Lacustrine Time Series and Cross-Ecosystem Perspectives on Aquatic Biogeochemistry

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Three iconic limnological time series
Lake Washington

Effects of nutrient loading and grazing on lake ecosystems.

Involving the public.
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

![Graphs showing concentration and flux of calcium in streamwater and precipitation.](image)
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

Redfield Ratio = 106:16:1
“Redfield” balancing of N:P ratio

Denitrification

Fixation

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
Winter of 2009-10
Lake Superior ice virtually nil.
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

![Graph showing NO3 vs Annual primary productivity](image)
TP = 0.08 µmol L⁻¹

TN:TP = 30/0.08 = 375,

NO₃:PO₄ ~ 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?
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?
### Table 1. Present Day NO$_3^-$ Inputs and Outputs in Lake Waters

<table>
<thead>
<tr>
<th>Source</th>
<th>Nitrates Flux, mmol m$^{-2}$ yr$^{-1}$</th>
<th>Notes</th>
<th>Sources of Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct precipitation onto lake surface</td>
<td>12.5 (wet) 3.9 (dry plus droplet) 17.2 (total)</td>
<td>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. as is as reported for Ontario</td>
<td>U.S.: Based on 87 site-years of annual NO$_3^-$ deposition data from 7 sites in the Lake Superior region (<a href="http://nadp.sws.uiuc.edu/">http://nadp.sws.uiuc.edu/</a>) Canada: Rates given by Chen et al. [2000] for Ontario.</td>
</tr>
<tr>
<td>Watershed, surface runoff</td>
<td>5.92</td>
<td>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</td>
<td></td>
</tr>
<tr>
<td>Watershed, direct groundwater inputs to lake</td>
<td>0.96</td>
<td>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</td>
<td>Hydrologic budget [Lenters, 2004] with groundwater concentrations for the Lake Superior watershed in WI and MN reported by state agencies</td>
</tr>
<tr>
<td>Outflow</td>
<td>22.4</td>
<td>Present day concentration (25 µM) times hydrologic outflow 70.6 km$^3$ yr</td>
<td>Lake concentration, this study. Outflow, mean for 1948–1999 [Lenters, 2004].</td>
</tr>
<tr>
<td>Buildup</td>
<td>23.4</td>
<td>Coefficient of linear fit</td>
<td>This study</td>
</tr>
</tbody>
</table>

**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.
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

Drifter with 100 m of cable

R/V Blue Heron
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.
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
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.

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


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

Actual regional runoff (runoff multiplied by area):
- $1 \cdot (3/9) = 1/3$
- $2 \cdot (3/9) = 2/3$
- $5 \cdot (3/9) = 5/3$
- Total = $8/3$

This corresponds to the “mean of the function”.

Prediction from mean field:
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 $(2)$. 