

Title: enaR: An R package for Ecosystem Network Analysis

Running Title: R ecosystem network analysis package

Word Count: 3110

Authors: Stuart R. Borrett, Matthew K. Lau

Addresses:

- SRB: Department of Biology and Marine Biology, University of North Carolina Wilmington, Wilmington, NC 28403
- MKL: Department of Biological Sciences and the Merriam-Powell Center for Environmental Research, Northern Arizona University, 617 S. Beaver St., Flagstaff, AZ 86011
Current Address: Harvard Forest, Harvard University, 324 N. Main St., Petersham, MA 01366

Contact Details:

- Email: borretts@uncw.edu
- Phone: 910.962.2411
- Fax: 910.962.4066

enaR: An R package for Ecosystem Network Analysis

Stuart R. Borrett^{a,*} and Matthew K. Lau^b

^a Department of Biology and Marine Biology,

University of North Carolina Wilmington, Wilmington, NC 28403

^b Department of Biological Sciences and the Merriam-Powell Center for Environmental Research,
Northern Arizona University, 617 S. Beaver St., Flagstaff, AZ 86011

Current Address: Harvard Forest, Harvard University, 324 N. Main St., Petersham, MA 01366

* Corresponding author, borretts@uncw.edu

July 24, 2014

Abstract

- Network analysis is a useful approach for investigating complex and relational datasets in many fields including ecology, molecular, and evolutionary biology.
- Here, we introduce **enaR**, an R package for Ecosystem Network Analysis (ENA). ENA is an analytical tool set rooted in ecosystem ecology with over 30 years of development that examines the structure and dynamics of matter and energy movement between discrete ecological compartments (e.g., a food web).
- In addition to describing the primary functionality of the package, we highlight several features including a library of 100 empirical ecosystem models, the ability to analyze and compare multiple models simultaneously, and connections to other ecological network analysis tools in R.

KEYWORDS: network analysis, ecosystem, open-source software, network environ analysis, ascendancy, input–output analysis, food web, urban metabolism, Ecopath, NETWRK, WAND

14 Introduction

15 Network ecology – the study of ecological systems using network models and analyses to characterize
16 their structure, function, and evolution – is a large and rapidly growing area of ecology (Proulx
17 *et al.*, 2005). For example, Ings *et al.* (2009) discovered that a notable fraction of 2008 publications
18 in 11 select journals were related to food webs ($\approx 2.4\%$), mutualistic networks ($\approx 0.9\%$), and host-
19 parasitoid networks ($\approx 0.06\%$). Likewise, Borrett *et al.* (2014) found that the percent of ecology and
20 evolutionary biology papers indexed by Web of Science that could be classified as network ecology
21 increased from 1.3% in 1991 to more than 5% in 2012. This rise of network ecology contributes to,
22 mirrors, and builds on the more general growth of network sciences (Barabási, 2012; Borgatti &
23 Foster, 2003; Freeman, 2004; Newman, 2003; Wasserman & Faust, 1994).

24 Ecosystem Network Analysis (ENA) is a branch of network ecology that has been used to address
25 a range of key ecosystem questions (Borrett *et al.*, 2012; Fath & Patten, 1999; Ulanowicz, 1986). For
26 example, in the food web of Big Cypress National Preserve (Florida, USA) Bondavalli & Ulanowicz
27 (1999) found evidence of an indirect mutualism between the American alligator and some of its
28 prey items. Applications of ENA have also lead to new insights into the classic trophic questions of
29 “What limits food-chain length?” (Ulanowicz *et al.*, 2014) and “Are food webs modular?” (Allesina
30 *et al.*, 2005; Borrett *et al.*, 2007; Krause, 2004). Hines *et al.* (2012) used ENA to quantify the relative
31 importance of coupling between biogeochemical processes (e.g., nitrification) in the Cape Fear River
32 estuary sedimentary nitrogen cycle. Further, scientists have used ENA to investigate differences in
33 urban sustainability (Bodini & Bondavalli, 2002; Bodini *et al.*, 2012; Chen & Chen, 2012; Zhang
34 *et al.*, 2010). Collectively, this work consistently shows the power of a transactional network to
35 generate unexpected ecological relationships that then influence the system function and evolution
36 (Jørgensen *et al.*, 2007; Patten, 1991; Ulanowicz, 1997).

37 **enaR** is an open-source software to facilitate ENA. The currently available ENA software pack-

38 ages (Allesina & Bondavalli, 2004; Christensen & Walters, 2004; Fath & Borrett, 2006; Kazanci,
 39 2007; Ulanowicz & Kay, 1991) each have critical limitations, which led us to three primary design
 40 objectives for **enaR**. The first objective was to collect the major ENA functions into a single software
 41 package. While multiple investigators have contributed to algorithmic development (e.g., Allesina
 42 & Bondavalli, 2003; Fath & Patten, 1999; Finn, 1976; Ulanowicz, 1986; Ulanowicz & Kay, 1991), the
 43 broad set of tools is not available in a single existing software. The second objective was to increase
 44 the availability and extensibility of the software. We chose to use R in part because of its increasing
 45 popularity as an analytical tool in the biological sciences (e.g., Dixon, 2003; Metcalf *et al.*, 2012;
 46 Revell, 2012). Further, users can freely download a stable version of the package from the CRAN
 47 website (<http://cran.r-project.org/web/packages/enaR>), and the code for every function in
 48 R is available from within R (e.g., `edit(function_name)`). In addition, **enaR** development is being
 49 managed via GitHub (<https://github.com/TheSeeLab/enaR>) to encourage collaborative devel-
 50 opment. The third design objective was to enable **enaR** users access to network analysis tools from
 51 other disciplines. To enable this, **enaR** was designed to work directly with two existing R network
 52 analysis packages: **network** (Butts, 2008a) and **sna** (Butts, 2008b). In summary, the aim of the
 53 **enaR** package is to make ENA tools more available and easier to use, adapt, and extend.

54 In this paper, we present an overview of **enaR** and highlight some of its functionality. A full
 55 description of the ENA algorithms and their use and interpretation is beyond the scope of this short
 56 paper, but we refer interested readers to a selection of reviews as an entry point to ENA (Fath &
 57 Borrett, 2006; Fath & Patten, 1999; Jørgensen *et al.*, 2007; Schramski *et al.*, 2011; Ulanowicz, 1997).
 58 For a more comprehensive description on how to use the **enaR** package, please refer to the package
 59 vignette: <http://cran.r-project.org/web/packages/enaR/vignettes/enaR-vignette.pdf>.

Overview of enaR

ENA is an agglomeration of algorithms developed to analyze network models of energy or matter movement in ecosystems (e.g., [Fath & Patten, 1999](#); [Hannon, 1973](#); [Ulanowicz, 1986](#)), but it can generally be applied to any Input-Output system that follows a thermodynamically conserved unit among the compartments. Thus, it is a family of related algorithms to analyze the ecosystem from several perspectives including its structure, flow, storage, and utility. Together, these analyses function as a “macroscope” to investigate (1) whole system organization, (2) the direct and indirect effects among system components, and (3) the processes that create and sustain ecological systems. In this section we provide an overview of the algorithms and tools included in the **enaR** software. After describing the required model information, we highlight the primary ENA algorithms included in **enaR**. We then walk through an example application of the **enaR** Flow analysis.

Data Requirements and Input

ENA is a data-intensive methodology. The system is modeled as a set of compartments or network nodes that represent species, species-complexes (i.e., trophic guilds or functional groups), or non-living components of the system in which energy or matter is stored. These nodes are connected by a set of direct energy or matter transactions among the nodes, termed directed edges or links. These models also have energy–matter inputs into the system and output losses from the system. In summary, the full set of data required includes: (1) internal flows, (2) boundary inputs, (3) boundary exports, (4) boundary respiration, (5) boundary outputs, which may be the sum of exports and respiration, (6) biomass or storage values, and (7) designation of living status of each node. While all seven elements are required for a full analysis, the specific data requirements varies among the ENA algorithms.

The primary ENA algorithms in **enaR** assume the model data is presented as an R network data

object defined in the **network** package. Given the data elements, users can use the **pack** function to combine the data elements into the R network data object. While a standard data format for an ENA model does not yet exist, there are two commonly used formats. First, there is the Scientific Committee for Ocean Research (SCOR) format that is the required input to NETWRK (Ulanowicz & Kay, 1991), and the second format is the Excel sheet formatted data that is the input to WAND (Allesina & Bondavalli, 2004). The **enaR** package includes a **read.scor** and a **read.wand** function to read in these common data formats (Table 1).

Visualization

Visualization of network models can be an essential analytical tool (Lima, 2011; Moody *et al.*, 2005). Because **enaR** is built specifically to use the **network** package and data type, it is possible to quickly create network plots of the model internal structure. Fig. 1a shows an example visualization of Dame & Patten’s (1981) Oyster Reef ecosystem model. The **network** package includes three network layout algorithms: circle, Fruchterman-Reingold, and Kamada-Kawai. The Fruchterman-Reingold algorithm used here is the default. The R script to generate this visualization is included in the online supplementary information (Item S1).

Algorithm Overview

enaR includes many of the most commonly used ENA algorithms (Table 2), along with a number of work flow tools and specialty analyses (Tables 1 and 3). The nine primary ENA functions begin with the prefix ‘ena’ followed by the specific analysis name (see Table 2). There are a total of 34 functions in the **enaR** package. Comparison of the **enaR** package to previous implementations of ENA algorithms (i.e., NETWRK, NEA.m, EcoNet) shows high agreement in function output and significant expansion of the available ENA algorithms (Table S1 online).

Scharler & Fath (2009) identify two schools of ENA. The first school is based on the work of Robert Ulanowicz and colleagues at the University of Maryland (Ulanowicz, 1986, 1997, 2009). Primarily focused on trophic ecology, this approach uses information theory and the ascendancy concept to characterize ecosystem growth and development (Ulanowicz, 1986, 1997). This work is often referred to as “Ecological Network Analysis” as it predates many other types of network ecology. The second school is based on the work of Bernard Patten at the University of Georgia (Fath & Patten, 1999; Matis & Patten, 1981; Patten, 1982; Patten *et al.*, 1976). Steeped in dynamic equations, simulations, and systems analysis, this approach developed around the environ concept that formalizes the concept of environment (Patten, 1978), and has often been referred to as “Network Environ Analysis.” `enaR` currently captures all of the Patten School algorithms previously implemented in `NEA.m` (Fath & Borrett, 2006). Presently, the Ulanowicz School algorithms are more limited, including the ascendancy calculations (Ulanowicz, 1997) and mixed trophic impacts analyses (Ulanowicz & Puccia, 1990); however, we expect the package capabilities to continue to grow, especially with the assistance of new users. This combination of the Patten and Ulanowicz schools of analyses is rare in existing software.

Example Application

Given a network model, applying ENA algorithms with `enaR` is straightforward. We demonstrate how to use the package with an example Flow analysis on Dame & Patten’s (1981) model of energy flow in an Oyster Reef ecosystem. Figure 2 shows the example script. The analysis involves: (1) loading the model data, (2) checking and balancing the model if necessary, and (3) inputting the balanced model into the analysis function. The final step is interpreting the analytical output. This is a typical workflow for ENA.

After loading the `enaR` package, the next step is to enter the model data. Here, we extract the

128 model information from the paper and create a vector of node names, the flow matrix (**F**), inputs
 129 (**z**), outputs (**y**), and the logical vector indicating whether or not the nodes are living (Fig. 2). We
 130 then use the **pack** function to create the required network data object. The next step is to apply
 131 the **ssCheck** function ensure that the model is at steady-state, which is one of the assumptions of
 132 the flow analysis (Fath & Borrett, 2006; Finn, 1976). If the model had not been at steady-state,
 133 we could have then applied one of four automated balancing algorithms (AVG, Input-Output,
 134 Output-Input, AVG2; Allesina & Bondavalli, 2003) to force the model into a steady-state. We then
 135 apply the **enaFlow** function to the model to perform the desired ENA flow analysis. As shown
 136 with the **attributes** function, this analysis returns 4 matrices (**G**, **GP**, **N**, **NP**) and two vectors
 137 (throughflow, *T*, and a vector of 20 whole-network statistics, *ns*).

138 Interpreting the ENA results is the final challenge. Here, we provide a few illustrative interpre-
 139 tations of the Flow analysis. Starting with the whole-network flow statistics, we see that the total
 140 system throughflow (TST) of the oyster reef model is 83.6 Kcal m⁻² d⁻¹. TST is a measure of
 141 the total activity of the system, which is often referred to as the size or power of the system. The
 142 Finn Cycling Index (FCI) indicates that 11% of this activity was generated by recycling. Further,
 143 the average path length (APL = 2.02) shows that an average input passes over two paths before
 144 exiting the system, and the ratio of indirect to direct flows (ID.F = 1.58) indicates that the indirect
 145 flow exceeds the direct flow in this system. Together, these whole network indicators show the
 146 importance of indirect interactions in the system. A next analytical step might be to apply the
 147 Utility or Mixed Trophic Impacts analyses to determine the net relationships among the ecosystem
 148 components when we consider the direct and indirect interactions, but this is beyond our analysis
 149 here. More detailed guidance for how to interpret ENA results can be found in previously published
 150 literature (Fath & Borrett, 2006; Jørgensen *et al.*, 2007; Schramski *et al.*, 2011).

Value Added Features

There are several features of the **enaR** package beyond the core analyses that add substantive value for users. In this section we highlight several of these features including a library of 100 ecosystem network models, methods for conducting batch analysis (i.e., simultaneous analysis of multiple models), and connections to other analytical software.

Model Library

To facilitate new systems ecology and network science, we included a library of 100 previously published ecosystem network models with the **enaR** package. These models each trace a thermodynamically conserved unit (e.g., C, N, P) through a particular ecosystem. The models in this set are empirically-based in that the authors attempted to model a specific system and parameterized the model to some degree with empirical estimates. While the library includes models used previously to test several systems ecology hypotheses (Borrett, 2013; Borrett & Salas, 2010; Borrett *et al.*, 2010; Salas & Borrett, 2011), and the set has a 47% overlap with the set of models previously collected by Dr. Ulanowicz (<http://www.cbl.umces.edu/~ulan/ntwk/network.html>), the full set has not previously been collected and distributed together.

We tentatively split these models into two classes. The most abundant class is the trophic network models. These models tend to have a food web at their core, but also include non-trophic fluxes generated by processes like death and excretion. The annual carbon flux model for the mesohaline region of the Chesapeake Bay is a typical example (Baird & Ulanowicz, 1989). The second class of models focuses on biogeochemical cycling. In contrast to the trophic networks, the biogeochemical cycling models tend to have more highly aggregated nodes (more species grouped into a compartment), include more abiotic nodes that could represent chemical species (e.g., ammonia in a nitrogen cycle), have a lower dissipation rate, and therefore they tend to have more

recycling (Borrett *et al.*, 2010; Christian *et al.*, 1996). Christian & Thomas’s (2003) models of nitrogen cycling in the Neuse River Estuary are good examples of the class. The package vignette has a full listing of the models included along with references to their original publications (Lau *et al.*, 2013).

Batch Analysis

Advances in ecosystem ecology have been made by comparing network metrics across multiple ecosystem models. For example, Christensen (1995) applied ENA to identify and compare the maturity of 41 ecosystem models, and van Oevelen *et al.* (2011) compared the organic matter processing of food webs in three sections of the Nazaré submarine canyon. The **enaR** tool simplifies the work flow for these types of comparison. Given a list of models like the model library, it is possible to quickly analyze multiple models using R’s **lapply** function (see **help**(“lapply”). This facilitates the kind of comparative network analysis often of interest to ecologists (Christian *et al.*, 2005; Monaco & Ulanowicz, 1997; Whipple *et al.*, 2007).

Batch analysis can be used in several additional ways. One application is for meta-analyses, such as tests of the generality of hypothesized ecosystem properties like network non-locality (Salas & Borrett, 2011), or to investigate how physical features might influence ENA results (Niquil *et al.*, 2012). Fig. 1b illustrates the rank-ordered network homogenization statistic for the 56 trophic-based ecosystem models in the library. The homogenization statistic is greater than one in all of these models indicating that the network of indirect interactions tend to more uniformly distribute the resources than is obvious from the direct interactions, which extends previous results of Borrett & Salas (2010) to include several new models. A second kind of application is the exploration of new ENA inter-relationships. With the collection of algorithms and the library of models, we can now investigate possible relationships among ENA indicators from different schools (Fig. 1c). The

R script to generate Fig. 1 is available as an online enhancement (Item S1). A third application of batch analysis is to investigate the previously unknown empirical ranges of ENA whole-network statistics, which may be useful for interpreting results from specific applications. Fig. 3 shows the observed distribution of values for selected network statistics from the 100 models in the library easily analyzed using `lapply` and the associated `enaR` functions.

New Connections

A third advantage of the `enaR` package design is that it enables network ecologists easier access to other network tools and analyses that might be useful. The `enaR` package uses the R network data structure defined in the `network` package (Butts, 2008a). This means that network ecologists using `enaR` can also use the network manipulation functions and visualization features of the `network` package. Further, the R Social Network Analysis (SNA) package, `sna`, (Butts, 2008b) also uses this network data object. This means that network ecologists can apply many of the SNA algorithms directly to their ecological network models. Fig. 1d illustrates applying the betweenness centrality function to the Chesapeake Bay trophic model (Baird & Ulanowicz, 1989) and visualizing the results using a target centrality plot (Brandes *et al.*, 2003). This analysis highlights the central role of Sedimentary Particulate Carbon and bacteria in the Sediment Particulate Organic Carbon (POC) in the carbon flux of the estuary.

In addition, `enaR` can be a starting point for ecosystem network ecologists to use other R network tools. For example, the `iGraph` package provides functions to apply classic graph theory (Csardi & Nepusz, 2006). The `limSolve` package provides capabilities to infer network model fluxes from empirical data by linear inverse modeling (Soetaert *et al.*, 2009), which can also be used for uncertainty analyses of ENA (Kones *et al.*, 2009). There are a wealth of additional R package that network ecologists may find useful including `bipartite` (Dormann *et al.*, 2008), `vegan` (Dixon,

220 2003), Cheddar (Hudson *et al.*, 2013), and packages in the `statnet` family (Handcock *et al.*, 2008).

221 Conclusion and Future Development

222 The `enaR` package encodes exiting ENA algorithms, and is designed to address limitations of current
223 ENA software and facilitate wider use and development. It does this by (1) providing greater
224 accessibility to the code (e.g., free and open source software available on multiple OS), (2) collecting
225 a broad set of available ENA algorithms and workflow management functions, and (3) creating the
226 potential for collaborative development (via GitHub and CRAN). Further, the software is extensible
227 for individual needs and it lets users integrate ENA into a broader workflow in R in a way that is
228 more challenging when using web based tools like EcoNet (Kazanci, 2007; Schramski *et al.*, 2011).
229 Finally, it lets users have access to other network and statistical analysis tools (e.g., social network
230 analysis) that are already part of R. These benefits come at the cost of having a steeper learning
231 curve (e.g., users must know R), which may make `enaR` more suited to advanced practitioners.

232 In the near future, we anticipate two initial lines of continued development for the `enaR` package.
233 The first is to increase the connections between the `enaR` package and other modeling and analytical
234 tools. For example, we are currently working with colleagues to enable users of Ecopath with Ecosim
235 (Christensen & Walters, 2004) to apply the `enaR` tools in a seamless way. We are also developing
236 functions to connect between `enaR` and the R `limSolve` package (Soetaert *et al.*, 2009) for creating
237 models using Linear Inverse Modeling and to enable uncertainty analysis (Kones *et al.*, 2009). The
238 second line of development is to extend the package’s capabilities. While it currently contains
239 most of the many commonly used ENA algorithms used by ecologists, it is far from complete. For
240 example, Ulanowicz’s (1983) decomposition of cycles is not yet included nor is his construction
241 for the Lindeman trophic spine (Ulanowicz & Kemp, 1979). Network model construction tools,
242 such as least-inference methods for building models from empirical data (Ulanowicz & Scharler,

2008) and Fath's (2004) algorithm for constructing plausible ecosystems models are also possible enhancements.

In conclusion, `enaR` is an R package intended to facilitate the use and the collaborative development of Ecosystem Network Analysis, a branch of network ecology. This domain is rapidly growing in part because the tools and techniques let ecologists address a wide range of relational questions at the core of ecology. We look forward to seeing new ecological discoveries made through the use of `enaR`.

Acknowledgments

We would like to acknowledge and thank David Hines for contributing to the initial code, and Pawandeep Singh for collecting the output for Table S1. We also thank several individuals who used the earlier versions of the software and provided helpful feedback for further development including Ursula Scharler, Shaoqing Chen, Emily Oxe, and John Mejaski. In addition, we thank the many ecosystem model authors who created, shared, and published their work. This work was funded in part by the US National Science Foundation (DEB1020944, DEB0425908), an NSF Integrative Graduate Education and Research Traineeship (MKL; DGE0549505) and a UNCW Cahill award (SRB).

References

- Allesina, S., Bodini, A. & Bondavalli, C. (2005) Ecological subsystems via graph theory: the role of strongly connected components. *Oikos*, **110**, 164–176.
- Allesina, S. & Bondavalli, C. (2003) Steady state of ecosystem flow networks: a comparison between balancing procedures. *Ecol Model*, **165**, 221–229.
- Allesina, S. & Bondavalli, C. (2004) Wand: an ecological network analysis user-friendly tool. *Environ Model Softw*, **19**, 337–340.

- Baird, D. & Ulanowicz, R.E. (1989) The seasonal dynamics of the Chesapeake Bay ecosystem. *Ecol Monogr*, **59**, 329–364.
- Barabási, A.L. (2012) The network takeover. *Nature Physics*, **8**, 14–16.
- Bodini, A. & Bondavalli, C. (2002) Towards a sustainable use of water resources: a whole-ecosystem approach using network analysis. *Int J Environmental Pollution*, **18**, 463–485.
- Bodini, A., Bondavalli, C. & Allesina, S. (2012) Cities as ecosystems: growth, development and implications for sustainability. *Ecol Model*, **245**, 185–198.
- Bondavalli, C. & Ulanowicz, R.E. (1999) Unexpected effects of predators upon their prey: the case of the American alligator. *Ecosystems*, **2**, 49–63.
- Borgatti, S.P. & Foster, P.C. (2003) The network paradigm in organizational research: a review and typology. *J Manage*, **29**, 991–1013.
- Borrett, S.R. (2013) Throughflow centrality is a global indicator of the functional importance of species in ecosystems. *Ecol Indic*, **32**, 182–196.
- Borrett, S.R., Christian, R.R. & Ulanowicz, R.E. (2012) Network ecology. A.H. El-Shaarawi & W.W. Piegorsch, eds., *Encyclopedia of Environmetrics*, pp. 1767–1772. John Wiley & Sons, 2nd edition.
- Borrett, S.R., Fath, B.D. & Patten, B.C. (2007) Functional integration of ecological networks through pathway proliferation. *J Theor Biol*, **245**, 98–111.
- Borrett, S.R., Moody, J. & Edelman, A. (2014) The rise of network ecology: maps of the topic diversity and scientific collaboration. *Ecol Model*, **in press**.
- Borrett, S.R. & Salas, A.K. (2010) Evidence for resource homogenization in 50 trophic ecosystem networks. *Ecol Model*, **221**, 1710–1716.
- Borrett, S.R., Whipple, S.J. & Patten, B.C. (2010) Rapid development of indirect effects in ecological networks. *Oikos*, **119**, 1136–1148.
- Brandes, U., Kenis, P. & Wagner, D. (2003) Communicating centrality in policy network drawings. *IEEE Transactions on Visualization and Computer Graphics*, **9**, 241–253.
- Butts, C. (2008a) network: a package for managing relational data in R. *J Stat Softw*, **24**.
- Butts, C. (2008b) Social network analysis with sna. *J Stat Softw*, **24**, 1–51.
- Chen, S. & Chen, B. (2012) Network environ perspective for urban metabolism and carbon emissions: a case study of Vienna, Austria. *Environ Sci Tech*, **46**, 4498–4506.
- Christensen, V. (1995) Ecosystem maturity—towards quantification. *Ecol Model*, **77**, 3–32.
- Christensen, V. & Walters, C.J. (2004) Ecopath with Ecosim: methods, capabilities and limitations. *Ecol Model*, **172**, 109–139.
- Christian, R.R., Baird, D., Luczkovich, J., Johnson, J.C., Scharler, U.M. & Ulanowicz, R.E. (2005) Role of network analysis in comparative ecosystem ecology of estuaries. A. Belgrano, J. Scharler U. M. Dunne & R. Ulanowicz, eds., *Aquatic Food Webs: An Ecosystem Approach*, pp. 25–40. Oxford University Press, New York, NY.

- Christian, R.R., Fores, E., Comin, F., Viaroli, P., Naldi, M. & Ferrari, I. (1996) Nitrogen cycling networks of coastal ecosystems: influence of trophic status and primary producer form. *Ecol Model*, **87**, 111–129.
- Christian, R.R. & Thomas, C.R. (2003) Network analysis of nitrogen inputs and cycling in the Neuse River Estuary, North Carolina, USA. *Estuaries*, **26**, 815–828.
- Csardi, G. & Nepusz, T. (2006) The igraph software package for complex network research. *Inter-Journal*, **Complex Systems**, 1695.
- Dame, R.F. & Patten, B.C. (1981) Analysis of energy flows in an intertidal oyster reef. *Mar Ecol Prog Ser*, **5**, 115–124.
- Dixon, P. (2003) VEGAN, a package of R functions for community ecology. *Journal of Vegetation Science*, **14**, 927–930.
- Dormann, C.F., Gruber, B. & Fründ, J. (2008) Introducing the bipartite package: analysing ecological networks. *R News*, **8**, 8–11.
- Fann, S.L. & Borrett, S.R. (2012) Environ centrality reveals the tendency of indirect effects to homogenize the functional importance of species in ecosystems. *J Theor Biol*, **294**, 74–86.
- Fath, B.D. (2004) Network analysis applied to large-scale cyber-ecosystems. *Ecol Model*, **171**, 329–337.
- Fath, B.D. & Borrett, S.R. (2006) A Matlab© function for network environ analysis. *Environ Model Softw*, **21**, 375–405.
- Fath, B.D. & Patten, B.C. (1999) Review of the foundations of network environ analysis. *Ecosystems*, **2**, 167–179.
- Finn, J.T. (1976) Measures of ecosystem structure and function derived from analysis of flows. *J Theor Biol*, **56**, 363–380.
- Freeman, L.C. (2004) *The development of social network analysis: A study in the sociology of science*. Empirical Press Vancouver.
- Handcock, M., Hunter, D., Butts, C., Goodreau, S. & Morris, M. (2008) statnet: software tools for the representation, visualization, analysis and simulation of network data. *J Stat Softw*, **24**, 1548.
- Hannon, B. (1973) The structure of ecosystems. *J Theor Biol*, **41**, 535–546.
- Hines, D.E., Lisa, J.A., Song, B., Tobias, C.R. & Borrett, S.R. (2012) A network model shows the importance of coupled processes in the microbial N cycle in the Cape Fear River estuary. *Estuar Coast Shelf Sci*, **106**, 45–57.
- Hudson, L.N., Emerson, R., Jenkins, G.B., Layer, K., Ledger, M.E., Pichler, D.E., Thompson, M.S.A., O’Gorman, E.J., Woodward, G. & Reuman, D.C. (2013) Cheddar: analysis and visualisation of ecological communities in R. *Methods Ecol Evol*, **4**, 99–104.
- Ings, T.C., Montoya, J.M., Bascompte, J., Blüthgen, N., Brown, L., Dormann, C.F., Edwards, F., Figueroa, D., Jacob, U., Jones, J.I., Lauridsen, R.B., Ledger, M.E., Lewis, H.M., Olesen, J.M., van Veen, F.J.F. & Warren, P. H. and Woodward, G. (2009) Review: ecological networks—beyond food webs. *J Anim Ecol*, **78**, 253–269.

- Jørgensen, S.E., Fath, B.D., Bastianoni, S., Marques, J.C., Müller, F., Nielsen, S., Patten, B.C., Tiezzi, E. & Ulanowicz, R.E. (2007) *A new ecology: Systems perspective*. Elsevier, Amsterdam.
- Kazanci, C. (2007) EcoNet: a new software for ecological modeling, simulation and network analysis. *Ecol Model*, **208**, 3–8.
- Kones, J.K., Soetaert, K., van Oevelen, D. & Owino, J.O. (2009) Are network indices robust indicators of food web functioning? a Monte Carlo approach. *Ecol Model*, **220**, 370–382.
- Krause, A. (2004) *The role of compartments in food-web structure and changes following biological invasions in southeast Lake Michigan*. Ph.d., Michigan State University.
- Lau, M.K., Borrett, S.R. & Hines, D.E. (2013) *enaR: tools for ecological network analysis in R*. R package version 2.6.
- Lima, M. (2011) *Visual complexity: mapping patterns of information*. Princeton Architectural Press.
- Matis, J.H. & Patten, B.C. (1981) Environ analysis of linear compartmental systems: the static, time invariant case. *Bull Int Stat Inst*, **48**, 527–565.
- Metcalf, C.J.E., McMahon, S.M., Salguero-Gómez, R. & Jongejans, E. (2012) IPMpack: an R package for integral projection models. *Methods Ecol Evol*, **4**, 195–200.
- Monaco, M.E. & Ulanowicz, R.E. (1997) Comparative ecosystem trophic structure of three us mid-Atlantic estuaries. *Mar Ecol Prog Ser*, **161**, 239–254.
- Moody, J., McFarland, D. & Bender-deMoll, S. (2005) Dynamic network visualization. *Am J Soc*, **110**, 1206–1241.
- Newman, M. (2003) The structure and function of complex networks. *SIAM review*, **45**, 167–256.
- Niquil, N., Chaumillon, E., Johnson, G., Bertin, X., Grami, B., David, V., Bacher, C., Asmus, H., Baird, D. & Asmus, R. (2012) The effect of physical drivers on ecosystem indices derived from ecological network analysis: comparison across estuarine ecosystems. *Estuar Coast Shelf Sci*, **108**, 132–143.
- Patten, B.C. (1978) Systems approach to the concept of environment. *Ohio J Sci*, **78**, 206–222.
- Patten, B.C. (1982) Environs: relativistic elementary particles for ecology. *Am Nat*, **119**, 179–219.
- Patten, B.C. (1991) Network ecology: indirect determination of the life–environment relationship in ecosystems. M. Higashi & T. Burns, eds., *Theoretical Studies of Ecosystems: The Network Perspective*, pp. 288–351. Cambridge University Press, New York.
- Patten, B.C., Bosserman, R.W., Finn, J.T. & Cale, W.G. (1976) Propagation of cause in ecosystems. B.C. Patten, ed., *Systems Analysis and Simulation in Ecology, Vol. IV*, pp. 457–579. Academic Press, New York.
- Proulx, S.R., Promislow, D.E.L. & Phillips, P.C. (2005) Network thinking in ecology and evolution. *Trends Ecol Evol*, **20**, 345–353.
- Revell, L.J. (2012) phytools: an R package for phylogenetic comparative biology (and other things). *Methods Ecol Evol*, **3**, 217–223.

- Salas, A.K. & Borrett, S.R. (2011) Evidence for dominance of indirect effects in 50 trophic ecosystem networks. *Ecol Model*, **222**, 1192–1204.
- Scharler, U. & Fath, B. (2009) Comparing network analysis methodologies for consumer–resource relations at species and ecosystems scales. *Ecol Model*, **220**, 3210–3218.
- Schramski, J.R., Kazanci, C. & Tollner, E.W. (2011) Network environ theory, simulation and EcoNet© 2.0. *Environ Model Softw*, **26**, 419–428.
- Soetaert, K., Van den Meersche, K. & van Oevelen, D. (2009) *limSolve: Solving Linear Inverse Models*. R package version 1.5.1.
- Ulanowicz, R.E. (1983) Identifying the structure of cycling in ecosystems. *Math Biosci*, **65**, 219–237.
- Ulanowicz, R.E. (1986) *Growth and Development: Ecosystems Phenomenology*. Springer–Verlag, New York.
- Ulanowicz, R.E. (1997) *Ecology, the Ascendent Perspective*. Columbia University Press, New York.
- Ulanowicz, R.E. (2009) *A third window, Natural life beyond Newton and Darwin*. Templeton Foundation Press, West Conshohocken, PA.
- Ulanowicz, R.E., Holt, R.D. & Barfield, M. (2014) Limits on ecosystem trophic complexity: insights from ecological network analysis. *Ecol Lett*, **17**, 127–136.
- Ulanowicz, R.E. & Kay, J. (1991) A package for the analysis of ecosystem flow networks. *Environ Softw*, **6**, 131–142.
- Ulanowicz, R.E. & Kemp, W.M. (1979) Toward canonical trophic aggregations. *Am Nat*, **114**, 871–883.
- Ulanowicz, R.E. & Puccia, C.J. (1990) Mixed trophic impacts in ecosystems. *Coenoses*, **5**, 7–16.
- Ulanowicz, R.E. & Scharler, U.M. (2008) Least-inference methods for constructing networks of trophic flows. *Ecol Model*, **210**, 278–286.
- van Oevelen, D., Soetaert, K., García, R., de Stigter, H.C., Cunha, M.R., Pusceddu, A. & Danovaro, R. (2011) Canyon conditions impact carbon flows in food webs of three sections of the Nazaré canyon. *Deep-Sea Res Pt II*, **58**, 2461–2476.
- Wasserman, S. & Faust, K. (1994) *Social network analysis: Methods and applications*. Cambridge University Press, Cambridge; New York.
- Whipple, S.J., Borrett, S.R., Patten, B.C., Gattie, D.K., Schramski, J.R. & Bata, S.A. (2007) Indirect effects and distributed control in ecosystems: Comparative network environ analysis of a seven-compartment model of nitrogen flow in the Neuse River Estuary, USA—time series analysis. *Ecol Model*, **206**, 1–17.
- Zhang, Y., Yang, Z.F., Fath, B.D. & Li, S.S. (2010) Ecological network analysis of an urban energy metabolic system: model development, and a case study of four Chinese cities. *Ecol Model*, **221**, 1865–1879.

Tables

Table 1: Selected data input, management, and export functions in `enaR`.

Function	Description	Example Reference
<code>pack</code>	This function lets users combine model elements into a network data object.	None
<code>unpack</code>	Extracts the individual model elements (e.g., flows, inputs, outputs) from the network data object.	None
<code>read.scor</code>	Creates a network data object from a SCOR formatted data file.	Ulanowicz & Kay (1991)
<code>read.wand</code>	Creates a network data object from a WAND formatted data file.	Allesina & Bondavalli (2004)
<code>ssCheck</code>	Checks to see if the model is at steady-state.	None
<code>balance</code>	Applies one of four balancing algorithms to a model not at steady-state.	Allesina & Bondavalli (2003)
<code>force.balance</code>	Runs balancing algorithm as many times as necessary to balance the model.	None
<code>write.nea</code>	Writes the model data to the file format used as input for NEA.m.	Fath & Borrett (2006)

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 <i>et al.</i> (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)

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 <i>et al.</i> (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

Figures

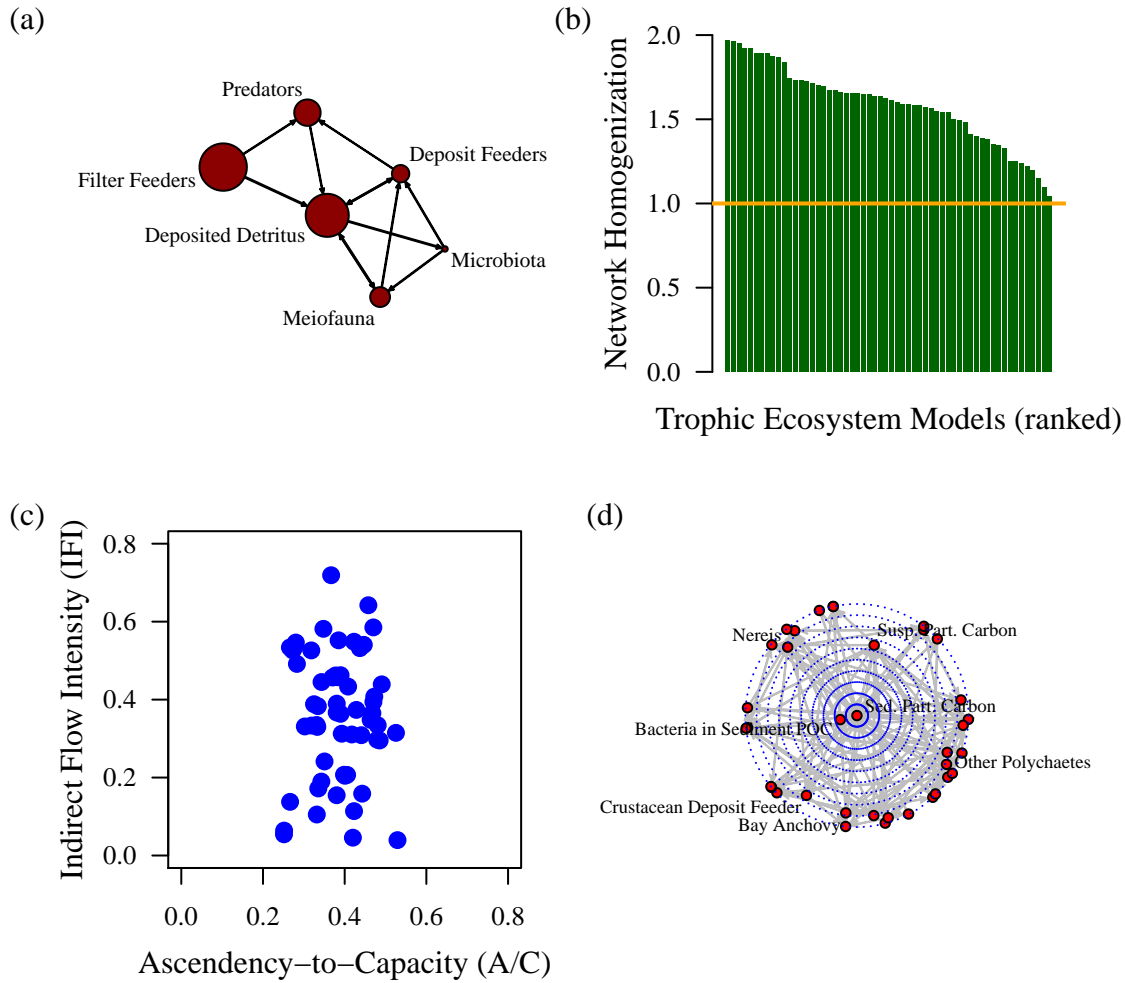


Figure 1: Example of analysis and visualizations created with **enaR** (a) network digraph of the internal flows of an oyster reef ecosystem model (Dame & Patten, 1981), (b) network homogenization statistic for 56 trophic ecosystem models (rank-ordered), (c) scatter plot showing the relationship between the ascendancy-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).

```

library(enaR) # load enaR package
> # -- ENTER MODEL DATA -- from Dame and Patten (1981)
> # node names
> names <- c("Filter Feeders","Microbiota","Meiofauna",
+           "Deposit Feeders","Predators","Deposited Detritus")
> # Internal Flows of model, as matrix (oriented row to column)
> F <- matrix(c(0, 0, 0, 0, 0, 0, 0, 0, 0,
+             0, 0, 8.1721, 0, 1.2060, 0, 0, 0, 7.2745,
+             0, 1.2060, 0.6609, 0, 0, 0.6431, 0.5135, 0, 0,
+             0.1721, 0, 0, 15.7910, 0, 4.2403, 1.9076, 0.3262, 0),
+           ncol=6)
> rownames(F) <- names # add node names to rows
> colnames(F) <- names # add node names to cols
> # boundary flows
> inputs <- c(41.47,0, 0, 0, 0, 0)
> outputs <- c(25.1650, 5.76, 3.5794, 0.4303, 0.3594, 6.1759)
> # Living
> Living <- c(TRUE,TRUE,TRUE,TRUE,TRUE,FALSE)
> # pack the model data into the R network data object
> m <- pack(flow=F,input=inputs, respiration=outputs, outputs=outputs, living=Living)
>
> ssCheck(m) # check to see if the model is at steady-state
[1] TRUE
> # perform flow analysis
> F <- enaFlow(m) # perform ENA flow analysis
> attributes(F) # show analysis objects created
$names
[1] "T" "G" "GP" "N" "NP" "ns"

> F$ns # show flow analysis network statistics
      Boundary      TST TSTp      APL      FCI      BFI      DFI      IFI
[1,] 41.47 83.5833 NA 2.015512 0.1101686 0.4961517 0.1950689 0.3087794
      ID.F ID.F.I ID.F.O HMG.I HMG.O AMP.I AMP.O mode0.F mode1.F
[1,] 1.582925 1.716607 1.534181 2.051826 1.891638 3 1 41.47 32.90504
      mode2.F mode3.F mode4.F
[1,] 9.208256 32.90504 41.47

> F$T
      Filter Feeders      Microbiota      Meiofauna      Deposit Feeders
      41.4700      8.1721      8.4805      2.5100
      Predators Deposited Detritus
      0.6856      22.2651

```

Figure 2: Example code for applying `enaR` Flow analysis to Dame & Patten's (1981) oyster reef model.



Figure 3: Distributions of selected ENA network statistics from the u 100 empirically-based ecosystem models included in **enaR**. The results are summarized using a histogram showing the distribution of the values of each network statistic between the observed minimum and maximum values. The median, mean, and coefficient of variation (ratio of standard deviation and mean) values are also reported. The network statistics are the number of nodes (n), the connectance ($C = L/n^2$), link density ($LD = L/n$), pathway proliferation rate (lam1A), Finn cycling index (FCI), average path length (APL), indirect flow intensity (IFI), output oriented network homogenization ratio (HMG.O), output-oriented network amplification ratio (AMP.O), average mutual information (AMI), the ascendancy-to-capacity ratio (ASC.CAP), flow-based network synergism (synergism.F) and mutualism (mutualism.F).