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enaR: Ecosystem Network Analysis with R

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Abstract

Ecosystem Network Analysis (ENA) provides a framework for investigating the structure, function and dynamics of ecological systems, primarily ecosystem models with physically conserved units. We present the *enaR* package, which provides a broad representation of many of the core tools developed by the ENA community, detailing how to use the primary functions of the package for the analysis of single models or simultaneous, synthetic analysis of multiple ecosystem models.

Keywords: ecology, ENA, ecosystems, species interactions, networks, R.

1. Introduction

Network models have been used to xx, yy, zz (insert examples of use/discipline). While the network models and analyses have deep roots (cite old papers), their use has been expanding rapidly in a variety of disciplines **????**. This due in part to the flexibility of the core representation, its utility in answering relational questions, and its applicability to "Big Data" problems. ■SUMMARY SENTENCE - Methods/Stats■

Ecosystem Network Analysis (ENA) is a family of algorithms for investigating the structure and function of ecological systems **???**. These systems are modeled as thermodynamically conserved energy–matter exchanges between species, groups of species, or non-living componets (e.g., dead organic matter) of the ecosystem, and the weighted, directed edges are the quantified transfers of energy or matter.

NEEDS REVISION ■ need to the 2 schools bit here.

Disparate software packages have been created to support ENA. Initially algorithms were developed and distributed as the DOS based NETWRK4 **?**, which is still available from http://www.cbl.umces.edu/~ulan/ntwk/network.html. Some of these algorithms were reimplemented in an Microsoft Excel based toolbox, WAND **?**. The popular Ecopath with Ecosim software that assists with model construction (**?**) also provides multiple ENA algorithms. **?** published NEA.m that collects many ENA algorithms together in a single MATLAB©function. Although these packages collectively provide access to a large set of powerful analytical tools, the fragmented distribution of these algorithms has inhibited the development of theory and the further implementation of important algorithms.

EcoNet?? Latham??

The *enaR* package brings together ENA algorithms into one common software framework that is readily available and extensible. The package is written in the language, which is free and open-source. Due largely to this, is now one of the most widely used analytical programming lanuages in the biological sciences. *enaR* builds on existing packages for network analysis. For example, it uses the *network* data structure developed by **?** and the network analysis tools built into the *network*, *sna* (social network analysis) (**?**), and other packages collectively called *statnet* (**?**). In this article we introduce the user to ENA concepts and algorithms, provide description of how to input ecosystem network models and give detailed description of how to conduct these analyses using *enaR*.

2. Data Input: General

In this section we describe the data necessary for the Ecological Network Analysis and show how to build the central network data object in that contains the model data for subsequent analysis. To start, we assume you have installed the enaR package, and then loaded the library as follows:

```
> library(enaR)
```

2.1. Model Data

ENA is applied to a network model of energy–matter exchanges among system components. The system is modeled as a set of n compartments or nodes that represent species, species-complexes (i.e., trophic guilds or functional groups), or non-living components of the system in which energy–matter is stored. Nodes are connected by L observed fluxes, termed directed edges or links. This analysis requires an estimate of the energy–matter flowing from node i to j over a given period, $\mathbf{F}_{n\times n} = [f_{ij}]$, $i, j = 1, 2, \ldots, n$. These fluxes can be generated by any process such as feeding (like a food web), excretion, and death. As ecosystems are thermodynamically open, there must also be energy–matter inputs into the system $\mathbf{z}_{1\times n} = [z_i]$, and output losses from the system $\mathbf{y}_{1\times n} = [y_i]$. While the Patten School treats all outputs the same, the Ulanowicz School typically partitions outputs into respiration $\mathbf{r}_{1\times n} = [r_i]$ and export $\mathbf{e}_{1\times n} = [e_i]$ to account for differences in energetic quality. Note that $y_i = r_i + e_i, \forall i$. Some analyses also require the amount of energy–matter stored in each node (e.g., biomass), $\mathbf{X}_{1\times n} = [x_i]$. The final required information is a categorization of each node as living or not, which is essential for algorithms from the Ulanowicz School. For our implementation, we have

created a logical vector $\mathbf{Living}_{1\times n}$ that indicates whether the i^{th} node is living (TRUE) or not (FALSE). Together, the model data $\mathcal{M}$ can be summarized as $\mathcal{M} = \{\mathbf{F}, \mathbf{z}, \mathbf{e}, \mathbf{r}, \mathbf{X}, \mathbf{Living}\}$.

The ENA methodology is an application and extension of economic Input–Output Analysis (**??**) that was first introduced into ecology by **?**. Two major schools have developed in ENA. The first is based on Dr. Robert E. Ulanowicz's work with a strong focus on trophic dynamics and a use of information theory (**???**). The second school has an environment focus and is built on the environ concept introduced by Dr. Bernard C. Patten (**???**). Patten's approach has been collectively referred to separately as *Network Environ Analysis*. At the core the two approaches are very similar; however, they make some different starting assumptions and follow independent yet braided development tracks. One example difference that has historically inhibited collaboration and applications is that the two schools orient their analytical matrices in different ways. The Ulanowicz school orients their matrices as flows from rows-to-columns, which is the most common orientation in the broader field of network science (e.g., **?**). In contrast, the Patten School has historically oriented their matricies from column-to-row. Recent research has started to bring the work of the two schools back together (e.g., **?**); we hope this software contributes to this.

Notice the row-to-column orientation of **F**. This is consistent with the Ulanowicz School of network analysis, as well as the orientation commonly used in Social Network Analysis and used in the *statnet* packages. However, this is the opposite orientation typically used in the Patten School of analysis that conceptually builds from a system of differential equations and thus uses the column-to-row orientation common in this area of mathematics. Even though the difference is only a matrix transpose, this single difference may be the source of much confusion in the literature and frustration on the part of users. We have selected to use row-to-column orientation for our primary data structure, as it is the dominant form across network analytics as evidenced by it use in the *statnet* packages. The package algorithms also return the results in the row-to-column orientation by default; however, we have built in functionality with the functions `get.orient` and `set.orient` that allows users to return output in the Patten School row-to-column orientation (see Section 5.12 for details).

2.2. Network Data Class

The *enaR* package stores the model data in the **network** class defined in the *network* package (see **?**, for details). Again, the primary network object components are:

- F = flow matrix oriented row-to-column
- z = inputs
- r = respiration
- e = exports
- y = respiration+exports
- X = biomass or storage values
- Living = logical vector indicating if the node is living (TRUE) or non-living (FALSE)

2.3. Building a Network Object

Users can assemble the necessary data elements described in Section 2.1 and then use the `pack` function to create the network data object. Here is an example of doing this with hypothetical data.

```
> # generate the flow matrix
> flow.mat <- array(abs(rnorm(100,4,2))*sample(c(0,1),100,replace=TRUE),
+                   dim=c(4,4))
> # name the nodes
> rownames(flow.mat) <- colnames(flow.mat) <- paste('node',(1:nrow(flow.mat)),sep='')
> # generate the inputs
> inputs <- runif(nrow(flow.mat),0,4)
> # generate the exports
> exports <- inputs
> # pack
> fake.model <- pack(flow=flow.mat,
+                    input=inputs,
+                    export=exports,
+                    living=TRUE)
> # model
> fake.model
```

Unfortunately, the attributes() function does not clearly identify the network data objects we are using.

```
> attributes(fake.model)
>
```

However, individual components can be extracted from the data object using the form specified in the *network* package. For example, we can pull out node of vertex attributes as follows:

```
> fake.model%v%'output'
> fake.model%v%'input'
> fake.model%v%'living'
```

The network flows are stored as edge weights in the network object, which lets users fully manipulate the network object with the `network` functions. The flow matrix can be extracted from the object as

```
> as.matrix(fake.model,attrname="flow")
```

There are times that it is useful to extract all of the ecosystem model data elements from the network data object. This can be accomplished using the `unpack` function. The `unpack` output is as follows:

```
> unpack(fake.model)
```

Note that we did not specify the storage values. In these instances `pack` produces `NA` values. Although the package is designed to help users navigate missing data issues be sure to check that you are providing the appropriate input for a given function. For more information, see the help file for the function in question.

2.4. Balancing for Steady-State

Many of the ENA functions assume that the network model is at steady-state (node inputs equal node outputs). Thus, this package has functions for (1) checking to see if the assumption is met and (2) automatically balancing the model so that input equal outputs.

To determine if the model is balanced and then balance it if necessary:

```
> ## --- Check to see if the model is balanced ---#
> ssCheck(fake.model)
> ## --- To BALANCE a model if needed --- #
> fake.model <- balance(fake.model,method="AVG2")
> ## --- To FORCE BALANCE a model if needed --- #
> fake.model <- force.balance(fake.model)
```

The automated balancing routines are based on those presented in **?**. These authors compare alternative balancing algorithms and further discuss the implications of using automated procedures. Caution is warranted when using these techniques, as they indiscriminately alter the model flow rates.

3. Data Input: Reading Common Data File Formats

Several software packages exist in the literature for running ENA. For convenience, we have written functions to read in a few of the more common data formats used by these software.

SCOR

The `read.scor` function reads in data stored in the SCOR format specified by **?** that is the input to the NETWRK4 programs. This function can be run as follows.

```
> scor.model <- readLines('http://people.uncw.edu/borretts/data/oyster.dat')
> m <- read.scor(scor.model,from.file=FALSE)
```

This constructs the network data object from the SCOR file that stores the ecosystem model data for an oyster reef model (**?**). The individual model elements are

```
> unpack(m)
```

This same data is stored as a network data object that is distributed with this package, which can be accessed as:

```
> data(oyster)
> m <- oyster
```

WAND

In part to make ENA more accessible to biologists, **?** recoded some of Ulanowicz's NETWRK4 algorithms into a Microsoft Excel based tool called WAND. For this tool, the model data is stored as a separate Excel file with two worksheets. The first contains many of the node attributes and the second contains the flow matrix. The `read.wand` function will create an network data object from a WAND model file. An example WAND file can be found at http://people.uncw.edu/borretts/data/MDmar02_WAND.xls.

```
>   m <- read.wand('./MDmar02_WAND.xls')
```

This code creates a network data object for *enaR* from the WAND formatted Mdloti ecosystem model data (**?**). This data is courtesy of U.M. Scharler.

ENAM

Another commonly used data format stores the necessary model data in a csv or Excel formatted file. We include an example Excel file of the Mdloti estuary stored in this form ("MDMAR02.xlsx", courtesy of U. M. Scharler). This format has not been described technically in the literature nor has it been named. We refer to it as ENAM as it is the ENA model data stored primarily as a square matrix with several preliminary rows that include meta-data, the number of nodes, and number of living nodes (similar to SCOR). The data format is generally similar in concept, if not exact form, to the data system matrix used as the input to the NEA.m function (**?**). However, the ENAM format includes information on whether nodes are living and partitions output into respiration and exports.

Using an example data file, http://people.uncw.edu/borretts/data/MDMAR02.xlsx, this data format can be read into the *enaR* package as:

```
>   m <- read.enam('./MDMAR02.xlsx')
```

The current read.enam function assumes the data are stored on the first worksheet of an Excel file. In the future, we expect to expand this function's capabilities to read the data from a CSV file.

NEA

For their Matlab function to perform network environ analysis (Patten School), **?** packaged the model flows, inputs, outputs, and storage values into what they called a system matrix $\mathrm{S} = \begin{bmatrix} \mathbf{F} & \vec{z} & \vec{X} \\ \vec{y} & 0 & 0 \end{bmatrix}_{(n+1)\times(n+2)}$. Flows in the system matrix are oriented from column to row. The *enaR* function `read.nea` reads in data with this format stored as a comma separated value file. The function `write.nea()` will write any network model to a CSV file with this format.

While convenient, this data format does not enable inclusion of the full range of model information included in the *enaR* network data object. This format does not partition outputs into exports and respiration values, nor does it identify the node labels are their living status. This missing information will prevent the use of some *enaR* functions.

Here is an example of using these functions:

```
> data(oyster)
> # write oyster reef model to a csv file
> write.nea(oyster, file.name="oyster.csv")
> # read in oyster reef model data from NEA.m formatted CSV file
> m <- read.nea("oyster.csv")
>
> # Again, this model object does NOT contain all
> # of the information in the "oyster" data object.
```

4. Network Visualization

The *enaR* package uses the *network* package plot tools. Here is one example of how to plot a network model. The figure scaling may need to be adjusted depending on computer and devices. Also note that the graph only shows internal system flows.

Figure 1 (left) is a very simple example of to plot a graph of the oyster reef model accomplished with default settings.

```
> data(oyster)  # load data
> m <- oyster
> set.seed(2)    # set random seed to control plot
> plot(m)       # plot network data object (uses plot.network)
```

We can use the excellent graphics capabilities of to make fancier plot of the same data (Fig. 1(right)).

```
> # set colors to use
> my.col=c("red","yellow",
+   rgb(204,204,153,maxColorValue=255),
+   "grey22")
> F=m%n%'flow'                    # extract flow information for later use.
> f=which(F!=0, arr.ind=T)        # get indices of positive flows
> opar <- par(las=1,bg=my.col[4],xpd=TRUE,mai=c(1.02, 0.62, 0.82, 0.42))
> set.seed(2)                     # each time the plot is called, the
>                                 # layout orientation changes.  setting
>                                 # the seed ensures a consistent
>                                 # orientation each time the plot
>                                 # function is called.
> plot(m,
+      vertex.cex=log(m%v%'storage'), # scale nodes with storage
```

Figure 1: Simple (left) and fancy (right) plot of the Oyster network model (Dame and Patten 1981).

Figure 2: A plot of the *enaR* function relationships. Edges point *from* a function that provides information *to* the function that receives that information.

```
+      label= m%v%'vertex.names',     # add node labels
+      boxed.labels=FALSE,
+      label.cex=0.65,
+      vertex.sides=45,   # to make rounded
+      edge.lwd=log10(abs(F[f])),     # scale arrows to flow magnitude
+      edge.col=my.col[3],
+      vertex.col=my.col[1],
+      label.col="white",
+      vertex.border = my.col[3],
+      vertex.lty = 1,
+      xlim=c(-4,1),ylim=c(-2,-2))
> rm(opar)             # remove changes to the plotting parameters
```

5. Analyzing Ecosystem Models

The primary ENA algorithms included in this package are summarized in Table 1 and Figure 2 illustrates the interdependecy of the functions in the package.

In practice, ENA is applied to a single model. Here, we walk through an example of applying multiple ENA algorithms to the oyster reef model (**?**). The main ENA algorithms encoded in *enaR* are summarized in Table 1.

Again, in this package results are reported in the row-to-column orientation by default – including the algorithms from the Patten school. Please see Section 5.12 for how to change this default if needed.

Table 1: Primary Ecological Network Analysis algorithms in *enaR*.

Analysis	**Function Name**	**School**
Structure	`enaStructure`	foundational, Patten
Flow	`enaFlow`	foundational, Patten
Ascendency	`enaAscendency`	Ulanowicz
Storage	`enaStorage`	Patten
Utility	`enaUtility`	Patten
Mixed Trophic Impacts	`enaMTI`	Ulanowicz
Control	`enaControl`	Patten
Environ	`enaEnviron`	Patten

5.1. Structural Network Analysis

Structural network analysis is common to many types of network analysis. The structural analyses applied here are based on those presented in NEA.m (**?**) following the Patten School. Output of the enaStructure function is summarized in Table 2

Table 2: Resultant matrices and network statistics returned by the `enaStructure` function in *enaR*.

Label	Description
Matrices	
A	$n \times n$ adjacency matrix
Network statistics	
n	number of nodes
L	number of directed edges
C	connectance ($C = L/n^2$); the proportion of possible directed edges connected.
LD	Link Density (L/n)
ppr	estimated rate of pathway proliferation (**?**)
lam1A	dominant eigenvalue of A ($lambda_1(\mathbf{A})$), which is the asymptotic rate of pathway proliferation (**?**)
mlam1A	multiplicity of the dominant eigenvalue (number of times repeated)
rho	damping ratio, an indicator of how quickly $[a_{ij}]^{(m)}/[a_{ij}]^{(m-1)}$ goes to $lam_1(\mathbf{A})$ (**?**, , p. 95)
R	distance of $lam_1(\mathbf{A})$ from the bulk of the eigen spectrum (**?**)
d	difference between dominant eigenvalue and link density (expected value for random graph)
no.scc	number of strongly connected components (SCC)
no.scc.big	number of SCC with more than one node
pscc	fraction of network nodes included in a big SCC

```
> St <- enaStructure(m)
> attributes(St)
> St$ns
```

The structural network statistics show that the oyster reef model has 6 nodes, a pathway proliferation rate of 2.14, and that the model is comprised of two strongly connected components but that only one has more than one node.

5.2. Flow Analysis

Flow analysis or throughflow analysis is one of the core ENA analyses for both the Ulanowicz and Patten Schools (**???**). The *enaR* implementation `enaFlow` mostly follows the NEA.m function, with small updates (e.g. calculating the ratio of indirect-to-direct flows **??**). Results returned by `enaFlow` are summarized in Table 3.

Here, we extract the flow statistics and then isolate and remove the output-oriented direct flow intensity matrix $\mathbf{G}$ matrix. Recall that ENA is partially derived from Input–Output analysis; the input and output orientations provide different information about the system. We also show the input-oriented integral flow matrix $\mathbf{N}'$.

Table 3: Matrices and network statistics returned by the `enaFlow` function in *enaR*.

***enaR* label**	**Description**
Matrices	
T	$n \times 1$ vector of node throughflows (M $L^{-2 \text{ or } -3}$ T^{-1})
G	output-oriented direct throughflow intensity matrix
GP	input-oriented direct throughflow intensity matrix
N	output-oriented integral throughflow intensity matrix
NP	input-oriented integral throughflow intensity matrix
Network statistics	
Input	Total input boundary flow
TST	Total System ThroughFLOW
TSTp	Total System ThroughPUT
APL	Average Path Length (**?**)
FCI	Finn Cycling Index (**?**)
BFI	Boundary Flow Intensity, *Boundary/TST*
DFI	Direct Flow Intensity, *Direct/TST*
IFI	Indirect Flow Intensity, *Indirect/TST* (**?**)
ID.F	Ratio of Indirect to Direct Flow **??**
ID.F.I	input oriented ratio of indirect to direct flow intensity (as in **?**)
IF.F.O	output oriented ratio of indirect to direct flow intensity (as in **?**)
HMG.F.I	input oriented network homogenization to direct flow intensity
HMG.F.O	output oriented network homogenization to direct flow intensity
AMP.F.I	input oriented network amplification
AMP.F.O	output oriented network amplification
mode0.F	Boundary Flow
mode1.F	Internal First Passage Flow
mode2.F	Cycled Flow
mode3.F	Dissipative Equivalent to mode1.F
mode4.F	Dissipative Equivalent to mode0.F

```
> F <- enaFlow(m)
> attributes(F)
> F$ns
> G <- F$G # output-oriented direct flow matrix
> rm(G)
> F$NP     # input-oriented integral flow matrix
```

Note: you can use the attach function to have access to the objects nested within an object. Since some objects may conflict in name, it's best to detach an object once it's not in use.

```
> attach(F)
> G
> detach(F)
```

Matrix powers – raising a matrix to a power is not a native operation in R. Thus, the *enaR* package includes a function `mExp` to facilitate this matrix operation commonly used in ENA.

```
> mExp(F$G,2)
```

Table 4: Graph-level network statistics returned by the *enaR* `enaAscendency` function (see **??**, for interpretations).

Label	Description
AMI	average mutual information (bits)
ASC	ascendency, AMI × TSTp
OH	overhead
CAP	capacity
ASC.CAP	ascendency-to-capacity ratio (dimensionless)
OH.CAP	overhead-to-capacity ratio (dimensionless)

5.3. Ascendency

A key contribution of the Ulanowicz School to ENA is Ascendency concept and the development of several information based indices (**??**). This analysis is based on all of the flows in the system and does not assume the modeled system is at steady-state. The `enaAscendency` function returns several of these information based measures (Table 4). This is run as follows:

```
>   enaAscendency(oyster)
```

5.4. Storage Analysis

Storage ENA was developed in the Patten School. It is similar to flow ENA, but divides the flows by storage (e.g., biomass) instead of throughflow. See **?** and **?** for an overview of this method. Output of this function is summarized in Table 5, and this is an example of its implementation.

```
> S <- enaStorage(m)
> attributes(S)
> S$ns
```

5.5. Utility Analysis

Utility analysis describes the relationship between node pairs in the ecosystem model when considering both direct and indirect interactions. It developed in the Patten School (**??**) and is similar to yet distinct from the Ulanowicz School mixed trophic impacts analysis (**?**). Utility analysis can be conducted from both the flow and storage perspectives, so the "type" argument needs to be set to suit the users needs. This is again implemented as in NEA.m. Table 6 summarizes the function output for the flow and storage versions. These analyses are executed as:

```
> UF <- enaUtility(m,eigen.check=TRUE,type="flow")
> US <- enaUtility(m,eigen.check=TRUE,type="storage")
> attributes(UF)
```

Table 5: Matrices and graph-level network statistics returned by the *enaR* `enaStorage` function.

Label	**Description**
Matrices	
X	$n \times 1$ vector of storage values [M L^{-2}]
C	$n \times n$ donor-storage normalized output-oriented direct flow intensity matrix (T^{-1})
P	$n \times n$ storage-normalized output-oriented direct flow matrix (dimensionless)
S	$n \times n$ donor-storage normalized output-oriented integral flow intensity matrix (T^{-1})
Q	$n \times n$ output-oriented integral flow intensity matrix (dimensionless)
CP	$n \times n$ recipient-storage normalized input-oriented direct flow intensity matrix (T^{-1})
PP	$n \times n$ storage-normalized input-oriented direct flow matrix (dimensionless)
SP	$n \times n$ donor-storage normalized input-oriented integral flow intensity matrix (T^{-1})
QP	$n \times n$ input-oriented integral flow intensity matrix (dimensionless)
dt	discrete time step
Network statistics	
TSS	Total System Storage
CIS	Storage Cycling Index
BSI	Boundary Storage Intensity
DSI	Direct Storage Intensity
ISI	Indirect Storage Intensity
ID.S	Ratio of Indirect-to-Direct storage (realized)
ID.S.I	storage-based input-oriented indirect-to-direct ratio (as in **?**)
ID.S.O	storage-based input-oriented indirect-to-direct ratio (as in **?**)
HMG.S.I	input-oriented storage network homogenization
HMG.S.O	output-oriented storage network homogenization
AMP.S.I	input-oriented storage network amplification
AMP.S.O	output-oriented storage network amplification
mode0.S	Storage from Boundary Flow
mode1.S	Storage from Internal First Passage Flow
mode2.S	Storage from Cycled Flow
mode3.S	Dissipative Equivalent to mode1.S
mode4.S	Dissipative Equivalent to mode0.S

Table 6: Matrices and graph-level network statistics returned by the *enaR* `enaUtility` function.

Label	Description
Matrices	
$D_{n\times n}$	throughflow-normalized direct utility intensity (dimensionless)
$U_{n\times n}$	integral flow utility (dimensionless)
$Y_{n\times n}$	integral flow utility scaled by original throughflow (M L^{-2} or $^{-3}$ T^{-1})
$DS_{n\times n}$	storage-normalized direct utility intensity (dimensionless)
$US_{n\times n}$	integral storage utility (dimensionless)
$YS_{n\times n}$	integral storage utility scaled by original throughflow (M L^{-2} or $^{-3}$ T^{-1})
Network Statistics	
lam1D	dominant eigenvalue of D
synergism.F	benefit-cost ratio or network synergism (flow)
mutualism.F	positive to negative interaction ratio or network mutualism (flow)
lam1DS	dominant eigenvalue of DS
synergism.S	benefit-cost ratio or network synergism (storage)
mutualism.S	positive to negative interaction ratio or network mutualism (storage)

Please note the function argument "eigen.check=TRUE". For this analysis to work, the power series of the direct utility matrices must converge, which is only true if the dominant eigenvalue of the direct utility matrix is less than 1. The function default prevents the analysis from being performed if this condition is not met. Users that wish to perform the analysis anyway can set "eigen.check=FALSE". Care should be used when doing this, as the meaning of the underlying mathematics is uncertain.

5.6. Environ Analysis

Environ Analysis finds the *n unit* input and output environs for the model (**??**). These unit environs are returned by the *environ* function as in NEA.m. They indicate the flow activity in each subnetwork generated by pulling a unit out of a node (input environs) or pushing a unit into a node (output environ). These unit environs can be converted into "realized" environs by multiplying each by the relevant observed input or output (**?**).

```
> E <- enaEnviron(m)
> attributes(E)
> E$output[1]
```

The `TET` function returns vectors of the unit and realized input and output total environ throughflow. The realized total environ throughflow is an environ based partition of the total system throughflow (TST).

```
> tet <- TET(m)
> show(tet)
```

The `TES` functions returns the both the realized and unit total environ storage for the input and output environs. Again, the realized TES is a partition of the total system storage (TSS).

Table 7: Matrices returned by the *enaR* `enaControl` function, which are based on (**????**).

Label	Description
Matrices	
$CN_{n\times n}$	Control matrix using flow values
$CQ_{n\times n}$	Control matrix using storage values
$CR_{n\times n}$	Schramski's Control Ratio Matrix
$CD_{n\times n}$	Schramski's Control Difference Matrix
$sc_{n\times 1}$	Schramski's System Control vector

```
> tes <- TES(m)
> show(tes)
```

5.7. Control Analysis

Control analysis was implemented as in the original NEA.m function, but we also include recent updates to control analysis (e.g., **??**). In general, these analyses determine the pairwise control relationships between the nodes in the network. Table 7 summarizes the function output.

```
>                                          #conduct control analysis
> C <- enaControl(m)
> attributes(C)
```

5.8. Mixed Trophic Impacts

Mixed Trophic Impacts is a popular analysis from the Ulanowicz School of ENA (**?**). The `enaMTI` function generates comparable results to the calculations in **?**. These are implemented as follows; Table 8 summarizes the function output.

```
>                                        #conduct mixed trophic impacts
> mti <- enaMTI(oyster)
> attributes(mti)
>                                        #shows the total impact matrix
> mti$M
```

In this case, the power series of the direct trophic impacts matrix does not converge (dominant eigenvalue is greater than one). Thus, the function returns the mti$M = NA. Like with Utility analysis, however, we can use the eigen.check argument to do the calculation despite the mathematical problem.

```
>   mti <- enaMTI(oyster,eigen.check=FALSE)
> attributes(mti)
> mti$M  # shows the total impact matrix
```

Table 8: Matrices returned by the *enaR* `enaMTI` function, which are based on (**?**).

Label	Description
Matrices	
$G_{n\times n}$	positive effect of prey on its predator
$F_{n\times n}$	negative impact of the predator on its prey
$Q_{n\times n}$	direct net impact of one node on another
$M_{n\times n}$	total impact of i on j (direct and indirect)

5.9. Cycle Analysis

The Cycle Analysis provides the detailed account of the cycling present in the network. It follows the algorithm by the DOS-based NETWRK 4.2b software by Ulanowicz (**??**) and provides results similar to NETWRK's 'Full Cycle Analysis'. Cycles in a network are grouped together into disjoint nexuses and each nexus is characterized by a weak arc. This function gives details of the individual cycles along with the disjoint nexuses present in the network. Table 9 summarizes the function output.

```
>   cyc <- enaCycle(m)
> attributes(cyc)
>                                          # Display information of individual cycles
> names(cyc$Table.cycle)
>                                          # Display information of the disjoint nexuses
> names(cyc$Table.nexus)
>
```

5.10. Trophic Aggregations

The Trophic Aggregation algorithm identifies the trophic structure of the given network based on the Lindeman's trophic concepts (**?**). The algorithm is implemented as in NETWRK 4.2b by Ulanowicz (**?**) and provides similar results as NETWRK's 'Lindeman Trophic Aggregations' (**?**). It apportions the nodes into integer trophic levels and estimates the corresponding inputs, exports, respirations and the grazing chain and trophic spine which represent the transfers between integer trophic levels.

It is crucial for this algorithm that the cycles among the nl living nodes of the network (Feeding Cycles) be removed beforehand to assign trophic levels to nodes. Hence the output for this function contains the Cycle Analysis output for the Feeding cycles in the network.

Following **?**, the non-living nodes are grouped together for this analysis and referred to as the detrital pool.

Table 10 summarizes the function output except the outputs for the feeding cycles which are similar to the enaCycle outputs.

```
> trop <- enaTroAgg(m)
> attributes(trop)
>                                          # Cycle analysis output for Feeding Cycles
> trop$Feeding_Cycles
```

Table 9: Data frames, matrices and graph-level network statistics returned by the *enaR* `enaCycle` function, which is based on (**?**).

Label	Description
Data frames	
Table.cycle	Data frame of cycles in the network. Up to 50 cycles are returned per nexus.
Table.nexus	Data frame with details of the disjoint nexuses present in the network
Matrices	
$\text{CycleDist}_{n\times 1}$	Vector of flows cycling in loops of increasing length (i.e., 1, 2, ...).
$\text{NormDist}_{n\times 1}$	Vector of Cycle Distributions normalized by the total system throughput
$\text{ResidualFlows}_{n\times n}$	Matrix of straight-through flows or the underlying acyclic graph
$\text{AggregatedCycles}_{n\times n}$	Matrix of all the cycled flows or the underlying cyclic graph
Network Statistics	
NCYCS	Number of cycles detected in the network
NNEX	Number of disjoint nexuses detected in the network
CI	Cycling index of the network based on flow matrix

5.11. Other Analyses

There are a number of additional tools in the package. Here we highlight a couple of them.

A quick way to get a list of all of the global network statistics reported in Structure, Flow, Ascendency, Storage, and Utility analysis is to use the `get.ns` function.

```
> ns <- get.ns(m)
> str(ns)    # examine the structure of ns
```

It is also possible to instantly return all of the main ENA output with `enaAll`:

```
> oyster.ena <- enaAll(oyster)
> names(oyster.ena)
```

Centrality analysis is a large topic in network science. **?** introduced an environ based centrality and contrasted it with the more commonly used eigenvector centrality. Both of these centralities can be calculated in *enaR* as follows:

```
> F <- enaFlow(oyster)
> ec <- environCentrality(F$N)
> show(ec)
> eigenCentrality(F$G)
```

These centrality values have been normalized to sum to one.

Figure 4 shows one way to visualize the Average Environ Centralities.

Table 10: Matrices and graph-level network statistics returned by the *enaR* `enaTroAgg` function, which are based on **?**.

Label	Description
Matrices	
$A_{nl \times nl}$	Lindeman transformation matrix that apportions nodes to integer trophic levels
$ETL_{n \times 1}$	Vector of the effective trophic levels of different nodes
$M.Flow_{nl \times 1}$	Migratory flows in living nodes (if present)
$CI_{n \times 1}$	Vector of canonical inputs to integer trophic levels (if migratory flows present)
$CE_{n \times 1}$	Canonical Exports. Vector of exports from Integer trophic levels
$CR_{n \times 1}$	Canonical Respirations. Vector of respiration from Integer trophic levels
$GC_{nl \times 1}$	Grazing Chain. Vector of inputs to Integer trophic levels from preceding level
$RDP_{nl \times 1}$	Vector of returns from each level to the detrital pool
$LS_{nl \times 1}$	Vector representing the Lindeman Spine
$TE_{nl \times 1}$	Vector of the trophic efficiencies for integer trophic levels
Network Statistics	
Detritivory	Flow from the detrital pool (non-living nodes) to the second trophic level
DetritalInput	Exogenous inputs to the detrital pool
DetritalCirc	internal circulation within the detrital pool
NCYCS	number of feeding cycles removed from the network
NNEX	number of disjoint nexuses detected for the feeding cycles
CI	cycling index of the living component of the network based on flow matrix

Figure 3: Bar plot of the Oyster Reef model Average Environ Centralities.

```
> # set plotting parameters
> opar <- par(las=1,mar=c(7,5,1,1),xpd=TRUE,bg="white")
> # find centrality order
> o <- order(ec$AEC,decreasing=TRUE)
> bp <- barplot(ec$AEC[o],     # create barplot
+               names.arg=NA,
+               ylab="Average Environ Centrality",
+               col="black",border=NA)
> text(bp,-0.008,                # add labels
+      labels=names(ec$AEC)[o],
+      srt=35,adj=1,cex=1)
> rm(opar)  # remove the plotting parameters
```

5.12. Output Orientation

To facilitate package use by the existing ENA community, some of which use the column-to-

row orientation (e.g. the Patten School), we have created orientation functions that enable the user to set the expected output orientation for functions written in a particular "school" of analysis. Thus, functions from either school will receive network models with the standard row-to-column, but will return output with flow matrices oriented in the column-to-row orientation when appropriate (i.e. Patten school functions) and return them in that same orientation.

Here is an example of how to use the model orientation functions to re-orient the output from `enaFlow`:

```
> ###Check the current orientation
> get.orient()
> ###enaFlow output in row-column
> flow.rc <- enaFlow(oyster)$G
> ###Set the global orientation to school
> set.orient('school')
> ###Check that it worked
> get.orient()
> ###enaFlow output in column-row
> flow.cr <- enaFlow(oyster)$G
> ###Check. Outputs should be transposed from each other.
> all(flow.rc == flow.cr)
> all(flow.rc == t(flow.cr))
> ###Now change back to the default orientation ('rc')
> set.orient('rc')
>
```

6. Model Library

The *enaR* package includes a library of 100 empirically based ecosystem models. There are two general classes of ecosystem models. First, there are 58 of the models are trophically-based models with food webs at their core (Tables 11). Second, there are 42 models are focused on biogeochemical cycling in ecosystems (Table 12). **?**, **?**, and **?** have previously suggested this model class distinction. In summary, these models were originally published for a number of different types of ecosystems, though predominantly aquatic, by a number of author teams. Models in the library range in size from 4 nodes to 125 nodes with connectance values ranging from 7% to 45%.

This collection of models overlaps with other data sets. For example, twenty-seven of the models (47%) are included in the set of models compiled and distributed by Dr. Ulanowicz (http://www.cbl.umces.edu/ ulan/ntwk/network.html). All 50 of the models analyzed by **?** and **?** and the 45 models analyzed in **?** are included in this model library.

The trophic models are grouped as the `troModels` object and the biogeochemically-based models are available as the `bgcModels` object. Both data objects return a list of the model network objects. To use these models simply use the R *base* `data` function. This will load the models into the working memory as a named list of network objects:

```
> ### Import the model sets
```

```
> data(bgcModels)
> data(troModels)
> ### Check the first few model names
> head(names(bgcModels))
> head(names(troModels))
> ### Isolate a single model
> x <- troModels[[1]]
> x <- troModels$"Marine Coprophagy (oyster)"
> ### Check out the model
> summary(x)
```

7. Multi-Model Analyses (Batch Processing)

While many investigators analyze single models, much of ENA is used to compare ecosystem models (e.g., **????**). Investigators have also analyzed large set of models to determine the generality of hypothesized ecosystem properties (e.g., **???**). For both of these applications, investigators need to analyze multiple models. One advantage of the *enaR* package is that it simplifies this batch processing. Here we illustrate how to batch analyze a selection of models.

Our first step is to read in the model data for a set of trophic models:

```
> data(troModels)
```

Now that we have the raw data loaded, we can start to manipulate it. The first step is to balance the models and then we can run the flow analysis. We are using the `lapply` function to apply the analysis across the list of models stored in model.list.

```
> # balance models as necessary
> m.list <- lapply(troModels[1:10],balance)
> # check that models are balanced
> unlist(lapply(m.list,ssCheck))
> # if balancing fails, you can use force.balance
> # to repeatedly apply the balancing procedure
> # although this is not the case with our model set
>
> m.list <- lapply(m.list,force.balance)
> ##Check that all the models are balanced
> all(unlist(lapply(m.list,ssCheck)))
> # Example Flow Analysis
> F.list <- lapply(m.list, enaFlow)
> # the full results of the flow analysis is now stored in the elements
> # of the F.list.  To get the results for just the first model...
> F.list[[1]]
>
```

We can use the same technique to extract specific information, like just the ratio of Indirect-to-Direct flow for each model.

```
> # Example of extracting just specific information - Indirect Effects Ratio
> IDs <- unlist(lapply(m.list, function(x) enaFlow(x)$ns[8]))
> #Look at the first few ID's
> head(IDs)
```

We can also collect the set of output-oriented integral flow matrices.

```
> # Here is a list containing only the output-oriented integral flow matrices
> N.list <- lapply(m.list,function(x) enaFlow(x)$N)
```

We can also apply the `get.ns` function to extract all of the network statistics for each model. We then use the `do.call` function to reshape the network statistics into a single data frame.

```
> # Collecting and combining all network statistics
> ns.list <- lapply(m.list,get.ns) # returns as list
> ns <- do.call(rbind,ns.list)  # ns as a data.frame
> # Let's take a quick look at some of the output
> colnames(ns)    # return network statistic names.
> dim(ns)         # show dimensions of ns matrix
> ns[1:5,1:5]     # show selected results
```

Given this data frame of network statistics, we can construct interesting plots for further analysis. Here we focus on results of the St. Marks Seagrass ecosystem (**?**).

```
> opar <- par(las=1,mar=c(9,7,2,1),xpd=TRUE,mfrow=c(1,2),oma=c(1,1,0,0))
> x=dim(ns)[1] # number of models
> m.select <- 40:45
> bp=barplot(ns$ID.F[m.select],ylab="Indirect-to-Direct Flow Ratio (I/D, Realized)",
+         col="darkgreen",border=NA,ylim=c(0,2))
> text(bp,-0.05,                # add labels
+      labels=rownames(ns)[m.select],
+        srt=45,adj=1,cex=0.85)
> opar <- par(xpd=FALSE)
> abline(h=1,col="orange",lwd=2)
> #
> plot(ns$FCI,ns$ID.F,pch=20,col="blue",cex=2,
+      ylab="Indirect-to-Direct Flow Ratio (I/D, Realized)",
+      xlab="Finn Cycling Index (FCI)",
+      xlim=c(0,0.8),ylim=c(0,8))
> #
> rm(opar)  # remove the plotting parameters
```

8. Connecting to Other Useful Packages

Another advantage of building the *enaR* package in is that it lets ecologists take advantage of other types of network analysis and statistical tools that already exist in . We highlight two examples here.

Figure 4: Ratio of Indirect-to-Direct Flow for six ecosystem models (left) and relationship between the Finn Cycling Index and the ratio of Indirect-to-Direct flow in the 56 trophic models.

8.1. sna: Social Network Analysis

The *sna* package for Social Network Analysis is bundled in the *statnet* package and uses the same network data object defined in *network* that we selected to use for *enaR*. Thus, the design decision to use the network data object gives users direct access to *sna* tools.

Multiple measures of network centrality have been proposed, and the *sna* package provides a way of calculating several. Thus, ecologists can now use the sna algorithms to determine different types of centrality for their models.

```
> betweenness(oyster)
> closeness(oyster)
```

The *sna* package introduced new graphical capabilities as well. For example, it will create a target diagram of centralities.

```
> m <- troModels[[38]]
> b <- betweenness(m)          # calculate betweenness centrality
> nms <- m%v%'vertex.names'    # get vertex names
> show(nms)
> nms[b<=(0.1*max(b))] <- NA  # exclude less central nodes
> set.seed(3)
> opar <- par(xpd=TRUE,mfrow=c(1,1))
> # create target plot
> gplot.target(m,b,#circ.lab=FALSE,
+              edge.col="grey",
+              label=nms) # show only labels of most central nodes
>              #xlim=c(-1,4))
> rm(opar)
```

Figure 5: Target plot of node betweenness centrality for the Chesapeake Bay model (meso-haline, carbon, annual).

In addition to the node-level measures, *sna* includes graph-level indices.

```
> centralization(oyster, degree)
> centralization(oyster,closeness)
> centralization(oyster,betweenness)
```

8.2. iGraph

The *iGraph* package can also be useful for analyzing network data. Here are a few examples of using the package. Note that some functions in *iGraph* conflict with other functions already defined, so care is required when using *iGraph*.

Figure 6: Plot of Oyster reef model using *iGraph*

```
> library(igraph)
> ### The adjacency matrix
> A <- St$A
> ### creating an iGraph graph
> g <- graph.adjacency(A)
> plot(g)  # uses iGraph plot tools
```

iGraph has a different set of visualization tools and generates a different looking graph (Fig. 6).

```
> # betweenness centrality (calculated by iGraph and sna)
> betweenness(g)
> # shortest path between any two nodes
> shortest.paths(g)
> # average path length in the network (graph theory sense)
> average.path.length(g,directed=TRUE)
> diameter(g)  # diameter of the graph
> vertex.connectivity(g)  # connectivity of a graph (group cohesion)
> subcomponent(g,1,'in')  # subcomponent reachable from 1 along inputs
> subcomponent(g,2,'in')  # subcomponent reachable from 2 along inputs
> subcomponent(g,1,'out') # subcomponent reachable from 1 along outputs
> subcomponent(g,2,'out') # subcomponent reachable from 2 along output
> edge.connectivity(g)
> detach(package:igraph)  # detach igraph package
```

There are other packages that have graph and network analysis tools, like Bioconductor, that might also be useful for ecologists

9. Summary and Future

This vignette shows how to use several of the key features of the *enaR* package that enables scientists to perform Ecological Network Analysis in . The vision for this package is that it will provide access to ENA algorithms from both the Ulanowicz and Patten Schools. In its current form it replicates, updates, and extends the functionality of the NEA.m function (**?**). It also includes both ascendency calculations and mixed trophic impacts from the Ulanowicz school of ENA, but there remains many possibilities for future development. We hope to do this in collaboration with users. This vignette also illustrates how users can further analyze their data with other packages for graph and network analysis like *sna* and *iGraph*. In summary, we hope you find this package useful for your ENA needs.

References

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Table 11: Trophic ecosystem networks (58) included in the *enaR* model library.

Models	Units	$n^{\dagger}$	$C^{\dagger}$	$Input^{\dagger}$	$TST^{\dagger}$	$FCI^{\dagger}$	Reference
Marine Coprophagy (oyster)	kcal m^{-2} yr^{-1}	4	0.25	379	549	0.12	?
Lake Findley	gC m^{-2} yr^{-1}	4	0.38	21	50	0.30	?
Mirror Lake	gC m^{-2} yr^{-1}	5	0.36	72	217	0.32	?
Lake Wingra	gC m^{-2} yr^{-1}	5	0.40	478	1517	0.40	?
Marion Lake	gC m^{-2} yr^{-1}	5	0.36	87	242	0.31	?
Cone Springs	kcal m^{-2} yr^{-1}	5	0.32	11819	30626	0.09	?
Silver Springs	kcal m^{-2} yr^{-1}	5	0.28	21296	29175	0.00	?
English Channel	kcal m^{-2} yr^{-1}	6	0.25	1096	2280	0.00	?
Oyster Reef	kcal m^{-2} yr^{-1}	6	0.33	41	83	0.11	?
Baie de Somme	mgC m^{-2} d^{-1}	9	0.30	876	2034	0.14	?
Bothnian Bay	gC m^{-2} yr^{-1}	12	0.22	44	183	0.23	?
Bothnian Sea	gC m^{-2} yr^{-1}	12	0.24	117	562	0.31	?
Ythan Estuary	gC m^{-2} yr^{-1}	13	0.23	1258	4181	0.24	?
Sundarban Mangrove (virgin)	kcal m^{-2} yr^{-1}	14	0.22	111317	440931	0.19	?
Sundarban Mangrove (reclaimed)	kcal m^{-2} yr^{-1}	14	0.22	38484	103056	0.05	?
Baltic Sea	mg C m^{-2} d^{-1}	15	0.17	603	1973	0.13	?
Ems Estuary	mg C m^{-2} d^{-1}	15	0.19	282	1067	0.32	?
Swartkops Estuary 15	mg C m^{-2} d^{-1}	15	0.17	3544	13996	0.47	?
Southern Benguela Upwelling	mg C m^{-2} d^{-1}	16	0.23	714	2545	0.31	?
Peruvian Upwelling	mg C m^{-2} d^{-1}	16	0.22	14927	33491	0.04	?
Crystal River (control)	mg C m^{-2} d^{-1}	21	0.19	7357	15062	0.07	?
Crystal River (thermal)	mg C m^{-2} d^{-1}	21	0.14	6018	12032	0.09	?
Charca de Maspalomas Lagoon	mg C m^{-2} d^{-1}	21	0.12	1486230	6010331	0.18	?
Northern Benguela Upwelling	mg C m^{-2} d^{-1}	24	0.21	2282	6611	0.05	?
Swartkops Estuary	mg C m^{-2} d^{-1}	25	0.17	2859	8949	0.27	?
Sunday Estuary	mg C m^{-2} d^{-1}	25	0.16	4440	11937	0.22	?
Kromme Estuary	mg C m^{-2} d^{-1}	25	0.16	2571	11087	0.38	?
Okefenokee Swamp	g dw m^{-2} y^{-1}	26	0.20	2533	12855	0.48	?
Neuse Estuary (early summer 1997)	mg C m^{-2} d^{-1}	30	0.09	4385	13827	0.12	?
Neuse Estuary (late summer 1997)	mg C m^{-2} d^{-1}	30	0.11	4639	13035	0.13	?
Neuse Estuary (early summer 1998)	mg C m^{-2} d^{-1}	30	0.09	4568	14025	0.12	?
Neuse Estuary (late summer 1998)	mg C m^{-2} d^{-1}	30	0.10	5641	15031	0.11	?
Gulf of Maine	g ww m^{-2} yr^{-1}	31	0.35	5053	18381	0.15	?
Georges Bank	g ww m^{-2} yr^{-1}	31	0.35	4380	16889	0.18	?
Middle Atlantic Bight	g ww m^{-2} yr^{-1}	32	0.37	4869	17916	0.18	?
Narragansett Bay	mgC m^{-2} yr^{-1}	32	0.15	693845	3917246	0.51	?
Southern New England Bight	g ww m^{-2} yr^{-1}	33	0.35	4717	17597	0.16	?
Chesapeake Bay	mg C m^{-2} yr^{-1}	36	0.09	888791	3227453	0.19	?
Mondego Estuary (*Zostera* sp. Meadows)	g AFDW m^{-2} yr^{-1}	43	0.19	4030	6822	0.03	?
St. Marks Seagrass, site 1 (Jan.)	mg C m^{-2} d^{-1}	51	0.08	514	1315	0.13	?
St. Marks Seagrass, site 1 (Feb.)	mg C m^{-2} d^{-1}	51	0.08	601	1590	0.11	?
St. Marks Seagrass, site 2 (Jan.)	mg C m^{-2} d^{-1}	51	0.07	602	1383	0.09	?
St. Marks Seagrass, site 2 (Feb.)	mg C m^{-2} d^{-1}	51	0.08	800	1921	0.08	?
St. Marks Seagrass, site 3 (Jan.)	mg C m^{-2} d^{-1}	51	0.05	7809	12651	0.01	?
St. Marks Seagrass, site 4 (Feb.)	mg C m^{-2} d^{-1}	51	0.08	1432	2865	0.04	?
Sylt-Rømø Bight	mg C m^{-2} d^{-1}	59	0.08	683448	1781028	0.09	?
Graminoids (wet)	g C m^{-2} yr^{-1}	66	0.18	6272	13676	0.02	?
Graminoids (dry)	g C m^{-2} yr^{-1}	66	0.18	3472	7519	0.04	?
Cypress (wet)	g C m^{-2} yr^{-1}	68	0.12	1418	2571	0.04	?
Cypress (dry)	g C m^{-2} yr^{-1}	68	0.12	1035	1919	0.04	?
Lake Oneida (pre-ZM)	g C m^{-2} yr^{-1}	74	0.22	1034	1697	0.00	?
Lake Oneida (post-ZM)	g C m^{-2} yr^{-1}	76	0.22	810	1462	0.00	?
Bay of Quinte (pre-ZM)	g C m^{-2} yr^{-1}	74	0.21	984	1509	0.00	?
Bay of Quinte (post-ZM)	g C m^{-2} yr^{-1}	80	0.21	1129	2039	0.01	?
Mangroves (wet)	g C m^{-2} yr^{-1}	94	0.15	1531	3265	0.10	?
Mangroves (dry)	g C m^{-2} yr^{-1}	94	0.15	1531	3272	0.10	?
Florida Bay (wet)	mg C m^{-2} yr^{-1}	125	0.12	738	2720	0.14	?
Florida Bay (dry)	mg C m^{-2} yr^{-1}	125	0.13	547	1778	0.08	?

† n is the number of nodes in the network model, $C = L/n^2$ is the model connectance when L is the number of direct links or energy–matter transfers, $Input = sumz_i$ is the total amount of energy–matter flowing into the system, $TST = \sum\sum f_{ij} + \sum z_i$ is the total system throughflow, and FCI is the Finn Cycling Index (?). Flow based network statistics ($Input$, TST, and FCI) were calculated after models were balanced using the AVG2 algorithm.

Table 12: Biogeochemical ecosystem networks (42) included in the *enaR* model library.

Model	Units	$n^\dagger$	$C^\dagger$	$Input^\dagger$	$TST^\dagger$	$FCI^\dagger$	Reference
Hubbard Brook (Waide)	kg Ca Ha^{-1} yr^{-1}	4	0.25	11	168	0.76	?
Hardwood Forest, NH	kg Ca Ha^{-1} yr^{-1}	4	0.31	11	200	0.80	?
Douglas Fir Forest, WA	kg Ca Ha^{-1} yr^{-1}	4	0.31	4	54	0.74	?
Douglas Fir Forest, WA	kg K Ha^{-1} yr^{-1}	4	0.31	0	45	0.97	?
Puerto Rican Rain Forest	kg Ca Ha^{-1} yr^{-1}	4	0.31	43	274	0.57	?
Puerto Rican Rain Forest	kg K Ha^{-1} yr^{-1}	4	0.31	20	433	0.86	?
Puerto Rican Rain Forest	kg Mg Ha^{-1} yr^{-1}	4	0.31	10	70	0.58	?
Puerto Rican Rain Forest	kg Cu Ha^{-1} yr^{-1}	4	0.31	0	2	0.37	?
Puerto Rican Rain Forest	kg Fe Ha^{-1} yr^{-1}	4	0.31	0	7	0.95	?
Puerto Rican Rain Forest	kg Mn Ha^{-1} yr^{-1}	4	0.38	0	7	0.98	?
Puerto Rican Rain Forest	kg Na Ha^{-1} yr^{-1}	4	0.31	64	140	0.24	?
Puerto Rican Rain Forest	kg Sr Ha^{-1} yr^{-1}	4	0.31	0	1	0.71	?
Tropical Rain Forest	g N m^{-2} d^{-1}	5	0.24	10	71	0.48	?
Neuse River Estuary (AVG)	mmol N m^{-2} $season^{-1}$	7	0.45	795	41517	0.89	?
Neuse River Estuary (Spring 1985)	mmol N m^{-2} $season^{-1}$	7	0.45	133	9120	0.91	?
Neuse River Estuary (Summer 1985)	mmol N m^{-2} $season^{-1}$	7	0.45	119	20182	0.96	?
Neuse River Estuary Fall 1985)	mmol N m^{-2} $season^{-1}$	7	0.45	181	8780	0.88	?
Neuse River Estuary Winter 1986)	mmol N m^{-2} $season^{-1}$	7	0.43	187	6880	0.85	?
Neuse River Estuary (Spring 1986)	mmol N m^{-2} $season^{-1}$	7	0.45	128	12915	0.94	?
Neuse River Estuary (Summer 1986)	mmol N m^{-2} $season^{-1}$	7	0.45	165	11980	0.91	?
Neuse River Estuary (Fall 1986)	mmol N m^{-2} $season^{-1}$	7	0.45	100	9863	0.94	?
Neuse River Estuary (Winter 1987)	mmol N m^{-2} $season^{-1}$	7	0.45	691	7907	0.62	?
Neuse River Estuary (Spring 1987)	mmol N m^{-2} $season^{-1}$	7	0.45	334	11533	0.84	?
Neuse River Estuary (Summer 1987)	mmol N m^{-2} $season^{-1}$	7	0.45	90	15621	0.96	?
Neuse River Estuary (Fall 1987)	mmol N m^{-2} $season^{-1}$	7	0.45	85	7325	0.93	?
Neuse River Estuary (Winter 1988)	mmol N m^{-2} $season^{-1}$	7	0.45	171	8680	0.89	?
Neuse River Estuary (Spring 1988)	mmol N m^{-2} $season^{-1}$	7	0.45	176	6898	0.85	?
Neuse River Estuary (Summer 1988)	mmol N m^{-2} $season^{-1}$	7	0.45	132	16814	0.95	?
Neuse River Estuary (Fall 1988)	mmol N m^{-2} $season^{-1}$	7	0.45	128	5732	0.87	?
Neuse River Estuary (Winter 1989)	mmol N m^{-2} $season^{-1}$	7	0.45	291	5739	0.75	?
Cape Fear River Estuary (Oligohaline)	nmol N cm^{-3} d^{-1}	8	0.36	3802	7088	0.20	?
Cape Fear River Estuary (Polyhaline)	nmol N cm^{-3} d^{-1}	8	0.36	3068	5322	0.17	?
Lake Lanier (AVG)	mg P m^{-2} day^{-1}	11	0.21	95	749	0.40	?
Baltic Sea	mg N m^{-3} day^{-1}	16	0.15	2348	44510	0.67	?
Chesapeake Bay	mg N m^{-2} yr^{-1}	36	0.12	73430	484325	0.33	?
Chesapeake Bay	mg P m^{-2} yr^{-1}	36	0.12	9402	101091	0.51	?
Chesapeake Bay (Winter)	mg P m^{-2} $season^{-1}$	36	0.08	1009	11926	0.53	?
Chesapeake Bay (Spring)	mg P m^{-2} $season^{-1}$	36	0.10	1932	27325	0.57	?
Chesapeake Bay (Summer)	mg P m^{-2} $season^{-1}$	36	0.12	4184	42935	0.46	?
Chesapeake Bay (Fall)	mg P m^{-2} $season^{-1}$	36	0.10	2276	18904	0.40	?
Sylt-Rømø Bight	mg N m^{-2} yr^{-1}	59	0.09	99613	363693	0.23	?
Sylt-Rømø Bight	mg P m^{-2} yr^{-1}	59	0.09	2508	57739	0.66	?

† n is the number of nodes in the network model, $C = L/n^2$ is the model connectance when L is the number of direct links or energy–matter transfers, $Input = sumz_i$ is the total amount of energy–matter flowing into the system, $TST = \sum\sum f_{ij} + \sum z_i$ is the total system throughflow, and FCI is the Finn Cycling Index (?). Flow based network statistics ($Input$, TST, and FCI) were calculated after models were balanced using the AVG2 algorithm.