Ecosystem Network Analysis

1. ENA Introduction
2. Ecosystem Model Requirements
3. ENA Family of Analyses – Overview
4. ENA Hypotheses

Stuart R. Borrett
University of North Carolina Wilmington

Connectivity

a fundamental principle of ecology

"When we try to pick out anything by itself we find that it is bound fast by a thousand invisible cords that cannot be broken, to everything in the universe"
John Muir

Landscape Ecology

http://www4.ncsu.edu/~haddad/

Meta-populations & Conservation Genetics

http://advocacy.britannica.com

Predator—Prey

http://www.flickr.com/photos/yorick/

Ecosystem Ecology: Energy and Biogeochemical Cycling

Connectivity

~~"Everything is connected to everything else"~~

A tautology - Peters 1991

Misses the more interesting and fundamental point

How are things connected? - Direct or Indirect

What are the relationships?

What are consequences of the connectivity?

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Ecological Network Analysis

General Approach

Patterns reflect **development constraints** and **system function**

Form ↔ Function

Ecological Network Analysis (ENA)

Economic Input–Output Analysis (Leontief)

Networks of energy–matter flows and storages

- trace a single conservative currency (e.g. nitrogen, carbon)
- usually assume steady-state

"Macroscope" to investigate

- organization & **connectivity**
- direct & **indirect** interactions
- Resilience & sustainability

Family of Algorithms

ENA Applications: Examples

Trophic Ecology

1999

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

Cristina Bondavalli* and Robert E. Ulanowicz

Alligators enhance frog populations
- Indirect mutualisms

Biogeochemistry

2012

Estuarine, Coastal and Shelf Science

A network model shows the importance of coupled processes in the microbial N cycle in the Cape Fear River Estuary

Strength of coupling between BGC processes
- Nitrification + Denitrification
- Nitrification + Anammox

Urban Metabolism/Sustainability

2012

Environmental Science & Technology

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

Shaoqing Chen† and Bin Chen*,†

Urban metabolism of Vienna
- Carbon perspective
- Energy production, Construction key

Two Schools of ENA

Ulanowicz School

University of Maryland
Trophic Focus
Phenomenological Graph
Information Theory
Ascendency Concept

Patten School

University of Georgia
Environment Focus
Diff Eqs
Environ Concept
Network Environ Analysis

Distinct but interwoven development of ENA

ENA Software

Tools for Science & Innovation

Ulanowicz School

NETWRK 4.2

Ulanowicz &
Environmer
http://www.cbl.u

Fortran Coc

WAND

Allesina & Bondavalli 2004
Environ. Model. Softw.

Excel based, more user friendly

Patten School

NEA.m

arch.html

EcoNet

Kazanci 2007 Ecol. Mod.
http://eco.engr.uga.edu

C++, Web Server

Ecopath

Christensen & Pauly 1992
Focus on model construction

enaR

Lau, Borrett, Hines 2012
http://cran.r-project.org/web/packages/enaR/
R package, all Patten, some Ulanowicz
Open Source, Extensible, Programming required

No software covers both schools

Different availability, use, extensibility

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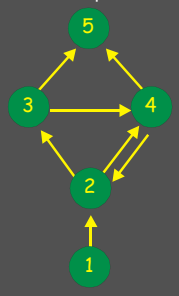
Ecosystem Network Representation

Network Representation for Ecosystems

Graph



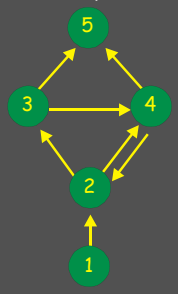
Components

Node = species, group of species, or non-living resource pool (e.g. plants, detritus)

Link = transfer of energy-matter by one or more processes (e.g. consumption)

Network Representation for Ecosystems

Graph



Descriptive Statistics

n = 5

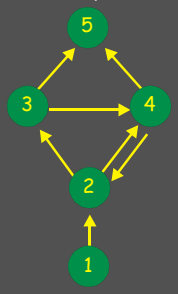
L = 7

$C = L/n^2 = 0.28$

L/n = 1.4

Network Representation for Ecosystems

Graph



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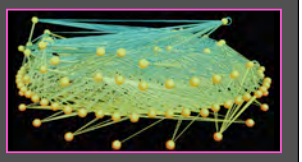
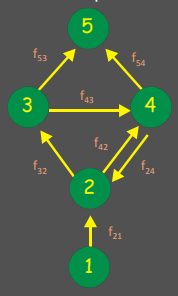


Little Rock Lake Food Web, Martinez 1991

Network Representation for Ecosystems

Graph

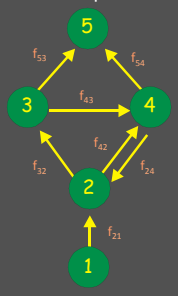


Matrix

from column to row

Network Representation for Ecosystems

Graph



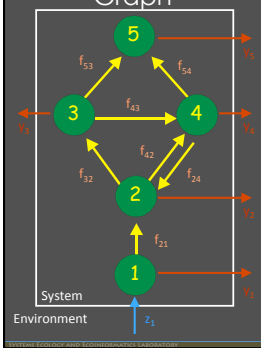
Matrix

from column to row

$$\mathbf{F} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ f_{21} & 0 & 0 & f_{24} & 0 \\ 0 & f_{23} & 0 & 0 & 0 \\ 0 & f_{42} & f_{43} & 0 & 0 \\ 0 & 0 & f_{53} & f_{54} & 0 \end{bmatrix}$$

Network Representation for Ecosystems

Graph



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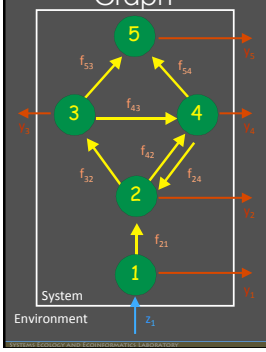
$$\vec{z} = \begin{bmatrix} z_1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \vec{y}^{\mathrm{T}} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix}$$

Network Representation for Ecosystems

Graph



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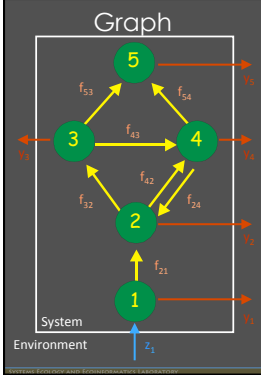
T_j = node throughflow

TST = total system throughflow

Network Representation for Ecosystems



Matrix
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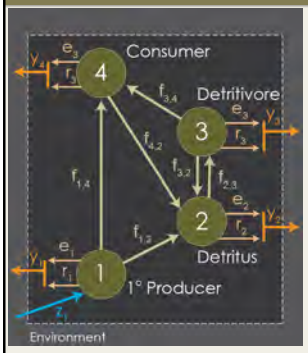
$$\vec{z} = \begin{bmatrix} z_1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \vec{y}^T = \begin{bmatrix} y_1 & y_2 & y_3 & y_4 & y_5 \end{bmatrix}$$

Ulanowicz distinguishes between two output types: respiration and export

Model Data Summary



Node Names
F: Flows from i to j
z: Inputs
e: Exports
r: Respirations
y: Outputs (e + r)
Living: logical (T or F)

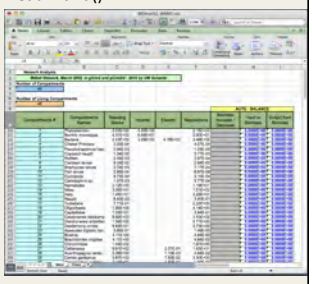
In enaR,
Data stored as a ***network*** object (Butts 2008)

Model Data Storage Formats

NETWRK 4.2 - SCOR
read.scor()

Plain text file

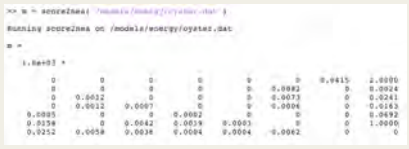
WAND
read.wand()



Model Data Storage Formats

NEA.m Format

$$S = \begin{bmatrix} [\mathbf{F}] & [\vec{z}] & \left[\vec{X}\right] \\ [\vec{y}] & 0 & 0 \end{bmatrix}$$



This is sufficient for **Patten School** analyses, but **Ulanowicz School** analyses require more information

Fath and Borrett 2006

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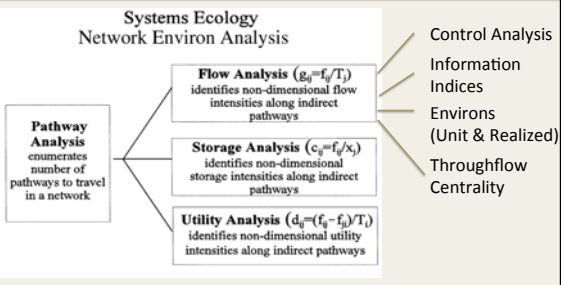
ENA



enaR

Borrett, 2013

Software Design Objectives

Tools for Science & Innovation

Collect — Algorithms from both Ulanowicz and Patten ENA Schools

Available — Increase availability
- Low cost software
- Run on multiple OS (PC, Mac, Unix)

Extensible — Users can
- access original code
- add new functionality

Connect — Additional *network science* tools
- Social network analysis
- ERGM

Borrett, 2013

enaR package for R

Tools for Science & Innovation

Collect

Algorithms

Patten
- structure, flow, storage, environs, control, utility

Ulanowicz
- ascendency, mixed trophic impact, balance

Available

R: a statistical programming environment
- Wide use
- Free, Open source
- PC, Mac, Unix
- CRAN

Extensible

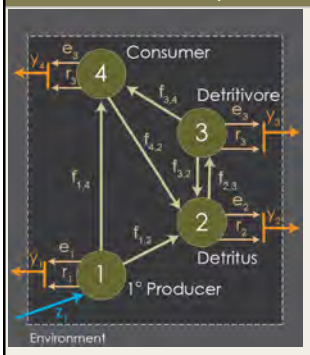
Existing Packages
- network (Butts, 2008)
- sna (Butts, 2008)
- statnet (Handcock, 2008)
- iGraph
- bioconductor

Connect

Illustrate some *ena* package functionality

Borrett, 2013

Data Input: Model Data



Node Names

F: Flows from i to j

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y: Outputs (e + r)

Living: logical (T or F)

Data stored as a ***network*** object (Butts 2008)

pack() and **unpack()**

Collect — Data Input: read.x

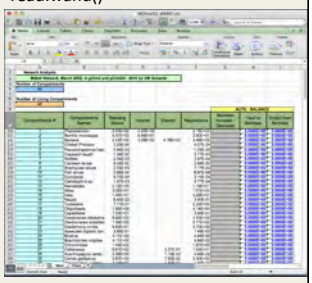
NETWRK 4.2 - SCOR

read.scor()

Plain text file

WAND

read.wand()



Borrett, 2013

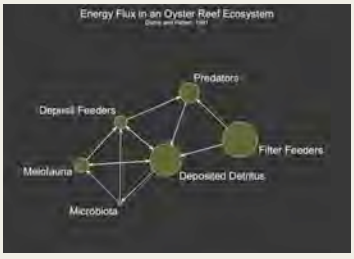
Connect — Visualization

Simple Plot

```
> data(oyster)
> plot(oyster)
```

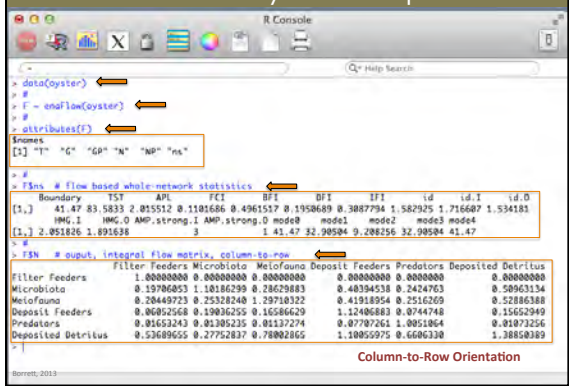
Internal Fluxes

Fancier Plot

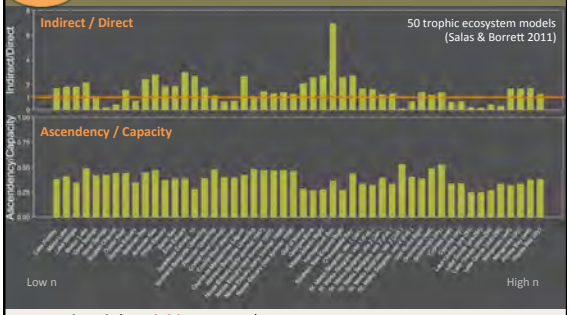


Borrett, 2013

Flow Analysis Example



Extend — Simultaneously Analyze Multiple Models



> ns = lapply(model.list, get.ns)
> barplot(ns$id)
> barplot(ns$ASC.CAP)

model.list = list of Network Model data objects

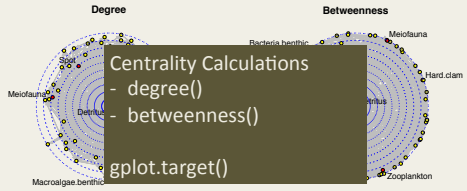
get.ns() = ena function to calculate *network statistics*

Connect — *sna*: Centrality

Centrality – relative importance of node, many types

Core Sound, NC ecosystem Model (Deheer, 2012)

Closed to Shrimp Trawling



Future Work

Collect

Add Additional Algorithms
- Lindeman's Spine
- Cycle Basis
- Schramki's control analysis revisions

Connect

Connection to Ecopath
- Shiela Heymans, Villy Chistensen

Connect

- What will you do with the package?
- How will you extend it?

enaR: package for Ecological Network Analysis

Collect	Available	Extensible	Connect
Ulanowicz Patten	Free PC, Mac, Unix CRAN	Open Source Users can grow	Existing Packages - network - sna - bioconductor

SYSTEMS ECOLOGY AND ECOINFORMATICS LABORATORY
UNIVERSITY OF NORTH CAROLINA WILMINGTON

borretts@uncw.edu
http://people.uncw.edu/borretts/

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ENA Cardinal Hypotheses

Patten, unpublished

- CH1 Networks allow pathway proliferation
- CH2 Network imply non-locality
- CH3 Control of networks is distributed
- CH4 Networks homogenize influences
- CH5 Networks imply internal amplification
- CH6 Network unfolding
- CH7 Networks have synergism
- CH8 Network mutualism
- CH9 Network aggradation
- CH10 Network boundary amplification
- CH11 Network enfolding
- CH12 Network environ autonomy
- CH13 Networks imply a holistic evolution

See Chapter 12, Jorgensen 2012

Suggested References

- Proulx, S.R., DEL Promislow, PC Phillips. 2005. Network thinking in ecology and evolution. TREE 20:345-353
- Newman, MEJ. 2003. The structure and function of complex networks. SIAM review. 45: 167-256.
- Fath BD and BC Patten. 1999. Review of the foundations of network environ analysis. Ecosystems 2:167-179.
- Borrett, SR, RR Christian, RE Ulanowicz. 2012. Network Ecology (Revised). In: A.H. El-Shaarawi and W.H. Piegorsch (Eds.). **Encyclopedia of Environmetrics** (2nd edition). John Wiley and Sons: Chinchester, pp. 1767-1772. doi:10.1002/9780470057339.van011.pub2 [PDF]

Where to learn more …

Mark Newman's papers and website
http://www-personal.umich.edu/~mejn/
Albert-Laszlo Barabasi
http://nd.edu/~alb/
SAMSI Complex Networks Tutorial
http://legacy.samsi.info/workshops/2010cn-opening201008.shtml
International Network for Social Network Analysis
http://www.insna.org/
Robert Ulanowicz (Ecological Network Analysis)
http://www.cbl.umces.edu/~ulan/
Growth and Development: Ecosystem Phenomenology
Brian Fath's work (Ecological Network Analysis)
http://pages.towson.edu/bfath/