Systems Ecology Case Studies

Systems Ecology for Aquatic Resource Management

Systems Ecology
Beijing 2013

Earth System

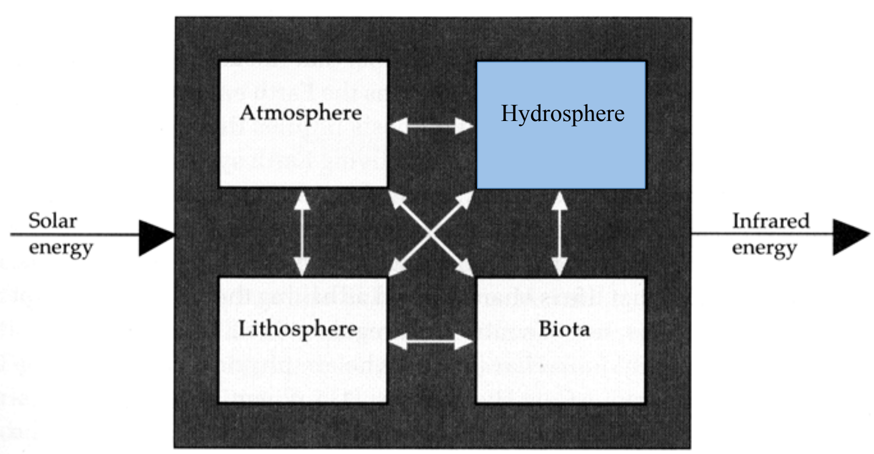
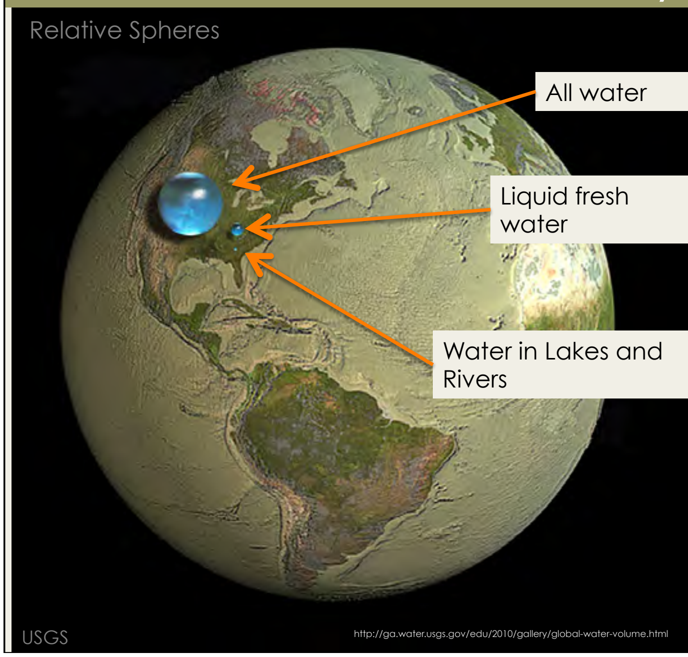


Fig. 4.2 The Earth system described in a systems context. Golley 1998

Earth is an open system (both energy and matter can cross the boundary), but we often treat it as a closed system

Water Quantity



1,386,000,000 km^3

10,633,450 km^3
(99% is ground water)

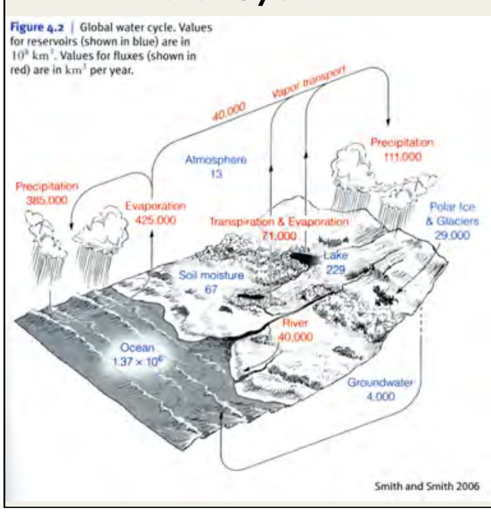
70% of earth surface is covered by water

Hydrosphere

Oceans and freshwater bodies on Earth

Jacobson et al. 2000

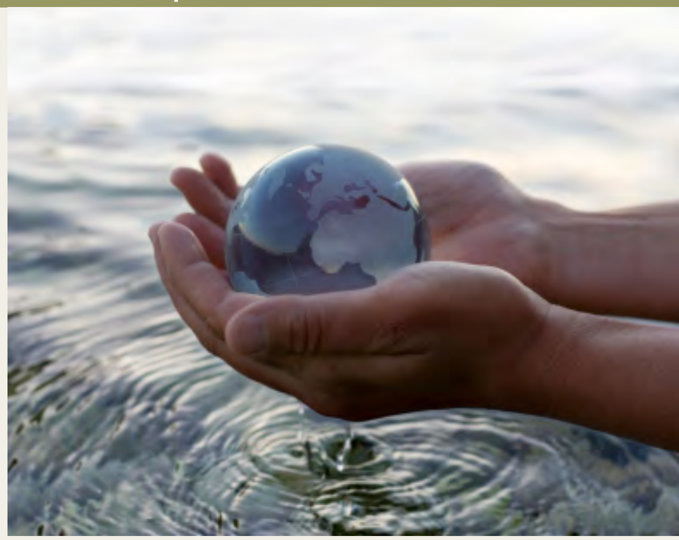
Water Cycle



World Ocean Currents

Fig 2.15

Importance of Water



http://www.lccdnet.org/wp-content/uploads/2011/01/importance-of-water-conservation.jpg

Importance for life, biogeochemistry, ecosystem services

Aquatic Ecosystem Services

Some Examples

- Food Production
- Waste water processing
- Nutrient Recycling
- Recreation
- Transportation
- Drinking Water

Case Studies

1. Shrimp Trawling in Core Sound, NC (USA)
2. Lake Sidney Lanier, GA (USA)
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Application of Throughflow Centrality

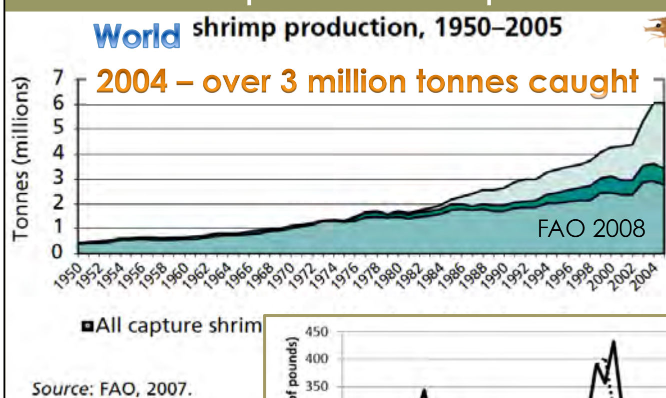
Ecosystem Impacts of Shrimp Trawling

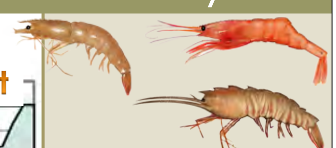
Jeff Johnson Becky Deehr
Joe Luckovich Stuart Borrett

American Fisheries Society 2012

Borrett et al. in prep.

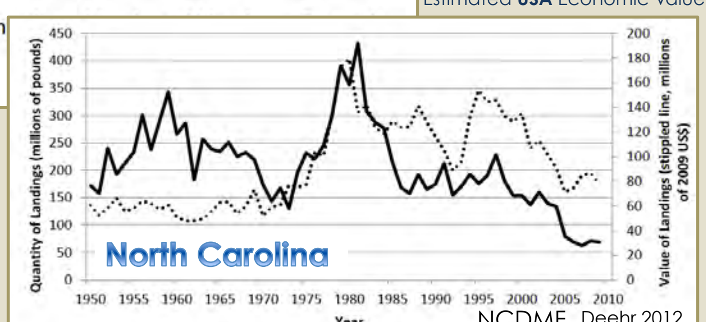
Shrimp – An important Fishery





$425 mil yr⁻¹

Estimated **USA** Economic Value

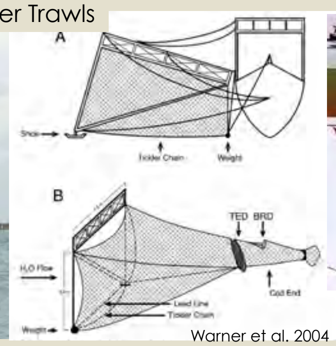


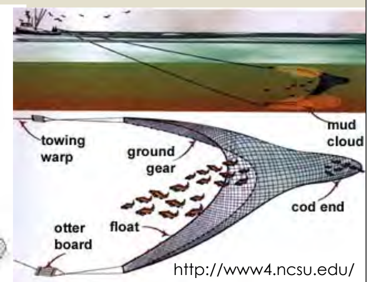
Deehr 2012

Shrimp images from fishwatch.gov

Ecosystem Impacts of Shrimp Trawling

Skimmer Trawls and Otter Trawls





Impacts

Direct impacts on shrimp populations

Bycatch (5:1)

Physical disruption of benthic habitats

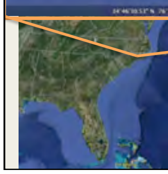
Solutions

TEDs, BRDs

Gear Type

Regulate Access (space & time)

Core Sound NC and Shrimp Nursery Areas



Nursery Areas Closed to Shrimping

Figure 11. Map of Core Sound, primary and secondary nursery areas, and the 12 sites selected for this study.

Deehr 2012

Objectives & Approach

Assess the whole ecosystem impact of shrimp trawling on the Core Sound, NC ecosystem

- Direct and indirect effects (e.g., trophic cascades)
- Focus: Relative functional importance of species (T)
- Ecosystem understanding → adaptive management

Approach

- Construct food web based ecosystem models
  - Open and Closed to trawling
- Compare areas with *Ecological Network Analysis*

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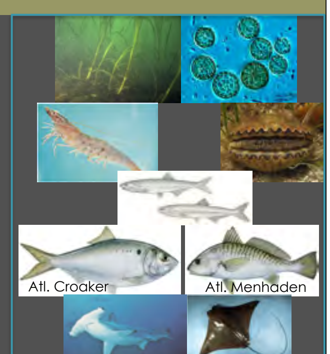
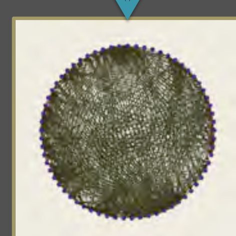
Food web ecosystem model

- **Ecopath** model
- n = 65 compartments (g C m^{-2})
  - 2 non-living compartments: bycatch and detritus
- L = 614 carbon flows (g C m^{-2} y^{-1})
  - e.g., feeding relationships
- Parameterized with primary data and literature values as needed
  - NCDMF Trip Ticket Program
- Ecopath estimated trophic level *corroborated* with stable isotopes





Deehr 2012 Dissertation

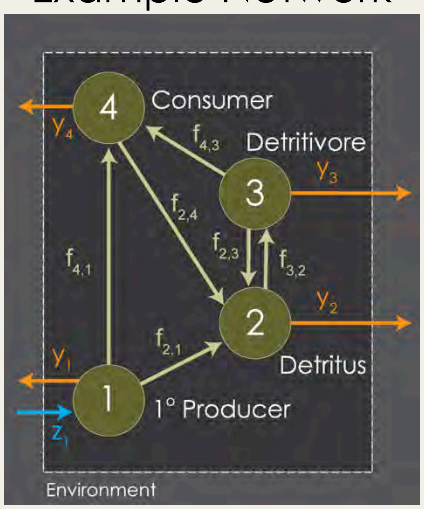
http://core.ecu.edu/BIOL/luczkovichj/core_sound/core_sound.html

Models for Comparisons

	Spring (April, May, June)	Fall (Aug., Sept., Oct.)
Closed	Least impact	
Open		Most impact

ENA Statistics (response variables)

Example Network



Throughflow

$$\vec{T} = (T_j) = \sum_{i=1}^{n} f_{ij} + y_j$$

Total System Throughflow

$$TST = \sum T_j$$

Like GDP

Finn Cycling Index

$$FCI = \frac{Cycled}{TST}$$

Recycling

Average Path Length

$$APL = \frac{TST}{\sum z_i}$$

Like multiplier effect

Centralization

characterizes the concentration or dispersion of the centrality (throughflow activity)

$$FC = \frac{\sum_i^n (T_{\max} - T_j)}{n-1}$$

Where T_{max} is the maximum value f T_j

Interpretation

Lower FC → More dispersed

Higher FC → More centralized

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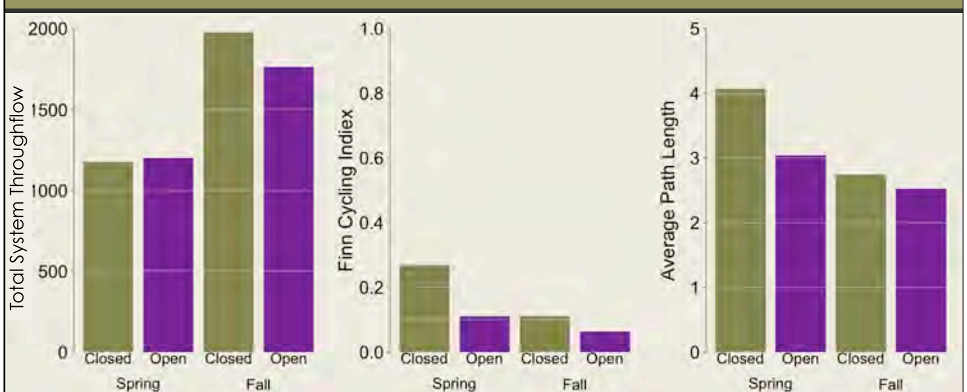
TST, FCI, and APL



Fall > Spring

Open > Closed in Spring
Closed > Open in Fall

Cycling is less in the Fall

Cycling is less with Trawling

There is more TST per unit input in the Spring-Closed model

APL is less with Trawling

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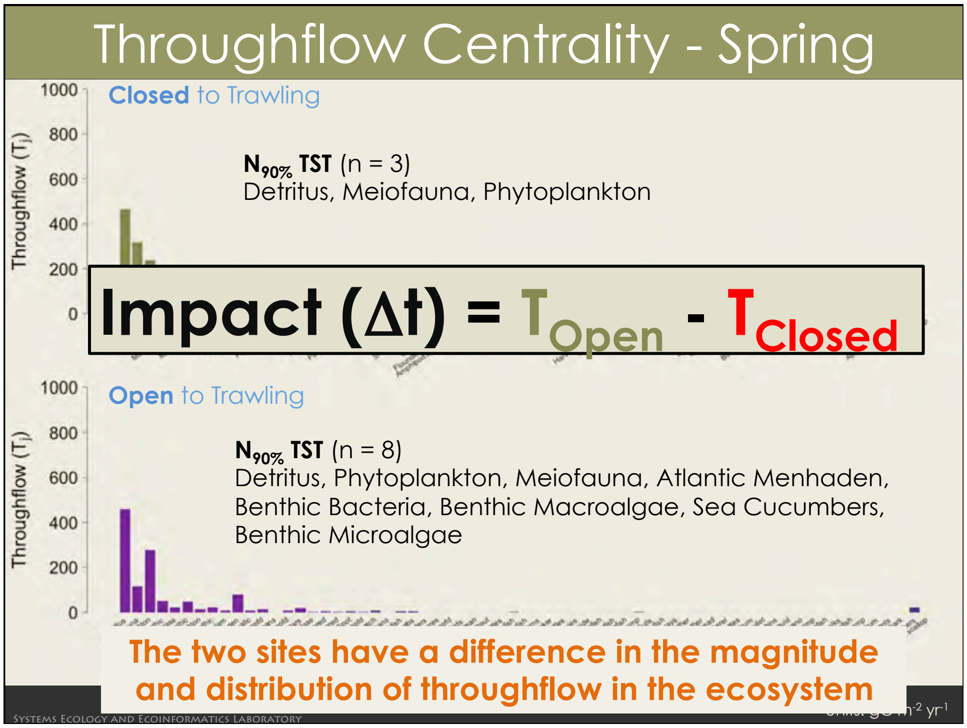
Throughflow Centrality - Spring
Closed to Trawling
Throughflow (T_j)
1000
800
600
400
200
0
N90% TST (n = 3)
Detritus, Meiofauna, Phytoplankton
Impact (Δt) = T Open - T Closed
Open to Trawling
N90% TST (n = 8)
Detritus, Phytoplankton, Meiofauna, Atlantic Menhaden,
Benthic Bacteria, Benthic Macroalgae, Sea Cucumbers,
Benthic Microalgae
The two sites have a difference in the magnitude
and distribution of throughflow in the ecosystem
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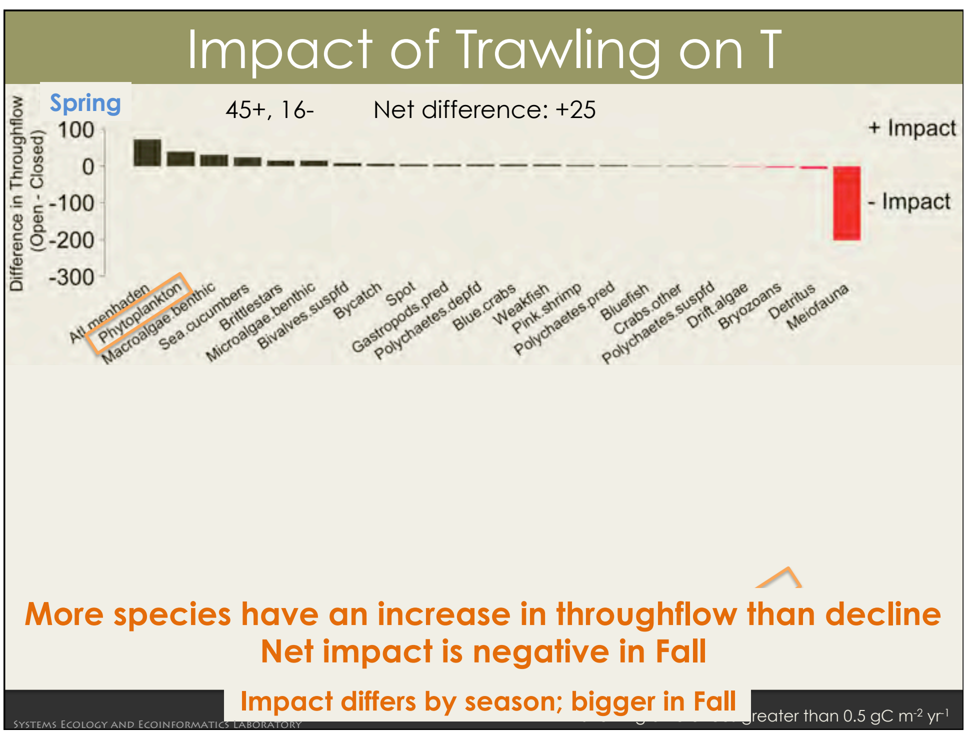
Impact of Trawling on T
Spring
45+, 16-
Net difference: +25
Difference in Throughflow
(Open - Closed)
100
0
-100
-200
-300
+ Impact
- Impact
Atl.menhaden
Phytoplankton
Macroalgae.benthic
Sea.cucumbers
Brittlestars
Microalgae.benthic
Bivalves.suspfd
Bycatch
Spot
Gastropods.pred
Polychaetes.depfd
Blue.crabs
Weakfish
Pink.shrimp
Polychaetes.pred
Bluefish
Crabs.other
Polychaetes.suspfd
Drift.algae
Bryozoans
Detritus
Meiofauna
More species have an increase in throughflow than decline
Net impact is negative in Fall
Impact differs by season; bigger in Fall
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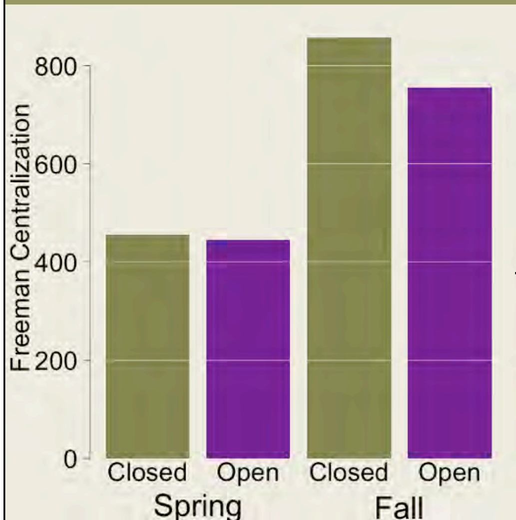
Centralization



Ecosystems open to trawling are *less* centralized.

The ecosystems are *more* centralized in the Fall

Units of dispersion are the same as T

The disturbance spreads the activity across more species.

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Summary & Discussion

- Detritus and Phytoplankton are consistently two of the most central nodes
  - Meiofauna and Atlantic Menhaden
- Trawling appears to stimulate throughflow activity in more compartments than are reduced
- Magnitude of negative impacts were greater with trawling in Fall, less in Spring
  - Suggests closing nursery areas may be appropriate
- Shrimp trawling tends to de-centralize the ecosystem activity
  - Unexpected consequence
- Network analysis shows whole ecosystem impacts (direct and indirect) of Shrimp trawling

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Case Studies

1. Shrimp Trawling in Core Sound, NC (USA)
2. Lake Sidney Lanier, GA (USA)
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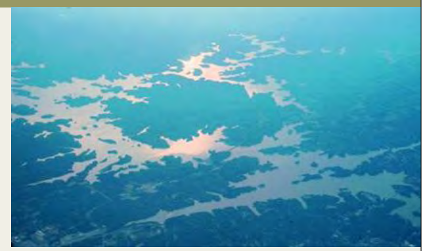
4. Cape Fear River Estuary, NC (USA)

Lake Sidney Lanier, GA, USA

Metropolitan Population 2011
5,457,831 (Wikipedia)

Lake Sidney Lanier, GA, USA



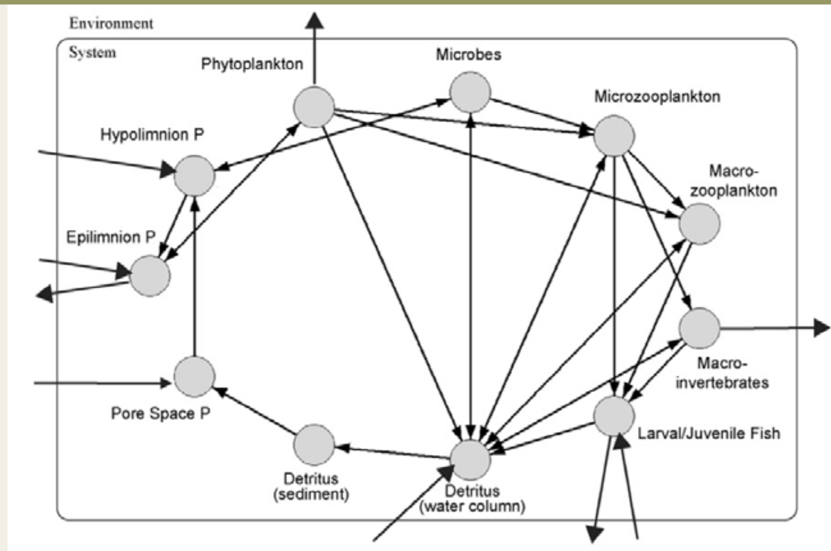
- 150 km^2 Reservoir, 1958
- Uses
  - Drinking Water Supply
  - Waste Water Discharge
  - Recreation
  - Navigation
- Challenges
  - Competing demands, stakeholders
  - Small watershed, sensitive to environmental variation
  - Eutrophication, excess Phosphorus
  - Data limitations

Project Goals

- Characterize Lake Lanier ecosystem
- Construct a phosphorus model to evaluate system state
  - Consider data uncertainty
- Apply Network Environ Analysis
  - Whole system indicators
  - Characterize sensitivity of indicators to model uncertainty

Borrett & Osidele. 2007. Ecological Modelling
Kaufman & Borrett. 2010. Ecological Modelling

Conceptual Model: P in Reservoir

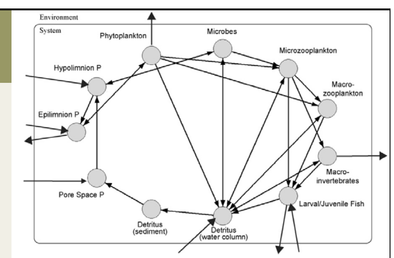


Modified from Osidele & Beck (2004)

Consistent currency: Phosphorus

Units: Flow: mg P m^{-2} d^{-1} Storage: mg P m^{-2}

Model Construction

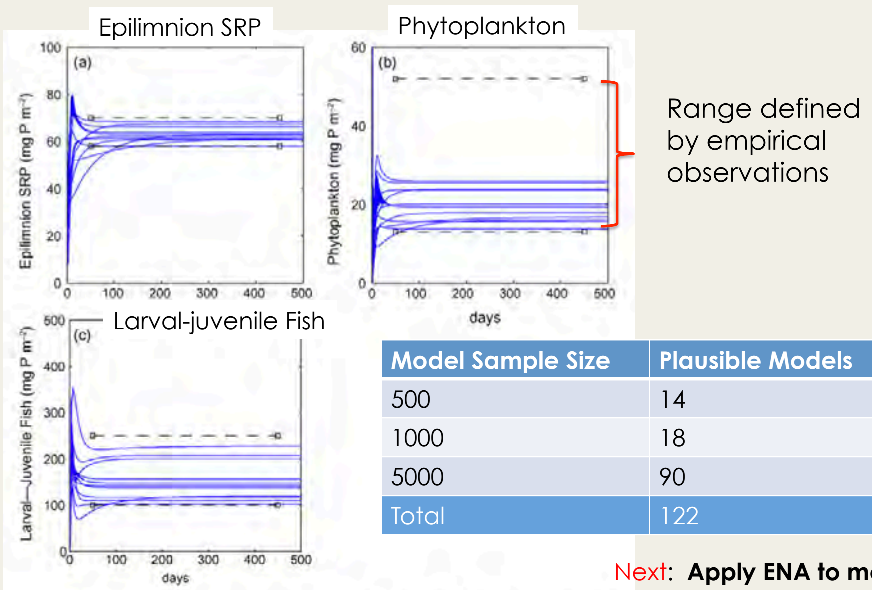


- Constant Structure (conceptual Model) →
  - 11 compartments
  - 26 within system connections
  - 5 boundary inputs, 4 boundary losses
- Identify Plausible Model Parameterizations
  - Used Regionalized Sensitivity Analysis to identify parameterizations that fit known empirical data for SRP, phytoplankton, fish, and detritus.
  - Donor controlled transfer functions
  - Monte Carlo Simulations (500, 1000, 5000)
    - Randomly select parameters from uniform distribution
    - Range based on biological knowledge
    - Compare model behavior to observed system behavior

Variable Flow and Storage → Plausible parameterizations

Examples of Plausible Model Simulations

Plausible models generated behavior within known constraints.



Model Sample Size	Plausible Models
500	14
1000	18
5000	90
Total	122

Next: **Apply ENA to models**

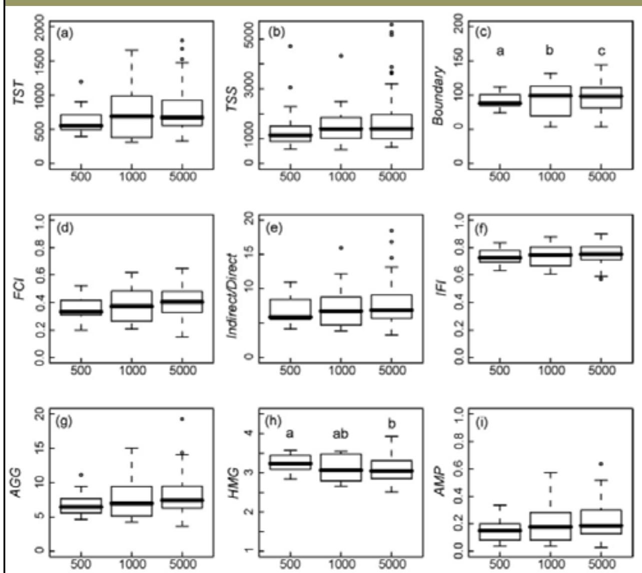
NEA Whole System Indicators

Table 1 – Network environ analysis indicators of whole-system organization

Indicator	Symbol	Description	Formula
Total system throughflow	TST	Sum of total flow into or out of nodes	$\sum_{k=1}^{n} T_k = \sum_{k=1}^{n}\sum_{k=1}^{n}(f_{kj} + z_k) = \sum_{k=1}^{n}\sum_{k=1}^{n}(f_{ik} + y_k)$
Total system storage	TSS	Total amount of model currency stored in nodes	$\sum_{k=1}^{n} x_k$
Total boundary flow	Boundary	Total amount of boundary input or output	$\sum_{i=1}^{n} z_i = \sum_{j=1}^{n} y_j$
Finn cycling index	FCI	Cyclic portion of TST	$\sum_{i=1}^{n}((n_{ii} - 1)z_i)$
Indirect/direct	Indirect/Direct	Ratio of indirect to direct flow	$\frac{\sum(\mathbf{N} - \mathbf{I} - \mathbf{G})\mathbf{z}}{\sum \mathbf{G}\mathbf{z}}$
Indirect flow index	IFI	Proportion of TST derived from indirect flows	$\frac{\sum(\mathbf{N} - \mathbf{I} - \mathbf{G})\mathbf{z}}{\mathrm{TST}}$
Homogenization	HMG	Tendency to uniformly distribute causality across the network	$\frac{\mathrm{CV(G)}}{\mathrm{CV(N)}}$
Amplification	AMP	Proportion of flows obtaining more than face value	$\frac{\# n_{ij} > 1\,(i \neq j)}{n(n-1)}$
Aggradation[a]	AGG	Average number of times an average input passes through the system	$\frac{\mathrm{TST}}{\mathrm{Boundary}}$

[a] Aggradation is also known as average path length (Finn, 1976), flow multiplying ability (Han, 1997), and multiplier effect (Samuelson, 1948).

Indicator Results

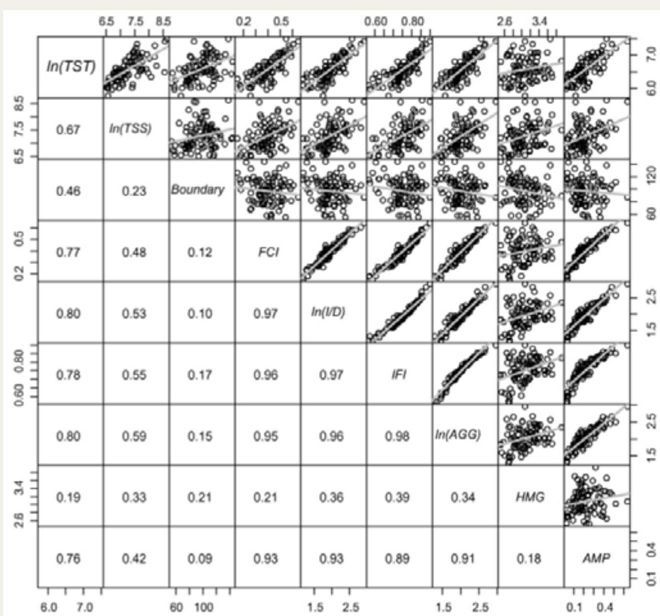


14, 18, 90 models

Conclusions

1. 90 models is sufficient sample size of plausible models,
2. Considerable uncertainty remains
3. Network non-locality, aggradation, homogenization, and amplification are present
4. Average Phosphorus recycling 39%

Indicator Correlations



Not all Indicators are independent!

Indicator redundancy?

Significance?

Borrett & Osidele 2007

Statistical Factor Analysis

Table 5 – Principle components factor analysis

Variable	Factor 1	Factor 2	Uniqueness
ln(TST)	0.84	0.53	0.01
ln(TSS)	0.61	0.28	0.55
Boundary	−0.09	0.99	0.01
FCI	0.95	−0.04	0.09
ln(Indirect/Direct)	0.96	−0.02	0.07
IFI	0.98	−0.09	0.04
ln(AGG)	1.00	−0.07	0.01
HMG	0.34	−0.18	0.85
AMP	0.91	−0.01	0.17
Loading sums of squares	5.81	1.40	
Proportion of variance	0.65	0.16	
Cumulative variance	0.65	0.80	

2 key latent factors
Explain 80% variation

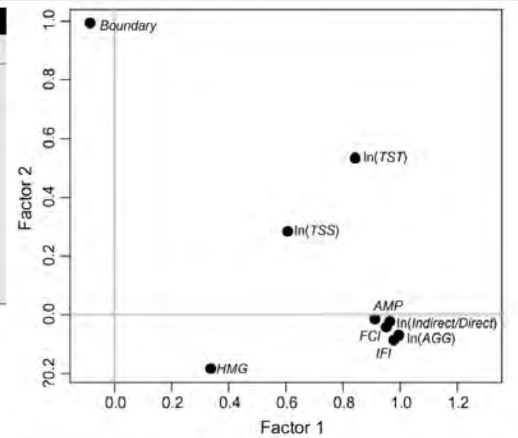


Fig. 5 – Factor analysis loadings plot. Distance from the origin to an indicator implies the strength of its association with a factor. For example, Boundary is highly associated with Factor 2 and has little common variation with Factor 1.

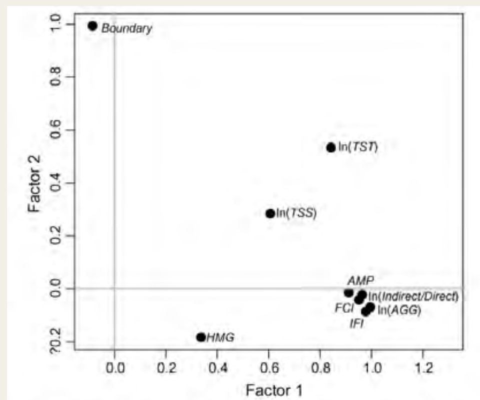
Borrett & Osidele 2007

Conclusions (1)

- Small variability in the ecosystem indicators lets us
  - circumvent part of the modeling and data uncertainty
  - draw more robust conclusions regarding the condition of the Lake Lanier ecosystem
- FCI, Indirect/Direct, IFI, AGG, and HMG are robust to to model uncertainty
- Internal processes heavily influence phosphorus flow and storage
  - Well developed ecosystem
  - P is well mixed (HMG)
  - Changing system dynamics would be difficult by simply changing the nutrient inputs

Conclusions (2)

- Common indicator variation can be mapped onto two factors
- Tentative Interpretation
  - Factor 1
    - system integration
    - Network growth
    - Growth Form II
  - Factor 2
    - Boundary growth
    - Growth Form 0



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Temporal Variation of Indirect Effects in the Neuse River Estuary


ECOLOGICAL MODELLING 194 (2006) 178–188

available at www.sciencedirect.com

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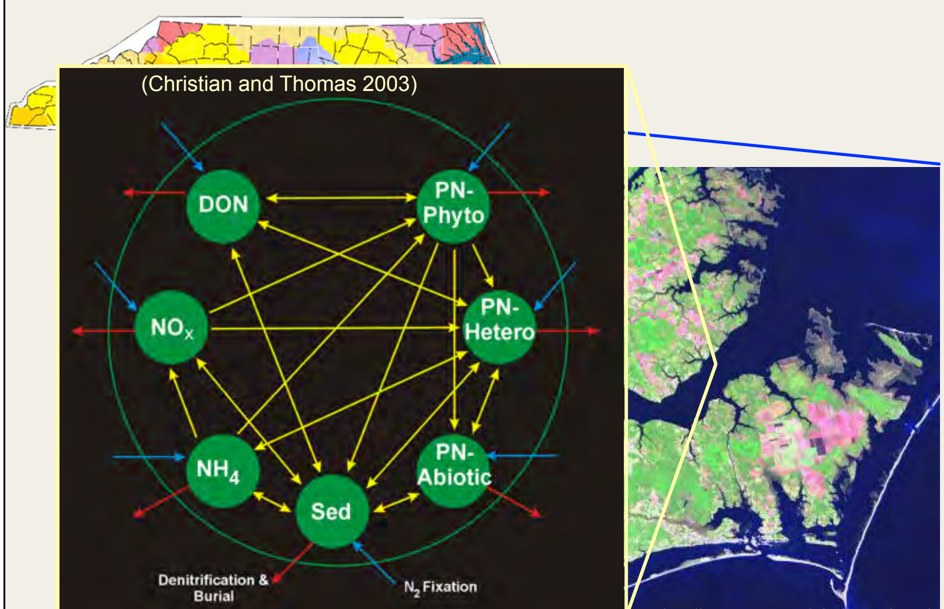
journal homepage: www.elsevier.com/locate/ecolmodel

Indirect effects and distributed control in ecosystems: Temporal variation of indirect effects in a seven-compartment model of nitrogen flow in the Neuse River Estuary, USA—Time series analysis

Stuart R. Borrett[a,b,*], *Stuart J. Whipple*[b], *Bernard C. Patten*[a], *Robert R. Christian*[c]

[a] *Institute of Ecology, University of Georgia, Athens, GA 30606, USA*
[b] *Skidaway Institute of Oceanography, 10 Ocean Science Circle, Savannah, GA 31411, USA*
[c] *Biology Department, East Carolina University, Greenville, NC 27858, USA*

Neuse River Estuary, NC



Objectives

Q: Should the 30% decrease in N loading rapidly alter the system's trophic state?

H_1: Indirect effects are dominant

If indirect effects are dominant, then we would not expect rapid change

H_2: Indirect effects vary seasonally; moderate inter-annual variation

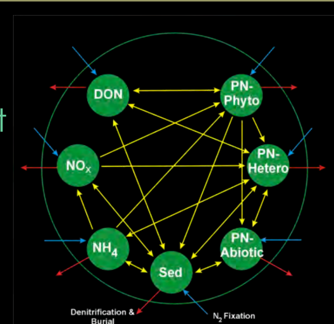
discrete-time series analysis

Throughflow Decompositions & Indirect Flows

1. TST = Boundary + Direct + Indirect

   Indirect/Direct

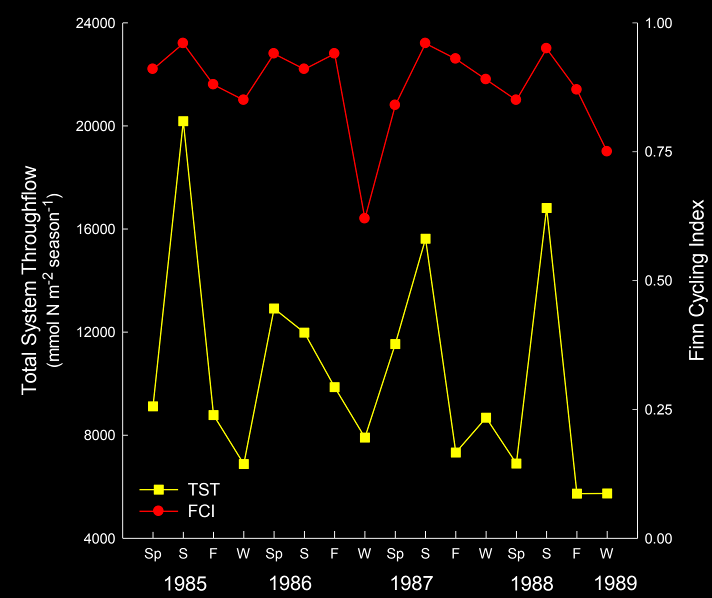
   Indirect/TST



2. TST = non-Cycled + Cycled (Finn 1976)

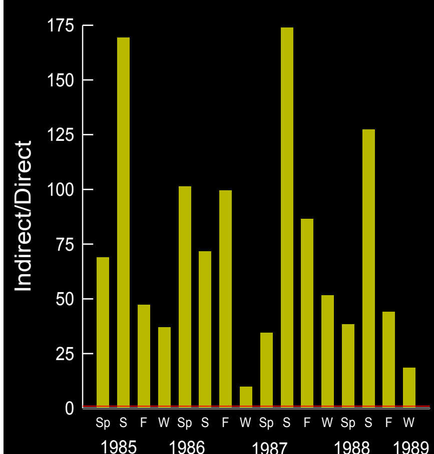
   Finn Cycling Index = Cycled/TST

TST and FCI



Indirect Effects

H_1: Indirect flows are dominant

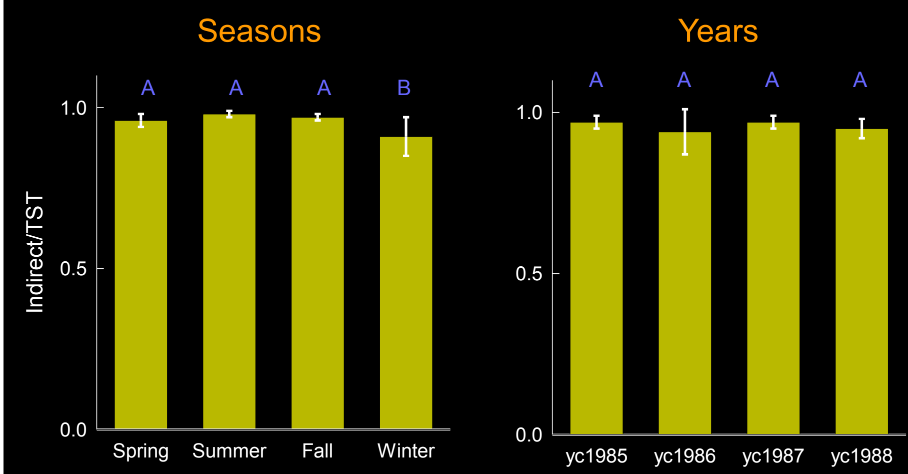


System	Currency	Indirect/Direct
cold spring	energy	1.02
oyster reef, SC	energy	1.58
forest, Puerto Rico	nitrogen	6.14
Lake Lanier, GA	phosphorus	7.45

Indirect Flows Dominate

Temporal Variation

H_2: Indirect flows vary seasonally; moderate inter-annual variation



Little Temporal Variation

Summary & Conclusions

- Indirect flow dominates direct
- Stable ecosystem organization
- N load reduction will not have rapid effect on trophic state of estuary

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Hines et al. 2012, Hines et al. in review

Nutrients in Estuarine Waters

Ecosystem Services

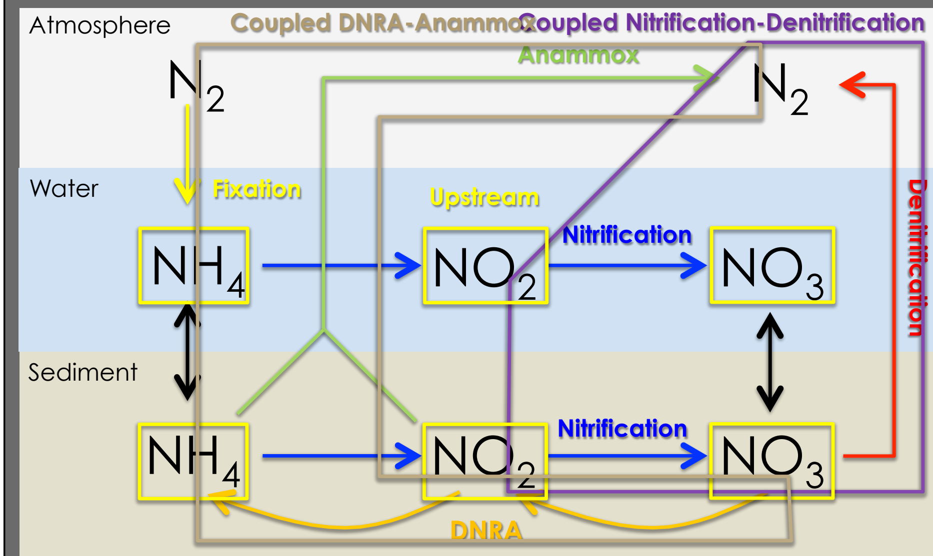
Recycling and removal of nutrients

(Costanza et al., 1998)

Eutrophication

Nitrogen Cycling and Removal

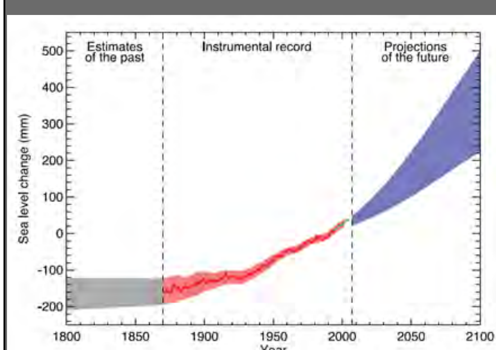
Simplified Nitrogen Cycle



Coupled processes → indirect pathways

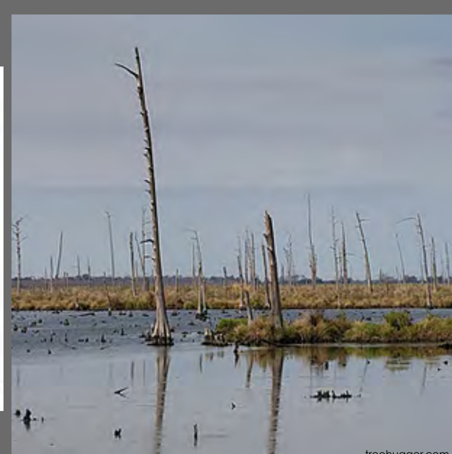
Complications

Sea level rise



Average rise of 1.7mm $year^{-1}$

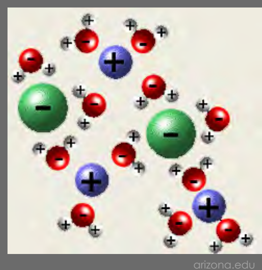
(IPCC, 2007)

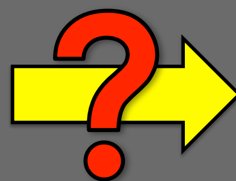


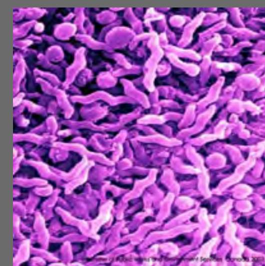
Salt water intrusion

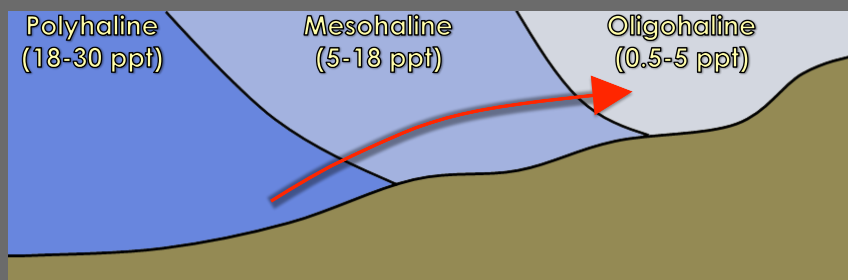
(Giese et al. 1985)

Effects on Microbes









Hypotheses

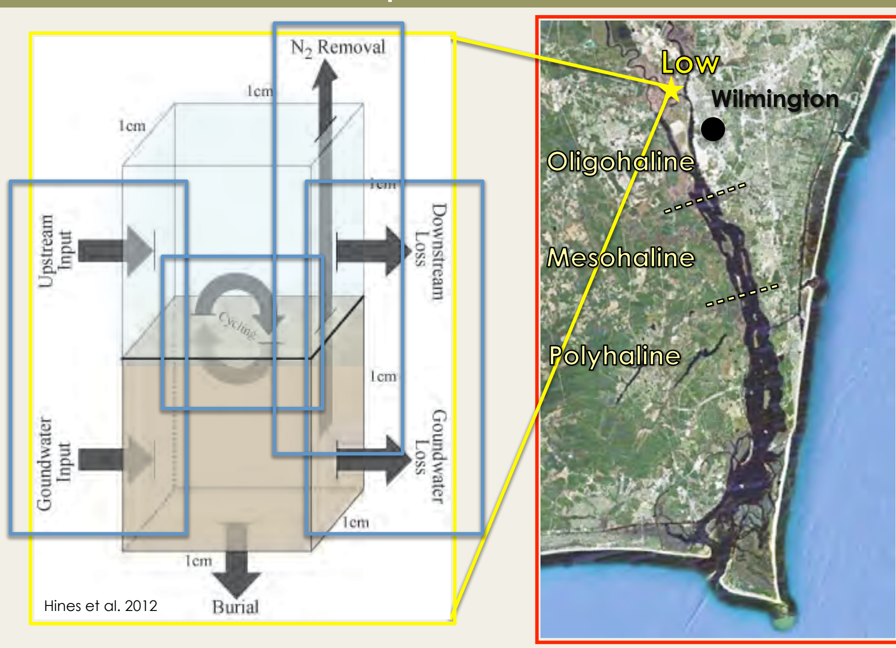
H_1: Coupled nitrification-denitrification will be higher in the oligohaline portion of the estuary compared to polyhaline sites

H_2: Coupled DNRA-anammox will be lower in the oligohaline portion of the estuary compared to polyhaline sites

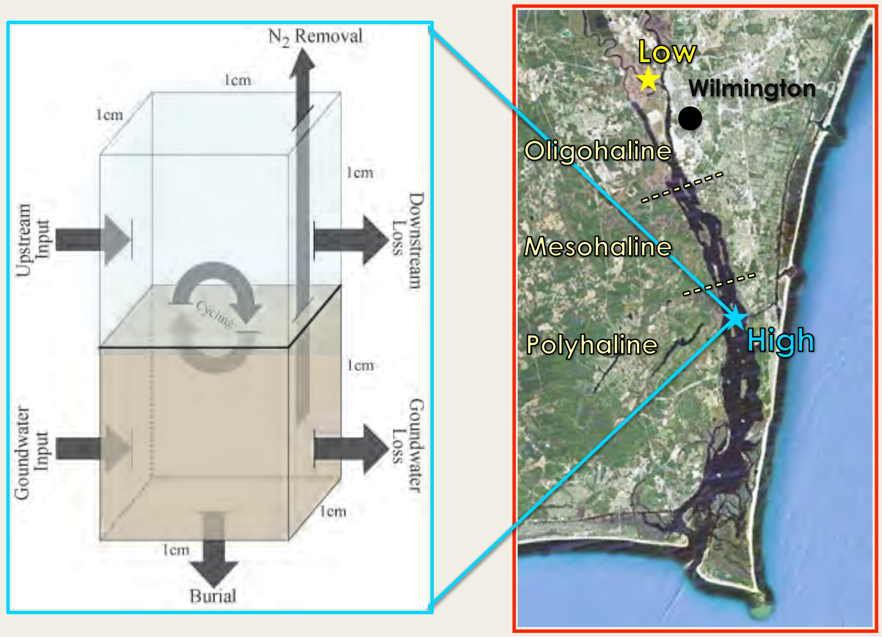
H_3: Microbial nitrogen removal capacity will be higher in the oligohaline portion of the estuary compared to polyhaline sites

Study Sites

Conceptual Model

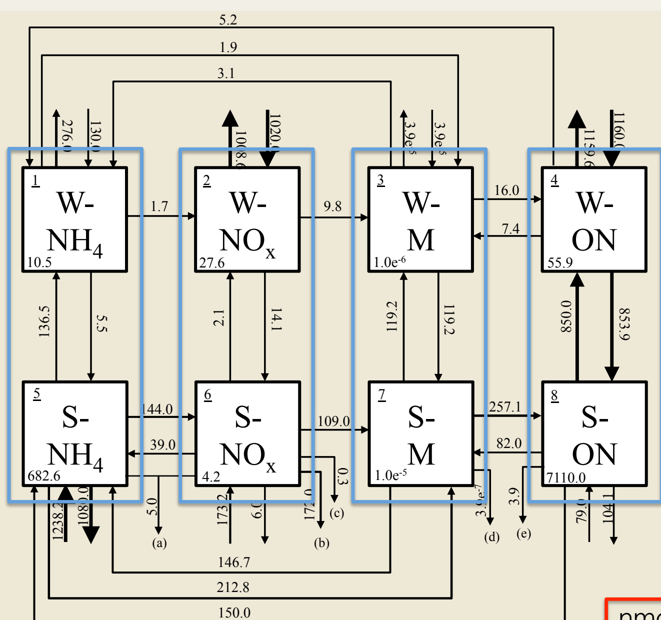


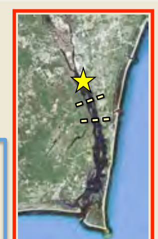
Conceptual Model



Low Network Model

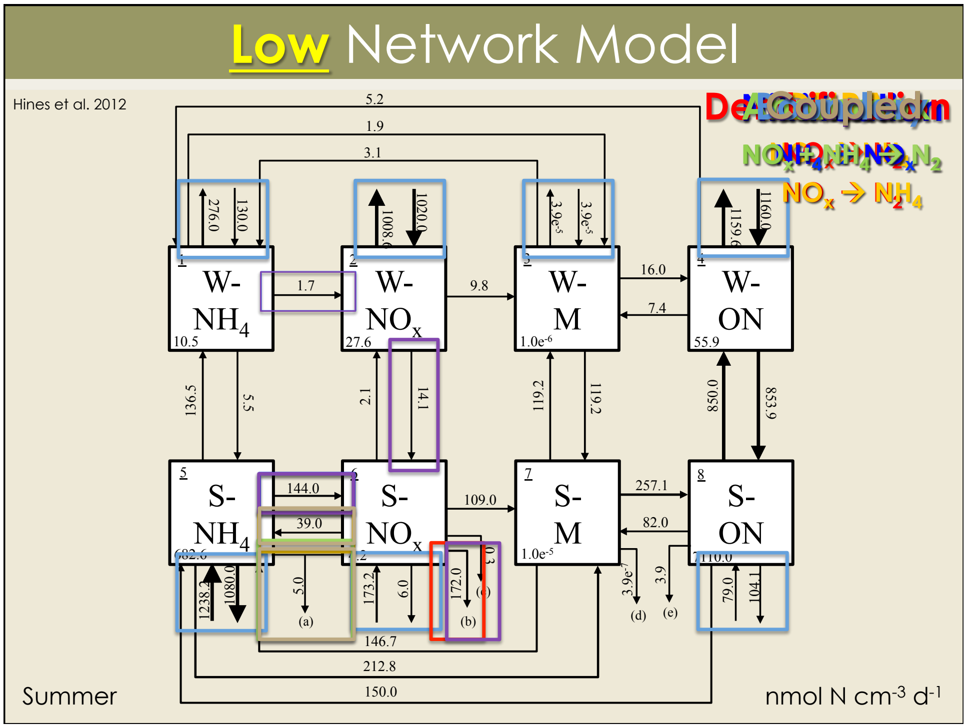
Hines et al. 2012

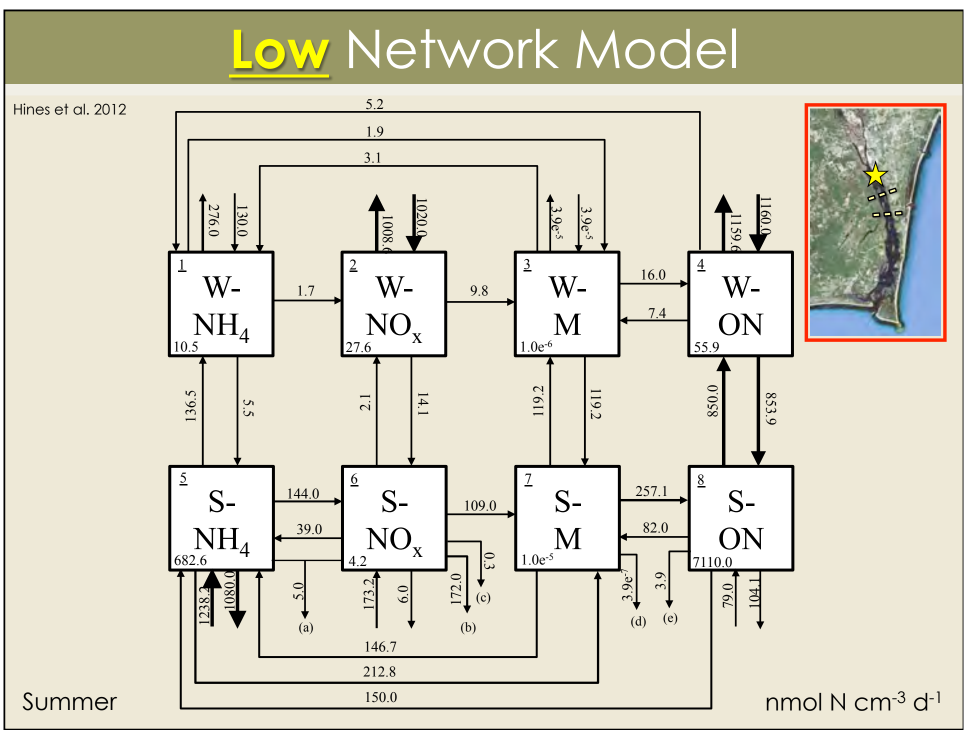




Summer

nmol N cm^{-3} d^{-1}


Low Network Model
Hines et al. 2012
NOx → NH4
W-NH4 10.5
W-NOx 27.6
W-M 1.0e-6
W-ON 55.9
S-NH4 682.6
S-NOx 4.2
S-M 1.0e-5
S-ON 7110.0
5.2
1.9
3.1
276.0
130.0
1008.0
1020.0
3.9e-5
3.9e-5
1159.6
1160.0
1.7
9.8
16.0
7.4
136.5
5.5
2.1
14.1
119.2
119.2
850.0
853.9
144.0
39.0
109.0
257.1
82.0
0.3
1238.2
1080.0
5.0
173.2
6.0
172.0
3.9e-7
3.9
79.0
104.1
(a)
(b)
(c)
(d)
(e)
146.7
212.8
150.0
Summer
nmol N cm-3 d-1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W-NH4 10.5
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6.0
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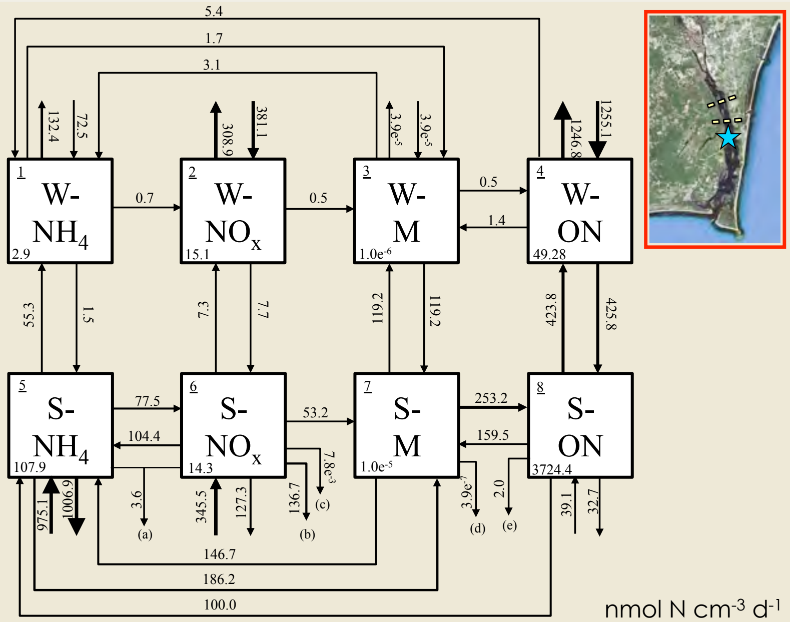
3.9e-7
3.9
79.0
104.1
(a)
(b)
(c)
(d)
(e)
146.7
212.8
150.0
Summer
nmol N cm-3 d-1

High Network Model



Summer

nmol N cm^{-3} d^{-1}

Polyhaline Model Parameterization Evaluation

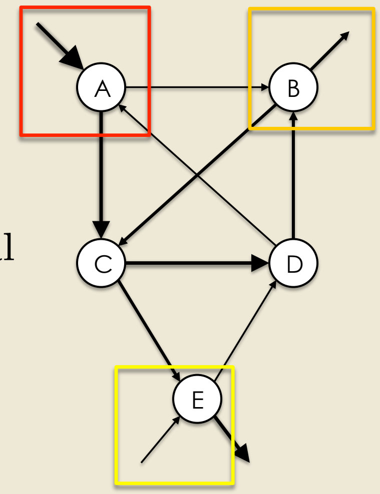
Table 1
List of the CFRE N cycle model fluxes, parameters values (nmol N cm^{-3} d^{-1}), and data sources. Confidence levels (High (H), Medium (M) and Low (L)) were assigned to parameters based on the quality ranking scale developed by Costanza (1992).

Flux	Value	Source	Confidence
Boundary → W–NH_4	130.0	Direct measurements Hirsch (2010); Ensign et al. (2004)	H
Boundary → W–NO_x	1020.0	Direct measurements Hirsch (2010); Ensign et al. (2004)	H
Boundary → W–ON	1160.0	Direct measurements Mallin et al. (2010); Ensign et al. (2004)	H
Boundary → S–NO_x	173.2	Direct measurements Hirsch (2010); Ensign et al. (2004)	H
W–NH_4 → Boundary	276.0	Direct measurements Hirsch (2010); Ensign et al. (2004)	H
W–NO_x → Boundary	1008.6	Direct measurements Hirsch (2010); Ensign et al. (2004)	H
W–ON → Boundary	1159.6	Direct measurements Mallin et al. (2010); Ensign et al. (2004)	H
S–NH_4 Anammox	2.5	Direct measurements Hirsch (2010)	H
S–NO_x Anammox	2.5	Direct measurements Hirsch (2010)	H
S–NO_x Denitrification	172.0	Direct measurements Hirsch (2010)	H
S–NO_x → S–NH4	39.0	Graham (2008)	H
Boundary → W–M	$3.9e^{-5}$	Whitman et al. (1998)	M
Boundary → S–ON	79.0	Jordan et al. (1983)	M
W–M → Boundary	$3.9e^{-5}$	Whitman et al. (1998)	M
S–NO_x → Boundary	6.0	Tobias et al. (2001)	M
S–ON → Boundary	104.1	Jordan et al. (1983)	M
W–NH_4 → S–NH_4	5.5	Cowan et al. (1996)	M
W–NO_x → S–NO_x	14.1	Cowan et al. (1996)	M
W–M → S–M	119.2	Cowan et al. (1996)	M
S–NO_x → W–NO_x	2.1	Cowan et al. (1996)	M
S–M → W–M	119.2	Cowan et al. (1996)	M
S–ON → W–ON	850.0	Grant et al. (1997)	M
W–NH_4 → W–NO_x	1.7	Berounsky and Nixon (1993); Kemp et al. (1990)	M
W–NH_4 → W–M	1.9	Veuger et al. (2004)	M
W–NO_x → W–M	9.8	Veuger et al. (2004)	M
W–ON → W–NH_4	5.2	Pujo-Pay et al. (1997)	M
W–ON → W–M	7.4	Veuger et al. (2004)	M
S–NH_4 → S–NO_x	144.0	Henriksen and Kemp (1988); Kemp et al. (1990)	M
S–NH_4 → S–M	212.8	Veuger et al. (2004)	M
S–NO_x → S–M	109.0	Veuger et al. (2004)	M
S–ON → S–NH_4	150.0	Blackburn (1988)	M
S–ON → S–M	82.0	Veuger et al. (2004)	M
S–NH_4 → Boundary	1080.0	Tobias et al. (2001)	M
Boundary → S–NH_4	1238.2	Mass balance	L
S–NO_x Burial	0.3	Estimation from sea level rise	[illegible]
S–M Burial	$3.9e^{-7}$	Estimation from sea level rise	[illegible]
S–ON Burial	3.9	Estimation from sea level rise	[illegible]
W–ON → S–ON	853.9	Estimation from sea level rise	[illegible]
S–NH_4 → W–NH_4	136.5	Mass balance	[illegible]
W–M → W–NH_4	3.1	Mass balance	[illegible]
W–M → W–ON	16.0	Mass balance	[illegible]
S–M → S–NH_4	146.7	Mass balance	[illegible]
S–M → S–ON	257.1	Mass balance	L

77% of parameters were high or medium quality

ENA Environ Analysis

Environs are the internal system environments
- Input & Output for each node
- sub-networks



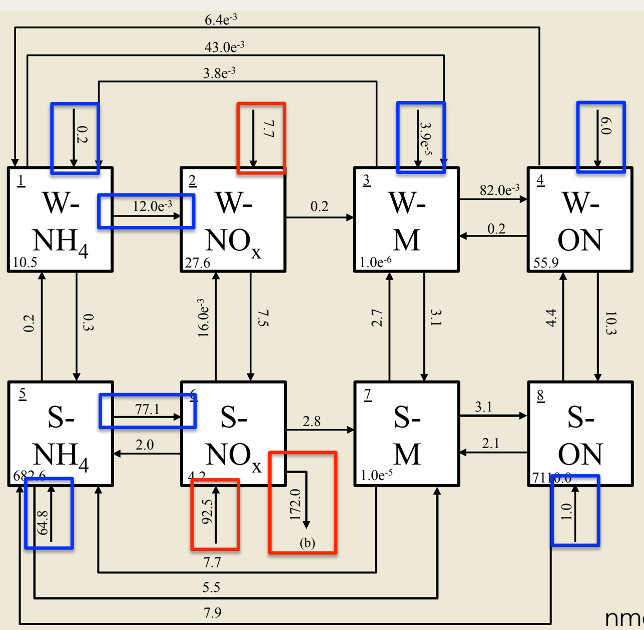
Input Environs

↳ Input history of material in a given output

Analysis performed using NEA.m
(Fath & Borrett, 2006)

Patten 1978, Patten 1982

Denitrification Environ at Low

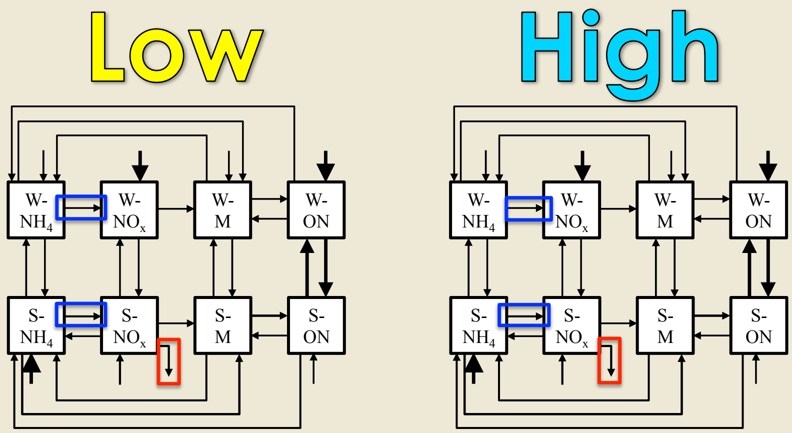


Sub-Network

nmol N cm^{-3} d^{-1}

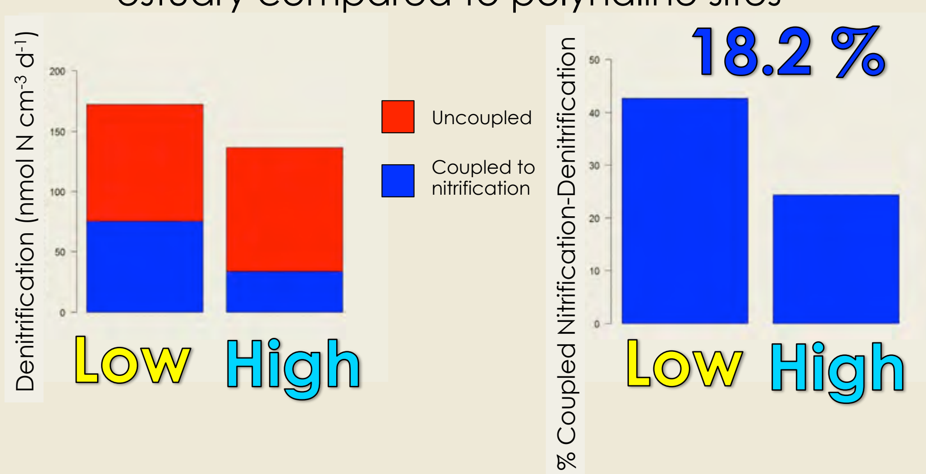
Hypothesis Testing

H$_1$: Coupled nitrification-denitrification will be higher in the oligohaline portion of the estuary compared to polyhaline sites



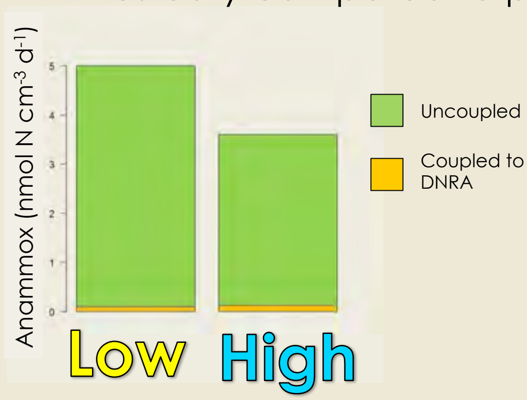
Hypothesis Testing

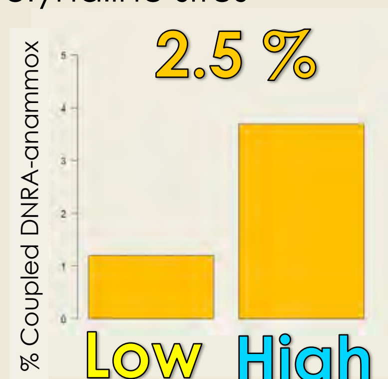
H$_1$: Coupled nitrification-denitrification will be higher in the oligohaline portion of the estuary compared to polyhaline sites



Hypothesis Testing

H_2: Coupled DNRA-anammox will be lower in the oligohaline portion of the estuary compared to polyhaline sites





Findings

H_1: Coupled nitrification-denitrification will be higher in the oligohaline portion of the estuary compared to polyhaline sites

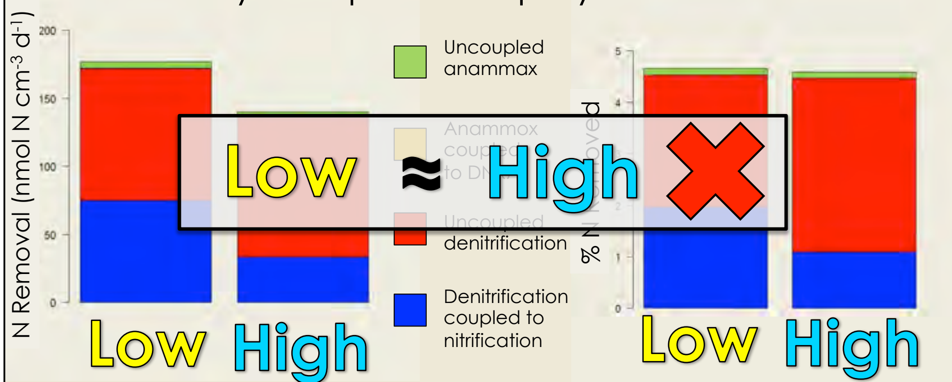
18.2 % ↑

H_2: Coupled DNRA-anammox will be lower in the oligohaline portion of the estuary compared to polyhaline sites

2.5 % ↓

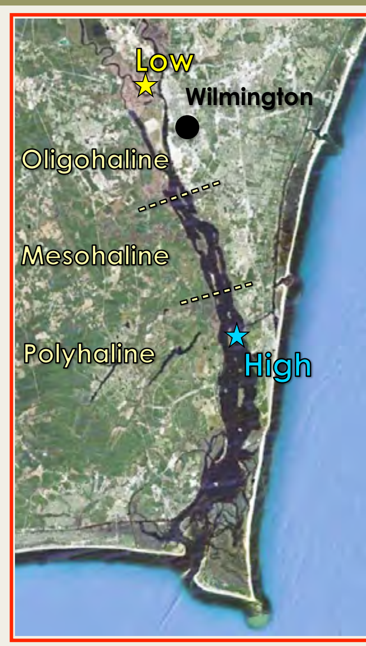
Hypothesis Testing

H_3: Microbial nitrogen removal capacity will be higher in the oligohaline portion of the estuary compared to polyhaline sites



Implications

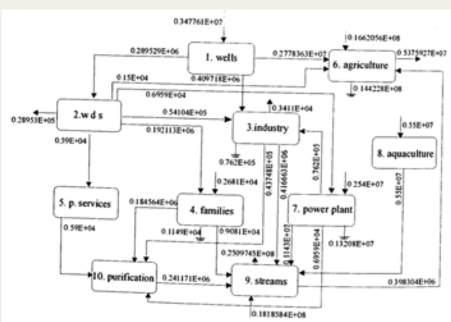
- Rising sea level may result in a decreased coupling of nitrification-denitrification
- DNRA coupled to anammox may become more important
- Overall N_2 removal may not be significantly altered



Additional Examples

Urban Water Metabolism

Sarmato, Italy

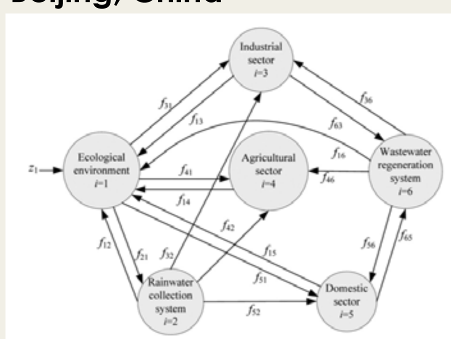


Bodini and Bondavalli 1992

Considered options to improve system sustainability

Scenario Analysis

Beijing, China



Zhang et al. 2010

Evaluate changes from 2003 to 2007

Apply Utility analysis to characterize changing nature of relationships.

Hydrology

Okefenokee Swamp, Georgia, USA

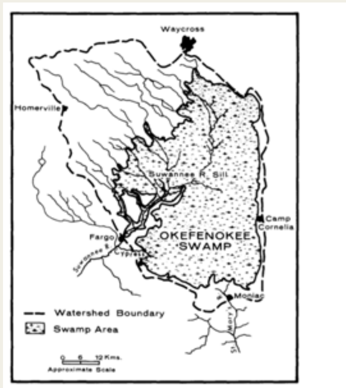
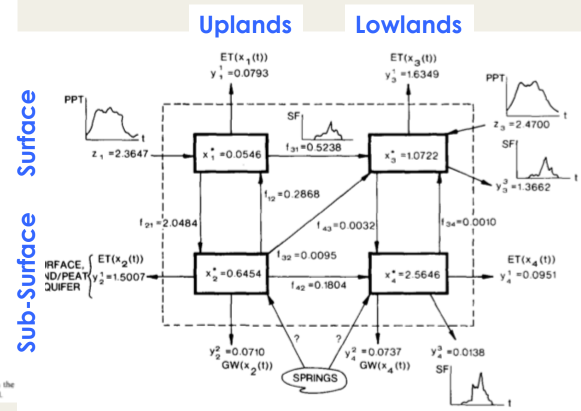


Fig. 1. The Okefenokee swamp–upland watershed. Most of the area of the uplands is in the northwest quadrant. The three output streams and the Suwannee River Sill are indicated.



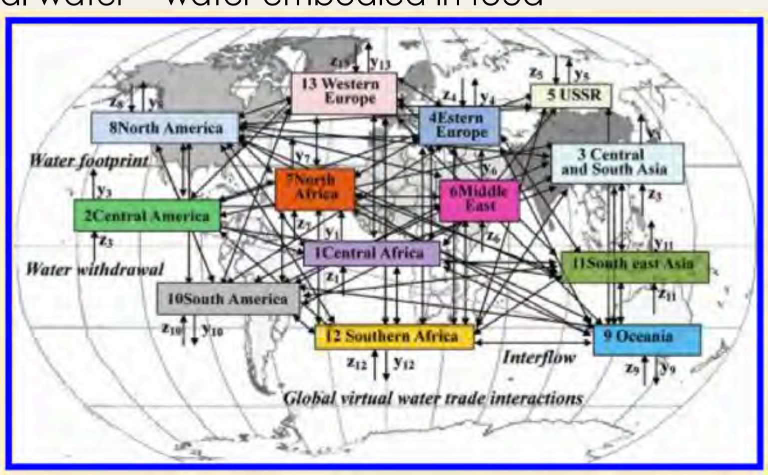
Characterizes flow of water through the system

Origin & Fate

Patten & Matis 1982
Mao et al. 2013

Virtual Water Trade

Virtual water = water embodied in food



Analyzed complex interdependencies among regions

Used control and utility analysis (ENA)

"Virtual water is useful as it globalizes perspectives on water scarcity, ecological sustainability, food production, and consumption" Yang et al. 2012

Summary

Examples of using systems ecology and ecological network analysis to study water resources

- Water quality
- Water quantity
- Aquatic ecosystem structure and function
- Ecosystem services

- Model Construction & Evaluation
- Systems Analysis
- Applications of ENA are still a frontier of the science