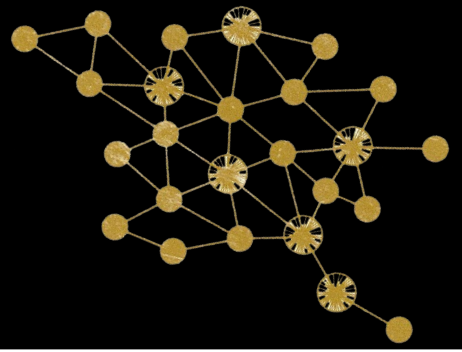
Multilayer ecological networks

Sonia Kéfi



BioDICée Lab

SANTA FE INSTITUTE

cnrs

isem

Institut des Sciences de l'Evolution-Montpellier

Black out : ce 28 septembre 2003, l'Italie plonge dans l'obscurité

Le pays ayant abandonné le nucléaire en 1987 est alors jugé trop dépendant de ses importations électriques. Depuis, il a misé sur les énergies renouvelables

Temps de lecture estimé : 1 minute

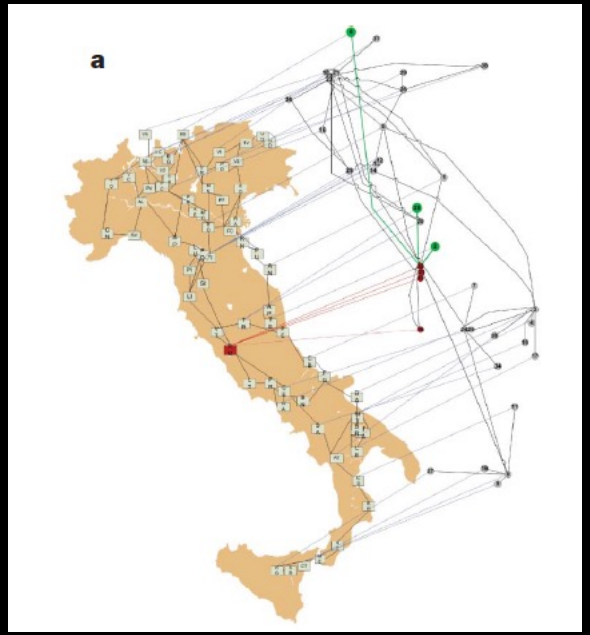
Publié le 12 décembre 2016 à 17:48 - Maj 24 octobre 2021 à 20:49

Blackout en Italie en 2003 - Sipa Press

Buldyrev et al. 2010, Nature

Interdependent networks

power network

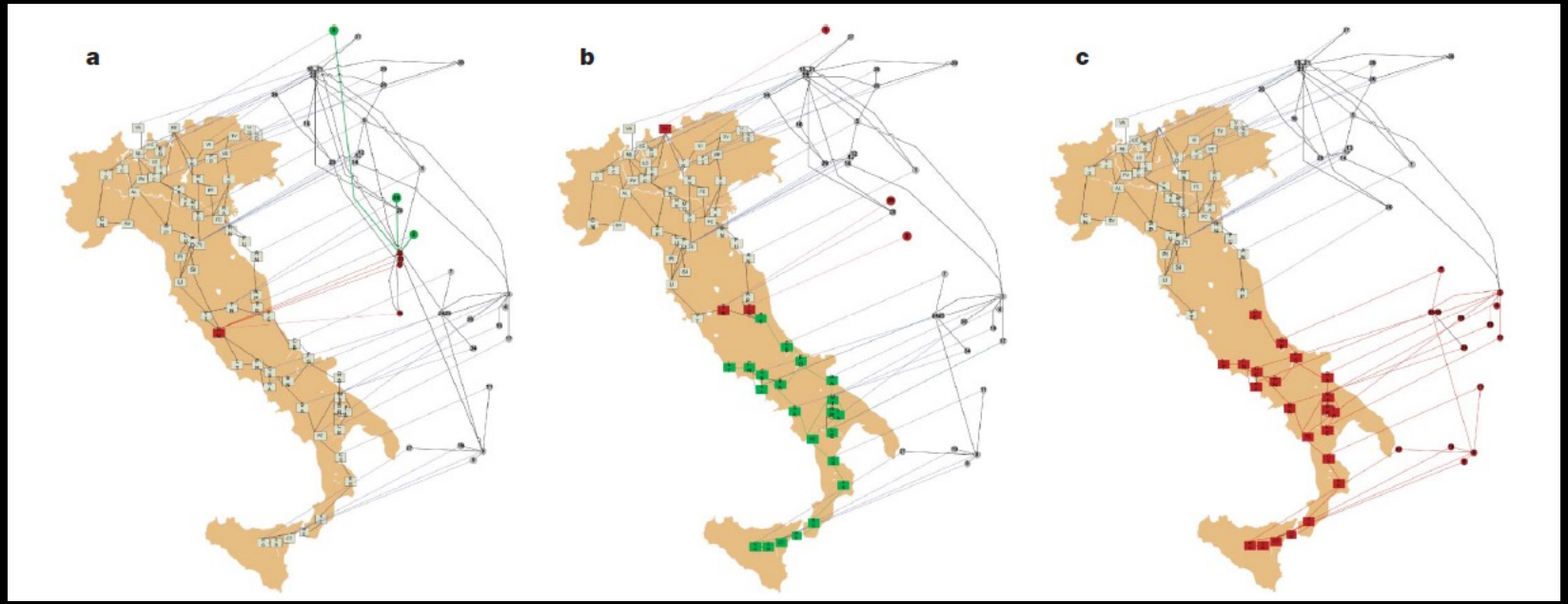


Internet network

One power station removed (red)
→ nodes removed from internet network (red)
→ Isolated power station removed next (green)

Buldyrev et al. 2010, Nature

power network



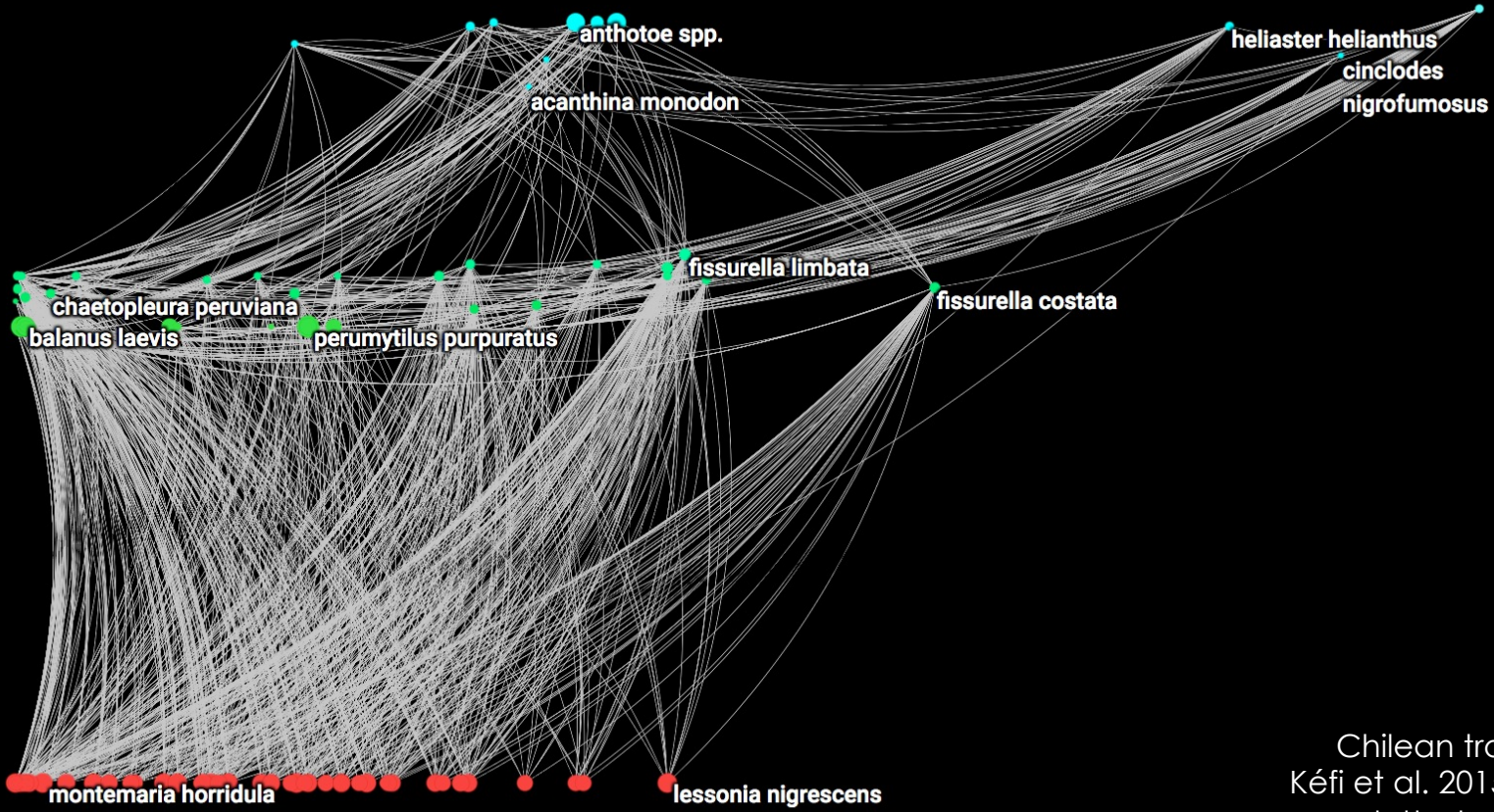
Internet network

Buldyrev et al. 2010, Nature

Modern systems are interdependent networks
→ Cascades of failures possible

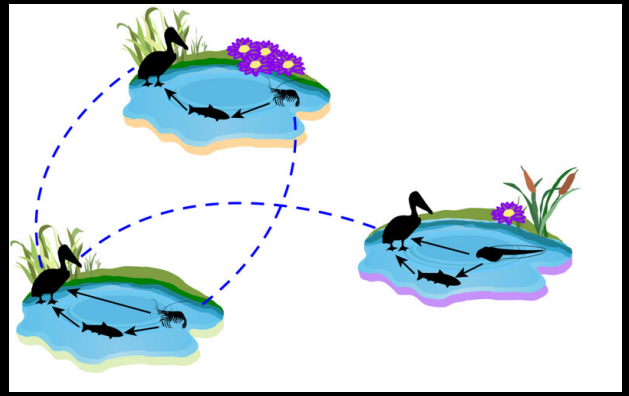
Buldyrev et al. 2010, Nature

What about ecological networks?

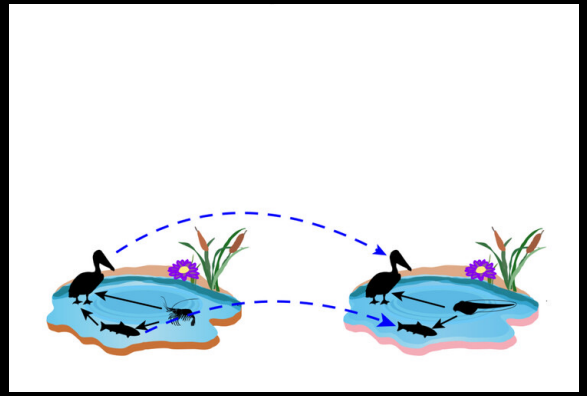


Chilean trophic web
Kéfi et al. 2015, Ecology
plotted with mappr

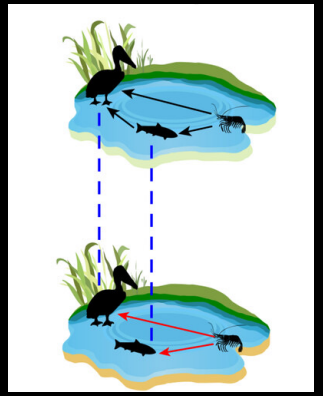
Spatial



Temporal



Multi-interactions



Frydman et al. 2023, MEE

multilayer ecological networks

Pilosof et al. 2017, NEE

PHYSICAL REVIEW X 3, 041022 (2013)

Mathematical Formulation of Multilayer Networks

Manlio De Domenico,[1] Albert Solé-Ribalta,[1] Emanuele Cozzo,[2] Mikko Kivelä,[3] Yamir Moreno,[2,4,5] Mason A. Porter,[6] Sergio Gómez,[1] and Alex Arenas[1]

Journal of Complex Networks (2014) **2**, 203–271
doi:10.1093/comnet/cnu016
Advance Access publication on 14 July 2014

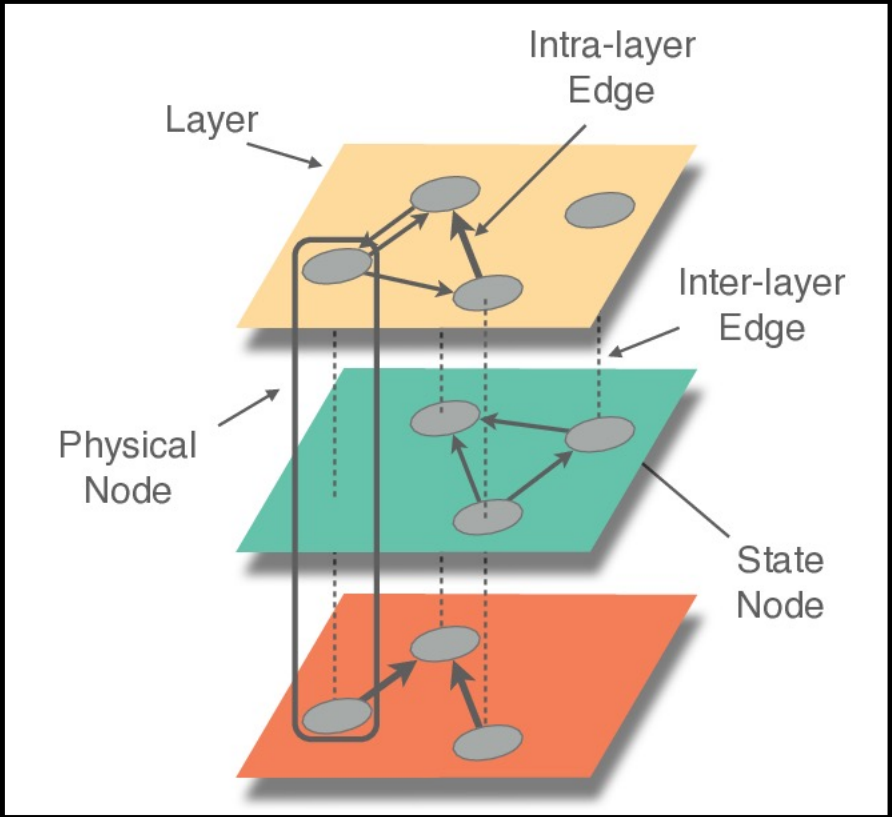
Multilayer networks

MIKKO KIVELÄ
Oxford Centre for Industrial and Applied Mathematics, Mathematical Institute, University of Oxford, Oxford OX2 6GG, UK

The structure and dynamics of multilayer networks

S. Boccaletti[a,b,*], G. Bianconi[c], R. Criado[d,e], C.I. del Genio[f,g,h], J. Gómez-Gardeñes[i], M. Romance[d,e], I. Sendiña-Nadal[j,e], Z. Wang[k,l], M. Zanin[m,n]

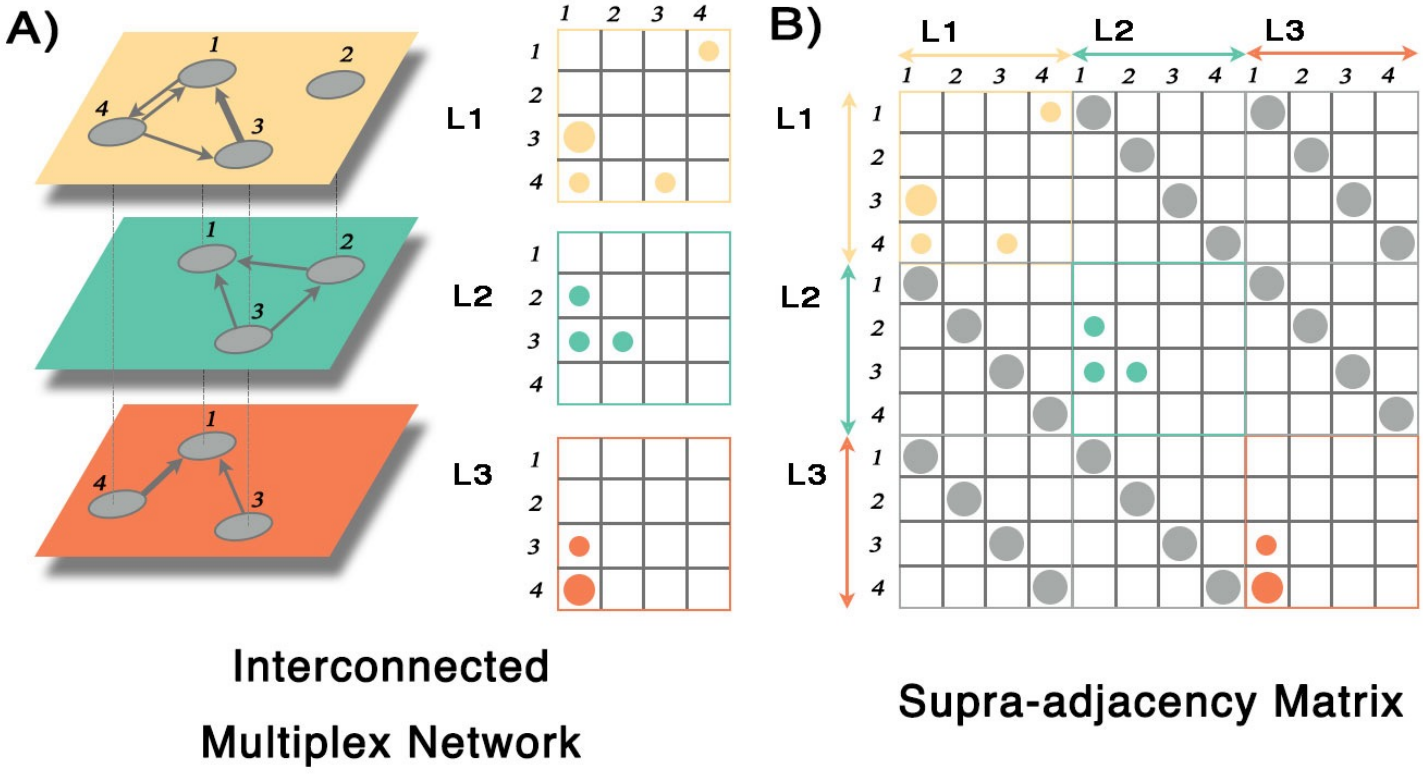
De Domenico et al. 2013, PRE
Kivela et al. 2014, J. Complex Net
Boccaletti et al. 2014, Physics Reports



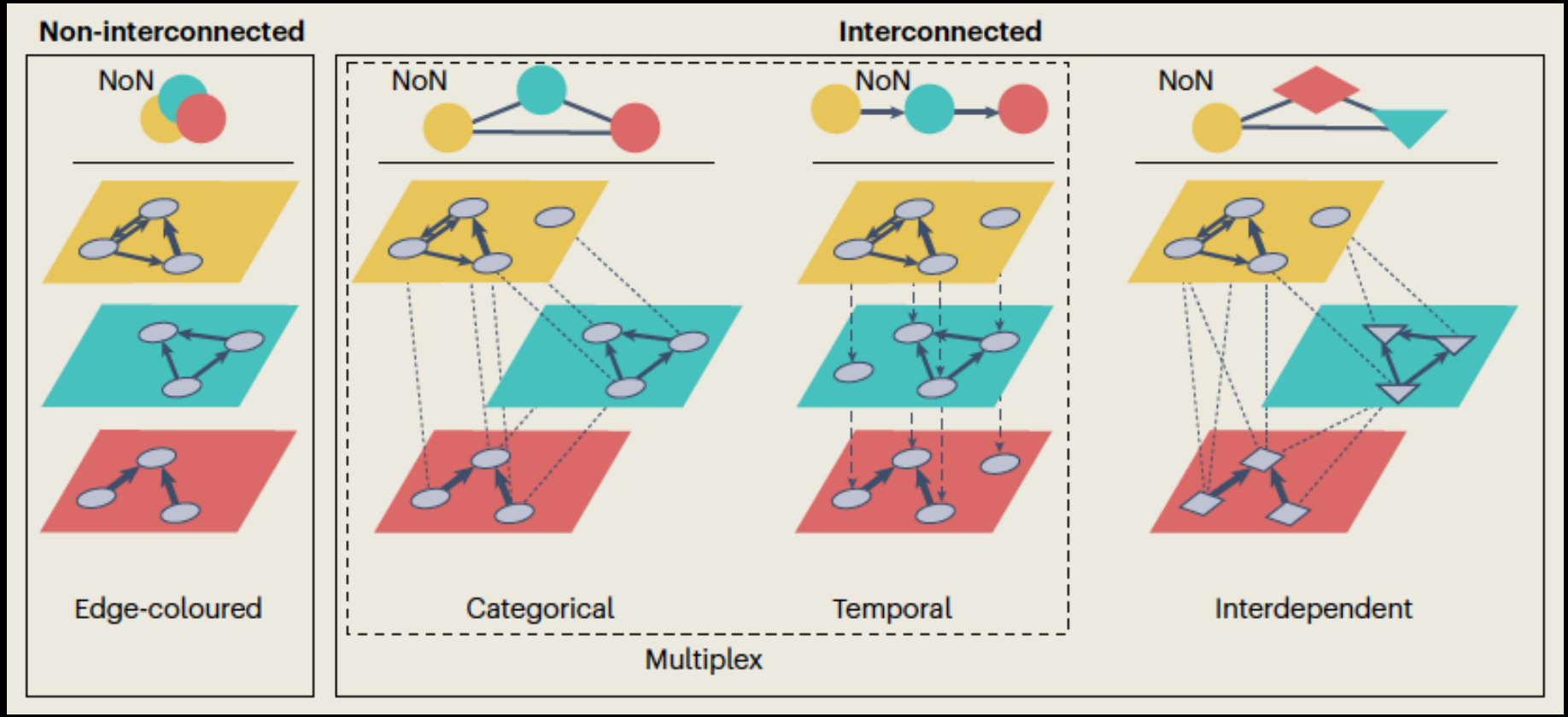
4 components:

- layers (patches, interaction types, time points)
- nodes (physical vs state)
- intralayer links
- **interlayer links**

https://github.com/manlius/muxViz

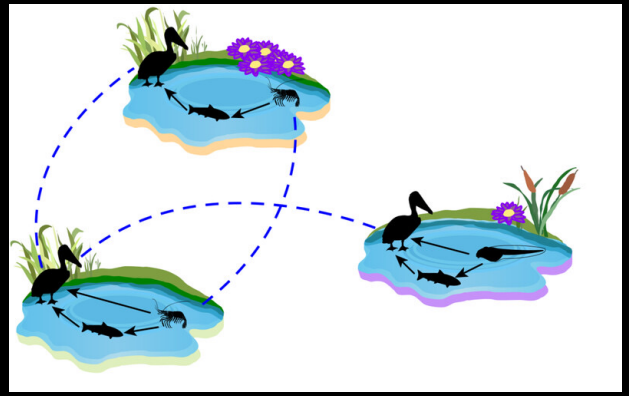


https://github.com/manlius/muxViz

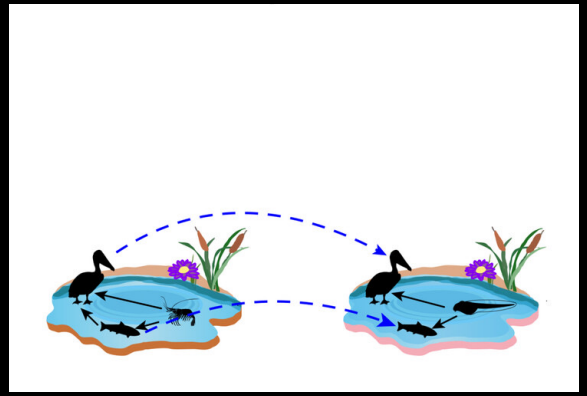


De Domenico 2023, Nature Physics
https://github.com/manlius/muxViz

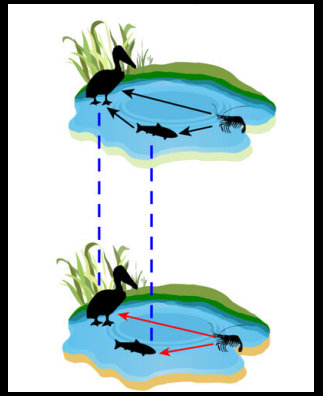
Spatial



Temporal



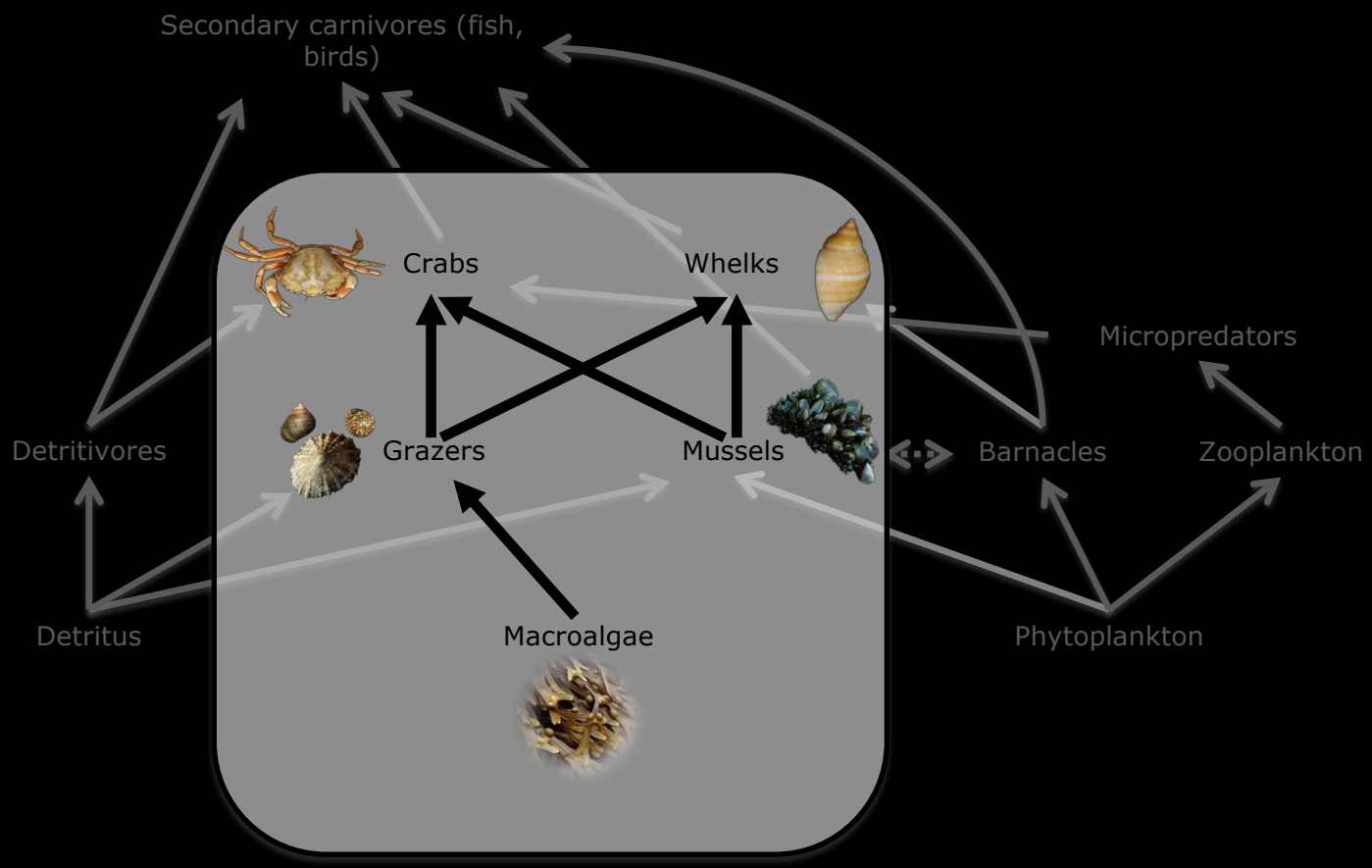
Multi-interactions



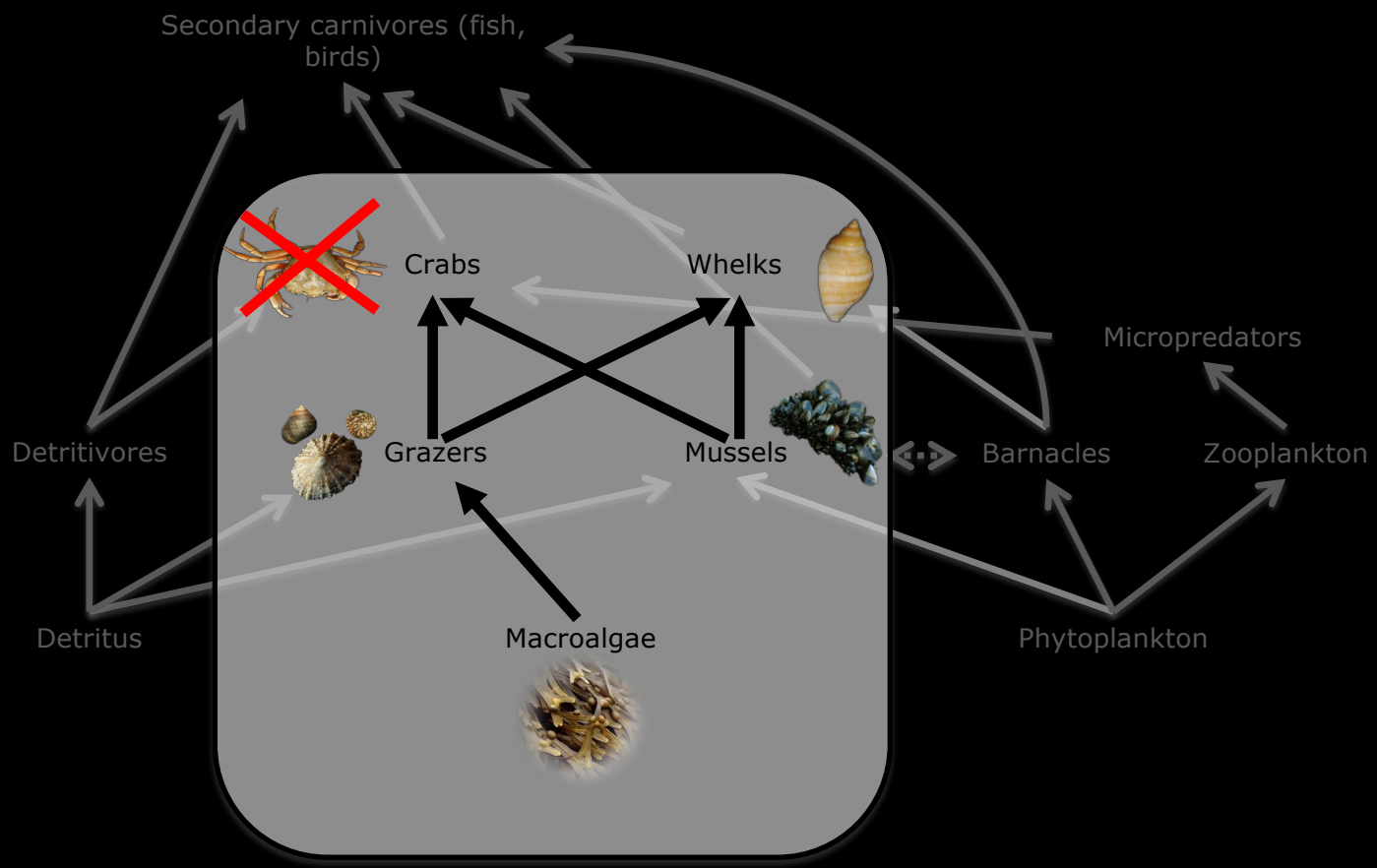
Frydman et al. 2023, MEE

multi-interaction networks

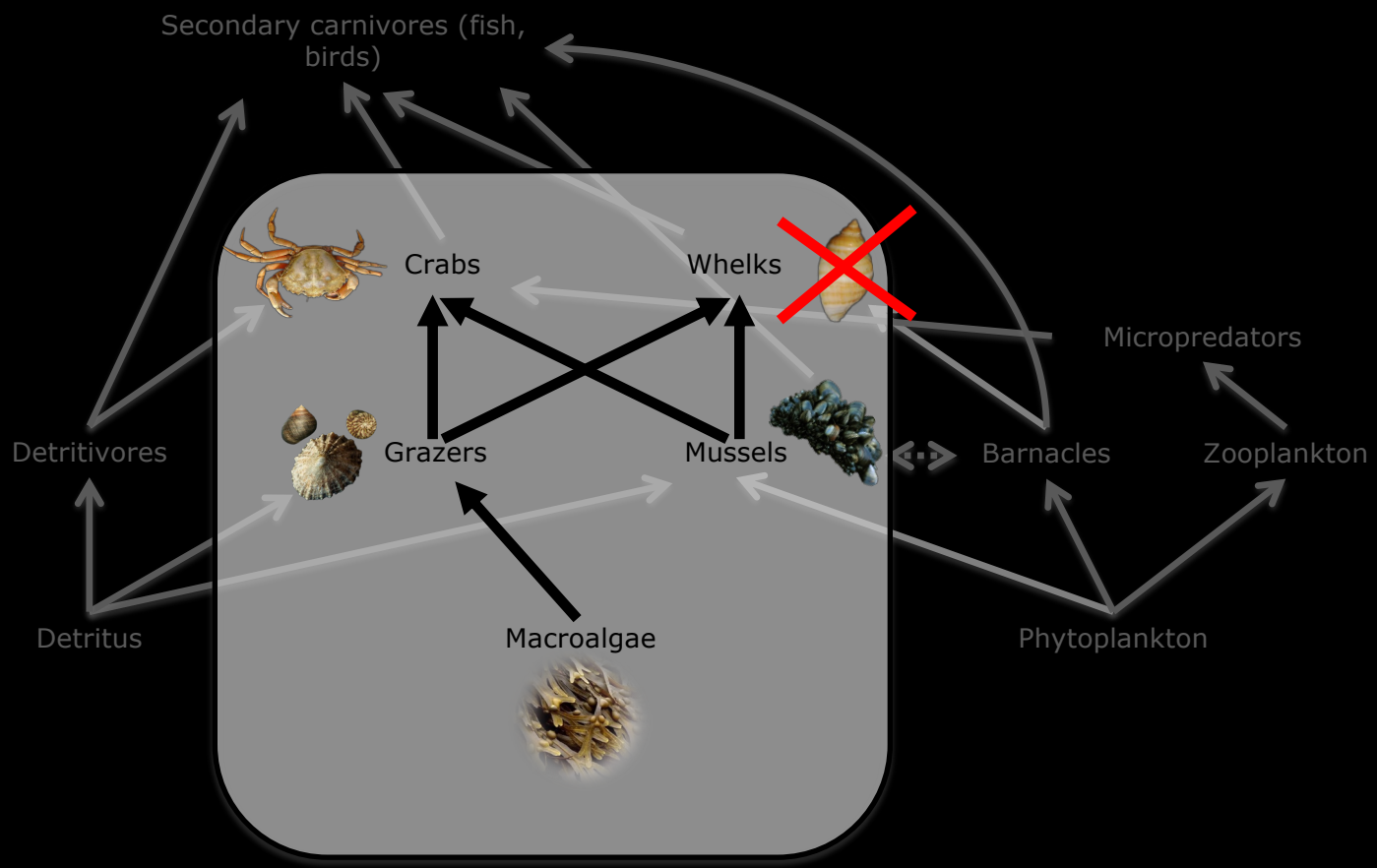
@Ian Donohue



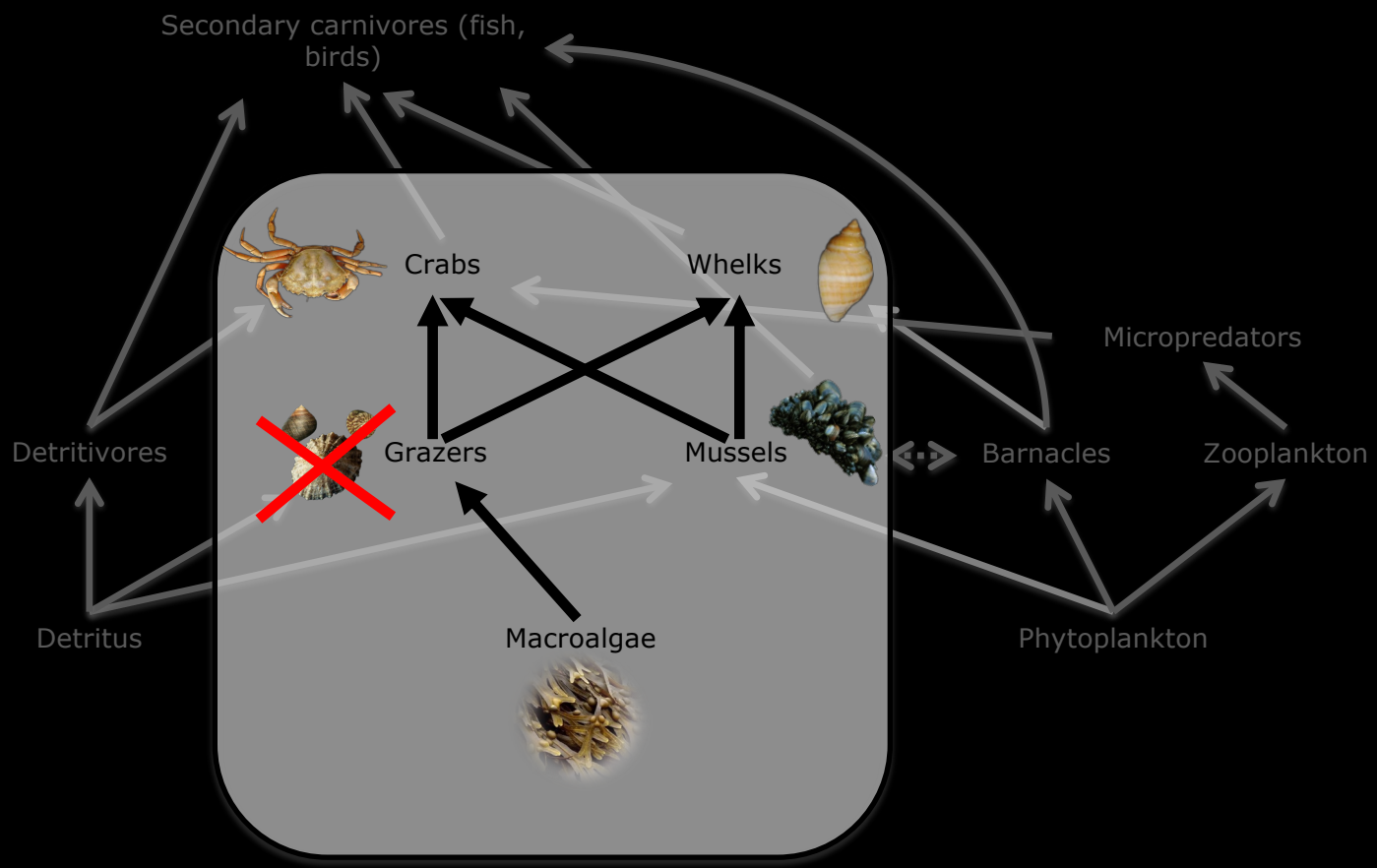
Donohue *et al.* 2017, GCB



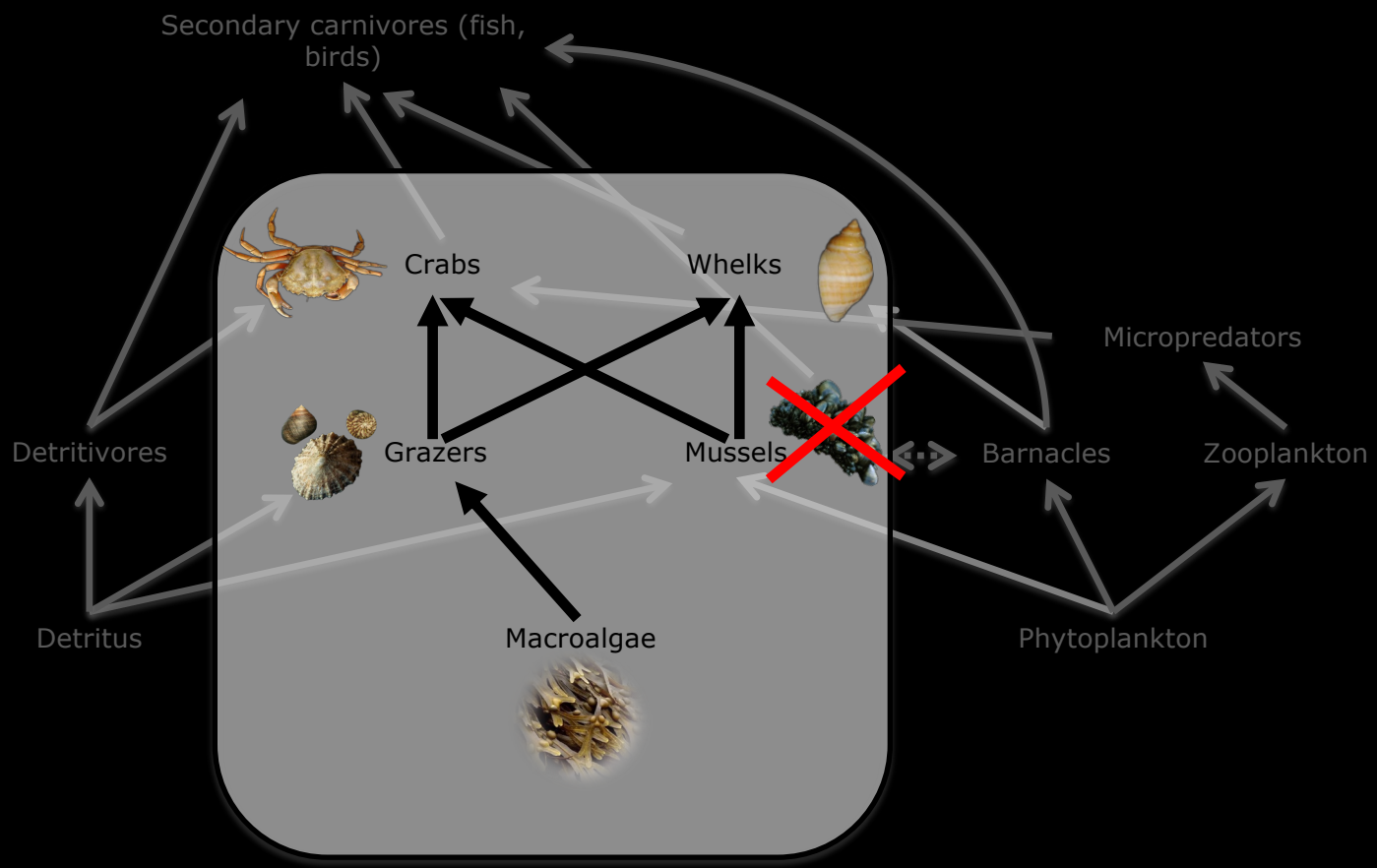
Donohue *et al.* 2017, GCB



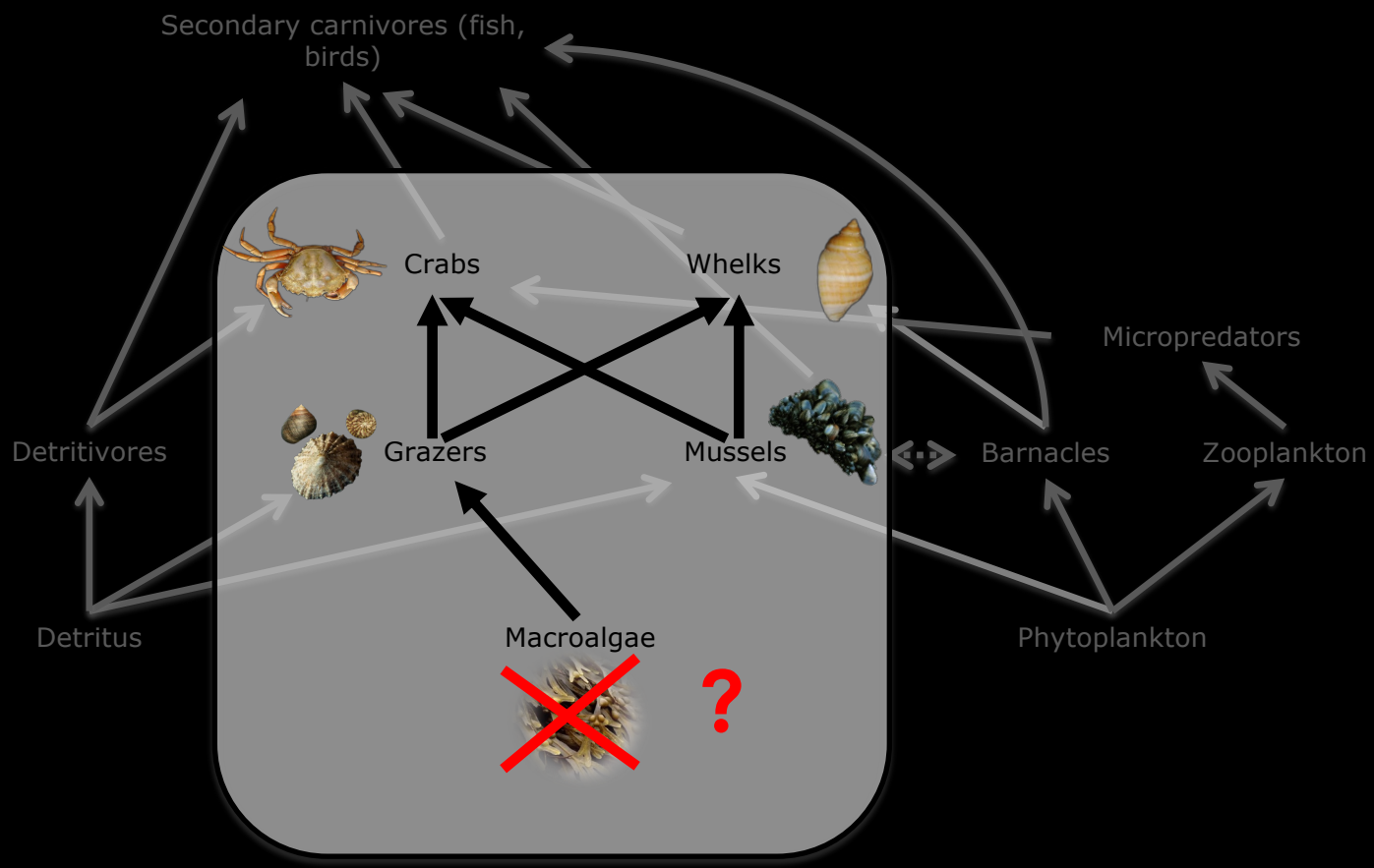
Donohue *et al.* 2017, GCB



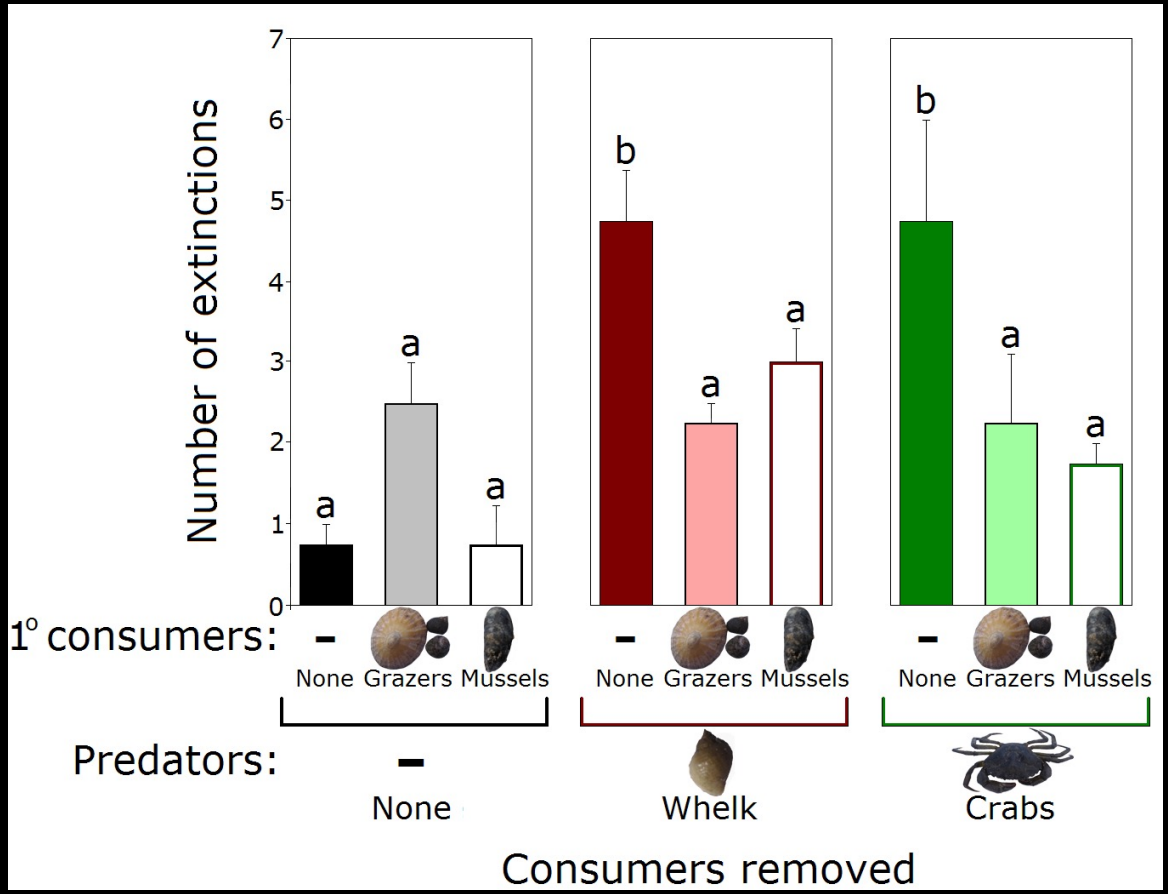
Donohue *et al.* 2017, GCB



Donohue *et al.* 2017, GCB



Donohue *et al.* 2017, GCB


Number of extinctions
7
6
5
4
3
2
1
0
a
a
a
b
a
a
b
a
a
1° consumers:
–
None
Grazers
Mussels
–
None
Grazers
Mussels
–
None
Grazers
Mussels
Predators:
–
None
Whelk
Crabs
Consumers removed

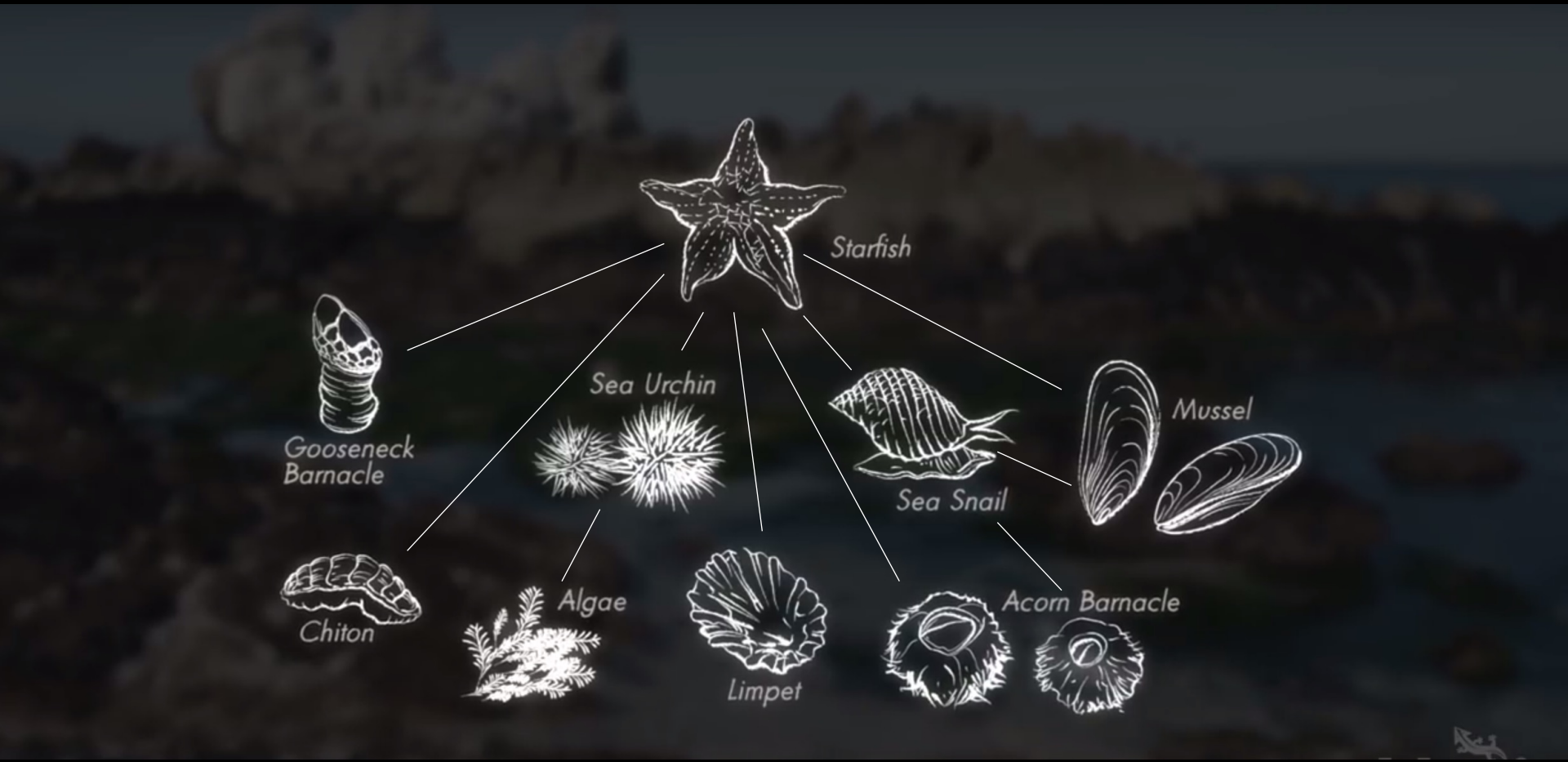
1/3 of the macroalgal taxa lost following the removal of either predator species

Donohue *et al.* 2017, GCB

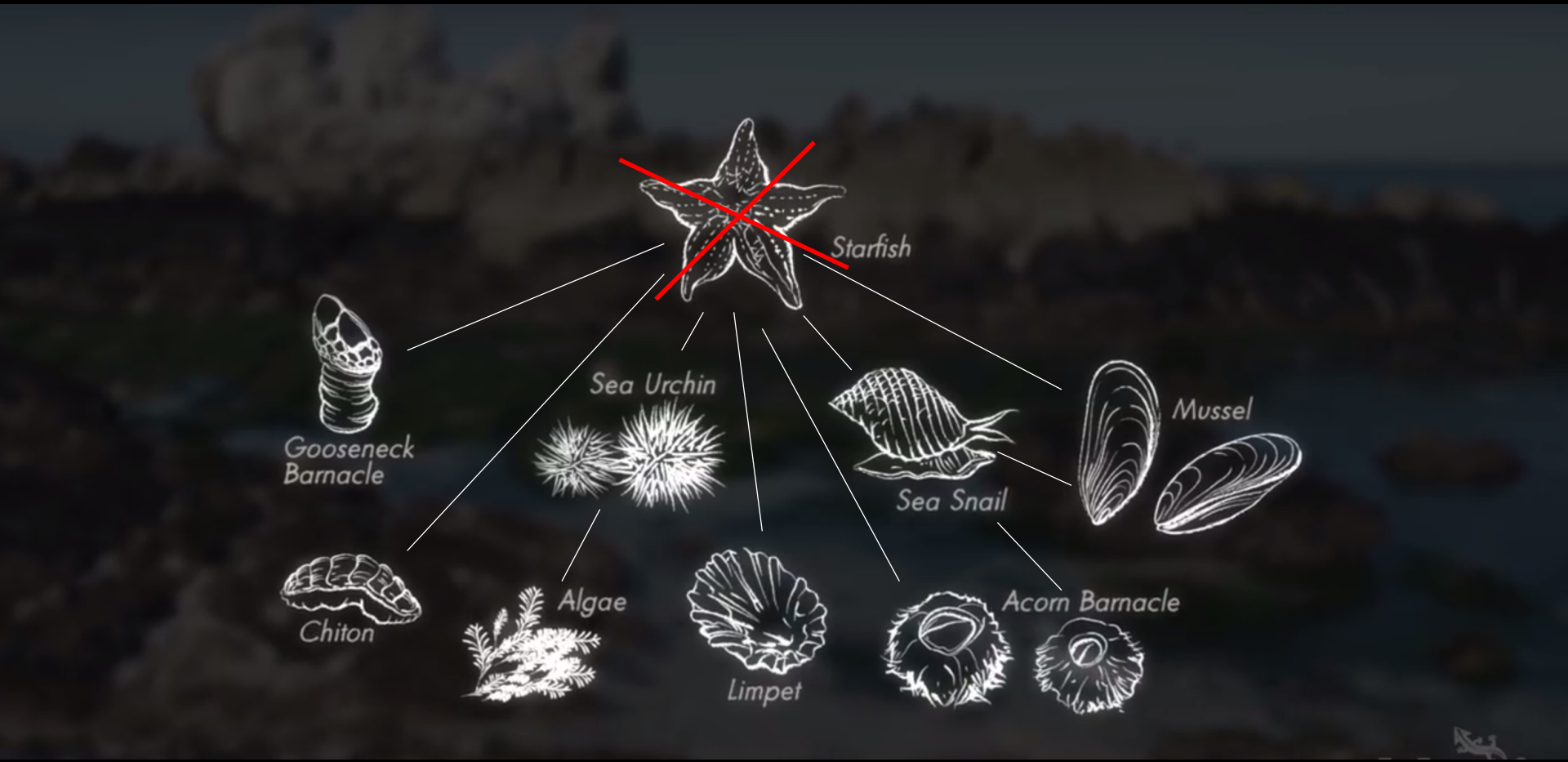
an order of magnitude greater than in models

e.g. Ebenman *et al.* 2006
Eklöf and Ebenman 2006
Quince *et al.* 2005
Petchey et al. 2008

Robert Paine
Credit: Alamy. Telegraph obituary

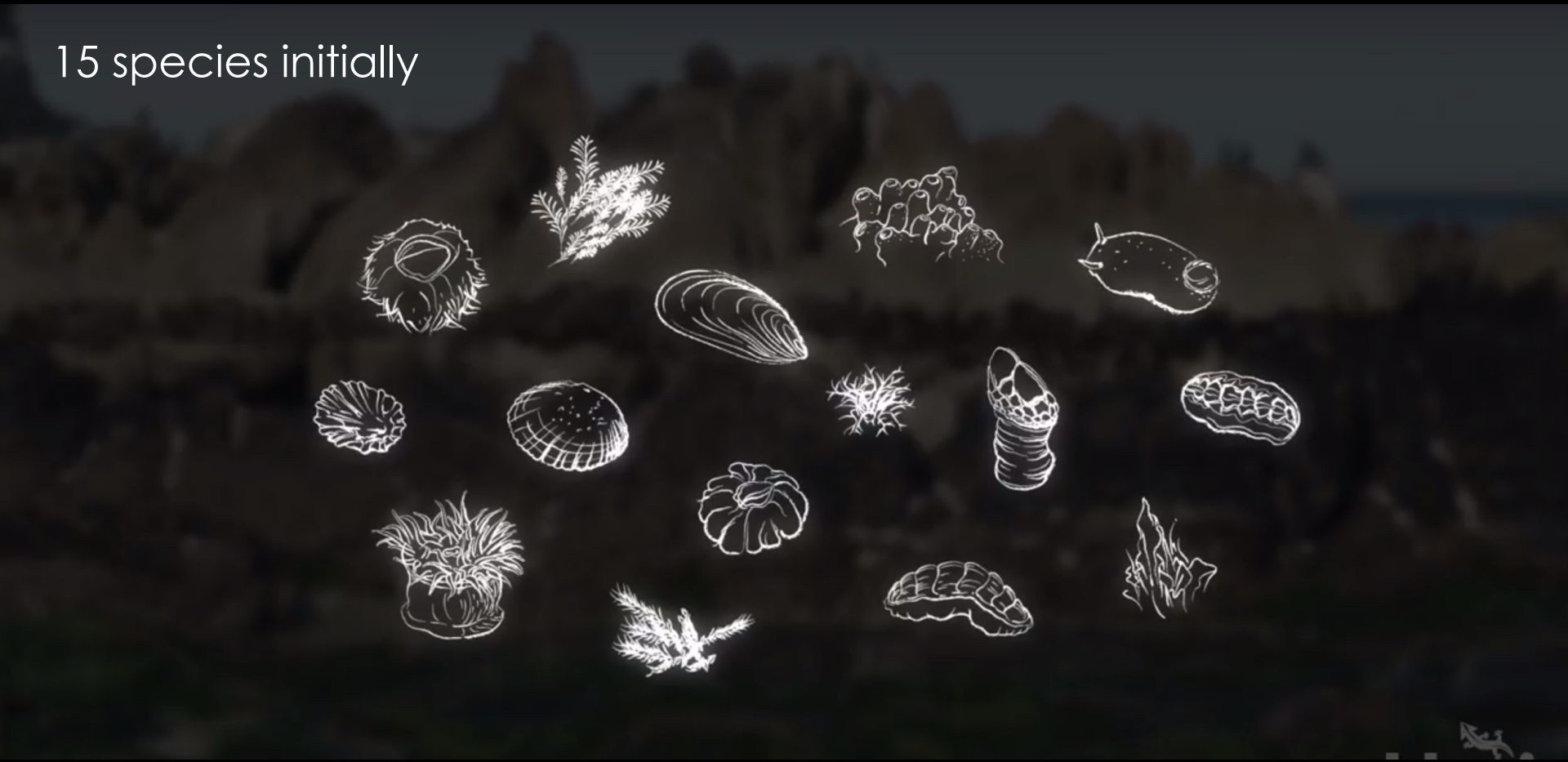


hhmi biointeractive
« Some Animals Are More Equal than Others: Keystone Species and Trophic Cascades »



hhmi biointeractive
« Some Animals Are More Equal than Others: Keystone Species and Trophic Cascades »

15 species initially



hhmi biointeractive
« Some Animals Are More Equal than Others: Keystone Species and Trophic Cascades »

7 species after 1,5 year

hhmi biointeractive
« Some Animals Are More Equal than Others: Keystone Species and Trophic Cascades »

1 species after 7 years

hhmi biointeractive
« Some Animals Are More Equal than Others: Keystone Species and Trophic Cascades »

→ puzzling discrepancy between observations and the prediction of most theoretical models

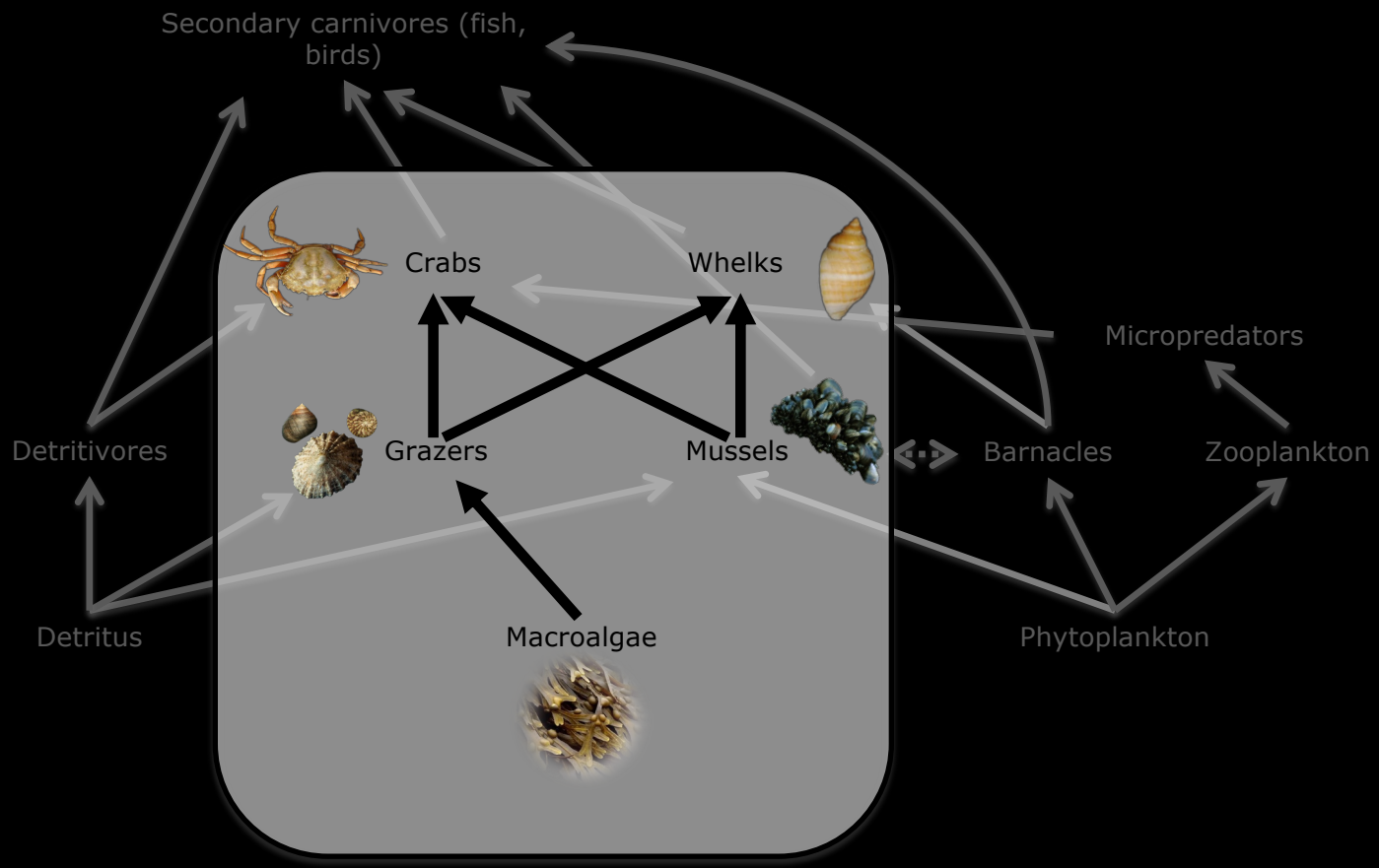
feeding interactions

@Evie Wieters

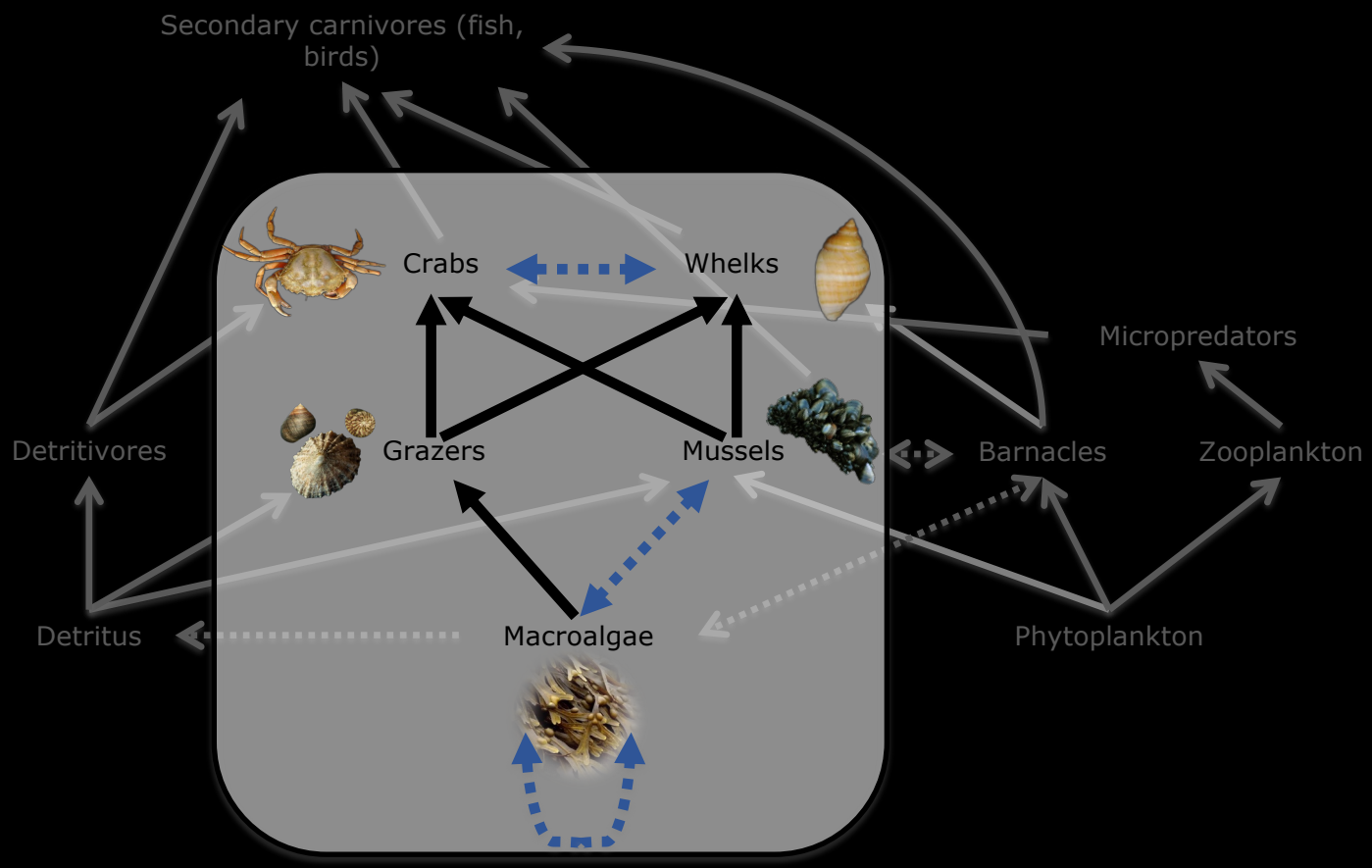
@Evie Wieters

@Evie Wieters

@Evie Wieters



Donohue *et al.* 2017, GCB



Donohue *et al.* 2017, GCB

dynamical model

[bioenergetic consumer-resource model]

$$\frac{\mathrm{d}B_i}{\mathrm{dt}} = r_i\left(1 - \frac{B_i}{K_i}\right)B_i + eB_i\sum_j F_{ij} - \sum_k F_{ki}B_k - x_iB_i$$

Yodzis and Innes 1992
Brose et al. 2005, 2006
Stouffer et al. 2011

primary producers

non-primary producers

$$\frac{\mathrm{d}B_i}{\mathrm{dt}} = r_i\left(1-\frac{B_i}{K_i}\right)B_i + eB_i\sum_j F_{ij} - \sum_k F_{ki}B_k - x_iB_i$$

growth

consumption (eats)

consumption (is eaten)

metabolism

Yodzis and Innes 1992
Brose et al. 2005, 2006
Stouffer et al. 2011

$$\frac{\mathrm{d}B_i}{\mathrm{dt}} = \underbrace{r_i\left(1-\frac{B_i}{K_i}\right)B_i}_{\text{growth}} + \underbrace{eB_i\sum_j F_{ij}}_{\text{consumption (eats)}} - \underbrace{\sum_k F_{ki}B_k}_{\text{consumption (is eaten)}} \underbrace{- x_iB_i}_{\text{metabolism}}$$

$$F_{ij} = \frac{w_i b_{ij} B_j^{1+q}}{1 + w_i h_i \sum_k b_{ik} B_k^{1+q}}$$

Yodzis and Innes 1992
Brose *et al.* 2005, 2006
Stouffer *et al.* 2011

dynamical model

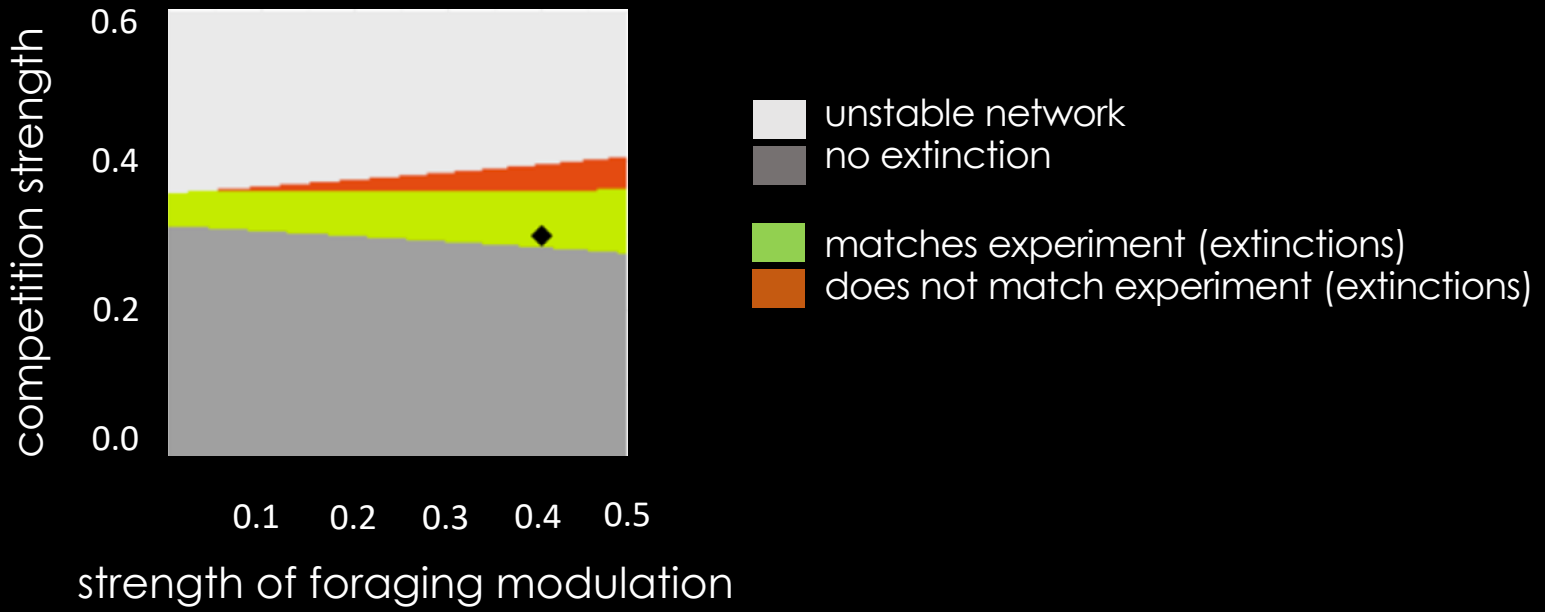
[bioenergetic consumer-resource model]

+ non-trophic interactions

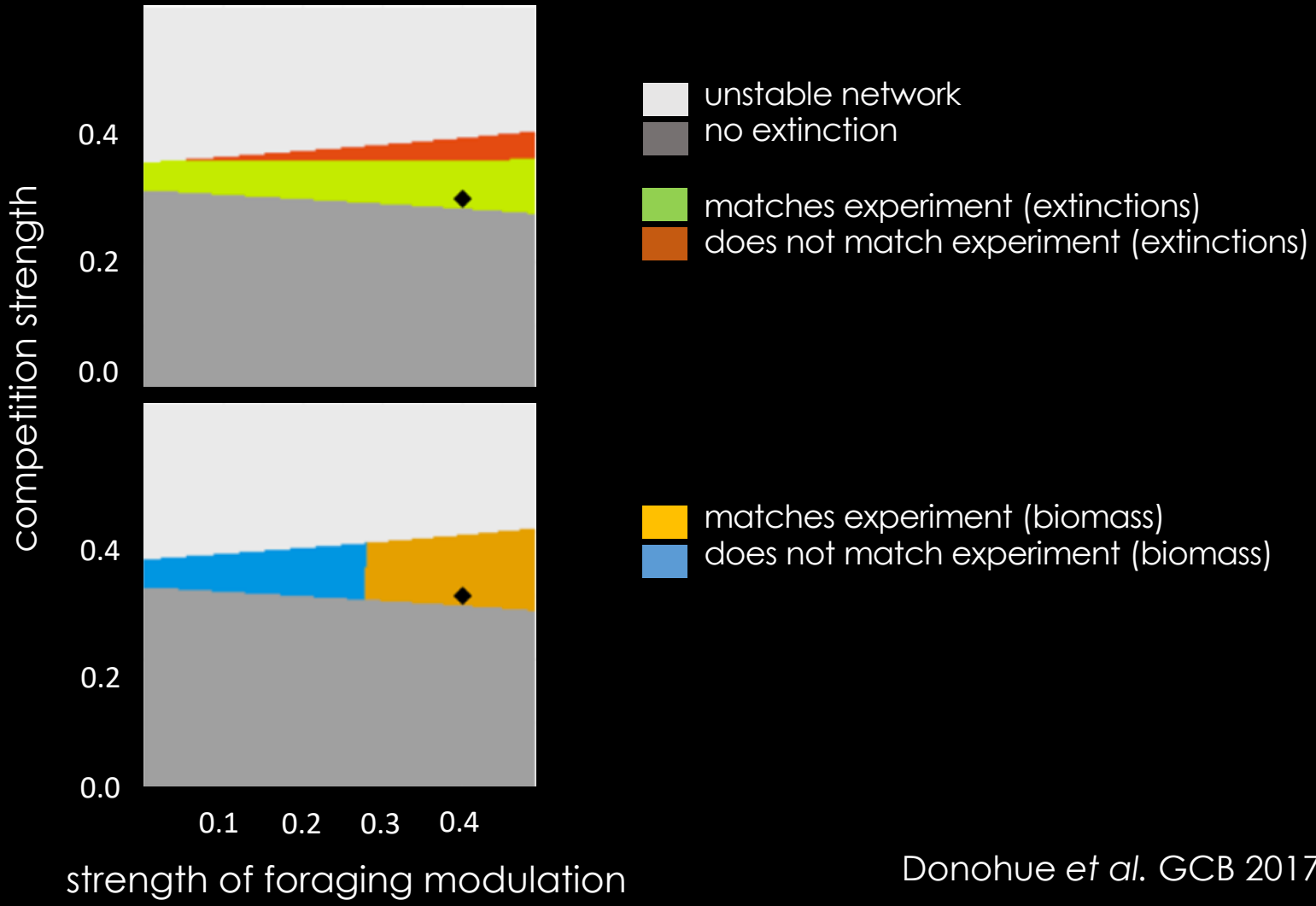
competition for space

foraging modulation

Kéfi *et al.* 2012 Eco. Lett.

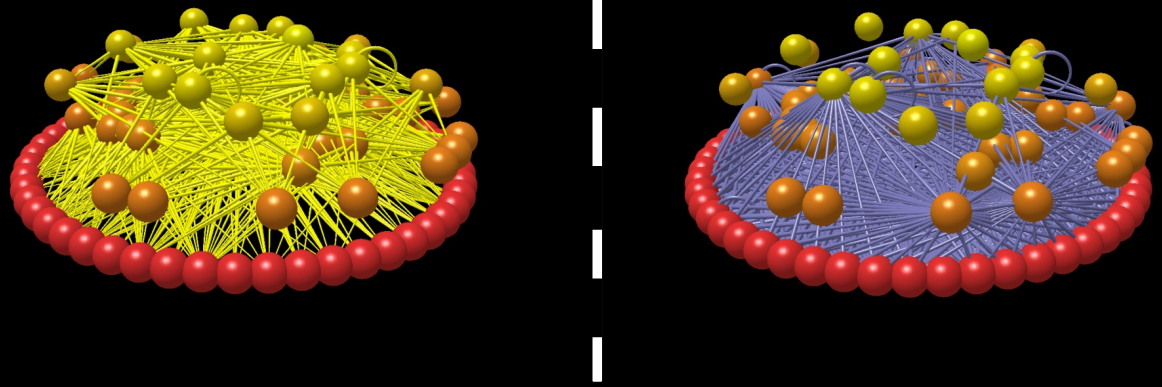


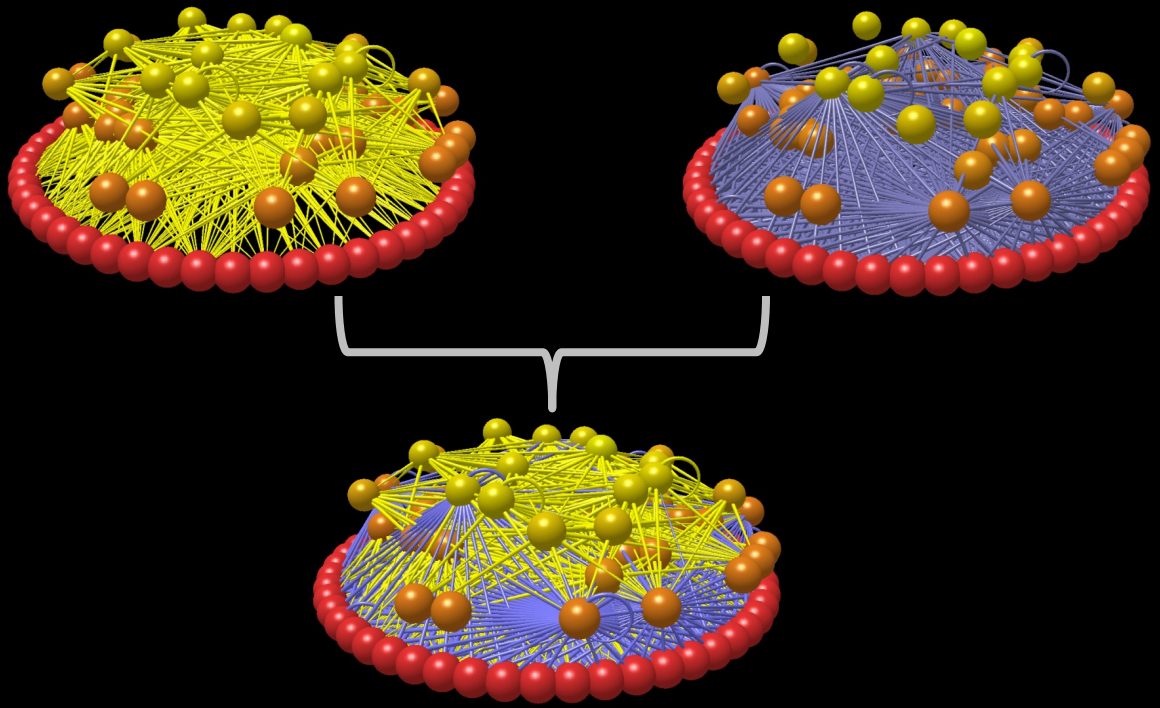
Donohue *et al.* GCB 2017

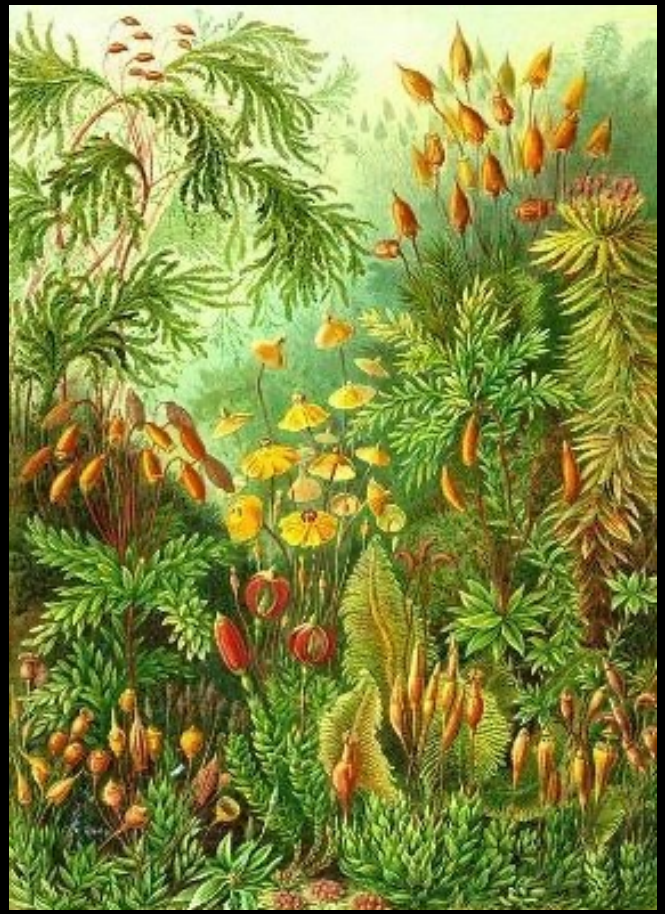


Donohue *et al.* GCB 2017

The diversity of interaction types is needed to reproduce the results of the experiments







« So dependent on each other in so complex a manner »

Charles Darwin, 1859

DARWIN'S "ENTANGLED BANK" (HAECKEL, CIRCA 1904)

A need for **integrating** several interaction types in ecological network studies

Berlow et al. 2004
Ings et al. 2009
Olff et al. 2009
Fontaine et al. 2011
Kéfi et al. 2012

How does the diversity of interaction types affect functioning?

dynamical model

[bioenergetic consumer-resource model]

+ non-trophic interactions

Competition for space
Predator interference
Recruitment facilitation
Refuge provisioning
Positive and negative effects on survival

Kéfi *et al.* 2012 Eco. Lett.

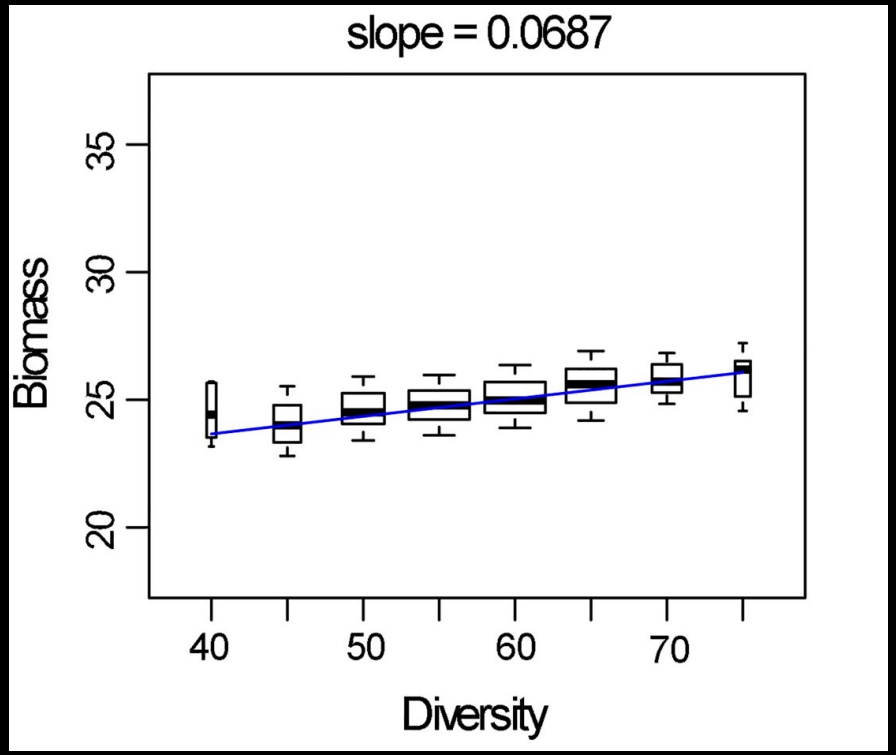
Simulations

Niche model for food web skeleton, 100 species incl. 20 plants
Plug NTI 'links randomly'
Run dynamics with and without NTI

Calculate species diversity and total biomass

Miele *et al.* 2019

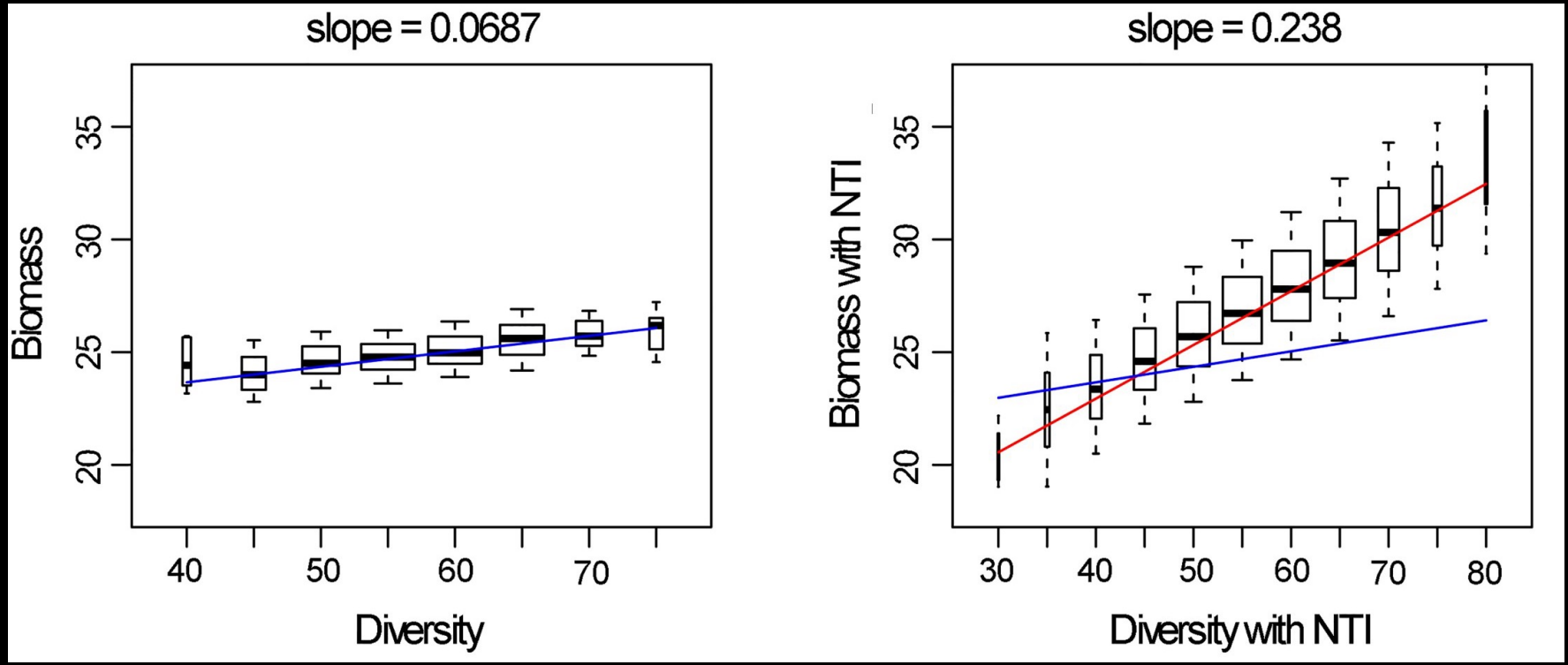
One interaction type (trophic)



Miele *et al.* 2019

One interaction type (trophic)

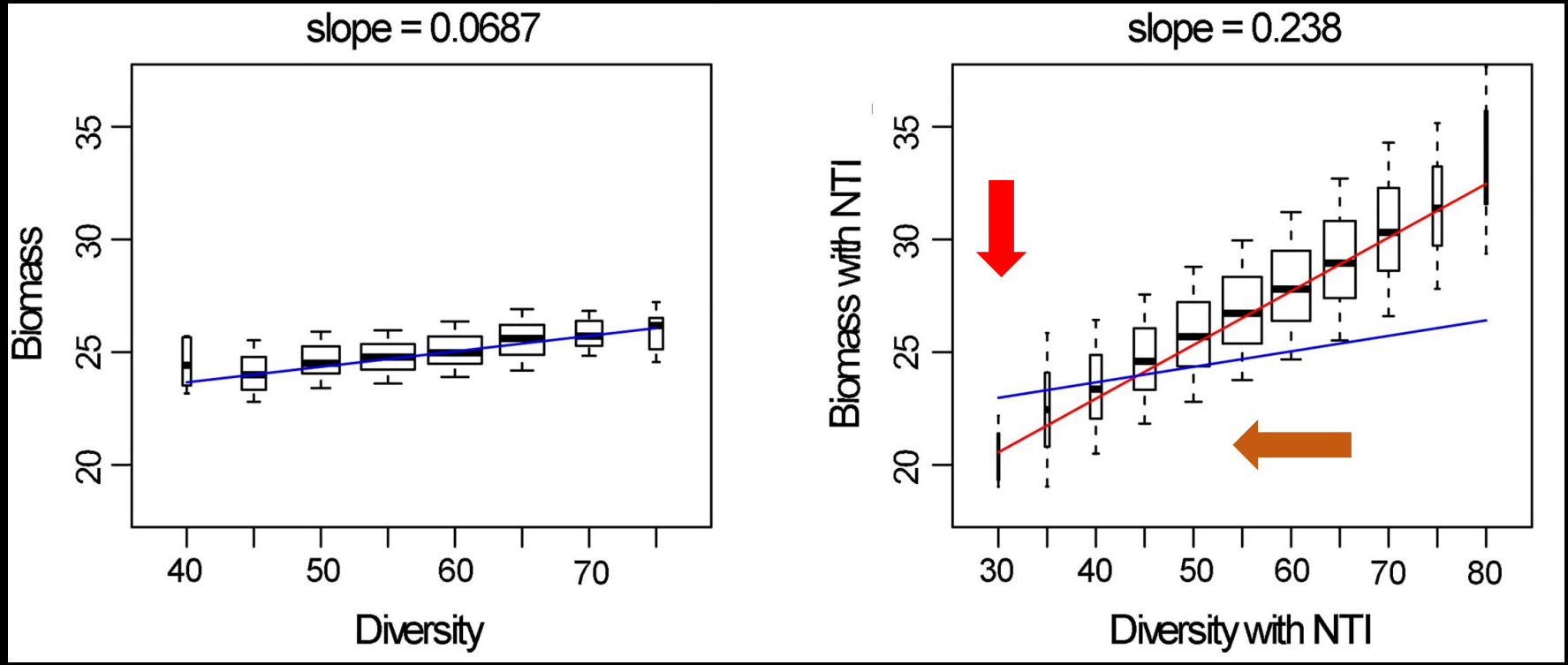
Diverse interactions types (multiplex)



Miele *et al.* 2019

One interaction type (trophic)

Diverse interactions types (multiplex)



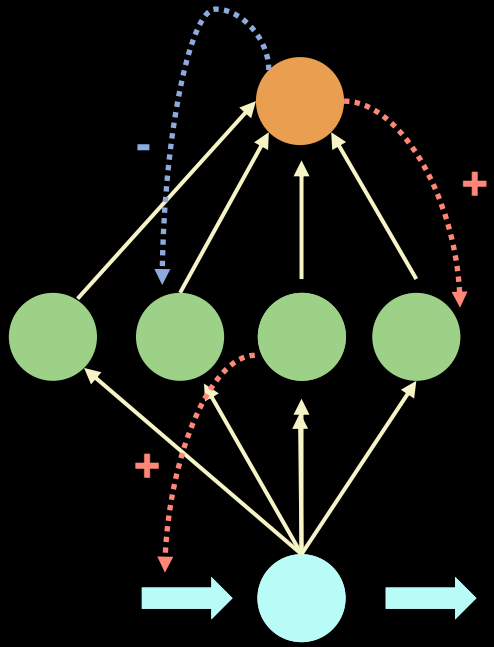
Miele *et al.* 2019

NTIs affect species diversity, community functioning and their relationship

Miele *et al.* 2019

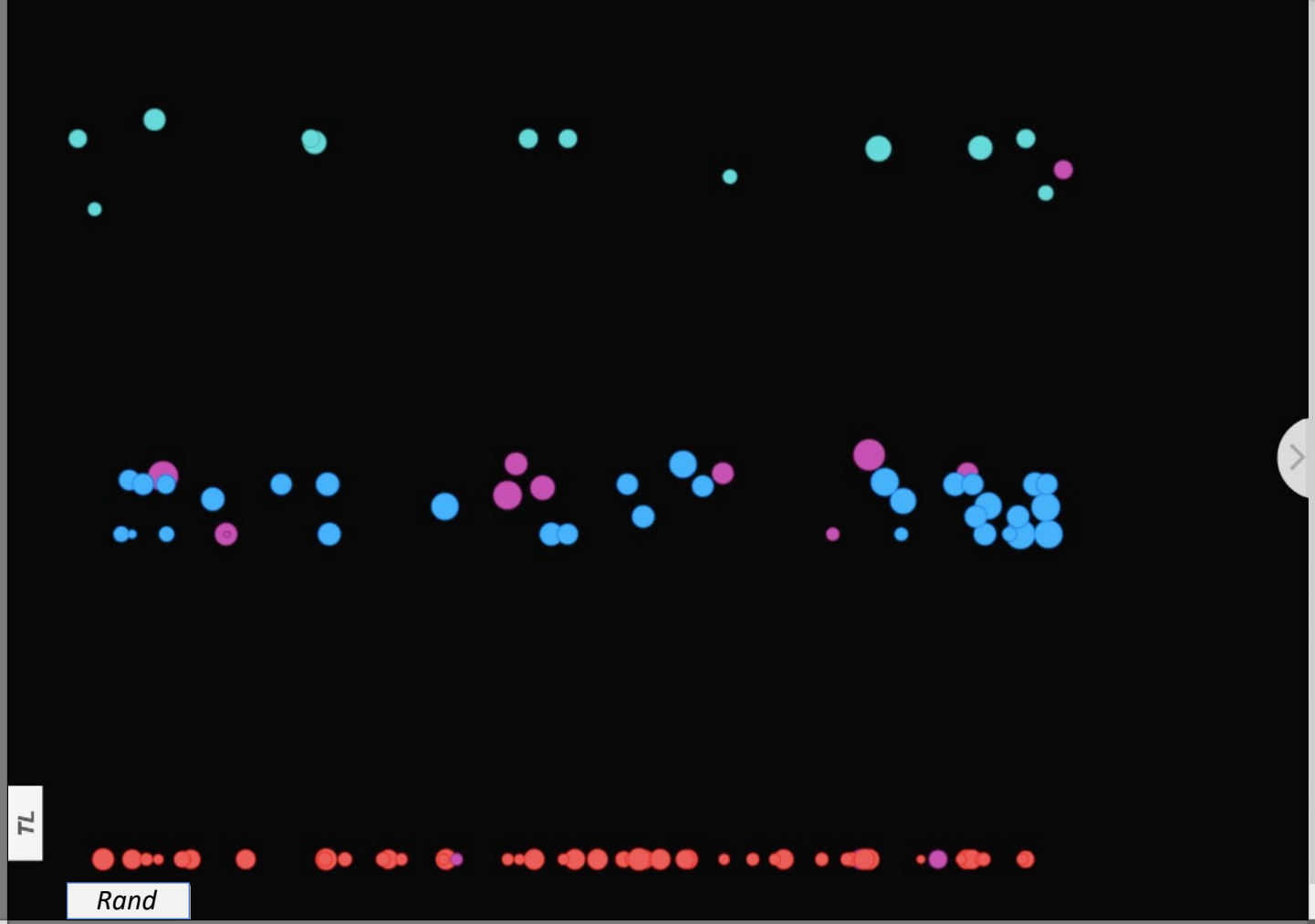
How do different interaction types map onto each other?

What’s the relative abundance of different interaction types?



multiplex ecological network


Sergio Navarrete,
Evie Wieters
Kéfi *et al.* 2015



CHILEAN MARINE ECOLOGICAL NETWORK

NODES 104

46	Basal
32	Intermediate
12	Top
14	zHarvested

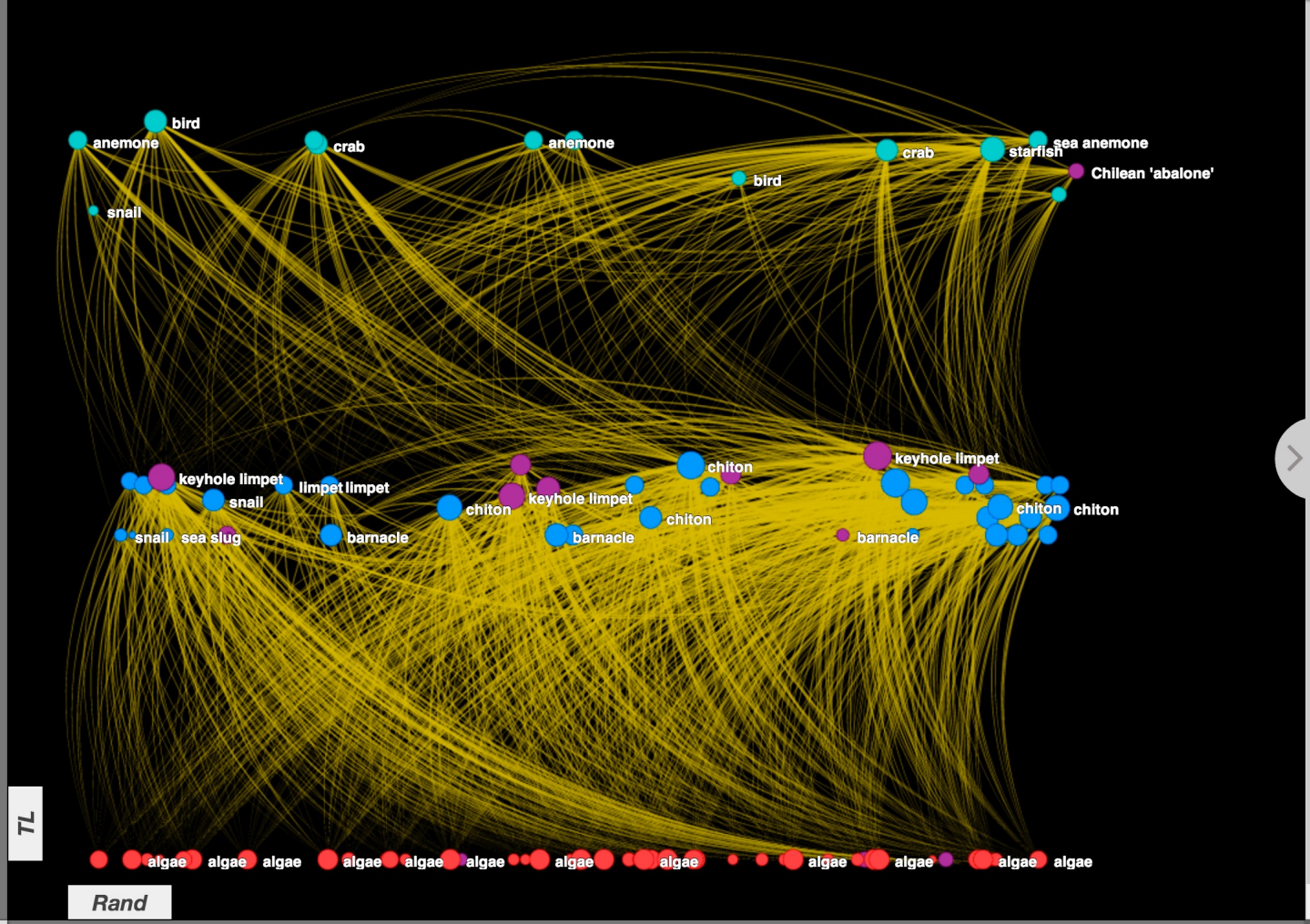
EDGES 1611

1456	Feeding
155	Non-Feeding Positive

1 2 3

Kéfi *et al.* 2015 Ecology

mappr



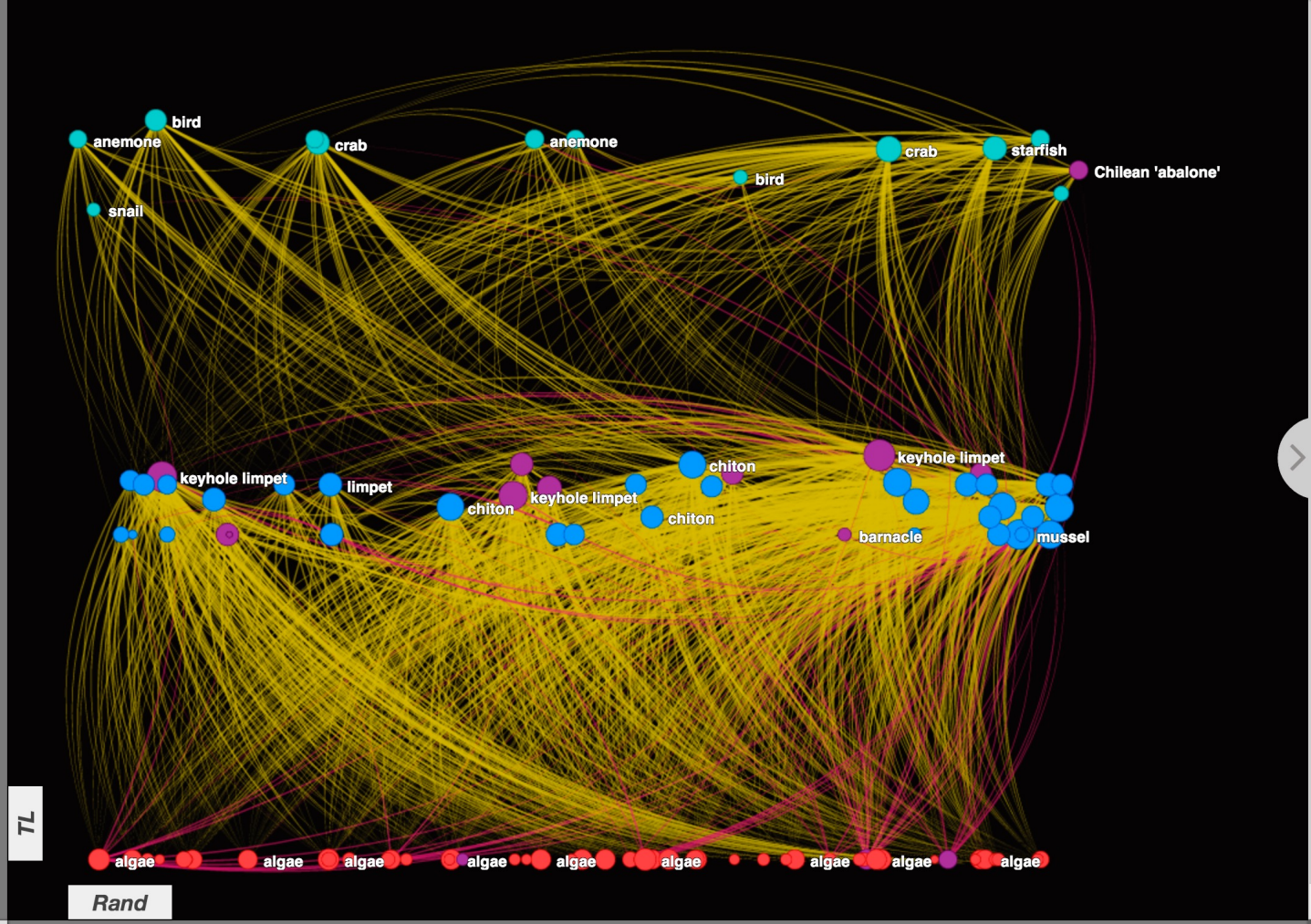
CHILEAN MARINE FOOD WEB

NODES 104	
46	Basal
32	Intermediate
12	Top
14	zHarvested

1 2

Kéfi *et al.* 2015 Ecology

mappr



CHILEAN MARINE ECOLOGICAL NETWORK

NODES 104

46	Basal
32	Intermediate
12	Top
14	zHarvested

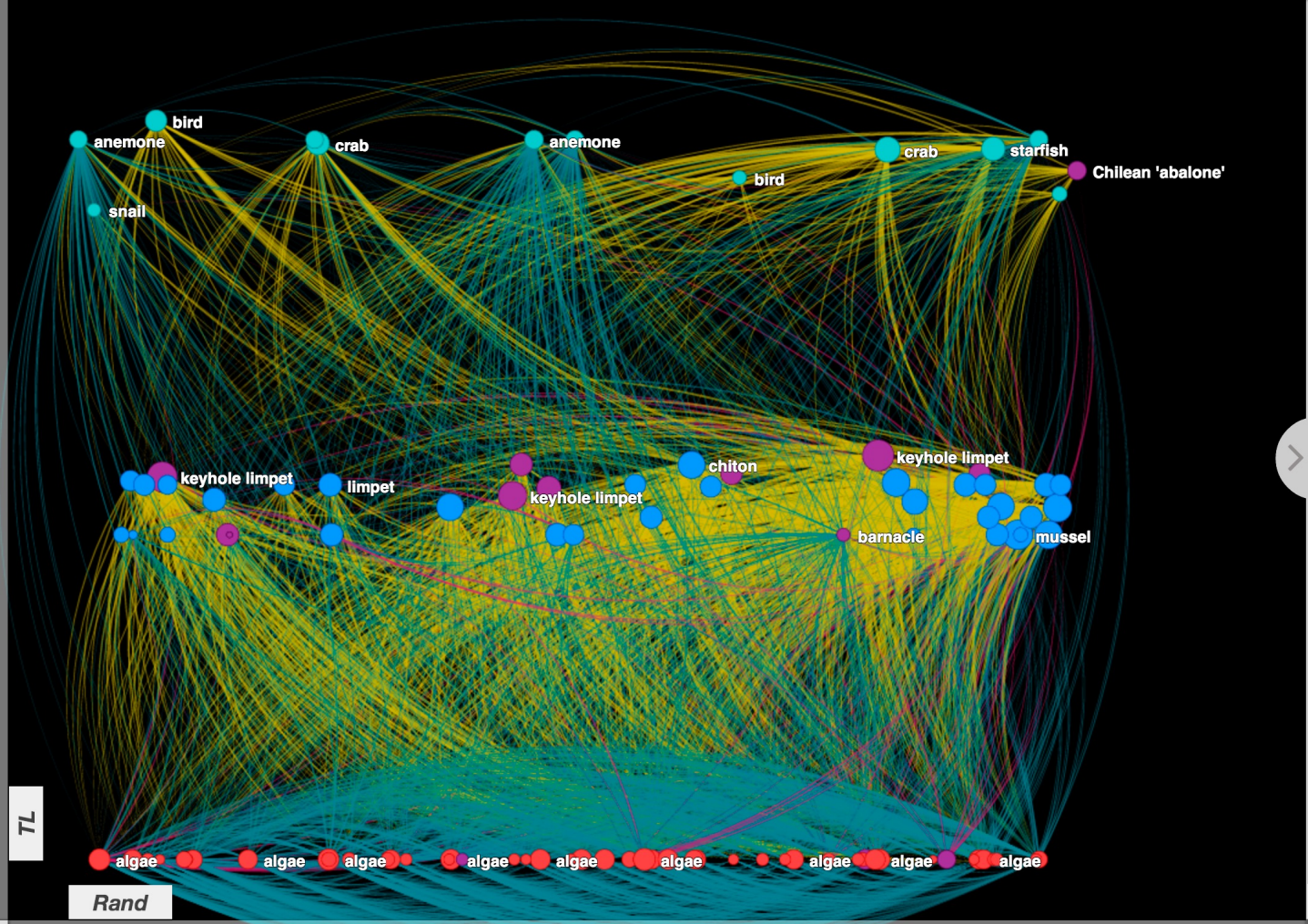
EDGES 1611

1456	Feeding
155	Non-Feeding Positive

1 2 3

Kéfi *et al.* 2015 Ecology

mappr



CHILEAN MARINE ECOLOGICAL NETWORK

NODES 104

46	Basal
32	Intermediate
12	Top
14	zHarvested

EDGES 4720

1424	Feeding
3141	Non-Feeding Negative
155	Non-Feeding Positive

1 2 3

Kéfi *et al.* 2015 Ecology

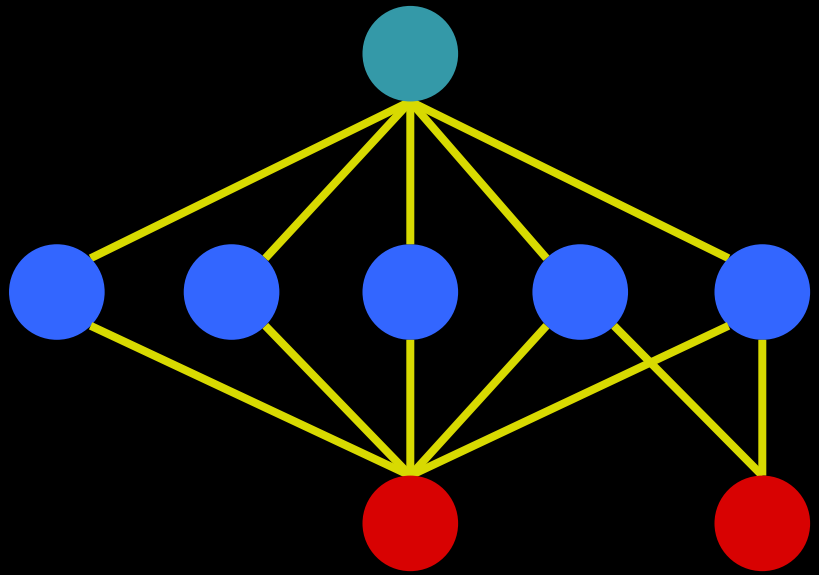
mappr

Do species collapse into a smaller set of multiplex clusters?

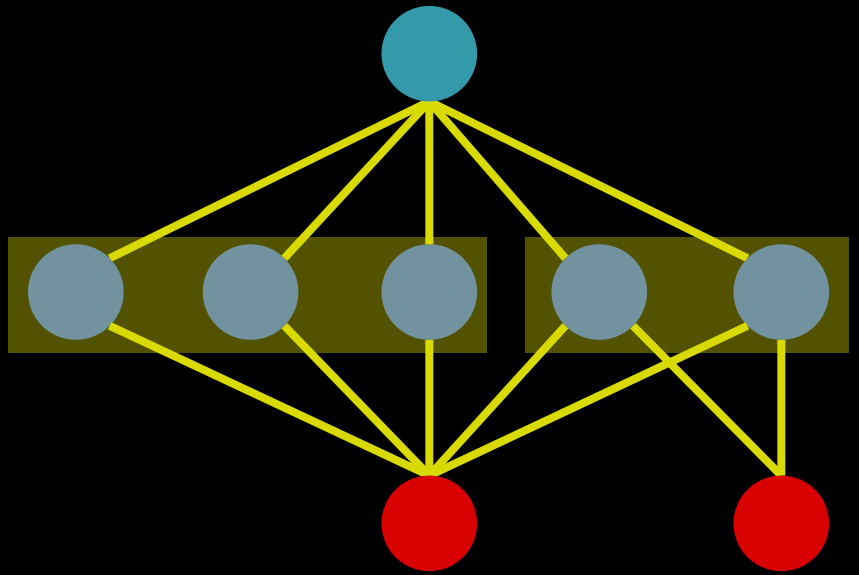
stochastic block model

Newman and Leicht 2007
Daudin *et al.* 2008
Miele *et al.* 2014

FEEDING



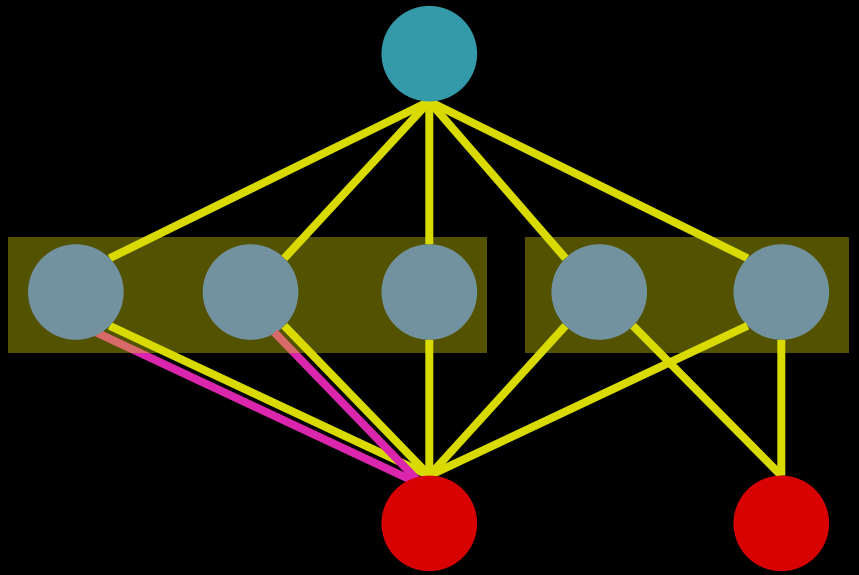
FEEDING



"TROPHIC SPECIES"

FEEDING

FACILITATION

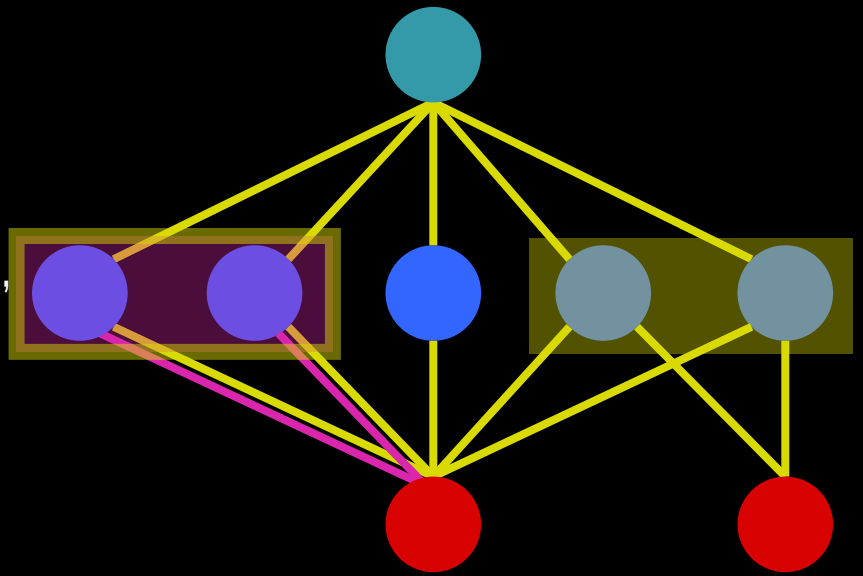


"TROPHIC SPECIES"
(1 DIMENSION)

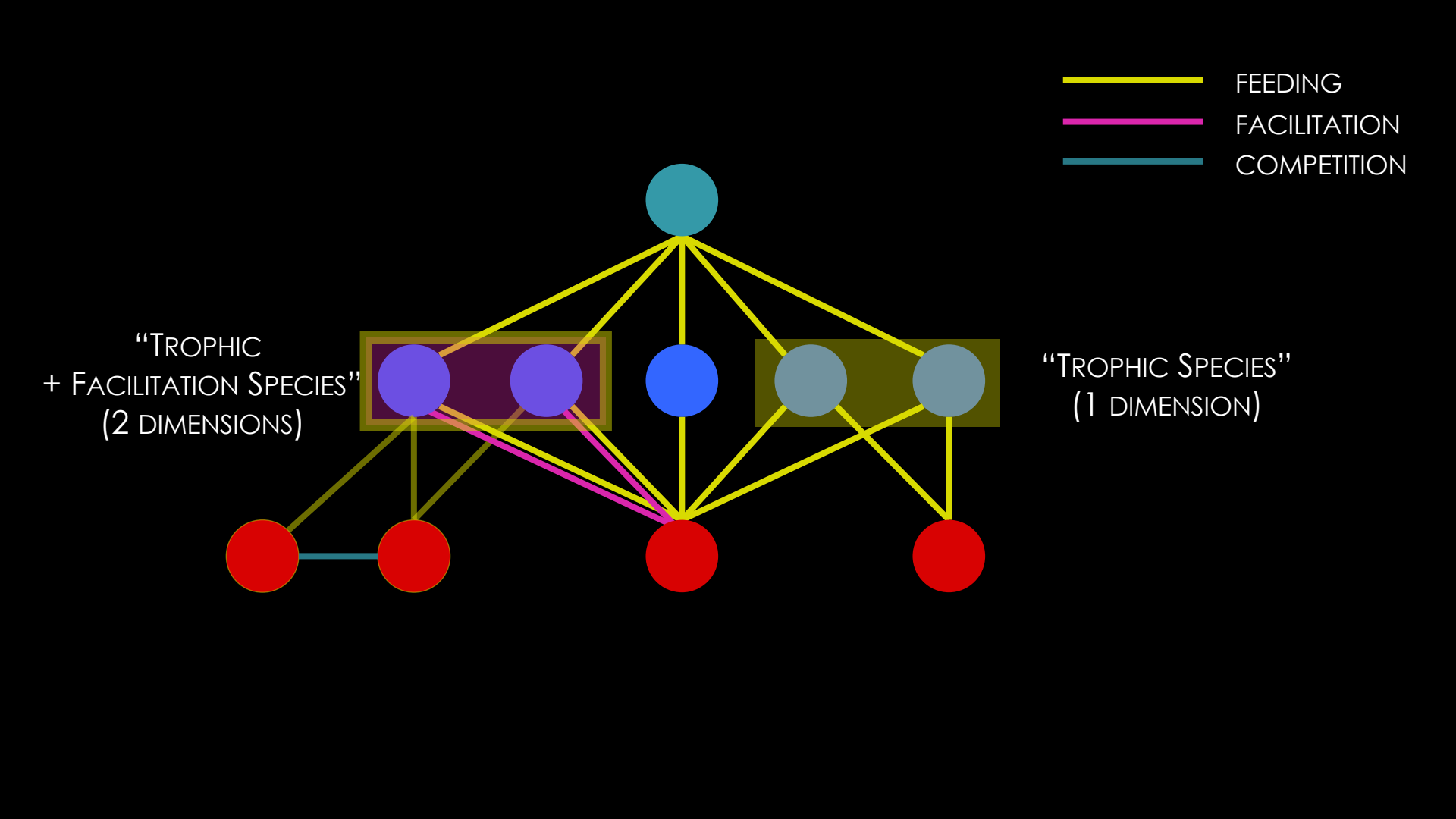
FEEDING

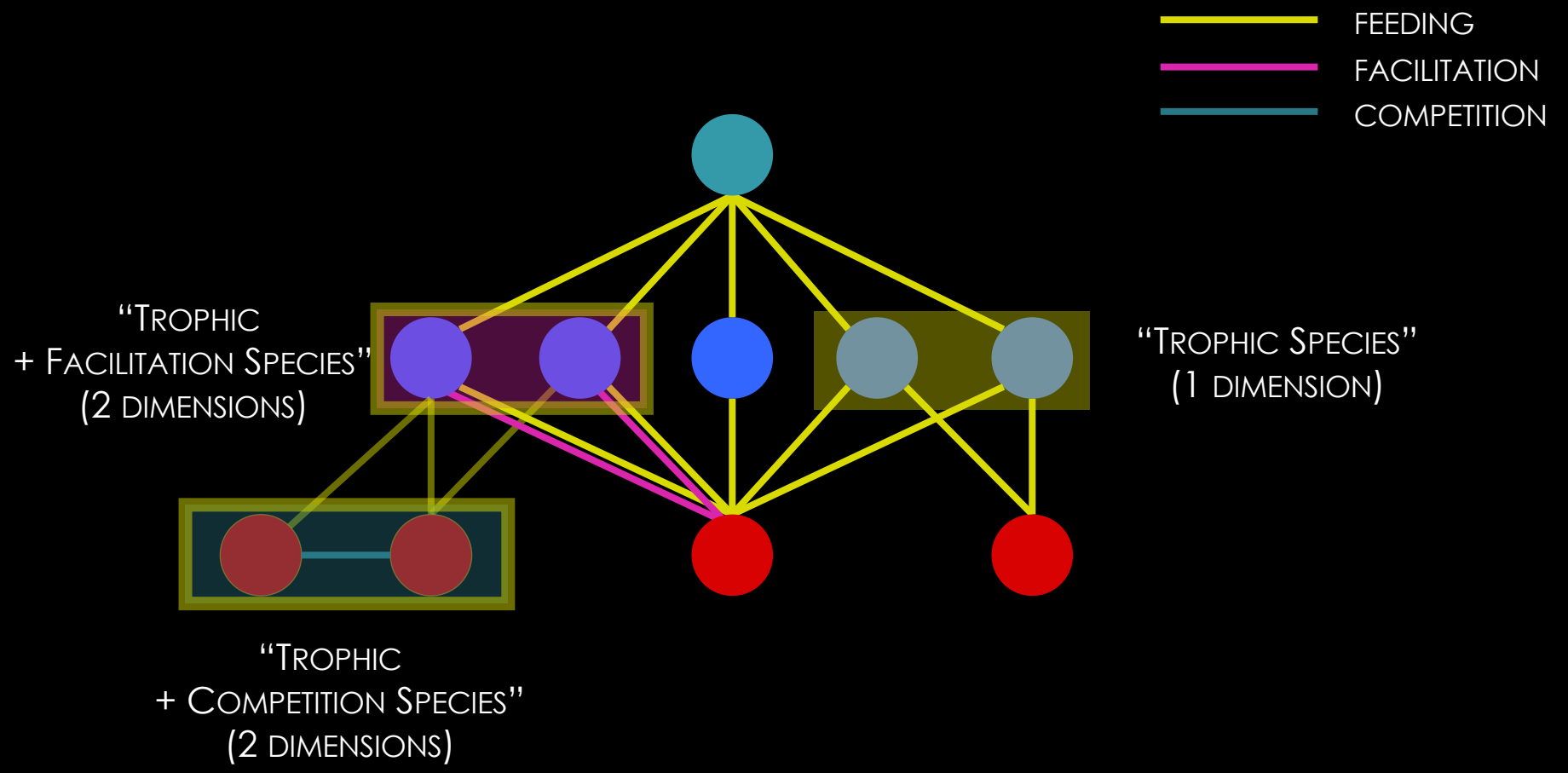
FACILITATION

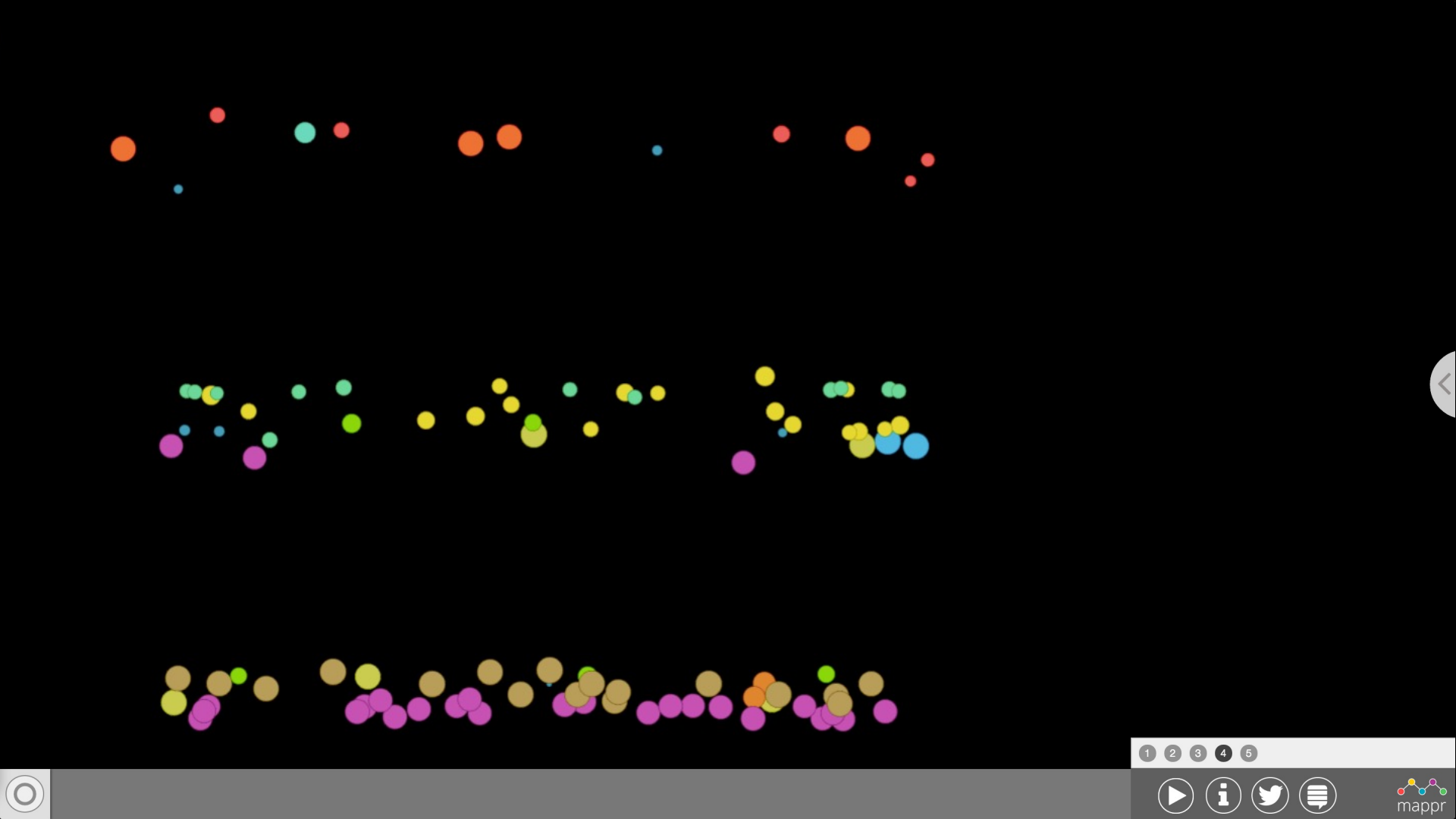
"TROPHIC
+ FACILITATION SPECIES"
(2 DIMENSIONS)

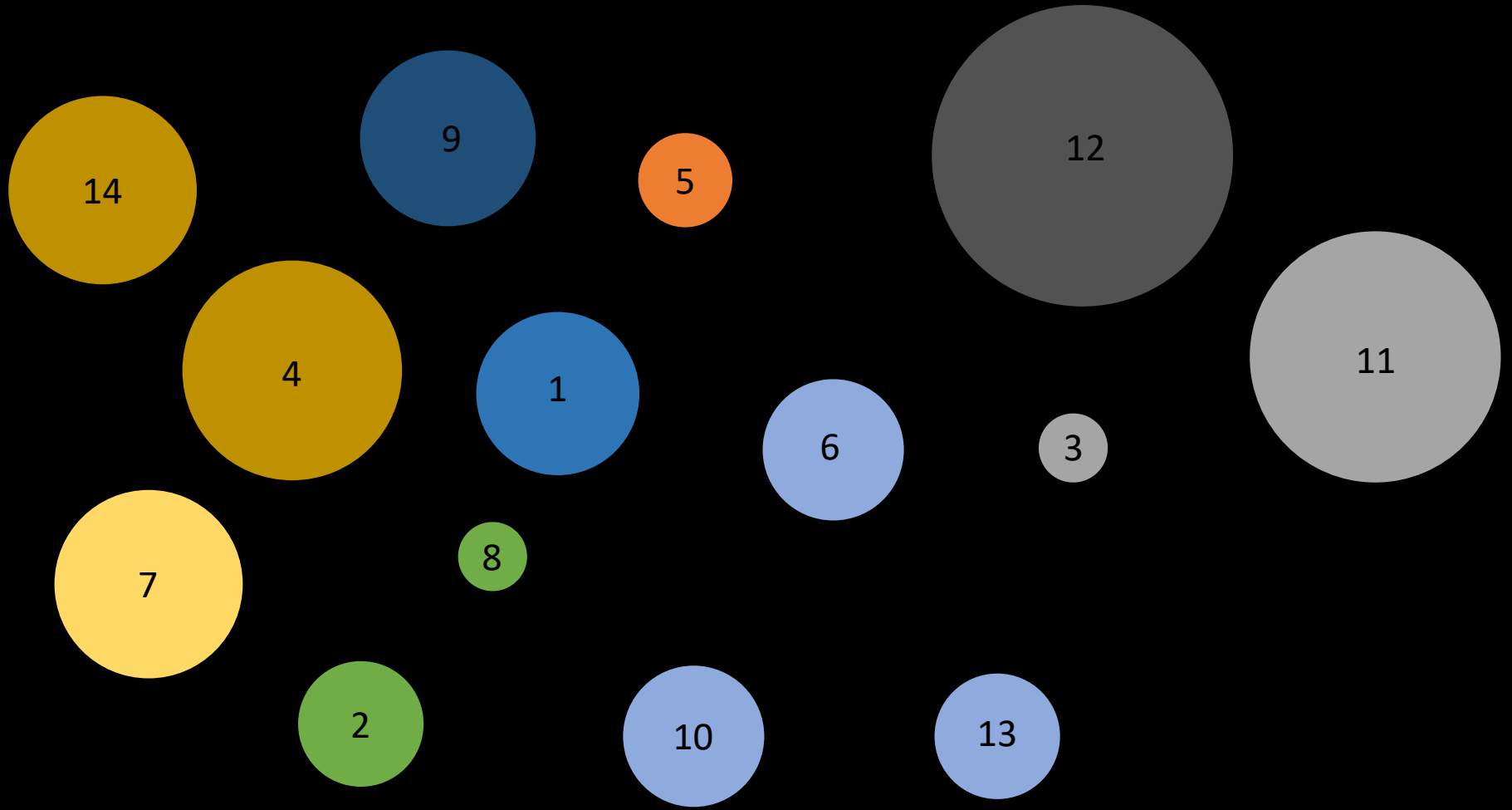


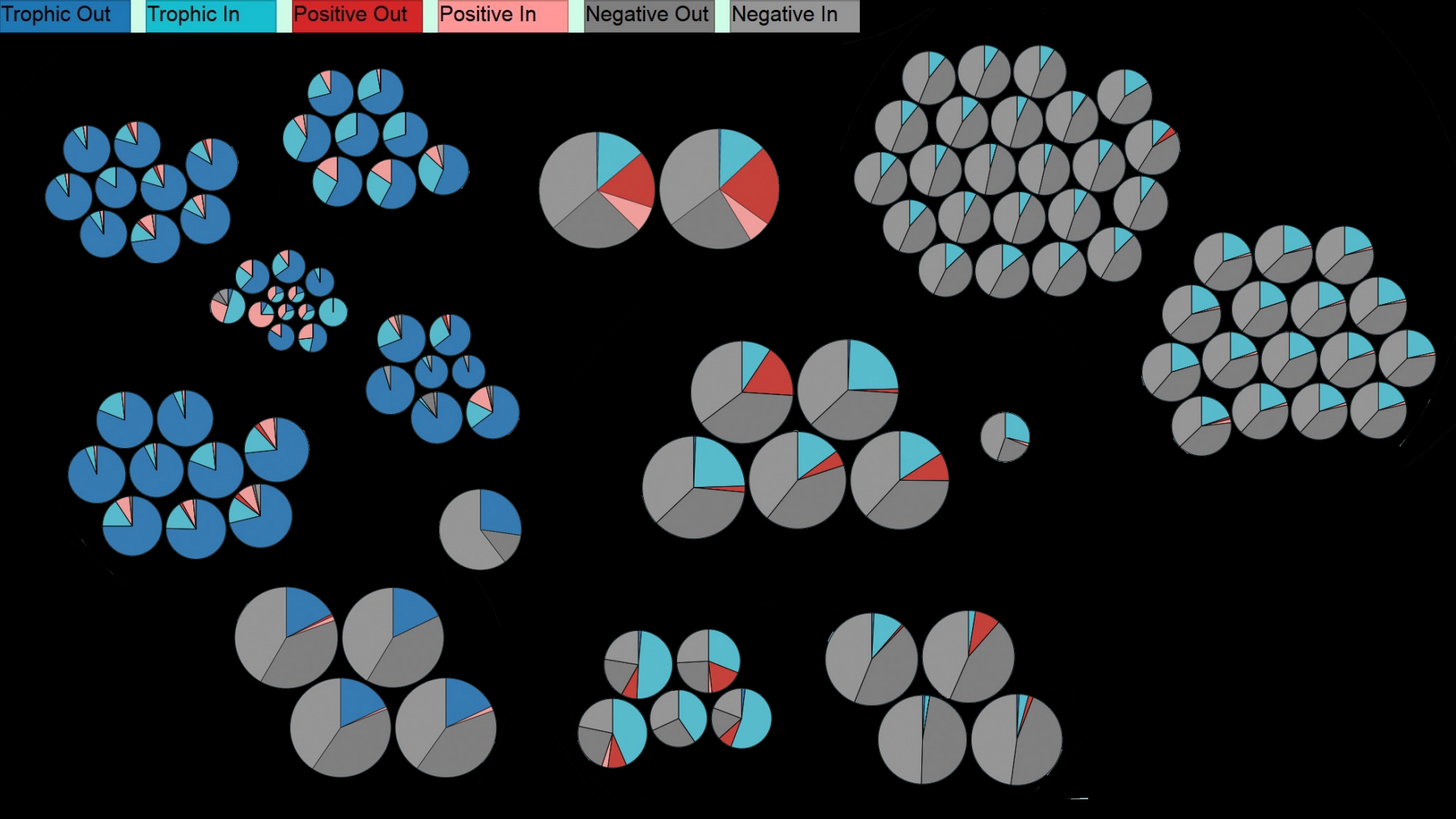
"TROPHIC SPECIES"
(1 DIMENSION)


FEEDING
FACILITATION
COMPETITION
"TROPHIC
+ FACILITATION SPECIES"
(2 DIMENSIONS)
"TROPHIC SPECIES"
(1 DIMENSION)

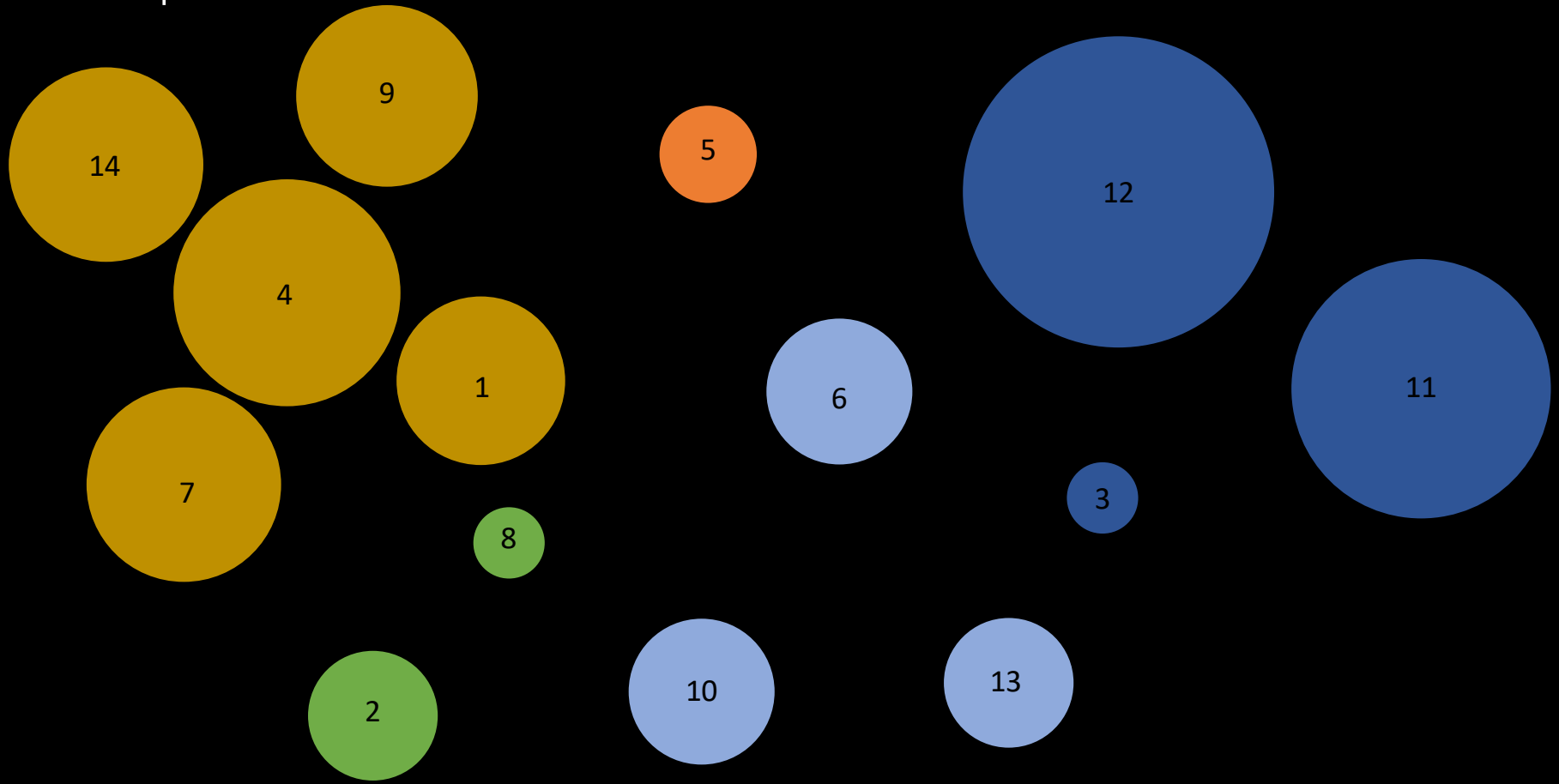

FEEDING
FACILITATION
COMPETITION
"TROPHIC
+ FACILITATION SPECIES"
(2 DIMENSIONS)
"TROPHIC SPECIES"
(1 DIMENSION)
"TROPHIC
+ COMPETITION SPECIES"
(2 DIMENSIONS)




14
9
5
12
4
1
6
3
11
7
8
2
10
13

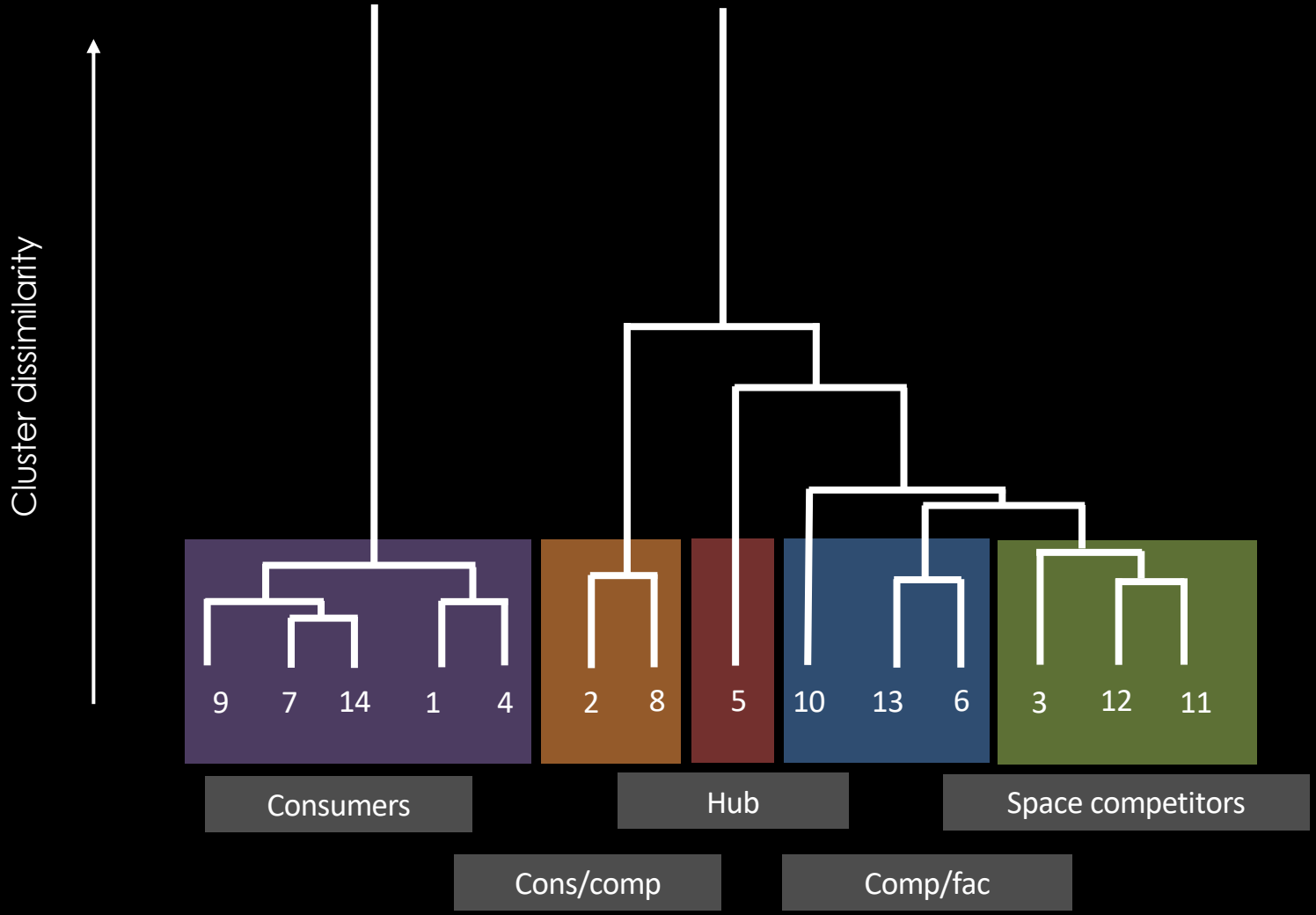

Trophic Out
Trophic In
Positive Out
Positive In
Negative Out
Negative In

14 multiplex clusters



Kéfi, Miele *et al.* 2016 PLOS Biol.

Species collapse into a small set of multiplex clusters


Cluster dissimilarity
9
7
14
1
4
2
8
5
10
13
6
3
12
11
Consumers
Hub
Space competitors
Cons/comp
Comp/fac

What are the functional consequences of the 3-dimensional connectivity pattern?

dynamical model

[bioenergetic consumer-resource model]

+ non-trophic interactions

Competition for space
Predator interference
Recruitment facilitation
Refuge provisioning
Positive and negative effects on survival

Kéfi *et al.* 2012 Eco. Lett

Simulations

14 nodes
('typical' species of the cluster)

(i) Connectivity of the Chilean web

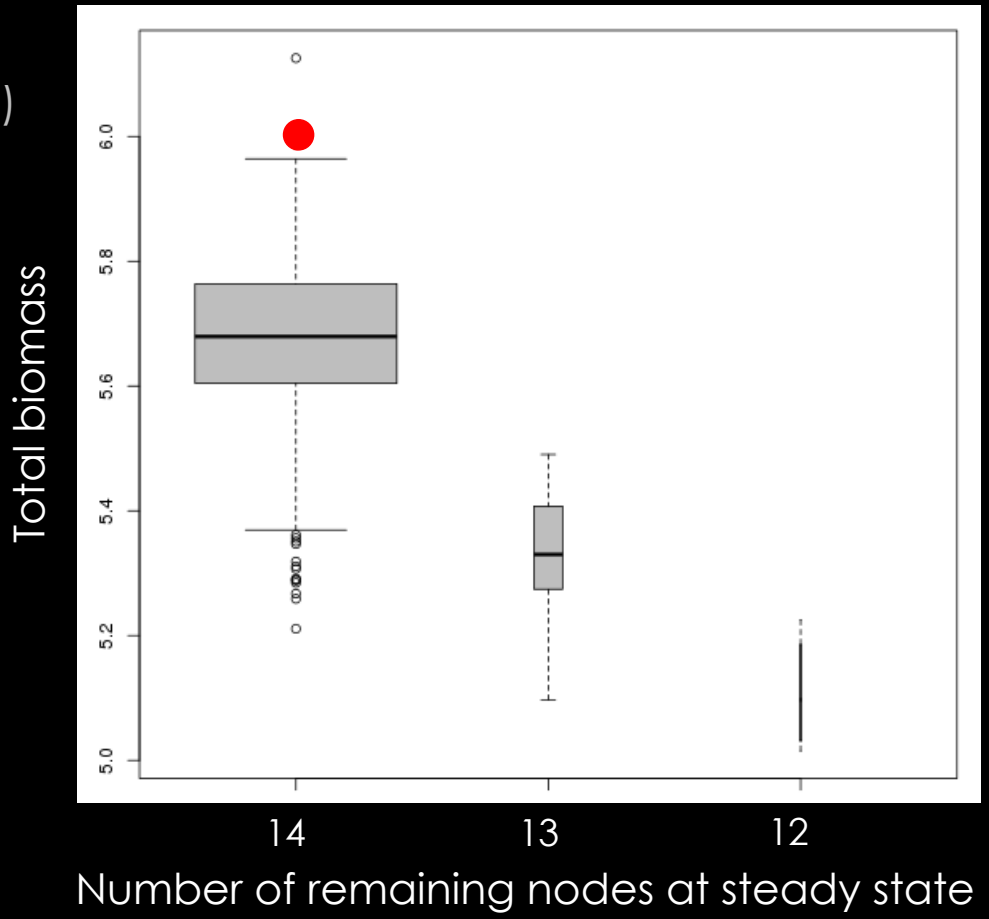
(ii) 500 random networks (keep degree sequence)

Calculate species diversity and total biomass

Kéfi, Miele *et al.* 2016 PLOS Biol.

Chilean web

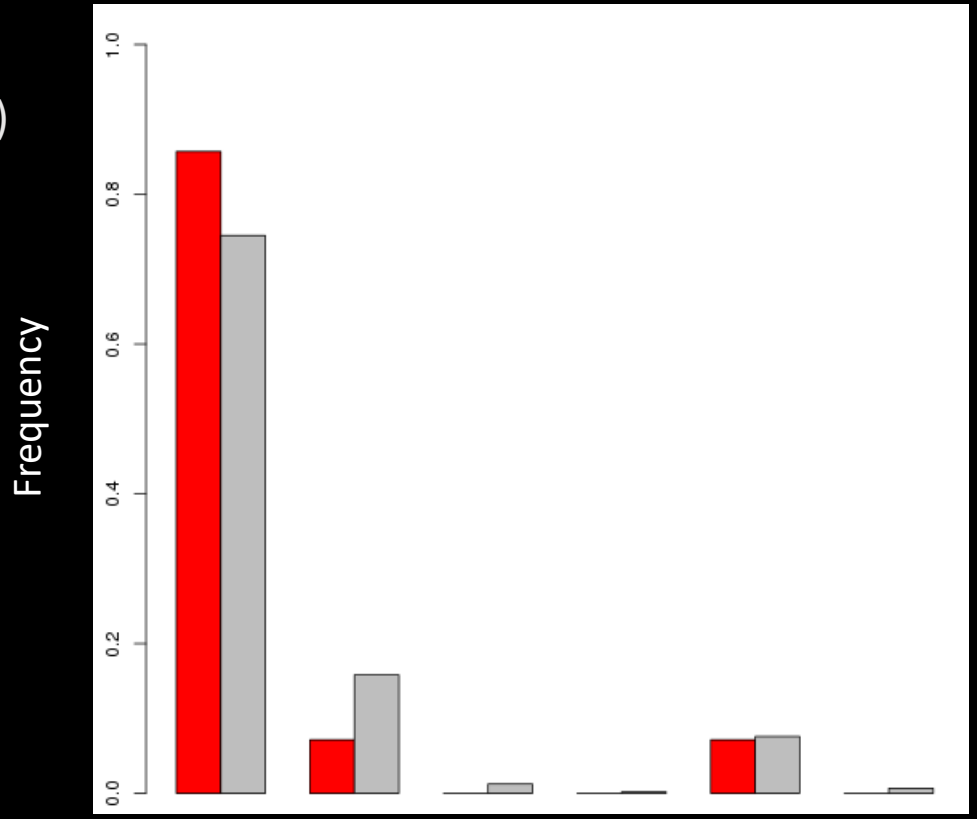
Random webs (500)



Kéfi, Miele *et al.* 2016 PLOS Biol.

Chilean web

Random webs (500)



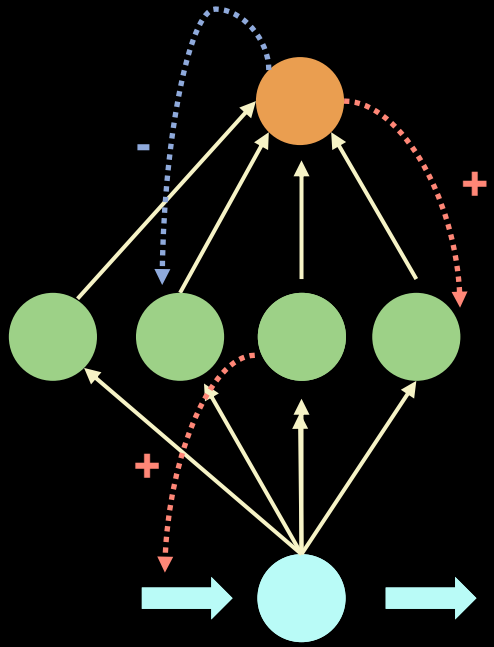
Differential number of clusters after primary extinction

Kéfi, Miele *et al.* 2016 PLOS Biol.

The specific 3-dimentional signature of the clusters in the Chilean web promotes:

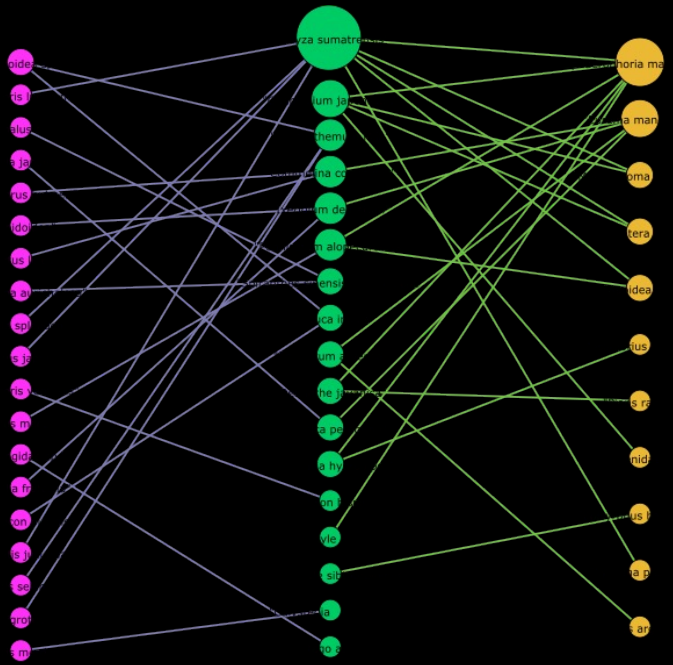
- high species persistence
- high total biomass
- tends to decrease the number of secondary extinctions

Kéfi, Miele *et al.* 2016 PLOS Biol.



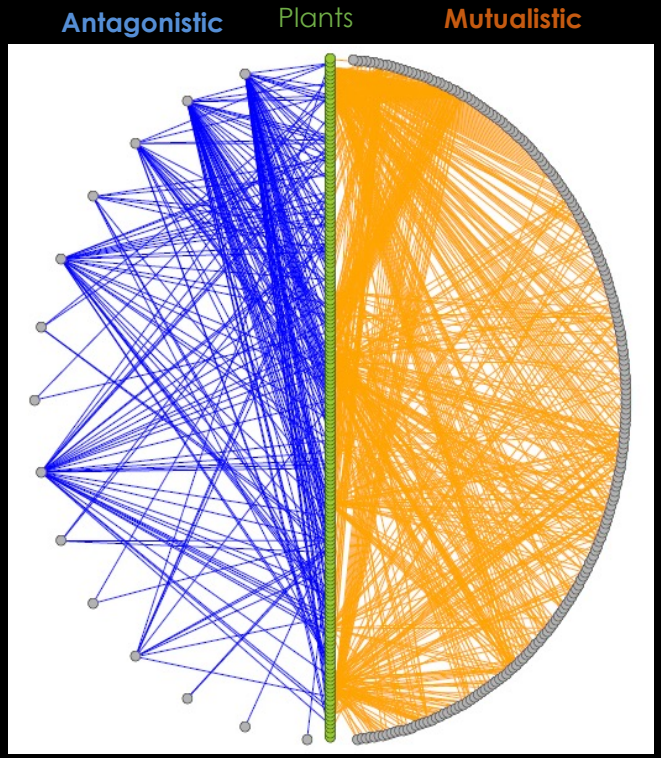
multiplex networks

Herbivores Plants Pollinators



multipartite networks

Doñana Biological Reserve, Spain



390 species
(170 plants, 180 pollinators, 26 dispersors, 14 herbivores)

2 layers
798 interactions (578 mutualistic, 220 antagonistic)

binary and quantitative links

Melian *et al.* 2009 Oikos

Doñana Biological Reserve, Spain

How are different interactions combined in natural communities?
How does that affect stability?

Two metrics:
- the presence of the simplest module
(a plant with a mutualistic and an antagonistic link)

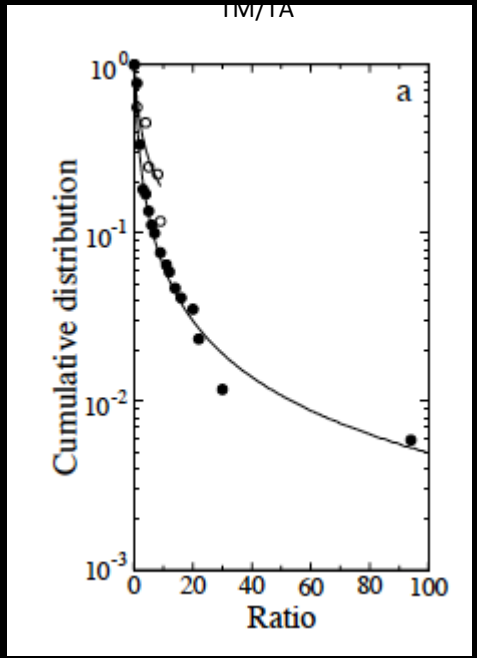
- the ratio of the total number of mutualistic to antagonistic interactions per plant species, TM/TA

Null model:
randomize links keeping the nb of links of animal constant (i.e. randomization with respect to the plants)

Melian *et al.* 2009 Oikos

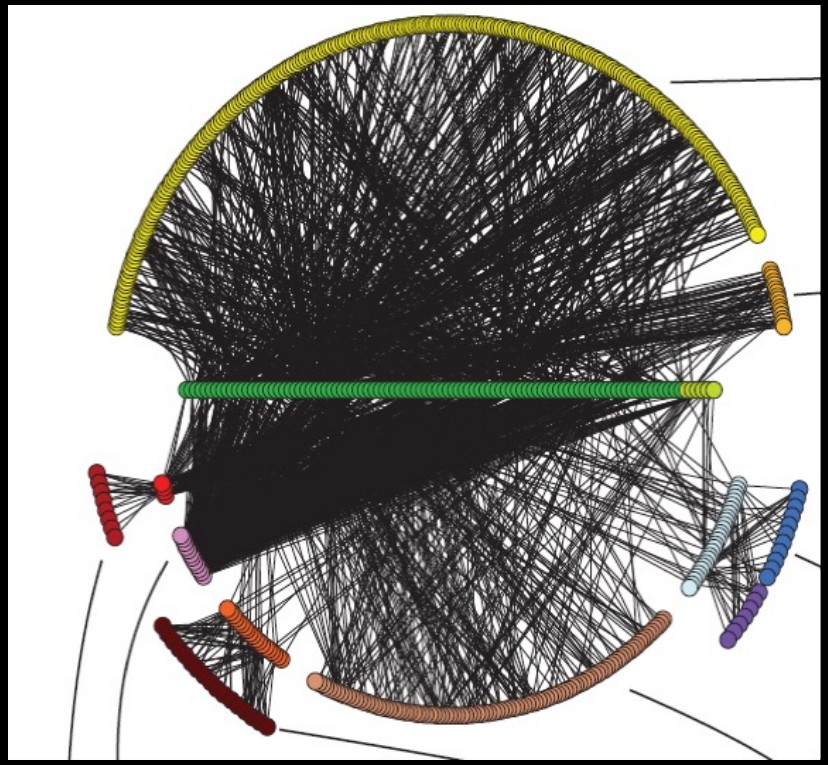
Doñana Biological Reserve, Spain

→ a few plants are involved in many modules and have a high ratio TM/TA
→ very heterogeneous multilayer role of species
→ promotes diversity (model)



Melian *et al.* 2009 Oikos

Norwood farm, Somerset, UK



560 taxa
(plants + 11 groups of animals)

7 sub-networks
1501 interactions (trophic, mutualistic, parasitic)

Pocock *et al.* 2012 Science

Norwood farm, Somerset, UK

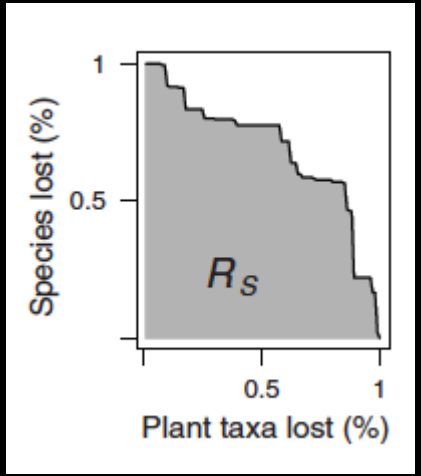
How does the robustness of different species interaction networks vary?

robustness:

sequential (random) removal of plant species

→some sub-networks (layers) are more robust than others

→ Identification of keystone plants (that have the most important cascading effects)



Pocock *et al.* 2012 Science

Key results

- Different layers have different structural properties
- Different layers have different robustness
- → id of key species that create a disprop amount of secondary extinctions

- species have different roles in different layers
- A few species have disproportional multiplex roles

multi-interaction networks

multilayer ecological networks

temporal networks

Received: 19 January 2020 | Accepted: 9 February 2020
DOI: 10.1111/1365-2656.13217

RESEARCH ARTICLE

Journal of Animal Ecology | BRITISH ECOLOGICAL SOCIETY

Core–periphery dynamics in a plant–pollinator network

Vincent Miele[1] | Rodrigo Ramos-Jiliberto[2] | Diego P. Vázquez[3,4,5]

How does species role change through time?

Dynamic stochastic Block model (on 6 years of data)
→ Core-periphery structure stable through time
→ But role of species variable through time

spatial networks

ARTICLE

DOI: 10.1038/s41467-017-02658-y OPEN

Multilayer networks reveal the spatial structure of seed-dispersal interactions across the Great Rift landscapes

Sérgio Timóteo [1], Marta Correia[1], Susana Rodríguez-Echeverría [1], Helena Freitas[1] & Ruben Heleno[1]

seed–dispersal interactions across the Gorongosa National Park, Mozambique

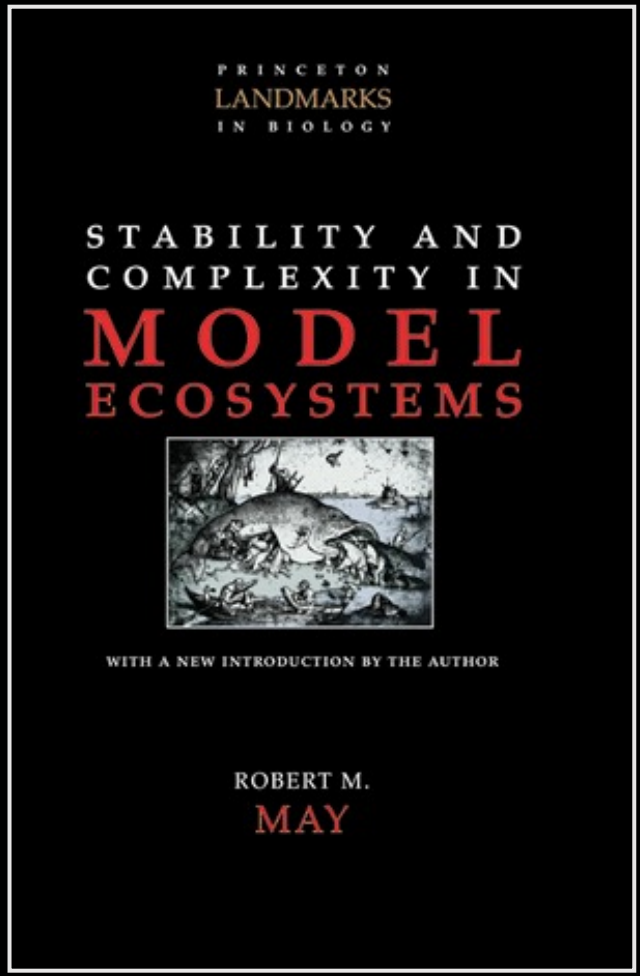
→ id of highly versatile species that disperse many plant species across multiple habitats

→ Not predicted by monolayer approaches

« Complexity begets stability »

Odum 1953
MacArthur 1955
Elton 1958

Robert May


PRINCETON
LANDMARKS
IN BIOLOGY
STABILITY AND
COMPLEXITY IN
MODEL
ECOSYSTEMS
WITH A NEW INTRODUCTION BY THE AUTHOR
ROBERT M.
MAY

« In general mathematical models of multispecies communities, complexity tends to beget instability »

Robert May, 1973

« The task, therefore, is to elucidate the **devious strategies** which make for stability in enduring natural systems »

Complex ecological communities
Many species
Many interaction types
Spatio-temporal dynamics

Thank you very much for your attention

SANTA FE
INSTITUTE

Institut des Sciences de l'Evolution-Montpellier