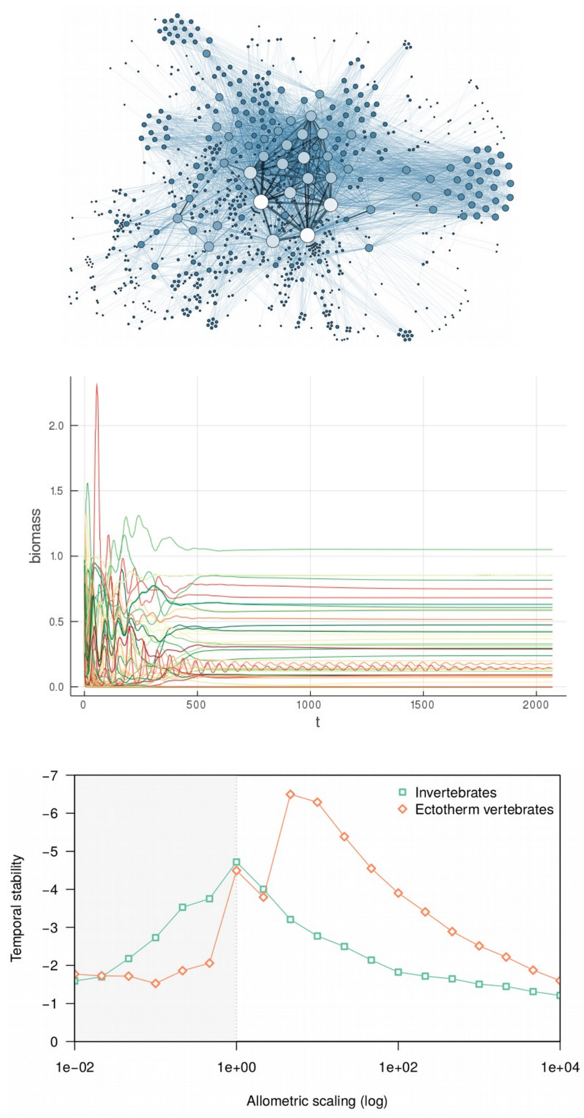


A Bioenergetic Model for Food Webs

→ Modelling population dynamics in terms of biomass flows through trophic interactions, using the principle of bioenergetics

Eva Delmas, 2019-08-21
Summer school in biodiversity modelling 2019

Outline

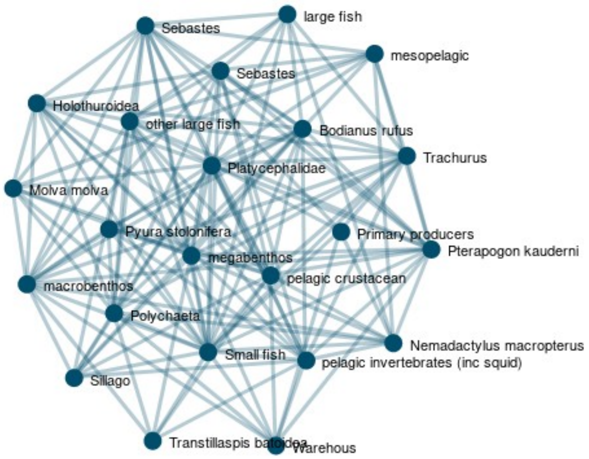
→ How to build, parameterize and use bio-energetic models to model population dynamics in food webs

- Food webs: a useful abstraction of ecological communities
- The principle of mass balance
- Growth of basal species
  - Intro. to solving differential equation
- Consumption
- Metabolic losses
- The bio-energetic food-web model
- Setting parameters values
- Model application: food web robustness to extinctions
- A brief review and discussion

Food Webs

→ Map trophic interaction => biomass routes through the community

→ powerful abstraction to investigate stability / functioning of ecological communities



Dietary matrix of demersal fishes of the south-eastern Australian shelf

Mangal network ID #1102, measurement date: 1993-07-01

Public | Unrecorded absences

Number of nodes	Number of interactions	Connectance
23	141	0.27

From mangal.io

Software notes

Ecography 39: 384–390, 2016
doi: 10.1111/ecog.00976
© 2015 The Authors. Ecography © 2015 Nordic Society Oikos
Subject Editor: Michael Borregaard. Editor-in-Chief: Miguel Araújo. Accepted 7 April 2015

mangal – making ecological network analysis simple

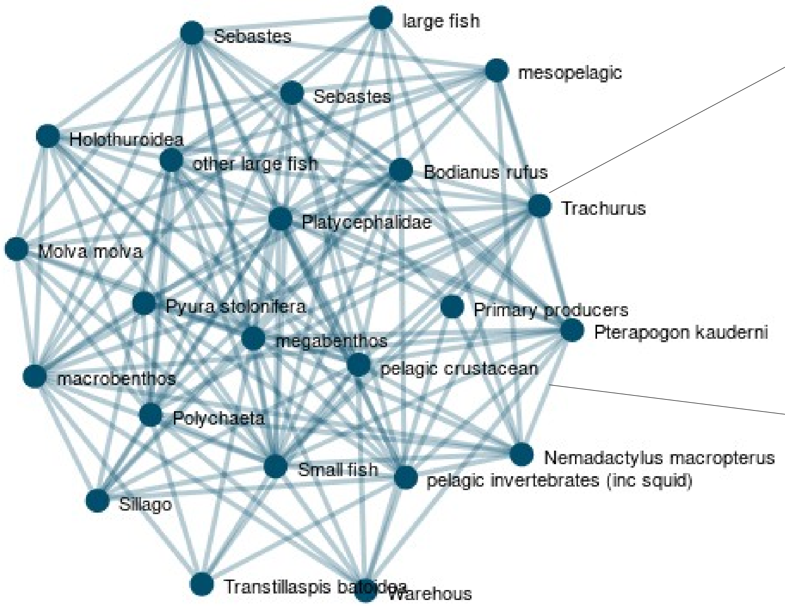
Timothée Poisot, Benjamin Baiser, Jennifer A. Dunne, Sonia Kéfi, François Massol, Nicolas Mouquet, Tamara N. Romanuk, Daniel B. Stouffer, Spencer A. Wood and Dominique Gravel

iwdb Interaction Web DataBase

Food Webs

→ Map trophic interaction => biomass routes through the community

→ powerful abstraction to investigate stability / functioning of ecological communities



From mangal.io

Node: population, species, trophospecies, ...

Metadata → name, traits, ...

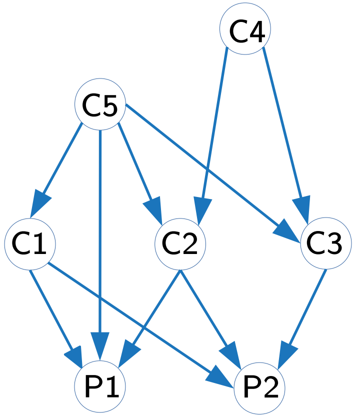
Edge: trophic interaction

Metadata → interaction strength, direction

Food Webs

→ Map trophic interaction => biomass routes through the community

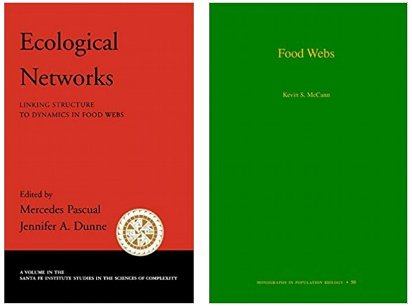
→ powerful abstraction to investigate stability / functioning of ecological communities

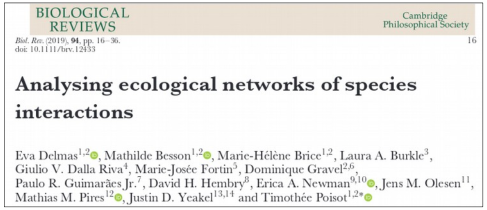


	P1	P2	C1	C2	C3	C4	C5
P1	0	0	0	0	0	0	0
P2	0	0	0	0	0	0	0
C1	1	1	0	0	0	0	0
C2	1	1	0	0	0	0	0
C3	0	1	0	0	0	0	0
C4	0	0	0	1	1	0	0
C5	1	0	1	1	1	0	0

A = S*S interaction matrix
A[i,j] = 1 means i eats j
A[i,j] = 0 otherwise

Structural properties of the food web (connectance, modularity, degree distribution, etc.)




BIOLOGICAL REVIEWS
Cambridge Philosophical Society
Biol. Rev. (2019), 94, pp. 16–36.
doi: 10.1111/brv.12433
16

Analysing ecological networks of species interactions

Eva Delmas[1,2], Mathilde Besson[1,2], Marie-Hélène Brice[1,2], Laura A. Burkle[3], Giulio V. Dalla Riva[4], Marie-Josée Fortin[5], Dominique Gravel[2,6], Paulo R. Guimarães Jr.[7], David H. Hembry[8], Erica A. Newman[9,10], Jens M. Olesen[11], Mathias M. Pires[12], Justin D. Yeakel[13,14] and Timothée Poisot[1,2*]

Mass balance

→ **Conservation of mass**: in a closed physical system mass can neither be produced nor destroyed.

Mass balance is the application of the physical principle of **conservation of mass** to the analysis of systems **flux an stocks**.

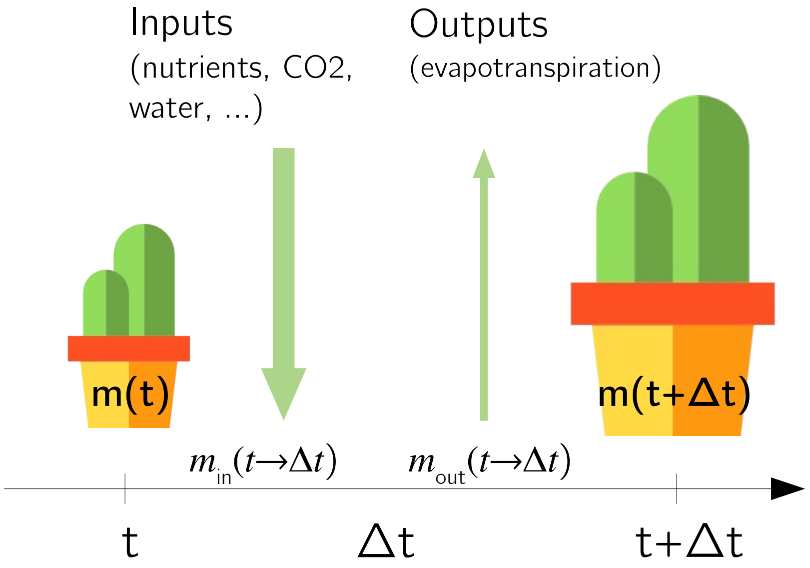
$$\textit{Storage} = \textit{Inputs} - \textit{Outputs}$$

Mass balance

Storage = Inputs - Outputs

time

$$m(t+\Delta t)=m(t)+m_{in}(t\rightarrow\Delta t)-m_{out}(t\rightarrow\Delta t)$$



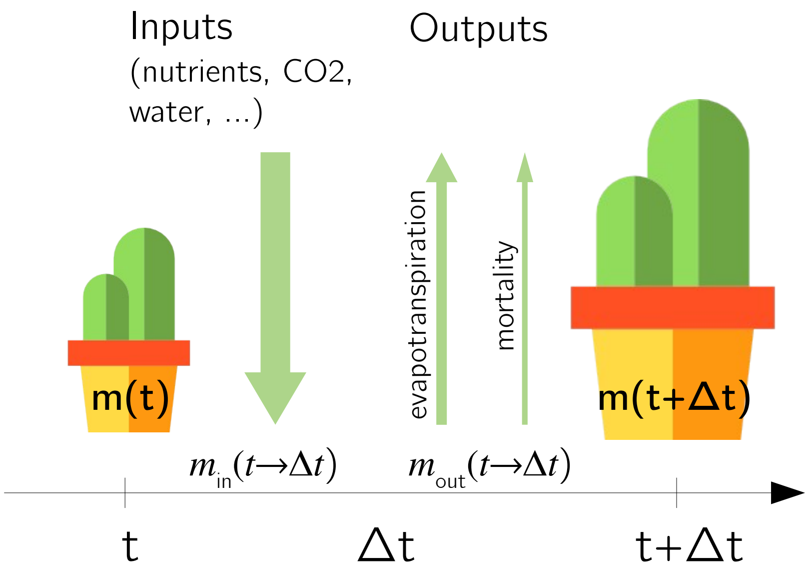
Mass balance

Each term can be decomposed to reflect the diversity of mechanisms / compartments involved

Storage = Inputs - Outputs

time

$$m(t+\Delta t)=m(t)+m_{in}(t\rightarrow\Delta t)-m_{out}(t\rightarrow\Delta t)$$



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Storage = Inputs - Outputs

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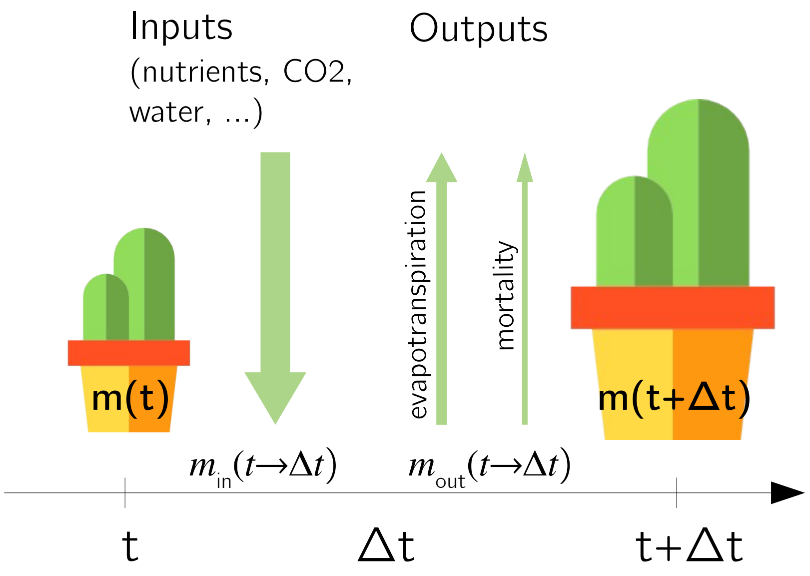
$$m(t+\Delta t)=m(t)+m_{\mathrm{in}}(t\rightarrow\Delta t)-m_{\mathrm{out}}(t\rightarrow\Delta t)$$



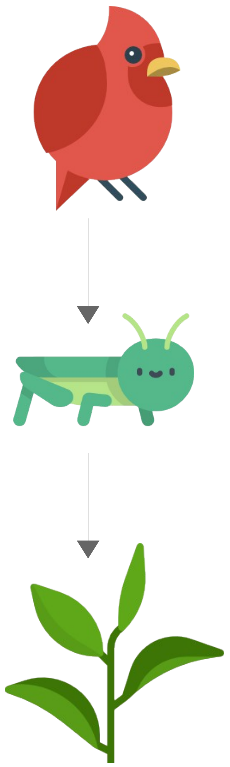
From stocks to flux: **the mass accumulation rate**

$$\frac{m(t+\Delta t)-m(t)}{\Delta t}=\frac{m_{input}(t\rightarrow\Delta t)}{\Delta t}-\frac{m_{output}(t\rightarrow\Delta t)}{\Delta t}$$

$$\frac{\Delta m}{\Delta t}=m_{input}-m_{output}$$

The bio-energetic food-web model

→ Using the principle of mass balance, we can build a general model for trophic interactions



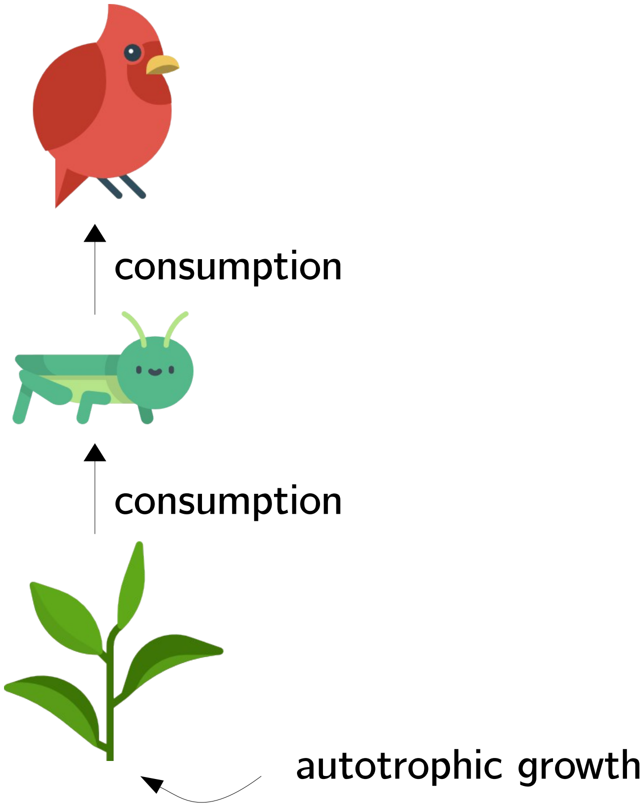
The bio-energetic food-web model

→ Using the principle of mass balance, we can build a general model for trophic interactions

autotrophic growth

The bio-energetic food-web model

→ Using the principle of mass balance, we can build a general model for trophic interactions



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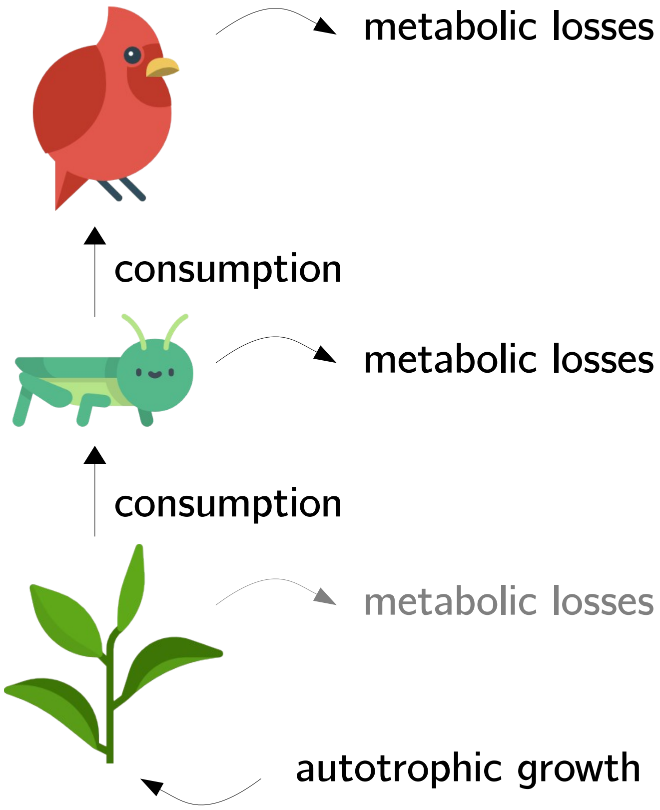
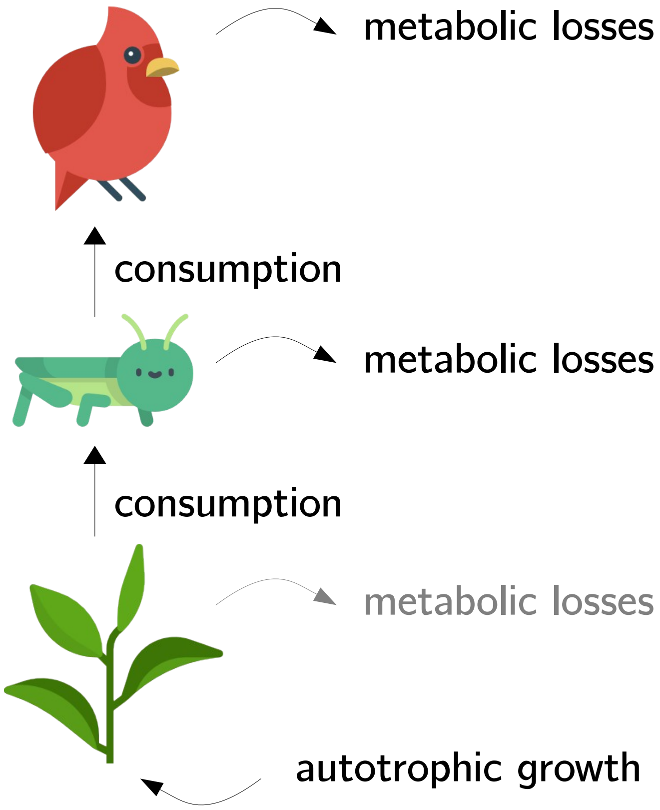


Mass in:
- growth
- gains from consumptions

Mass out:
- loss to consumption
- metabolic losses

The bio-energetic food-web model

→ Using the principle of mass balance, we can build a general model for trophic interactions



Mass in:
- growth
- gains from consumptions

Mass out:
- loss to consumption
- metabolic losses

For each population:

$$\boxed{\Delta B \,/\, \Delta t = G + C_{in} - C_{out} - M}$$

1^{st} term: growth of basal species

$\Delta B / \Delta t = \mathbf{G} + C_{in} - C_{out} - M$

→ Basic equation: $r_i \; G_i(B) \; B_i$

Intrinsic growth rate

Net growth rate

Biomass of the focus species

$$G_i(B) = 1 - \frac{\textit{Sum biomass pop. in competition for the same resources}}{\textit{Carrying capacity}}$$

1^{st} term: growth of basal species

$\Delta B / \Delta t = G + C_{in} - C_{out} - M$

→ General equation: $r_i \, G_i(B) \, B_i$

Intrinsic growth rate

Net growth rate

Biomass of the focus species

Logistic growth

$G_i(B_i) = 1 - B_i / K$

Differential equations solvers in Julia and R

Julia BOX

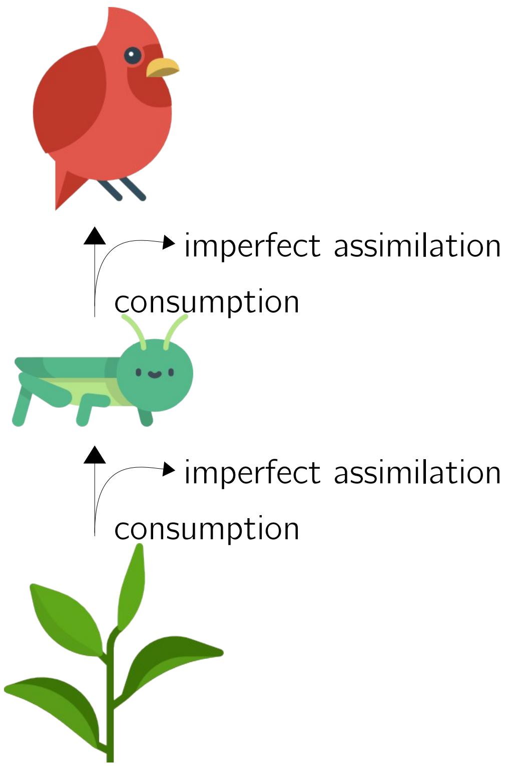
Introducing direct competition

$G_i(B_i) = 1 - (\Sigma_j \alpha_{ij} B_j) / K$

Julia BOX

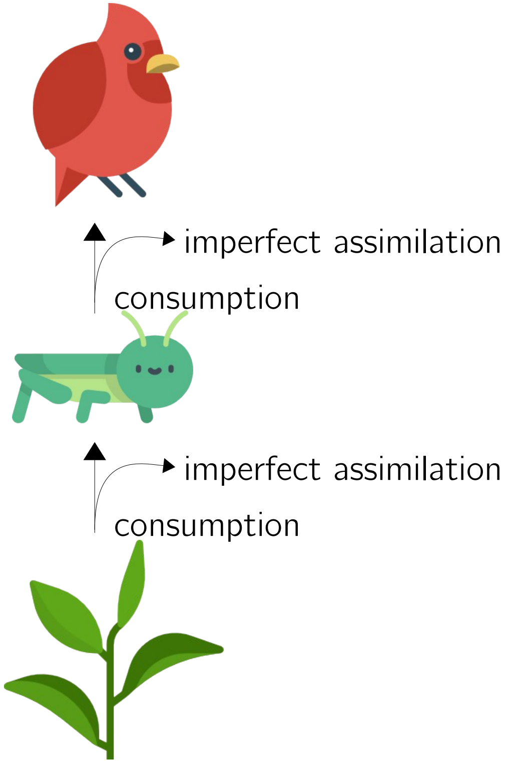
2nd and 3rd terms: consumption

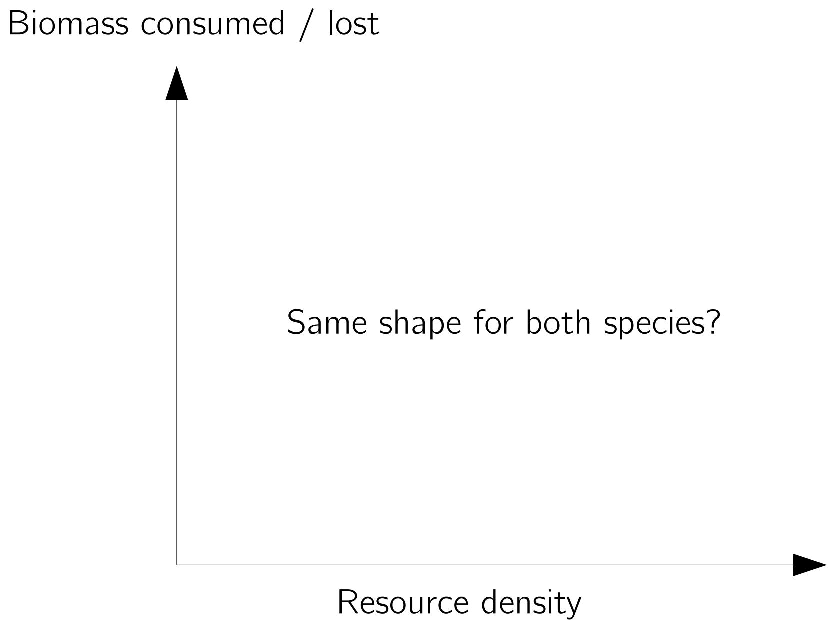
$$\Delta B / \Delta t = G + C_{in} - C_{out} - M$$



$\Delta B / \Delta t = G + C_{in} - C_{out} - M$

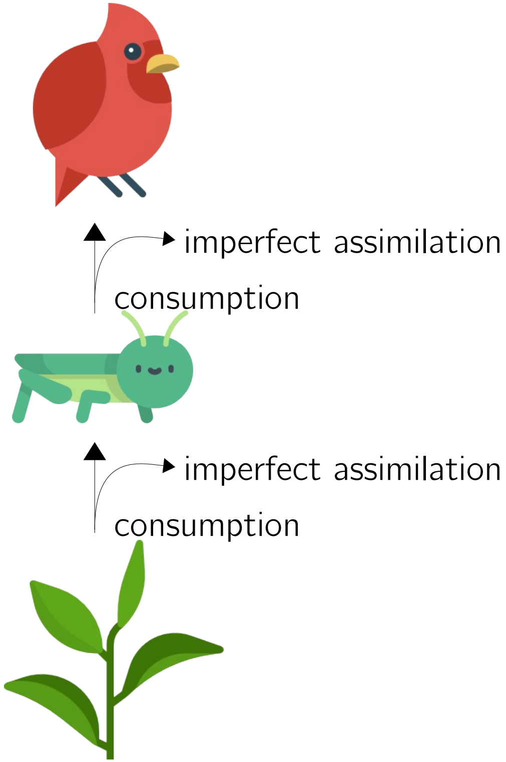
2nd and 3rd terms: consumption

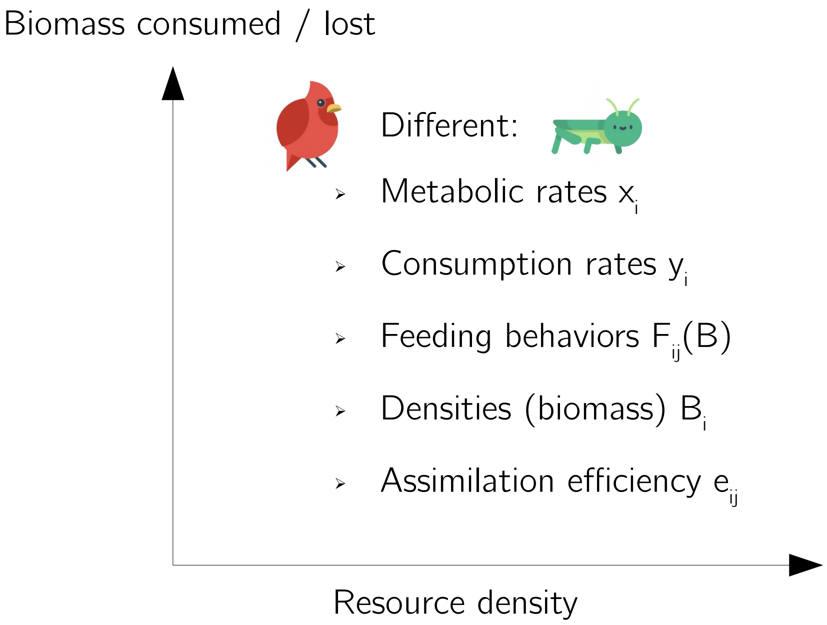




$\Delta B / \Delta t = G + C_{in} - C_{out} - M$

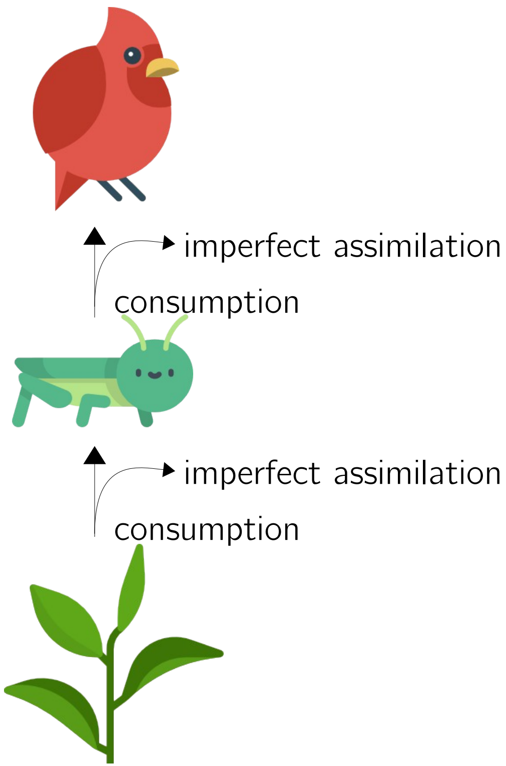
2nd and 3rd terms: consumption





2nd and 3rd terms: consumption

$\Delta B / \Delta t = G + C_{in} - C_{out} - M$



Biomass consumed / lost

Different:

- Metabolic rates x_i
- Consumption rates y_i
- Feeding behaviors $F_{ij}(B)$
- Densities (biomass) B_i
- Assimilation efficiency e_{ij}

Resource density

$$\text{Gain} = \Sigma_{j=pred.}\ x_i\ y_i\ B_i\ F_{ij}$$

$$\text{Loss} = \frac{\Sigma_{j=pred.}\ x_j\ y_j\ B_j\ F_{ji}}{e_{ji}}$$

2^{nd} and 3^{rd} terms: consumption

$\Delta B / \Delta t = G + C_{in} - C_{out} - M$

→ Functional response: intake rate of a consumer as a function of food density

Consumer time budget:
Consumer time = searching resources + handling and consuming

The Components of Predation as Revealed by a Study of Small-Mammal Predation of the European Pine Sawfly[1]
By C. S. Holling
Forest Insect Laboratory, Sault Ste. Marie, Ont.

$$f(R)=\frac{aR^{1+q}}{1+ahR^{1+q}}$$

Max. biomass possibly captured

Time lost searching / consuming preys

a: attack rate
h: handling time
q: holling coef. controls the shape of the curve

Holling type II and III functional responses

Compare type II and type III functional response and the associated resource mortality rates.

Julia BOX

$\Delta B / \Delta t = G + C_{in} - C_{out} - M$

2nd and 3rd terms: consumption

→ Multi-species functional response

Vol. 111, No. 978 The American Naturalist March–April 1977

THE KINETICS OF FUNCTIONAL RESPONSE

LESLIE A. REAL

Department of Zoology, University of Michigan, Ann Arbor, Michigan 48109

$$F_{ij}(B_j) = \frac{a_{ij} B_j^{1+q}}{1 + \sum_{k=resources} a_{ik} B_k^{1+q}} \quad \longleftrightarrow \quad F_{ij}(B_j) = \frac{\alpha_{ij} B_j^{1+q}}{B0_i + \sum_{k=resources} \alpha_{ik} B_k^{1+q}}$$

Multi-species functional response

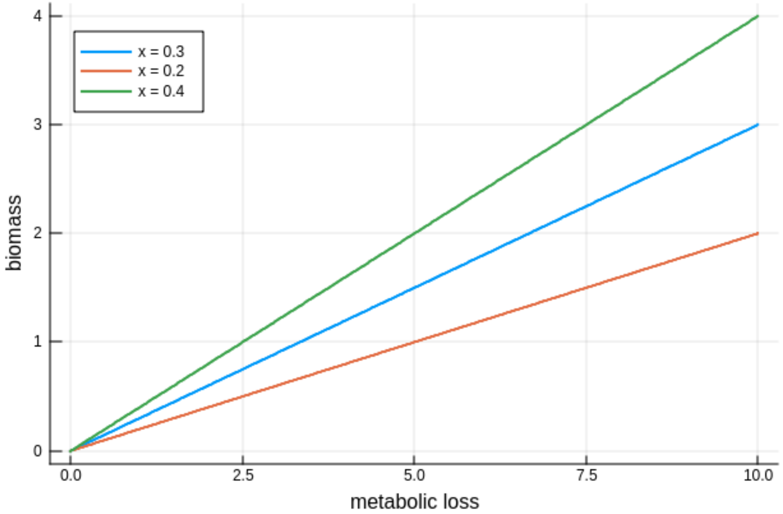
Implementation and analysis of the multi-species functional response

Julia BOX

$\Delta B / \Delta t = G + C_{in} - C_{out} - M$

4^{th} term: metabolic losses

→ $M = x_i B_i$



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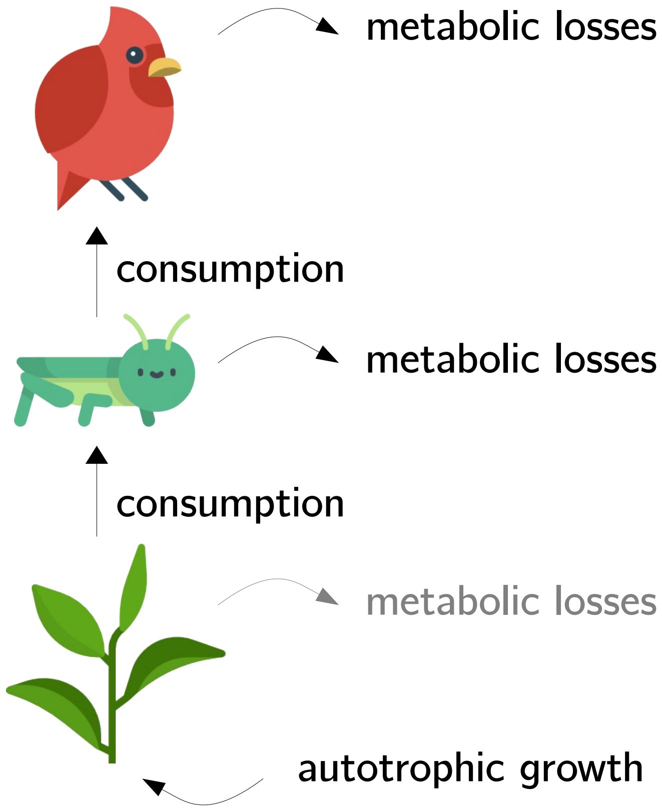
→ Using the principle of mass balance, we can build a general model for trophic interactions



$$\boxed{\Delta B / \Delta t = G + C_{in} - C_{out} - M}$$

$$\frac{\Delta B_i}{\Delta t} = r_i G_i(B) B_i + \sum_{j=resources} x_i y_i F_{ij} B_i - \sum_{j=consumers} \frac{x_j y_j F_{ji} B_j}{e_{ij}} - x_i B_i$$

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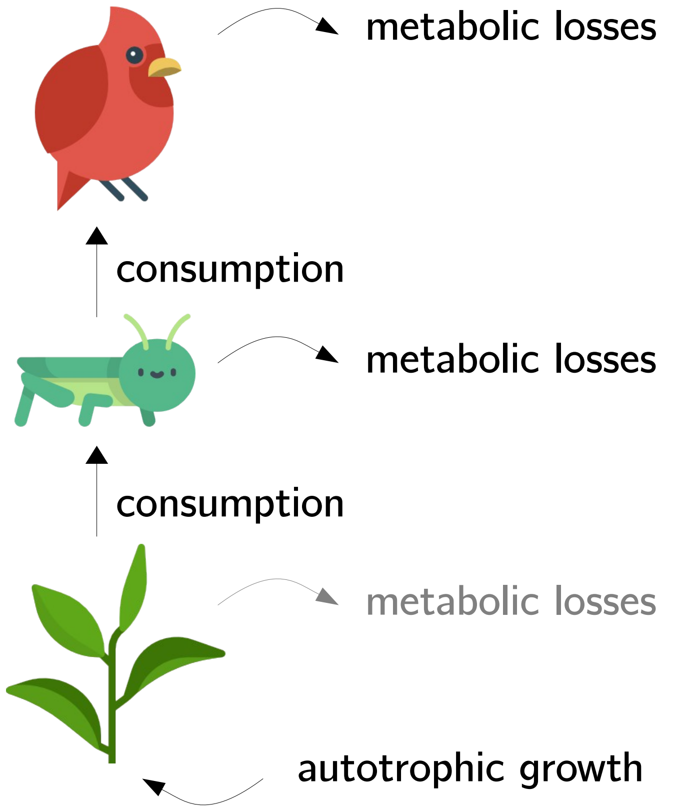
→ Using the principle of mass balance, we can build a general model for trophic interactions



$$\frac{\Delta B_i}{\Delta t} = r_i G_i(B) B_i + \sum_{j=resources} x_i y_i F_{ij} B_i - \sum_{j=consumers} \frac{x_j y_j F_{ji} B_j}{e_{ij}} - x_i B_i$$

Vol. 139, No. 6 The American Naturalist June 1992

BODY SIZE AND CONSUMER-RESOURCE DYNAMICS

P. YODZIS* AND S. INNES†

*Department of Zoology, University of Guelph, Guelph, Ontario N1G 2W1, Canada;
†Freshwater Institute, 501 University Crescent, Winnipeg, Manitoba R3T 2N6, Canada

Submitted September 5, 1990; Revised June 13, 1991; Accepted July 25, 1991

CHAPTER 2

HOMAGE TO YODZIS AND INNES 1992: SCALING UP FEEDING-BASED POPULATION DYNAMICS TO COMPLEX ECOLOGICAL NETWORKS

RICHARD J. WILLIAMS*

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PO Box 10106, Berkeley, CA 94709, USA
**Corresponding author:Phone: 1-510-848-9850, E-mail: rich@sfsu.edu*

ULRICH BROSE

Pacific Ecoinformatics and Computational Ecology Lab, PO Box 10106, Berkeley, CA 94709, USA; Darmstadt Technical University, Department of Biology, Schnittspahnstr, 10, 64287 Darmstadt, Germany

NEO D. MARTINEZ

Pacific Ecoinformatics and Computational Ecology Lab, PO Box 10106, Berkeley, CA 94709, USA

Rooney, N., McCann, K. S., & Noakes, D. L. (Eds.). (2006). *From energetics to ecosystems: the dynamics and structure of ecological systems* (Vol. 1).

Allometric scaling of biological rates

→ Almost all organisms biological rates vary predictably with body sizes

Whole organism $$Y = Y_0 M^{0.75}$$

Mass specific $$rate = a\,M^{-0.25}$$

Ecology, 85(7), 2004, pp. 1771–1789
© 2004 by the Ecological Society of America

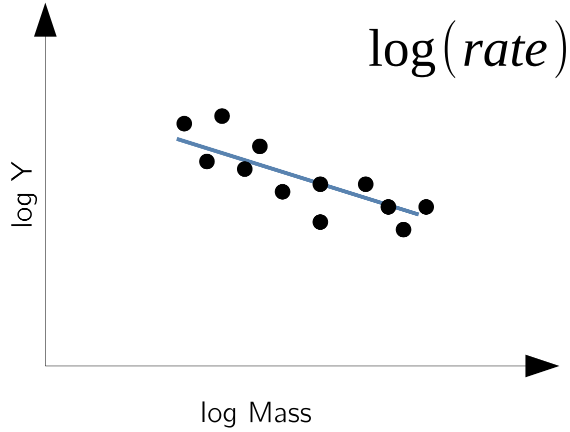
TOWARD A METABOLIC THEORY OF ECOLOGY

JAMES H. BROWN,[1,2,4]
with JAMES F. GILLOOLY,[1] ANDREW P. ALLEN,[1] VAN M. SAVAGE,[2,3] AND GEOFFREY B. WEST[2,3]

[1]*Department of Biology, University of New Mexico, Albuquerque, New Mexico 87131 USA*
[2]*Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, New Mexico 87501 USA*
[3]*Theoretical Division, MS B285, Los Alamos National Laboratory, Los Alamos, New Mexico 87545 USA*

$$\log(rate) = intercept - 0.25\log(M)$$

Oxygen consumption,
resource consumption,
heat loss, …



Choosing parameters values

→ Empirically measured parameters

Maximum consumption rate

Use the data from Yodzis and Innes (1992) paper to find y_i value

Julia BOX

→ Sensitivity analysis: how the uncertainty in the output of a mathematical model can be divided and allocated to different sources of uncertainty in its inputs (model parameters).

1. Define output (e.g. total biomass)
2. Fix all parameters values except for one (e.g. y_i)
3. Run the model
4. Calculate the percentage change in both output (%B) and input (%y)
5. The model sensitivity to this parameter is %B / %y

Choosing parameters values

Sensitivity analysis

Perform a sensitivity analysis: how a food web total biomass varies when changing herbivores assimilation efficiency

→ Should we use this type of sensitivity analysis on non-linear dynamical systems?

Choosing parameters values

Sensitivity analysis

Perform a sensitivity analysis: how a food web total biomass varies when changing herbivores assimilation efficiency

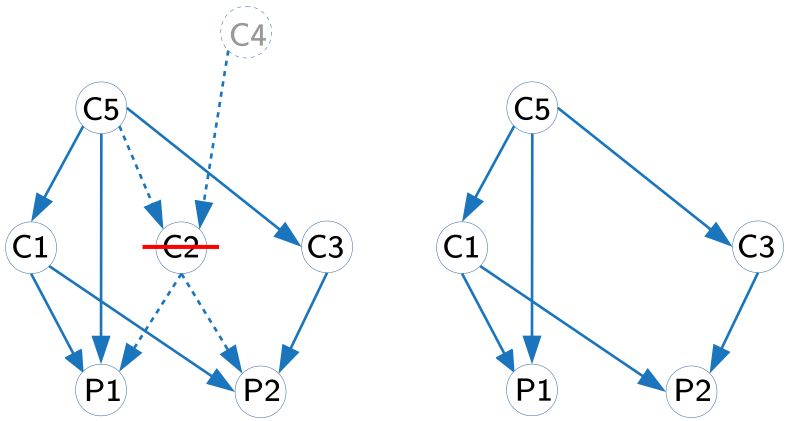
→ Should we use this type of sensitivity analysis on non-linear dynamical systems?

- Variance-based sensitivity analysis: decomposes the variance of the output of the model into fractions which can be attributed to inputs (or sets of inputs).
- Parameter optimization: finding the best set of parameters to optimize output (robustness, temporal stability...)
- Visual inspection: are the shape of the focus relationship sensitive to changes in parameters?

Application: Robustness analysis

→ Simulate primary extinction and analyze secondary loss of species

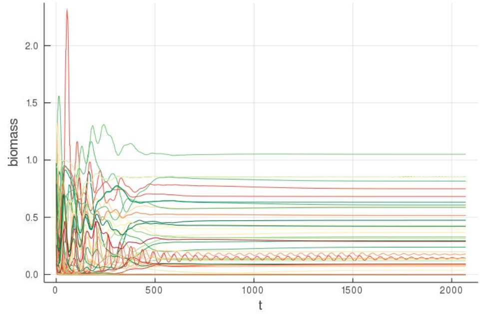
Topological



Only bottom-up secondary extinctions

Dynamical

Meso-predator release after extinction of a top-predator can lead to overexploitation



Bottom-up **and** Top-down secondary extinctions

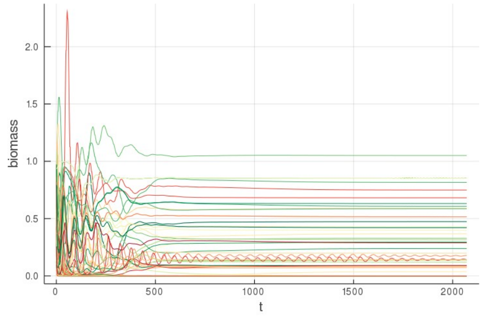
Application: Robustness analysis

→ Simulate primary extinction and analyze secondary loss of species

1. Simulate the food web dynamics without primary extinctions to remove transient dynamics
2. Choose a deletion sequence (highest to lowest body mass, generality, ...)
3. Remove the first species of the sequence
4. Simulate the food web dynamics and record secondary extinctions
5. Repeat 3 and 4 until end of sequence
6. Calculate R50: number of primary extinctions necessary to remove 50% of the species

Dynamical

Meso-predator release after extinction of a top-predator can lead to overexploitation



Bottom-up **and** Top-down secundary extinctions

Robustness analysis

Perform a robustness analysis using the `BioEnergeticFoodWebs` model

Julia BOX

Brief review and discussion

Ecology Letters / Volume 13, Issue 2

Full Access

Understanding food-web persistence from local to global scales

Daniel B. Stouffer, Jordi Bascompte

Letter | Published: 20 December 2007

Allometric degree distributions facilitate food-web stability

Sonja B. Otto, Björn C. Rall & Ulrich Brose

Research article

Complex food webs prevent competitive exclusion among producer species

Ulrich Brose

Published: 22 July 2008 | https://doi.org/10.1098/rspb.2008.0718

Oikos / Volume 117, Issue 2

Full Access

Food-web connectance and predator interference dampen the paradox of enrichment

Björn C. Rall, Christian Guill, Ulrich Brose

Robustness to secondary extinctions: Comparing trait-based sequential deletions in static and dynamic food webs

Alva Curtsdotter [a], Amrei Binzer [b], Ulrich Brose [b], Francisco de Castro [c], Bo Ebenman [a], Anna Eklöf [d], Jens O. Riede [b], Aaron Thierry [e, f], Björn C. Rall [b]

Effects of network and dynamical model structure on species persistence in large model food webs

Authors | Authors and affiliations

Richard J. Williams

Complexity Increases Predictability in Allometrically Constrained Food Webs

Alison C. Iles* and Mark Novak†

Department of Integrative Biology, Oregon State University, Corvallis, Oregon 97331

How Structured Is the Entangled Bank? The Surprisingly Simple Organization of Multiplex Ecological Networks Leads to Increased Persistence and Resilience

Sonia Kéfi, Vincent Miele, Evie A. Wieters, Sergio A. Navarrete, Eric L. Berlow

Compartmentalization increases food-web persistence

Daniel B. Stouffer and Jordi Bascompte

PNAS March 1, 2011 108 (9) 3648-3652; https://doi.org/10.1073/pnas.1014353108

Edited* by Robert May, University of Oxford, Oxford, United Kingdom, and approved January 7, 2011 (received for review September 24, 2010)

Animal diversity and ecosystem functioning in dynamic food webs

Florian D. Schneider, Ulrich Brose, Björn C. Rall & Christian Guill

Brief review and discussion

→ Theoretical work
→ Mostly used to study food webs stability/resistance/resilience

What are the model limits? Why is it not used to do empirical studies, like predicting the future of a community under different scenarios?

Ecology Letters / Volume 13, Issue 2
Full Access
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Letter | Published: 20 December 2007
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