

### Appendix A: Virtual Seminars Schedule and Presentations

<b>Seminar I - Thursday, Nov 3, 2022</b>	<b>Presenter</b>
Introduction: Investigating Food Webs: State of Knowledge and Investigative Approaches	Tom Stewart
A fisheries management perspective on food web information needs	Randy Claramunt
Applications of ecological tracers in the Great Lakes	Aaron Fisk et al.
The adaptive capacity of lake food webs	Bailey McMeans
Break	
Phosphorus to fish	Marten Koops
Integration of water quality objectives and fisheries objectives	Tim Johnson
Integrated Ecosystem Assessment	Mike Fraker
Adjourn	

<b>Seminar II- Thursday, Nov 10, 2022</b>	<b>Presenter</b>
Opening remarks	Tom Stewart
Understanding material and energy flow in aquatic ecosystems using linear inverse modeling	Dick van Oevelen
LIM approach to Ecopath mass balance and hypotheses testing	Tom Stewart
Modelling chance and necessity in natural systems	Benjamin Planque
Break	
Applications of Ecopath/Ecosim in the Great Lakes	Ed Rutherford
Atlantis: Potential Great Lakes applications	Doran Mason
Ecosystem behaviors	Bob Ulanowicz
Wrap-up and next steps	Tom Stewart

# Investigating Food Webs: State of Knowledge and Investigative Approaches

Tom Stewart

Brian Weidel, USGS

Dick van Oevelen, Royal Netherlands Institute for Sea  
Research

Investigating Food Webs: Sate of Knowledge and Investigative Approaches

## Acknowledgements

### Funding

Great Lakes Fishery Commission  
Cooperative Institute for Great Lakes Research

### Steering Committee and Advisors

Nicholas Boucher, Aaron Fisk, Roger Knight, Doran  
Mason, Kevin McCann, Bailey McMeans, Lars  
Rudstam, Ed Rutherford, Heidi Swanson

### Workshop Hosts

Cornell Biological Field Station

Investigating Food Webs: Sate of Knowledge and Investigative Approaches

What's this all about?

Investigating Food Webs: Sate of Knowledge and Investigative Approaches

What's this all about?



# FOOD WEBS

Investigating Food Webs: Sate of Knowledge and Investigative Approaches

# What's this all about?

**Why-** Fisheries  
management information  
needs, key questions

**Where-** Great Lake focus,  
but....

**How-** tools, measurements, indices

**When-** timely research, practical, funded

**Who-** designs, methods, collaborations

## FOOD WEBS

Investigating Food Webs: State of Knowledge and Investigative Approaches

## Objectives

1) Review and share the current state of food web investigative methods,

2) Determine food web-scale fisheries management information needs and possible investigative approaches, and

3) Develop collaborative study designs and proposals for potential funding addressing food web knowledge gaps relevant to fisheries management information needs.

Seminars  
Nov 3 & 10

Workshop  
Nov 14-16

Investigating Food Webs: State of Knowledge and Investigative Approaches

## House keeping

- Presentation timer
- Presentation recordings
- Questions during seminar – please raise your hand
- Workshop registration – link is in the Zoom chat

**To request recorded talks**  
**[nboucher@glfc.org](mailto:nboucher@glfc.org)**

**Any other questions**  
**[tomstewart54321@gmail.com](mailto:tomstewart54321@gmail.com)**

Investigating Food Webs: State of Knowledge and Investigative Approaches

## A Fisheries Management Perspective on Food Web Informational Needs

Seminar 1 - 8:15am, Thursday, November 3, 2022

Randy Claramunt - Lake Huron Basin Coordinator, Fisheries Division



## Elevator Pitch for Food Webs

- ▶ The pitch 'theme': make smart decisions.
- ▶ Credibility booster: my background.
- ▶ Short and sweet pitch: GLs  $\Delta$  + complex.
- ▶ What's the twist: food web information too complicated or theoretical for management.
- ▶ Call to action: What is needed or not needed.
- ▶ One-liner: Hey look, without an understanding of food web dynamics, managing GLs fisheries is like driving at high speeds, in the dark, with no headlights!



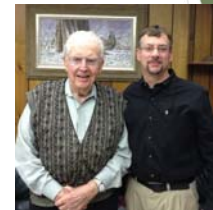
## Make Smart Decisions

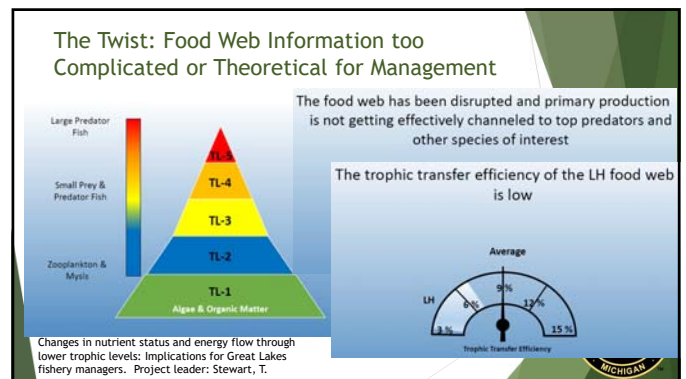
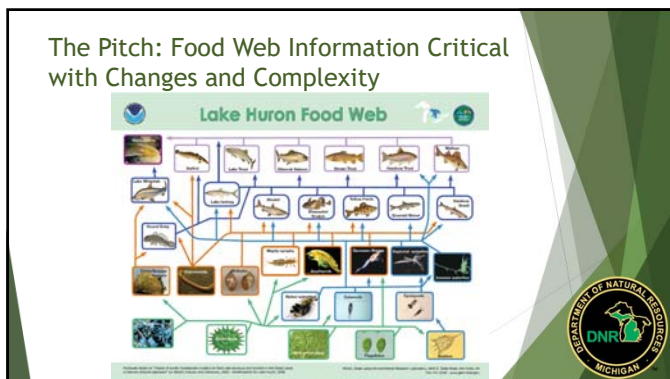
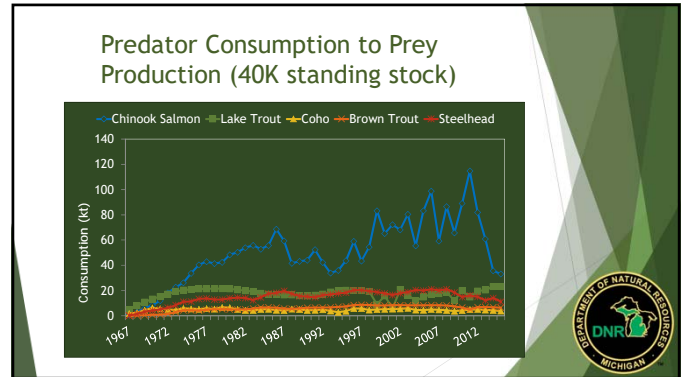
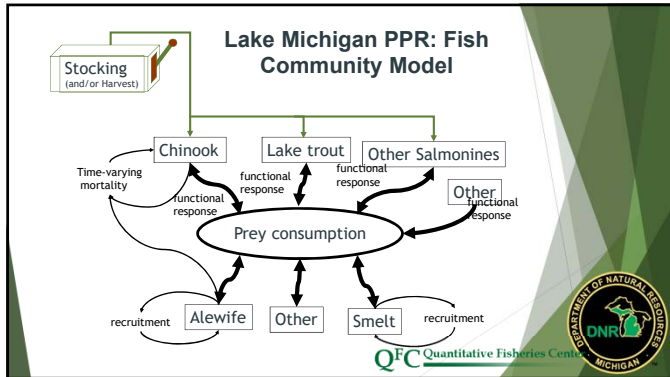
- ▶ Cost of Actions: a move from single species/agency management to fish community decisions in a shared management framework has exponentially increased the cost of said actions.
- ▶ Timeline: the diversity of stakeholder input has substantially increased the duration for complex decisions and management actions.
- ▶ Context: each decision / action is linked with or should be referred to previous actions and could include a range of data review, literature, and reports.
- ▶ Economics: management agencies with jurisdiction often lack the financial resources to adequately address the aforementioned challenges.
- ▶ Information needed from investigation of food webs are as follows:
  - ▶ Compensation
  - ▶ Stability and resiliency
  - ▶ Species interactions, prey preferences and habitat linkages
  - ▶ Productivity and trophic efficiency
  - ▶ Predictability (with or without management actions)



## Background

- ▶ Lake Michigan Research Biologist with a focus on stock assessment and predator-prey dynamics.
- ▶ Worked as a manager for both State and Tribal Fisheries Agencies.
- ▶ Predator-Prey dynamics substantial changes in the GLs and observed:
  - ▶ Single-species management to fish community
  - ▶ Need to balance productivity with mortality rates
  - ▶ Invasive species impacts
  - ▶ Advancing science and models
  - ▶ Continued challenges





## Management Actions

- Coordinated stocking strategies
- Regulations linked with adaptive management strategies
- Habitat restoration with community-wide impacts
- Food web information and models to allow the capacity for ecosystem-level, bio-manipulation, to restore healthy food webs and promote a stable fishery (e.g., mussel collaborative)

## A Changing Lake Huron

### The Lake Huron Food Web

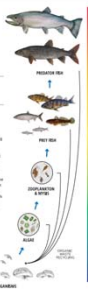
The present state of Lake Huron's food web is the result of a complex interplay of factors, including changes in the abundance and distribution of various species, changes in the physical and chemical environment, and changes in the management of the fishery.

### Phytoplankton and Fish Biomass

Phytoplankton are the primary producers in the food web, and their biomass is a key indicator of the health of the ecosystem. In Lake Huron, phytoplankton biomass has declined significantly over the past several decades, which has led to a corresponding decline in the biomass of the fish that depend on them for food.

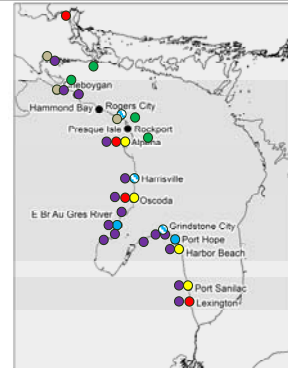
### Food Web Complexity

Food web complexity refers to the number of different species and the strength of the interactions between them. In Lake Huron, the food web has become increasingly complex over time, with the addition of new species and the strengthening of existing interactions.



## Potential Ports for Salmon & Trout Stocking

- Coho Yearlings
- Coho Fingerlings
- Atlantic Salmon
- Chinook Salmon
- Steelhead
- Lake Trout



## Lake Huron Mission Statement for Salmon and Trout Management

*A sustainable and diverse salmon and trout fishery that maximizes the lakes production potential to provide exceptional fisheries for communities across Lake Huron.*

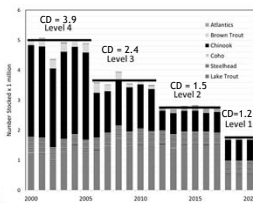


## Species, predator equivalency ratios (PER), and factors considered in the stocking strategy for Lake Huron.

Species	Predator Equivalency Ratio (PER)	Catchability	Cost effectiveness	Feeding Ecology	Movement-Straying	Wild Recruitment Potential	Social-Economical Benefits
Atlantic Salmon	2.4	Medium	Not available	Highly Diverse	Medium	Low	High
Brown Trout	2.2	Low	Low	Moderately Diverse	Low	Low	Medium-Low
Chinook Salmon	1.0	High	High	Pelagic/Planktivorous	High	High	High
Coho	3.2	Medium	Medium	Moderately Diverse	Medium	Medium	Medium-High
Lake Trout	2.3	High	Medium	Benthic/Prey	Low	High	Medium-Low
Steelhead	2.4	Medium	Medium	Moderately Diverse	Medium	Medium	Medium-High



## Major Components of the Plan



### Predator Equivalency Ratio



- Stocking levels 1-4 defined by total number of fish and associated consumption demand (CD) based on predator equivalent
- Agreement at the time of the plan development that Level 1 was in balance with overall prey fish production
- Adjustment to stocking levels would be set in concert with State of the Lake (SOL) process which is on a five-year rotation
- Within a level, species compositions could vary within predator equivalency ratios (PERs).



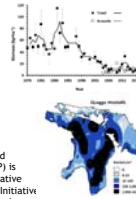
## Lake Huron Salmon and Trout Management Process



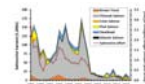
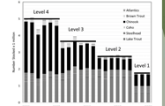
The State of Lake Huron Report (SOL) is completed every 5 years. The last report was 2018 and based on data from 2012-2017 and was used to set the current stocking policy (Level 2). The next report will be in 2023 based on data from 2018-2022.



The Lakewide Action and Management Plan (LAMP) is informed by the Cooperative Science and Monitoring Initiative (CSMI) under the Science Annex to the 2012 Great Lakes Water Quality Agreement to coordinate science and monitoring activities in one of the five Great Lakes each year, on a rotating basis, to generate data and information for management agencies.



Harvest, SOL and CSMI will provide information on food web production, prey fish biomass, and other indicators of the overall predator-prey balance.



Year	Superior	Huron	Ontario	Erie	Michigan
2016	CSMI	LAMP	Priorities	SOL	
2017	CSMI	LAMP	Priorities	SOL	
2018	SOL	Process	CSMI	LAMP	Priorities
2019	Priorities	SOL	SOL	CSMI	LAMP
2020	LAMP	Priorities	SOL	CSMI	LAMP
2021	CSMI	LAMP	Priorities	SOL	LAMP
2022	CSMI	LAMP	Priorities	SOL	LAMP
2023	SOL	Process	CSMI	LAMP	Priorities
2024	Priorities	SOL	SOL	CSMI	LAMP
2025	LAMP	Priorities	SOL	CSMI	LAMP
2026	CSMI	LAMP	Priorities	SOL	LAMP
2027	CSMI	LAMP	Priorities	SOL	LAMP
2028	SOL	Process	CSMI	LAMP	Priorities
2029	Priorities	SOL	SOL	CSMI	LAMP
2030	LAMP	Priorities	SOL	CSMI	LAMP
2031	CSMI	LAMP	Priorities	SOL	LAMP
2032	CSMI	LAMP	Priorities	SOL	LAMP

5-yr periods for each lake

### Timing of Framework Implementation

Priorities = Lake Comm. Priorities

LAMP = new Lakewide Mgt Plan

CSMI = CSMI field year

Process = CSMI & SOL Data Analyses

■ = Set Stocking Level

SOL = SOL Conference/Presentation

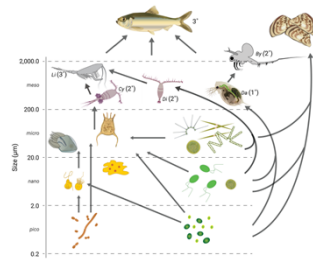


## Limitations of the Lake Huron Plan

- Lower trophic level understanding and predictions up the food web



Citation (online): Bousset, D.B., Curick, H.J., Madenjian, C.P., Rotherford, E.S., Vanderploeg, H.A., Barberon, R.P., Hunsaker-Mulvey, E., Padavan, S.A., Rensig, C.M., Clinehamer, R.M., and eight others. 2018. Are changes in lower trophic levels limiting prey-fish biomass and production in Lake Michigan? [online]. Available from: [www.afs.oregonstate.edu/2018-01.pdf](http://www.afs.oregonstate.edu/2018-01.pdf) [accessed 24 May 2018].



Illustrations by Kim Koser, Terey Sady, Jane Thomas, and Lucy Van Tuyn. Fisheries, Integration and Application Network, University of Maryland Center for Environmental Science (<http://sea.umd.edu/central/>)

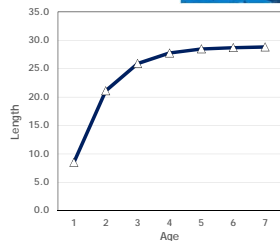
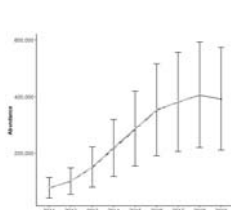


## Limitations of the Lake Huron Plan

- Lower trophic level understanding and predictions up the food web
- Biomass and production estimates for major trophic levels and species



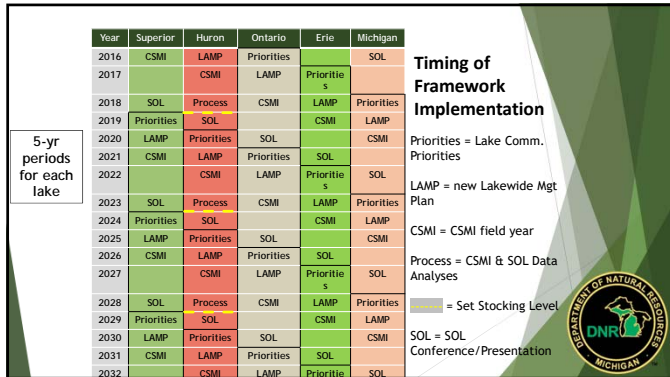
## Lake Huron Atlantic Salmon Population Assessment: Matt Zink's Project



## Limitations of the Lake Huron Plan


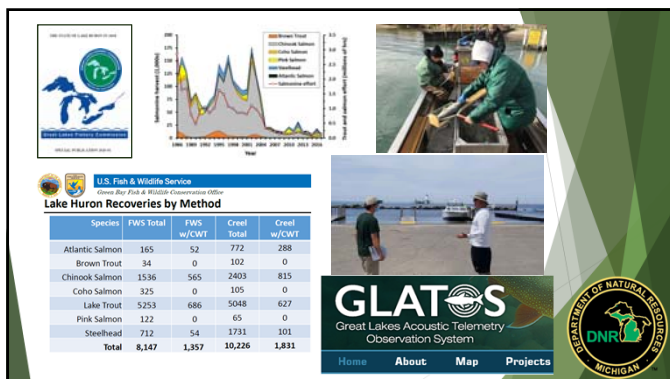
- Lower trophic level understanding and predictions up the food web
- Biomass and production estimates for major trophic levels and species
- Timeframe for integrating SOL, CSMI, and LAMP evaluations into models and analyses to impact management decisions






### Limitations of the Lake Huron Plan



- Lower trophic level understanding and predictions up the food web
- Biomass and production estimates for major trophic levels and species
- Timeframe for integrating SOL, CSMI, and LAMP evaluations into models and analyses to impact management decisions
- Evaluating management actions, in an adaptive management framework, continues to be a challenge for management agencies

Coho Salmon stomach: 20 Bloater Chubs and 1 smelt



Lake Trout: 1 duck

## Limitations of the Lake Huron Plan

- ▶ Lower trophic level understanding and predictions up the food web
- ▶ Biomass and production estimates for major trophic levels and species
- ▶ Timeframe for integrating SOL, CSMI, and LAMP evaluations into models and analyses to impact management decisions
- ▶ Evaluating management actions, in an adaptive management framework, continues to be a challenge for management agencies
- ▶ Strategy is based on top predator interactions in the food web without a clear link to lower trophic level predictions



## Questions?

Randy Claramunt - [claramuntr@michigan.gov](mailto:claramuntr@michigan.gov)  
231-622-3820



## Investigating Food Webs: State of Knowledge and Investigative Approaches

Aaron Fisk  
School of the Environment, University of Windsor

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## Stable isotopes - 101

- Most elements exist as multiple stable isotopes – 1 or more additional neutron (same # of protons and electrons)
  - Isotopes of an element form the same chemical bonds but extra mass of neutron influences bonding strength (i.e., stronger bonds – longer to break) and movement in the environment (i.e., slower movements)
- Stable isotopes of the same element (e.g.,  $^{15}\text{N}$  and  $^{14}\text{N}$ ) have different abiotic and biotic process kinetics – resulting in **predictable** changes in the relative amounts of the stable isotopes between pools in the environment (e.g.,  $\delta^{15}\text{N}_{\text{predator}} > \delta^{15}\text{N}_{\text{prey}}$ )

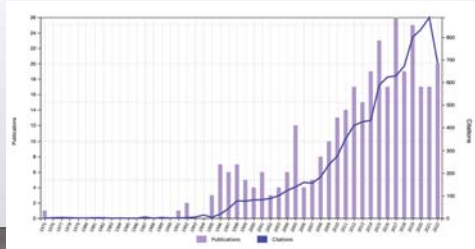
$$\delta^{15}\text{N} = \left[ \left( \frac{^{15}\text{N}}{^{15}\text{N} + ^{14}\text{N}} \right)_{\text{sample}} / \left( \frac{^{15}\text{N}}{^{15}\text{N} + ^{14}\text{N}} \right)_{\text{standard}} - 1 \right] \times 1000$$

-parts per thousands or per mil - symbol ‰



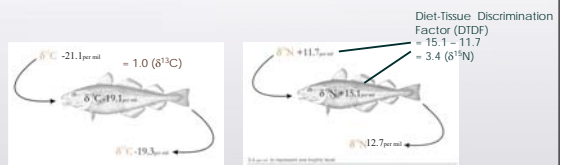
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Web of Science search: "Stable isotope" AND ("lake michigan" OR "lake erie" or "lake huron" or "lake ontario" or "lake superior")



2

## Stable isotopes - 101



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## Stable isotopes in food web ecology

### Pros

- Overcomes some / many limitations of stomach content analysis (SCA)
- Habitat/carbon sources
- Time integrated assessment
- Multi-tissue – multiple integration times
- Otoliths/spines – life-time assessment
- Simple to collect, analyze and archive
- Affordable
- Non-lethal

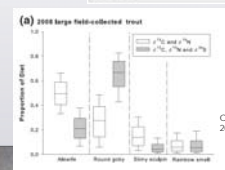
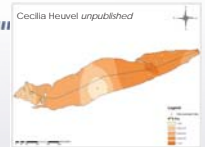
### Cons

- Small samples difficult for analysis (lower trophic levels)
- Uncertainties about DTDFs
- Variation in turnover between species / taxa causes disconnections
- Temporal and spatial variation – especially lower trophic levels
- Prey/sources can have similar values – confounds diet assessment

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## Sulfur ( $\delta^{34}\text{S}$ )

- Tracer of marine vs freshwater / terrestrial resource use
- Processes and distribution in freshwater ecosystems poorly understood – but does provide insights into trophic pathways likely linked to sediment processes
- DTDFs – 0

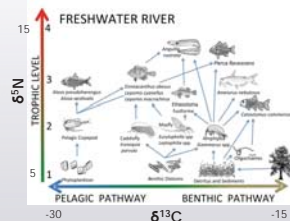


Colborne et al. 2016. JGLR

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## Nitrogen ( $\delta^{15}\text{N}$ ) and Carbon ( $\delta^{13}\text{C}$ )

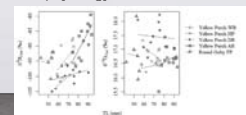
- $\delta^{15}\text{N}$  tracer of relative trophic position/level (DTDF = 3.4 in FW) but also a tracer of nitrogenous inputs (e.g., fertilizers)
- $\delta^{13}\text{C}$  tracer of carbon source/habitat use but also tracer of trophic level
- %C, %N and C:N indicators of lipid and chitin levels



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## Oxygen ( $\delta^{18}\text{O}$ ) and Hydrogen ( $\delta^2\text{H}$ )

- $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  used for studies of migratory origin
- Large differences between  $\delta^2\text{H}$  between terrestrial and aquatic systems (allochthonous vs autochthonous)
- $\delta^2\text{H}$  may serve as a trophic marker
- Relative coupling of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  may contribute insights on diet and physiology



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## Isotopic baseline variation

Annie Scofield  
US EPA GLNPO, Life Scientist  
Scofield.Annie@epa.gov

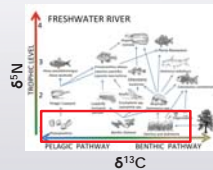


Baseline isotopes of primary producers are not static (even within taxa)

$\delta^{13}\text{C}$ : Driven by concentration of aqueous carbon dioxide ( $\text{CO}_2\text{aq}$ )  
→ Primary producers  $^{13}\text{C}$ -enriched in productive, warm waters

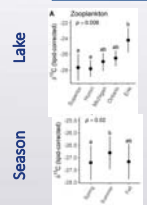
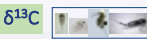
$\delta^{15}\text{N}$ : Largely driven by differences in nitrogen sources  
• Biogeochemical processes  
• Anthropogenic sources of nitrogen: fertilizers  
→ Difficult to predict nitrogen isotopic ratios across systems

Because of this variation, cross-system studies can be very difficult



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## $\delta^{13}\text{C}$



### $\delta^{13}\text{C}$ Key Results

- Consistent with trophic state
- Consistent with seasonal changes to productivity
- Smelt have variable diet (across lakes & seasons)

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## Cross-lake comparisons: study organisms

"Baseline" Organisms: Primary Consumers

Zooplankton



n = 899

Benthic Invertebrates



n = 254

Fishes (with different feeding ecology)

Rainbow Smelt (*Osmerus mordax*)

Zooplankton, Mysids, benthos, larval fish



n = 1279

Lake Trout (*Salvelinus namaycush*)

Piscivore, diverse and variable diet

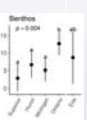
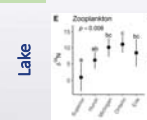


n = 1006

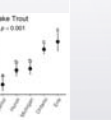
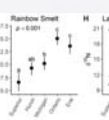
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## $\delta^{15}\text{N}$

### Invertebrates



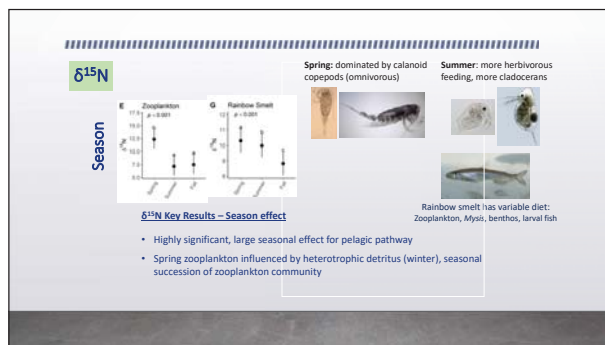
### Fishes



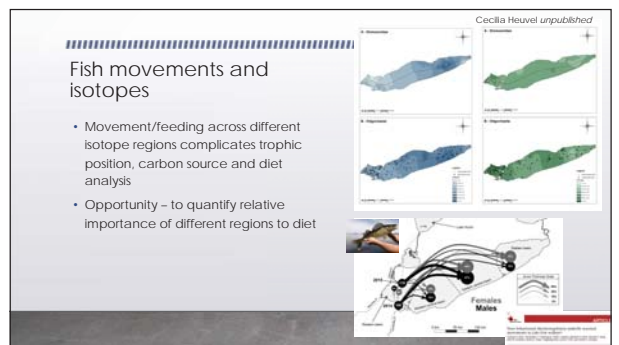
### $\delta^{15}\text{N}$ Key Results – Lake effect

- Consistent with trophic state (except Erie – cyanobacteria, fertilizers)
- Benthos potentially confounded by different taxa, sampling depths
- Fishes also show consistent gradient from Superior → Erie

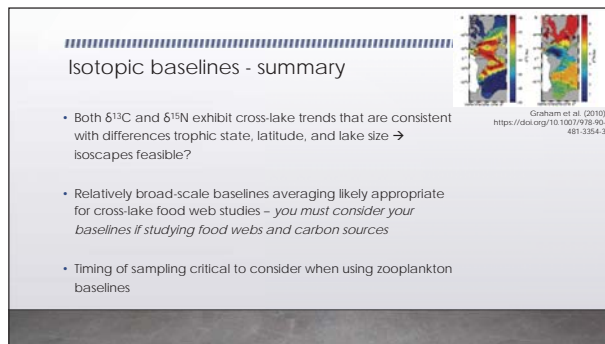
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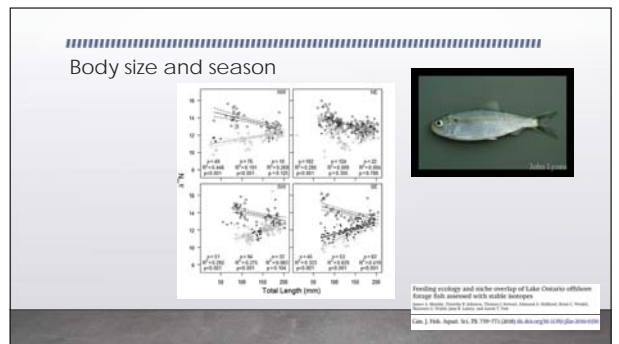
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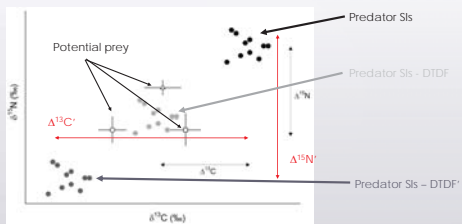


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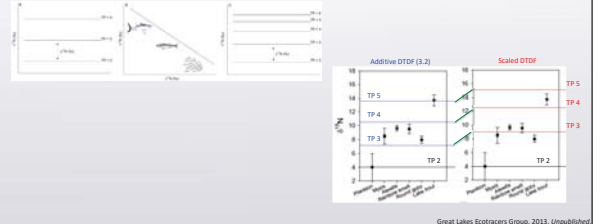
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## Diet tissue discrimination factors (DTDFs)



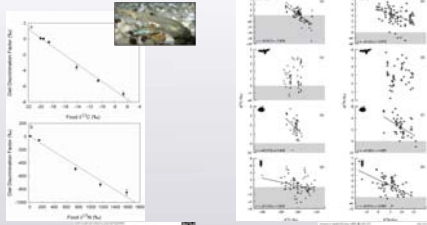
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## Scaling DTDFs



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## Scaling DTDFs



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## Scaling DTDFs

- Scaled DTDFs were generally constant with SCA and were higher and greater range/variability than constant DTDF
- Scaled DTDFs not as influenced by baseline species chosen nor carbon sources
- Scaled suggested a more complex trophic structuring of the Detroit River food webs



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## Estimating diet – Lake Ontario Lake trout

Table 2. Stable isotope mixing model (MixSIAR) diet predictions for 2008 collected Lake Ontario lake trout length classes. Estimates represent per cent diet contribution obtained using MixSIAR.

Lake trout length class (mm)	Alewife	Round goby	Rainbow smelt	Slimy sculpin	Myxodiplosis
290-349	40.6 (36.3-45.0)	37.8 (21.4-54.1)	8.9 (0.0-25.2)	9.5 (0.11-21.5)	0.09 (0.01-0.37)
350-449	38.7 (34.5-39.5)	43.8 (31.5-45.2)	6.4 (0.0-19.4)	6.0 (0.0-16.1)	0.8 (0.01-3.3)
450-549	38.4 (4.1-41.1)	51.7 (28.1-71.5)	7.3 (0.0-25.4)	5.8 (0.5-18.5)	2.2 (0.3-8.2)
550-649	46.3 (24.9-58.4)	37 (26.7-44.7)	7.8 (0.0-18.4)	7.7 (0.1-14.7)	0.4 (0.1-1.6)
650-749	53.6 (44.4-62.0)	36.2 (30.5-42.1)	5.7 (0.0-12.5)	3.0 (0.3-7.9)	0.2 (0.0-0.9)
750-849	55.5 (44.4-67.5)	38.4 (28.7-47.0)	2.9 (0.0-8.5)	1.7 (0.01-5.0)	0.06 (0.0-2.0)
Contribution to all size classes	50.2 (42.9-57.1)	41.3 (37.0-46.0)	7.8 (0.4-17.7)	4.2 (0.0-6.8)	0.4 (0.1-1.3)

Median values are presented with the 5th and 95th per cent credibility intervals included in the parentheses.



Stomach contents: 2008

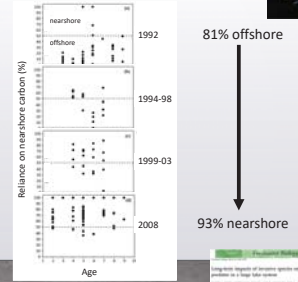
Sensitive to DTDf, prey chosen...

Long-term impacts of invasive species on a native top predator in a large lake system

Long-term impacts of invasive species on a native top predator in a large lake system

## Estimating carbon sources through time – Lake Ontario Lake trout

Sensitive to DTDf, prey chosen...



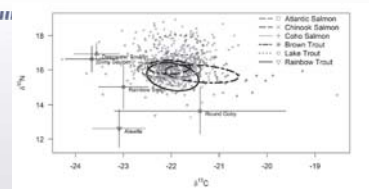
81% offshore  
93% nearshore

## Estimating diet for lake Ontario salmonids

Sensitive to DTDf, prey chosen...

Species	Prey item	Dietary contribution	Estimated prey proportion
Atlantic salmon (Dietary n = 61; Sample n = 41)	Alewife	16.4	0.08 (0.00, 0.16)
	Round goby	16.4	0.08 (0.00, 0.16)
	Rainbow smelt	16.4	0.08 (0.00, 0.16)
	Slimy sculpin	16.4	0.08 (0.00, 0.16)
Chinook salmon (Dietary n = 40; Sample n = 28)	Alewife	16.4	0.08 (0.00, 0.16)
	Round goby	16.4	0.08 (0.00, 0.16)
	Rainbow smelt	16.4	0.08 (0.00, 0.16)
	Slimy sculpin	16.4	0.08 (0.00, 0.16)
Coho salmon (Dietary n = 71; Sample n = 45)	Alewife	16.4	0.08 (0.00, 0.16)
	Round goby	16.4	0.08 (0.00, 0.16)
	Rainbow smelt	16.4	0.08 (0.00, 0.16)
	Slimy sculpin	16.4	0.08 (0.00, 0.16)
Brook trout (Dietary n = 27; Sample n = 47)	Alewife	16.4	0.08 (0.00, 0.16)
	Round goby	16.4	0.08 (0.00, 0.16)
	Rainbow smelt	16.4	0.08 (0.00, 0.16)
	Slimy sculpin	16.4	0.08 (0.00, 0.16)
Lake trout (Dietary n = 127; Sample n = 107)	Alewife	16.4	0.08 (0.00, 0.16)
	Round goby	16.4	0.08 (0.00, 0.16)
	Rainbow smelt	16.4	0.08 (0.00, 0.16)
	Slimy sculpin	16.4	0.08 (0.00, 0.16)
Rainbow trout (Dietary n = 21; Sample n = 128)	Alewife	16.4	0.08 (0.00, 0.16)
	Round goby	16.4	0.08 (0.00, 0.16)
	Rainbow smelt	16.4	0.08 (0.00, 0.16)
	Slimy sculpin	16.4	0.08 (0.00, 0.16)

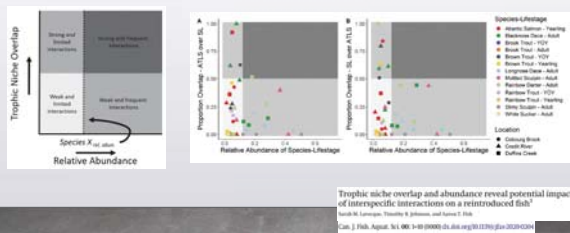
## Isotopic niches



Species	Atlantic salmon	Chinook salmon	Coho salmon	Brook trout	Lake trout	Rainbow trout	δ15N (‰)	Trophic position (TP)
Atlantic salmon	-	75	35	0	50	1.0	4.0	
Chinook salmon	51	-	10	17	0	0.0	4.0	
Coho salmon	61	81	-	18	0	0.0	4.0	
Brook trout	42	50	47	-	0	1.2	3.0	
Lake trout	0	0	0	0	-	0.0	4.4	
Rainbow trout	61	74	62	17	0	1.8	3.8	

Isotopic niches of Lake Ontario salmonids

## Combining isotopes and abundance



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## Moving forward with stable isotopes in food web ecology

- Use of  $\delta^{34}\text{S}$ ,  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ , developing isoscapes
- Methods for analyzing smaller samples
- Need a better understanding of drivers of stable isotope dynamics in lower trophic levels
- More lab studies of DTDFs and turnover rates
- Combining stable isotopes with acoustic telemetry and biomass

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## Other things to consider with stable isotopes in food web ecology

- Lipids have with more negative  $\delta^{13}\text{C}$  because they are synthesized by the organism, need to extract or correct using models when C:N > -3.5
- Exoskeletons have more negative  $\delta^{13}\text{C}$  (zooplankton, benthic invertebrate), need to acid treat when C:N > -3.5
- Tissue turnover times effect how long isotopes reflect feeding, in general: muscle (6-12 months) > liver (1-2 months) > blood plasma (2-3 days)
- Challenges to measuring stable isotopes in small organisms (algae, zooplankton)
- Compound specific stable isotope analysis (fatty acids and amino acids) can provide very specific information – analytically challenging and expensive

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## Acknowledgements

- Tim Johnson, Gord Paterson, Scott Rush, Doug Haffner, Scott Colborne, Sarah Larocque, James Mumby, Don Uzarski, Annie Scofield, Tom Stewart
- Funding: NSERC, CRC, GLFC, OMNRF

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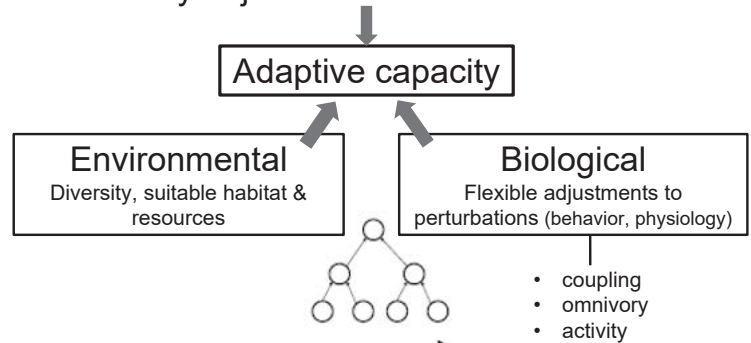
## The adaptive capacity of lake food webs

Bailey McMeans<sup>1</sup>, Kevin McCann<sup>2</sup>

<sup>1</sup>University of Toronto, <sup>2</sup>University of Guelph



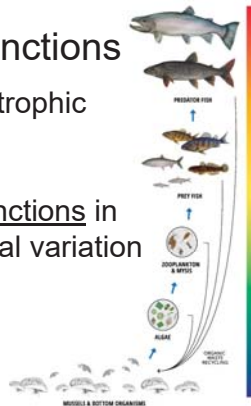
## What structures within complex systems flexibly adjust and sustain functions?



## Food webs serve key functions

- energy is transferred through trophic interactions, creates structure
- are not static
- dynamic structures sustain functions in the face of spatial and temporal variation

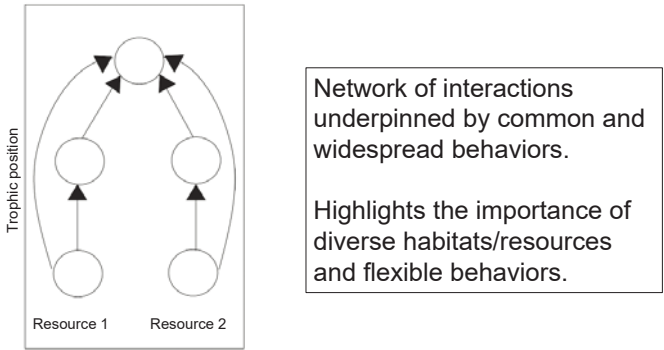
**flexible behavior**



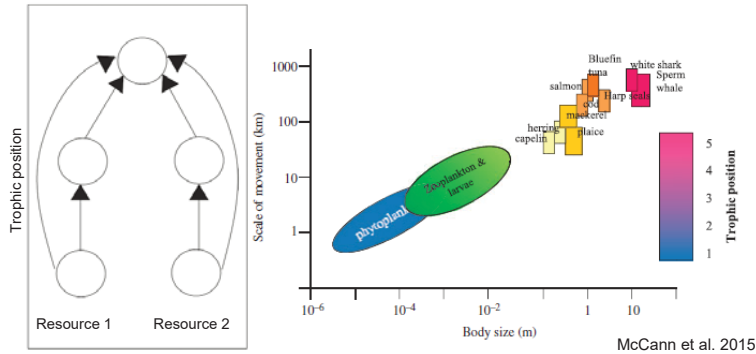
Credit: T. Stewart et al. 2018

## Dynamic food web structures, behavior & adaptive capacity

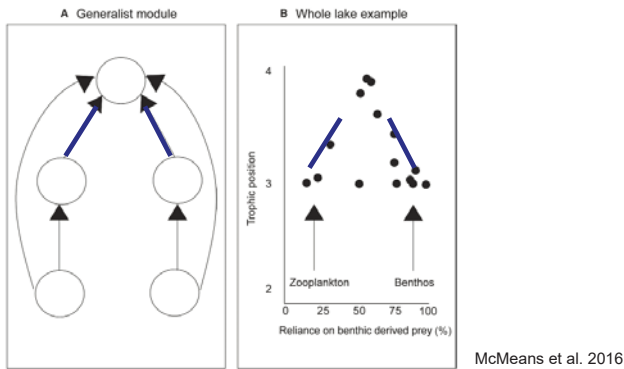
Simple but useful module within real food webs



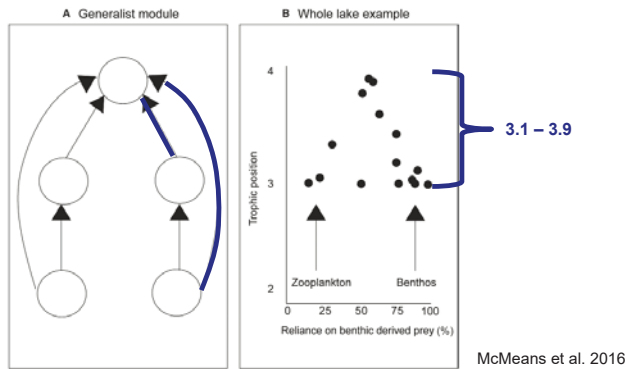
Body size and mobility increase with trophic position



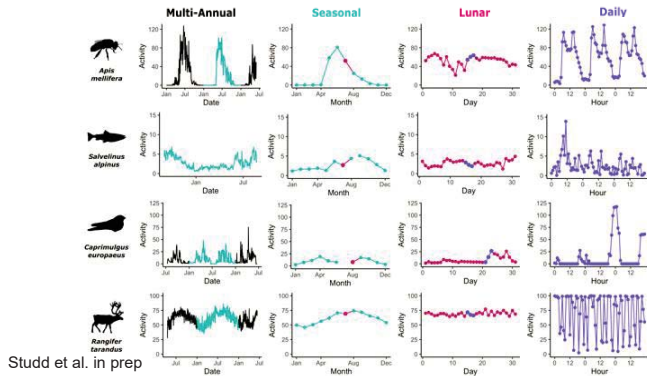
Real food webs are replete with coupling



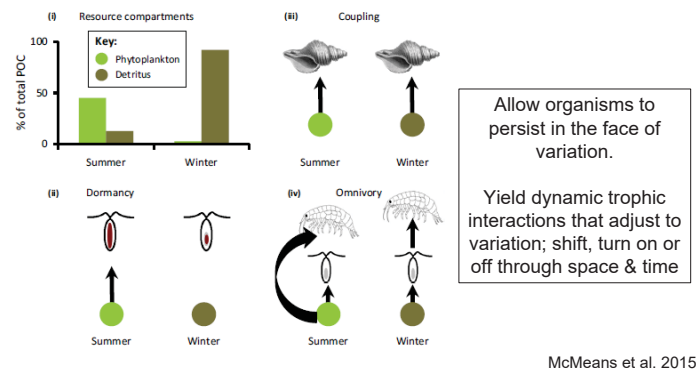
Real food webs are replete with coupling and omnivory



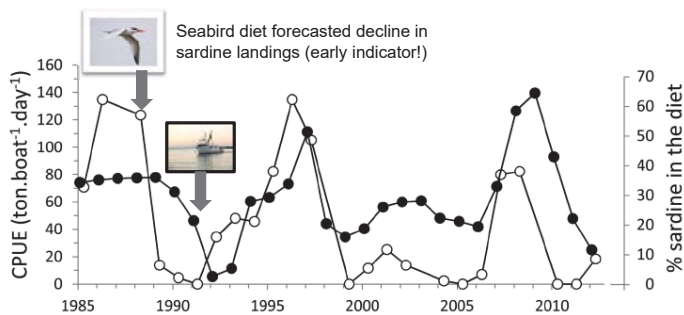
## All organisms vary in their activity



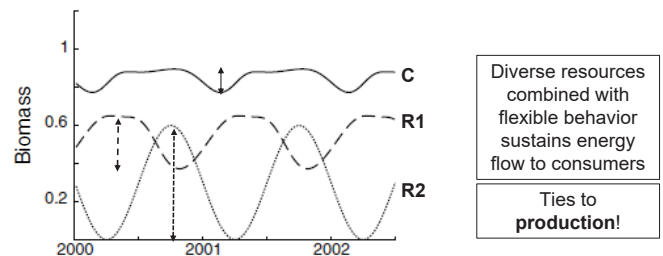
## 1. Behaviors are flexible and responsive



## 2. Behaviors are rapid



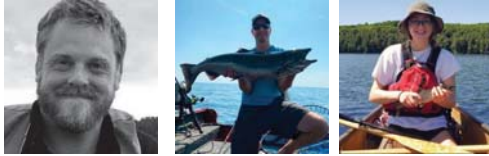
## 3. Flexible behaviors are important for stability



## Empirical case study

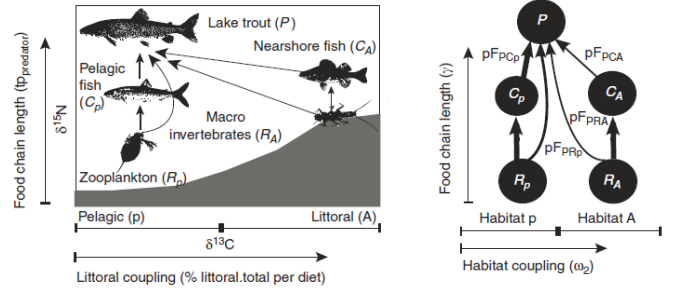


Tyler Tunney, Matthew Guzzo, Emma Bloomfield



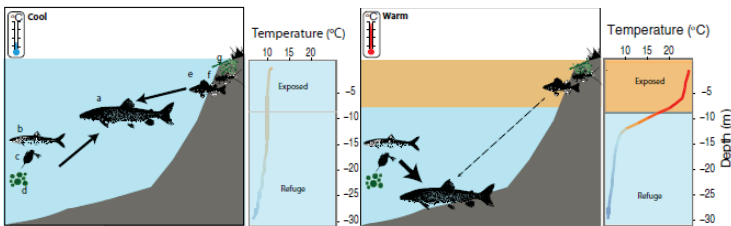
Liset Cruz-Font, Jake Vander Zanden, Paul Blanchfield, Mike Rennie, and many others!

## Lake trout food web



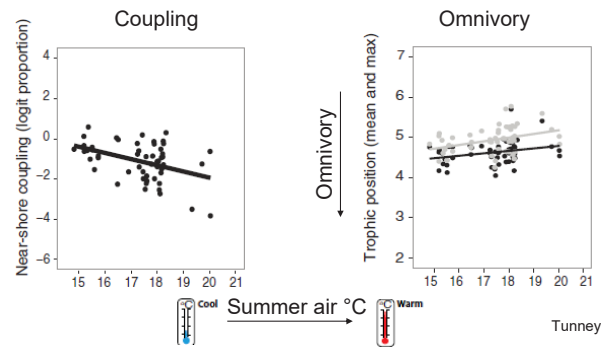
Tunney et al. 2012

## Spatial temperature gradient



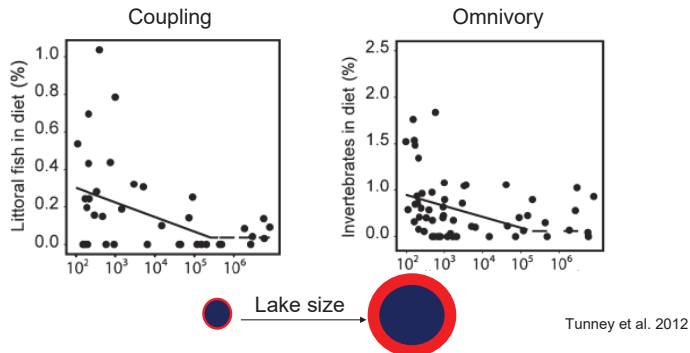
Tunney et al. 2014

## Coupling and omnivory increase in cooler lakes

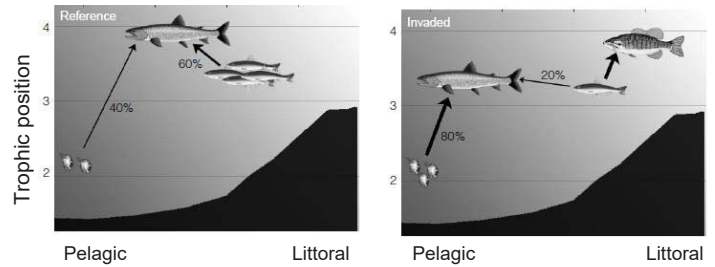


Tunney et al. 2014

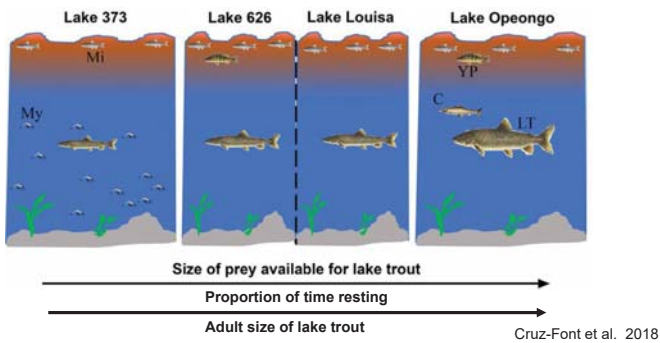
## Coupling and omnivory increase in smaller lakes



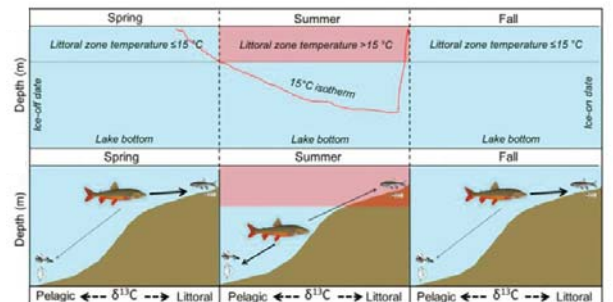
## Coupling decreases in lakes with invasive competitors



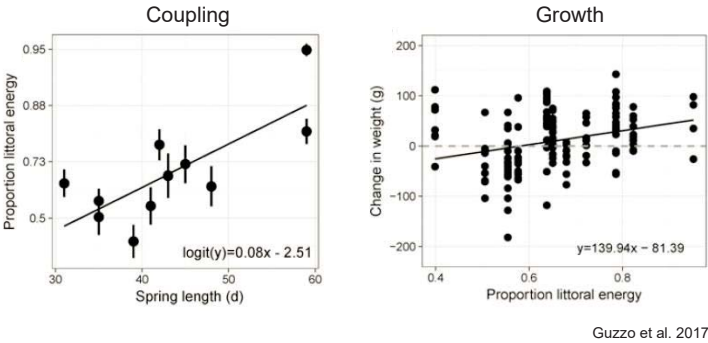
## Activity increases in lakes with smaller prey



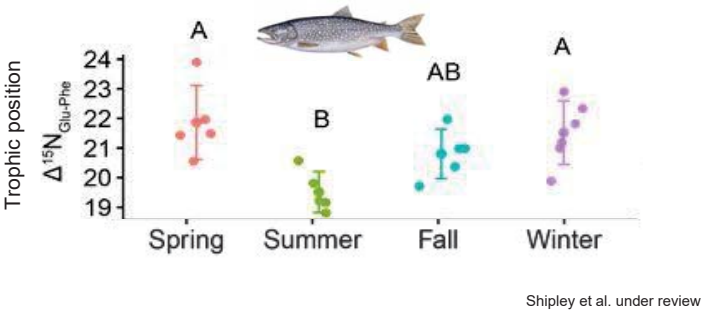
## Seasonal temperature gradient



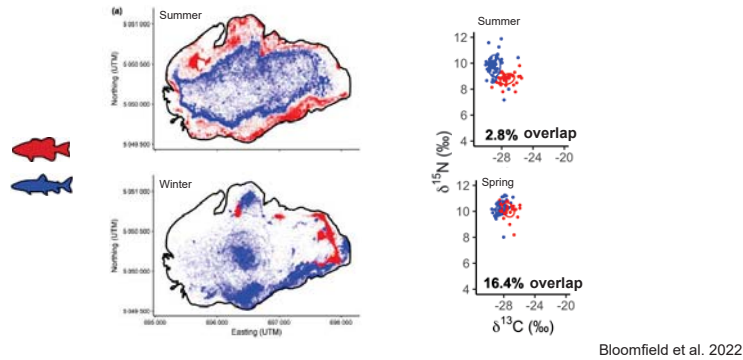
Coupling increases when cooler seasons are long



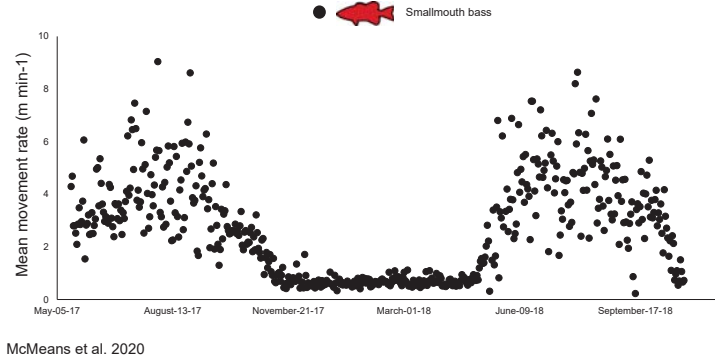
Omnivory increases in warmer seasons



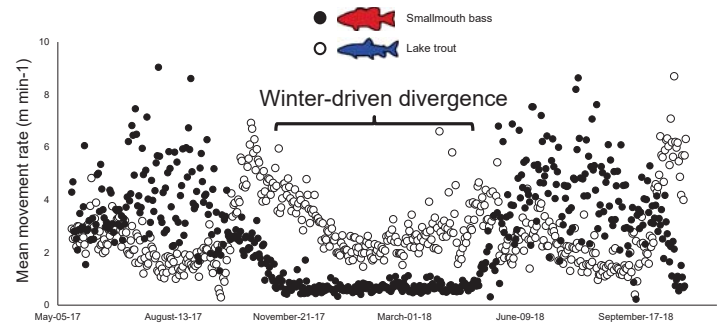
Overlap with competitors increases in cooler seasons



Competitors decrease activity during cooler seasons

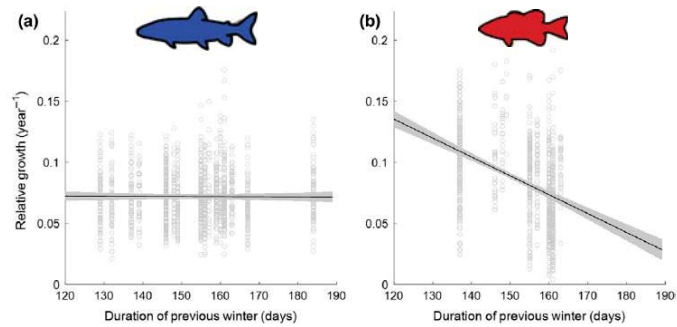


Competitors decrease activity during cooler seasons



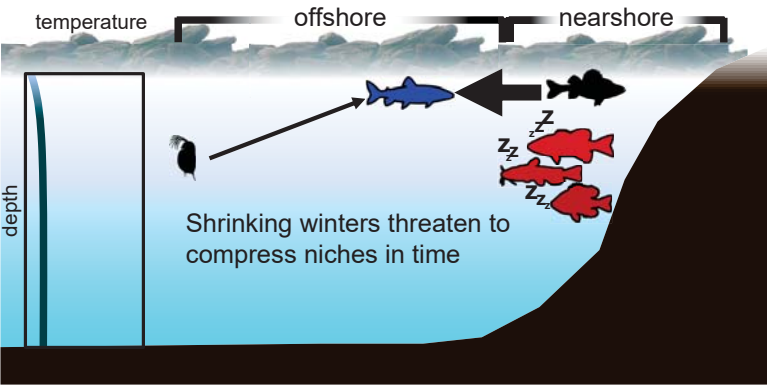
McMeans et al. 2020

Consequences for growth



McMeans et al. 2020

Consequences for climate warming



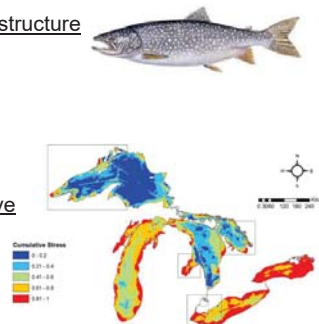
Summary

Common behaviors structure dynamic food webs:

- coupling
- omnivory
- activity

Contribute to adaptive capacity:

- flexible
- rapid
- stabilizing




## Summary

Common behaviors structure

REVIEW WILEY Freshwater Biology

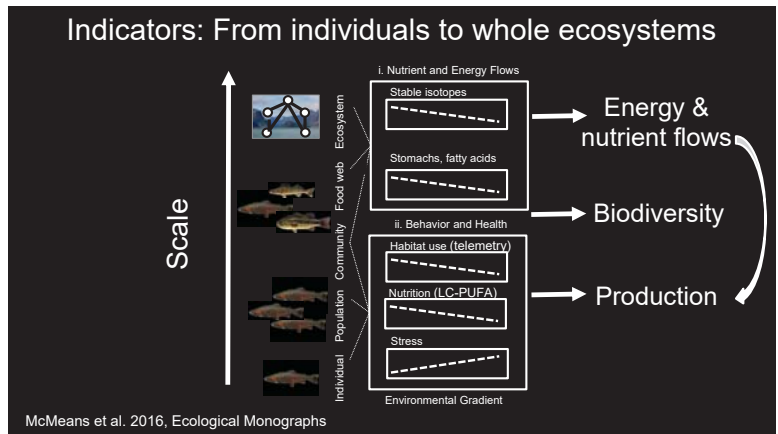
### Food-web structure and ecosystem function in the Laurentian Great Lakes—Toward a conceptual model

Jessica T. Ives<sup>1</sup> | Bailey C. McMeans<sup>2</sup> | Kevin S. McCann<sup>3</sup> | Aaron T. Fisk<sup>4</sup> | Timothy B. Johnson<sup>5</sup> | David B. Bunnell<sup>6</sup> | Kenneth T. Frank<sup>7</sup> | Andrew M. Muir<sup>1</sup> 

flexible

- rapid
- stabilizing

Allan et al. 2013



## Workshop: Towards Multi-scale Management of Great Lakes Ecosystems in a Changing World

### Participants:

Great Lakes managers and scientists

### Goals:

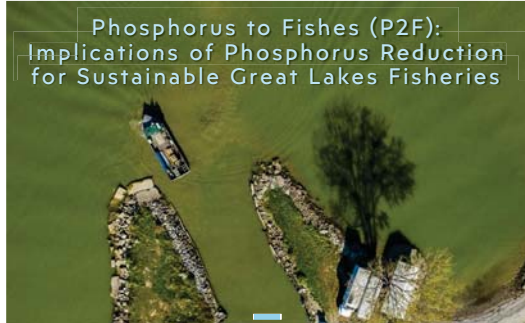
Synthesize efforts, apply biotracers to management? Incorporate relatively simple food web modules into models?

### Interested?

bailey.mcmeans@utoronto.ca  
ksmccann@uoguelph.ca



## Phosphorus to Fishes (P2F): Implications of Phosphorus Reduction for Sustainable Great Lakes Fisheries



Marten Koops, Monir Hossain, Hongyan Zhang, Ed Rutherford, Doran Mason, George Arhonditsis, Lars Rudstam, Randy Jackson, William Fetzer, Cindy Chu, Dak de Kerckhove, Travis Hartman

## Core Project Team Affiliations

Environment and Fisheries of Ontario  
Canada



Eureka Aquatic Research, LLC



Marten, Monir,  
Cindy

Ed, Doran

Hongyan

George



UNIVERSITY OF WYOMING



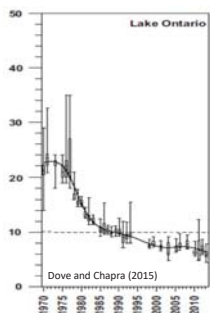
Lars, Randy

Willie

Dak

Travis

## Rationale



- Eutrophication was a major issue when the original Great Lakes Water Quality Agreement (GLWQA) was signed
- Efforts to manage TP have been generally successful
- TP targets have been met or exceeded in many areas
- Most of the Great Lakes are now experiencing an oligotrophication

## Rationale

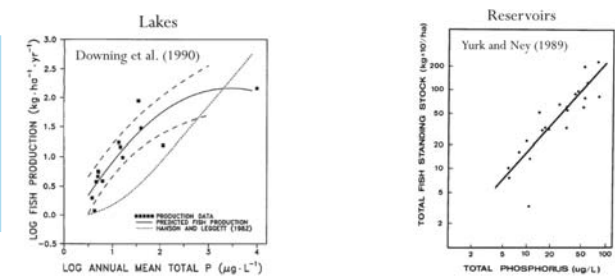


- In some locations, eutrophication and algal blooms have again been an issue
- Especially Lake Erie and some other nearshore areas
- The renewed GLWQA lowered TP targets for Lake Erie; committed to reviewing TP targets for the other lakes
- It is well established that fish production is related to ecosystem productivity
- In theory, these relationships can help to inform management of the consequences of TP reductions on fish and fisheries

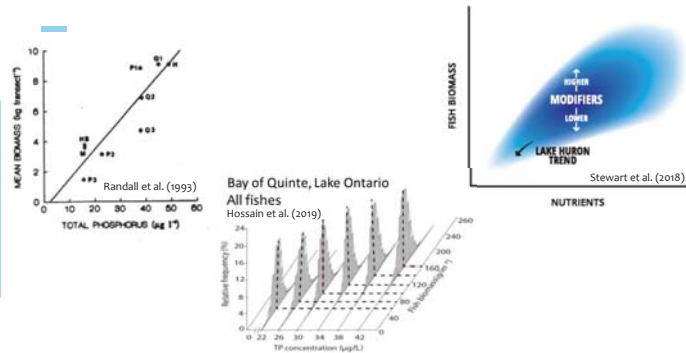
## Examples of Published TP Relationships

Dependent variable	Independent variable	r <sup>2</sup>	Location (N)	Source
<b>Fish and primary production</b>				
Fish yield	Phytoplankton standing stock	0.84	Natural Lakes, Northern-hemispheres (19)	Oglesby (1977)
Sport fish yield	Chlorophyll a	0.83	U.S. lakes & reservoirs (25)	Jones & Hoyer (1982)
<b>Fish and phosphorus</b>				
Fish yield	Total Phosphorus	0.84	North-temperate lakes (43)	Hanson & Leggett (1982)
Fish standing stock	Total Phosphorus	0.84	Southern Appalachian reservoirs (21)	Ney et. al., (1990)
<b>Phytoplankton and phosphorus</b>				
Phytoplankton	Phosphorus	0.97	North America (30)	Dillon and Rigler (1974)
Phytoplankton	Phosphorus	0.88	Worldwide [38°S-75°N] (81)	Schindler (1978)

## Fish Production and Biomass as a Function of Total Phosphorus



## Within the Great Lakes too

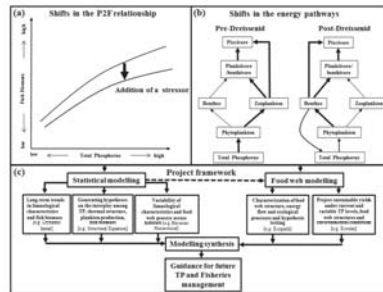


## Objectives

- Examine the phosphorus to fishes (P2F) relationship across the Great Lakes basin.
- Relate nutrient reduction scenarios to fish biomass and harvest levels.
- Compare the P2F relationships to examine how energy dynamics may have changed.
- Evaluate how current and future TP reductions may affect sustainable biomass and yields.
- Project sustainable yields given TP, food web structures and environmental conditions.

## Project Framework

- Compile data.
- Statistical analyses to examine the P2F relationships.
- Ecopath with Ecosim models to explore scenarios.
- Modelling synthesis.



## P2F Fish Data Contributors

### GILLNET SURVEYS

Lake	Site	Agency	Collaborator(s)
Superior	Ontario waters	OMNR	Eric Bengtson
	Michigan waters	MDNR	Dray D. Carl
	Wisconsin waters	WDNR	Cory Goldsworthy
	Minnesota waters	MNDNR	Shawn Star
Huron	Michigan waters	MDNR	Ji He
	Les Cheneaux Islands	MDNR	David Fielder
	Saginaw Bay	MDNR	David Fielder
	Georgian Bay	OMNR	Chris Davis
Michigan	Charlevoix	MDNR	Ben Turschak
	Bay de Noc	MDNR	Troy Zern
	Illinois waters	INHS	Scott Peterson
	Indiana waters	INDNR	Ben Dickinson
	Ontario waters	OMNR	Andy Cook, Paulette M. Peniston
	Long Point Bay	OMNR	Arthur Bonvall, Theresa Warbler
	Ohio waters	ODNR	Ann M. Gorman
	Pennsylvania waters	PFBC	Michael Husack
	New York waters	NYSDEC	Jason M. Robinson
	Michigan waters	MDNR	Todd Wells
Ontario	Oswego Lake	CBFS	Lars Rudstam
	Bay of Quinte	OMNR	Eric Brown
	Ontario waters	OMNR	Eric Brown
	New York waters	NYSDEC	Jessica Goretzke, Michael Conventry, Legard, Christopher

### TRAWL SURVEYS

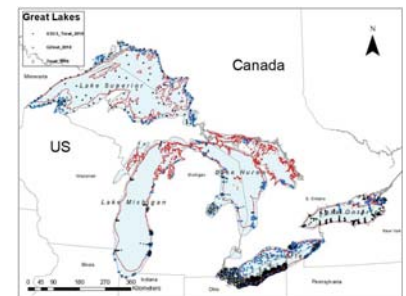
Lake	Site	Agency	Collaborator(s)
Superior	Main Lake	USGS	Mark Venzon
Huron	Saginaw Bay	MDNR	Andrew S. Briggs, David Fielder
	Main Basin	USGS	Tim O'Brien, Darryl W. Hondorp
Michigan	Bay de Noc	MDNR	Troy Zern
	Charlevoix	MDNR	Ben Turschak
	Indiana water	INDNR	Ben Dickinson
	Main Basin	USGS	David Burnell
	Central basin South	ODNR	Ann M. Gorman
	Western basin South	ODNR	Mark Dufner
	Ontario waters	OMNR	Andy Cook, Paulette M. Peniston
	Western basin North	OMNR	Andy Cook, Paulette M. Peniston
	Long Point Bay	OMNR	Arthur Bonvall, Theresa Warbler
	PA waters	PFBC	Michael Husack
	New York waters	NYSDEC	James Markham
	Main Lake	USGS	Richard Kraus
Ontario	Bay of Quinte	OMNR	Eric Brown
	Ontario waters	OMNR	Eric Brown
	Oswego Lake	CBFS	Lars Rudstam
	Main Lake	USGS	Brian Whited

## P2F Phosphorus Data Contributors

Agency	Contributor
ECCC	Alice Dove
ECCC	Violeta Richardson
USEPA	Anne Scofield
USEPA	Elizabeth Hinchey
USEPA	Eric Osantowski
USEPA	Kenneth Klewin
USEPA	Santina Wortman

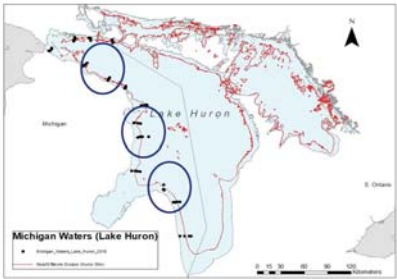
## Locations Of Compiled Fish Data

- 13 partner agencies:
  - CBFS, ECCC, InDNR, INHS, MDNR, MnDNR, NYSDEC, ODNR, OMNRF, PFBC, USEPA, USGS, WDNR
- 33 collaborators
- 22 gill net surveys
- 17 trawl surveys
- TP data from EPA, GLAHF, and ECCC



# Statistical Models

- Gillnet survey data from Michigan waters (MDNR)
- Three nearshore sites:
  - Hammond Bay
  - Thunder Bay
  - Port Austin
- TP data from USEPA and ECCC
- Three simple regression models



# Regression Models

## Model 1 (M1): simple P2F model

$$\ln[\text{Fish } B]_t = \alpha_{0(M)} + \alpha_1 \text{std}[\text{TP}]_t$$

error ~ G(0.001, 0.001)  
k = 1 for ECCC and 2 for USEPA TP data

## Model 2 (M2): test the effect of TP data source on P2F relationship

$$\ln[\text{Fish } B]_t = \alpha_{0(M)} + \alpha_{1(M)} \text{std}[\text{TP}]_t$$

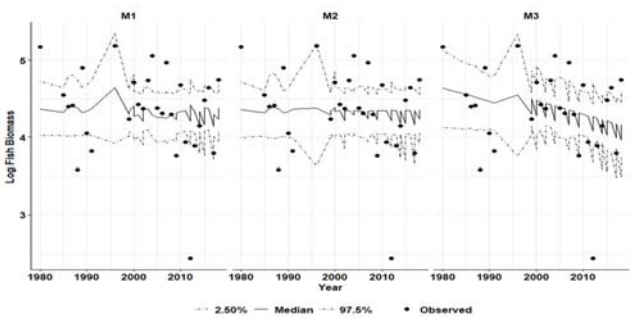
error ~ G(0.001, 0.001)  
k = 1 for ECCC and 2 for USEPA TP data

## Model 3 (M3): test the effect of time on the prediction of fish biomass

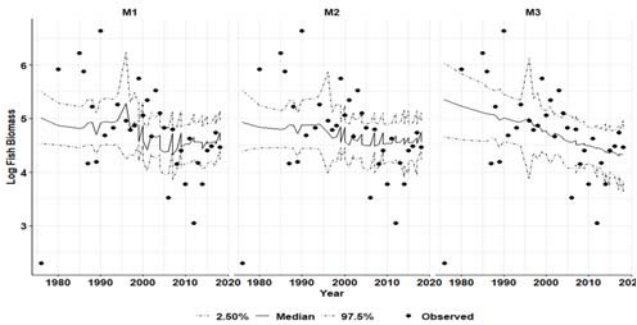
$$\ln[\text{Fish } B]_t = \alpha_{0(M)} + \alpha_1 \text{std}[\text{TP}]_t + \alpha_2(t - t_0)$$

error ~ G(0.001, 0.001)  
k = 1 for ECCC and 2 for USEPA TP data

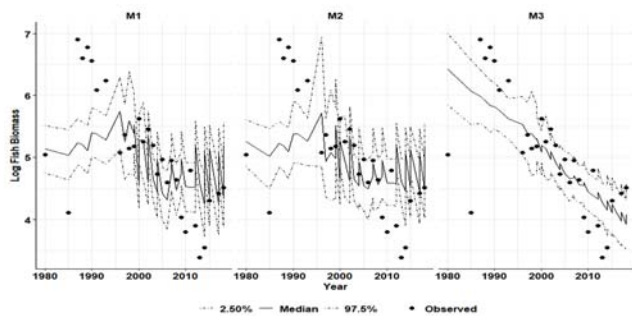
## Preliminary Results: Hammond Bay, Nearshore Lake Huron



## Preliminary Results: Thunder Bay, Nearshore Lake Huron



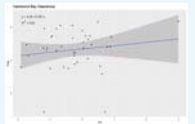
# Preliminary Results: Port Austin, Nearshore Lake Huron



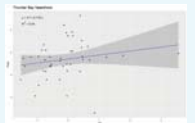
# Preliminary Results: Nearshore Lake Huron

- Source of the TP data (EPA vs. ECCC) is not determining the P2F relationship
- Weak relationships between fish biomass and TP
- TP alone cannot explain the declines in fish biomass
- The time parameter suggests additional drivers of fish biomass need to be explored

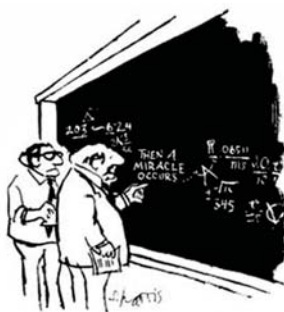
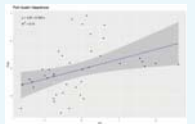
## Hammond Bay



## Thunder Bay

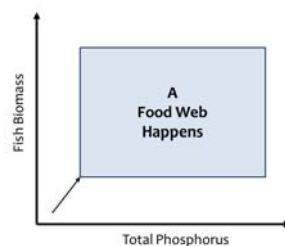


## Port Austin



"I think you should be more explicit here in step two."

## Ecosystem Models

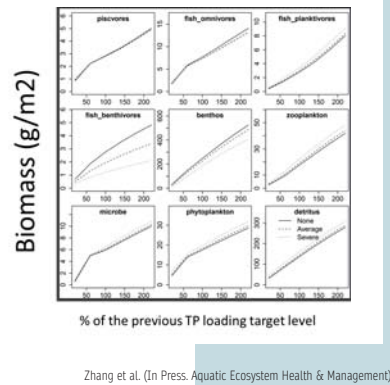


## Ecopath with Ecosim (EwE) Models

Lake	Trophic status	Dominant predators	Ecopath year	Ecosim years	Model Status
Lake Michigan (LM)	Oligotrophic	Salmonids	1994-1998	1994-2015	Rutherford et al. (2021)
Lake Huron (LH)	Oligotrophic	Salmonids	1981-1984	1984-2006	Kao et al. (2016)
Lake Erie (LE)	Mesotrophic	Percids, Trout	1999-2001	1999-2010	Zhang et al. (2016)
Lake Ontario (LO)	Mesotrophic	Percids, Salmonids	2003-2008	2005-2018	Developed
Muskegon Lake, LM (ML)	Eutrotrophic	Percids	2001-2006	2003-2010	Developed
Saginaw Bay, LH (SB)	Eutrotrophic	Percids	1988-1990	1990-2010	Kao et al. (2014)
Western Lake Erie (WLE)	Eutrotrophic	Percids	1999-2001	1999-2016	Developed
Central Lake Erie (CLE)	Mesotrophic	Percids	1996-1998	1996-2020	Zhang et al. (in press)

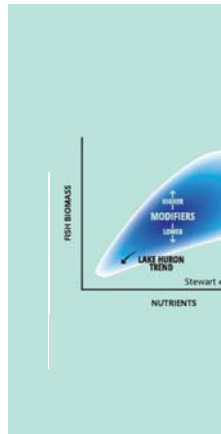
## Central Basin, Lake Erie

- Changing nutrients affects biomass of all model food web groups
- Some groups respond more strongly to nutrient changes than other groups
- Hypoxia has negative effects on some groups (e.g. benthos and benthivorous fishes) but had positive effects on some groups (e.g. plankton and planktivorous fishes)
- Nutrients have greater food web effects than hypoxia



## Next Steps

- Complete statistical analyses across Great Lakes sites
- Add stressors as potential drivers
- Statistical comparisons across sites
- Models synthesis



## Acknowledgements

- All the Great Lakes agencies who have invested in collecting both the fisheries and water quality data
- All the data contributors who have engaged in providing data and working with us on the data
- Great Lakes Fishery Commission for funding



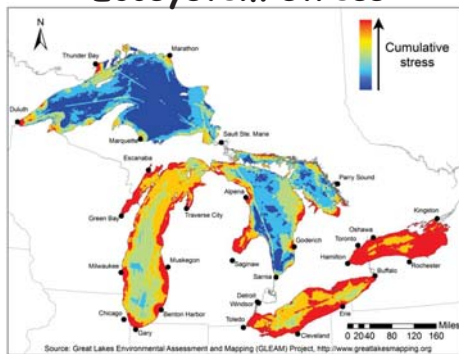
## Managing multiple objectives

Tim Johnson  
Glenora Fisheries Station

## An amazing resource

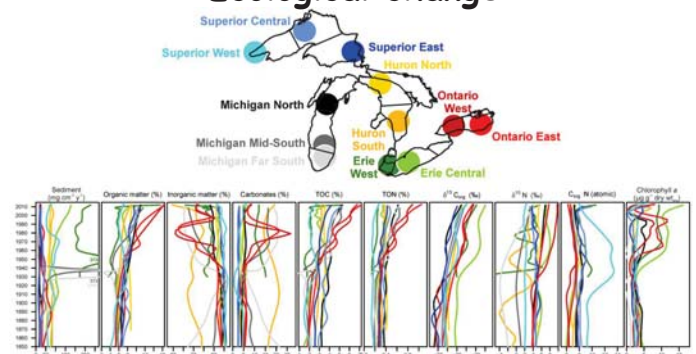


## Ecosystem stress



Allan et al. (2013) PNAS 110:32-377

## Ecological change



Reavie et al. 2021 J Paleolimnol 65: 299-314

# Great Lakes Governance

- Two countries (Canada and U.S.)
- 2 provinces & 8 states
- Dozens of First Nations and tribes
- Thousands of local governments



Ontario



- **Objective:** restore and maintain the chemical, physical, and biological integrity of the Great Lakes
- **Principles:** cooperate and collaborate; develop programs, practices and technology to better understand the Great Lakes basin ecosystem; eliminate or reduce threats to the Great Lakes



- **Objective:** promote science and establish working relationships among the players to improve and perpetuate the fishery and combat sea lampreys
- **Principles:** consensus; accountability; information sharing; and ecosystem-based management

Ontario



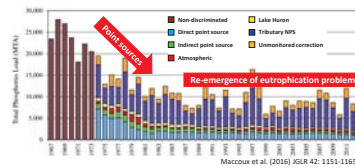
- **Objective:** restore and maintain the chemical, physical, and biological integrity of the Great Lakes

- **Principles:** cooperate and collaborate; develop programs, practices and technology to better understand the Great Lakes basin ecosystem; eliminate or reduce threats to the Great Lakes

## Water Quality



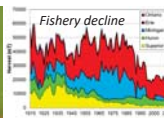
- **Objective:** promote science and establish working relationships among the players to improve and perpetuate the fishery and combat sea lampreys
- **Principles:** consensus; accountability; information sharing; and ecosystem-based management



Great progress !!



Swimmable, drinkable, fishable!



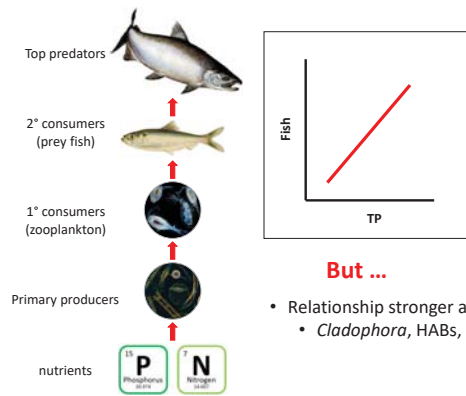
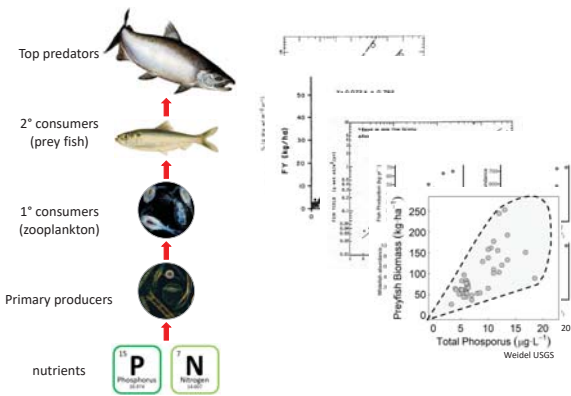
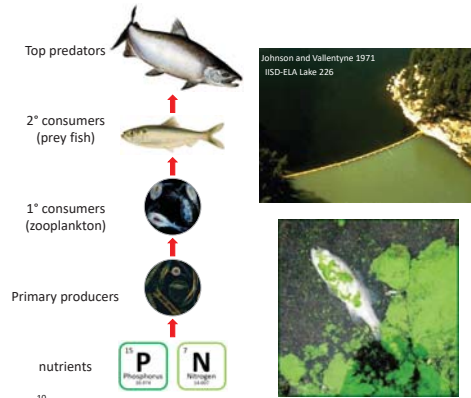
- Revised GLWQA (2012) – revisit P loadings and targets
- Concern by fishery managers P reduction would further impact fisheries

Ontario

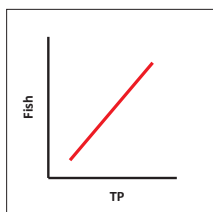
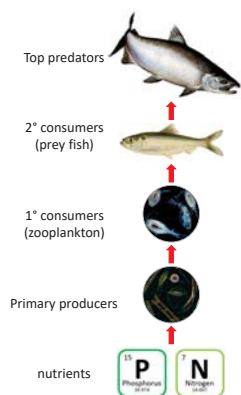
Ontario



Wait, this is a food web workshop - I should probably talk about food webs!

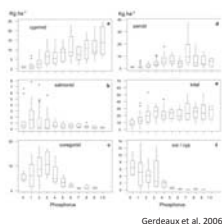


- But ...**
- Relationship stronger at lower trophic levels
  - Cladophora*, HABs, hypoxia

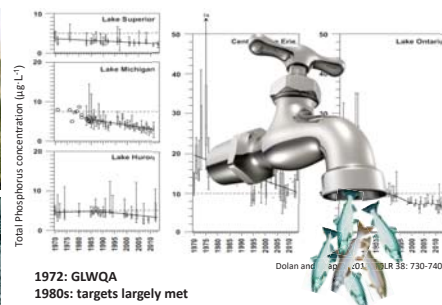


But ...

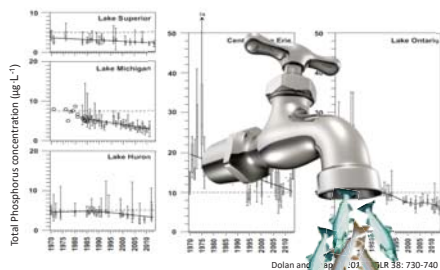
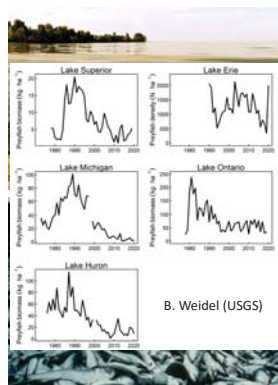
- Relationship stronger at lower trophic levels
  - Cladophora*, HABs, hypoxia
- lower TP → more desirable fish species
  - But overall, lower P → lower desired fish biomass



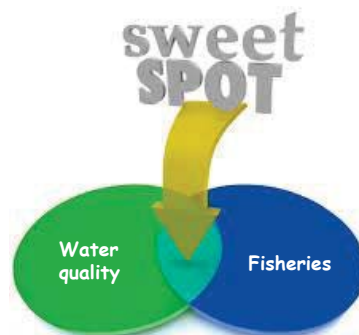
Jeppesen et al. 2005

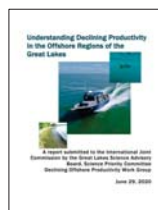


- 1972: GLWQA
- 1980s: targets largely met
- dreissenid mussels invade
- 1990s: re-emergence of eutrophication symptoms
- concerns over declining fish production
- 2000s: collapse of offshore fishery in Lake Huron
- 2010s: agencies reduce predator stocking
- 2020s: prey fish at historic lows



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- 1980s: targets largely met
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- 1990s: concerns over declining fish production
- re-emergence of eutrophication symptoms
- 2000s: collapse of offshore fishery in Lake Huron
- 2010s: agencies reduce predator stocking
- 2020s: prey fish at historic lows





#### Objectives:

1. Literature review on how P reductions influence upper food web
2. Update basin wide time series used by Bunnell et al. (2014) to investigate relationship among nutrients, lower food web, and fish production
3. Review models to link P to upper food web and fishery production

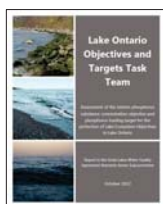
#### Recommendation Form cooperative monitoring and modelling committee to:

1. Review ecosystem **forecasting** science
2. Identify critical data and **foster exchange** to support integrative decision support
3. Evaluate **trade-offs and benefits** between nutrient management and fisheries
4. Promote **joint decision making**
5. Improve public **communication** w.r.t. consistency and clarity

"Major reductions in upstream nutrient loading to Lake Erie together with stakeholder concerns about increased coastal, nuisance *Cladophora* growth and declining salmonid biomass present a 'nearly-perfect storm' for both water quality and fisheries managers."

"It is incumbent on the SAB to advise the IJC of this risk that may result from taking a narrow view of the coastal *Cladophora* issue while neglecting possible impacts on pelagic food webs and ecosystem productivity."

18



#### Objectives:

- Conduct a scientific assessment to recommend whether **phosphorus concentration and loading target should be revised** to achieve any or all of the five Lake Ecosystem Objectives (LEOs) for Lake Ontario
  - Hypoxia; nuisance algae; healthy algal community nearshore; cyanobacteria; oligotrophy and healthy ecosystem offshore

**Main recommendation:** "... cannot recommend a revision of the Lake Ontario phosphorus concentration objective or phosphorus loading target at this time."

#### Recommendations:

- Maintain offshore water quality **monitoring**
- Improve understanding of **inputs, distribution and fate** of phosphorus
- Advance understanding of extent, drivers, and processes contributing to **nuisance benthic algae** in nearshore
- Establish **modelling working group** to inventory, review, and evaluate models, including nearshore *Cladophora* dynamics, food webs, and linkages between them
- Continue interdisciplinary **collaboration** between water quality, food web and fisheries researchers

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Are you listening or just waiting to talk?

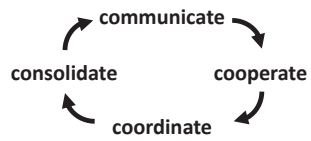
"... greater **cooperation** between water quality and fisheries agencies will be **essential** to maintaining a healthy and valuable fishery in the lakes."

Hecky and DePinto 2020

20

## Conclusions

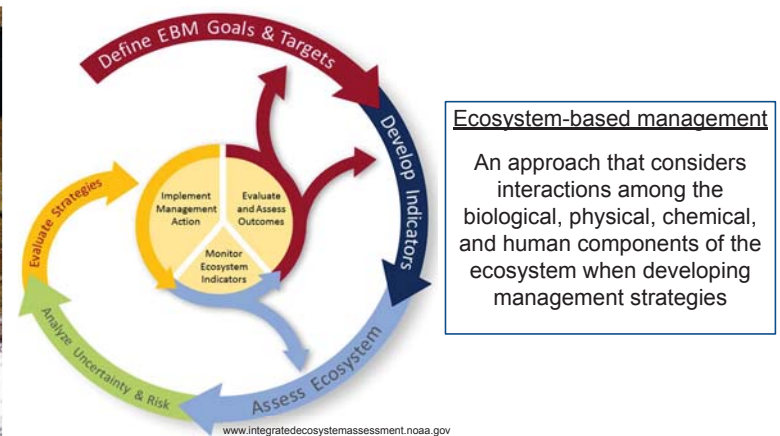
- Change in loading → change in biomass at all trophic levels
  - Interacts with other stressors (AIS, climate, population growth) to affect biomass, structure and trophic efficiency
- Water quality and fish groups are talking
- Scientifically based decision support tools are common ground
- Lakes are dynamic and complex
  - Goals and objectives of today may not be appropriate tomorrow



Ontario 



Ontario 



## Integrated Ecosystem Assessment

The IEA process:

- gives a holistic context to trends in the overall ecosystem and indicators of ecosystem state (e.g., GLFC Fish Community Objectives indicators, LAMP and SOLEC indicators)
- better explains why trends occur and how they are linked
- sets up management strategy evaluation by giving a strong quantitative basis for model development
- helps guide management and restoration decision-making by identifying possible tradeoffs between ecosystem goals and helps managers avoid surprises from management actions due to ecosystem interconnectedness

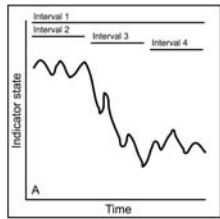
## Assessing drivers of ecosystem change: the role of temporal perspective



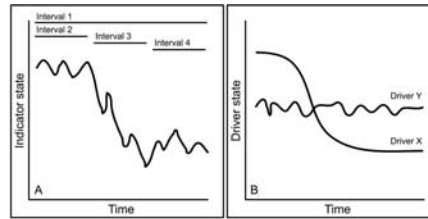
### Collaborators

Jim Hood, Stu Ludsin, James Sinclair      Ken Frank

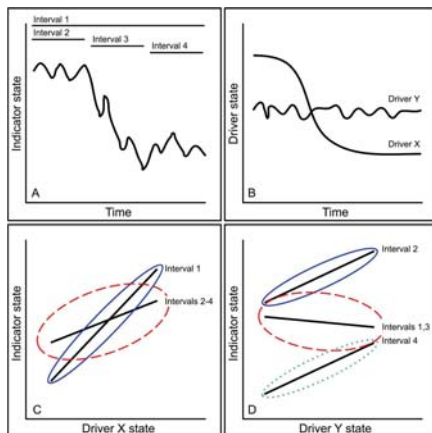




Pattern of an indicator time series can depend on length of time interval and dates covered



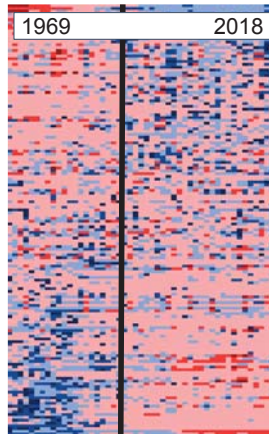
Pattern of driver variables may also vary (slow vs. fast drivers)



Relationships between drivers and ecosystem indicators may depend on chosen perspective of analysis

Western Lake Erie watershed is ~70% agricultural

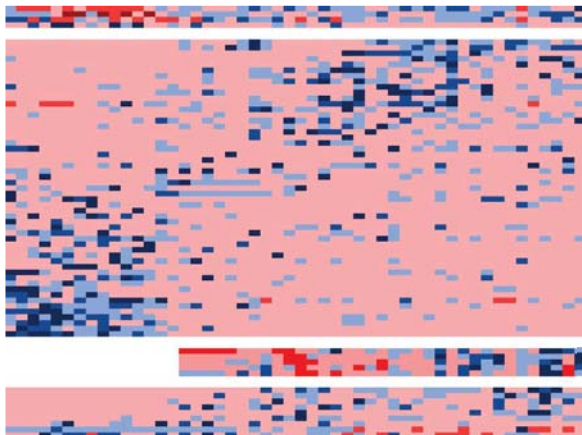




Increasing: soybean agriculture, charter boat fishing licenses, AMO, surface temperature, water clarity, white perch, round goby, lesser scaup, cormorants

Red = below long-term mean  
Blue = above long-term mean  
Darker shades are larger anomalies

Decreasing: ice cover, bottom oxygen, gizzard shad, yellow perch, carp, pelagic:benthic ratio of forage fish



Fish eco. ind.

Fishes

Zooplankton

Birds

Anthropogenic drivers (particularly soybean ag) are best long-term predictors, but physicochemical drivers become better in shorter intervals

	1969-2018	1984-2018	1999-2018
Bird abundances	Agriculture (0.13)	Meteorology (0.11)	Meteorology (0.08)
	River Discharge (0.09)	Lake Trophic (0.08)	Fishing (0.05)
	Meteorology (0.07)	Agriculture (0.08)	River Discharge (0.01)
Fish abundances	Agriculture (0.15)	Meteorology (0.12)	Lake Trophic (0.16)
	Fishing (0.15)	Lake Trophic (0.07)	Meteorology (0.08)
	Meteorology (0.03)	Agriculture (0.05)	Fishing (0.07)
Fish-derived ecosystem indicators	Fishing (0.16)	Meteorology (0.07)	Lake Trophic (0.17)
	Agriculture (0.15)	Agriculture (0.07)	Meteorology (0.09)
	Meteorology (0.03)	Lake Trophic (0.05)	Fishing (0.02)
Zooplankton abundances	NA	Meteorology (0.08)	Lake Chemistry (0.15)
		Agriculture (0.06)	Meteorology (0.08)
		Lake Trophic (0.05)	Fishing (0.07)

Anthropogenic drivers (particularly soybean ag) are best long-term predictors, but physicochemical drivers become better in shorter intervals

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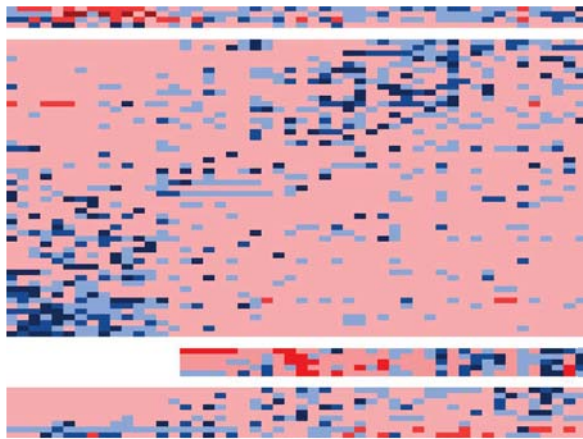
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Slower and faster drivers co-occur



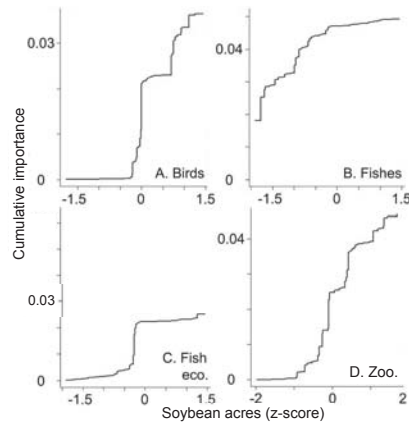


Fish eco. ind.

Fishes

Zooplankton

Birds



Soybean agriculture influences all three taxa, but at different thresholds

50-year mean = 3.2 million acres (standard deviation = 0.6)

#### Management implications:

1. Need to be clear about long-term vs. short-term planning
2. Greater uncertainty may exist if only short time series available
3. Following a tiered approach (multiple time intervals and indicator groups) will provide the most complete understanding of the key drivers of patterns in ecosystem state and their most relevant operative time scales

#### Future work:

1. Modeling of focal species (walleye, yellow perch, whitefish) using structural equation modeling and fuzzy cognitive mapping
2. Effects of spatial scale (e.g., Heim et al. 2021)
3. Comparisons of driver-response relationships across all lakes

Tradeoffs between HABs, hypoxia, and fisheries related to nutrient loading targets

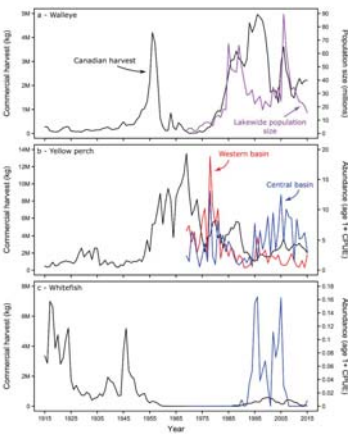
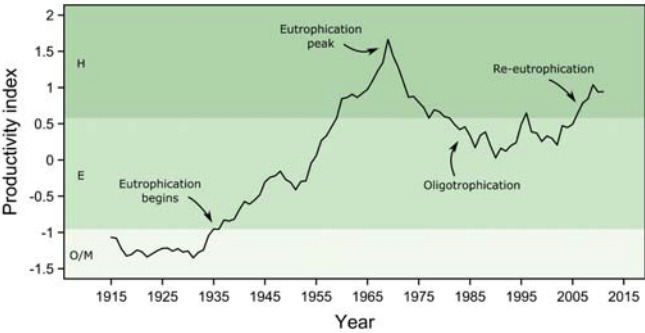


#### Collaborators

Jim Hood, Stu Ludsin, James Sinclair Euan Reavie

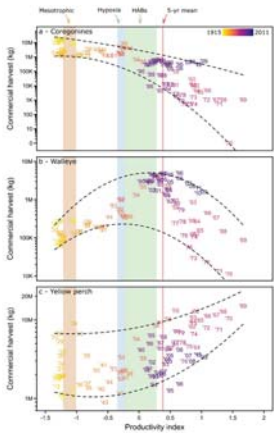


Western Lake Erie has experienced large changes in productivity



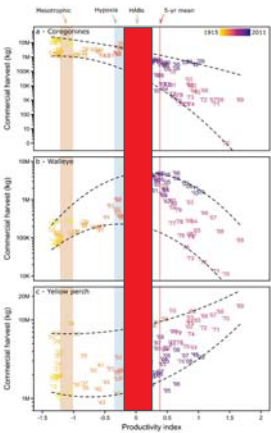
We have harvest data back to 1800s, but fishery-independent surveys only back to 1960s

However, both time series are reasonably well correlated during recent decades



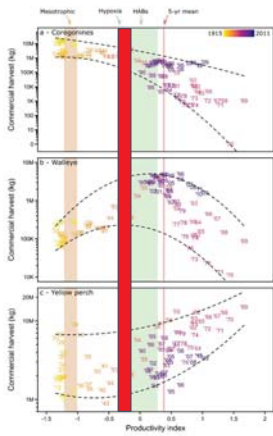
Analysis suggests potential tradeoffs with nutrient loading targets:

Walleye harvest is optimized under somewhat eutrophic conditions, yellow perch under hypereutrophic, and whitefish under mesotrophic



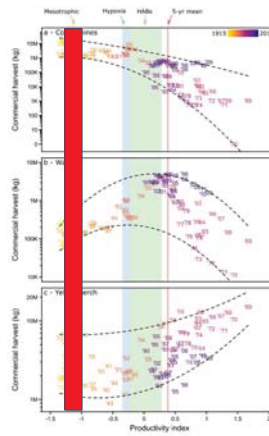
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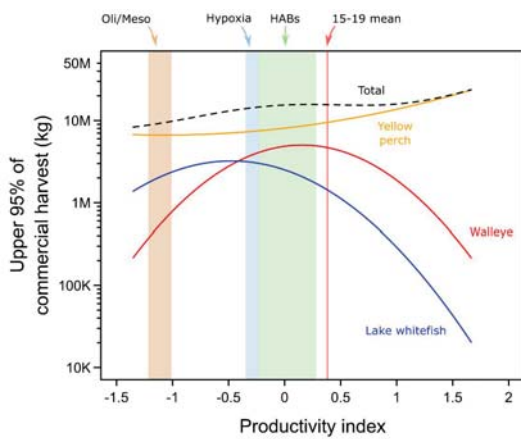
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Analysis suggests potential tradeoffs with nutrient loading targets:

Walleye harvest is optimized under somewhat eutrophic conditions, yellow perch under hypereutrophic, and whitefish under mesotrophic



Total harvest of the three species together is more stable across a range of trophic conditions (although it does decline with lower lake productivity)

Thank you!  
mfraker@umich.edu



Funding provided by:



# Investigating Food Webs: State of Knowledge and Investigative Approaches

Tom Stewart

Brian Weidel, USGS

Dick van Oevelen, Royal Netherlands Institute for Sea  
Research

Investigating Food Webs: Sate of Knowledge and Investigative Approaches

## Acknowledgements

### Funding

Great Lakes Fishery Commission  
Cooperative Institute for Great Lakes Research

### Steering Committee and Advisors

Nicholas Boucher, Aaron Fisk, Roger Knight, Doran  
Mason, Kevin McCann, Bailey McMeans, Lars  
Rudstam, Ed Rutherford, Heidi Swanson

### Workshop Hosts

Cornell Biological Field Station

Investigating Food Webs: Sate of Knowledge and Investigative Approaches

What's this all about?

Investigating Food Webs: Sate of Knowledge and Investigative Approaches

What's this all about?



FOOD WEBS

Investigating Food Webs: Sate of Knowledge and Investigative Approaches

# What's this all about?

**Why-** Fisheries management information needs, key questions

**Where-** Great Lake focus, but....

**How-** tools, measurements, indices

**When-** timely research, practical, funded

**Who-** designs, methods, collaborations

## FOOD WEBS

Investigating Food Webs: State of Knowledge and Investigative Approaches

## Objectives

1) Review and share the current state of food web investigative methods,

2) Determine food web-scale fisheries management information needs and possible investigative approaches, and

3) Develop collaborative study designs and proposals for potential funding addressing food web knowledge gaps relevant to fisheries management information needs.

Seminars  
Nov 3 & 10

Workshop  
Nov 14-16

Investigating Food Webs: State of Knowledge and Investigative Approaches

## Webinar I (Nov 3<sup>rd</sup>)

- Management information needs
  - Need for simple food web metrics
  - Dealing with critical unknowns (e.g. Goby production)
  - Linking food web "re-building" to habitat restoration
  - Linking LTL dynamics to fish recruitment
  - Consumptive demand on prey fish remains important
  - Linking stock assessment models to food web models
  - Phosphorus & Fish policy and scientific challenge
- Novel Approaches
  - Continued development of isotope applications
  - Linking isotopes and sub-models (interaction modules) into analysis to develop new metrics
  - Integrated Ecosystem Assessment

Investigating Food Webs: State of Knowledge and Investigative Approaches

## Webinar II (Today)

- Diverse set of speakers
  - More emphasis on methods and modelling
  - Management and policy relevant
- Special welcome to colleagues from "across the pond"
  - Dick van Oevelen – Royal Netherlands Institute for Sea Research
  - Benjamin Planque- Institute for Marine Research, Norway
- Special welcome to Robert Ulanowicz, University of Florida
  - Pioneering leader in ecological theory and network analysis
- AND--Some other guys ! (Myself, Doran Mason, Ed Rutherford and colleagues)

Investigating Food Webs: State of Knowledge and Investigative Approaches

## House keeping

- Presentation timer
- Presentation recordings
- Questions during seminar – please raise your hand
- Workshop registration - closed

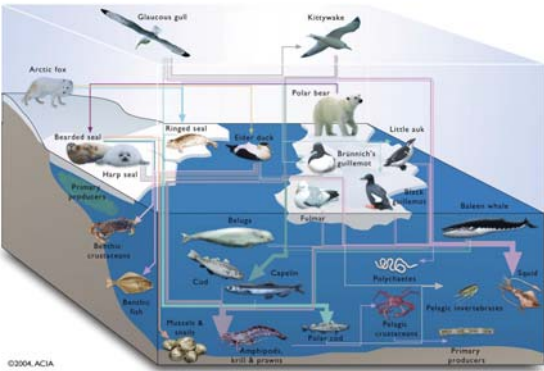
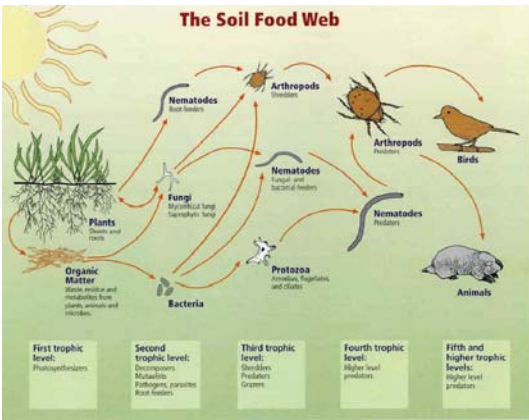
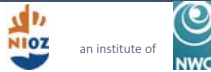
**To request recorded talks**  
**[nboucher@glfc.org](mailto:nboucher@glfc.org)**

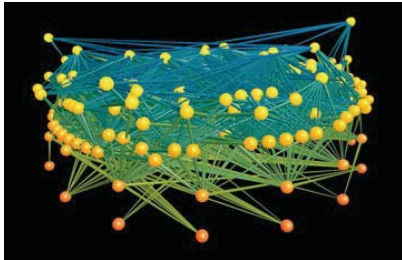
**Any other questions**  
**[tomstewart54321@gmail.com](mailto:tomstewart54321@gmail.com)**

Investigating Food Webs: State of Knowledge and Investigative Approaches

Understanding material and energy flow in aquatic ecosystems using linear inverse modeling

Dick.van.Oevelen(@nioz.nl)  
Department of Estuarine and Delta Systems  
Netherlands Institute for Sea Research (NIOZ), Yerseke (NL)

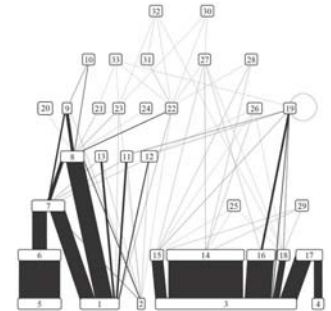




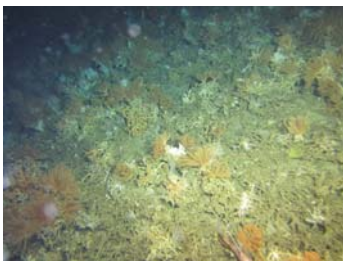
Connectance / binary food web, food web links 0 (absent) or 1 (present)  
(e.g. Pimm et al. Nature 1991)



Chesapeake Bay mesohaline ecosystem



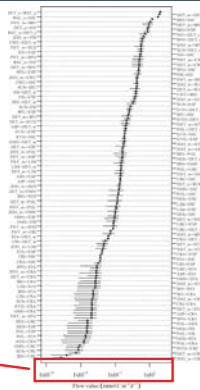
Banašek-Richter et al. Ecology 2009



Cold-water coral ecosystem

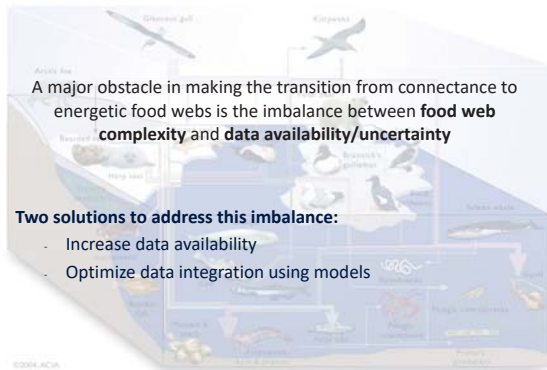
Van Oevelen et al. L&O 2009

Flow magnitudes range  
>6 orders of magnitude



Is it important to account for the differences in the magnitude of food web flows? Yes! (at least in some cases...)

- Weak trophic interactions in long trophic loops dampens the destabilizing effect of these long loops (De Ruiter et al. 1995; Neutel et al. 2002)
- Food webs are structured such that top predators couple energy channels that differ in productivity and turnover rate (Rooney et al. 2006)
- Decoupling of C (food quantity) and P (food quality) uptake by zooplankton fostered omnivory in a lake food web (Gaedke et al. 2002)
- Food web descriptors, e.g. trophic level/omnivory, are more robust when magnitude of link is considered (Banašek-Richter et al. 2004)

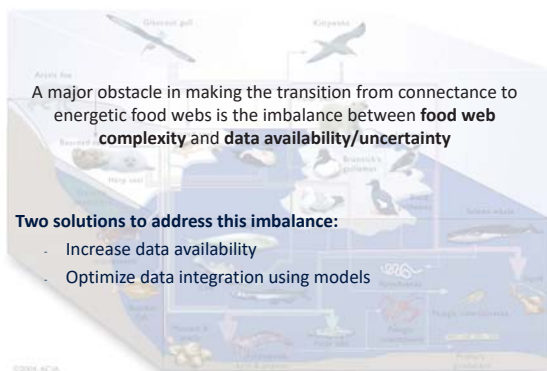


## Increase data availability

10

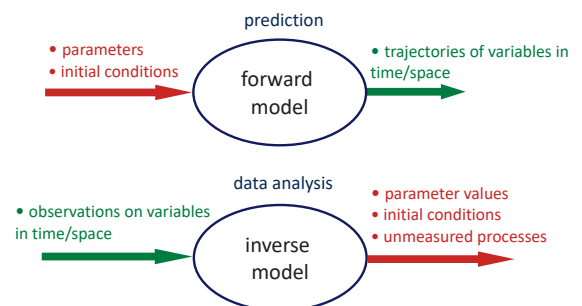
### Data used to resolve fluxes in food webs:

- Abundance / biomass
- Stoichiometric composition (C, N, P, +)
- Organism physiology, e.g. assimilation efficiency, growth efficiency
- Process rates, e.g. primary production, grazing, (community) respiration
- Feeding relations, e.g. gut contents, relation based on size and/or functional type,  $^{13}\text{C}/^{34}\text{S}$  stable isotopes, fatty acid composition,  $^{13}\text{C}/^{15}\text{N}$  isotope tracer experiments
- Trophic level, e.g.  $^{15}\text{N}$ -bulk or  $^{15}\text{N}$ -amino acid stable isotopes
- ...



## Linear *inverse* modelling

12



Note that I refer to **data analysis models**, not conceptual models

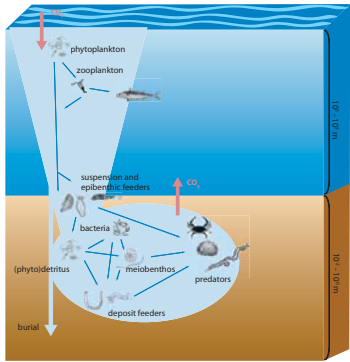
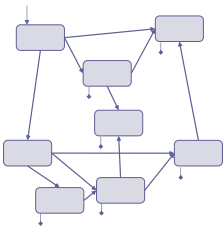
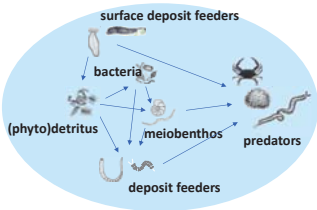


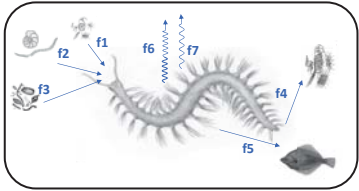
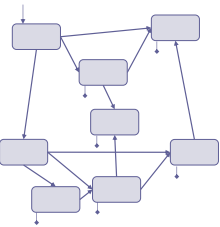
Figure 1. Scheme of a simplified deep-sea benthic food web.

Soetaert & Van Oevelen et al. Oceanogr. 2009

Mass balances couple the components in a food web



Soetaert & Van Oevelen et al. Oceanogr. 2009



$$\frac{dB}{dt} = \underbrace{f1 + f2 + f3}_{\text{ingestion}} - \underbrace{f4}_{\text{defecation}} - \underbrace{f5}_{\text{predation}} - \underbrace{f6}_{\text{basal respiration}} - \underbrace{f7}_{\text{growth respiration}}$$

Soetaert & Van Oevelen et al. Oceanogr. 2009



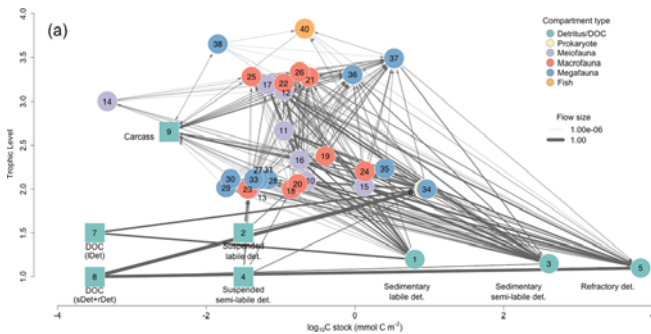
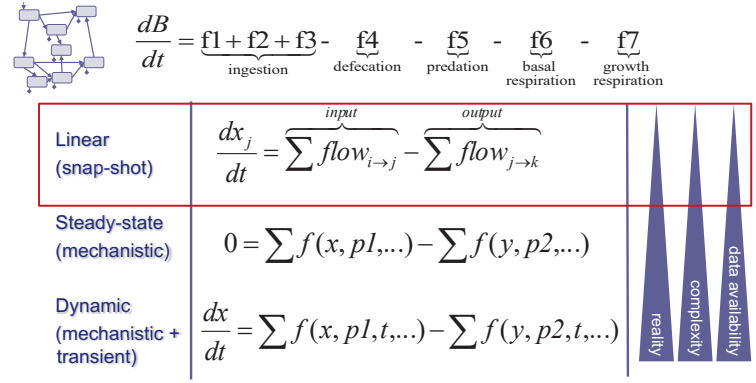
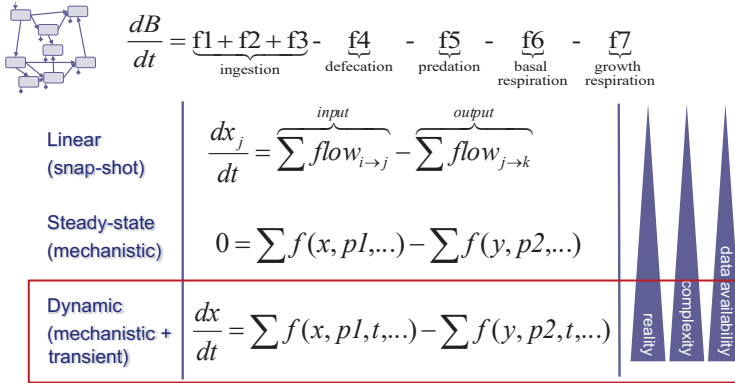
$$\frac{dB}{dt} = \underbrace{f1 + f2 + f3}_{\text{ingestion}} - \underbrace{f4}_{\text{defecation}} - \underbrace{f5}_{\text{predation}} - \underbrace{f6}_{\text{basal respiration}} - \underbrace{f7}_{\text{growth respiration}}$$

Linear (snap-shot)	$\frac{dx_j}{dt} = \sum \overbrace{flow_{i \rightarrow j}}^{\text{input}} - \sum \overbrace{flow_{j \rightarrow k}}^{\text{output}}$	
Steady-state (mechanistic)	$0 = \sum f(x, p1, \dots) - \sum f(y, p2, \dots)$	
Dynamic (mechanistic + transient)	$\frac{dx}{dt} = \sum f(x, p1, t, \dots) - \sum f(y, p2, t, \dots)$	

reality

complexity

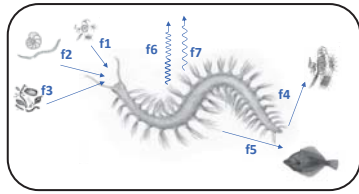
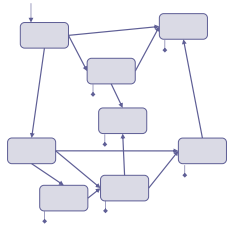
data availability



We often get the critique that (food web) processes are **non-linear**, so that a **linear** representation is therefore inherently problematic and unrealistic

*Underlying processes are undoubtedly non-linear, however ...*

a linear inverse model evaluates mass balances over a 'certain' time interval and while the underlying processes may be highly non-linear, the terms over that time interval **are** linear



$$\frac{dB}{dt} = \underbrace{f1 + f2 + f3}_{\text{ingestion}} - \underbrace{f4}_{\text{defecation}} - \underbrace{f5}_{\text{predation}} - \underbrace{f6}_{\text{basal respiration}} - \underbrace{f7}_{\text{growth respiration}}$$

Soetaert &amp; Van Oevelen et al. Oceanogr. 2009

$$\frac{dB}{dt} = \underbrace{f1 + f2 + f3}_{\text{ingestion}} - \underbrace{f4}_{\text{defecation}} - \underbrace{f5}_{\text{predation}} - \underbrace{f6}_{\text{basal respiration}} - \underbrace{f7}_{\text{growth respiration}}$$



$$\begin{pmatrix} 1 & 1 & 1 & -1 & -1 & -1 & -1 & \dots & n \\ & & & & & & & \dots & n \\ & & & & & & & & n \\ & & & & & & & & n \end{pmatrix} \cdot \underbrace{\begin{pmatrix} f1 \\ f2 \\ f3 \\ \vdots \\ fn \end{pmatrix}}_{\text{food web flows}} = \underbrace{\begin{pmatrix} dB/dt \\ \vdots \end{pmatrix}}_{\text{numerical data}}$$

## Data collected to resolve food webs:

$$\frac{dB}{dt} = \underbrace{f1 + f2 + f3}_{\text{ingestion}} - \underbrace{f4}_{\text{defecation}} - \underbrace{f5}_{\text{predation}} - \underbrace{f6}_{\text{basal respiration}} - \underbrace{f7}_{\text{growth respiration}}$$

## Abundance / biomass

Biomass data are always used with other data, such as ingestion:  $f1 + f2 + f3 = \text{biomass} \cdot \frac{Q}{B}$ 

## Stoichiometric composition

Stoichiometric coupling of fluxes in a food web:  $f1_N = f1_C \cdot \frac{N}{C_{\text{prey}}}$ 

## Physiology

Ratio of fluxes, e.g. assimilation efficiency:  $\frac{f1 + f2 + f3 - f4}{f1 + f2 + f3} = (AE) \cdot f2 + (1 - AE) \cdot f3 - f4 = 0$ 

## Process rates:

Single or combination of fluxes:  $f6 + f7 = \text{respiration}$ 

## Feeding relations:

Stable isotopes:  $\delta^{13}C \left( \frac{f1 \cdot \delta^{13}C_1 + f2 \cdot \delta^{13}C_2 + f3 \cdot \delta^{13}C_3}{f1 + f2 + f3} \right) - \delta^{13}C = 0$ 

Trophic level: similar to feeding relations, but taking trophic level fractionation into account

## Topological food web

- "who eats who"
- primary sources
- export terms

## Flux measurements

- biomass-based flows
- flow measurements
- respiration

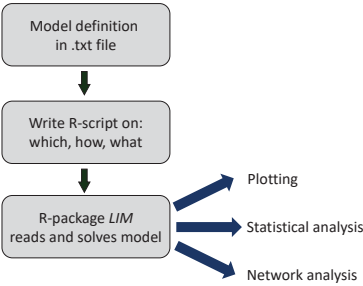
## Physiological constraints

- growth rates
- growth efficiency
- assimilation efficiency

## LIM equations

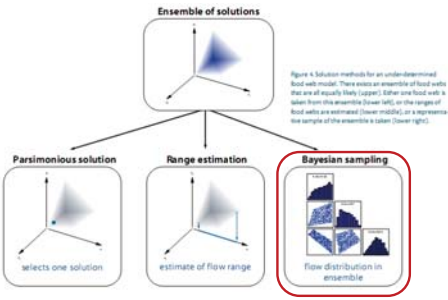
$$\mathbf{A} \cdot \mathbf{x} = \mathbf{b} \quad \text{Mass balances and data equations}$$

$$\mathbf{G} \cdot \mathbf{x} \geq \mathbf{h} \quad \text{Constraints on and relations between flows}$$



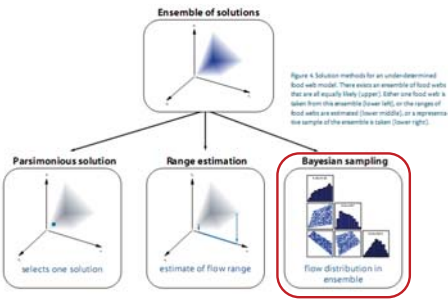
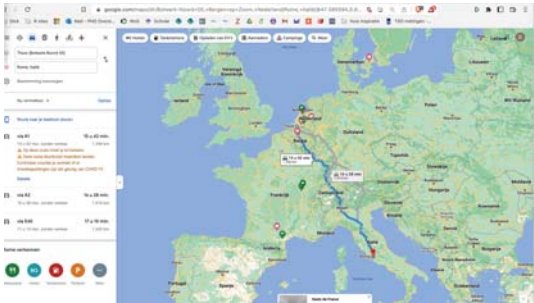
R-package LIM with examples available online:  
[www.rforscience.com/linear-equations.html](http://www.rforscience.com/linear-equations.html)

```
# R code
# ...
# ...
# ...
```

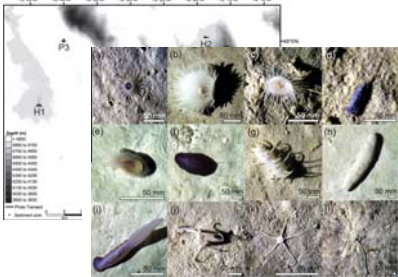


Soetaert and Van Oevelen (2009) Oceanography

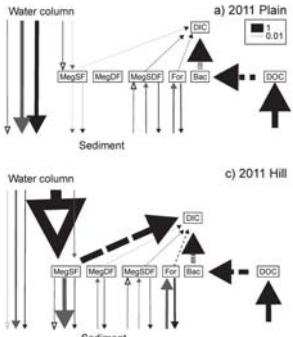
The google maps analogy, different options but consistent with car, highways, etc



Soetaert and Van Oevelen (2009) Oceanography



Durden et al. 2015 (Prog Oceanogr)



Durden et al. 2017 (L&O)



Quantification of Barents Sea food web to determine food web transfer in phytoplankton- and microbial-dominated food webs

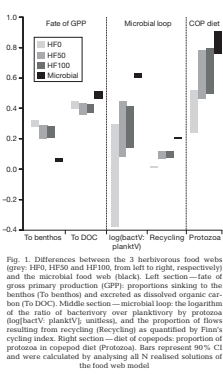
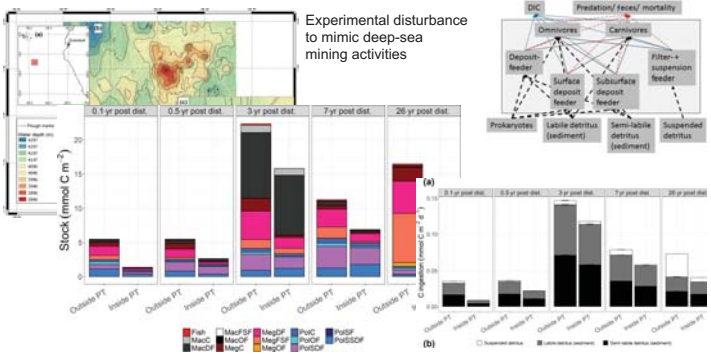


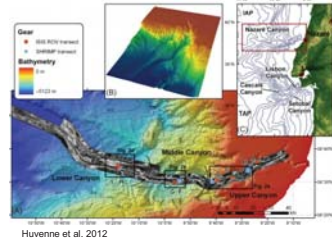
Fig. 4. Food web efficiency (FWE, expressed as fraction) calculated by dividing the production of young cod (YCO), adult cod (COD), copepods (COP) and all fish (ALL FISH) by the sum of net primary production and input of copepod biomass by the Atlantic current. Dashed line: FWEs for copepod production found by Berglund et al. (2007). Bars represent 90% CI and were calculated by analysing all N realised solutions of the food web model

De Laender et al. 2010 (MEPS)

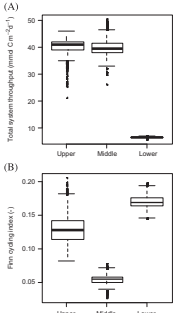


Stratmann et al. 2018 BGS

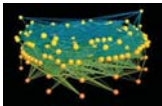
Food web differences between head, middle and lower section of the Nazare Canyon (Portugal)



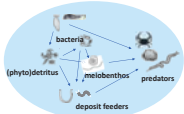
LIM food webs analyzed with network indices



Van Oevelen et al. 2011 (DSRII)



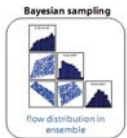
Food webs are not binary



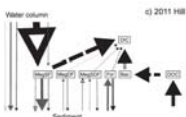
Mass balances in a food web **and** data represented in matrix equations to create a LIM



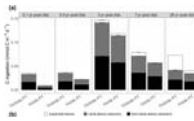
Use R package *LIM* to setup and solve LIM  
[www.rforscience.com](http://www.rforscience.com)



Sampling the solution space generates many possible solutions (google/maps)



A LIM provides a single snapshot of a food web



and can be used for time series as repeated LIMs and network analysis

## LIM approach to Ecopath mass balance and hypotheses testing

Tom Stewart  
Dick van Oevelen  
Brian Weidel

## Origins of the project

- A workshop in 2017, illustrated the potential for comparative studies of GL food webs to provide fisheries management insights
- The comparison of food metrics (e.g. TTE) relied primarily on Ecopath descriptions of food webs
- While valuable, I thought comparative analysis could benefit from methods that better accounted for uncertainty.
- Linear inverse model (LIM) approach to Ecopath is conceptually straightforward, and offers advantages for both comparative studies, and other applications, but had been rarely applied in Great Lakes context

## Advantages of LIM

- Flexibility to deal with different types of data and sources of variation and uncertainty using stochastic computational methods
- Ability to generate objective ensembles of mass-balance solutions and associated metrics to facilitate statistical treatment
- Allows for ancillary trophic information, (e.g. isotopes), stoichiometry, spatial flows (e.g. nearshore/offshore) to be reconciled with mass-balance

## Disadvantages of LIM

- Not as user-friendly or as easy to understand as Ecopath
- Requires coding knowledge and experience
- Requires explicit coding of all system flows and bioenergetics parameters, and constraints
- If observational variation is to be applied as a constraint, must be able to estimate

## Objectives

- Demonstrate the potential for LIM in a Great Lakes context by,
  - Designing a LIM coding application that exploits existing Great Lakes Ecopath frameworks and available data sets
    - Basic data requirements are essentially the same
  - Consider how best to account for uncertainty across multiple model inputs
  - Apply LIM in a Great Lakes comparative analysis as “proof of concept”

## Methods

- Applied method to existing Ecopath comparative analysis of Lake Ontario offshore food web (Stewart and Sprules, 2011)
  - Updated alewife and dreissenid mussel biomass
- Compared pre-dreissenid (1987-91) to post-dreissenid establishment (2001-05)
- Included multiple sources of variation

## Principle of mass balance in a food web

**Species-group production is either consumed, exported (harvested), or dies and becomes detritus (recycled)**

**Species-Group Growth =  $dB/dt$  =  
ingestion – predation mortality – defecation – respiration**

**Food web flows, as defined over space and time, must balance all inputs and outputs under these constraints**

## Configuring Ecopath in LIM

### Ecopath Parameters

### LIM Parameters (this study)

**Topology** (whom eats whom)

**Diet Proportions**

Production =  $P/B \times \text{Biomass}$

Consumption =  $Q/B \times \text{Biomass}$

**Defecation** (% of Consumption),  
**Respiration** (calculated as  
a residual component)

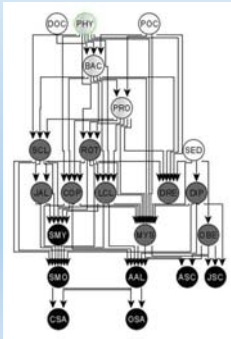
## Configuring Ecopath in LIM

### Ecopath Parameters

### LIM Parameters (this study)

Topology (whom eats whom) →

Same



## Configuring Ecopath in LIM

### Ecopath Parameters

### LIM Parameters (this study)

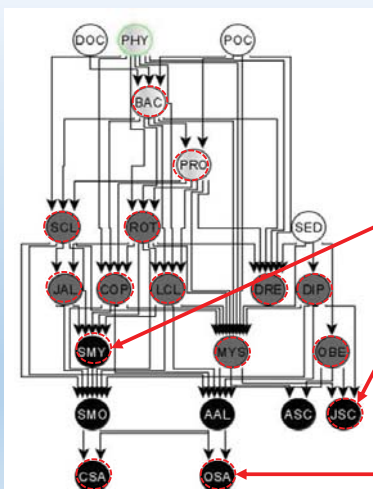
Topology (whom eats whom) →

Same

Diet Proportions →

LTL and larval fish – topology only  
Top Predators – topology only  
Adult Prey Fish –  $\pm 1$  SD

## Annual Diet Proportions



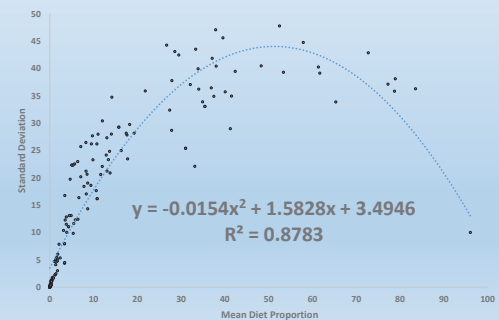
Diet proportions not specified (just what they eat)

Larval/YOY smelt and alewife

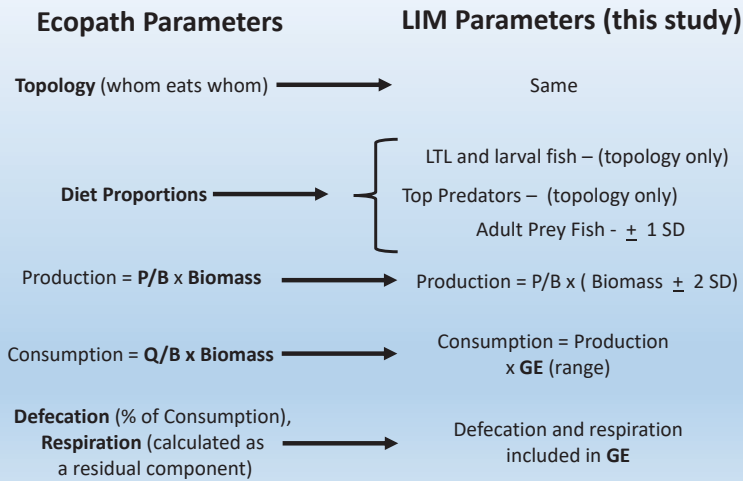
Salmon and Trout

## Variation in Adult Prey Fish Diet Proportions

- Determined variance in adult Alewife, Rainbow Smelt and Sculpin diet proportions
- Used independent sets of samples over space and time to develop a generalized mean vs variance plot



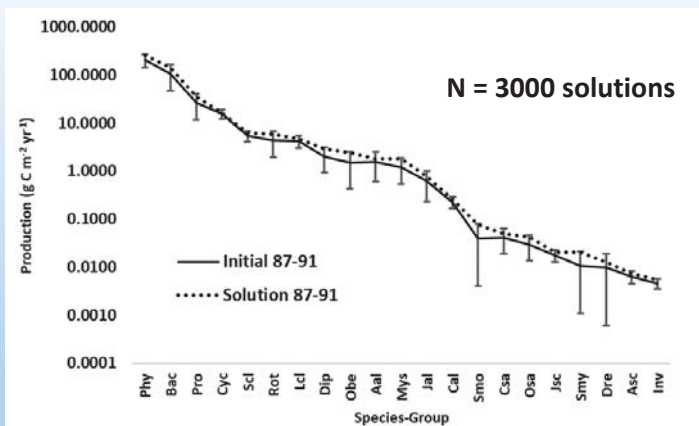
## Configuring Ecopath in LIM



## Achieving mass-balance

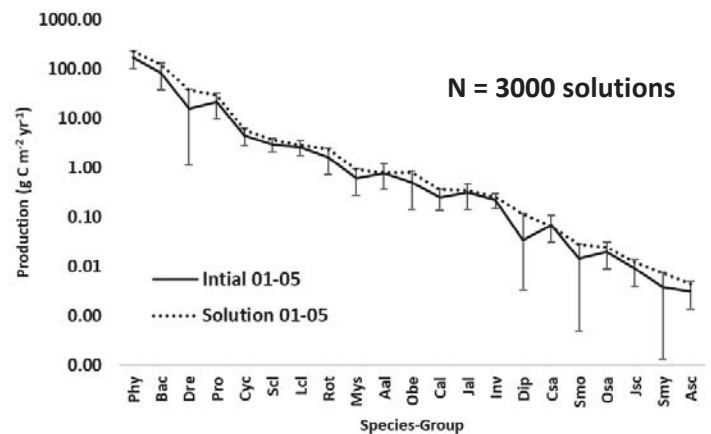
- General LIM
  - Numerous options (parsimonious, range, Monte Carlo randomization) while maintaining internal consistency and user-specified constraints
- This study (LIM)
  - Monte Carlo randomization with constraining bounds based on observed variation in species-specific diet proportions (or unconstrained topology), production, and consumption.

## Results



Initial and mean solution production values for 1987-91 time-period. Error bars are the initial production bounds. The species-groups for each time-period are plotted in order from highest solution production to lowest solution production.

## Results



Initial and mean solution production values for 2001-05 time-period. Error bars are the initial production bounds. The species-groups for each time-period are plotted in order from highest solution production to lowest solution production.

## Hypotheses

- The overall food web trophic transfer efficiency declined between time periods due to a re-direction of primary production and detritus to invasive mussels

## Hypotheses Testing

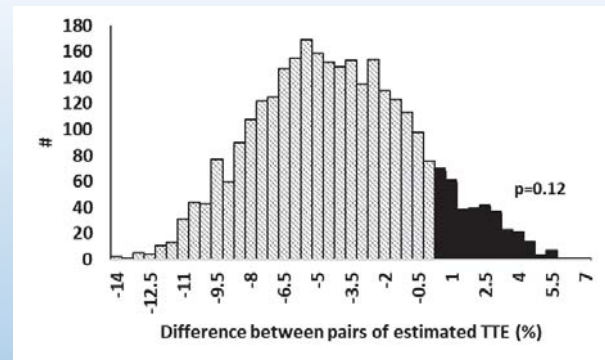
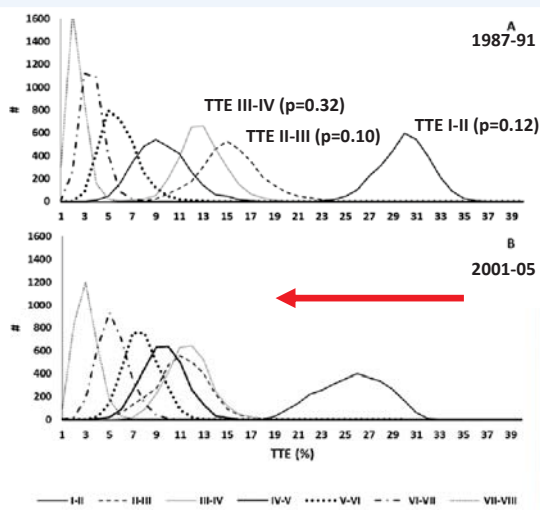
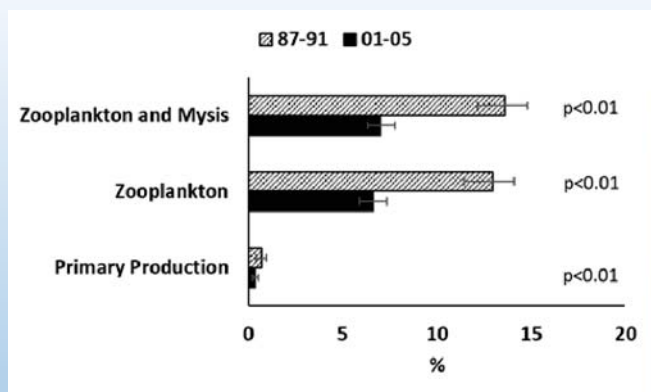


Illustration of how test-statistic probabilities are determined for the difference between trophic transfer efficiency from trophic levels I-II for 1987-1991 and 2001-2005. The dark bars are the number of times independent pairs of 3000 solutions had a difference  $> 0$  (m). The p-values is the probability that the difference  $> 0$  (null hypotheses) occurred by chance, calculated as  $m/3000$ .



## Hypotheses

- The decline in nutrients, and increased flows of primary production (PP) to dreissenid mussels reduced PP flows to Alewife and production efficiency declined

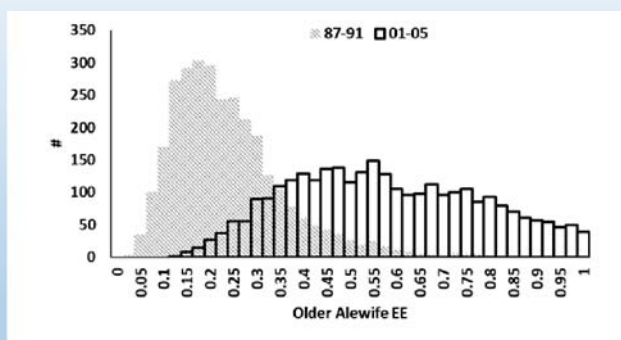


Median older alewife production efficiency for each time-period. Error bars are the 5% and 95% percentiles (N=3000).

## Hypotheses

- The risk to alewife over-consumption and potential predator response (measured as Alewife ecotrophic efficiency), increased, due to system wide production declines and invasive species establishment

## Shift in the risk of alewife over-consumption



Distribution of older alewife ecotrophic efficiency (EE) values for each time-period (N=3000).

## Caveats

- This is a prototype model, and it needs some tweaking
  - GEs were too liberal for some species and need to use more system-specific or Great Lake specific data from existing bioenergetics models or a general literature review
- Need to consider some constraints on un-bounded diet proportions
  - However, a cursory look indicated that un-bounded diets associated with solutions were very reasonable and realistic

## Conclusions

- Coding of Ecopath structures and data sets into LIM is relatively straightforward
- Flexible approaches for handling uncertainty
- Unknowns can be objectively dealt with (e.g. diet proportions, uncertain levels of production, bioenergetics)
- Results in objective ensemble of mass-balance solutions
  - Facilitates comparative statistical approaches (CI, probability distributions, hypotheses testing)
- User-defined metrics can be tabulated and evaluated

## Future Applications

- Design comparative Great Lake food web studies that exploit existing Ecopath data sets (likely close to 20 such data sets available)
- Include isotope values flow process and constraints in models
  - i.e. diets must be consistent with measured isotope values
  - increases confidence in outcomes and decrease the need for difficult and variable diet studies
- Use it to explore hypothetical data deficient food webs
  - Explore pre-colonization endemic food web function
  - Predict the potential range of food web responses to introduced species
- Flexibility to link other sub-model constraints into the mass balance models
  - Nearshore to offshore exchanges
  - Nearshore mussel dynamics could be described as a separate model and linked to more general food web model
  - Bailey et al. predator-prey “interaction modules” or variations could be included as constraints

## Acknowledgements

- GLFC provided funding for this project through the Technical Assistance for Fisheries Research Program (TARF)

# Dynamic linear inverse modeling to quantify food web dynamics

Benjamin Planque  
benjamin.planque@hi.no



## 2009: minimal ecosystem model V1.0

### FISH and FISHERIES

FISH and FISHERIES, 2009, 10, 115-131

#### A minimal model of the variability of marine ecosystems

Christian Mullon<sup>1</sup>, Pierre Friot<sup>1</sup>, Philippe Cury<sup>1</sup>, Lyne Shannon<sup>2</sup> & Claude Roy<sup>1</sup>



Christian Mullon

No anthropogenic forcing  
No environmental forcing  
No trophic functional relationships

BUT

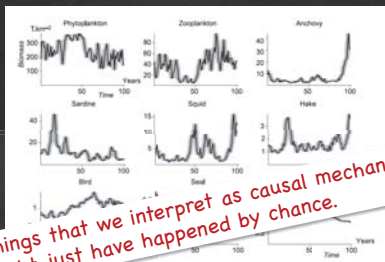
Few ecological constraints

AND

Chance in operation



## 2009: minimal ecosystem model V1.0



Things that we interpret as causal mechanisms might just have happened by chance.



## 2010: LIM for food-webs

ECOSYSTEMS

### Quantifying Food Web Flows Using Linear Inverse Models

Dick van Oevelen<sup>1,2,\*</sup>, Karel Van den Meersche<sup>1,3</sup>, Filip J. R. Meysman<sup>2</sup>, Karlina Soetaert<sup>1</sup>, Jack J. Middelburg<sup>1,4</sup> and Alain F. Vézina<sup>5</sup>

Complex quantification problem

Under observed/sampled

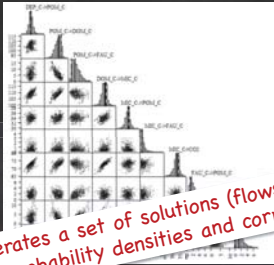
Finding a unique solution requires additional assumptions

BUT

It's possible to identify a set of possible solutions using LIM



## 2010: LIM for food-webs



LIM generates a set of solutions (Flows) from which marginal probability densities and correlations can be derived.

## 2020: Constraining food web dynamics with observations



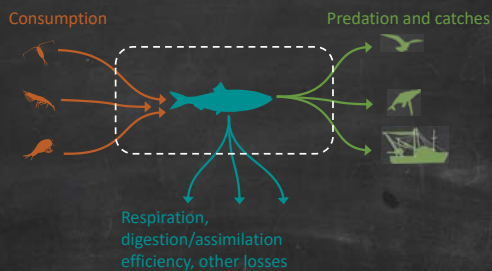
No anthropogenic forcing  
No environmental forcing  
No trophic functional relationships

BUT + historical data

Few ecological

CaN generates a set of solutions (Flows dynamics) from which marginal probability densities and correlations can be derived

## The principles of RCaN\*: mass-balanced



Changes in biomass = what comes in minus what comes out

\*RCaN = Chance and Necessity modelling in R

## Formulating the problem: inputs

- Components (species)
- Life-history input parameters (satiation, max growth, metabolic rates)
- Flows (who eats whom)
- Observations (biomasses, diets, consumption, relative or absolute)
- Constraints

## Examples of constraints

- Equalities
  - Biomass of spA = observed biomass of spA
  - Flow from spA to fisheries = reported catches of spA
- Inequalities
  - Biomass of sp. A  $\geq$  lower confidence bound for biomass of sp. A
  - Biomass of sp. A  $\leq$  upper confidence bound for biomass of sp. A
- Constant constraints
  - Biomass of sp. A  $\geq$  fixed value
- Proportional constraints
  - Biomass spA/mean(biomass spA) = observed biomass of spA/mean(observed biomass of spA)
- Constraints across components or flows
  - Flow from spA to spB = 20% of the total flow to spB
  - Flow from spA to spC  $\geq$  flow from spB to spC



## Formalising the problem: matrix construction

- Symbolic Math library: Symengine



## Sampling the solution space

- Gibbs sampler



## Visualising the outputs

- Individual trajectories
- Diets
- Density dependence (growth | biomass)
- Trophic functional relationships (inflow | prey biomass)
- Trophic controls (growth | consumption, predation)
- Competition (consumption pred 1 | consumption pred 2)

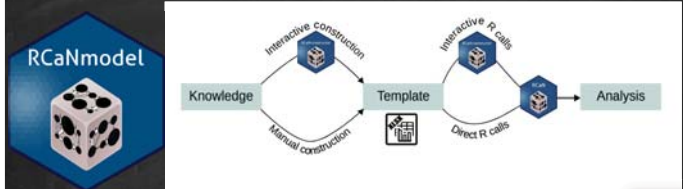


## Building – running – revising in participatory mode

- Graphical user interface for inputs & outputs
- Transparent modelling framework: all-in-one xlsx input file
  - inputs (components, flows, input parameters, constraints, observations)
  - Meta-information
  - Model development tracking
- Model diagnostic tools
- Next step: automated report generator



## 2021: RCaModel and RCaNconstructor



<https://github.com/inrae/RCaModel>



Hilaire Drouineau



Christian Mullon

Drouineau, H., B. Planque, and C. Mullon. In prep. RCaM: a software for Chance and Necessity modelling.

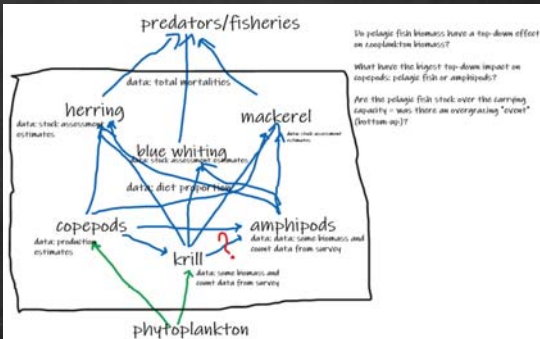


## An example of participatory modelling using CaN

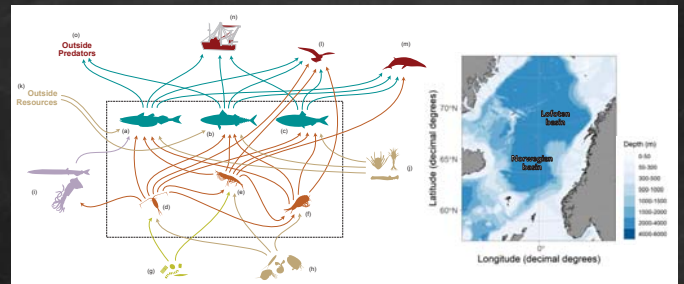
- ICES – WGINOR
- Participatory modelling – workshops
- Master project



Aurélien Favreau



## An example of participatory modelling using CaN



Dynamic reconstructions: 1988-2019. Biomass, catches, diet and consumption data

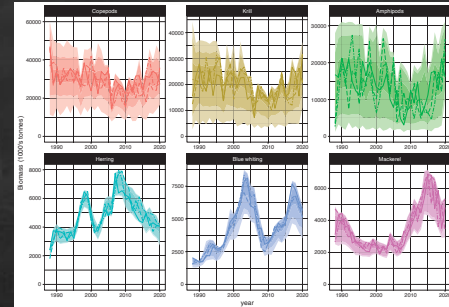


## Dimension of the problem

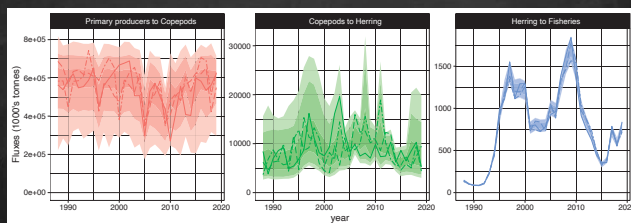
- 6 species in the model domain (9 components outside)
- 39 fluxes
- 40 observational series
- 120 constraints
- 33 years
- Polytope dimension: 33 years x 39 fluxes + 6 initial values = 1293
- LIM problem:  $A \cdot f \leq b$  with  $\dim(A) = 5077 \times 1293$



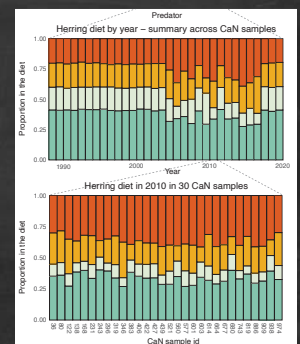
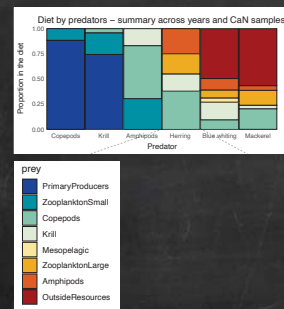
## Individual biomass trajectories



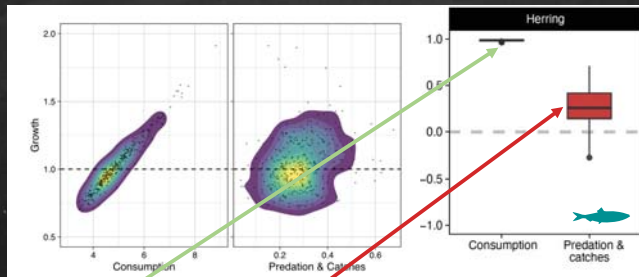
## Individual trophic fluxes trajectories



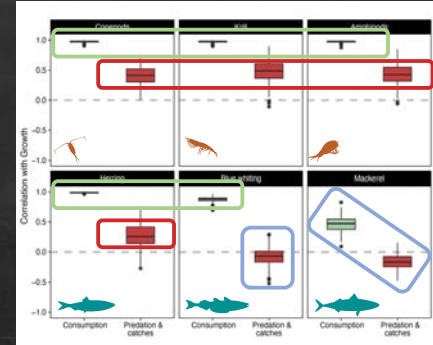
## Diets



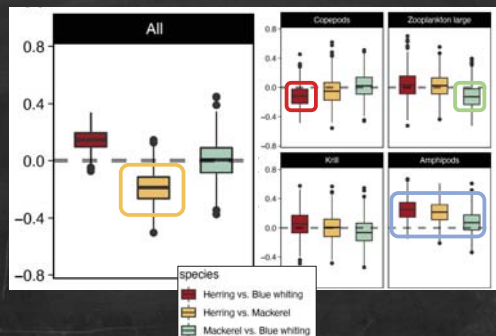
## combining biomass and fluxes



## Trophic controls for small pelagics and plankton



## Competition for resources



## RCaN modelling resources



- <https://github.com/inrae/RCaNmodel>
- Planque, Benjamin, and Christian Mullan. "Modelling Chance and Necessity in Natural Systems." *ICES Journal of Marine Science* 77, no. 4 (July 1, 2020): 1573–88. <https://doi.org/10.1093/icesjms/fsz173>.
- Drouineau, Hilaire, Benjamin Planque, and Christian Mullan. "RCaN: A Software for Chance and Necessity Modelling." *BioRxiv*, 2021, 2021.06.09.447734. <https://doi.org/10.1101/2021.06.09.447734>.
- Planque, Benjamin, Aurélien Favreau, Bérangère Husson, Erik Askov Mousing, Cecilie Hansen, Cecilie Broms, Ulf Lindstrøm, and Elliot Sivel. "Quantification of Trophic Interactions in the Norwegian Sea Pelagic Food-Web over Multiple Decades." *ICES Journal of Marine Science*, July 14, 2022, fsac111. <https://doi.org/10.1093/icesjms/fsac111>.


benjamin.planque@hi.no

Ecopath with Ecosim overview 

## Driving with Headlights On? Investigating Food Webs with Ecopath with Ecosim Can Shed Light on Fishery Management and Water Quality Information Needs

Ed Rutherford<sup>1</sup>  
Hongyan Zhang<sup>2</sup>, Yu-Chun Kao<sup>3, 4</sup>, Doran Mason<sup>1</sup>, Marten Koops<sup>5</sup>

<sup>1</sup> NOAA GLERL, <sup>2</sup>Eureka Aquatic Research LLC, <sup>3</sup>USGS-GLSC and  
<sup>4</sup>US FWS, <sup>5</sup>Dept Fisheries and Oceans Canada

Background: 

## Nutrients have positive, nonlinear effect on fish biomass, modified by env't.

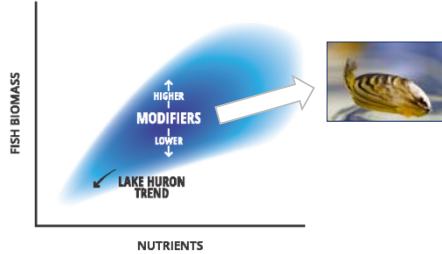




Figure from Tom Stewart, 2020. "A Changing Lake Huron" Great Lakes Fishery Commission


Background 

## Current Status in Deep Lakes


Coastal eutrophication




Offshore oligotrophication



(Figures from Limnotech Final Report to IJC. 2018.)

Background: 

## Why Use Ecopath with Ecosim (EwE)?



- EwE is freely available as download. Used worldwide to evaluate stressor and harvest effects on fisheries. Over 35 years of development.
- EwE can be used to address managers' concerns (eg. increased water quality vs productive fisheries; balance prey production with predator demand; evaluate stocking strategy for predators; restore habitats and native species to promote stable fisheries).
- Scenario simulations can inform hypotheses on how food webs may respond differently to drivers (invasive species, fisheries, eutrophication, etc.) over time and space.
- Can incorporate uncertainty and be linked to other models (hydrodynamics, economics, land use)
- Drawbacks: requires lots of data and some time to construct balanced food web

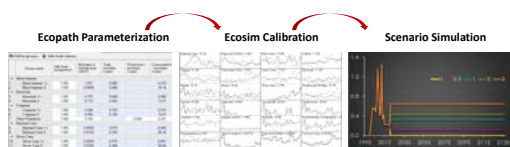
## Great Lakes EwE models now applied to food webs in all Great Lakes



## Ecopath with Ecosim- components

- Ecopath – a static, mass-balanced snapshot of the food web and interactions, with biomass groups consisting of a single species, or species groups representing ecological guilds.;
- Ecosim – a time dynamic simulation module for policy exploration;
- Ecospace – a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas

## EwE modeling a 3-Step Process



## Ecopath – master equation

- Production = consumption + predation mortality + biomass accumulation + net migration + other mortality

$$B_i \cdot \left( \frac{P}{B} \right)_i = \sum_{j=1}^n \left[ B_j \cdot \left( \frac{Q}{B} \right)_j \cdot DC_{ji} \right] - \left( \frac{P}{B} \right)_i \cdot B_i \cdot (1 - EE_i) - Y_i - E_i - BA_i$$

Biomass (B)\*

Total mortality (P/B) \*

Consumption (Q/B)\*

Ecotrophic Efficiency (EE)\*

Diet composition (DC<sub>ji</sub>)\*Fishery catch (Y<sub>i</sub>)Migration- immigration and emigration (E<sub>i</sub>)

Biomass accumulation (BA)

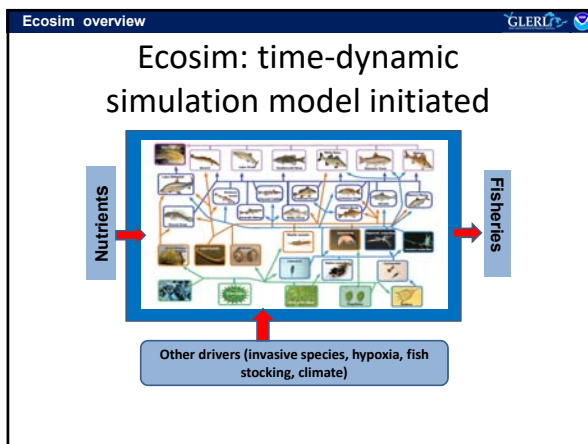
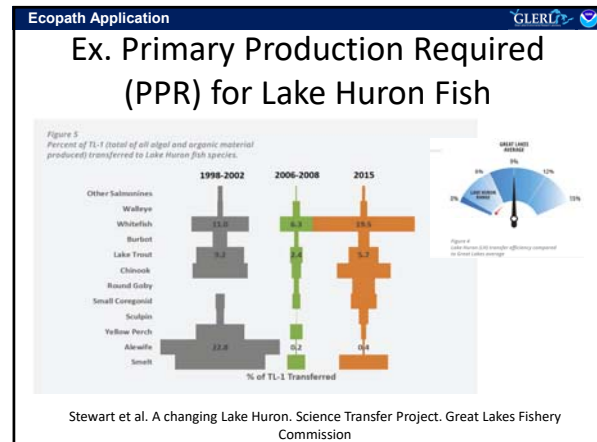
\* Required estimates

Ecopath

GLERL

### Ecopath: Some basic applications

- Estimate of the trophic level (TL) occupied by a species or functional group
- Indices of structure, function and energy flow in the food web and changes from invasive species.
- Network analysis metrics (not shown)



Ecosim overview

GLERL

### Ecosim- time dynamics

Governing equation

$$dB_i / dt = g_i \sum_j Q_{ij} - \sum_k Q_{ki} + I_i - (M_i + F_i + e_i) B_i$$

$i$ , predators  
 $j$ , prey

Consumption

Predation mortality

Fishing mortality rate

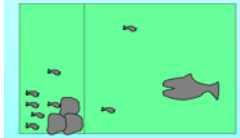
$g$ : gross food conversion efficiency ( $P/Q$ )  
 $P/Q = P/B \times Q/B$   
 $I$ : immigration  
 $M$ : non-predation natural mortality  
 $e$ : emigration rate

Dynamics driven by external forcing, e.g., time series data:  
 P loading  
 Fish harvest  
 Stocking

## Ecosim: Foraging Arena Theory

- Foraging modeled as multispp functional response with prey biomass partitioned into vulnerable and invulnerable states.
- Exchange between these states can limit overall trophic flow and stabilize or destabilize predator or prey dynamics

Foraging arena model

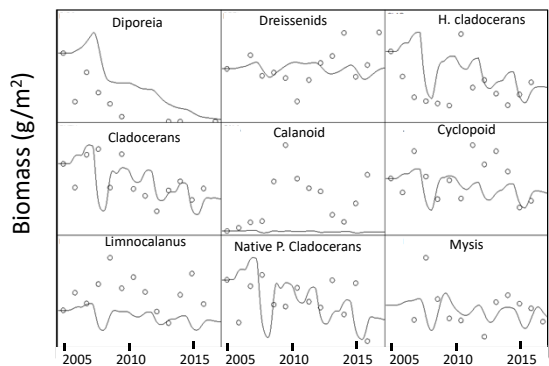


## It Takes a Village, & a lot of data, to develop a EwE model

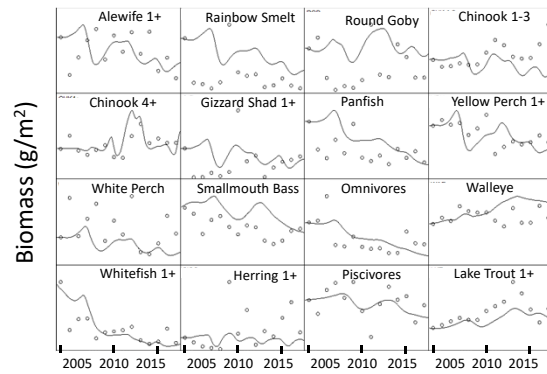
\*E. Rutherford<sup>1</sup>, H. Zhang<sup>2</sup>, D. Mason<sup>2</sup>, B. Weidel<sup>3</sup>, B. Lantry<sup>3</sup>, M. Koops<sup>4</sup>, M. Hossain<sup>4</sup>, K. Boston<sup>4</sup>, L. Rudstam<sup>5</sup>, J. Watkins<sup>5</sup>, K. Holeck<sup>5</sup>, K. Fitzpatrick<sup>5</sup>, T. Johnson<sup>6</sup>, J. Holden<sup>6</sup>, M. Yuille<sup>6</sup>, E. Brown<sup>6</sup>, C. Chu<sup>7</sup>, G. Arhonditsis<sup>7</sup>, L. Burlakova<sup>8</sup>, E. Hinchey<sup>9</sup>, R. Portiss<sup>10</sup>, L. Cartwright<sup>10</sup>, M. Connerton<sup>11</sup>, T. Stewart<sup>12</sup>

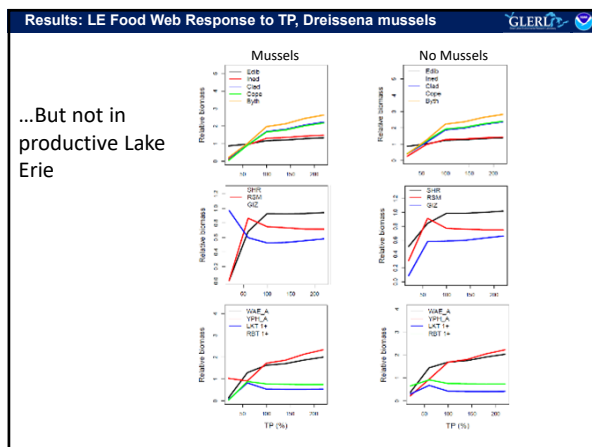
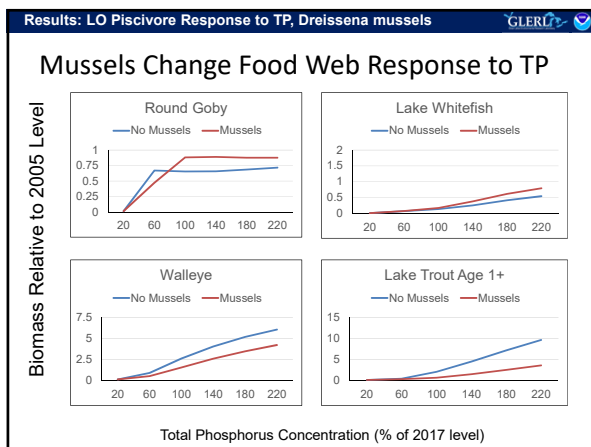
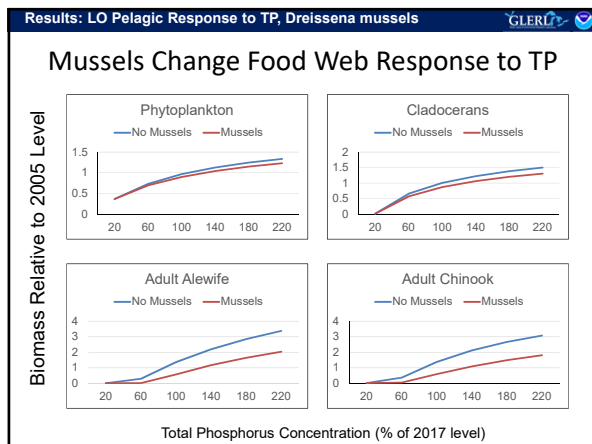
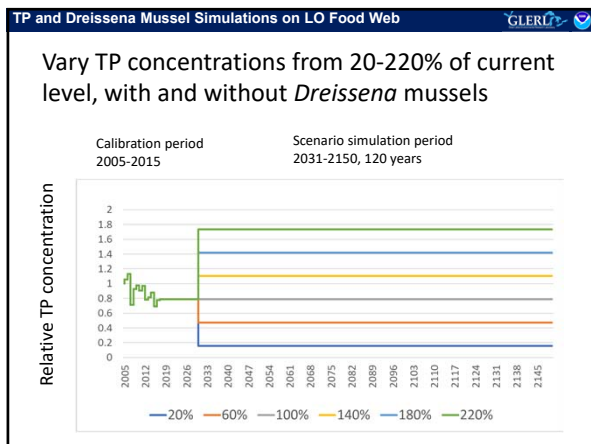
<sup>1</sup>NOAA GLERL, <sup>2</sup>Eureka Aquatic Research LLC, <sup>3</sup>USGS-GLSC, <sup>4</sup>DFO Canada, <sup>5</sup>Cornell Univ., <sup>6</sup>OMNRF, <sup>7</sup>U Toronto, <sup>8</sup>Buffalo State College, <sup>9</sup>EPA GLNPO, <sup>10</sup>Toronto and Region Conservation Authority, <sup>11</sup>NY DEC, <sup>12</sup>Retired!

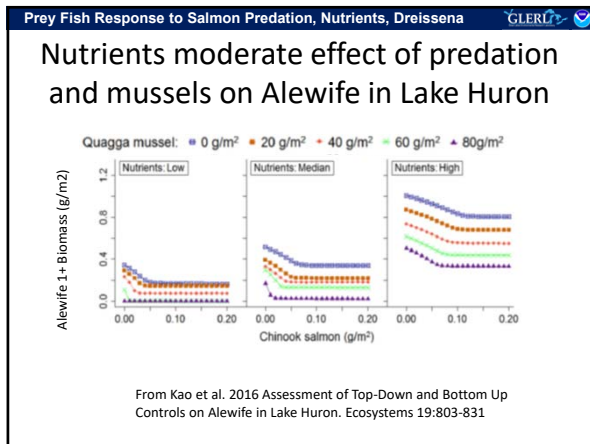
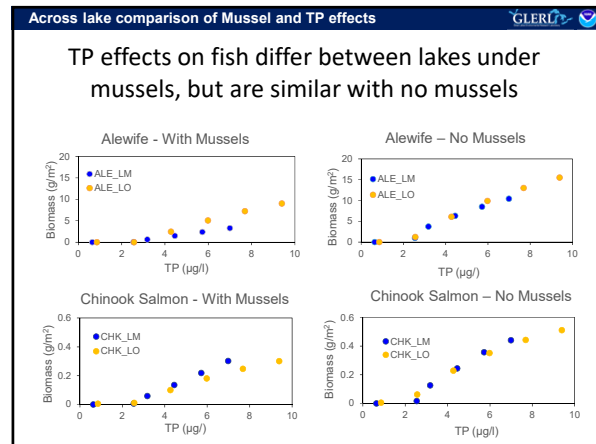
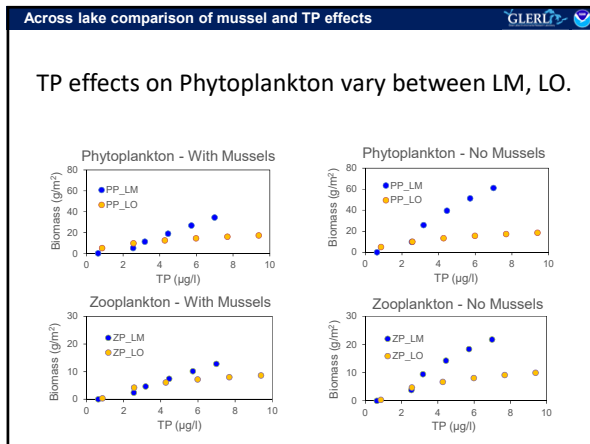
## Model Calibration – Lower Trophic Levels

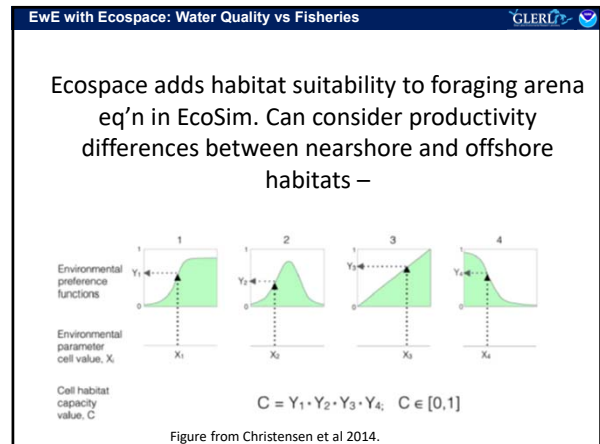
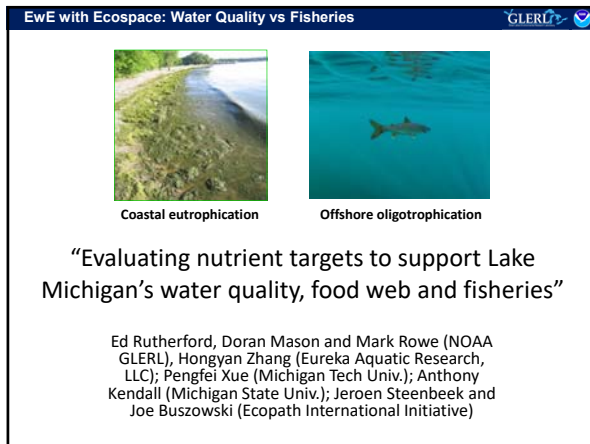
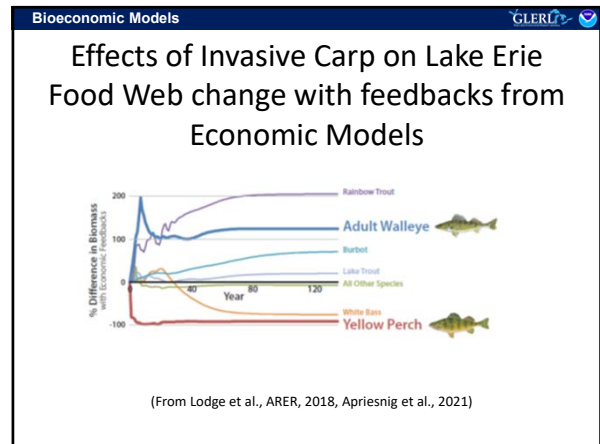
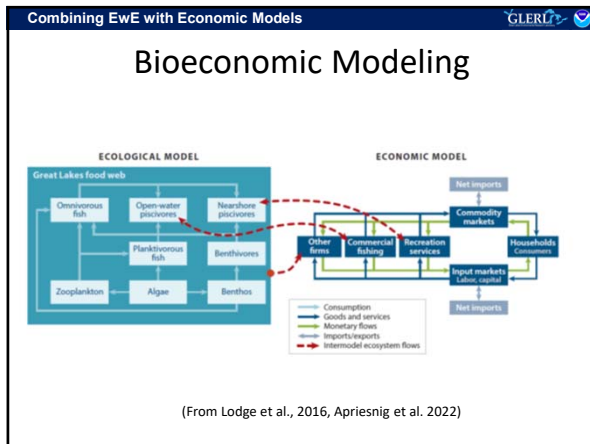


## Model Calibration - Fishes









## EwE in Coupled Model Framework

### Inputs:

- Downscaled current and past climate (precip; temperature)
- Landscape nutrient delivery model (point & non-point nutrient inputs)
- Hydrodynamic and water quality model (currents, nutrients, primary production, light, etc)
- Food web model (spatially explicit biomass, movement, predator-prey dynamics and harvest potential for model groups/species)

### Outputs:

- Assessment and implications of nutrient variability for water quality and fisheries in nearshore and offshore habitats

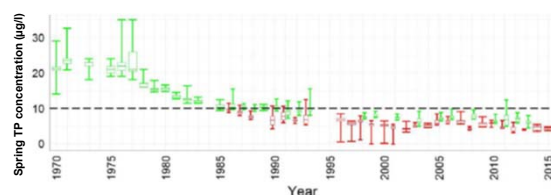
## Conclusions

- EwE models are useful, and can be used to inform managers how current and future stressors will affect fisheries production, and allow evaluation of potential actions.
- Continued dialogue and meetings between Managers and Modelers will improve these models and their usefulness to Managers. In turn, managers may grow to trust the information provided by the models
- Let's keep the lights on!

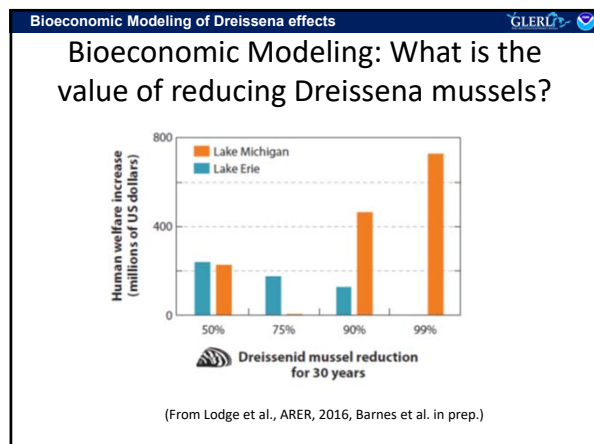
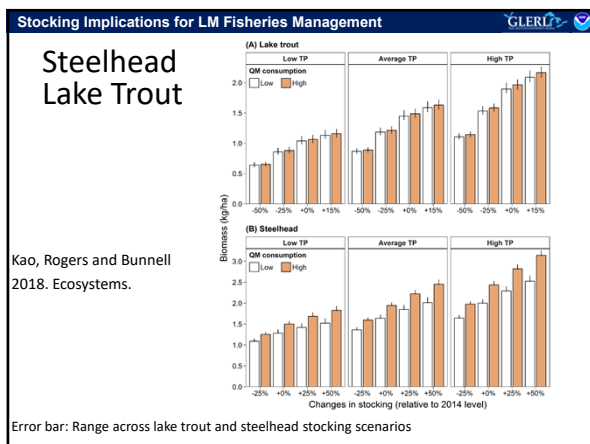
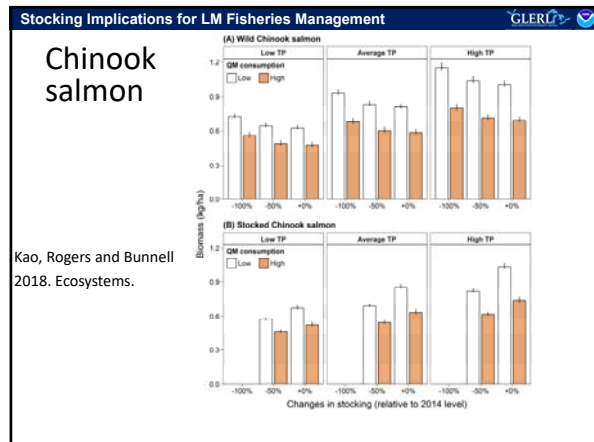
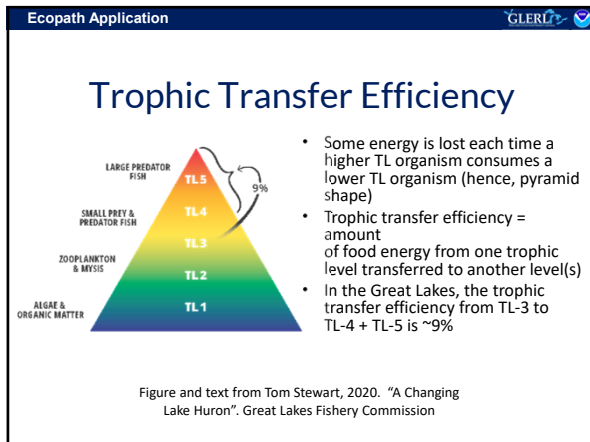
## Acknowledgments

- Funding agencies: GLFC, EPA GLRI, NOAA GLERL
- Scientists and managers at Provincial, State, and Federal Agencies and universities who collaborated and shared data

## TP concentrations have declined in several Great Lakes



Lake Ontario data and figure from Limnotech 2018: Final report to International Joint Commission



# Atlantis Ecosystem Modeling Framework

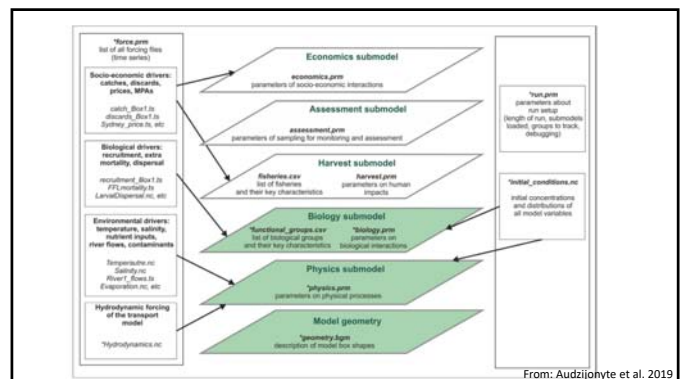
Nick Boucher, David Cannon, Ayume Fujisake-Manome, Beth Fulton, Bec Gordon, Haoguo Hu, James Kessler, Doran Mason, Edward Rutherford, Jia Wang, Hongyan Zhang

## Outline

- What is the Atlantis Ecosystem Modeling Framework?
- How has it been used?
- How can it be used in the Great Lakes?

## What is it?

- Deterministic, dynamic, 3-dimensional, end-to-end model integrating physics, geochemistry, biology, fisheries management and assessment, and economics
- Modular by design
- Developed by scientists at the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO)



# Processes modeled

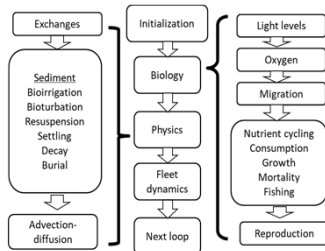
```

graph TD
    Exchanges[Exchanges] --> Sediment[Sediment  
Bioirrigation  
Bioturbation  
Resuspension  
Settling  
Decay  
Burial]
    Sediment --> Advection[Advection-diffusion]
    Initialization[Initialization] --> Biology[Biology]
    Biology --> Physics[Physics]
    Physics --> Fleet[Fleet dynamics]
    Fleet --> NextLoop[Next loop]
    Light[Light levels] --> Oxygen[Oxygen]
    Oxygen --> Migration[Migration]
    Migration --> Nutrient[Nutrient cycling  
Consumption  
Growth  
Mortality  
Fishing]
    Nutrient --> Reproduction[Reproduction]
    Exchanges -.-> Initialization
    Exchanges -.-> Light
    Exchanges -.-> Migration
    Exchanges -.-> Nutrient
    Exchanges -.-> Reproduction
  
```

The diagram illustrates the modeled processes in a sediment model, organized into three main vertical columns connected by a central bracket and a right-side bracket.

- Left Column:**
  - Exchanges** (top box)
  - Sediment Bioirrigation Bioturbation Resuspension Settling Decay Burial** (middle box, containing multiple processes)
  - Advection-diffusion** (bottom box)
- Middle Column:**
  - Initialization** (top box)
  - Biology** (second box)
  - Physics** (third box)
  - Fleet dynamics** (fourth box)
  - Next loop** (bottom box)
- Right Column:**
  - Light levels** (top box)
  - Oxygen** (second box)
  - Migration** (third box)
  - Nutrient cycling Consumption Growth Mortality Fishing** (fourth box, containing multiple processes)
  - Reproduction** (bottom box)

Flow arrows indicate the primary sequence of processes: Exchanges → Sediment processes → Advection-diffusion; Initialization → Biology → Physics → Fleet dynamics → Next loop; and Light levels → Oxygen → Migration → Nutrient processes → Reproduction. A large bracket on the left connects the three columns, and a large bracket on the right connects the three columns.



## Highlights of some of the features

- Passively advected tracers (e.g., nutrients, oxygen) and actively moving tracers (e.g., organism movement driven by habitat quality, foraging, season, and/or density)
- Primary producers dependent upon nutrients, light, space, and species specific growth rate and mortality
- Predation is determined by predator-prey interaction matrix modified by prey availability (e.g., spatial overlap, refuge, spawning time, gape-limitations) in a functional response model
- Maintenance costs modeled (e.g., respiration)
- Early life stages not modeled, however use stock-recruitment relationships

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## Some challenges

- Very complex model
- Data needs are intense
- Requires a multi-disciplinary team of people
- Traditional sensitivity analysis is not possible
- Parameter uncertainty is often evaluated by bounding the particular parameters

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Locations of existing Atlantis models (over 30)



A world map with a light gray background showing the locations of existing Atlantis models. Over 30 orange dots are plotted on the map, indicating the geographical distribution of these models. The dots are concentrated in North America (USA and Canada), Europe, Africa, and Southeast Asia, with a few scattered dots in the Pacific and South America.



## Applications

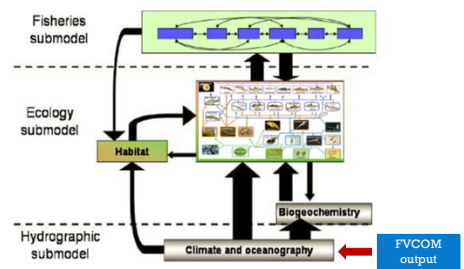
- Best used for scenario-based evaluations of competing forcing factors and simulating what-if scenarios
- Ecosystem-based applications have included:
  - Fisheries assessment and management
  - Assessment of ecosystem indicators
  - Evaluation of marine protected areas
  - Effects of anthropogenic stressors:
    - Climate change
    - Invasive species
    - Fishing pressure
    - Ocean acidification
    - Eutrophication
    - Oil spills

## Lake Michigan example

## Objectives

- Use outputs of Lake Michigan FVCOM hydrodynamics model, and nutrient inputs from GLERL watershed hydrology model, as inputs to the Atlantis Ecosystem Model;
- Calibrate the Atlantis Ecosystem Model for the 1994-2020 period;
- Use linked model system to simulate food web and fisheries response to nutrients, invasive mussels, and climate (cold vs warm years).
- Funding for this projects: Great Lakes Restoration Initiative, Great Lakes Fishery Trust

## Atlantis Ecosystem Model for Lake Michigan

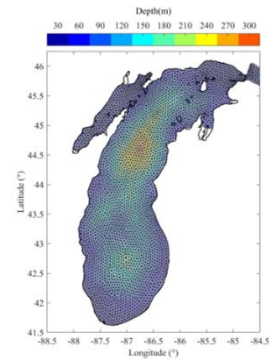


## Data sources

- Nutrients (GLERL, EGGLE, EPA, GLNPO)
- Plankton, benthos, and fish: Ecopath for LM (Rutherford et al. 2021, USGS fish surveys, EPA GLNPO)
- Water temperature and hydrodynamics (FVCOM)
- Solar radiation (Field observations)
- Fish stocking data (Great Lakes fish stocking database)
- Fisheries catch data (commercial and recreational)

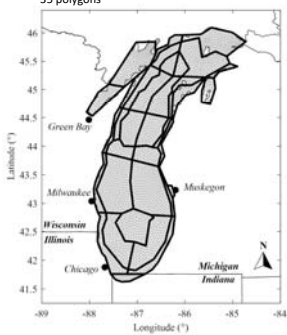
## Hydrodynamics Model

- Finite Volume Community Ocean Model
  - Resolution: ~5km: 21 sigma layers
  - Leapfrog integration scheme<sup>1</sup>
  - Mixing: MY 2.5b + wind waves<sup>2</sup>
  - Ice dynamics: CICE<sup>3</sup>
  - No Mass flux or data assimilation
- Atmospheric forcing
  - 1979 – 2021: NARR
  - 2010 – 2100: CMIP-GFDL
- Output
  - Water temperature
  - Horizontal and current direction and velocities
  - Vertical mixing rates

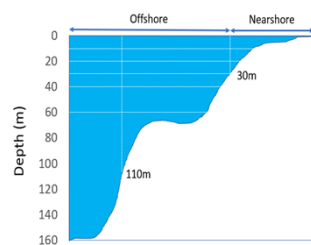


<sup>1</sup>Bai et al. 2020; <sup>2</sup>Bai et al. 2013; <sup>3</sup>Hunke & Dukowicz, 1997

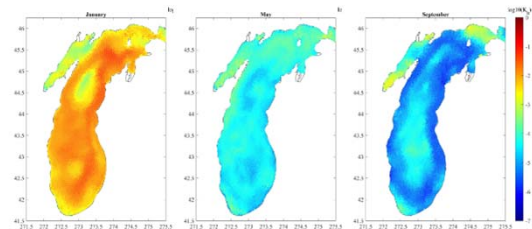
Horizontal spatial domain  
35 polygons



Vertical spatial domain  
Up to 6 layers

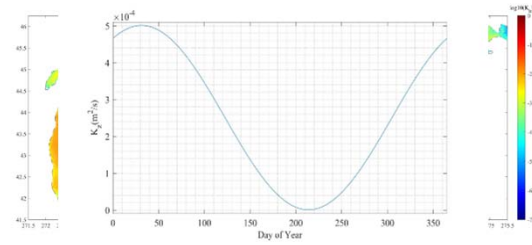


## Vertical mixing seasonality



- Need to account for highly variable seasonal mixing conditions

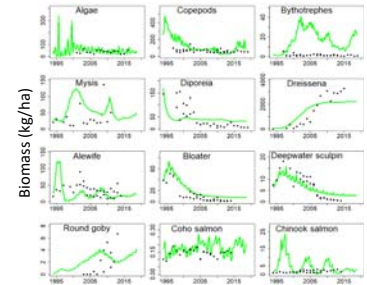
## Vertical mixing seasonality



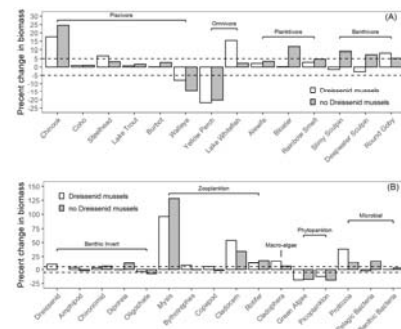
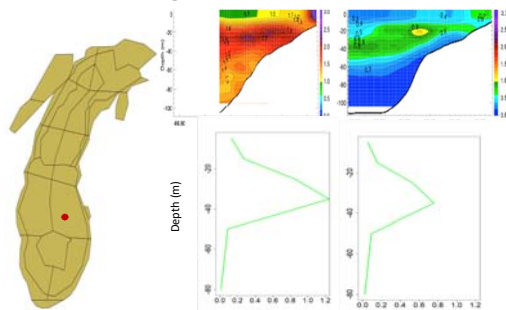
- Need to account for highly variable seasonal mixing conditions
- Atlantis modified to implement sinusoidal seasonal variability in grid cells

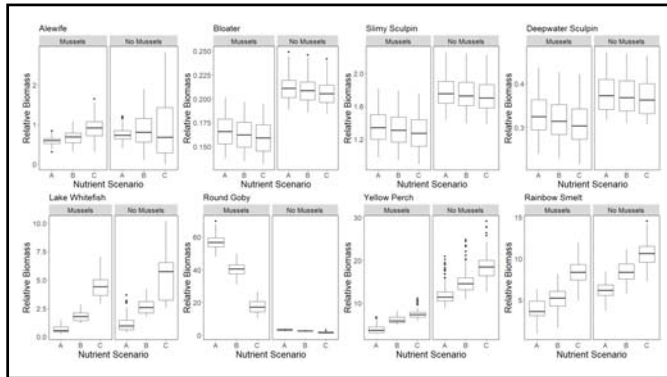
## Atlantis model calibration

- Green line: model output
- Black dots: observations
- Model is fairly good for some species, but poor for others (e.g., Bythotrephes)



## Calibration: algal vertical distribution





## Summary

- Atlantis Ecosystem Modeling Framework is best used as scenario-based exercise to evaluate competing factors or the effects of multiple factors (e.g., climate change, fisheries harvest, invasive species, nutrients, etc)
- Integrates physics, chemistry, biology, fisheries management and assessment, and economics in a 3-dimensional spatial domain
- The approach is extremely complex and is likely best used in the context of a multiple modeling approach using models of different complexities
- The application of this approach is best used in concert with discussions and interactions with managers to define needs and competing issues managers need to contend with.

***Ecosystem Behaviors:  
A World beyond the Scope of Physics***

Robert E. Ulanowicz

Arthur R. Marshall Laboratory  
University of Florida

Center for Environmental Science  
University of Maryland

Investigating Food Webs  
November 10, 2022

***Ultimate physical reductionism is impossible  
in a heterogeneous world.***

“All causality originates from below, and there is nothing ‘down there’ but the laws of physics.”

Nobel physicists Murray Gell-mann, Stephen Weinberg and David Gross (Kauffman 2008)

**Physics is all about objects moving according to universal laws.**

Whitehead & Russell (1913)  
*Principia Mathematica*

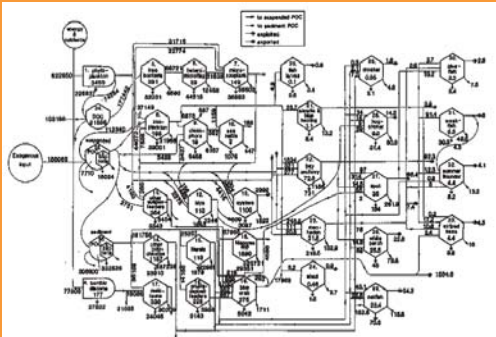
=> Logic of laws of physics limited to operations upon sets of homogeneous entities

**Ecology is all about relationships among heterogeneous processes.**

Walter Elsasser (1981) A Form of Logic Suitable for Biology

=> Any laws of biology cannot resemble the laws of physics.

Relationships are every bit as important as objects.  
Chesapeake mesohaline ecosystem flow network  
(Baird & Ulanowicz 1989)



*Configurations of process relationships  
constitute the causal foundations of life.*

Tiezzi's dead deer:

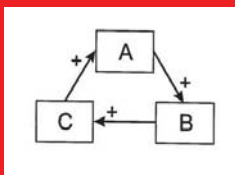
Same mass, molecules, genes, bound energy

So what's missing?

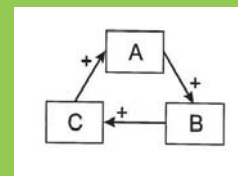
Answer: Configuration of processes

*Causality can be distributed over more than  
just two entities.*

Example: Autocatalysis



Autocatalysis can exert endogenous  
facultative selection within a system.



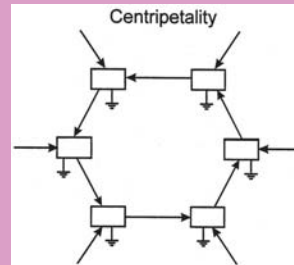
Can select beneficial changes in the performance of individual nodes.

**Autocatalysis can be self-stabilizing and possibly served as memory before the advent of genetic coding.**

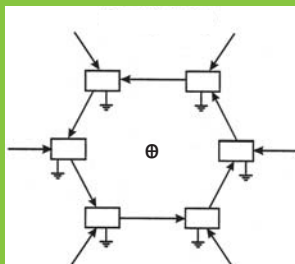
The obverse action of autocatalytic selection is to mitigate changes that diminish contingent disturbances. This effect tends to stabilize current configurations.

In higher systems and organisms the effect can also be described as “healing”.

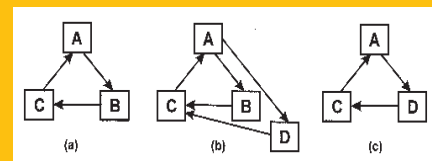
**Autocatalysis induces centripetality – the keystone to subjective tendencies.**



**Centripetality also creates a virtual center for the autocatalytic loop.**



**Can also select advantageous replacements of nodes and/or pathways, i.e., drive competition.**



## Competition is secondary to and derivative of mutual benefaction.

Competition occurs when two or more centripetal configurations overlap in a field of mutually necessary resources.

Without centripetal action (driven by mutuality) at some lower level, competition cannot occur.

## Autocatalysis imparts a temporal but non-determinate direction to system evolution.

Autocatalysis always selects changes that benefit the process of autocatalysis.

There is no fixed goal (endpoint) of the direction, which changes with each new incorporated contingency. (It is not teleology)

## Autocatalysis is semi-autonomous of universal laws (indeterminate), but not random in behavior

“Indeterminate, but non-random” sounds like an oxymoron, but simple examples exist. An analogy of such self-organization was given by John Wheeler in terms of an inventive parlor game.

## Information Theory can be invoked to quantify the degree of coherent action in a network as distinct from disordered events.

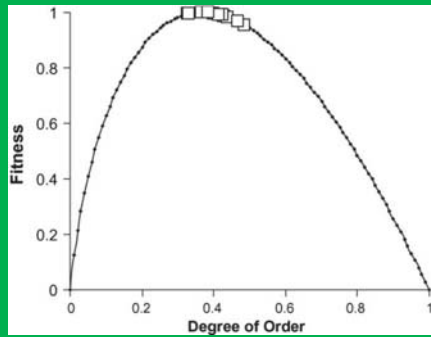
If  $T_{ij}$  represents the effect of node  $i$  upon node  $j$ , then

$$a = \{\Sigma_{ij} T_{ij} \log([T_{ij} \Sigma_{kl} T_{kl}] / [\Sigma_k T_{kj}] [\Sigma_l T_{il}])\} / \{-\Sigma_{p,q} T_{pq} \log(T_{pq} / \Sigma_{kl} T_{kl})\} \geq 0$$
 measures the degree of coherent action in the system, while

$$o = \{\Sigma_{ij} T_{ij} \log([T_{ij}^2] / [\Sigma_k T_{kj}] [\Sigma_l T_{il}])\} / \{\Sigma_{p,q} T_{pq} \log(T_{pq} / \Sigma_{kl} T_{kl})\} \geq 0,$$
 quantifies disorder among processes.

Since  $a + o = 1$ , the measures are strictly complementary (i.e., in dialectical opposition).

### Window of Vitality



**Indirect mutualism is the crux of agency – a dynamic that does not simply respond to events, but can make qualitatively new things happen.**

Simple physical forces are driven by external constraints. They can express no choice among what interacts with or guides them. Agency, however, selects from among the myriad of impinging actions those which benefit its own actions. It thereby “creates” its own new dynamics.

**Eugene P. Odum (Science Magazine 1977)**

*“To achieve a truly holistic or ecosystematic approach, not only ecology, but other disciplines in the natural, social and political sciences as well must emerge to new hitherto unrecognized and unrestricted levels of thinking and action.”*