enaR Tutorial: Worked example for the Cone Springs model

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10/2/2017

Introduction

This is a simplified tutorial for getting started with the **enaR** package. It illustrates how to apply selected Ecological Network Analyses (ENA) to single model. For breivity, it this tutorial does not explain how to interpret the results. This tutorial uses the "Cone Springs" model (Fig. 1) to illustrate the analyses and some of the results. This examplar model was used by Ulanowicz for his Netwrk 4.2 software (https://www.cbl.umces.edu/~ulan/ntwk/netwrk.txt), which may allow for comparisons. For a more detialed description of the **enaR** software please see the Vignette (https://cran.r-project.org/web/packages/enaR/vignettes/enaR-vignette.pdf).

Preparing the Workspace

To get started using **enaR**, the first step is to load the library along with the **network** library as follows. It is also a good idea to clear the working memory when we start a new analysis

```
rm(list = ls()) # clears the working memory
library(enaR)
library(network)
```

```
## network: Classes for Relational Data
## Version 1.13.0 created on 2015-08-31.
## copyright (c) 2005, Carter T. Butts, University of California-Irvine
##                     Mark S. Handcock, University of California -- Los Angeles
##                     David R. Hunter, Penn State University
##                     Martina Morris, University of Washington
##                     Skye Bender-deMoll, University of Washington
##  For citation information, type citation("network").
##  Type help("network-package") to get started.
```

The next step is to enter a model to analyze. There are several functions to assist users with entering your own model, but for this tutorial we will load the library of models that is distributed with the package, look at part of the list of model names included in the library, and then select the Cone Springs model.

```
data(enaModels)  # loads library of models (stored as a list)
model.names = names(enaModels)
model.names[c(6,9,20,36,47)]
```

```
## [1] "Cone Springs"            "Oyster Reef "
## [3] "Peruvian Upwelling"      "Narragansett Bay"
## [5] "Sylt-R{\\o}m{\\o} Bight"
```

```
model = enaModels[["Cone Springs"]]  # selects the Cone Springs model.
model
```

```
##  Network attributes:
##   vertices = 5
```

(a) Matrices

$$\mathbf{F} = \begin{bmatrix} 0 & 0 & 0 & 0 & 8881 \\ 0 & 0 & 75 & 0 & 1600 \\ 0 & 0 & 0 & 370 & 200 \\ 0 & 0 & 0 & 0 & 167 \\ 0 & 5205 & 2309 & 0 & 0 \end{bmatrix}$$

$$\mathbf{z} = [11184, 0, 0, 0, 635]$$

$$\mathbf{r} = [2003, 3275, 1814, 203, 3109]$$

$$\mathbf{e} = [300, 255, 0, 0, 860]$$

$$\mathbf{X} = [285, 117, 60, 17, 3580]$$

(b) Diagram

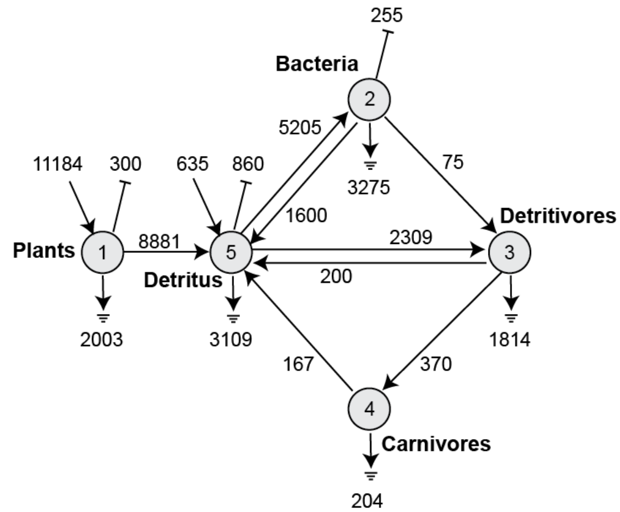

Figure 1: Cone Spring Model (Williams and Crouthamel, unpublished ms and Tilly 1968) with flows in units of kcal/m2/y: (a) model components in matrix and vector form and (b) in diagram form.

```
##   directed = TRUE
##   hyper = FALSE
##   loops = TRUE
##   multiple = FALSE
##   bipartite = FALSE
##   balanced = TRUE
##   total edges= 8
##     missing edges= 0
##     non-missing edges= 8
##
##  Vertex attribute names:
##     export input living output respiration storage vertex.names
##
##  Edge attribute names:
##     flow
```

The model is stored as a network data object with attributes for the network, nodes (vertices), and edges.

As many (but not all) of the ENA algorithms assume that the model is at steady state, we should first check this condition.

```
ssCheck(model)
```

```
## [1] TRUE
```

This model is at steady-state. If it had not been, we could have applied the *balance()* function to apply one of several automated model balancing algorithms (Allesina and Bondavalli 2003).

Ecological Network Analysis

The core ENA algorithms are collected into functions named based on the type of analysis performed. I illustrate some of the more freqeuently used functions. Notice that all matrices are oriented from row to column.

Structural Analysis

The structural analysis returns the system adjacency matrix (A) and a vector of structural network metrics (ns).

```
s = enaStructure(model)
attributes(s)
```

```
## $names
## [1] "A"  "ns"
```

```
show(s)
```

```
## $A
##                  PLANTS BACTERIA DETRITUS FEEDERS CARNIVORES DETRITUS
## PLANTS                0        0                0          0        1
## BACTERIA              0        0                1          0        1
## DETRITUS FEEDERS      0        0                0          1        1
## CARNIVORES            0        0                0          0        1
## DETRITUS              0        1                1          0        0
##
## $ns
##      n L    C  LD      ppr    lam1A mlam1A      rho         R         d
## [1,] 5 8 0.32 1.6 1.839287 1.839287      1 1.839287 0.6691441 0.2392868
##      no.scc no.scc.big pscc
## [1,]      2          1  0.8
```

In this case we see that the model has 5 nodes, a network density (connectance) of 0.32, and a pathway proliferation rate of 1.83 ($\lambda_1(\mathbf{A})$). This last indicator shows that the number of walks increase without bound as walk length increases at a rate of 1.83. We can construct a plot to illustrate this phenomenon (Fig. 2).

```
tw.34 = NA # initialize total walks from 3 to 4
max.w.length = 20
for(k in 1:max.w.length){
  tw = mExp(s$A,k)
  tw.34[k] = tw[3,4]
}

par(las = 1, mar = c(4,5,1,1))
plot(1:max.w.length, tw.34,
     type = "b",
     lwd = 3,
     col = "blue",
     pch = 20,
     xlab = "Walk Length",
     ylab = "Number of Walks")
```

Flow Analysis

Flow anlayses are comprised of methods based on Input–Output Analyses and Informtion based approaches.

Input–Output Flow Analyses

This analysis uses the **enaFlow** function as follows.

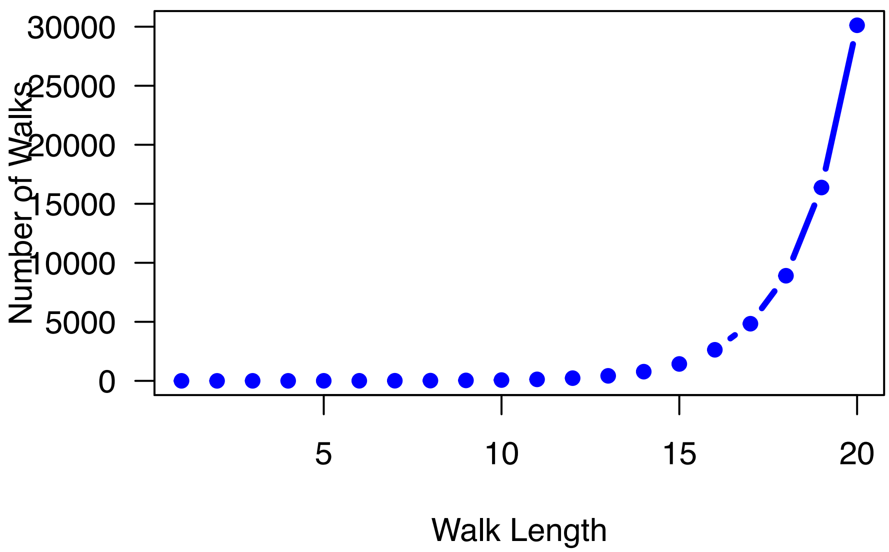

Figure 2: The number of walks from node 3 to 4 increases as the walk length increases.

```
f = enaFlow(model)
attributes(f)
```

```
## $names
## [1] "T"    "G"    "GP"   "N"    "NP"   "TCC"  "TDC"  "ns"
```

```
f$T  # the throughflow vector
```

```
##           PLANTS         BACTERIA DETRITUS FEEDERS       CARNIVORES
##            11184             5205             2384              370
##         DETRITUS
##            11483
```

```
f$N  # output oriented flow intensity matrix
```

```
##                  PLANTS   BACTERIA DETRITUS FEEDERS CARNIVORES  DETRITUS
## PLANTS                1 0.43434119       0.19893744 0.03087536 0.9582209
## BACTERIA              0 1.16935117       0.09197564 0.01427474 0.3736137
## DETRITUS FEEDERS      0 0.08420272       1.03856662 0.16118693 0.1857637
## CARNIVORES            0 0.24687724       0.11307499 1.01754939 0.5446477
## DETRITUS              0 0.54697352       0.25052543 0.03888188 1.2067045
```

```
f$ns # vector of whole-network metrics
```

```
##      Boundary   TST  TSTp      APL        FCI       BFI       DFI
## [1,]    11819 30626 42445 2.591251 0.09193899 0.3859139 0.3035499
##            IFI     ID.F    ID.F.I    ID.F.O    HMG.I   HMG.O AMP.I AMP.O
## [1,] 0.3105362 1.023016 1.414552 0.9126925 2.465946 1.87498     4     0
##      mode0.F  mode1.F  mode2.F  mode3.F mode4.F
## [1,]   11819 15991.28 2815.723 15991.28   11819
```

We can visualize some of our results to better understand them. For example Fig. 3 shows the ordered througflow vector.

```
par(las = 1, mar = c(7,6,0,0),
        oma = c(0,1,1,1), xpd=TRUE)
```

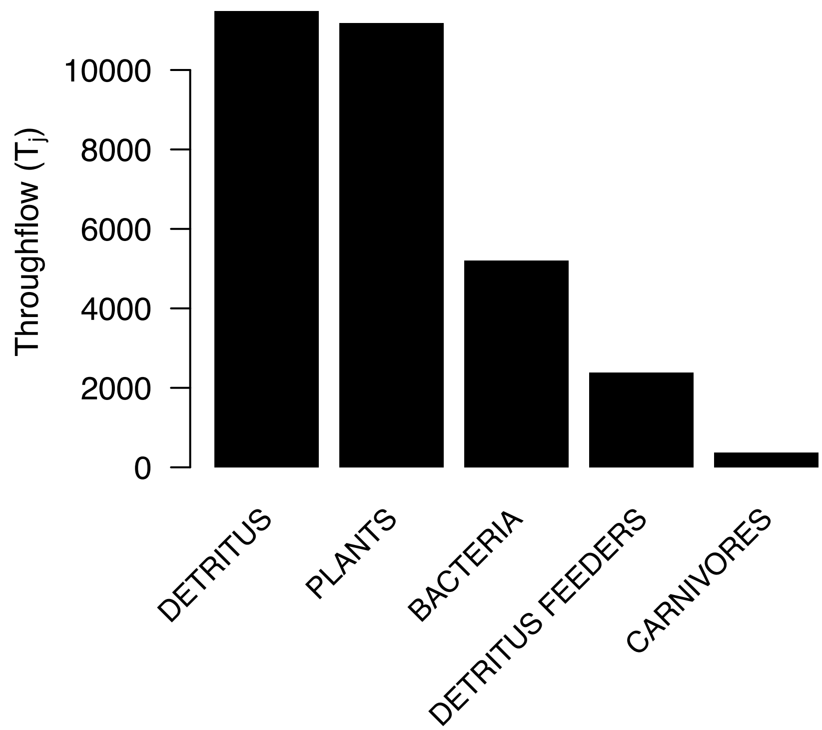

Figure 3: Rank ordered throughflow values for the Cone Springs model.

```
o = order(f$T, decreasing = TRUE)
bp = barplot(f$T[o], col = "black",
             border = NA, names.arg = NA )
mtext(bquote(paste("Throughflow (",T[j],")")),
        side = 2, las = 3, line = 3.5,
        outer = FALSE)
text(bp,-(.10 * max(f$T)),                # add node names
     labels = names(f$T[o]),
     srt = 45, adj = 1,
     cex = 0.95)
```

The Input-Output flow analysis also calculates the the proportions of system throughFLOW (TST) derived from boundary, direct, and indirect flows. This is a true partition of TST, so we can visualize it as portions of the whole (Fig. 4).

```
ns = as.data.frame(f$ns)  # lets us access ns by name
flow.partition = as.matrix(c(ns$BFI, ns$DFI, ns$IFI))
bp = barplot(flow.partition, horiz = TRUE, xlim = c(0,1),
        col = c("black","red","orange"),
        xlab = "Proportion of Total System Throughflow")
text(c(0.2,0.5,0.85), bp,
     labels = c("Boundary", "Direct","Indirect"), col = "white", cex = 0.85)
```

Information Based Flow Analyses

The information based analyses generates a set of whole netowrk metrics that includes informaiton like the *Flow Diversity* (H), *Ascendency* (ASC), the ratio of *Ascendency* and *Capacity* (ASC.CAP), the tetr-partit

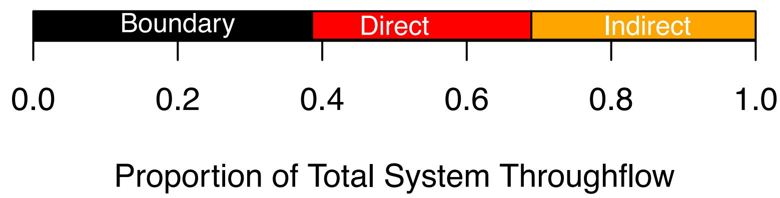

Figure 4: Proportion of Total System ThroughFLOW derived from boundary inputs, direct flows, and indirect flows.

division of *Ascendnecy*, *Overhead*, and *Capacity* among the *Inputs*, *Internal*, *Respirations*, and *Exports*, as well as the *robustness* measure (A/C * log(A/C)).

```
enaAscendency(model)
```

```
##             H      AMI       Hr      CAP      ASC       OH   ASC.CAP
## [1,] 3.20096 1.336447 1.864513 135864.7 56725.49 79139.25 0.4175144
##         OH.CAP robustness      ELD       TD  A.input A.internal A.export
## [1,] 0.5824856  0.3646722 1.908258 2.525286 19147.85   29331.98 1051.765
##      A.respiration OH.input OH.internal OH.export OH.respiration CAP.input
## [1,]      7193.894 6221.751    29832.46  7810.812       35274.22   25369.6
##      CAP.internal CAP.export CAP.respiration
## [1,]     59164.44   8862.578        42468.11
```

Trophic Analyses

Ulanowicz introduced a number of flow analyses to consider food webs including the Lindeman Trophic Spine and the Cycle Distribution. These analyses can be applied as follows. Note that the cycle analysis is computationally intensive and will be slow on larger models.

Lindeman Spine

```
tro = enaTroAgg(model)
attributes(tro)
```

```
## $names
##  [1] "Feeding_Cycles" "A"              "ETL"            "CE"
##  [5] "CR"             "GC"             "RDP"            "LS"
##  [9] "TE"             "ns"
```

```
tro$ETL  # effective trophic levels
```

```
## [1] 1.00000 2.00000 2.03146 3.03146 1.00000
```

```
tro$ns   # network metrics
```

```
##           ATL Detrivory DetritalInput DetritalCirc NCYCS NNEX CI Herbivory
## [1,] 1.812584      7514           635            0     0    0  0     11184
##             DH
## [1,] 0.6718526
```

Cycles

```
cyc = enaCycle(model)
attributes(cyc)
```

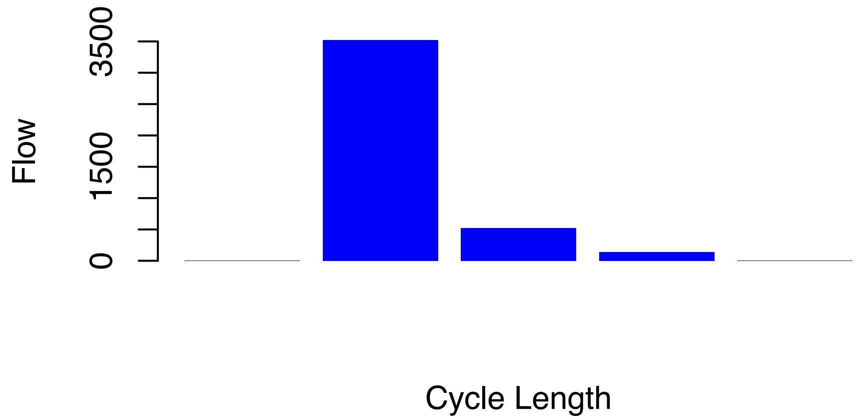

Figure 5: Flow over cycles of increasing lengths.

```
## $names
## [1] "Table.cycle"      "Table.nexus"      "CycleDist"
## [4] "NormDist"         "ResidualFlows"    "AggregatedCycles"
## [7] "ns"
```

```
barplot(cyc$CycleDist, col = "blue", border = NA,
        ylab = "Flow",
        xlab = "Cycle Length")
```

Storage Analysis

```
enaStorage(model)
```

```
## $X
## [1]  285.0  117.0   60.0   17.0 3579.4
##
## $C
##                     PLANTS   BACTERIA DETRITUS FEEDERS CARNIVORES
## PLANTS           -39.24211   0.000000        0.0000000   0.000000
## BACTERIA           0.00000 -44.487179        0.6410256   0.000000
## DETRITUS FEEDERS   0.00000   0.000000      -39.7333333   6.166667
## CARNIVORES         0.00000   0.000000        0.0000000 -21.764706
## DETRITUS           0.00000   1.454154        0.6450802   0.000000
##                   DETRITUS
## PLANTS           31.161404
## BACTERIA         13.675214
## DETRITUS FEEDERS  3.333333
## CARNIVORES        9.823529
## DETRITUS         -3.208080
##
## $P
##                     PLANTS   BACTERIA DETRITUS FEEDERS CARNIVORES
## PLANTS           0.1279532 0.00000000       0.00000000  0.0000000
## BACTERIA         0.0000000 0.01139601       0.01424501  0.0000000
## DETRITUS FEEDERS 0.0000000 0.00000000       0.11703704  0.1370370
## CARNIVORES       0.0000000 0.00000000       0.00000000  0.5163399
```

```
## DETRITUS         0.0000000 0.03231454       0.01433512  0.0000000
##                   DETRITUS
## PLANTS           0.69247563
## BACTERIA         0.30389364
## DETRITUS FEEDERS 0.07407407
## CARNIVORES       0.21830065
## DETRITUS         0.92870934
##
## $S
##                      PLANTS    BACTERIA DETRITUS FEEDERS   CARNIVORES
## PLANTS           0.02548283 0.009763289      0.005006815 0.0014185975
## BACTERIA         0.00000000 0.026285127      0.002314823 0.0006558665
## DETRITUS FEEDERS 0.00000000 0.001892741      0.026138422 0.0074058862
## CARNIVORES       0.00000000 0.005549402      0.002845847 0.0467522693
## DETRITUS         0.00000000 0.012295082      0.006305170 0.0017864649
##                    DETRITUS
## PLANTS           0.29868988
## BACTERIA         0.11646024
## DETRITUS FEEDERS 0.05790494
## CARNIVORES       0.16977375
## DETRITUS         0.37614544
##
## $VS
##                        PLANTS     BACTERIA DETRITUS FEEDERS   CARNIVORES
## PLANTS           0.0006493748 0.000000e+00     0.000000e+00 0.0000000000
## BACTERIA         0.0004179368 6.909079e-04     9.591942e-05 0.0002609376
## DETRITUS FEEDERS 0.0002366723 1.156532e-04     6.832171e-04 0.0001406731
## CARNIVORES       0.0001306329 6.089633e-05     6.376368e-04 0.0021857747
## DETRITUS         0.1354860282 7.404899e-02     4.020838e-02 0.0988961183
##                      DETRITUS
## PLANTS           0.0000000000
## BACTERIA         0.0004951865
## DETRITUS FEEDERS 0.0002898592
## CARNIVORES       0.0001638511
## DETRITUS         0.1414853915
##
## $Q
##                    PLANTS   BACTERIA DETRITUS FEEDERS CARNIVORES  DETRITUS
## PLANTS           1.146727 0.43934800        0.2253067 0.06383689 13.441045
## BACTERIA         0.000000 1.18283072        0.1041670 0.02951399  5.240711
## DETRITUS FEEDERS 0.000000 0.08517336        1.1762290 0.33326488  2.605722
## CARNIVORES       0.000000 0.24972308        0.1280631 2.10385212  7.639819
## DETRITUS         0.000000 0.55327869        0.2837327 0.08039092 16.926545
##
## $CP
##                     PLANTS  BACTERIA DETRITUS FEEDERS CARNIVORES
## PLANTS           -39.24211   0.00000          0.00000    0.00000
## BACTERIA           0.00000 -44.48718          1.25000    0.00000
## DETRITUS FEEDERS   0.00000   0.00000        -39.73333   21.76471
## CARNIVORES         0.00000   0.00000          0.00000  -21.76471
## DETRITUS           0.00000  44.48718         38.48333    0.00000
##                     DETRITUS
## PLANTS            2.48114209
## BACTERIA          0.44700229
```

```
## DETRITUS FEEDERS  0.05587529
## CARNIVORES        0.04665586
## DETRITUS         -3.20807957
##
## $PP
##                     PLANTS   BACTERIA DETRITUS FEEDERS CARNIVORES
## PLANTS           0.1279532 0.00000000       0.00000000  0.0000000
## BACTERIA         0.0000000 0.01139601       0.02777778  0.0000000
## DETRITUS FEEDERS 0.0000000 0.00000000       0.11703704  0.4836601
## CARNIVORES       0.0000000 0.00000000       0.00000000  0.5163399
## DETRITUS         0.0000000 0.98860399       0.85518519  0.0000000
##                     DETRITUS
## PLANTS           0.055136491
## BACTERIA         0.009933384
## DETRITUS FEEDERS 0.001241673
## CARNIVORES       0.001036797
## DETRITUS         0.928709343
##
## $SP
##                      PLANTS     BACTERIA DETRITUS FEEDERS  CARNIVORES
## PLANTS           0.02548283 0.0237823704     0.0237823704 0.023782370
## BACTERIA         0.00000000 0.0262851271     0.0045139050 0.004513905
## DETRITUS FEEDERS 0.00000000 0.0009706365     0.0261384218 0.026138422
## CARNIVORES       0.00000000 0.0008063233     0.0008063233 0.046752269
## DETRITUS         0.00000000 0.3761454393     0.3761454393 0.376145439
##                      DETRITUS
## PLANTS           0.0237823704
## BACTERIA         0.0038067410
## DETRITUS FEEDERS 0.0009706365
## CARNIVORES       0.0008063233
## DETRITUS         0.3761454393
##
## $VSP
##                        PLANTS     BACTERIA DETRITUS FEEDERS   CARNIVORES
## PLANTS           0.0006493748 0.0000000000     0.000000e+00 0.000000e+00
## BACTERIA         0.0006846441 0.0006909079     5.008447e-05 4.173846e-05
## DETRITUS FEEDERS 0.0006776661 0.0002155974     6.832171e-04 4.150188e-05
## CARNIVORES       0.0016581584 0.0004016953     1.760844e-03 2.185775e-03
## DETRITUS         0.0173256592 0.0028492853     7.292589e-04 6.059395e-04
##                    DETRITUS
## PLANTS            0.0000000
## BACTERIA         -0.1217113
## DETRITUS FEEDERS -0.1218217
## CARNIVORES       -0.1063141
## DETRITUS          0.1414854
##
## $QP
##                    PLANTS    BACTERIA DETRITUS FEEDERS CARNIVORES
## PLANTS           1.146727  1.07020667       1.07020667  1.0702067
## BACTERIA         0.000000  1.18283072       0.20312572  0.2031257
## DETRITUS FEEDERS 0.000000  0.04367864       1.17622898  1.1762290
## CARNIVORES       0.000000  0.03628455       0.03628455  2.1038521
## DETRITUS         0.000000 16.92654477      16.92654477 16.9265448
##                     DETRITUS
```

```
## PLANTS            1.07020667
## BACTERIA          0.17130334
## DETRITUS FEEDERS  0.04367864
## CARNIVORES        0.03628455
## DETRITUS         16.92654477
##
## $dt
## [1] 0.02222222
##
## $RT
## [1] 0.12375163 0.03314448 0.03307607 0.08374384 0.90183925
##
## $ns
##         TSS       CIS        BSI        DSI     ISI     ID.S   ID.S.I
## [1,] 4058.4 0.8477217 0.06471625 0.05363378 0.88165 16.43833 17.07625
##          ID.S.O    HMG.S.O   HMG.S.I NAS NASP  mode0.S  mode1.S  mode2.S
## [1,] 14.38192 0.9422994 0.9971809   4    8 262.6444 355.3617 3440.394
##       mode3.S  mode4.S       ART
## [1,] 355.3617 262.6444 0.2351111
```

Environ Analysis

```r
environs = enaEnviron(model)  # unit input and ouput environs
attributes(environs)
```

```
## $names
## [1] "input"  "output"
```

```r
environs$input
```

```
## $PLANTS
##                  PLANTS BACTERIA DETRITUS FEEDERS CARNIVORES DETRITUS y
## PLANTS               -1        0                0          0        0 1
## BACTERIA              0        0                0          0        0 0
## DETRITUS FEEDERS      0        0                0          0        0 0
## CARNIVORES            0        0                0          0        0 0
## DETRITUS              0        0                0          0        0 0
## z                     1        0                0          0        0 0
##
## $BACTERIA
##                      PLANTS  BACTERIA DETRITUS FEEDERS  CARNIVORES
## PLANTS           -0.9332703  0.000000      0.000000000  0.00000000
## BACTERIA          0.0000000 -1.169351      0.001213296  0.00000000
## DETRITUS FEEDERS  0.0000000  0.000000     -0.038566625  0.01754939
## CARNIVORES        0.0000000  0.000000      0.000000000 -0.01754939
## DETRITUS          0.0000000  1.169351      0.037353329  0.00000000
## z                 0.9332703  0.000000      0.000000000  0.00000000
##                    DETRITUS y
## PLANTS            0.93327028 0
## BACTERIA          0.16813787 1
## DETRITUS FEEDERS  0.02101723 0
## CARNIVORES        0.01754939 0
## DETRITUS         -1.20670450 0
## z                 0.06672972 0
```

```
##
## $`DETRITUS FEEDERS`
##                        PLANTS   BACTERIA DETRITUS FEEDERS  CARNIVORES
## PLANTS            -0.9332703  0.0000000       0.00000000  0.00000000
## BACTERIA           0.0000000 -0.2008109       0.03267303  0.00000000
## DETRITUS FEEDERS   0.0000000  0.0000000      -1.03856662  0.01754939
## CARNIVORES         0.0000000  0.0000000       0.00000000 -0.01754939
## DETRITUS           0.0000000  0.2008109       1.00589360  0.00000000
## z                  0.9332703  0.0000000       0.00000000  0.00000000
##                      DETRITUS y
## PLANTS             0.93327028 0
## BACTERIA           0.16813787 0
## DETRITUS FEEDERS   0.02101723 1
## CARNIVORES         0.01754939 0
## DETRITUS          -1.20670450 0
## z                  0.06672972 0
##
## $CARNIVORES
##                        PLANTS   BACTERIA DETRITUS FEEDERS CARNIVORES
## PLANTS            -0.9332703  0.0000000       0.00000000   0.000000
## BACTERIA           0.0000000 -0.2008109       0.03267303   0.000000
## DETRITUS FEEDERS   0.0000000  0.0000000      -1.03856662   1.017549
## CARNIVORES         0.0000000  0.0000000       0.00000000  -1.017549
## DETRITUS           0.0000000  0.2008109       1.00589360   0.000000
## z                  0.9332703  0.0000000       0.00000000   0.000000
##                      DETRITUS y
## PLANTS             0.93327028 0
## BACTERIA           0.16813787 0
## DETRITUS FEEDERS   0.02101723 0
## CARNIVORES         0.01754939 1
## DETRITUS          -1.20670450 0
## z                  0.06672972 0
##
## $DETRITUS
##                        PLANTS   BACTERIA DETRITUS FEEDERS  CARNIVORES
## PLANTS            -0.9332703  0.0000000      0.000000000  0.00000000
## BACTERIA           0.0000000 -0.1693512      0.001213296  0.00000000
## DETRITUS FEEDERS   0.0000000  0.0000000     -0.038566625  0.01754939
## CARNIVORES         0.0000000  0.0000000      0.000000000 -0.01754939
## DETRITUS           0.0000000  0.1693512      0.037353329  0.00000000
## z                  0.9332703  0.0000000      0.000000000  0.00000000
##                      DETRITUS y
## PLANTS             0.93327028 0
## BACTERIA           0.16813787 0
## DETRITUS FEEDERS   0.02101723 0
## CARNIVORES         0.01754939 0
## DETRITUS          -1.20670450 1
## z                  0.06672972 0
```

Control Analysis

```
enaControl(model)
```

```
## $CN
##                  PLANTS  BACTERIA DETRITUS FEEDERS CARNIVORES  DETRITUS
## PLANTS                0 0.0000000         0.000000  0.0000000 0.0000000
## BACTERIA              1 0.0000000         0.000000  0.1865961 0.6903851
## DETRITUS FEEDERS      1 0.5806865         0.000000  0.0000000 0.8460570
## CARNIVORES            1 0.0000000         0.891124  0.0000000 0.5486486
## DETRITUS              1 0.0000000         0.000000  0.0000000 0.0000000
##
## $CQ
##                  PLANTS  BACTERIA DETRITUS FEEDERS CARNIVORES  DETRITUS
## PLANTS                0 0.0000000         0.000000  0.0000000 0.0000000
## BACTERIA              1 0.0000000         0.000000  0.1865961 0.6903851
## DETRITUS FEEDERS      1 0.5806865         0.000000  0.0000000 0.8460570
## CARNIVORES            1 0.0000000         0.891124  0.0000000 0.5486486
## DETRITUS              1 0.0000000         0.000000  0.0000000 0.0000000
##
## $CD
##                         PLANTS      BACTERIA DETRITUS FEEDERS
## PLANTS            0.000000e+00  8.344691e-05     8.344691e-05
## BACTERIA         -8.344691e-05  0.000000e+00     2.240311e-05
## DETRITUS FEEDERS -8.344691e-05 -2.240311e-05     0.000000e+00
## CARNIVORES       -8.344691e-05  8.850401e-06    -3.882096e-04
## DETRITUS         -8.344691e-05  7.254992e-05     8.890890e-05
##                     CARNIVORES      DETRITUS
## PLANTS            8.344691e-05  8.344691e-05
## BACTERIA         -8.850401e-06 -7.254992e-05
## DETRITUS FEEDERS  3.882096e-04 -8.890890e-05
## CARNIVORES        0.000000e+00 -5.765539e-05
## DETRITUS          5.765539e-05  0.000000e+00
##
## $CR
##                  PLANTS   BACTERIA DETRITUS FEEDERS CARNIVORES   DETRITUS
## PLANTS                0  1.0000000        1.0000000  1.0000000  1.0000000
## BACTERIA             -1  0.0000000        0.5806865 -0.1865961 -0.6903851
## DETRITUS FEEDERS     -1 -0.5806865        0.0000000  0.8911240 -0.8460570
## CARNIVORES           -1  0.1865961       -0.8911240  0.0000000 -0.5486486
## DETRITUS             -1  0.6903851        0.8460570  0.5486486  0.0000000
##
## $CA
##      PLANTS  BACTERIA DETRITUS FEEDERS CARNIVORES  DETRITUS
## [1,]      0 0.2677194        0.1226211 0.01903096 0.5906285
## [2,]      0 0.0000000        1.0000000 0.00000000 0.0000000
## [3,]      0 0.0000000        0.0000000 1.00000000 0.0000000
## [4,]      0 1.0000000        0.0000000 0.00000000 0.0000000
## [5,]      0 0.6181272        0.3469538 0.03491900 0.0000000
##
## $CDep
##      PLANTS  BACTERIA DETRITUS FEEDERS CARNIVORES DETRITUS
## [1,]      0 0.0000000        0.0000000  0.0000000        0
## [2,]      0 0.0000000        0.0622461  0.0000000        0
## [3,]      0 0.0000000        0.0000000  0.3093601        0
## [4,]      0 0.2352179        0.0000000  0.0000000        0
## [5,]      0 0.3940869        0.2212004  0.0222626        0
##
```

```
## $sc
##          PLANTS        BACTERIA DETRITUS FEEDERS       CARNIVORES
##    0.0003337877   -0.0001424441     0.0001934507    -0.0005204615
##        DETRITUS
##    0.0001356673
##
## $psc
##          PLANTS        BACTERIA DETRITUS FEEDERS       CARNIVORES
##        50.35221       -21.48784         29.18223        -78.51216
##        DETRITUS
##        20.46555
##
## $ns
##          TSC
## 0.0006629056
```

Impact Analyses

There are two forms of what I am calling *Impact Analyses*: Utility Anlaysis and Mixed Trophic Impacts. These analyses can be applied as follows.

```r
u = enaUtility(model)
attributes(u)
```

```
## $names
## [1] "D"                "SD"               "U"                "Y"
## [5] "SY"               "Relations.Table" "ns"
```

```r
u$ns
```

```
##             lam1D relation.change.F synergism.F mutualism.F
## r.change 1.015627             73.33    3.979433       2.125
```

```r
u$Relations.Table
```

```
##                From               To Direct Integral changed
## 1            PLANTS           PLANTS  (0,0)    (+,+)       *
## 2            PLANTS         BACTERIA  (0,0)    (+,+)       *
## 3            PLANTS DETRITUS FEEDERS  (0,0)    (+,+)       *
## 4            PLANTS       CARNIVORES  (0,0)    (+,-)       *
## 5            PLANTS         DETRITUS  (+,-)    (+,-)       -
## 6          BACTERIA         BACTERIA  (0,0)    (+,+)       *
## 7          BACTERIA DETRITUS FEEDERS  (+,-)    (-,-)       *
## 8          BACTERIA       CARNIVORES  (0,0)    (-,+)       *
## 9          BACTERIA         DETRITUS  (-,+)    (-,+)       -
## 10 DETRITUS FEEDERS DETRITUS FEEDERS  (0,0)    (+,+)       *
## 11 DETRITUS FEEDERS       CARNIVORES  (+,-)    (+,-)       -
## 12 DETRITUS FEEDERS         DETRITUS  (-,+)    (-,+)       -
## 13       CARNIVORES       CARNIVORES  (0,0)    (+,+)       *
## 14       CARNIVORES         DETRITUS  (+,-)    (+,+)       *
## 15         DETRITUS         DETRITUS  (0,0)    (+,+)       *
```

```r
mti = enaMTI(model)
attributes(mti)
```

```
## $names
```

```
## [1] "G"                "FP"               "Q"                "M"
## [5] "Relations.Table"
```

```
mti$Relations.Table
```

```
##                  From              To Net (direct) Mixed (integral) changed
## 1              PLANTS          PLANTS        (0,0)            (0,0)       -
## 2              PLANTS        BACTERIA        (0,0)            (-,+)       *
## 3              PLANTS DETRITUS FEEDERS       (0,0)            (+,+)       *
## 4              PLANTS      CARNIVORES        (0,0)            (+,+)       *
## 5              PLANTS        DETRITUS        (0,+)            (+,+)       *
## 6            BACTERIA        BACTERIA        (0,0)            (-,-)       *
## 7            BACTERIA DETRITUS FEEDERS       (-,+)            (-,-)       *
## 8            BACTERIA      CARNIVORES        (0,0)            (+,-)       *
## 9            BACTERIA        DETRITUS        (+,-)            (+,-)       -
## 10 DETRITUS FEEDERS DETRITUS FEEDERS        (0,0)            (-,-)       *
## 11 DETRITUS FEEDERS      CARNIVORES        (-,+)            (-,+)       -
## 12 DETRITUS FEEDERS        DETRITUS        (+,-)            (+,-)       -
## 13       CARNIVORES      CARNIVORES        (0,0)            (-,-)       *
## 14       CARNIVORES        DETRITUS        (0,+)            (+,+)       *
## 15         DETRITUS        DETRITUS        (0,0)            (-,-)       *
```

Exercises

1. Find the number of nodes and connectance of the *Swartkops Estuary* model.
2. Create a barplot of the throughflow vector of the *Bothnian Sea* model.
3. Plot the node throughflow vs. the effective trophic levels for the *Okefenokee Swamp* food web model.
4. Find the A/C (ASC.CAP) and FCI of the *Florida Bay (wet)* model.