Introduction to Network Ecology & Ecological Network Analysis

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@ UNIVERSITY OF NORTH CAROLINA WILMINGTON

Guest Lecture, University of Western Kentucky

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Ecology is fundamentally about Interactions

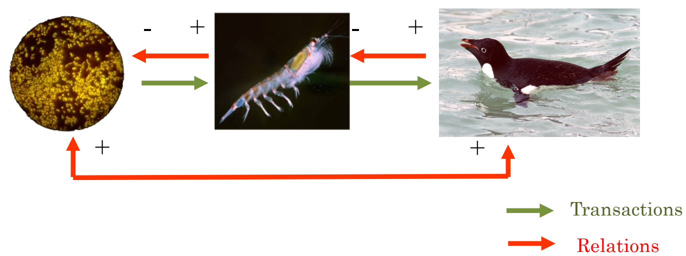
2

Interactions (Connectivity)

… enable Indirect Effects

Ability of one species to influence the distribution, abundance, behavior of another without direct contact

Interaction Chain Example



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1. Network Elements
2. Network Ecology
3. Ecological Network Analysis

4

1

Network Elements

a Relational Model

5

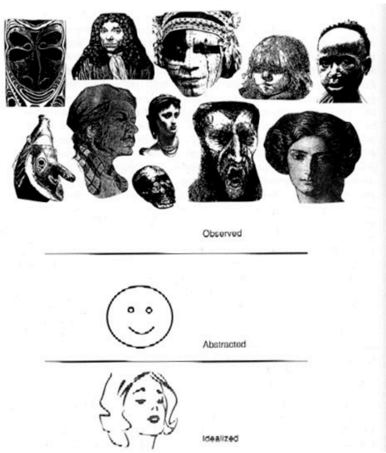
Network are one type of model

What is a model?

Model

A model is an abstract (perhaps idealized), non-unique, description of a natural system that captures its features essential for addressing the modeling objectives.

Patten, pers. Com.



Ahl & Allen 1996

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Formal Modeling Relation: Mapping

Q: What does the model tell you about the natural system?

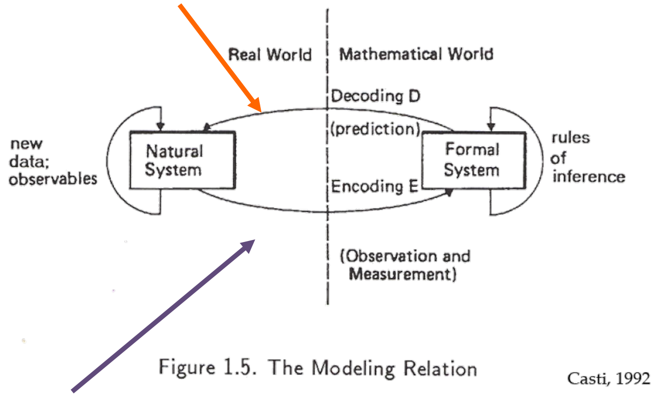

Figure 1.5. The Modeling Relation

Casti, 1992

This abstraction process is key to model making.

Q: What do you include in the model and how do you formally represent it?

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All Models are wrong, some are useful

George Box, 1979

How do we know if our model is sufficient?

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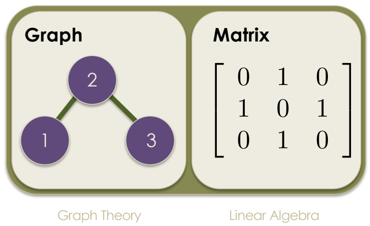
Network Models

Network models map relationships between objects

Networks are Graphs

G = {N, E}

- N = nodes → objects
- E = edges → relationship



$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Adjacency

Two nodes (i, j) are adjacent if there is an edge between them

Adjacency Matrix

$$A = (a_{ij}) = \begin{cases} a_{ij} = 1 & \text{if i, j adjacent,} \\ a_{ij} = 0 & \text{otherwise} \end{cases}$$

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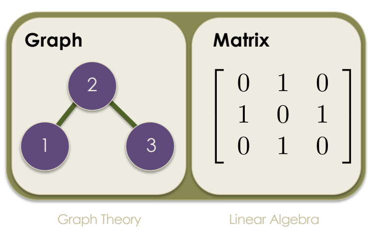
Network Models

Network models map relationships between objects

Networks are Graphs

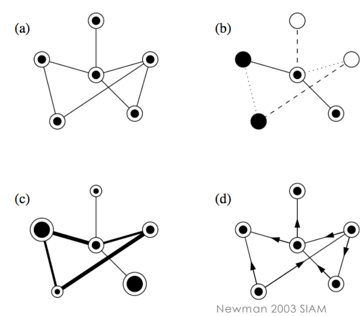
G = {N, E}

- N = nodes → objects
- E = edges → relationship



$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Graph Variations



Typically Simple Graphs

One edge to/from each node, no loops

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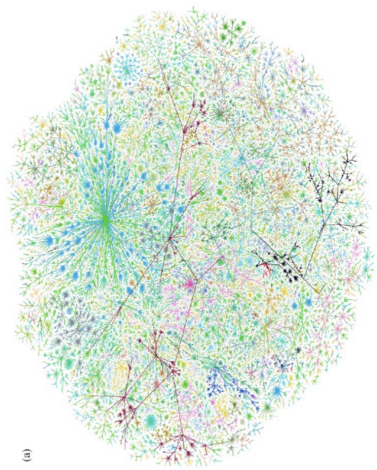
Internet



G = {N, E}

Nodes

Autonomous systems (computer groups)

Edges

Physical Internet connection

"…at the level of "autonomous systems"—local groups of computers each representing hundreds or thousands of machines. Picture by Hal Burch and Bill Cheswick, courtesy of Lumeta Corporation. " Newman 2003

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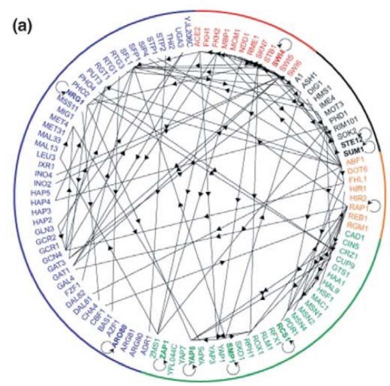
Gene Regulatory Network



G = {N, E}

Nodes

Genes

Edges

Directed regulation of transcription of other genes

As in Proloux et al. 2005. Network thinking in ecology and evolution

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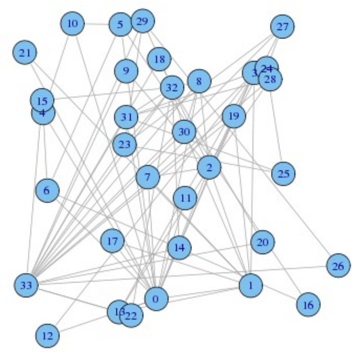
Zachary's Karate Club



Zachary 1977

G = {N, E}

Nodes

Individual people

Edges

Friendships

(note as drawn its undirected and thus assumes friendships are necessarily reciprocal)

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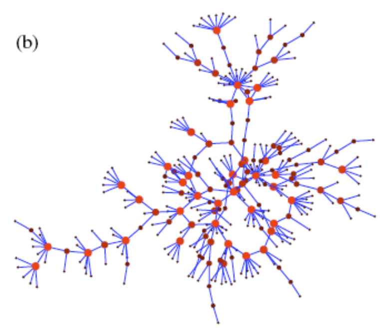
Sexual Contacts - HIV



Potterat et al. 2002, as in Newman 2003

G = {N, E}

Nodes

Individual people

Edges

Sexual Intercourse

How do the scientists get the data for this kind of model? How reliable is the data?

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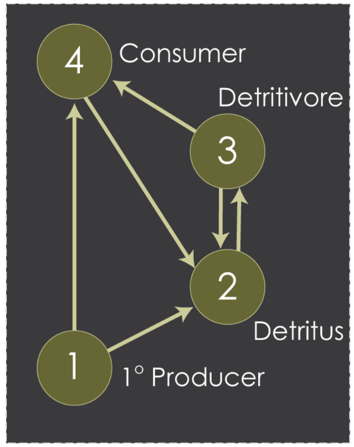
Describing a Network



$G = \{N, E\}$ N = ???; E = ????

Type of Graph → Simple, Directed

Number of Nodes (Vertices) $n = 4$

Number of Edges (Links) $L = 6$

Connectance or Density

$$C = \frac{L}{n^2} = \frac{6}{16} = 0.375$$ With loops

$$C = \frac{L}{n(n-1)} = \frac{6}{12} = 0.5$$ No loops

Loop (aka self loop)
Edge from a node to itself

Have not described patterns of connections

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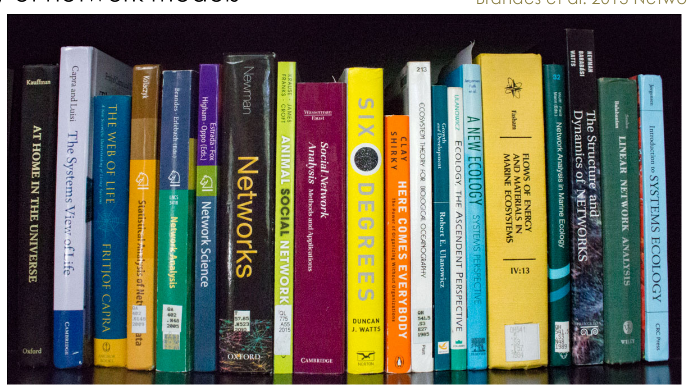
Network Science

"The study of the collection, management, analysis, interpretation, and presentation of relational data"

"the study of network models"

Brandes et al. 2013 Network Science



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Network Ecology

Study of ecological systems using network models

Borrett, Christian, Ulanowicz 2012
Encyclopedia of Environmetrics

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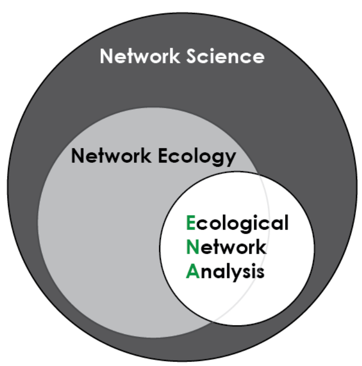
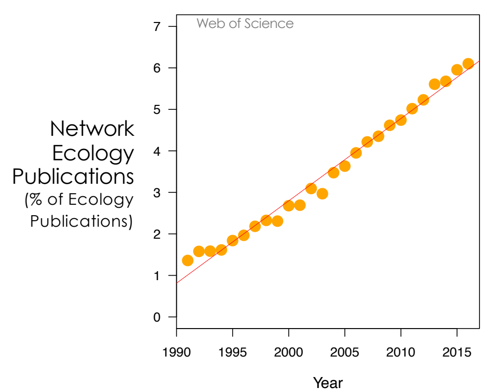
Network Ecology

Study of ecological systems using network models and analysis to characterize their structure, function, and evolution



Scharler & Borrett 2021



Extended from Borrett et al. 2014 in Lau et al. 2017

Network Ecology is a large, and rapidly growing domain

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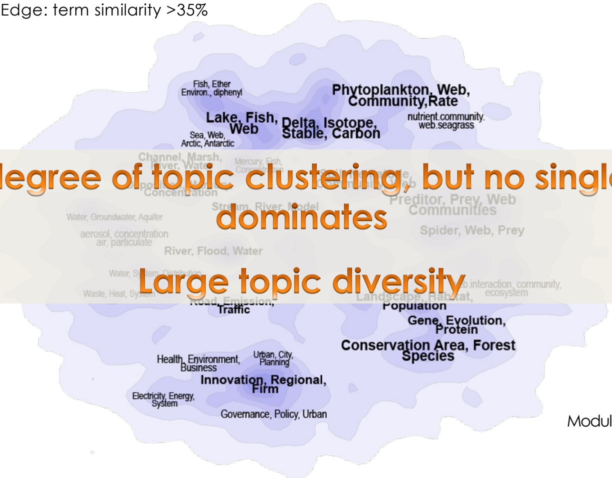
Diverse Topics

Topic Network Node: paper
Edge: term similarity >35%

29,513 publications (1900-2012) WOS



Large degree of topic clustering, but no single topic dominates

Large topic diversity

Modularity Score = 0.927

Borrett et al. 2014

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Animal Behavioral Network

Population

Social Network of Guppy Fish

Node = individual Guppy Fish *Poecilia reticulata* (male, filled; female, open)
Edge = individual co-occurance in shoal

Conclude: Highly structured social system

Croft et al. 2004

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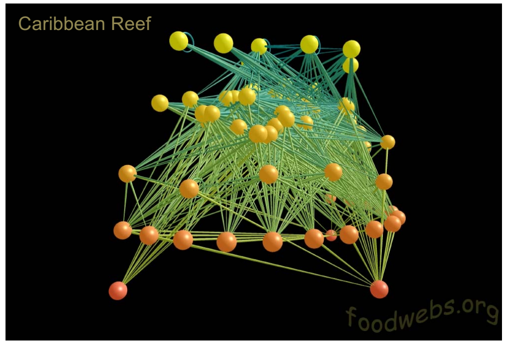
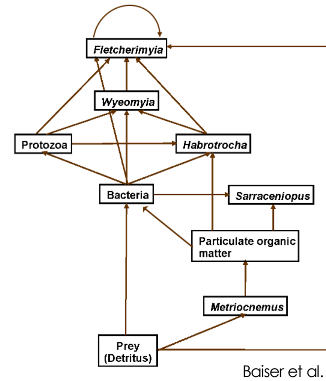
Food Webs

Community



http://foodwebs.org



Baiser et al. 2011

Nodes: Species, Trophospecies, Functional Group, or NL Resource

Edges: classically who **eats** whom

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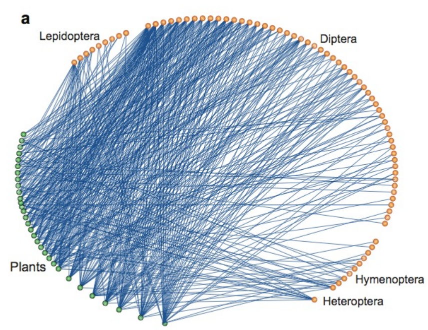
Mutualistic Networks

Community

Plant-Animal Interactions



G = {N, E}

Nodes

(a) Plant species

(b) Animal species

Edges

Pollination visit

Bipartite Graph

Bascompte & Jordano 2007

Discovered re-occurring **nested** pattern
What causes this pattern? Consequences?

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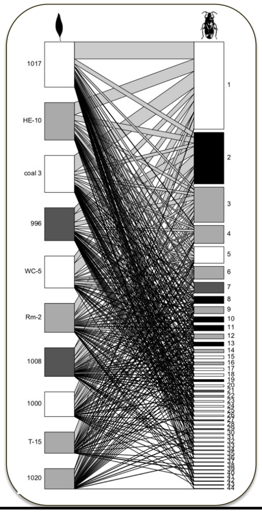
Genotype-Community



G = {N, E}

Nodes – Two Types

A: Tree Genotypes

B: Insect Species

Edges

Co-occurrence

Bipartite Graph

Clear effect of tree *genotype* on insect community composition

Lau et al. 2016

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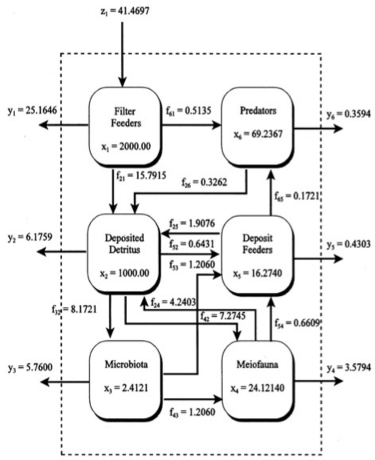
Trophic Ecosystem Model

Ecosystem

SC Oyster Reef Ecosystem (Dame and Patten 1981)

"Compartment Models"



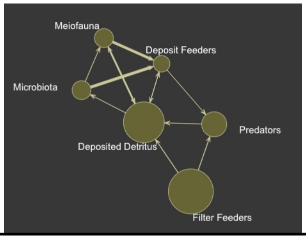
G = {N, E}

Nodes

Species, Functional Groups

Edges

Flux of energy kcal m^{-2} yr^{-1}



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Urban Water Metabolism

Ecosystem

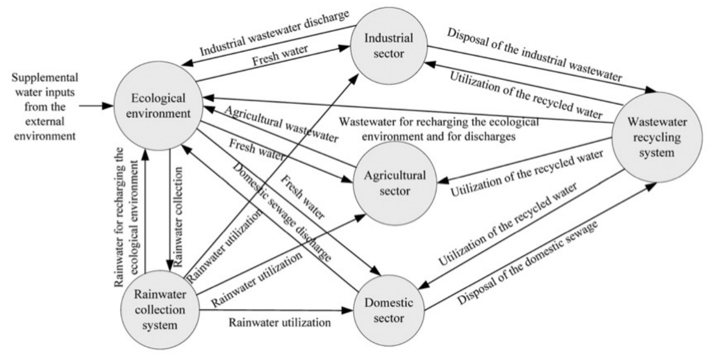

Fig. 1. A conceptual model of the water flows in the urban water metabolism.

G = {N, E}

Nodes: Economic Sector

Edges: Flux of water m^3 yr^{-1} (not certain of time unit)

Zhang et al. 2010

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Habitat Networks

Landscape

Animal movement across the landscape

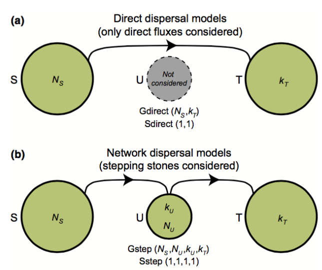
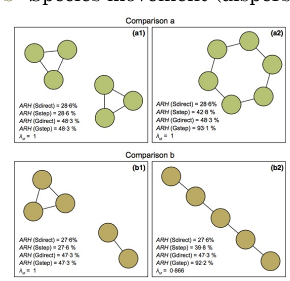


Fig. 1. Illustration of the assumptions and implications of the different connectivity models in a three-patch system. The system consists of a source patch S, a destination (target) patch T and a patch U that may act as a stepping stone facilitating dispersal from S to T. Patch S is fully occupied up to its carrying capacity by the focal species (with N_S individuals dispersing from S), whereas U and T are initially vacant. The species may get established in U or T if at least k_U or k_T individuals are able to colonize the patch, respectively. Many connectivity models (Sdirect, Gdirect) do not consider the potential role of U in facilitating the colonization of T (a), which is accounted for in models Sstep and Gstep through network analysis (b).

G = {N, E}

Nodes: Habitat Patches

Edges: Species movement (dispersal)



Spatial arrangement, patch quality

"Stepping Stones"

Saura et al. 2014

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Trophic Cascades & Pollination

Combination

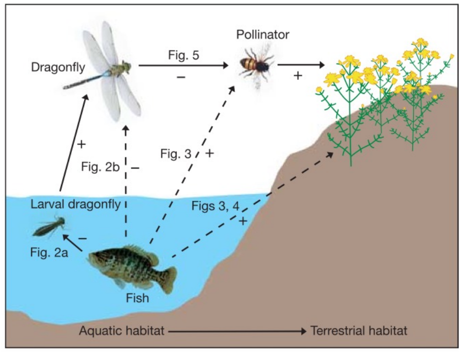

Figure 1 | Interaction web showing the pathway by which fish facilitate plant reproduction. Solid arrows indicate direct interactions; dashed arrows denote indirect interactions. The sign refers to the expected direction of the direct or indirect effect (see the text). Figure numbers indicate which figure presents data supporting each of the predicted effects. (Figure created by S. White and C. Stierwalt.)

Presence of **fish** in ponds decreases the **fitness** of nearby **plants**

Linked food web and pollination network

Knight et al. 2005

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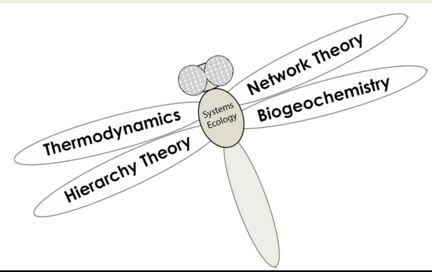
Ecological Network Analysis



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to understand ecosystems…
will be to understand networks
Patten & Witcamp 1967 Ecology
J. theor. Biol. (1973) 41, 535–546
1973
The Structure of Ecosystems
Bruce Hannon
Energy Research Group,
Center for Advanced Computation,
University of Illinois,
Urbana, Illinois 61801, U.S.A.
Application of Input-Output Economics
55+ years of Development
Ecological Network Analysis
Systems Analysis and Simulation in Ecology
1975
1981
1984
Growth and Development
1986
Network Analysis in Marine Ecology
1989

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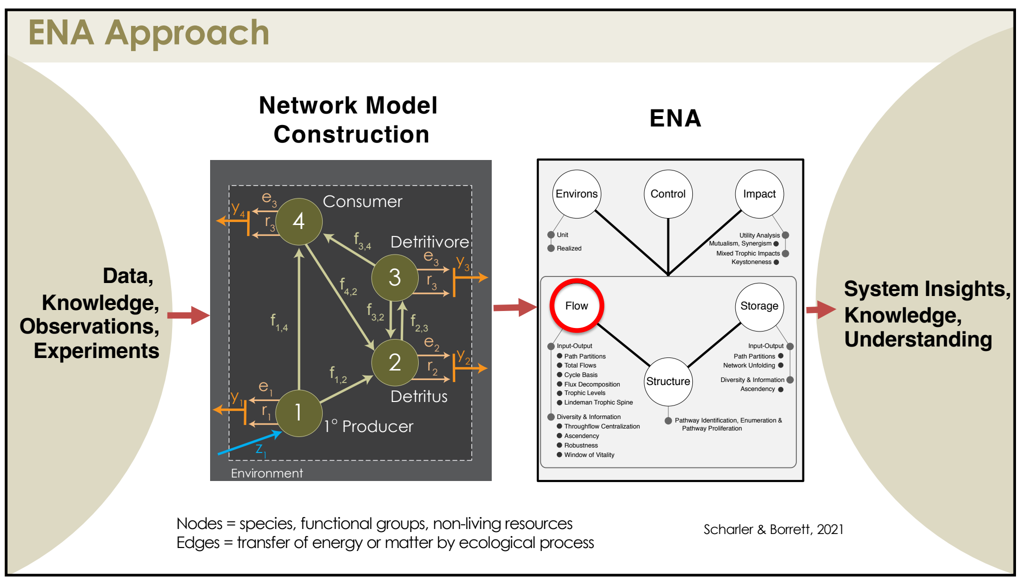
ENA Approach
Data, Knowledge, Observations, Experiments
Network Model Construction
Consumer
Detritivore
Detritus
1° Producer
Environment
ENA
Environs
Control
Impact
Flow
Storage
Structure
System Insights, Knowledge, Understanding
Nodes = species, functional groups, non-living resources
Edges = transfer of energy or matter by ecological process
Scharler & Borrett, 2021

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ENA Flow: Key Concepts & Metrics

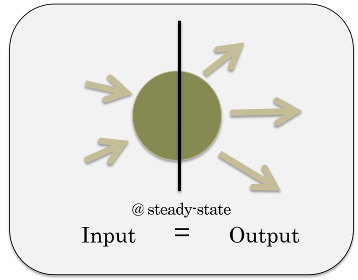
Throughflow

Total amount of energy–matter entering or exiting a node, T_j

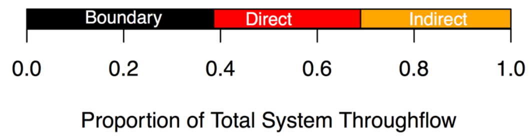
Interpretation

Node Activity, Node Power, Centrality (Borrett 2013)

Total System Throughflow = **TST** = $\Sigma\, T_j$



Input–Output Analysis



Indirect / Direct

Indirect / TST

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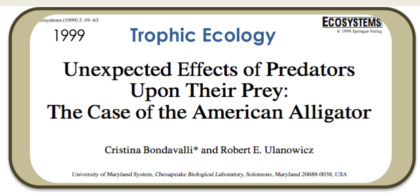
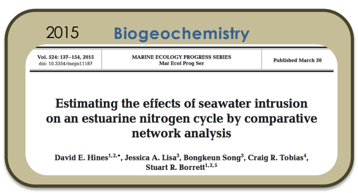
ENA Applications

How and to what degree do species **indirectly influence** each other through the food web?



Unexpected Effects of Predators Upon Their Prey: The Case of the American Alligator

Cristina Bondavalli* and Robert E. Ulanowicz



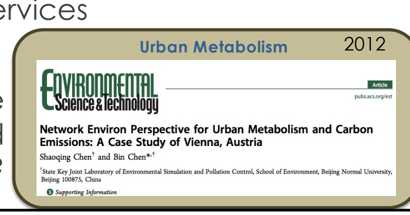
Estimating the effects of seawater intrusion on an estuarine nitrogen cycle by comparative network analysis

David E. Hines, Jessica A. Lisa, Bongkeun Song, Craig R. Tobias, Stuart R. Borrett

How important is **process coupling** in biogeochemical cycles?

Impact of **sea water intrusion** on ecosystem services

How **sustainable** are **cities** (materials & energy) and **economies**?



Network Environ Perspective for Urban Metabolism and Carbon Emissions: A Case Study of Vienna, Austria

Shaoqing Chen and Bin Chen*

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Ecosystem Management

Ocean & Coastal Management 68 (2012) 169–188
Contents lists available at SciVerse ScienceDirect
Ocean & Coastal Management
ELSEVIER
journal homepage: www.elsevier.com/locate/ocecoaman

Integrating ecological, economic and social aspects to generate useful management information under the EU Directives' 'ecosystem approach'

Victor N. de Jonge[a,b,*], Rute Pinto[c], R. Kerry Turner[d]
[a] Institute of Estuarine and Coastal Studies – IECS, University of Hull, Hull HU6 7RX, United Ki
[b] Advice and Research of Estuarine Areas, Augustinusga, The Netherlands
[c] Institute of Marine Research – IMAR, Department of Life Sciences, Faculty of Sciences and Te
[d] Centre for Social and Economic Research on the Global Environment – CSERGE, University of

Vol. 538: 257–272, 2015
doi: 10.3354/meps11502
MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser
Published October 28

REVIEW

Role of trophic models and indicators in current marine fisheries management

C. Longo[1,8,*], S. Hornborg[2], V. Bartolino[3], M. T. Tomczak[4], L. Ciannelli[5], S. Libralato[6], A. Belgrano[3,7]

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Dominance of Indirect Effects

Hypothesis

Indirect flows dominate direct flows in ecosystems

Indirect > Direct   Indirect / Direct > 1   Higashi & Patten 1989

Consequences

Alter species roles and who controls resources

Hidden relationships

Impact assessment and management implications

Conservation

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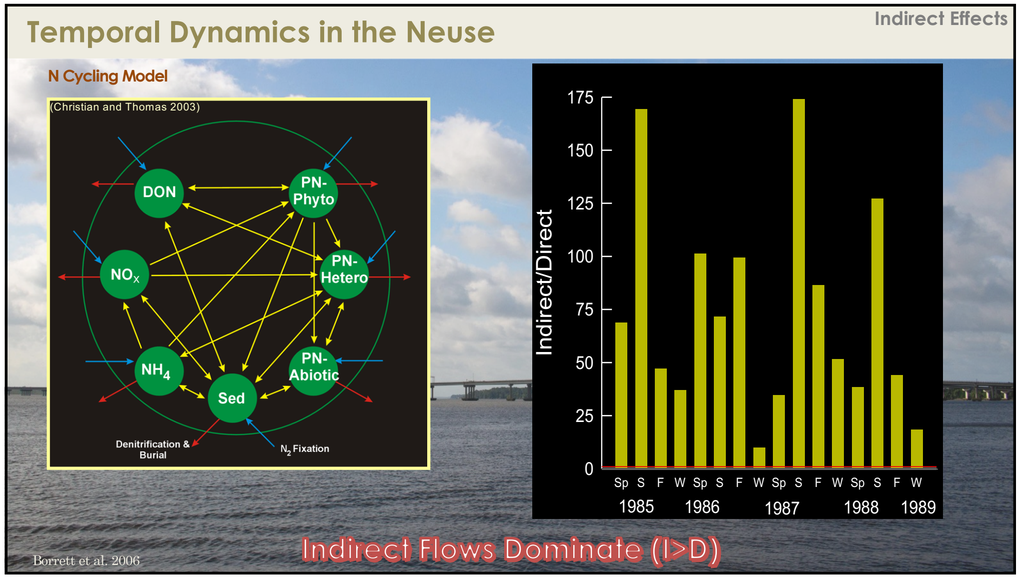
Temporal Dynamics in the Neuse
Indirect Effects
N Cycling Model
(Christian and Thomas 2003)
DON
PN-Phyto
NOx
PN-Hetero
NH4
Sed
PN-Abiotic
Denitrification & Burial
N2 Fixation
Indirect/Direct
175
150
125
100
75
50
25
0
Sp S F W Sp S F W Sp S F W Sp S F W
1985
1986
1987
1988
1989
Borrett et al. 2006
Indirect Flows Dominate (I>D)

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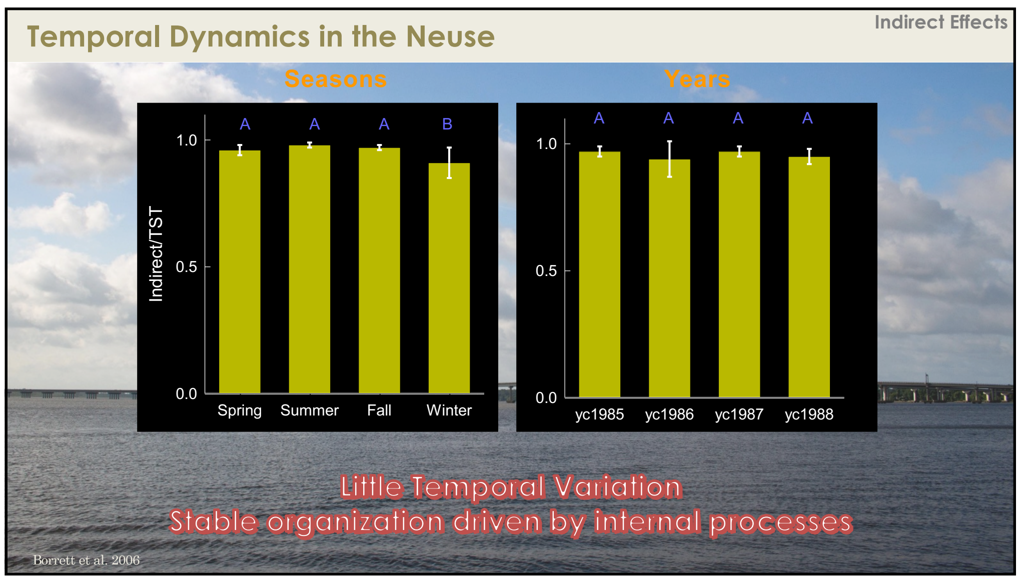
Temporal Dynamics in the Neuse
Indirect Effects
Seasons
Years
Indirect/TST
1.0
0.5
0.0
A A A B
Spring Summer Fall Winter
A A A A
yc1985 yc1986 yc1987 yc1988
Little Temporal Variation
Stable organization driven by internal processes
Borrett et al. 2006

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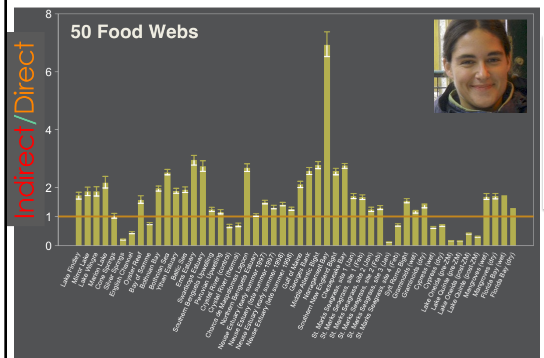
Generalization – Dominance of Indirect Effects

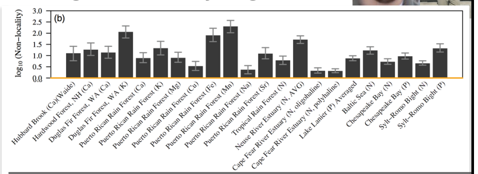
Indirect Effects



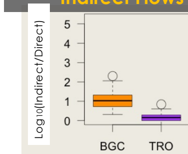
Indirect Flows Dominate Direct in 70%

Salas and Borrett 2011. Ecological Modelling

22 Biogeochemical Cycling Networks



Indirect Flows Dominate Direct in 100%



Borrett et al. 2016. J. Complex Networks

Network Power to transform relationships, to shift controls and impacts, and to modify system growth and development

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Indirect Effects

Evidence supports the
Dominance of Indirect Effects hypothesis

Temporal stability of organization (Neuse)

General ecosystem property
- trophic < biogeochemical cycles
  (perspective matters)

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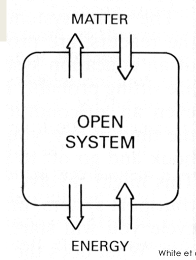
Network Imperative

Living Systems are

Open



White et al. 1992

Exchange energy & matter

Schrodinger 1946; Jorgensen et al. 1999

Claim

Living Systems must form exchange networks

A fundamental feature of life

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1. **Network Elements**
2. **Network Ecology**
3. **Ecological Network Analysis**

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Assemble the Pieces

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Summary

Ecosystem Network Analysis is one component of network ecology that is revealing the importance of **connectivity** and **indirect effects** in (eco)systems

Network Power to transform relationships, to shift controls and impacts, and to modify system growth and development

Applying ENA for
Ecosystem Assessment & Management
requires some additional development

Network Imperative
Living Systems form exchange networks to survive
Fundamental feature of Life

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