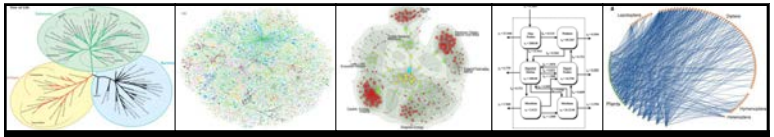


Ecological Network Analysis Tutorial

Stuart R. Borrett[1,2,3]

1. Department of Biology and Marine Biology, University of North Carolina Wilmington
2. Center for Marine Science, University of North Carolina Wilmington
3. Duke Network Analysis Center, Social Science Research Institute, Duke University

SYSTEMS ECOLOGY AND ECOINFORMATICS LABORATORY

@ UNIVERSITY OF NORTH CAROLINA WILMINGTON

@ ISEM2023, May 2023, Toronto, Canada

1

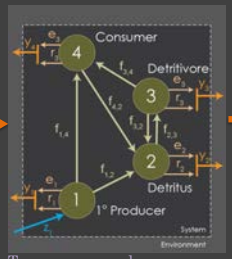
ENA Workflow - Generalized

Model

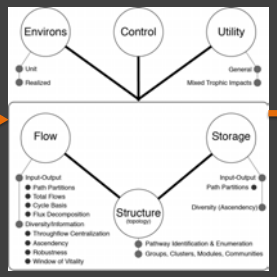
Analyses

Data
Theory

Obs.
Exp.



Trace conserved currency
(energy, C, N, P)



Knowledge, Insight, Understanding

Model Construction

Phenomenological, Budget, Simulation, LIM

Software Tools

Ecopath (EwE)

NETWRK 4.2

ena R

NetIndices

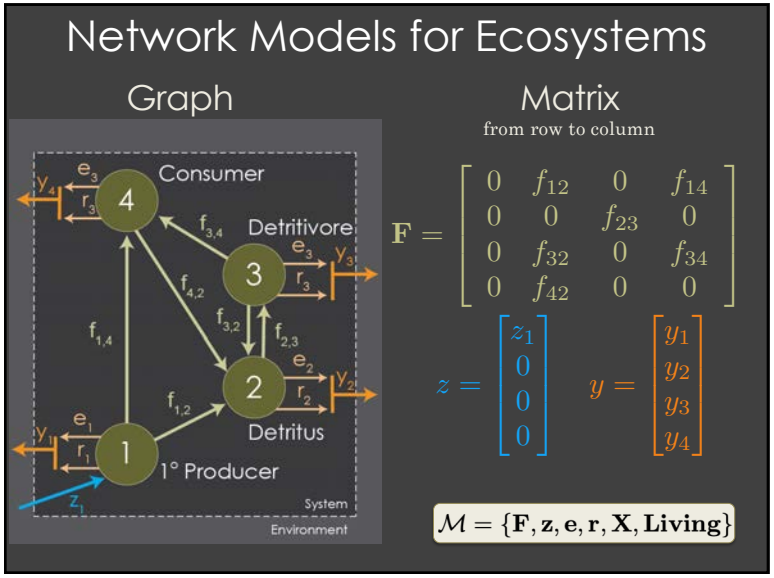
WAND

NEA.m MathWorks

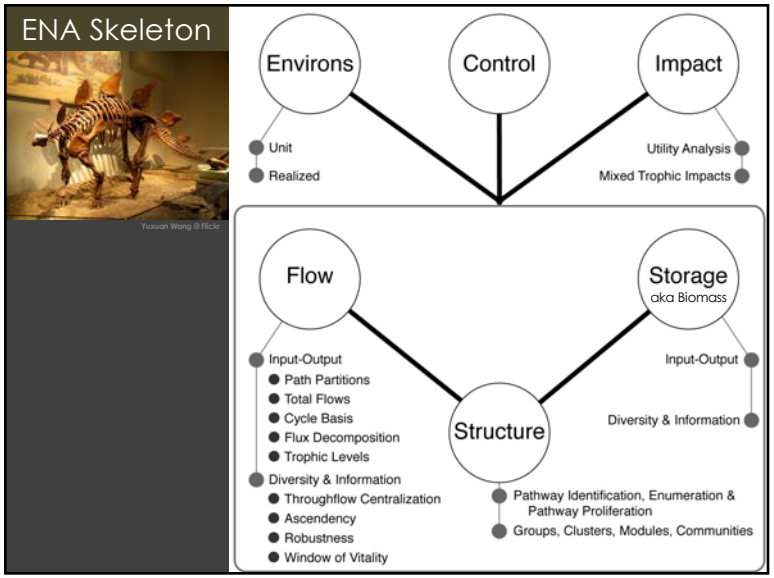
EcoNet 2.2

NCNA

2


Network Models for Ecosystems
Graph
Matrix
from row to column
Consumer
Detritivore
Detritus
1° Producer
System
Environment
$\mathbf{F} = \begin{bmatrix} 0 & f_{12} & 0 & f_{14} \\ 0 & 0 & f_{23} & 0 \\ 0 & f_{32} & 0 & f_{34} \\ 0 & f_{42} & 0 & 0 \end{bmatrix}$
$z = \begin{bmatrix} z_1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$
$y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}$
$\mathcal{M} = \{\mathbf{F}, \mathbf{z}, \mathbf{e}, \mathbf{r}, \mathbf{X}, \mathbf{Living}\}$

3


ENA Skeleton
Yuxuan Wang @ Flickr
Environs
Control
Impact
Unit
Realized
Utility Analysis
Mixed Trophic Impacts
Flow
Storage
aka Biomass
Input-Output
Path Partitions
Total Flows
Cycle Basis
Flux Decomposition
Trophic Levels
Diversity & Information
Throughflow Centralization
Ascendency
Robustness
Window of Vitality
Structure
Input-Output
Diversity & Information
Pathway Identification, Enumeration & Pathway Proliferation
Groups, Clusters, Modules, Communities

4

Levels of Analysis

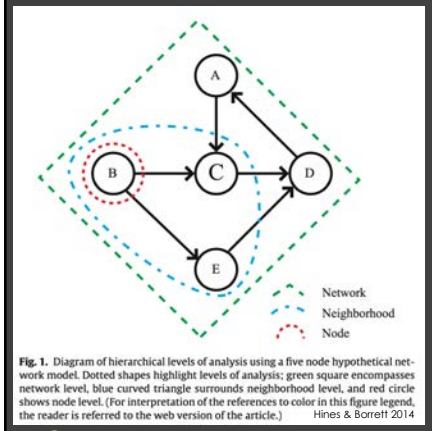


Fig. 1. Diagram of hierarchical levels of analysis using a five node hypothetical network model. Dotted shapes highlight levels of analysis; green square encompasses network level, blue curved triangle surrounds neighborhood level, and red circle shows node level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.) Hines & Borrett 2014

Compare
(a) across levels
(b) across systems

Network

How was the whole system organization impacted by an external perturbation?

Network Metrics
(Indicators?)

Neighborhoods

Are their relevant subgroups?

Nodes

- Node characteristics
- Roles
- Importance (centralities)

5

Introduction to ena R

Tool for Science & Innovation

6

enaR Software Design Objectives

Tools for Science & Innovation

- **Collect**
- **Available**
- **Extensible**
- **Connect**

Algorithms from both Ulanowicz and Patten ENA Schools

Illustrate some *enaR* functionality

Emphasize how it facilitates system comparisons

Additional *network* tools
- Social network analysis
- ERGM

Existing R tools
- Network (Butts 2008)
- sna (Butts 2008)
- Statnet (Handcock, 2008)

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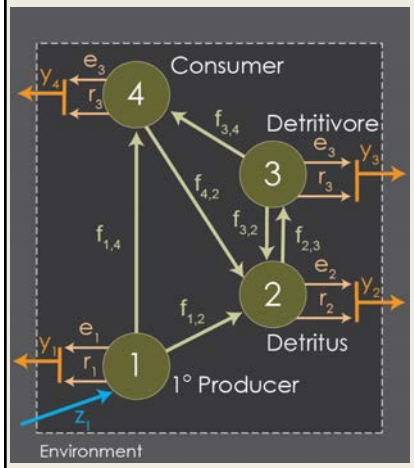
Data Input: Model Data



Node Names

F: Flows from *i* to *j*

z: Inputs

e: Exports

r: Respirations

y: Outputs (e + r)

X: storage or biomass

Living: logical (T or F)

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

pack() and **unpack()**

8

Collect

Data Input: read.x

NETWRK 4.2 - SCOR

read.scor()

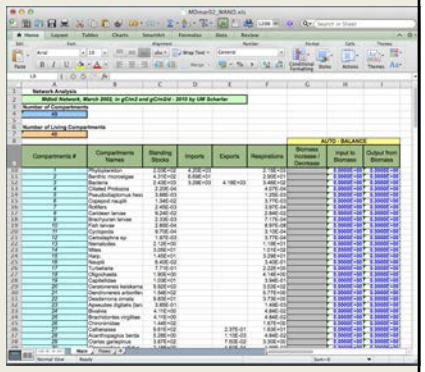
```
SYSTER REEF; DAME&PATTEN, MAR.ECOL.PROG.SER.5:115; KCAL/M2/D; SRB-FIXED;
  6  5
Filter Feeders
Microbiota
Meiofauna
Deposit Feeders
Predators
Deposited Detritus
  1 2.0000e+03
  2 2.4121e+00
  3 2.4121e+01
  4 1.6274e+01
  5 6.9237e+01
  6 1.0000e+03
 -1              \IMPORTS
  1 4.1470E+1
 -1              \EXPORTS
 -1              \RESPIRATION
  1 2.5165e-01
  2 5.7600e+00
  3 3.5794e+00
  4 4.3830e-01
  5 3.5940e-01
  6 6.1759e+00
 -1              \FLOWS
  6  2 8.1721e+00
  2  3 1.2060e+00
  6  3 7.2745e+00
  2  4 1.2060e+00
  3  4 6.6090e-01
  6  4 6.4310e-01
  1  5 5.1350e-01
  4  5 1.7210e-01
  1  6 1.5791e+01
  3  6 4.2403e+00
  4  6 1.9076e+00
  5  6 3.2620e-01
 -1 -1
```

Borrett, 2013

Plain text file

WAND

read.wand()



read.enam(), read.nea(), read.EcoNet()

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Main ENA functions

Table 2. Ecosystem Network Analysis functions in `enaR`

Function	Description	Example Reference
`enaStructure`	ENA Structural analysis returns the adjacency matrix and multiple common descriptive statistics (e.g. number of nodes, connectance, pathway proliferation rate)	Borrett, Fath & Patten (2007)
`enaFlow`	Calculates node throughflow and input- and output-oriented direct and integral flow intensity matrices. It also returns multiple whole-network descriptive statistics including total system throughflow, Finn Cycling Index, and average path length	Finn (1976)
`enaAscendency`	Performs ascendency analysis on the model flows and returns whole-network statistics including the average mutual information, ascendency, capacity and overhead	Ulanowicz (1997)
`enaStorage`	ENA Storage analysis considers how the model fluxes generate the node storage (e.g. biomass) in the system. This function returns the input- and output-oriented direct and integral storage matrices	Matis & Patten (1981)
`enaUtility`	ENA Utility analysis investigates the direct relationships among the network nodes as well as the integral relationships when all of the indirect interactions are also considered	Patten (1991)
`enaMTI`	Mixed trophic impacts assesses the net relationships among species in a food web	Ulanowicz & Puccia (1990)
`enaControl`	Control analysis determines the relative control one node exerts on another through the transaction network	Dame & Patten (1981)
`enaEnviron`	Returns the *n* unit and *n* realized input and output environs of the model	Patten (1978)

Functions require model input as network data object (e.g., created with pack())

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Selected Other Functions

Table 3. Selected `enaR` auxiliary functions and analyses

Function	Description	Example Reference
Specialty Analyses		
`enaAll`	Runs all of the primary ENA algorithms	None
`get.ns`	Returns the whole-network statistics from enaStructure, enaFlow, enaAscendency, enaStorage and enaUtility	None
`eigenCentrality`	Calculates the average eigenvalue centrality for any input matrix	Fann & Borrett (2012)
`environCentrality`	Returns the input, output and average environ centralities for a matrix	Fann & Borrett (2012)
`TET`	Returns the total environ throughflows	Whipple *et al.* (2007)
`TES`	Returns the total environ storages	Matis & Patten (1981)
Auxiliary Functions		
`get.orient`	Determine the orientation of the results (row-to-column vs. School)	None
`set.orient`	Set the orientation of the results (row-to-column vs. School)	None
`mExp`	This function lets users calculate matrix exponents	None

Currently more than 45 functions in the package

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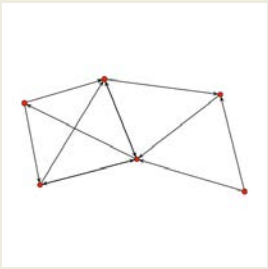
Connect

Visualization

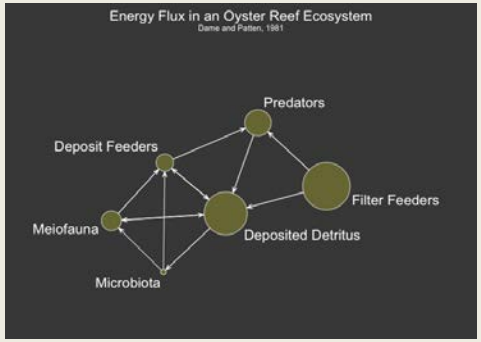
Simple Plot

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



Internal Fluxes

Fancier Plot



Borrett, 2013

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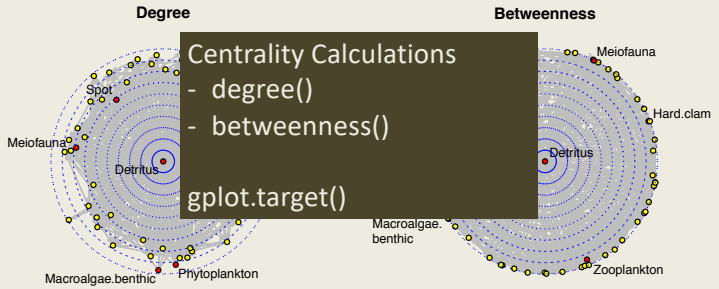
Connect

sna: Centrality

Which species are most important in the ecosystem?(throughflow perspective)

Core Sound, NC Ecosystem Model (Deheer, 2012)

Closed to Shrimp Trawling



Centrality – relative importance of node, many types

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Visualization of Data

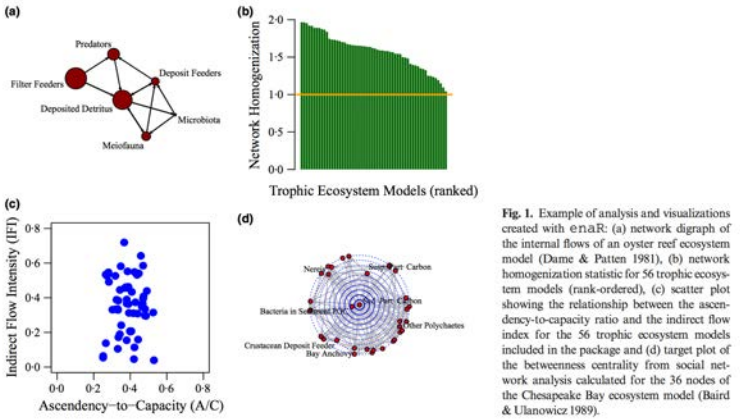

Fig. 1. Example of analysis and visualizations created with `enaR`: (a) network digraph of the internal flows of an oyster reef ecosystem model (Dame & Patten 1981), (b) network homogenization statistic for 56 trophic ecosystem models (rank-ordered), (c) scatter plot showing the relationship between the ascendency-to-capacity ratio and the indirect flow index for the 56 trophic ecosystem models included in the package and (d) target plot of the betweenness centrality from social network analysis calculated for the 36 nodes of the Chesapeake Bay ecosystem model (Baird & Ulanowicz 1989).

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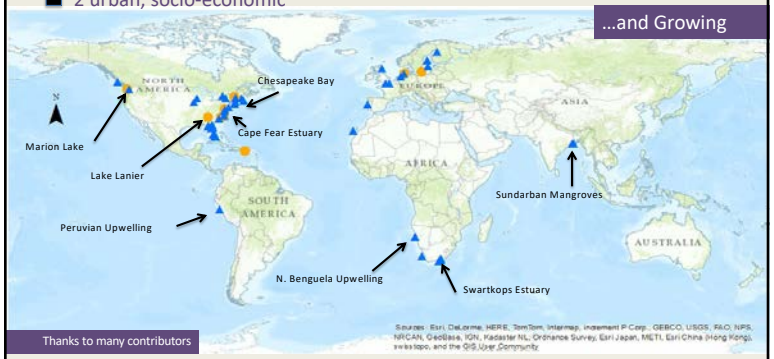
Model Library

Collect | Extend

104 Empirically-based ecosystem models (previously published)

- 59 Trophic networks (food-web core, carbon or energy)
- 43 Biogeochemical cycling networks (i.e., nitrogen, phosphorus)
- 2 urban, socio-economic



Library enables new, comparative, and meta-analyses.
Testing data for new theoretical developments

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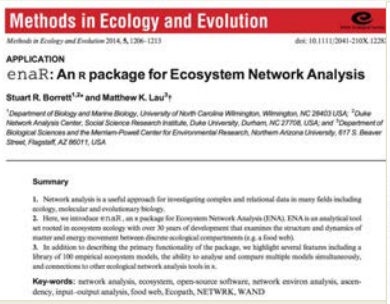
Where to get help

Introduction: MEE



Methods in Ecology and Evolution

APPLICATION

enaR: An R package for Ecosystem Network Analysis

Stuart R. Borrett and Matthew K. Lau

Summary

http://onlinelibrary.wiley.com/doi/10.1111/2041-210X.12282/abstract

Vignette

Ecosystem Network Analysis with R: A guide for using enaR

Matthew K. Lau, Stuart R. Borrett, and Pawandeep Singh

August 4, 2015

Abstract

1 Introduction

https://github.com/SEELab/enaR/blob/develop/vignettes/enaR-vignette.pdf

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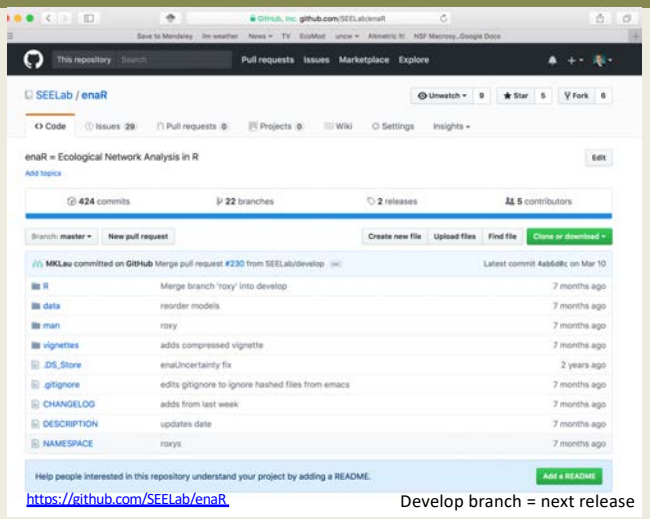
GitHub – enaR Development



https://github.com/SEELab/enaR

Develop branch = next release

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5

ENA Exercises

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Exercise #1 – Getting Started with enaR

Activity

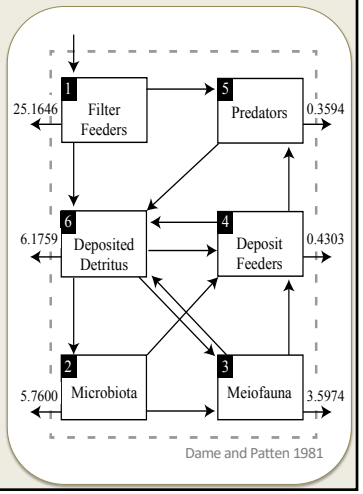
Download script from tutorial website

1. Open R
2. Load enaR library
3. Load model from model data(oyster)
4. Examine model properties
5. Plot model
6. Apply selected analyses

Challenge Problems -- Test Your Understanding

1. Find the number of nodes in the *Swartkops Estuary* model
2. Create a barplot of the effective trophic levels of the *Bothnian Sea* model
3. Find the A/C and FCI of the *Florida Bay (wet)* model

SC Oyster Reef Model



Dame and Patten 1981

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Exercise #2 – Loading a model into R

Activity

Method 1: Manual using pack()

Micro-modeling

M = {F, z, e, r, X, Living}

1. Draw a network model as a flow diagram with 3 nodes
2. Create objects for each of your model components
3. "Pack" your model into a network object
4. "Unpack" your network and look at the parts
5. Plot
6. Investigate some network metric you're interested in

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Exercise #2 – Loading a model into R

Activity

Method 1: Manual using pack()

Micro-modeling

M = {F, z, e, r, X, Li

1. Draw a netw
2. Create objec
3. "Pack" your
4. "Unpack" yo
5. Plot
6. Investigate s

Micro-modeling (Solution 1)

```
library(enaR)
F <- c(0,5,0,
       0,0,1,
       0,0,0)
F <- matrix(F,nrow=3,byrow=TRUE)
z <- c(10,0,0)
e <- c(3,3,3)
r <-c(1,1,1)
X <- c(10,3,1)
liv <- c(TRUE,TRUE,FALSE)
toy <- pack(F,z,e,r,X,liv)
```

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Exercise #3 – Comparing Models & Batch Processing

Activity

Download script from tutorial website

1. Load enaR library
2. Load model from model library (troModels)
3. Use lapply() function to apply selected analyses to a list of models
4. Plot results

Challenge Problems -- Test Your Understanding

1. Plot ID.F for troModels with n > 10
2. Find min, max, mean, and standard deviation of the troModels FCI
3. Look for correlations among selected indices by plotting FCI vs. A/C, IFI, synergism.F
4. Compare the TST and FCI of the two Crystal River Models

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