Network Environ Analysis

History and Background

Research Questions: Analyses in Context

Links to EcoNet and enaR

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What is Network Environ Analysis (NEA) ?

Network Environ Analysis (NEA) is a environmental systems theory developed by Bernard C Patten and colleagues, largely at the University of Georgia, USA, which seeks to provide an answer to the question:

What is the essential nature of the organism-environment relationship?
What is environment?

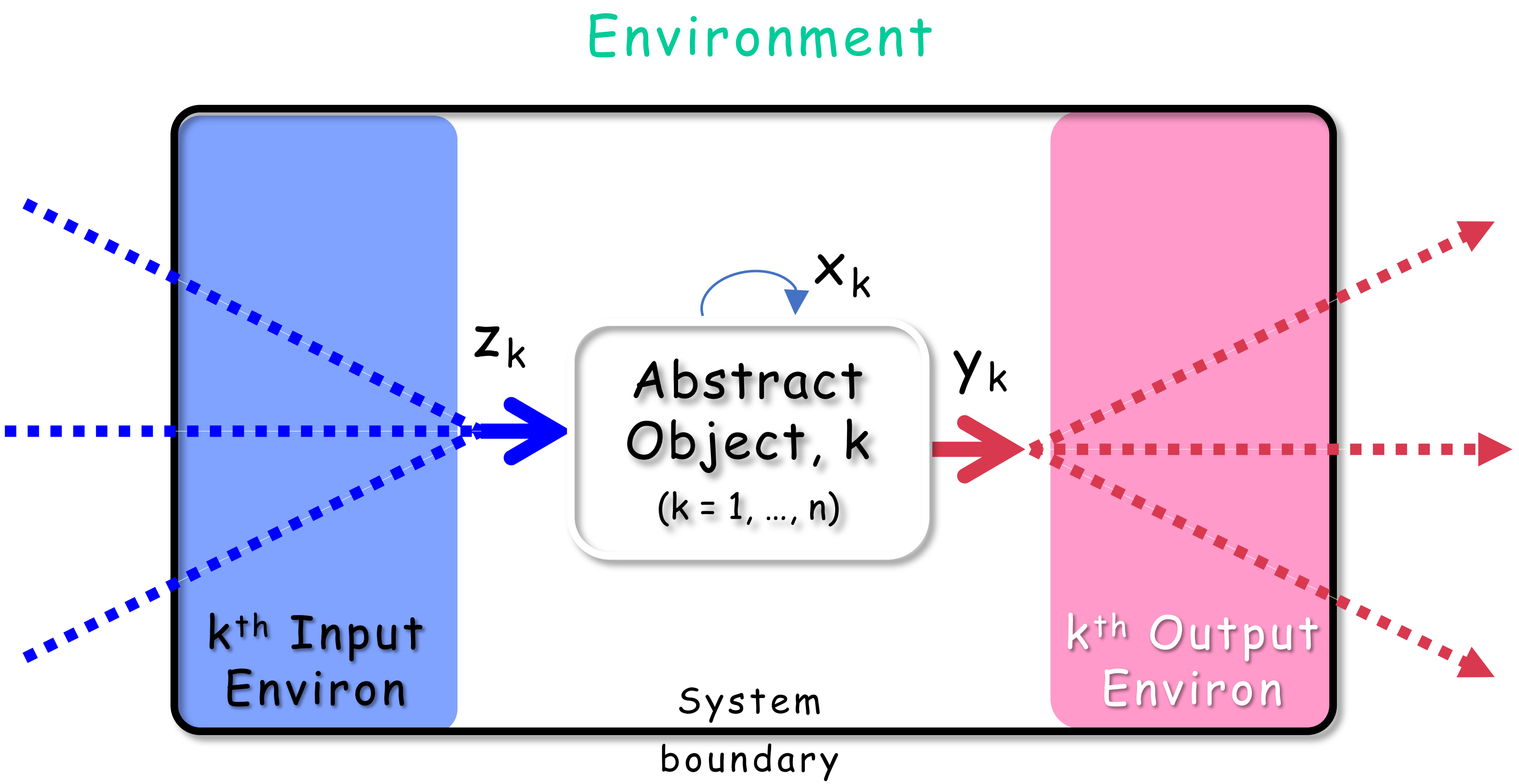
The methodology of NEA (Fath and Patten, 1999) is a set of numerical analyses based on Input-Output analysis, originally developed for economics by Leontief (1966), used to gain insight into the structure and function of weighted steady-state network models.

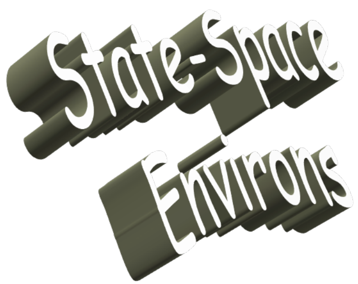
NEA is grounded in state space system theory and a differential equation representation of an open steady-state network with a conservative currency (matter or energy)

Leontief, W. 1966. *Input-Output Economics*. Oxford University Press. USA.

Fath, BD and Patten, BC. 1999. Ecosystems 2:167-179

The measurable intrasystem environments of all system components

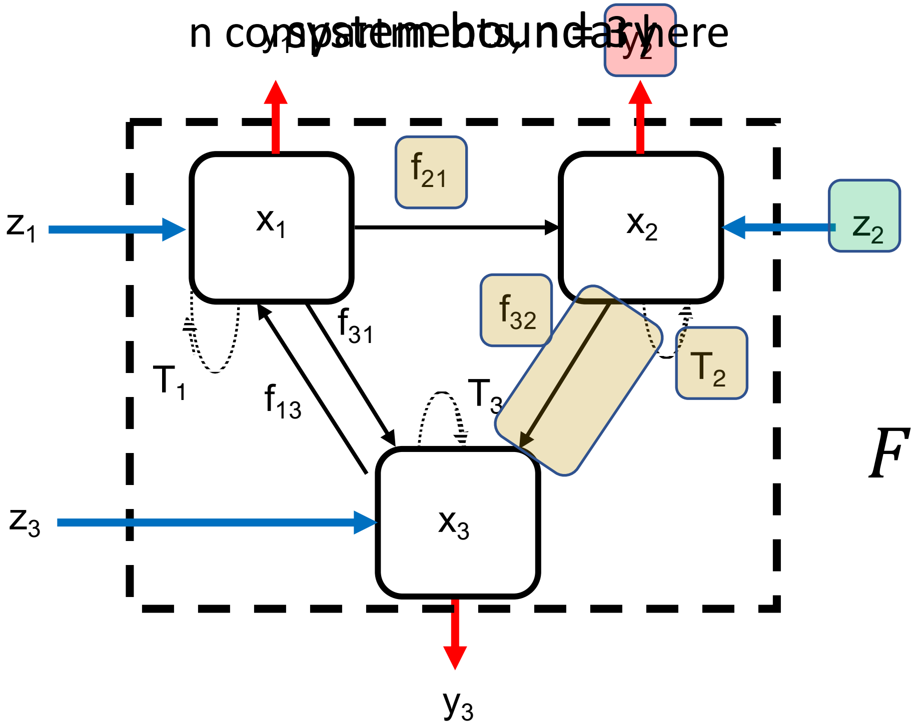




slide credit: BC Patten

Patten, BC. 1978. *Ohio J. Science* 78:206-222.

Steady-state model set up for NEA: terminology and matrices



$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \qquad z = \begin{pmatrix} z_1 \\ z_2 \\ z_3 \end{pmatrix} \qquad y = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}$$

$$F = \begin{pmatrix} 0 & 0 & f_{13} \\ f_{21} & 0 & 0 \\ f_{31} & f_{32} & 0 \end{pmatrix}$$

weighted Flow matrix (F)

$$T = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix}$$

throughflow vector

Matrices oriented from columns to rowns

$$A = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & \boxed{1} & 0 \end{pmatrix}$$

unweighted Adjacency matrix (A)

$T_i^{in} = \Sigma_{j=1,n}\, f_{ij} + z_i \qquad T_i^{out} = \Sigma_{i=1,n}\, f_{ij} + y_i$

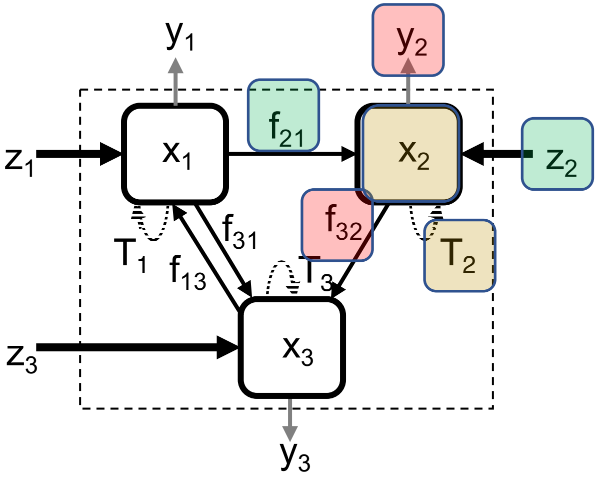
$$dx/dt = F \cdot 1 + z = 0$$

$$T_i^{in} = T_i^{out}$$

Total System Throughflow

$$TST = \sum_{i=1}^{n} T_i$$

NEA methods: Big picture theoretical background



$T_i^{in} = \Sigma_{j=1,n} f_{ij} + z_i$

$T_i^{out} = \Sigma_{i=1,n} f_{ij} + y_i$

$$T = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix}$$

$$dx/dt = F \cdot 1 + z = 0$$

$T_i^{in} = T_i^{out}$

There are analogous Input Environ (Time-Backward) analysis matrices

$$g_{32} = f_{32}/T_2$$

$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \quad z = \begin{pmatrix} z_1 \\ z_2 \\ z_3 \end{pmatrix} \quad y = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}$$

$$F = \begin{pmatrix} 0 & 0 & f_{13} \\ f_{21} & 0 & 0 \\ f_{31} & f_{32} & 0 \end{pmatrix}$$

<u>Output Environ Throughflow Analysis</u>

Time-Forward Analyses

$$dx/dt = GT + z = 0$$

Throughflow-Specific Coefficients

$$g_{ij} = f_{ij}/T_j$$

Steady-State Input(z) Mapping

$$T = (I - G)^{-1} z = Nz$$

N:
compartment-wise throughflow environ measures

system-wide throughflow environ measures

<u>Output Environ Storage Analysis</u>

Time-Forward Analyses

$$dx/dt = C \cdot x + z = 0$$

Stock-Specific Coefficients

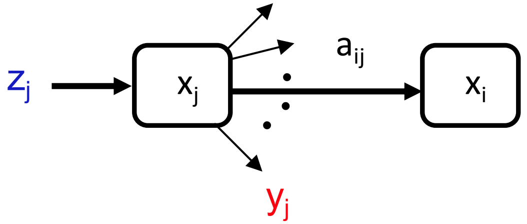
$$c_{ij} = f_{ij}/x_j$$

Steady-State Input(z) Mapping

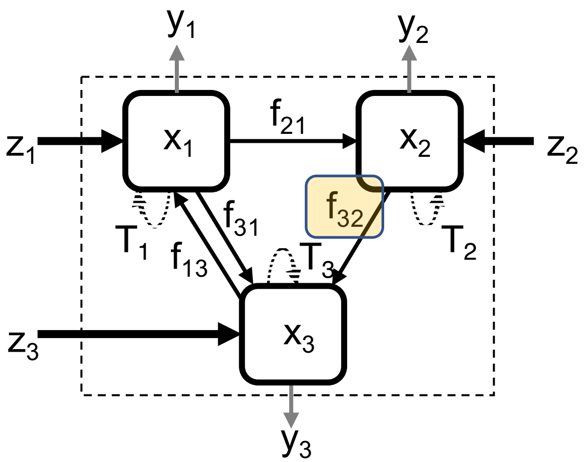
$$x = (-C)^{-1} z = Sz$$

S:
compartment-wise storage environ measures

system-wide storage environ measures



Unweighted adjacency matrix: Extended path structure – A-matrix power series



$$A = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & \boxed{1} & 0 \end{pmatrix}$$

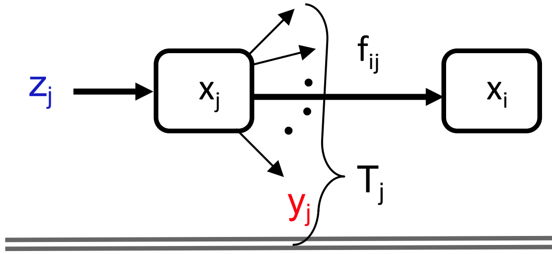
$a_{ij}^{(m)}$ represents the number of pathways from compartment j to compartment i of length m that exist for the model represented by the structure of the adjacency matrix A.

$$\underbrace{a_{ij}}_{\text{direct}} + \underbrace{a_{ij}^{(2)}\ a_{ij}^{(10)}\ a_{ij}^{(50)} \ldots\ a_{ij}^{(m)}}_{\text{indirect}}$$

$$A^2 = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 1 \end{pmatrix} \qquad A^{10} = \begin{pmatrix} 7 & 4 & 5 \\ 5 & 3 & 4 \\ 9 & 5 & 7 \end{pmatrix}$$

$$A^{50} = \begin{pmatrix} 525456 & 299426 & 396655 \\ 396655 & 226030 & 299426 \\ 696081 & 396655 & 525456 \end{pmatrix}$$

Adjacency matrix represents the **direct paths** within the system between compartments, while the A^m matrix powers represent **indirect paths** between the compartments of length m referred to as the **extended path structure**



Weighted flow matrix- Extended path structure: throughflow-specific and storage-specific matrix power series

$$N = (I - G)^{-1} \qquad T = Nz$$

$$T_{ij} = n_{ij} z_j$$

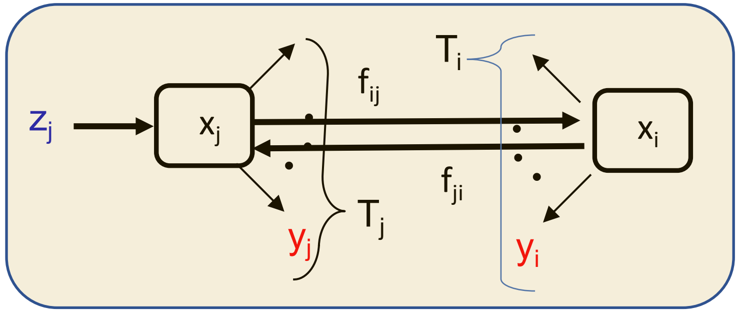
This extended path structure is the microscopic interpretation behind the concept that environ analysis traces the input (z_j) from first compartment contact through the extended path structure of the system until it is exhausted at output (y_i)

$$(I - G)^{-1} = (I + G + G^{(2)} + G^{(3)} + G^{(M)} + \ldots)$$

$$T_{ij} = (1 + \underbrace{g_{ij}}_{\text{direct}} + \underbrace{g_{ij}^{(2)} + g_{ij}^{(3)} \ldots}_{\text{indirect}})z_j$$

An analogous power series can be constructed for the storage-specific matrix

Extended path structure is also the mechanism behind dominance of indirect effects NEA results for most cyclic networks quantified by the indirect effects index



How does one conduct NEA 3. utility analysis methods

Intensive Utility measure

$$U = (I - D)^{-1}$$

D represents the net flow between x_j and x_i

$$d_{ij} = \frac{f_{ij}}{T_i} - \frac{f_{ji}}{T_i}$$

Intensive Utility measure is unitless

$$u_{ij} = (1 + \underbrace{d_{ij}}_{\text{direct}} + \underbrace{d_{ij}^{(2)} + d_{ij}^{(3)} \ldots}_{\text{indirect}})$$

What are the main types of NEA analyses ?

Unweighted adjacency matrix: A

Structural analysis: digraph

matrix power series: A^m

Determination of pathway numbers for paths of of lengths *m* using adjacency matrix power series

flux decomposition of matrix: A

Weighted flow matrix: F

Environ analysis: transactions

Throughflow (F): N matrix

Compartment-wise:
environ intercompartmental flows, boundary flows

number of compartment visits

System-wide: 2 examples
Finn cycling index
Indirect Effects Index

Storage (F,x): S matrix

Compartment-wise:
environ *storages* & flows
environ *residence time*

System-wide: 2 examples
Storage cycling index
Indirect Effects Index

Utility analysis: relations

Direct utilities (net F, T-normalized): D matrix

Ultimate Utilities

U matrix

Compartment-wise:

weighted utility values (U)
qualitative (0, +, −) interaction types (sgn(U))

System-wide:

Whole system utility measures:

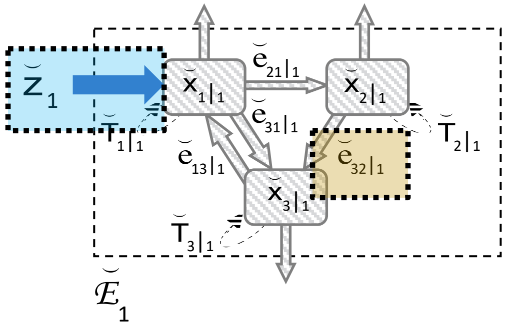
mutualism (sum of number of positives / sum of number of negatives in U matrix)

synergism (sum of weighted entries in U matrix)

What sorts of ecological questions can be answered with NEA

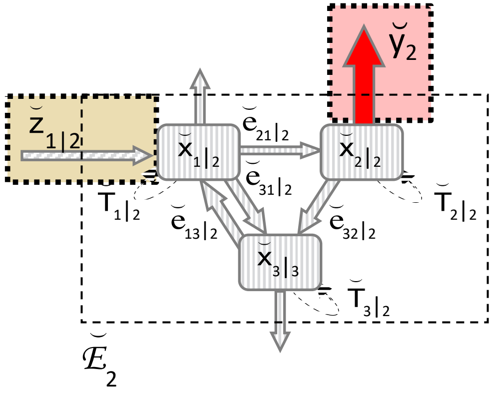
‘Analytical tracer’ and storage or residence time : NEA

1. ‘Analytical tracer’ for different inputs (system entry) or outputs (system exit)
2. Storage or residence time for input to or output from the system
3. Cycle analysis – Finn cycling index
4. Total Environ Throughflow (TET) : $TET_k = \sum_{j(\neq i)=1}^{n} e_{ij|k} + y_{j|k}$



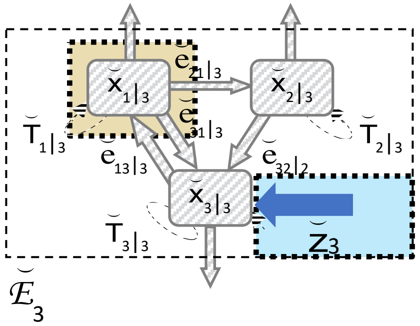
Environ flow from compartment 2 to 3 resulting from input to compartment 1

Throughflow Output Environ 1
(N)



Environ input to compartment 1 resulting from output from compartment 2

Throughflow Input Environ 2
(N’)



Environ residence time of compartment 1 resulting from input to compartment 3

Storage Output Environ 3
(S)

Example analysis - system and conceptual model

Okefenokee Swamp, Georgia, USA

Water budget model of Okefenokee watershed

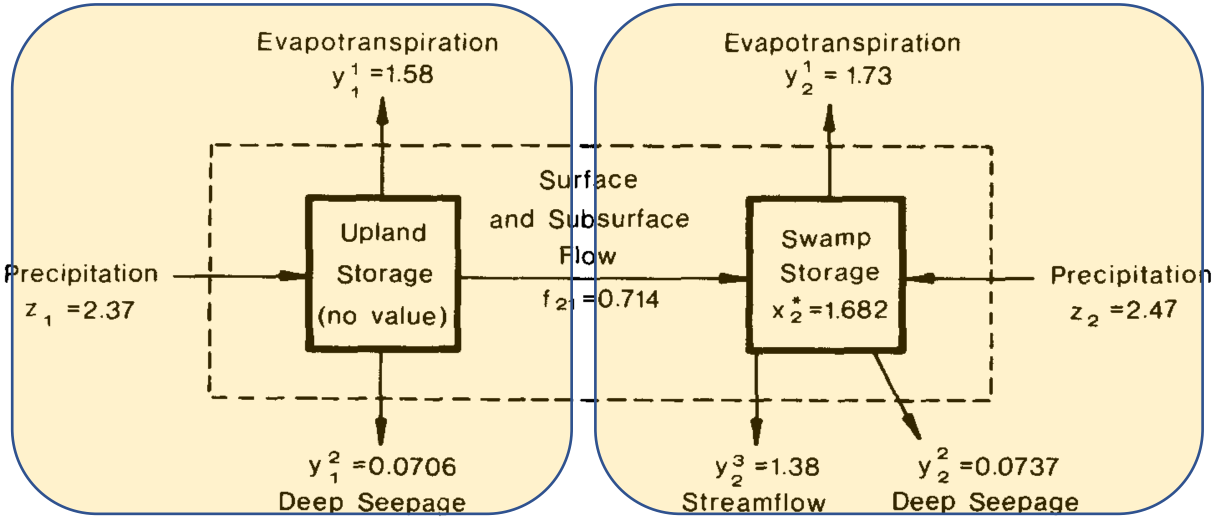


Fig. 2. Two compartment watershed water budget model of Rykiel (1977, 1982). Storage x_2^* is in units 10^9 m^3. Inputs z, outputs y and the internal flow f are in 10^9 m^3 y^{-1}.

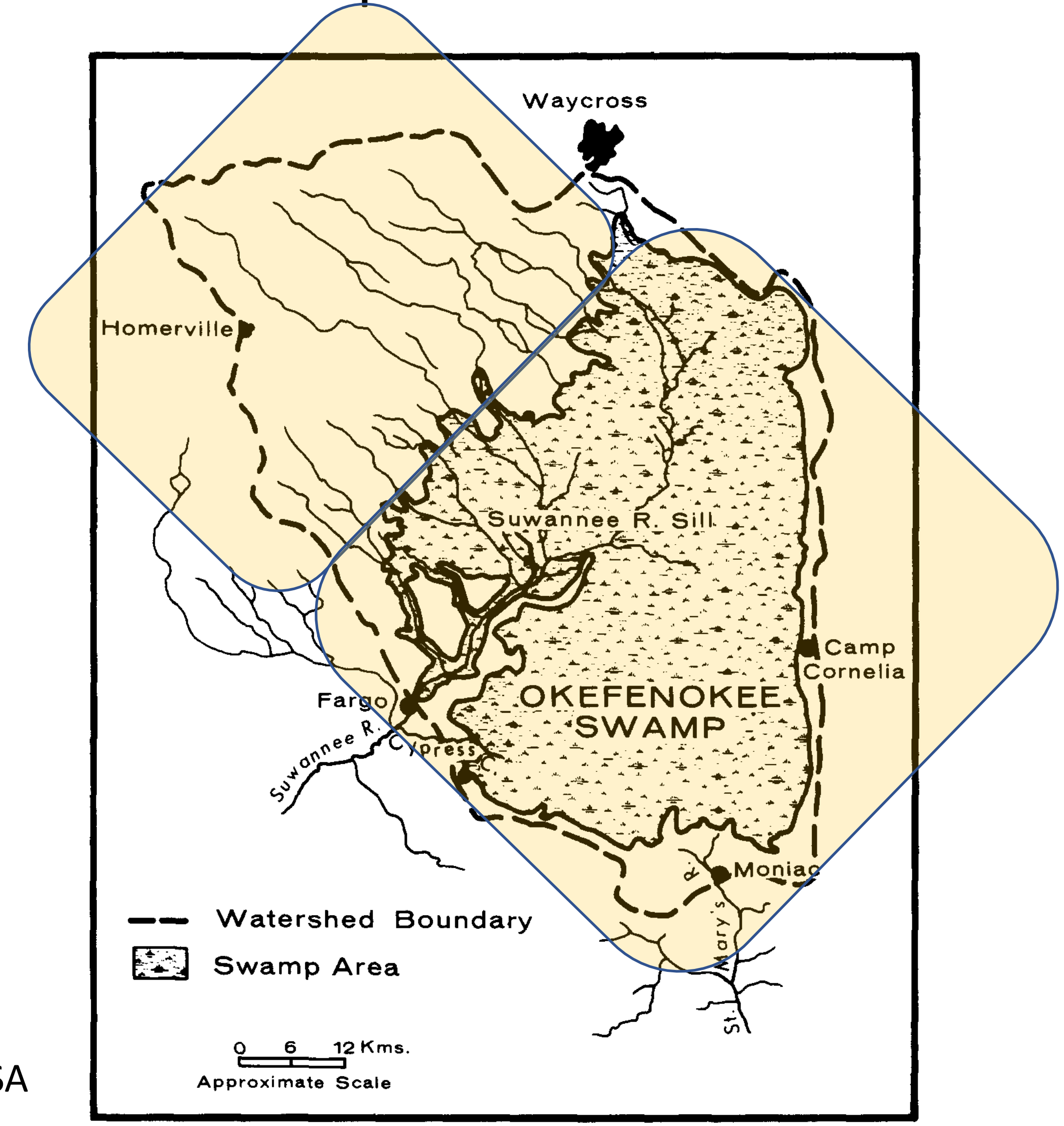
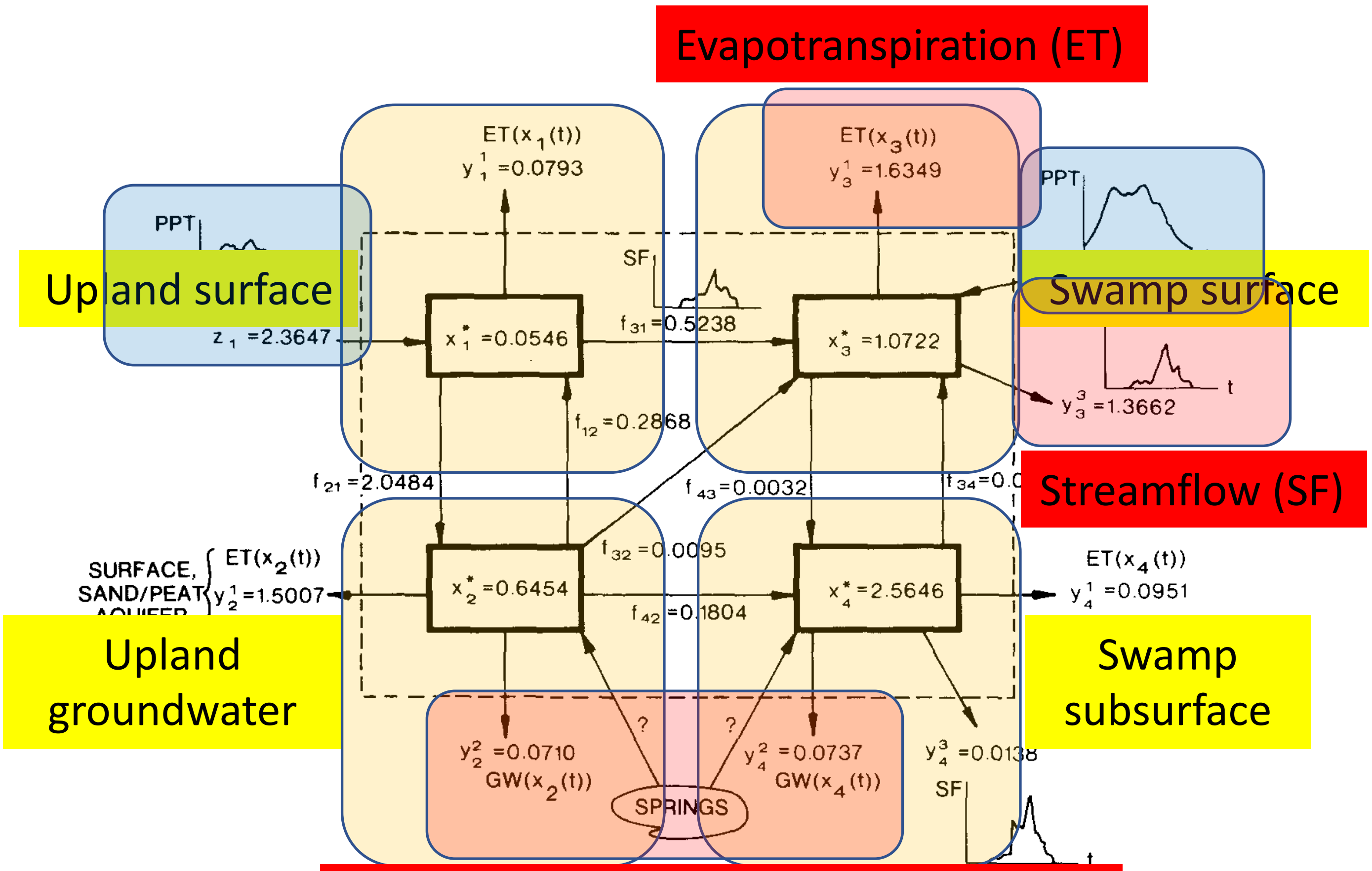


Fig. 1. The Okefenokee swamp–upland watershed. Most of the area of the uplands is in the northwest quadrant. The three output streams and the Suwannee River Sill are indicated.

Conceptual Model: Rykiel, EJ. 1977. PhD. Dissertation. University of Georgia, USA

Source: Patten, BC and Matis, JH. 1982. *Ecological Modelling* 16:1-50.

Water budget model of Okefenokee swamp watershed, Georgia, USA



Groundwater & subsurface losses (GW)

Units:

- storage: 10^9 m^3
- flows: 10^9 m^3 yr^{-1}
- areal basis is entire watershed

Compartments (x_i)

- x_1 upland surface
- x_2 upland groundwater
- x_3 swamp surface
- x_4 swamp subsurface

Inputs (z_i)

- z_1 upland precip
- z_2 swamp precip
- z_3
- z_4

Outputs (y_i)

- y_1 evapotranspiration (ET)
- y_2 deep seepage (GW), ET
- y_3 stream flow (SF), ET
- y_4 infiltration, ET, baseflow

Intercompartmental transfers (f_{ij})

- f_{21} infiltration & percolation
- f_{31} channel & overland flow
- f_{12} baseflow & interflow
- f_{32} baseflow
- f_{42} lateral seepage
- f_{43} infiltration & percolation
- f_{34} upwelling & water level rise

Source: Patten, BC and Matis, JH. 1982. *Ecological Modelling* 16:1-50.

Example 1 - Flow tracing and TET : storage analysis results

Okefenokee water budget model : Fate of water input

Output Environ analysis

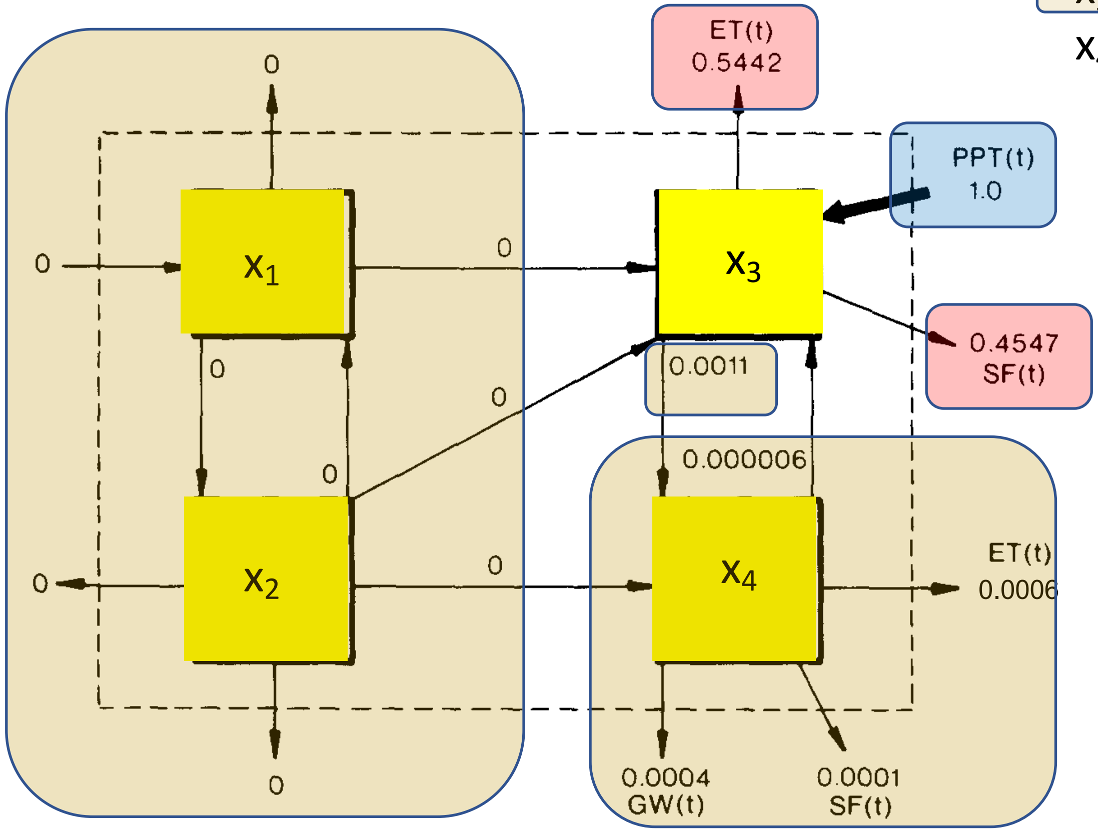
Fate of water input *precipitation* – z_3 input into swamp surface water - x_3

Compartments (x_i)

- x_1 upland surface
- x_2 upland groundwater
- x_3 swamp surface
- x_4 swamp subsurface

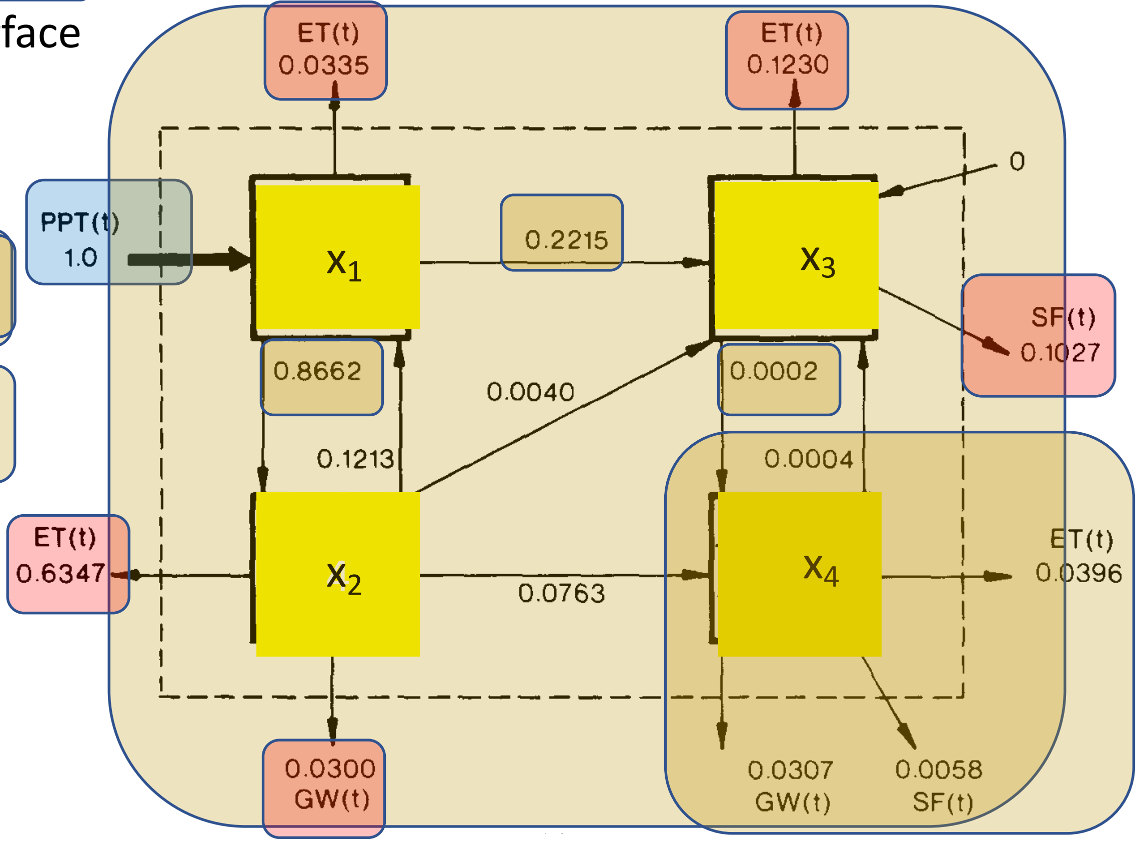
Output Environ analysis

Fate of water input *precipitation* – z_1 input into upland surface water - x_1



TET_3 : 1.001

TET_1 : 3.29



Source: Patten, BC and Matis, JH. 1982. *Ecological Modelling* 16:1-50.

Example 2 - Network properties : Finn cycling index

Nitrogen ecosystem model of Lake Okeechobee, USA

1-WC-ON	water column organic nitrogen
2-WC-IN	water column inorganic nitrogen
3-WC-PHYT	water column phytoplankton
4-SD-ON	sediment organic nitrogen
5-SD-IN	sediment inorganic nitrogen
6-SD-PHYT	sediment phytoplankton

Finn (1978) cycling index:

$$\frac{TST_c}{TST} = \frac{1}{TST}\sum_{i=1}^{n} T_i \frac{N_{ii}-1}{N_{ii}}$$

N model
Finn cycling index = 86%

compartment cycling efficiencies (%)

compartment cycling efficiencies (%)	N matrix	1-WC-ON	2-WC-IN	3-WC-PHYT	4-SD-ON	5-SD-IN	6-SD-PHYT
91.0	1-WC-ON	11.08566951					
61.0	2-WC-IN		2.565983832				
61.2	3-WC-PHYT			2.577169741			
91.0	4-SD-ON				11.16355879		
37.8	5-SD-IN					1.606961247	
24.2	6-SD-PHYT						1.320087578

Principal diagonal entries (N_{ii}), which quantify the number of compartment visits for a unit input into each column compartment, reveal a great deal of variation

Principal diagonal entries (N_{ii}) provide a quantitative measure of the amount of cycling in the model, when weighted by model throughflow (T_i / TST), as shown in Finn's cycling index algorithm.

N model is a steady-state snapshot of a simulation by Tom James and colleagues of the South Florida Water Management District, USA

Finn, JT. 1978. Cycling index: a general definition for cycling in compartment models. In: *Environmental Chemistry and Cycling Processes*. US-DOE Symp. vol. 45. National Technical Information Center. Springfield, VA., pp. 148-164.

What sorts of ecological questions can be answered with NEA

What can utility analysis tell us about ecosystem models?

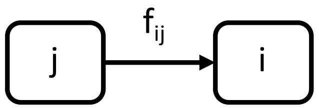
1. Ecosystem model interaction types

2. Whole-model utility measures: mutualism and synergism

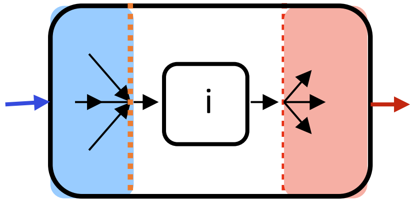
Energy–Matter Flows

Terminology

Transaction directed energy or matter flow f between two adjacent compartments



Environs afferent and efferent environments of compartments within a system boundary



Can we analyze a transaction network to derive relations?

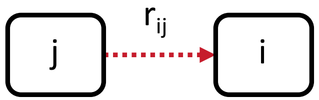
(+, –) nihilism (predation)

(–, +) altruism

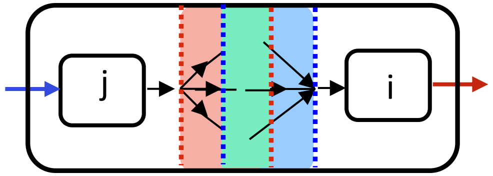
(–, –) competition

(+, +) mutualism

Relation directed proximate or ultimate relationship r between two adjacent or nonadjacent compartments



Utility system-wide measure of benefits vs. costs transmitted between compartment pairs



slide credit: BC Patten & SJ Whipple

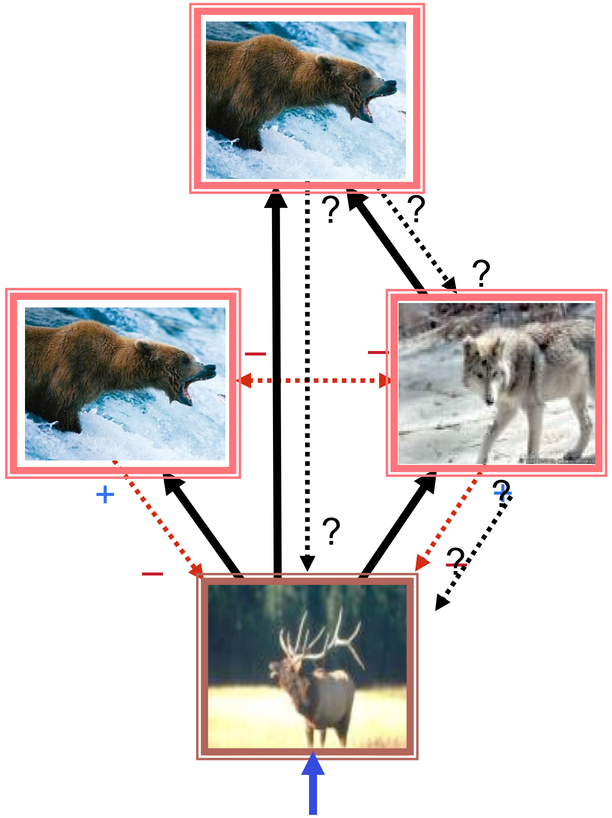
Example 3 - Intensive Utility analysis - Concepts

Intraguild predation: Flow weights determine interaction types for small food web model

Community Modules: Acyclic

Parametrically Determined

Interaction type determined by internal flow values



2.1 Omnivory, Intraguild Predation, etc.

Rules

Divergent competition (–,–) at a fixed trophic level within a feeding guild …

… becomes, on introduction of cross-level (intraguild) feeding, structurally indeterminate interaction types (?, ?)

Images:http://www.google.com

Patten & Whipple (2007) called this parametric determination

Source: Patten, BC and Whipple, SJ. 2007. *International Journal of Ecodynamics* 2(2):88-96.

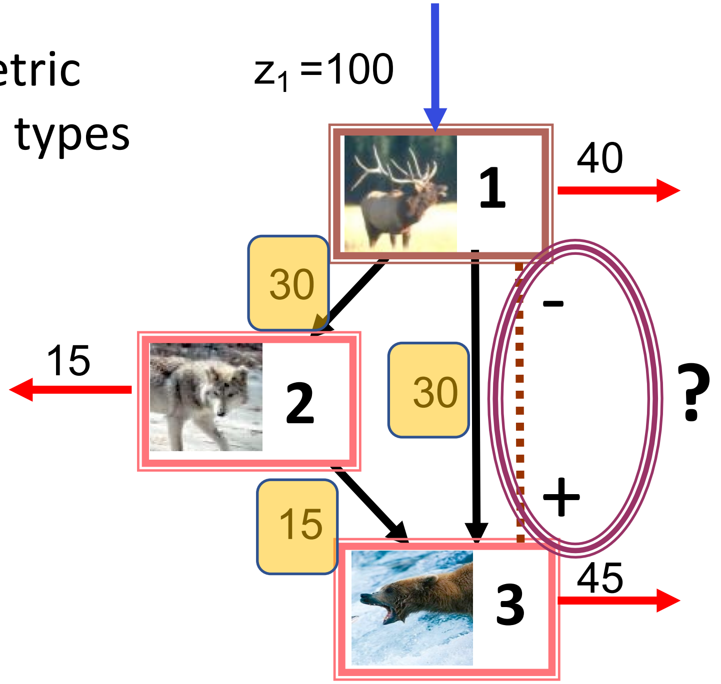
Example 3 - Intensive Utility analysis: Results

Intraguild predation: parametric determination of interaction types

The change in the weight of three intercompartmental flows results in two major utility effects:

1. Changed the sign of the interaction type in the Utility (U) matrix to indicate a change from nihilism (predation) to mutualism

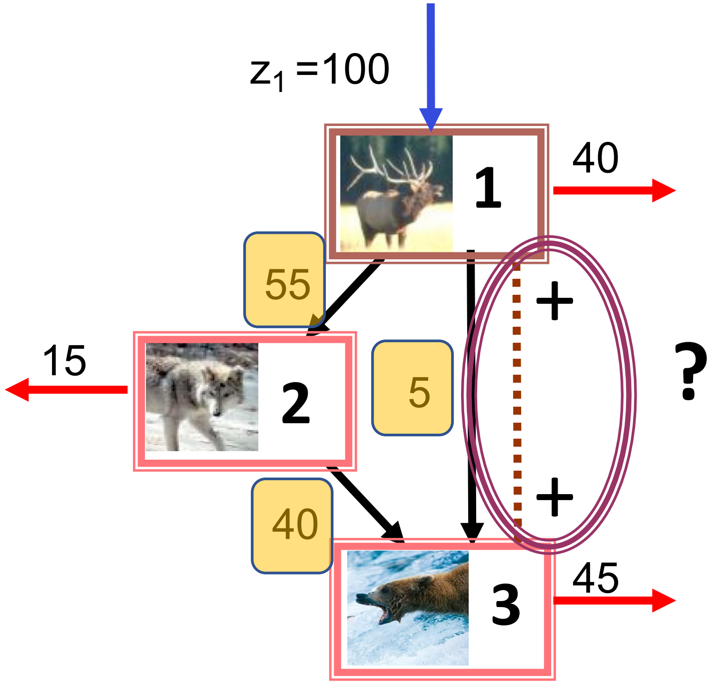
2. System wide mutualism for case 1: 6/3 = 2 ; while System wide mutualism for case 2: 7/2 = 3.5



Case 1

sU = 3 + ↔ - 1

	1	2	3
1	+	+	+
2	−	+	+
3	−	−	+



Case 2

sU = 3 + ↔ + 1

	1	2	3
1	+	+	+
2	−	+	+
3	+	−	+

slide credit: BC Patten and SJ Whipple

Flux decomposition analysis

Example figure based on Zhuang (2020)

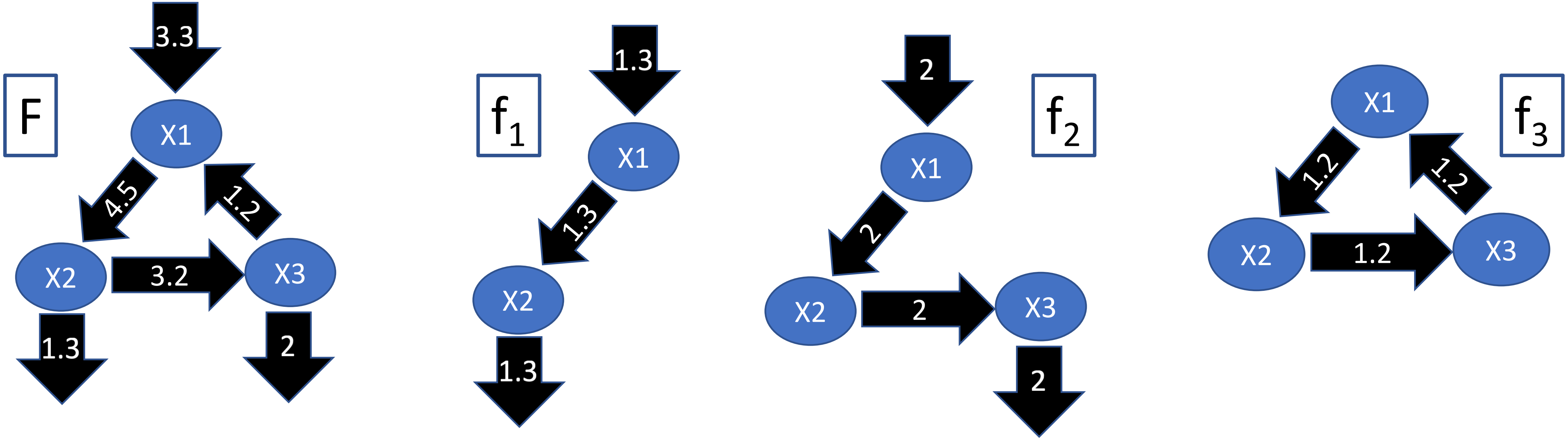
Flux decomposition analysis parses an arbitrary network into two sets of sub-networks.

Flux decomposition allows the steady-state model to be represented by a linear combination of its fluxes.

1. simple paths with no repeating nodes and exactly one input from and one output (f_1 and f_2)

2. simple cycles with only one repeating node and no inputs or outputs (f_3)

$$F = 1.3f_1 + 2f_2 + 1.2f_3$$



Zhuang, Yuling. 2020. *Sensitivity of system-wide ecosystem measures to model data*. Masters Thesis. University of Georgia. USA.

Connections to Econet

Econet conducts a simulation of a user-specified ODE model to create a steady state flow-storage network

Econet conducts NEA analysis of the steady-state network and provides the N and S matrices from environ analysis and the D and U matrices from utility analysis

Econet provides a large set of system-wide measures derived from the environ matrices and utility matrices

Econet provides the flux decomposition graphs for the given system model

Kazanci, C., 2007. Econet: a new software for ecological modeling, simulation and network analysis. *Ecological Modelling.* 208 (1), 3–8.

Connections to enaR

- **enaR** is an R package that allows for users to analyze their own models and generate a wide range of NEA results and other types of ecological network analyses results in a user-friendly package.

enaStructure: Analysis returns the adjacency matrix (A) and multiple common descriptive statistics

enaFlow: Calculates node throughflow and input- and output-oriented direct and integral flow intensity matrices (N) and whole-network descriptive statistics

enaStorage: Analysis returns the input- and output-oriented direct and integral storage matrices (S)

enaUtility: Analysis investigates the direct relationships (D) among the network nodes as well as the integral relationships (U)

enaEnviron: Returns the n unit and n realized input and output environs of the model)

Source: Borrett, SR and Lau, MK. 2014. enaR: an R package for ecosystem network analysis. *Methods in Ecology and Evolution* 5:1206-1213

Now, on to Caner to talk about Econet