Climate and carbon impacts on productivity, chemistry and invasive species in the Great Lakes

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Biogeochemistry is elemental cycling and flux between reservoirs, and interactions with lower food web

Sarmiento and Gruber, 2006, fig 4.4.1
Physics sets the stage

Talley et al., 2011, fig 9.1; NASA image
Physics sets the stage

Movie of modeled tracer advection in Lake Superior shown here (MITgcm.Superior)
Together, physics and biogeochemistry are the infrastructure on which ecosystems depend
Climate change has arrived

Record-Setting Heat Across the U.S. in 2012

The average temperature across the contiguous United States in 2012 was 55.3°F (3.2°F above normal). This ranks as the warmest year since records began in 1895.

New York Times, 8 Jan 2013
The Great Lakes are feeling the heat

Desai et al. 2009, Austin and Colman 2007
Impacts of climate change and other stressors on ecosystems? Non-linear effects? Need to understand physics, biogeochemistry.

Allan et al., 2013
Further, warming is due to anthropogenic CO$_2$
What is the Great Lakes role in the carbon cycle?

IPCC AR4, 2007, Figure 7.3
Advancing understanding of Great Lakes biogeochemistry and physics

1. Carbon budget of Lake Superior

1. Energy sources for *Diporeia* in Lake Superior

2. Warming and the Sea Lamprey in Lake Superior

1. Ocean Acidification in the Great Lakes
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1. Ocean Acidification in the Great Lakes
Inland waters may play significant role for carbon.

Cole et al. (2007), Tranvik et al. (2009)
Cotner et al., 2004; Urban et al., 2005; Sterner, 2010; Urban et al. in prep.
High-fidelity models offer lake-wide perspective
Physical Validation

Velocity and Temperature off the Keweenaw in 1999

Bennington et al. 2010
Lower food web / biogeochemistry module
Ecosystem Validation: Nearshore Respiration

River Mouth and EPA Station Locations

Respiration HN 1999

Respiration Ontonagon 1999

Model (sfc)  
Model (5-10m)  
KITES (sfc)  
KITES (5-10m)
LAKE SUPERIOR
CARBON BUDGET

Atmospheric Deposition
0.1 - 0.4

Efflux
3.0

Rivers
0.5 - 1.0

GPP
6 - 9.7

Burial
0.5

R
13 - 42

Outflow
0.1

∑ Inputs = 6.6 - 11.1

∑ Outputs = 16.6 - 45.6

Cotner et al, 2004; Urban et al., 2005; Sterner 2010; Urban et al. in prep
Model indicates a factor of 10 variation in respiration (volumetric)

Past estimates used a factor of 2 with respect to observations off the Keweenaw $\Rightarrow 13-42$ TgC/yr.

Modeled mean 1997-2001 = 5.45 TgC/yr

Bennington et al. 2012
LAKE SUPERIOR
CARBON BUDGET

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LAKE SUPERIOR
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TgC/yr

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Efflux
3.0

Rivers
0.5-1.0

GPP
6–9.7

Burial
0.5

Outflow
0.1

R
4.3 – 5.6

∑ Inputs = 6.6 - 11.1

∑ Outputs = 7.9-10.1

Cotner et al, 2004; Urban et al., 2005; Sterner 2010; Bennington et al. 2012, Urban et al. in prep
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Why do Diporeia cluster on the slope?

Auer and Kahn, 2004; Auer et al. in review
Productivity highest nearshore – as is Respiration

Chlorophyll, after removal of terrestrial dissolved matter signal

SeaWiFS satellite
August 31, 2006

Mouw et al. in review; in prep
How much and where does Production and Respiration of labile organic carbon occur? Evaluate with model

- R:P = 1 in nearshore and offshore
- Labile organic carbon is largely respired on slope, in a quantity equivalent to the river subsidy

McKinley and Bennington, in prep
Organic matter from nearshore may provide energy source to help support Diporeia community on slope

Auer and Kahn, 2004; Auer et al. in review
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Sea Lamprey and Climate Change

Kitchell et al. in press, Cline et al., 2013
Prey (trout) increasing

CPUE (kg/km) Temperature (°C) Weight (g)

CPUE = Catch per unit effort

Temperature increasing

Sea Lamprey weight increasing

Second lamprey increase starts mid-1980’s, after prey level off
Sea lamprey weight increase with more days of water at $>10C$; Model details the warming pattern

**Weight vs. Days $> 10C$ (annual data)**

- Days $> 10C$ have increased from 80’s to 00’s
- Sea lamprey weight increase with more days of water at $>10C$; Model details the warming pattern
Bioenergetic model of fish and Sea Lamprey

\[
C = (R + A + S) + (F + U) + (\Delta B + G)
\]

For Sea Lamprey: Kitchell and Breck (1980) through Madenjian et al. (2008)
Up to 10% increase blood consumption with recent warming

Change in blood consumption between 1979-84 and 2001-2006

Percent Change in Annual Blood Consumption (g/lamprey)

Kitchell et al. in press
Year

Prey (trout) increasing

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Ocean Acidification:

\[ \text{CO}_2 + \text{H}_2\text{O} = \text{CARBONIC ACID} \]

Carbonic acid lowers pH (increases H⁺)

With CO₂ emissions since 1800, surface ocean pH has declined 0.1 units = 10% increase in H⁺
Model Projection for CaCO$_3$ saturation in 2100

Southern Ocean becomes corrosive to CaCO$_3$
Impacts likely before – some observed already

Orr et al. 2005
Clearly not good for calcifiers…
What about ecosystem effects?
Will the Great Lakes experience OA?

TWO-BOX MODEL

Simple physics, imposed cycle of productivity, complete carbon chemistry

Phillips 2012,
Phillips et al. in prep
Will the Great Lakes experience OA?

"Business as Usual" scenario (solid) results in pH decline of 0.3 units by 2100, same as surface ocean
Observed trends?

Source: EPA bi-annual survey, average of April and August data, 8-20 sites per lake
Observed trends?

Source: EPA bi-annual survey, average of April and August data, 8-20 sites per lake
Is lake-wide, annual mean pH well-represented by these data?

Observing System Simulation Experiment (OSSE) with MITgcm.Superior

Model Sampled as data

True annual mean
Why not? Significant spatio-temporal variability

Modeled: April, August 2000
Why not? Significant spatio-temporal variability

Observed pH, June-Sept 2001, every 30 min
Is Ocean Acidification happening in the Great Lakes?

- Projections with full carbon chemistry indicate OA should occur at same rate as in the ocean in all Great Lakes

- However, the most comprehensive monitoring has not been designed to capture these trends

- High quality, high temporal resolution data, sited to capture lake-wide means, are needed

- Better understanding the mechanisms driving the observed spatio-temporal variability in pH is critical
Impacts of Ocean Acidification in the Great Lakes? Survey of Experts

Early Life Stages: Calcifying Organisms

Water Quality

Fish: Early life stages

Phillips 2012, Phillips et al. in prep

89 respondents, spring 2012
Conclusions

• Biogeochemistry and physics set the stage for ecosystems

• Predicting responses to changing climate requires better knowledge of all components

• Well-validated models are an important tool

• Shown here:
  • Lake Superior’s carbon budget can be balanced once we account for spatial heterogeneity of respiration
  • *Diporeia* in L. Superior may be supported by organic carbon fixed in the nearshore and advected to the slope
  • Warming increases Sea Lamprey blood consumption in L. Superior
  • Ocean Acidification is likely in the Great Lakes, but adequate monitoring has not yet been implemented
References

Questions?