Ecosystem Network Analysis

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

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?

Ecological Network Analysis

General Approach

Patterns reflect development constraints and system function

Form ↔ Function

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

Ecosystem Ecology: Energy and Biogeochemical Cycling

Landscape Ecology
Meta populations & Conservation Genetics
Predator—Prey

Ecosystem Ecology: Energy and Biogeochemical Cycling

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Ecological Network Analysis (ENA)

Economic Input–Output Analysis

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

Alligators enhance frog populations - indirect mutualisms

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

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

Two Schools of ENA

Ulanowicz School | Patten School

University of Maryland
Trophic Focus
Phenomenological Graph
Information Theory
Ascendency Concept

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

Distinct but interwoven development of ENA

ENA Software
Tools for Science & Innovation

Ulanowicz School | Patten School

NETWRK 4.2
Ulanowicz & Kay 1991
Fortran Code, DOS executable

WAND
Allesina & Bondavalli 2004
Exeler Mod. Selfex.
Excel based, more user friendly

Ecopath
Christensen & Pauly 1992
Focus on model construction

EcoNet
Kazanis 2007 Ecol. Mod.
http://www.r-project.org
C++, Web Server

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

Different availability, use, extensibility

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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

\[ n = 5 \]
\[ L = 7 \]
\[ C = L/n^2 = 0.28 \]
\[ L/n = 1.4 \]

Graph

Descriptive Statistics

\[ n = 5 \]
\[ L = 7 \]
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Network Representation for Ecosystems

Graph

Matrix

\[ F = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & f_{24} & 0 & 0 \\ 0 & f_{23} & 0 & 0 & 0 \\ 0 & f_{12} & f_{33} & 0 & 0 \\ 0 & 0 & f_{43} & f_{54} & 0 \end{bmatrix} \]

\[ T_j = \text{node throughflow} \]

\[ T_{ST} = \text{total system throughflow} \]
Network Representation for Ecosystems

Graph

Matrix

from column to row

\[ F = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & f_{13} & 0 & f_{24} & 0 \\
0 & 0 & f_{33} & 0 & 0 \\
0 & 0 & 0 & f_{43} & 0 \\
0 & 0 & 0 & 0 & f_{54}
\end{bmatrix} \]

Ulanowicz distinguishes between two output types: respiration and export

Model Data Summary

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

In enaR, Data stored as a network object

Model Data Storage Formats

- NETWRK 4.2 - SCOR
  - read.score()
- WAND
  - read.wand()

Model Data Storage Formats

NEA.m Format

\[ S = \begin{bmatrix}
F \\
z \\
0 \\
0
\end{bmatrix} \]

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

Fath and Borrett 2006

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ENA package for R

Tools for Science & Innovation

Collect

Available

Extensible

Connect

Algorithms
- structure, flow, storage, environs, control, utility
- ascendency, mixed trophic impact, balance

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

Existing Packages
- network (Butts, 2008)
- SNA (Butts, 2008)
- statnet (Handcock, 2008)
- igraph
- bioconductor

Collect

Available

Extensible

Connect

Data Input: Model Data

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

Data stored as a network object

pack() and unpack()

Data Input: read.x

NETWRK 4.2 - SCOR
read.scor()

WAND
read.wand()

Visualization

Simple Plot
> data(oyster)
> plot(oyster)

Fancier Plot
> data(oyster)
> plot(oyster)

Internal Fluxes
Flow Analysis Example

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

Extend Indirect / Direct Ascendency / Capacity

50 trophic ecosystem models (Salas & Borrett 2011)

Future Work

• Add Additional Algorithms
  – Lindeman’s Spine
  – Cycle Basis
  – Schramki’s control analysis revisions
• Connection to Ecopath
  – Shiea Heymans, Villy Chistensen
• What will you do with the package?
  • How will you extend it?

enaR: package for Ecological Network Analysis

enaR: Centrality

Centrality – relative importance of node, many types

Core Sound, NC ecosystem Model (Deheer, 2012)

Connect to Shrimp Trawling

Closed to Shrimp Trawling

Connect

Centrality Calculations
- degree()
- betweenness()
- gplot.target()

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ENA Cardinal Hypotheses

• 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

Suggested References


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/