook

**Deforestation**

**Acid Precipitation**



# Some characteristics of these time series studies

- Leadership
- Research problems with strong public interest (helps maintain $?)
- Priority placed on infrastructure that insures consistency of methods through time
- Input-output framework

# What I will cover today

1. A century-long lacustrine time series, available only by fortuity, that is instructive about basic biogeochemical processing.
2. Within vs. across habitat processes. Theoretical issues about scale dependence.
3. What this means for the network structure of doing science

# Subtexts

How aquatic time series have helped shaped our view of the ecology underlying regional to global scale ecosystem change

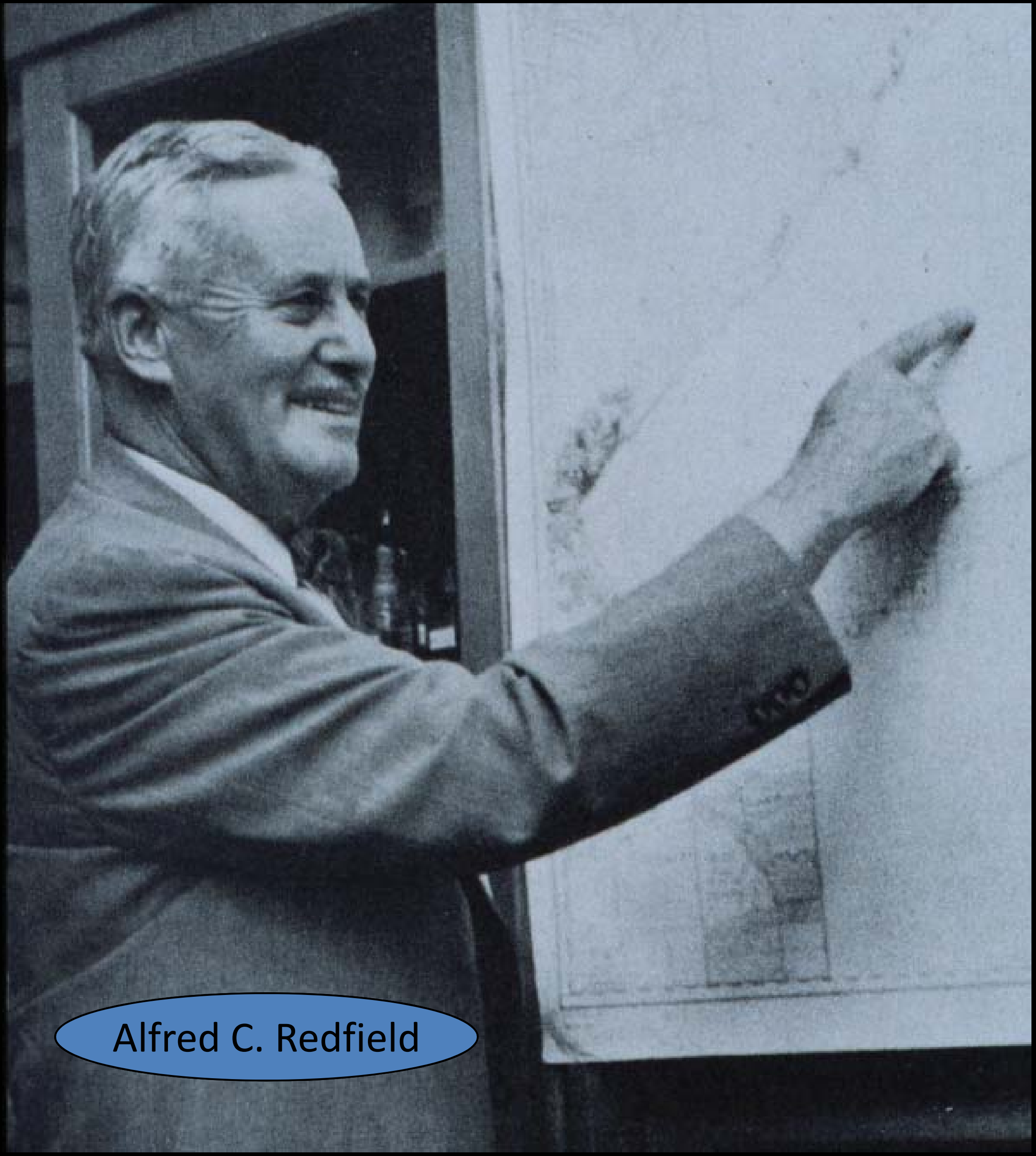
Thoughts on LTER, networking

Common threads among freshwater, marine, terrestrial ecosystems

Marine seston has C:N:P ratio that matches differences in C:N:P across samples in deepwater. Coincidence? Probably not. Biological imprint on ocean chemistry.

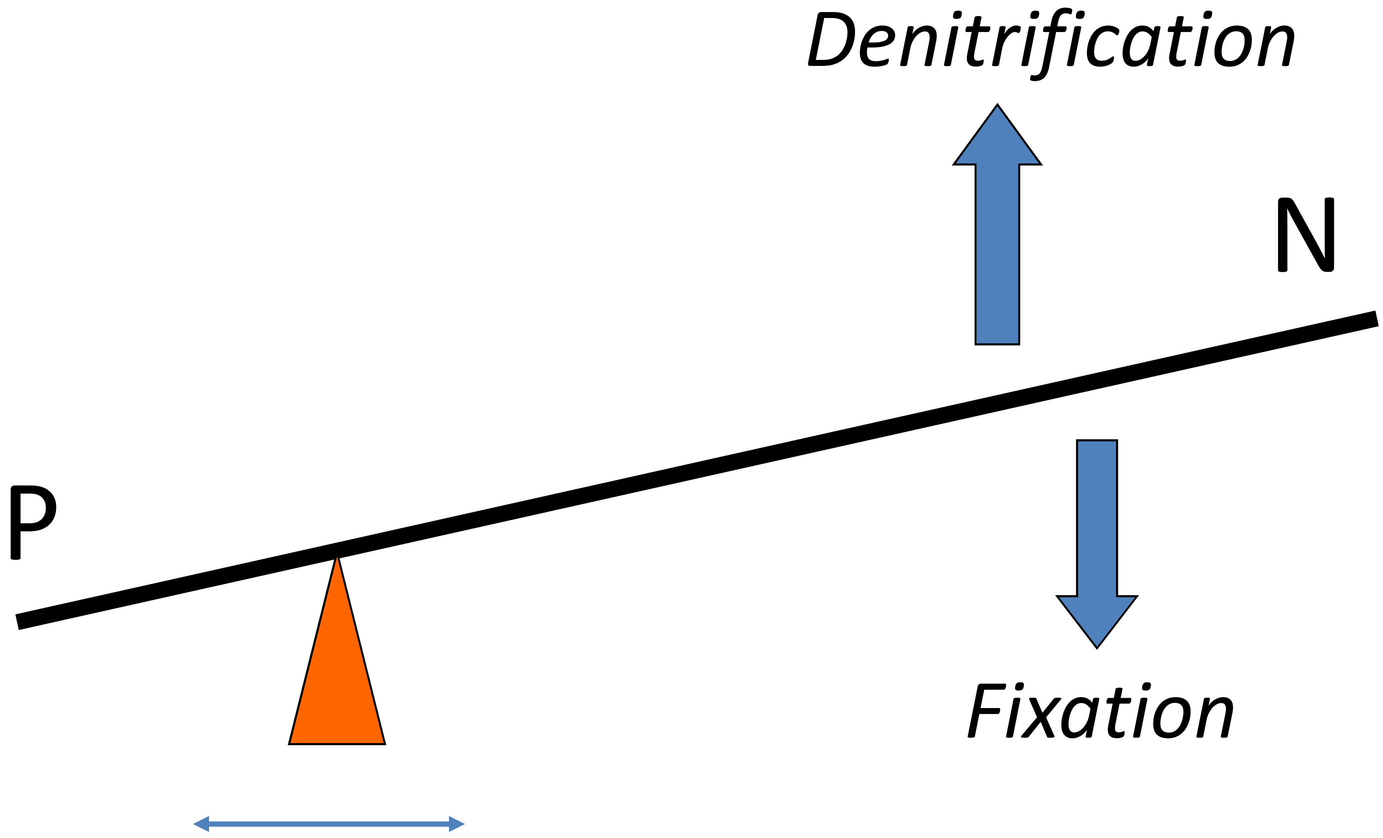
Redfield Ratio =

106:16:1



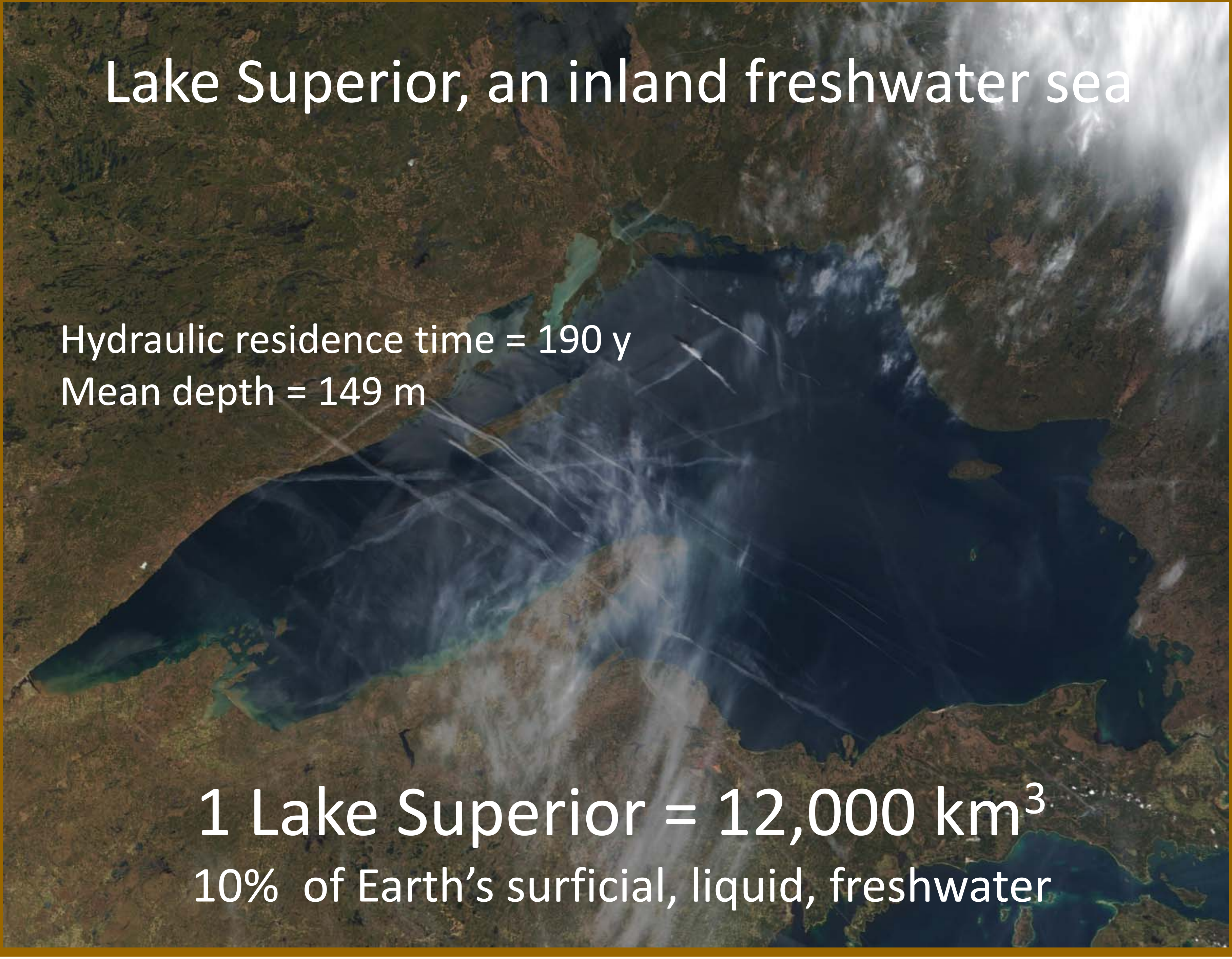
Alfred C. Redfield

# “Redfield” balancing of N:P ratio



***Something – cell biology? – sets the fulcrum at 16N:1P***

# Lake Superior, an inland freshwater sea

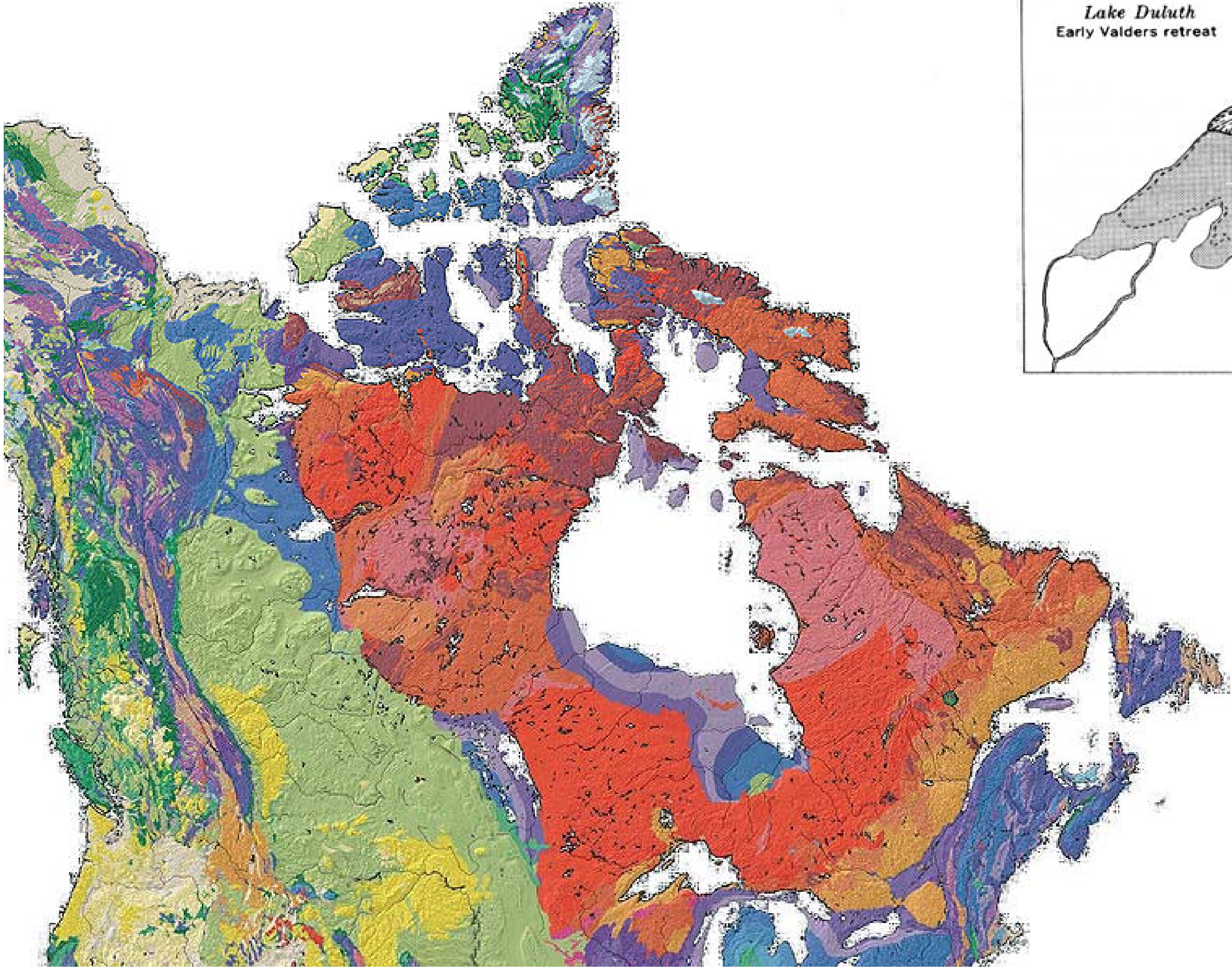


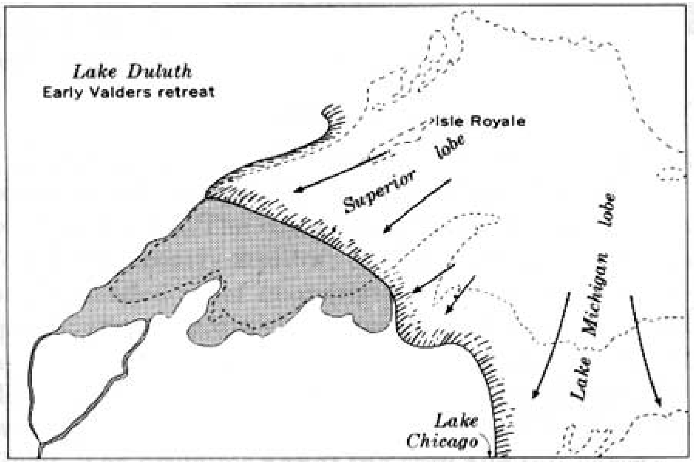
Hydraulic residence time = 190 y

Mean depth = 149 m

1 Lake Superior = 12,000 km$^3$

10%  of Earth’s surficial, liquid, freshwater



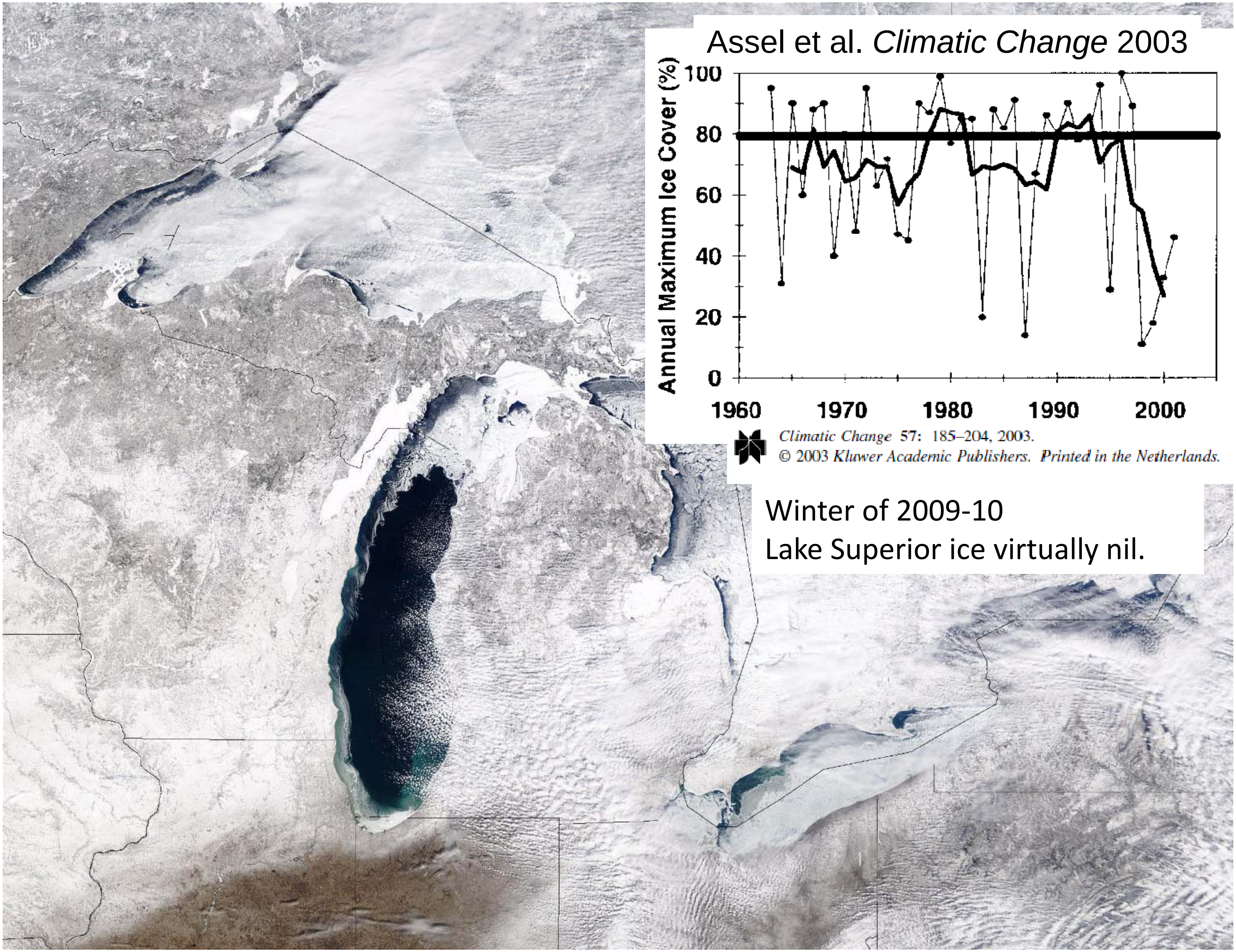


Ca. 11,000 ybp

Canadian Shield,

Precambrian bedrock

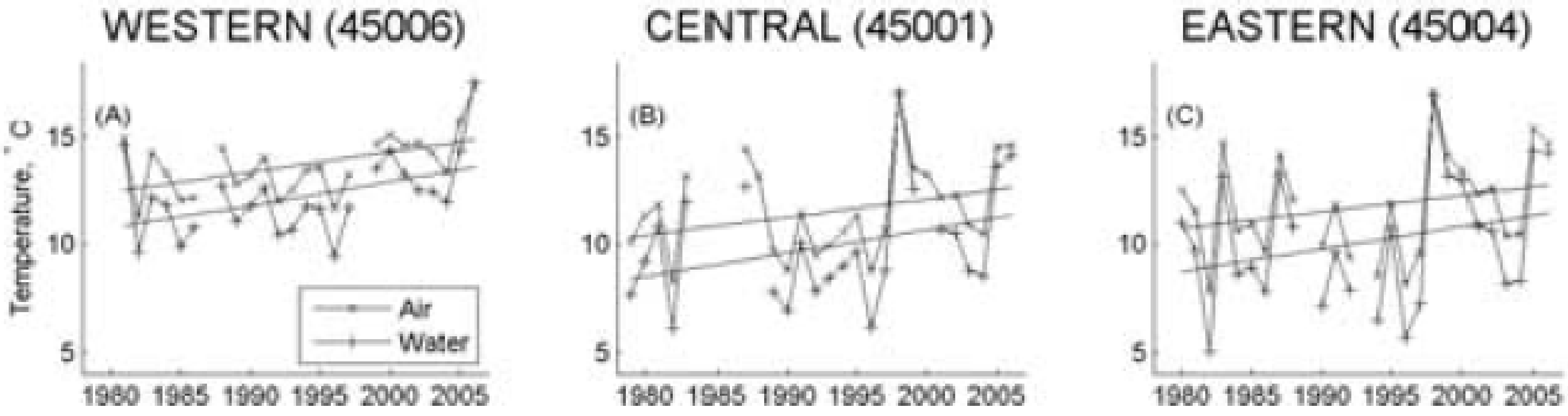
Assel et al. *Climatic Change* 2003



*Climatic Change* 57: 185–204, 2003.
© 2003 *Kluwer Academic Publishers. Printed in the Netherlands.*

Winter of 2009-10
Lake Superior ice virtually nil.

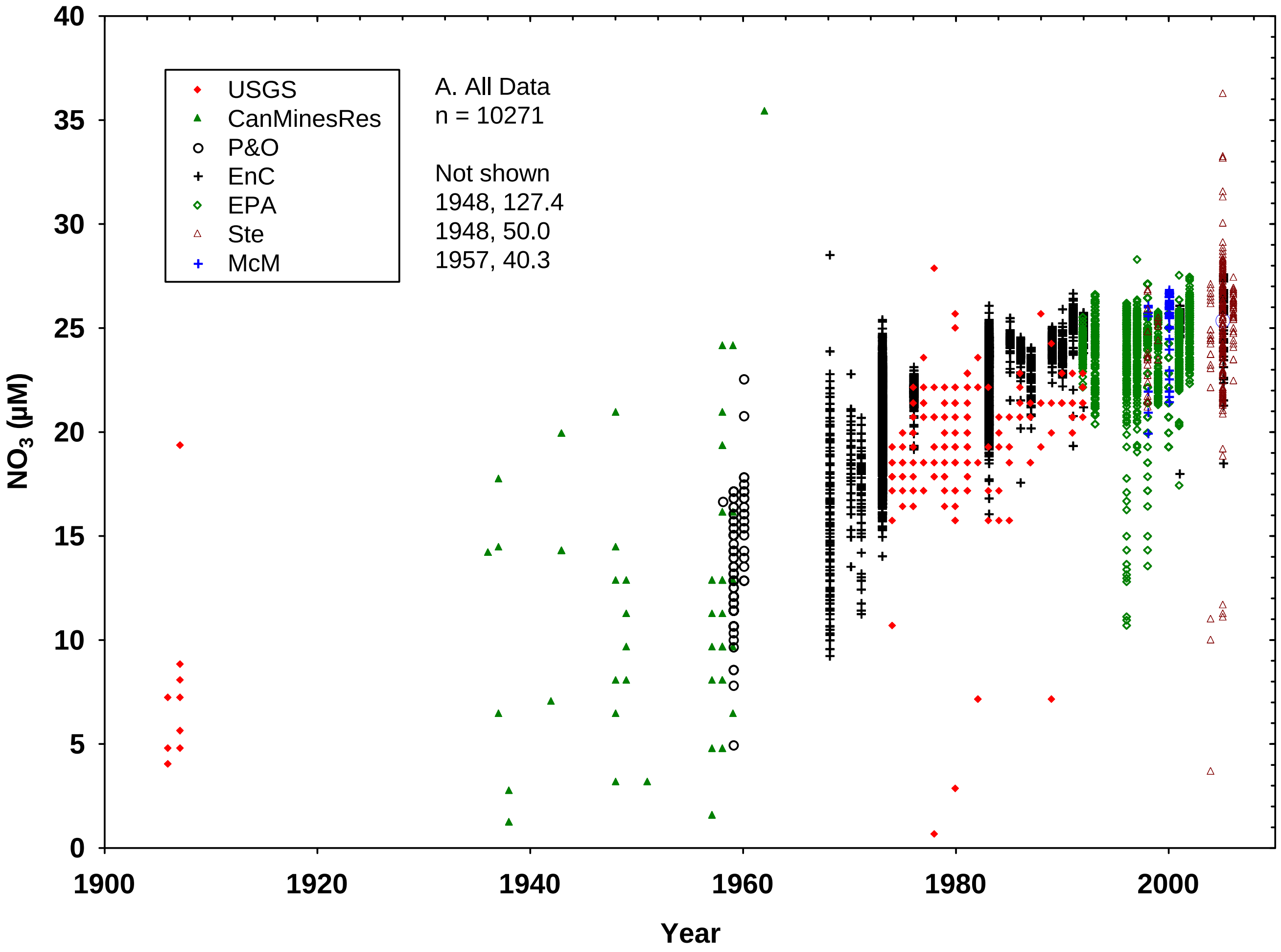
# Austin and Colman GRL 2007



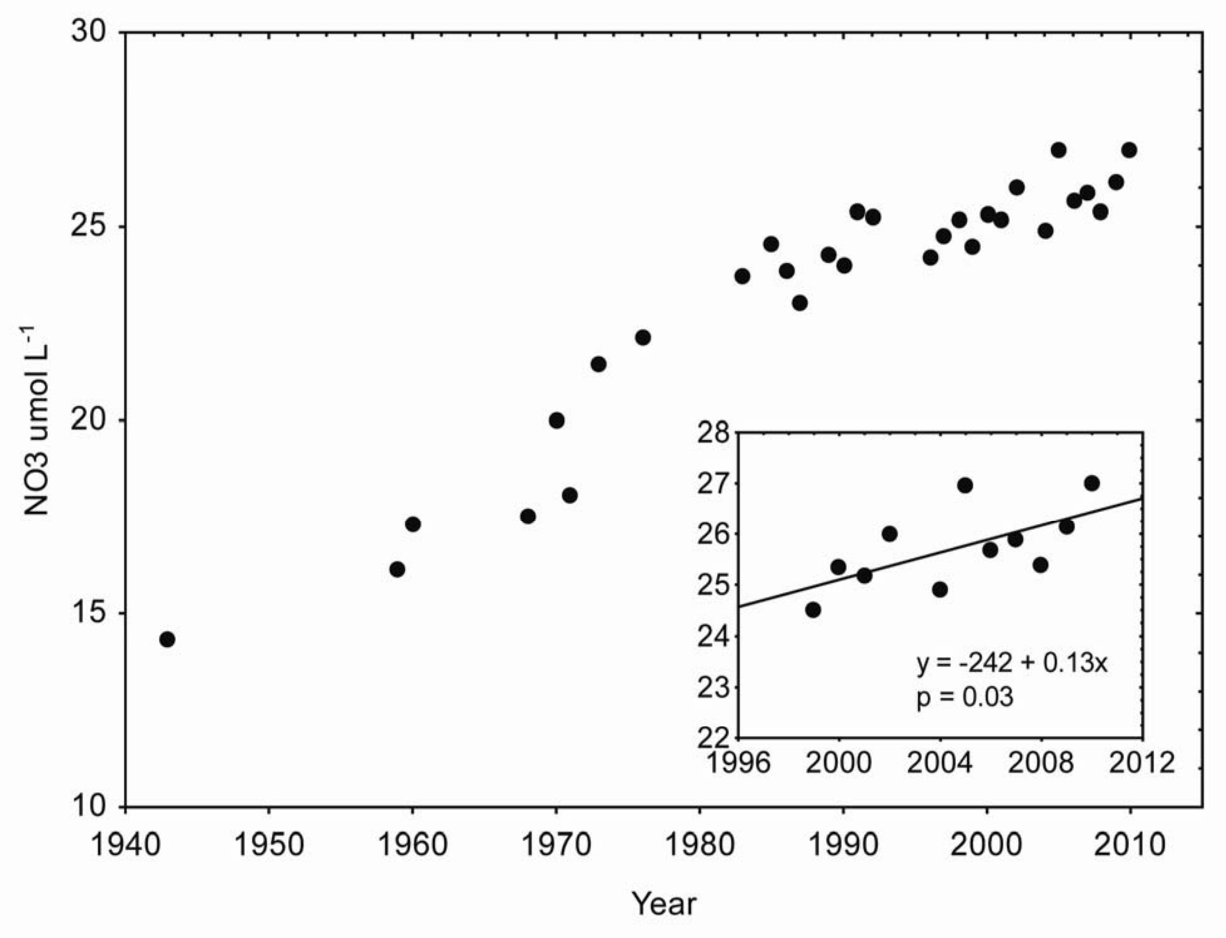
Lake Superior is warming at a rate of 0.11 C/y. This is faster than the increase of air temperature (0.053 C/y).

Declining ice cover lengthens stratified season. Also increases evaporation (falling lake levels).

# An unusually well documented, century long change in concentration of a nutrient ion



Sterner et al. GRL 2007

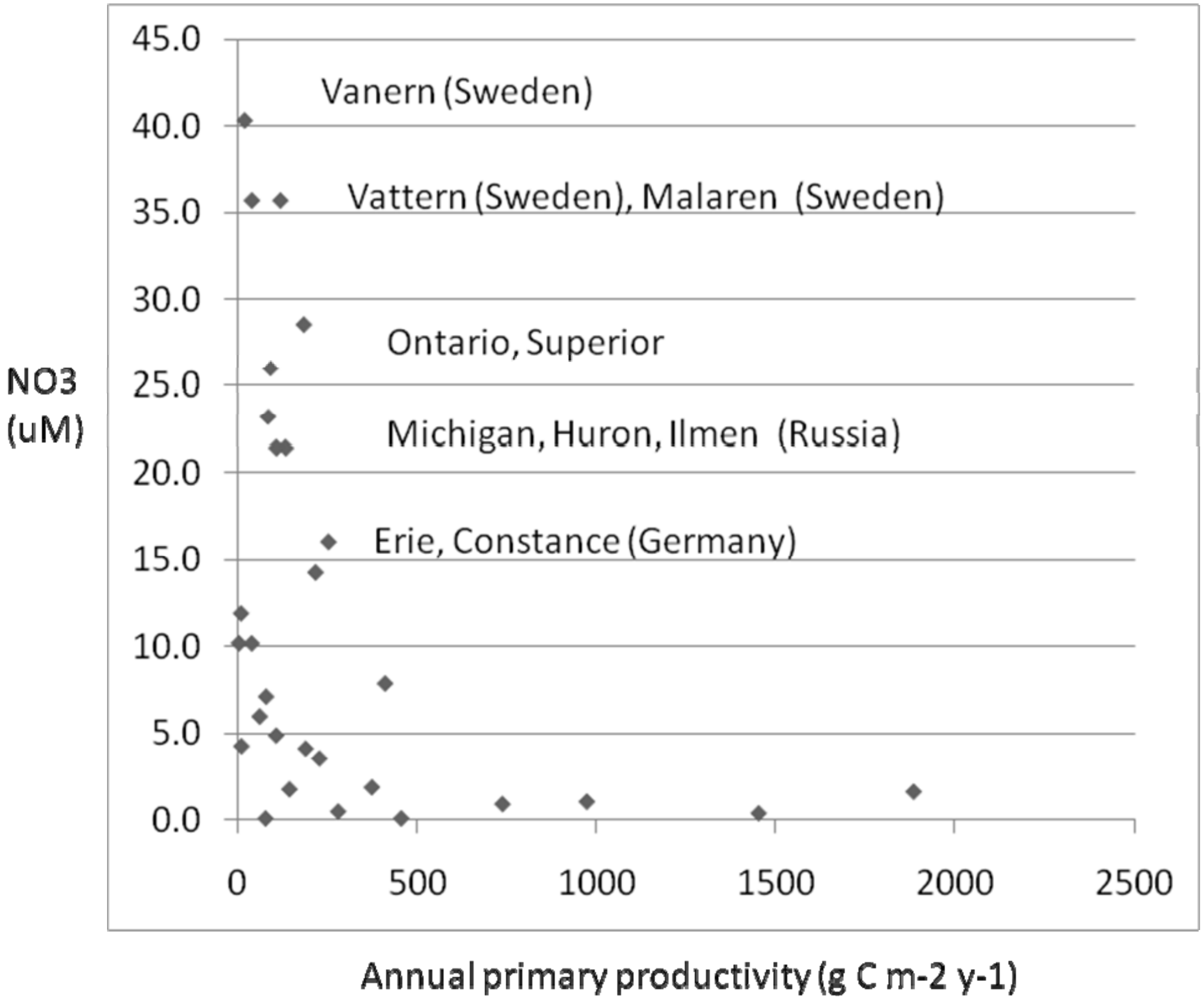


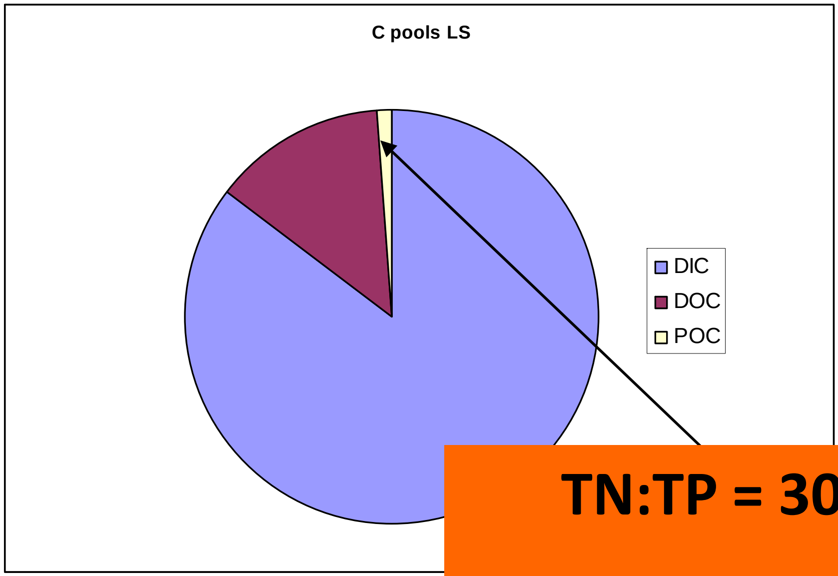
Nitrate, deepwater, average per year.

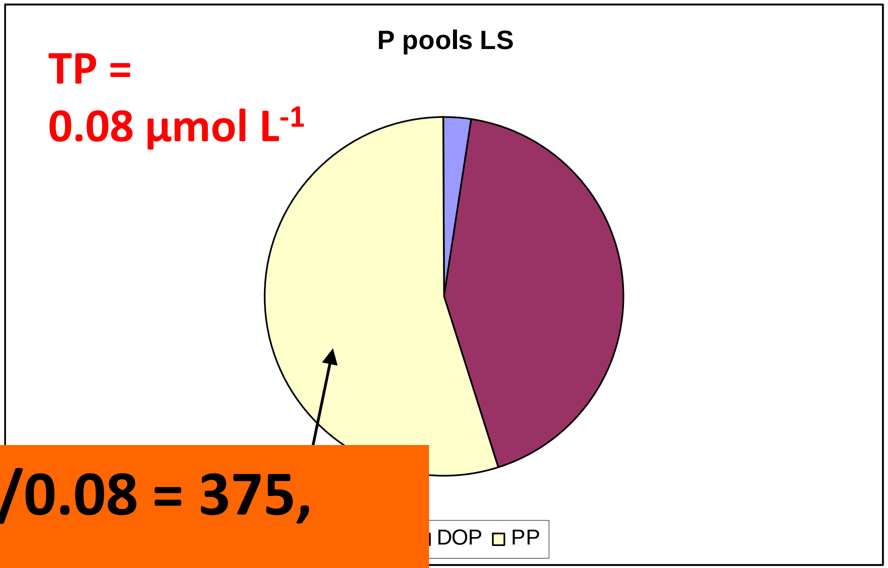
Inset: the nitrate rise appears to be continuing.

Sterner, submitted

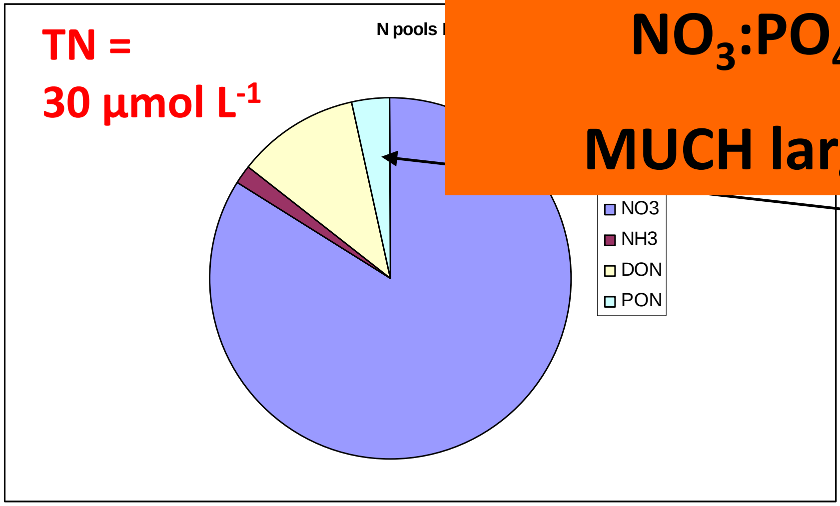
# Not apparently unlike some other large, low productivity lakes







**TP =**
**0.08 µmol $L^{-1}$**



**TN =**
**30 µmol $L^{-1}$**

**TN:TP = 30/0.08 = 375,**

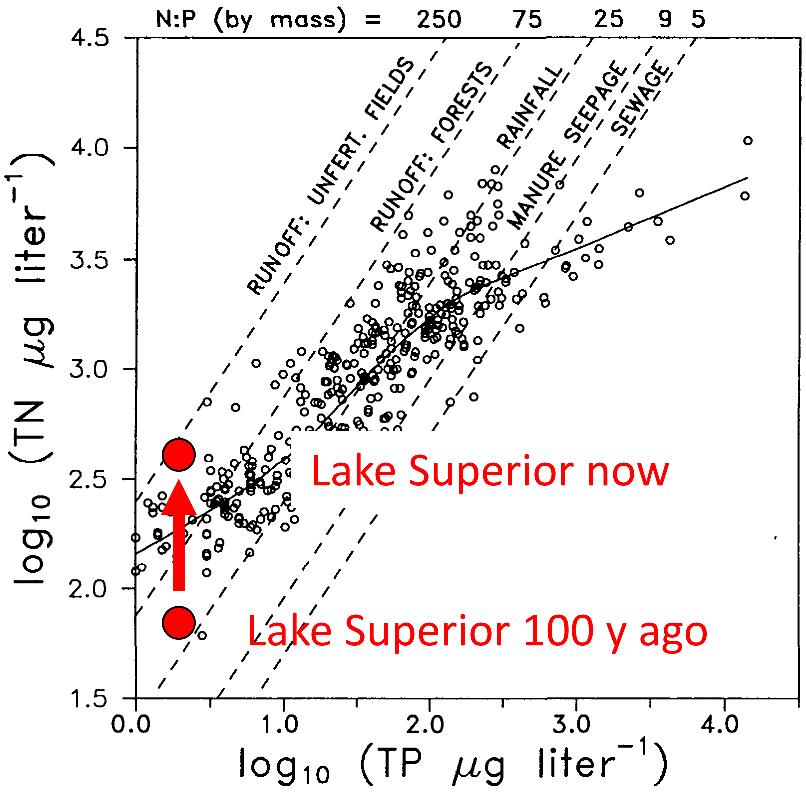
**$NO_3$:$PO_4$ ~ 10,000**

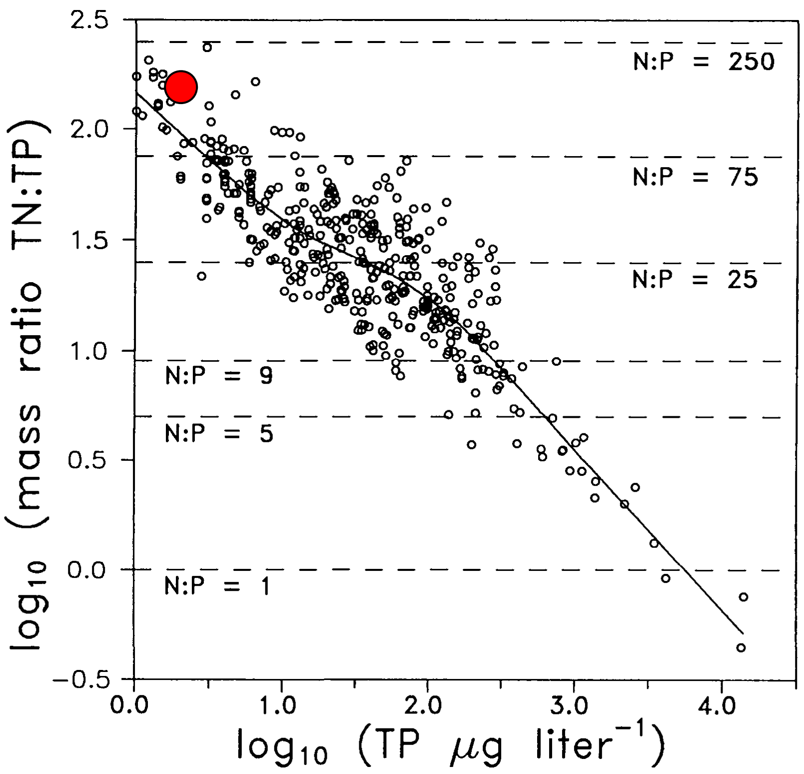
**MUCH larger than 16**

# Particles

Large pools of elements in dissolved phase, even for P.

# TN, TP of many lakes (Downing and McCauley 1992)





**Assuming small changes in TP and other forms of N,
Lake Superior's biogeochemistry has migrated from one edge of the envelope to the other. Will it continue?**

# This ecosystem is increasingly out of stoichiometric N:P balance

Why?

External loading?

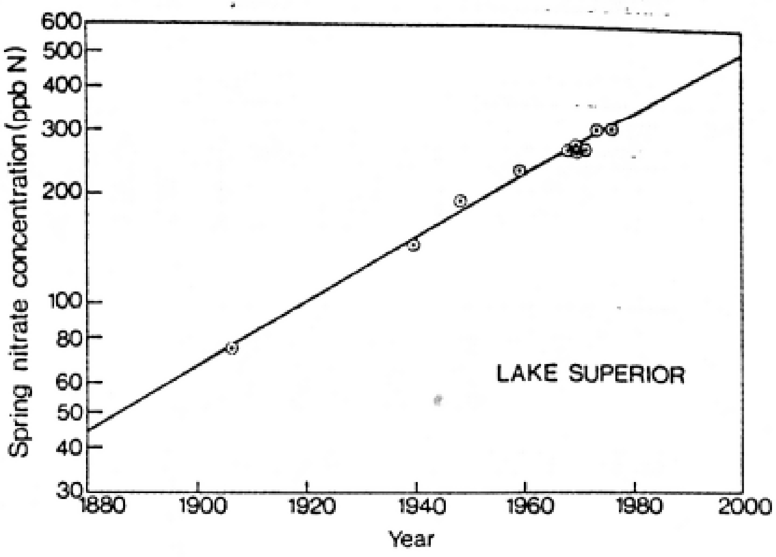
Internal ecosystem processes?

# The Nitrifying of Lake Superior

BY E.B. BENNETT

Ambio 15(5): 272-275
~~1980~~
1986

**Figure 1. Spring nitrate concentrations in Lake Superior, 1880–2000 (points are observations listed in Table 1; line is exponential relationship determined by least squares regression).**



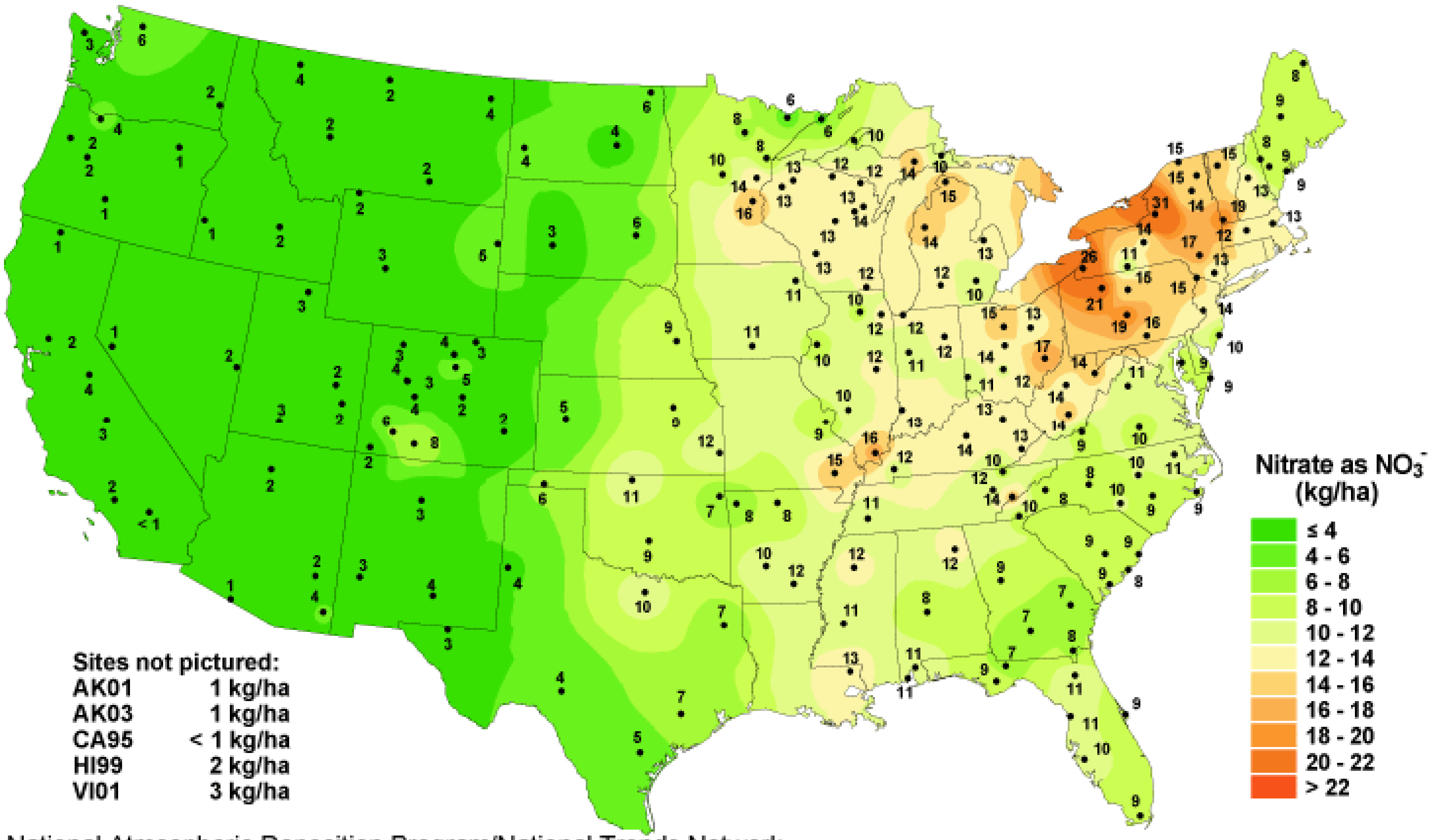
Original units (ppb N)

**This paper argued that it was atmospheric NOx that was building up.**

**But…timing? Too early? Hydraulic residence time ~200 y, N residence time ~50 y.**

**Enough NOx to increase lake 5x?**

# Nitrate ion wet deposition, 2002



**Sites not pictured:**

| | |
|---|---|
| **AK01** | **1 kg/ha** |
| **AK03** | **1 kg/ha** |
| **CA95** | **< 1 kg/ha** |
| **HI99** | **2 kg/ha** |
| **VI01** | **3 kg/ha** |

National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

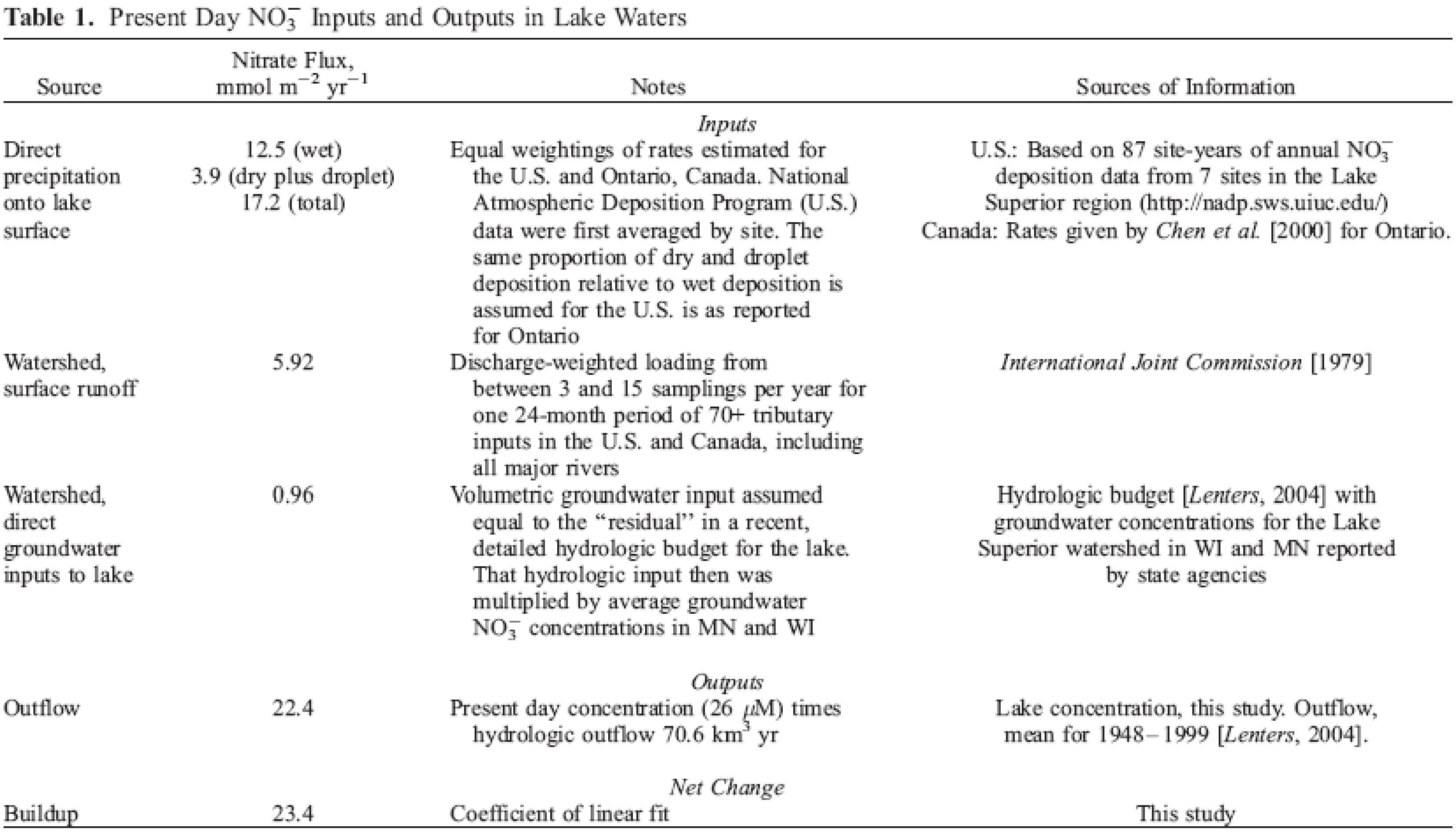


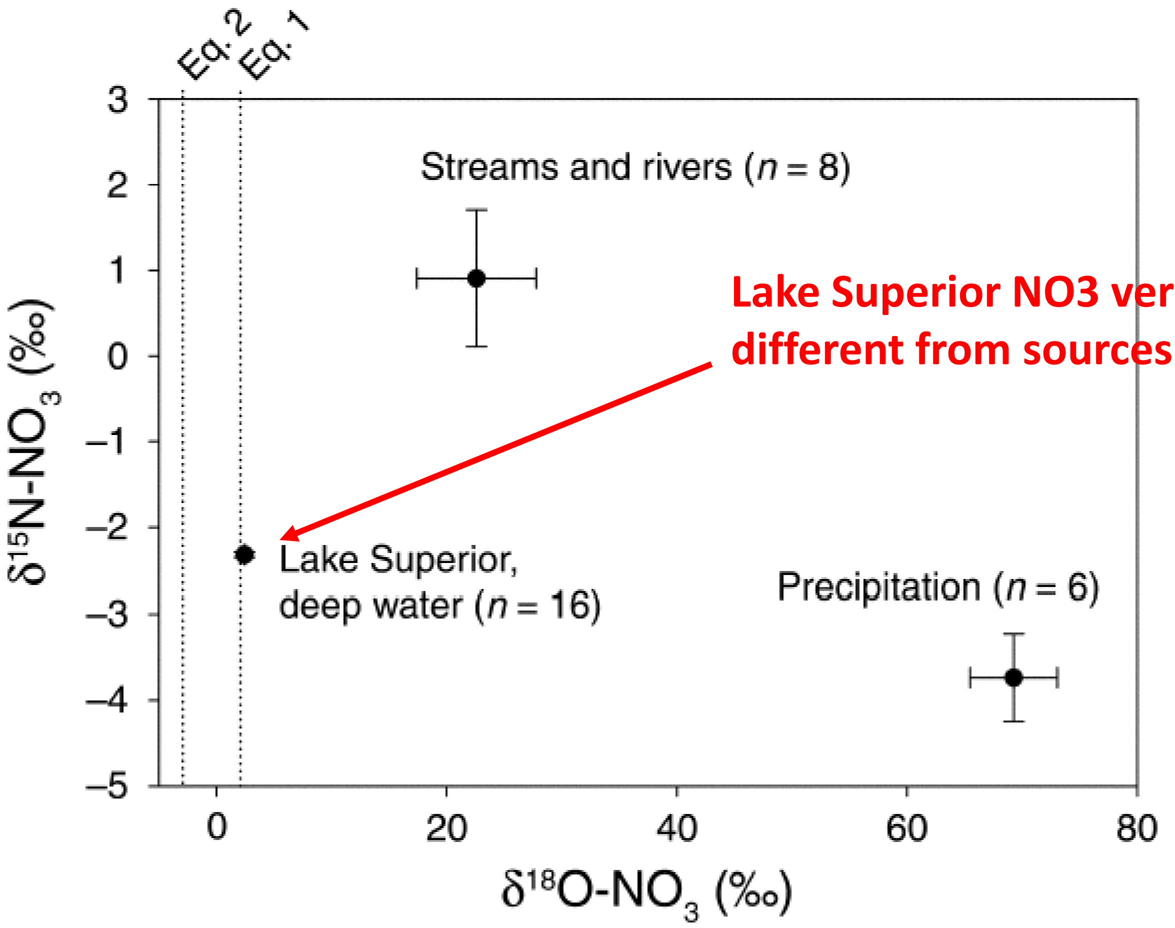
**Table 1.** Present Day $NO_3^-$ Inputs and Outputs in Lake Waters

| Source | Nitrate Flux, mmol $m^{-2}$ $yr^{-1}$ | Notes | Sources of Information |
|---|---|---|---|
| | | *Inputs* | |
| Direct precipitation onto lake surface | 12.5 (wet)<br>3.9 (dry plus droplet)<br>17.2 (total) | Equal weightings of rates estimated for the U.S. and Ontario, Canada. National Atmospheric Deposition Program (U.S.) data were first averaged by site. The same proportion of dry and droplet deposition relative to wet deposition is assumed for the U.S. is as reported for Ontario | U.S.: Based on 87 site-years of annual $NO_3^-$ deposition data from 7 sites in the Lake Superior region (http://nadp.sws.uiuc.edu/)<br>Canada: Rates given by *Chen et al.* [2000] for Ontario. |
| Watershed, surface runoff | 5.92 | Discharge-weighted loading from between 3 and 15 samplings per year for one 24-month period of 70+ tributary inputs in the U.S. and Canada, including all major rivers | *International Joint Commission* [1979] |
| Watershed, direct groundwater inputs to lake | 0.96 | Volumetric groundwater input assumed equal to the "residual" in a recent, detailed hydrologic budget for the lake. That hydrologic input then was multiplied by average groundwater $NO_3^-$ concentrations in MN and WI | Hydrologic budget [*Lenters*, 2004] with groundwater concentrations for the Lake Superior watershed in WI and MN reported by state agencies |
| | | *Outputs* | |
| Outflow | 22.4 | Present day concentration (26 $\mu$M) times hydrologic outflow 70.6 $km^3$ yr | Lake concentration, this study. Outflow, mean for 1948–1999 [*Lenters*, 2004]. |
| | | *Net Change* | |
| Buildup | 23.4 | Coefficient of linear fit | This study |

Input = 17.2 + 5.92 + 0.96 = 24.08
Outflow = 22.4
Buildup = 23.4

Not enough inputs of nitrate to account for buildup plus outflow.

Sterner et al. GRL 2007



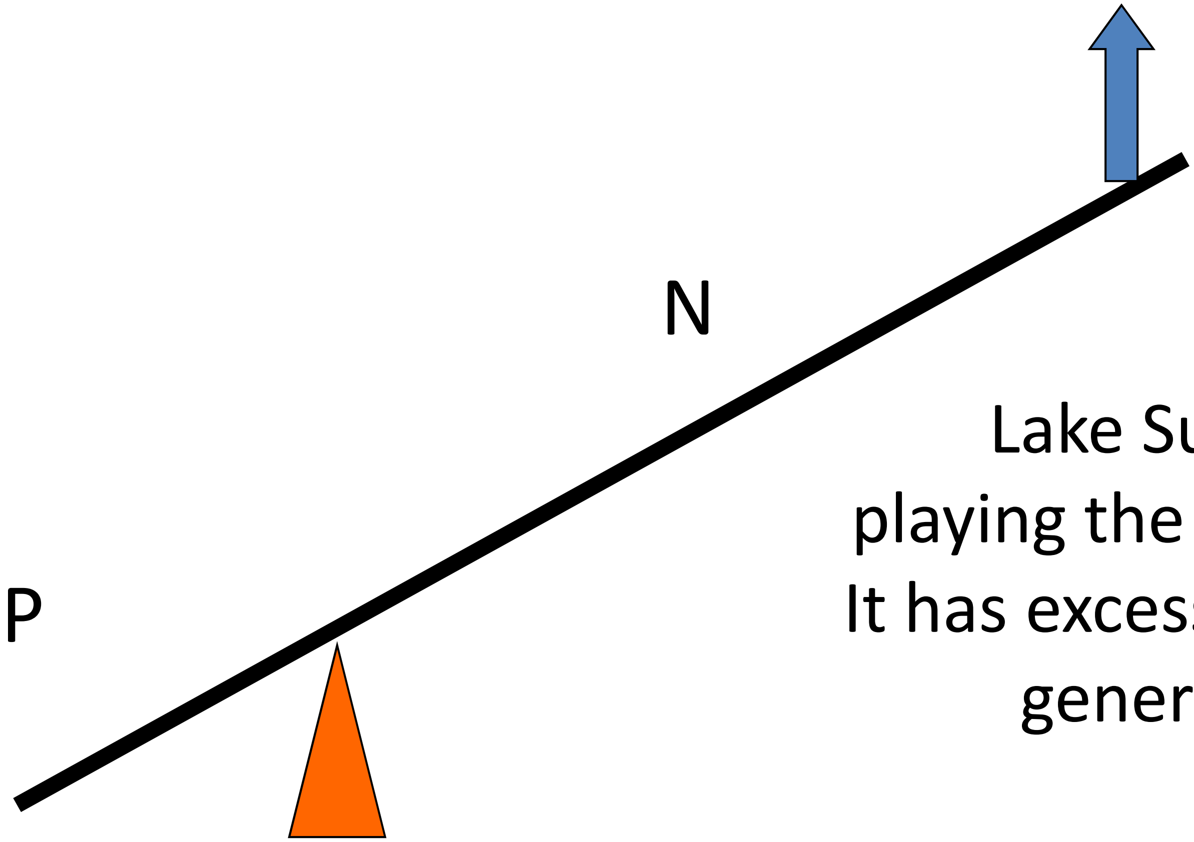
**Lake Superior NO3 very different from sources.**

*Ecological Applications*, 17(8), 2007, pp. 2323–2332

# ISOTOPIC EVIDENCE FOR IN-LAKE PRODUCTION OF ACCUMULATING NITRATE IN LAKE SUPERIOR

Jacques C. Finlay,[1] Robert W. Sterner, and Sanjeev Kumar[2]

*Department of Ecology, Evolution and Behavior, University of Minnesota, 1987 Upper Buford Circle, St. Paul, Minnesota 55108 USA*



Lake Superior isn’t
playing the right game.
It has excess N, but it is
generating more!

**More studies underway, measuring N transformation rates in lakes Superior and Erie. Project SINC with Co-PI’s Bullerjahn, Finlay, McKay, funded by NSF OCE.**

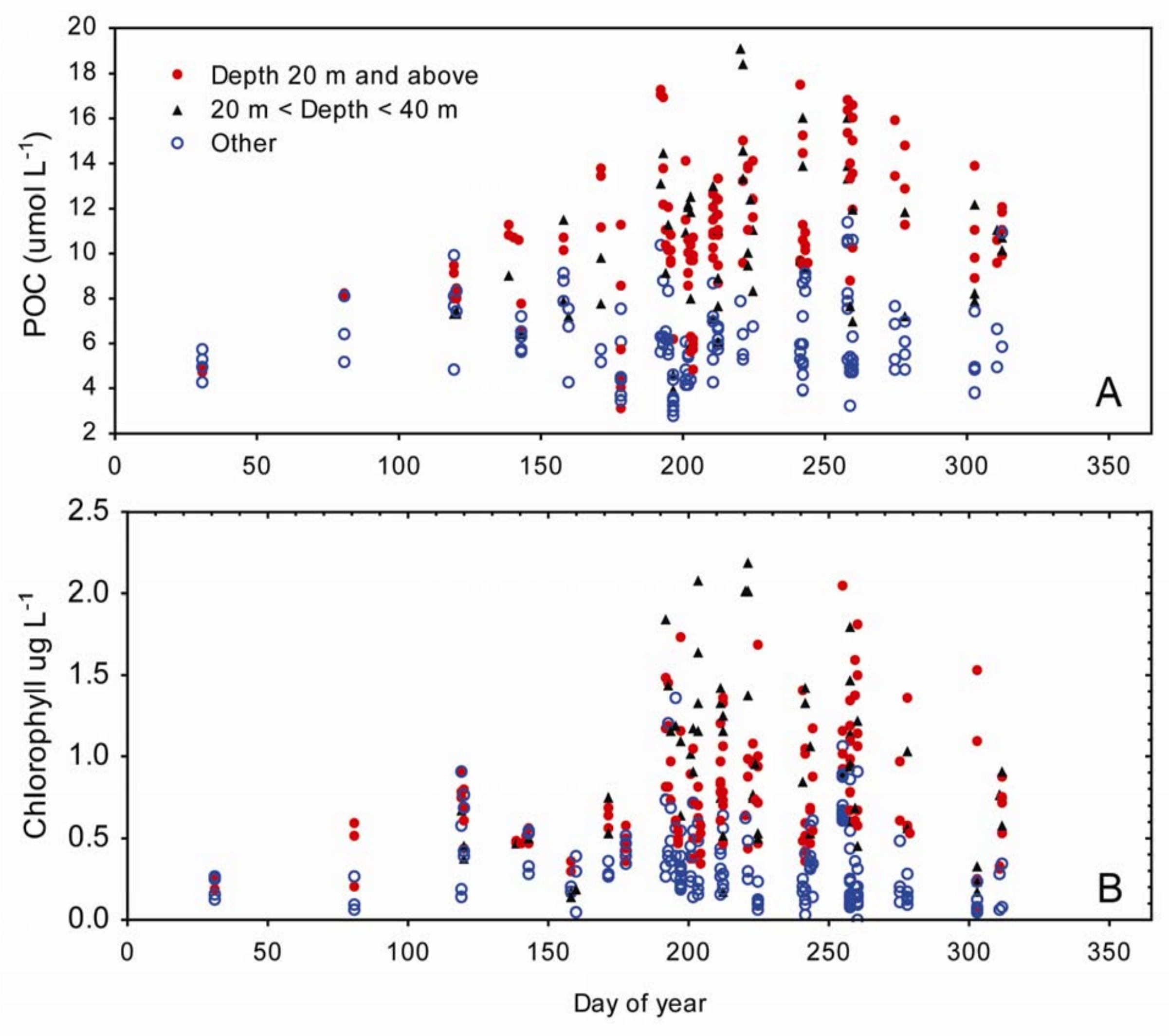
# Characteristics of the Lake Superior nitrate time series

- Multiple sources, multiple labs, multiple methods, but nitrate not hard to measure and spatial/temporal variability small
- Thus, signal to noise ratio high
- Trend unusually constant
- Missing almost all potentially useful linked parameters, e.g. chlorophyll, phosphorus, etc.

# Links to the carbon budget

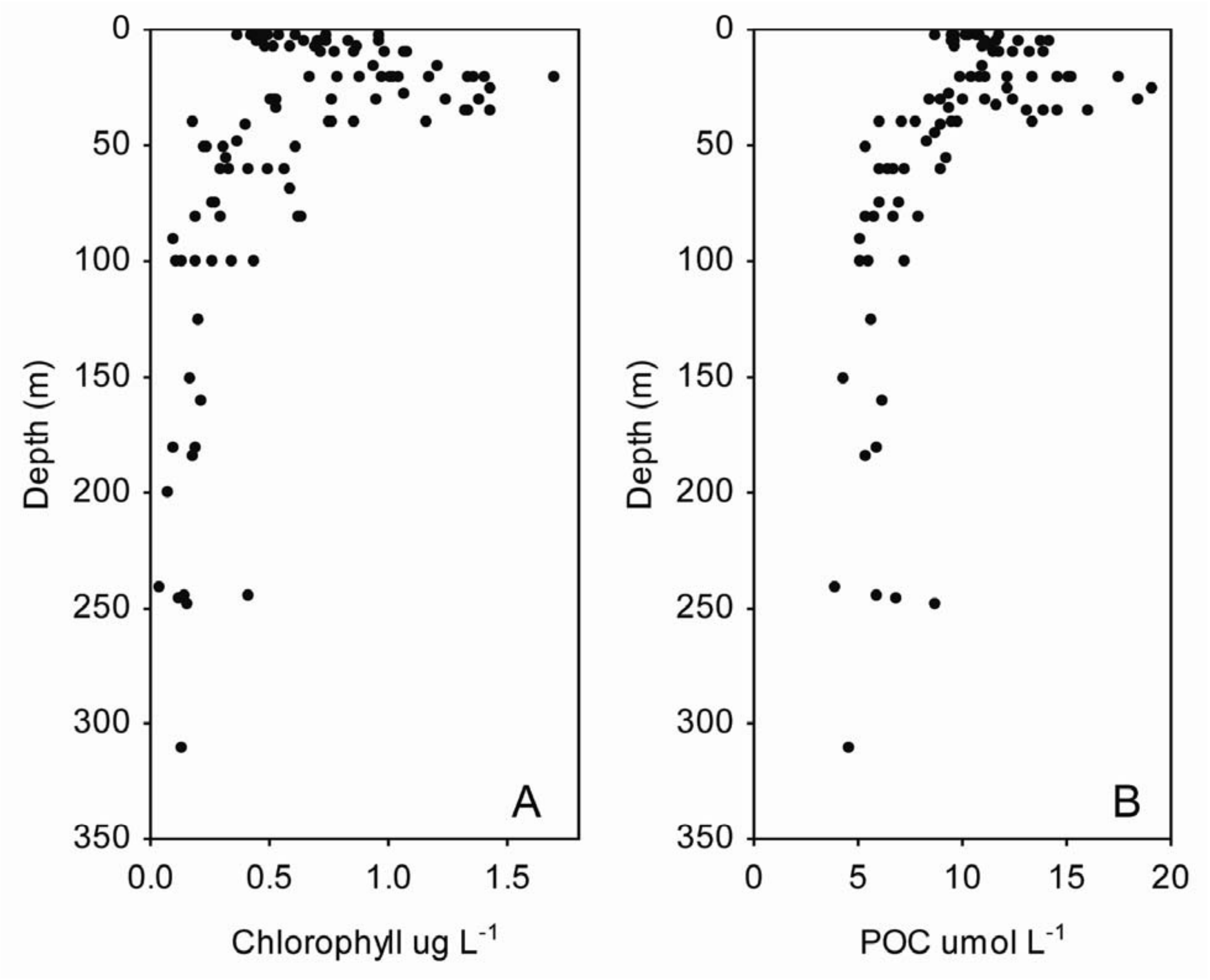
R/V Blue Heron

Drifter with 100 m of cable



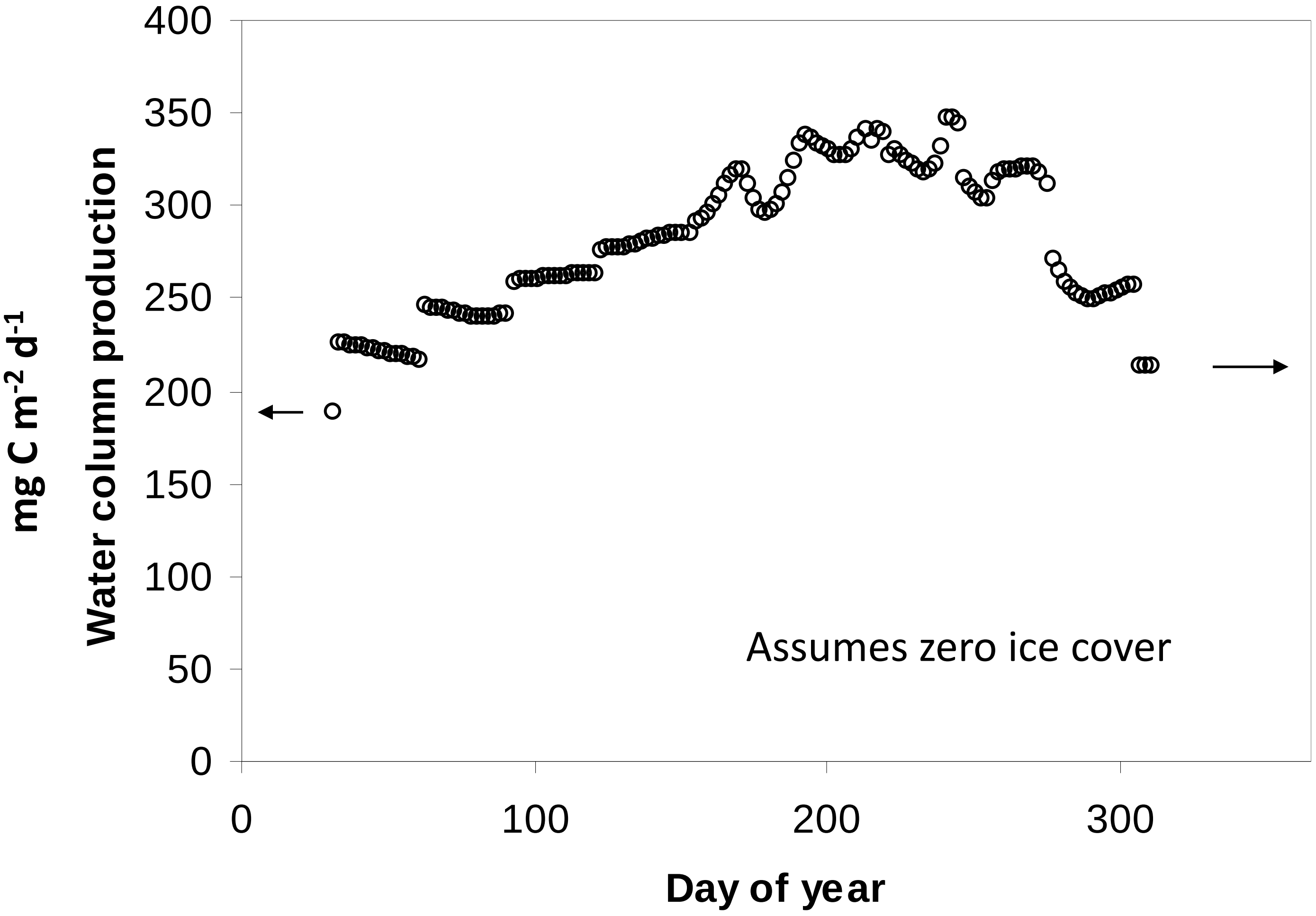
Buildup, breakdown of POC through the year. Obvious difference between surface and deep during summer.

(Use of multi-year studies to gain a first-order, mean field representation of seasonal cycle.)

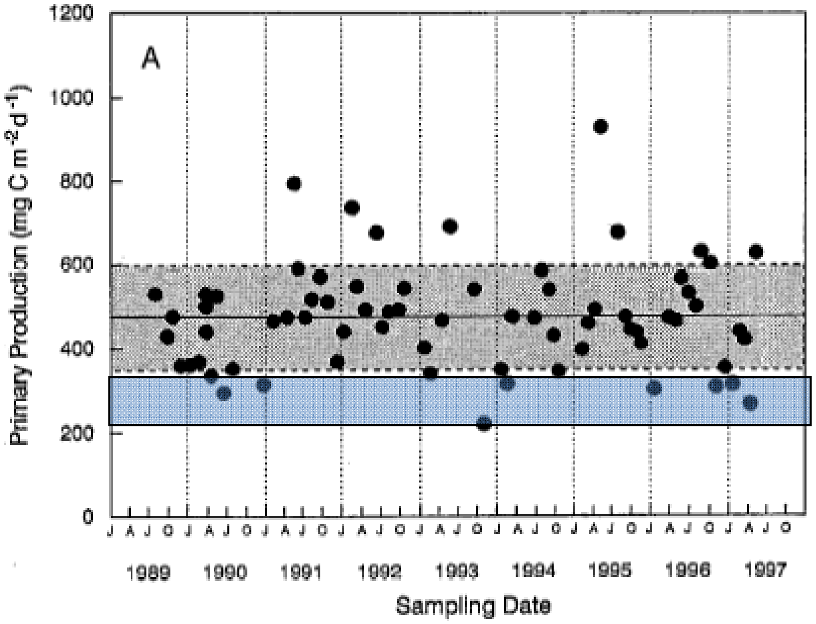


Very prominent DCM during most productive season. Large zone of respiration and decomposition.

After building a statistical model for primary production in a bottle as a function of light and temperature, then scaling up to the lake.



# Comparison to HOTS



# Comparison to BATS

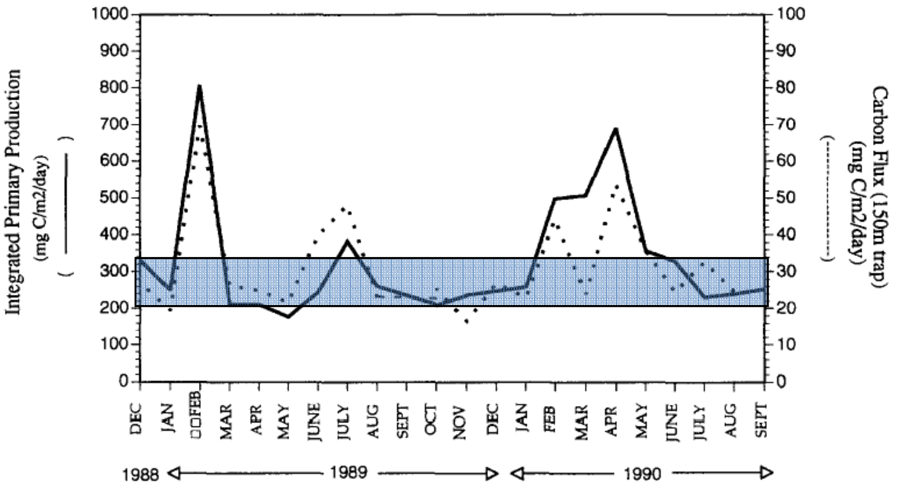
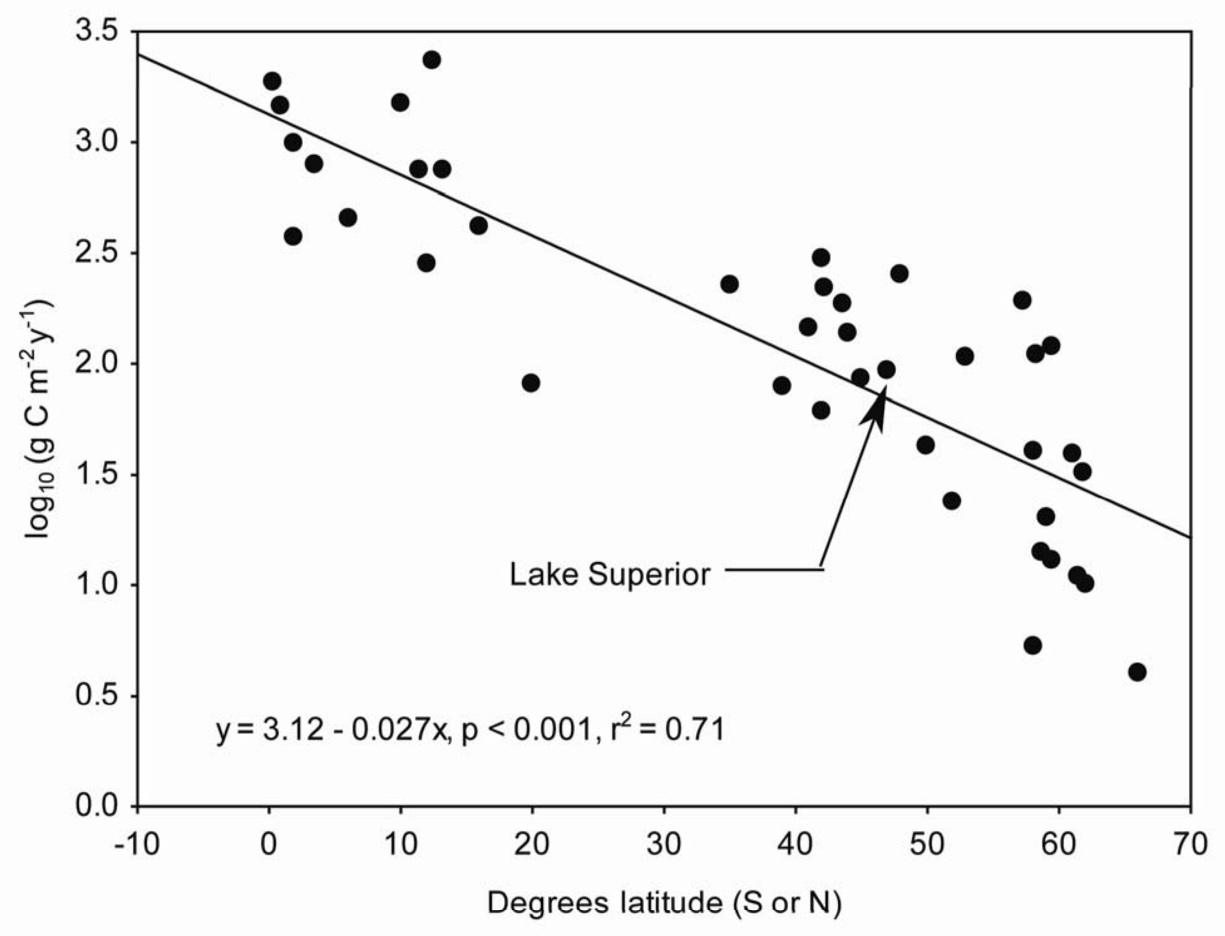


Fig. 14. The integrated primary production (0–150 m) and the sinking flux of particulate organic carbon as estimated by a sediment trap at 150 m at the BATS site. Data are also presented in Lohrenz *et al.* (1992).

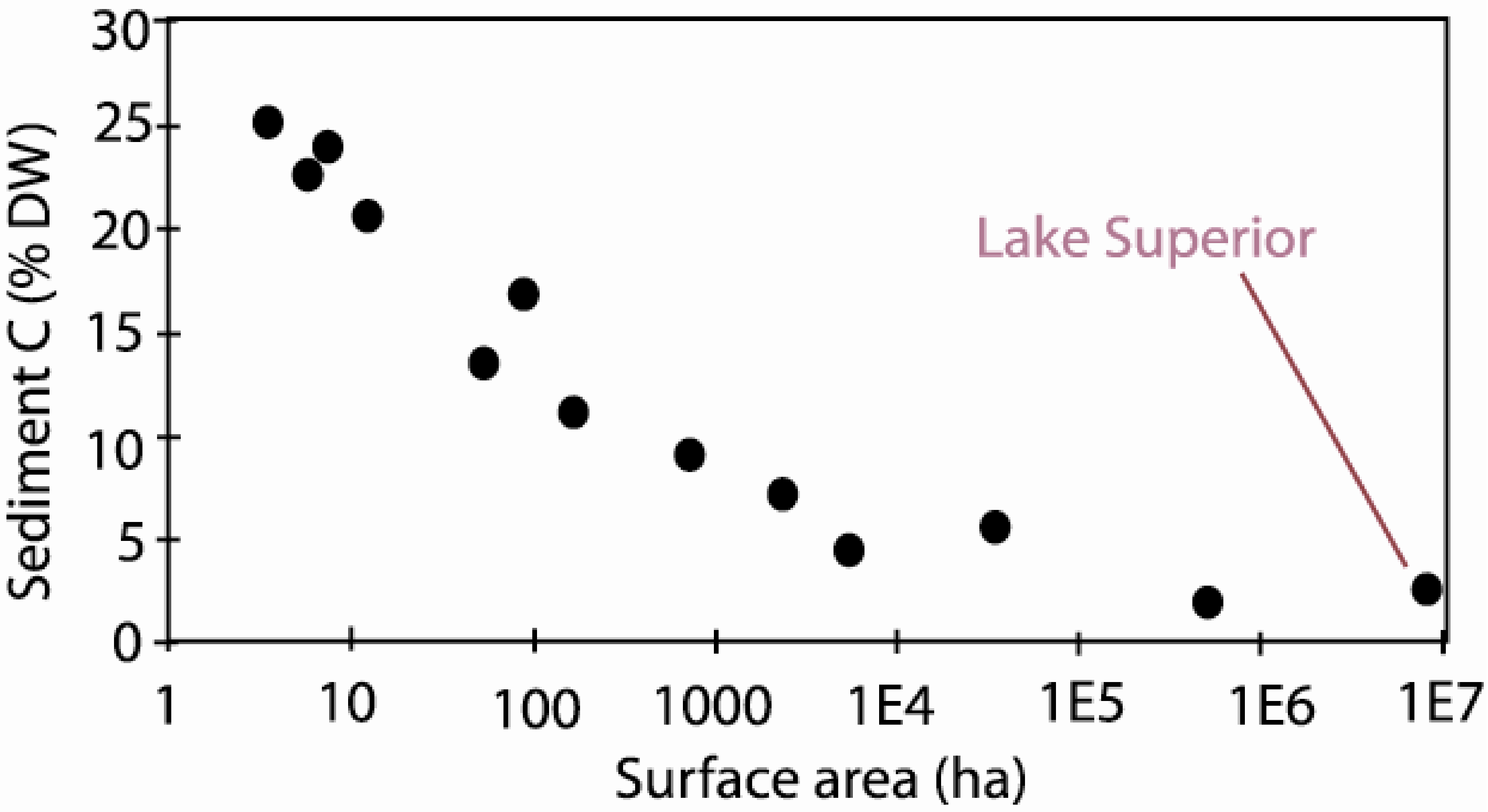
**Lake Superior's primary productivity is less than the North Pacific Central Gyre and is similar to non-bloom conditions at Bermuda.**

# But, Lake Superior production is as expected given latitude.



*Replotted from Alin and Johnson GBC 2007*

# Fate of OC.  Little of it makes it to lake bottom redox gradient.



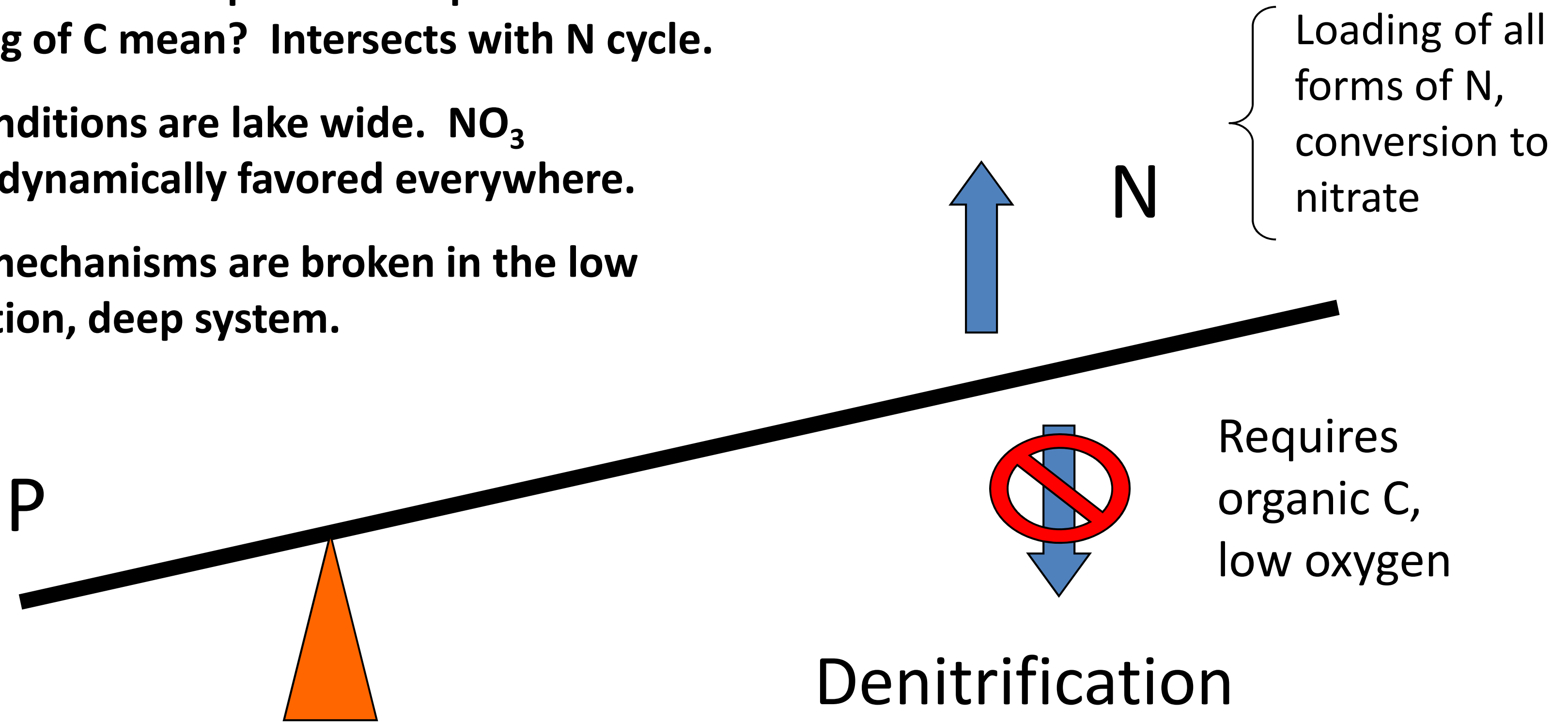
Couple modest levels of production with efficient surface harvesting (grazing) plus very deep water column for mineralization, C supply to sediments is extremely low.

# Lake Superior out of stoichiometric N:P balance
# The reason seems to lie with carbon.

**What does modest production plus efficient recycling of C mean? Intersects with N cycle.**

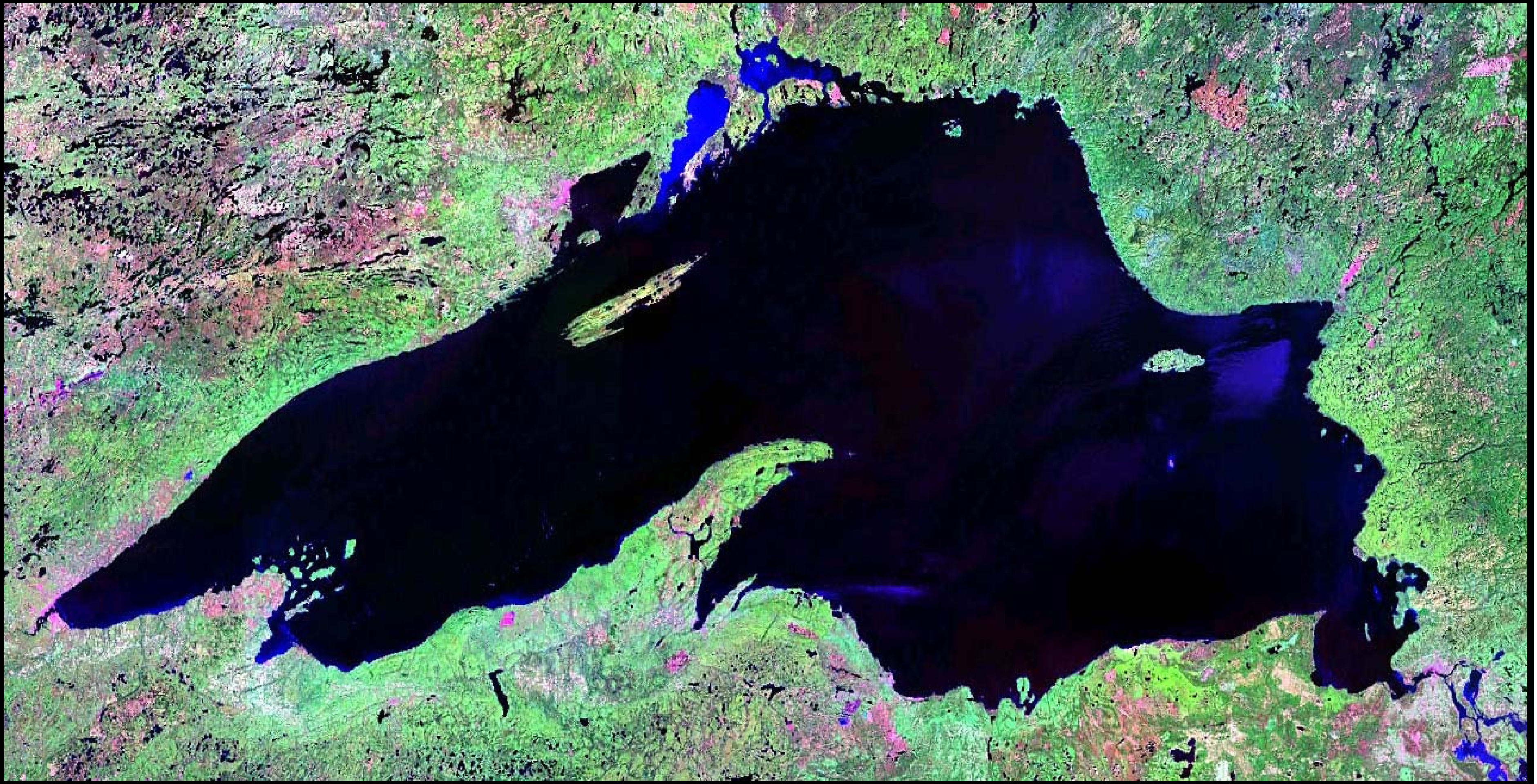
**Oxic conditions are lake wide. $NO_3$ thermodynamically favored everywhere.**

**N loss mechanisms are broken in the low production, deep system.**



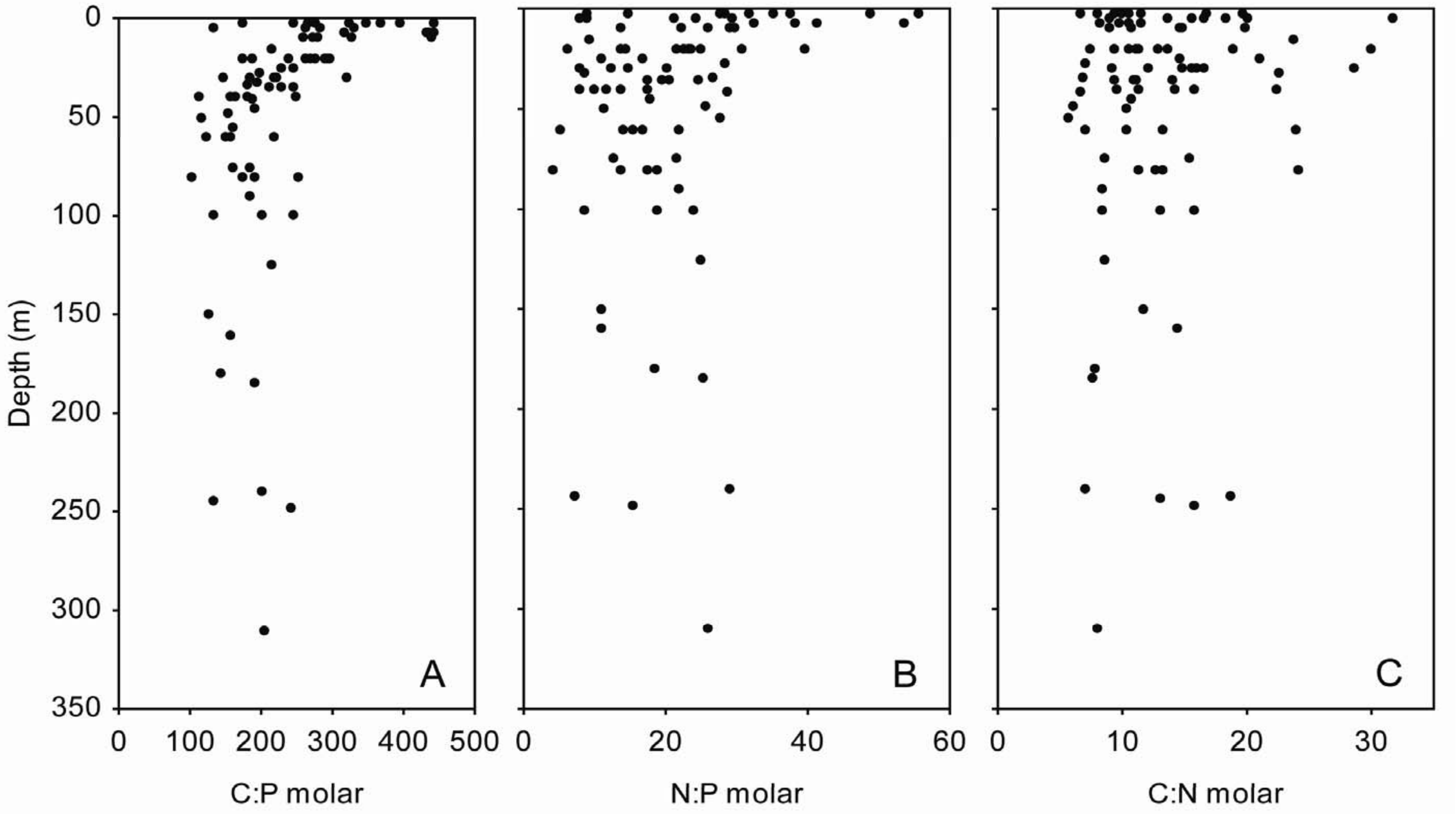
**Hypothesis: Origination and fate of C drives the system to extreme N:P balance.**

# Though large in size, Lake Superior is homogeneous in relevant C:N:P processes.



# Cross system stoichiometric comparisons

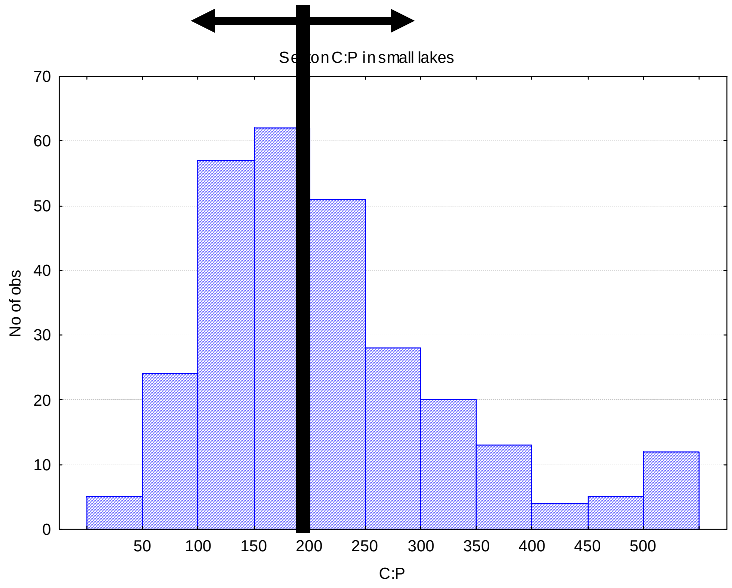
# Scale-dependence


Depth (m)
0
50
100
150
200
250
300
350
A
B
C
0
100
200
300
400
500
C:P molar
0
20
40
60
N:P molar
0
10
20
30
C:N molar

# Maybe elements are linked by a direct proportionality with some variance.

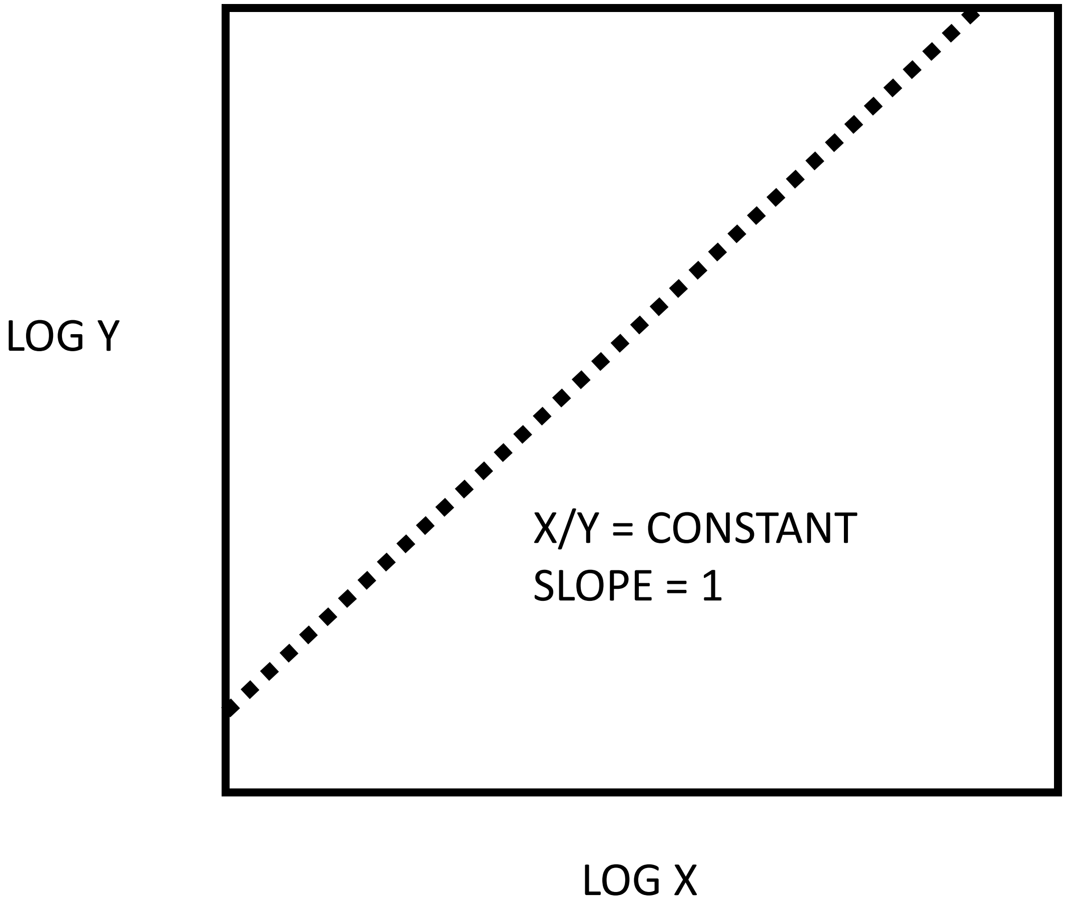
$$C = \alpha P + e$$

Stoichiometric coefficient



Implies a single, central tendency figure for seston nutrient ratios. Best estimate for seston C is seston P times some coefficient?

# Testing for a constant ratio…



A clean statistical test for whether X:Y is constant across the range of the data is to

test for slope = 1

in log-log space.

Additional issue: “error in x”. Approach taken here is to use

Standardized Major Axis

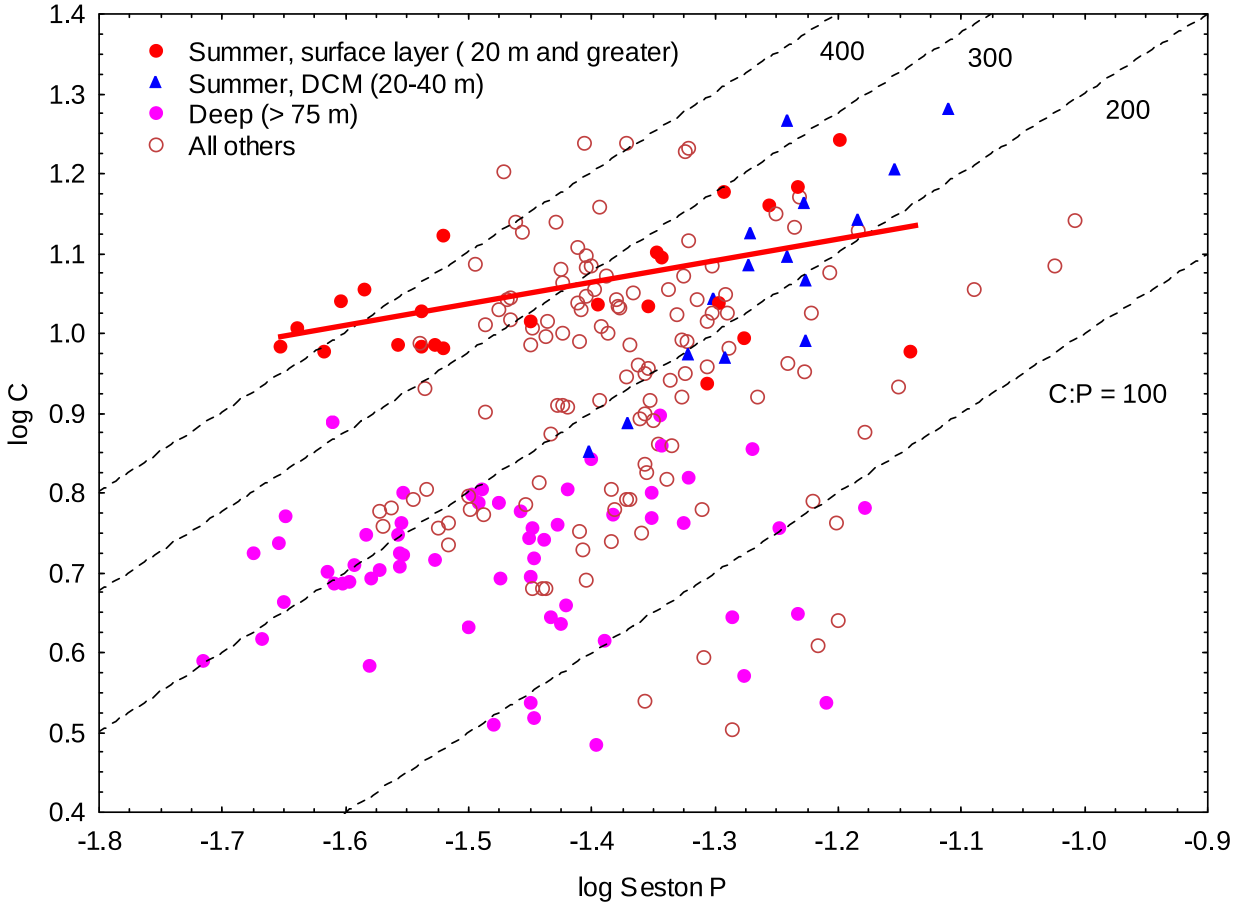
using program SMATR.

# Lake Superior within-lake couplings between seston C and P vary with depth.

| Layer | Mean C:P (SD) |
|---|---|
| Summer surface | 310 (89) |
| Summer DCM | 232 (43) |
| Deep | 162 (51) |

**Seston C and P in log space.**

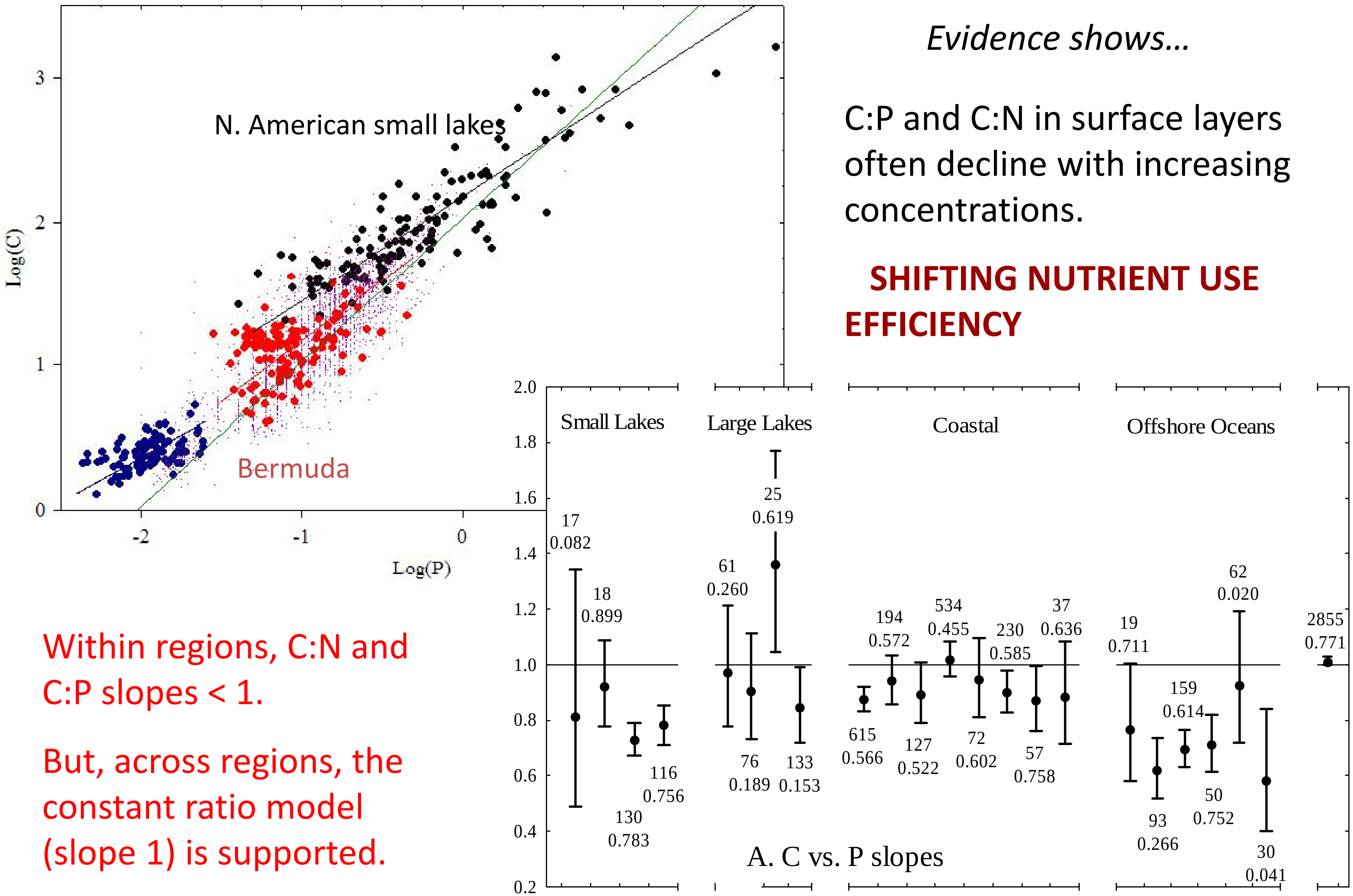
1. Similar seston P in surface and deep waters but higher seston C in surface waters.
2. Both surface and deep C/P couplings have shallow slopes – shifting C:P with overall particle abundance.
3. C/P couplings in DCM very different in terms of slope on this graph. Similar to a constant ratio (ca. 200) model.



*Evidence shows…*

C:P and C:N in surface layers often decline with increasing concentrations.

**SHIFTING NUTRIENT USE EFFICIENCY**



Within regions, C:N and C:P slopes < 1.

But, across regions, the constant ratio model (slope 1) is supported.

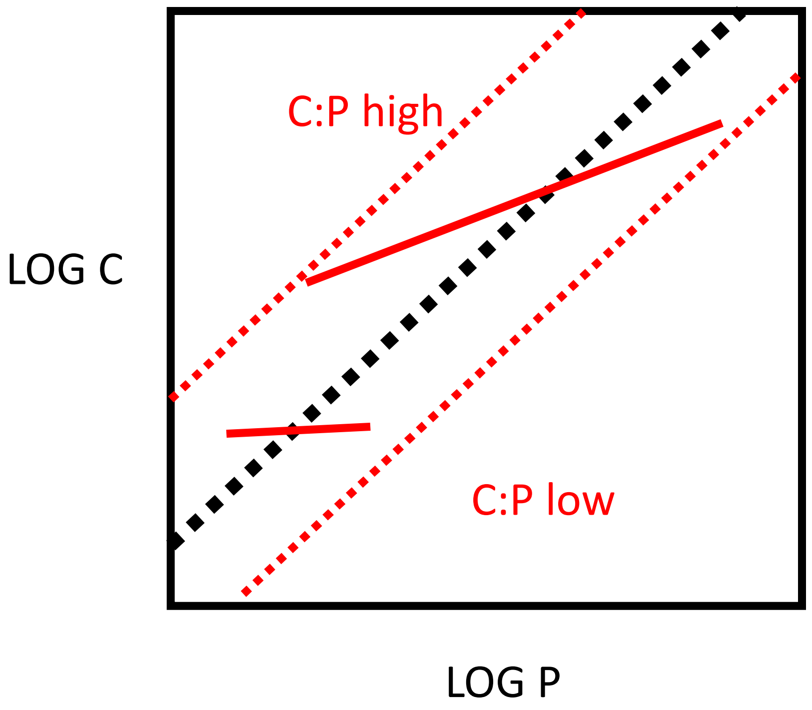
*Based on Sterner et al. L&O 2008*

*Limnol. Oceanogr.*, 53(3), 2008, 1169–1180

# What do shallow slopes in offshore ocean mean?

- C and P are coupled within these ecosystems, but not by a constant proportionality.
- C:N, C:N, N:P seston ratios in offshore ocean are less variable than in lakes, but they exhibited slopes different from one, seemingly even further from one than many lake data sets.
- Reduced variation in offshore ocean comes from a very flexible underlying coupling but a reduced range of the variables.

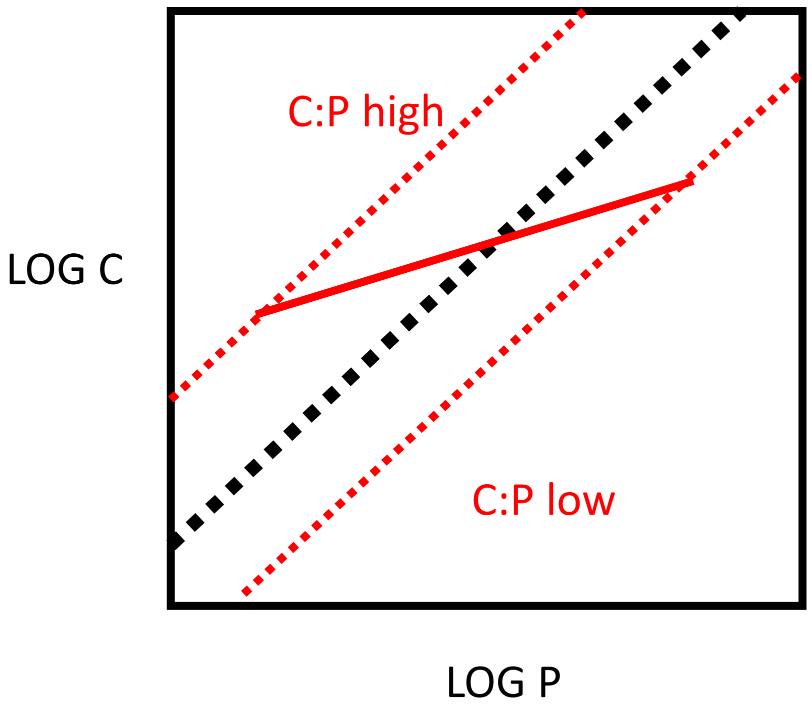
# A cross system contrast in stoichiometry and, possibly, functioning



## In cartoon form

Offshore marine sites have shallower slopes but reduced ranges, thus cover less range in C:P.

Small lakes have seston with an underlying coupling close to constant ratios, but have wider range of variation in the parameters, thus cover more range in C:P.

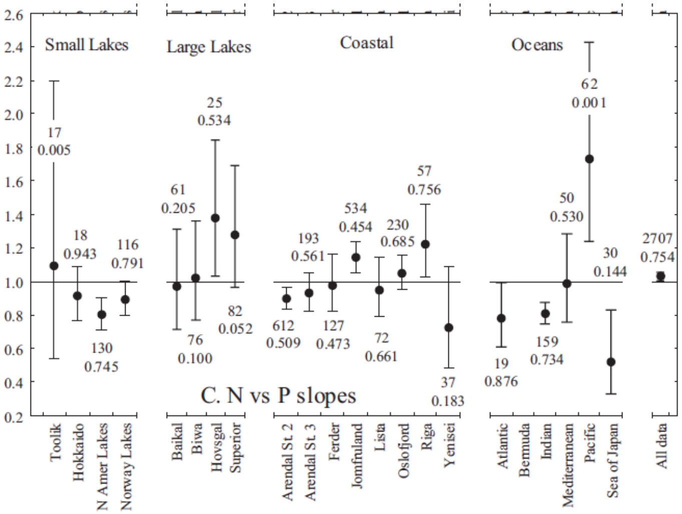


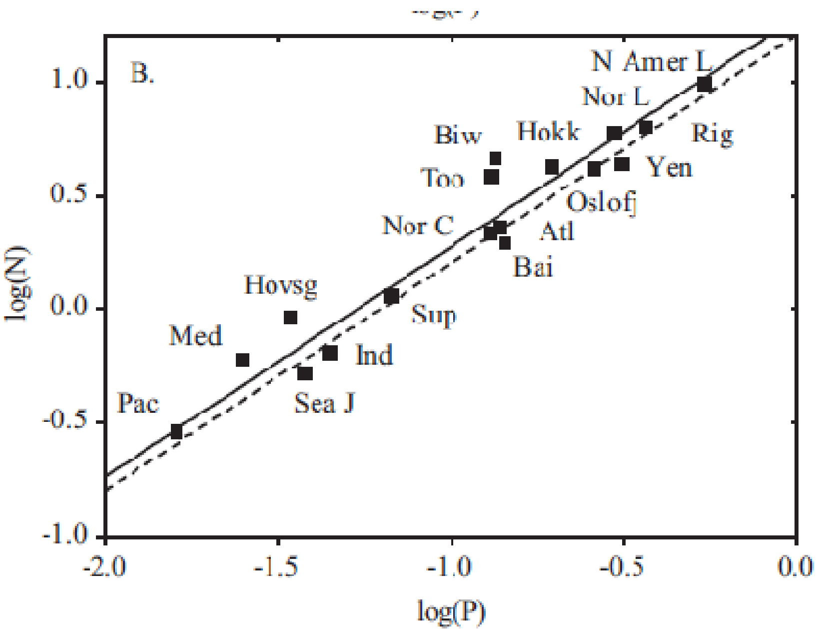
**At one scale, stoichiometric balancing is incomplete (slopes not equal to one).**

# Shifting Nutrient Use Efficiency (NUE)

Higher C:P at low P (lower particle abundance) than at high P (higher particle abundance). As one adds more of a limiting element (e.g. P) to an ecosystem, the carbon linked to it via biological processing does not increase as quickly meaning a direct proportionality is incorrect.

## No single, central tendency

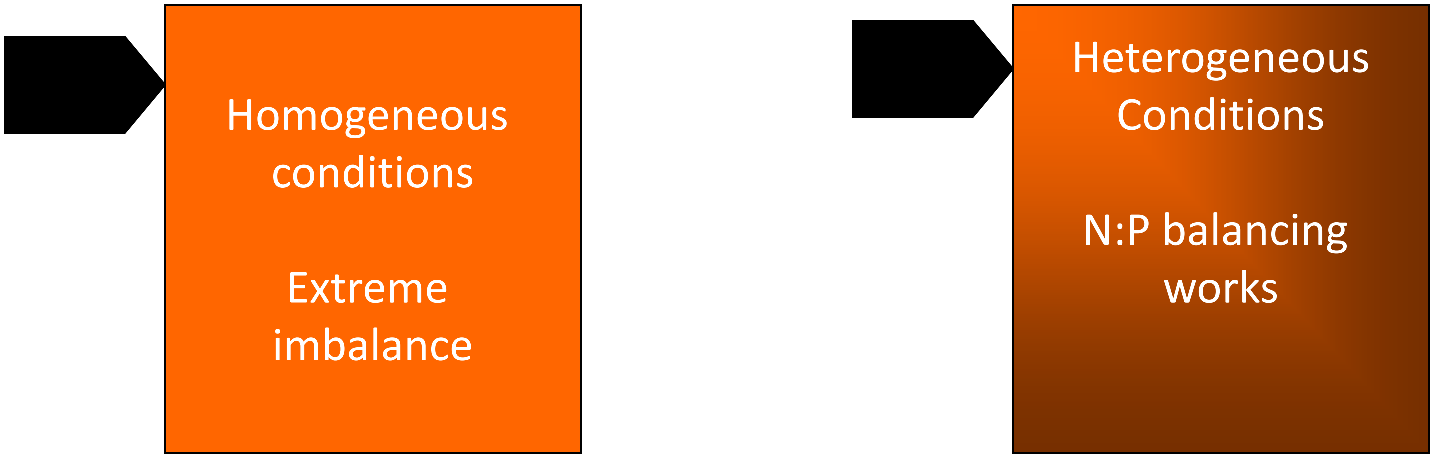




**At the biggest scale (e.g. across oceans), N and P related by constant stoichiometry (slope very close to one). Redfield balancing at work!**

Sterner et al. L&O 2008

# Biogeochemical Mosaic



Homogeneous conditions

Extreme imbalance

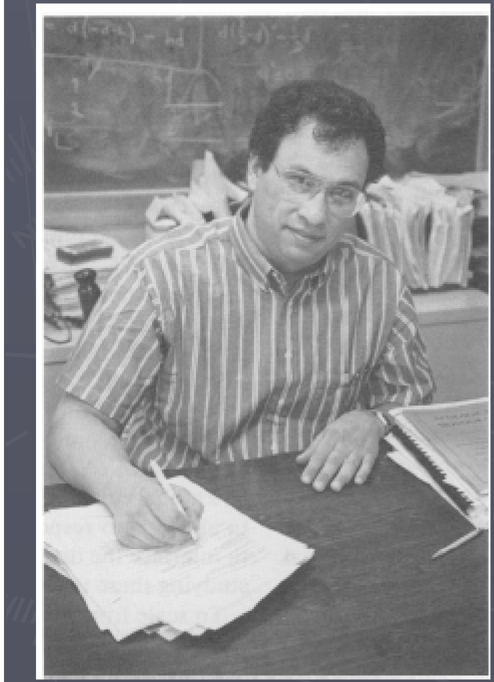
Heterogeneous Conditions

N:P balancing works

**Larger scale gives more opportunity to encompass full biogeochemical potentials, but even a big system can be but one tile in the mosaic if it is homogeneous in conditions.**

The patterns that are unique to any range of scales will have unique causes and biological consequences... Typically, these mechanisms operate at different scales than those on which the patterns are observed; in some cases, the patterns must be understood as emerging from the collective behaviors of large ensembles of smaller scale units. In other cases, the pattern is imposed by larger scale constraints. Examination of such phenomena requires the study of how pattern and variability change with the scale of description, and the development of laws for simplification, aggregation, and scaling.

Levin 1992, *Ecology* (MacArthur address)



**What does this mean for how we do science?**
**What does it mean for time series studies?**

# Science Policy
# and
# Time Series Studies

## A personal outlook

**I no longer not speak for NSF.**

# Some givens and observations

- Given: sustained, consistent observation series are valuable
  - for documenting long-term changes,
  - for providing context to short-term studies, increasing their value,
- They are part of a major paradigm shift in environmental studies, one that is fixated on short and long changes over time,
- They are much desired by U.S. PIs because federal funding can be unpredictable (contrast, say with NSERC).
- They are expensive.

The need for long-term, sustained data collection is broad, involving many interest groups. This includes EPA, NOAA, USACE, etc., etc. etc.

But each interest group has different, if sometimes overlapping needs.

Collaboration has obvious cost savings, but you better plan to support those pieces that are truly vital to you.

# One approach: LTER

- NSF established the LTER program in 1980 to support research on long-term ecological phenomena in the United States.
- Grown to involve > 1800 scientists and students.
- “Site based”. The 26 LTER Sites represent diverse ecosystems and research emphases.
- Evolution of LTER over decades to encompass networking and promoting synthesis and comparative research across sites and ecosystems and among other related national and international research programs.
- Grants renewed every 6 years. Reviewers looking for long term perspectives but also evolving ideas.

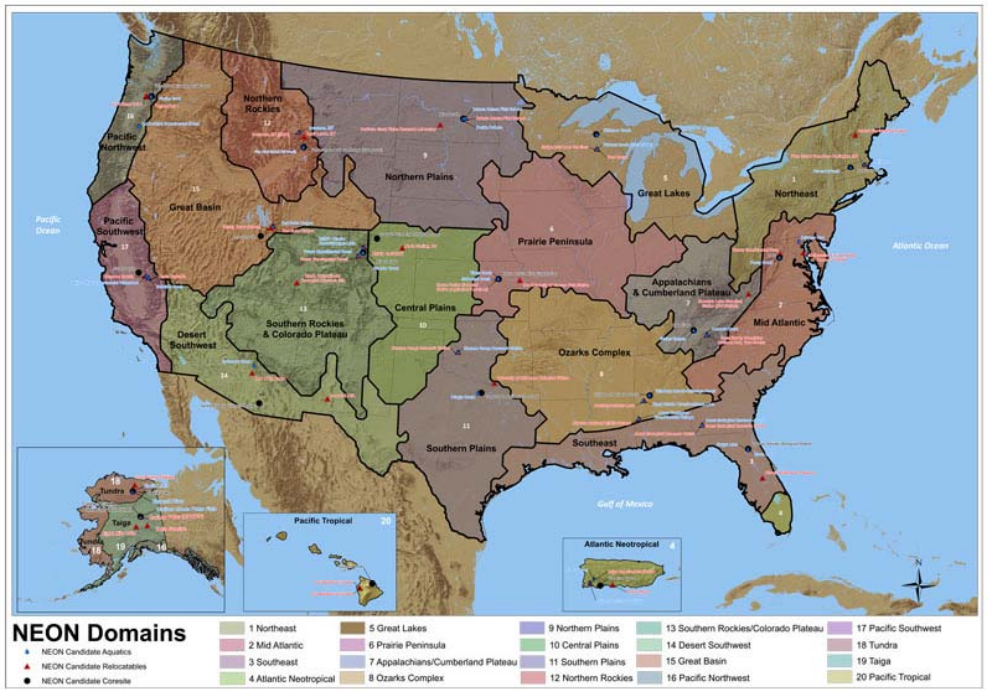
# Another program targeted at time series: LTREB

"Proposals that generate extended time series of biological and environmental data to address ecological and evolutionary processes and resolve important issues in organismal and environmental biology. Researchers must have collected at least six years of previous data to qualify for funding, and these data must motivate the proposed research. The proposal also must present a cohesive conceptual rationale or framework for ten years of research. Questions or hypotheses outlined in this conceptual framework must guide an initial 5-year proposal as well as a subsequent, abbreviated renewal. Together, these will constitute a decadal research plan appropriate to begin to address critical and novel long-term questions in organismal and environmental biology."

NSF web site

# NEON: The First Continental Ecological Observatory

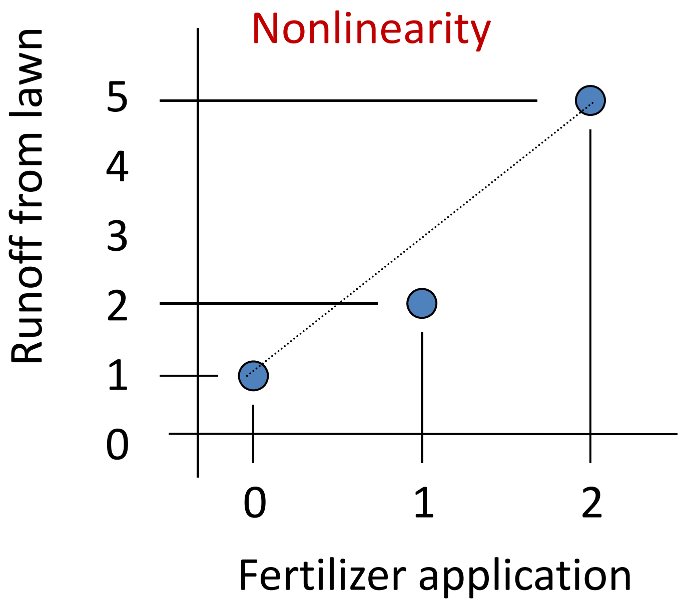
- NEON will be the first observatory designed to detect and enable forecasting of ecological change at continental scales over multiple decades.
- Distributed sensor networks, coordinated airborne observations and experiments, linked by advanced cyberinfrastructure, to collect ecological data across the continental United States, Alaska, Hawaii and Puerto Rico.



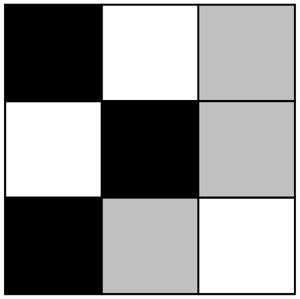
# Conclusions

- Environmental Science needs time series studies.
- Challenges of matching scales of observation to phenomena of interest
- Funding challenges
- Lessons learned across disciplinary boundaries.

# Scale transition: Variance operating across nonlinearities



Total area = 1



Spatial variance in fertilizer application (0, 1, 2 represented by darkness)

<u>Actual regional runoff (runoff multiplied by area):</u>

1·(3/9) = 1/3
2·(3/9) = 2/3
5·(3/9) = 5/3
Total = 8/3

This corresponds to the "mean of the function" .

<u>Prediction from mean field</u>:
Regional mean application = 3(0+1+2)/9 = 1
If we apply the mean application rate to the nonlinear function above, we predict regional runoff = 2
This corresponds to the "function of the mean".

Actual runoff (8/3) > Mean field prediction (2).