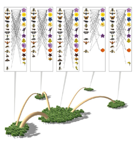
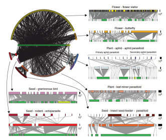
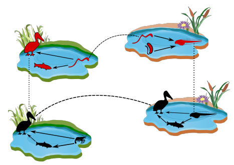
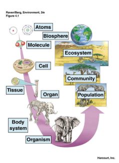
Week 6: Ecological Multilayer Networks



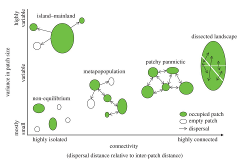




Higher dimensionality in ecology



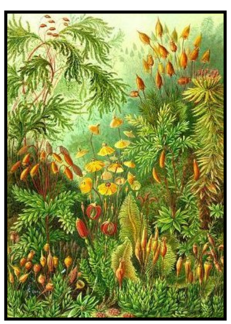
Organizational hierarchy



Space / time

Multiple kinds of interactions

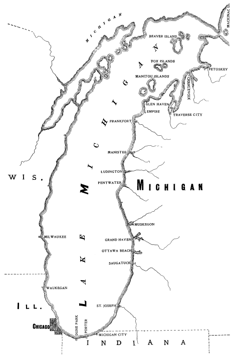
Metapopulation pic from a course by Kevin Shoemaker

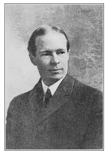


Ernst Haeckel,
Kunstformen der Natur (1904)

« It is interesting to contemplate an **entangled bank**, clothed with plants of many kinds, with birds singing… **so dependent on each other in so complex a manner**… »

Charles Darwin, 1859

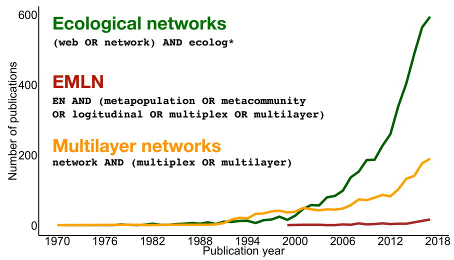




"...so ecologists seek to study those plant structures which are changing at the **present time**, and thus to throw light on the **origin of plant structures themselves.**"

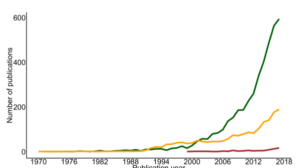
Cowles HC. Botanical Gazette, 1899

Ecological networks are usually studied in "isolation" or aggregated



Ecological networks are usually studied in "isolation" or aggregated

- Data
- Methodology
- Immature field



First explorations of (modern) ecological multilayer networks

Ecological Monographs, 60(3), 1990, pp. 331–367
© 1990 by the Ecological Society of America

SPATIAL AND TEMPORAL VARIATION IN TROPICAL FISH TROPHIC NETWORKS[1]

KIRK O. WINEMILLER
Department of Zoology and Texas Memorial Museum, The University of Texas, Austin, Texas 78712 USA

Ecological Monographs, 61(3), 1991, pp. 267–298
© 1991 by the Ecological Society of America

TEMPORAL VARIATION IN FOOD WEB STRUCTURE: 16 EMPIRICAL CASES[1]

KENNETH SCHOENLY AND JOEL E. COHEN
Rockefeller University, 1230 York Avenue, Box 20, New York, New York 10021-6399 USA

OIKOS 48: 280–288. Copenhagen 1987

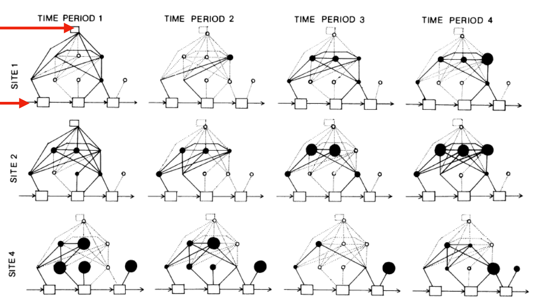
Spatial and temporal variation in food webs in water-filled treeholes

R. L. Kitching

OIKOS 55: 299–311. Copenhagen 1989

Spatial and temporal variation in the structure of a freshwater food web

Philip H. Warren



Kitching 1987 Oikos

Consumer (species number)

Resource (species number)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	22	23	24	25	27	28	29	30
0	·	1	1	2	·	2	1	·	·	·	·	·	·	2	2	2	2	2	2	2	·	·	·	·	·	·	·	1
1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
2	2	·	·	·	·	·	·	1	2	2	2	2	·	·	·	·	·	·	·	·	2	2	2	2	·	2	2	2
3	2	·	·	·	2	·	·	·	1	1	1	2	2	·	·	·	·	·	·	·	·	1	2	2	2	2	·	2
4	·	·	·	·	2	·	·	·	1	1	1	1	·	·	·	·	·	·	·	·	·	1b	2b	1b	2b	·	·	2
5	·	·	·	·	·	·	·	·	·	·	2	2	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
6	·	·	·	·	2	·	·	·	1	1	1	2	2	·	·	·	·	·	·	·	2	2	2	1	·	2	1	·
7	·	·	·	·	1	·	·	2	1	1	1	1	1a	·	·	·	·	·	·	·	2	·	·	·	·	1	1	·
8	·	·	·	·	2	·	·	2	1	1	1	1	2	·	·	·	·	·	·	·	·	2	2	2	·	1	1	·
9	·	·	·	·	·	·	·	·	1	1	1	1	1	·	·	·	·	·	·	·	·	1	2	2	2	·	·	·
10	·	·	·	·	·	·	·	·	2	1	1	2	2	·	·	·	·	·	·	·	·	1	2	2	2	·	·	·
11	·	·	·	·	·	·	·	·	·	·	1	·	·	·	·	·	·	·	·	·	·	·	·	·	2a	·	·	·
12	·	·	·	·	·	·	·	·	·	·	2a	·	·	·	·	·	·	·	·	·	·	·	·	·	2a	·	·	·
13	·	·	·	·	·	·	·	·	2c	2c	2c	2c	2	·	·	·	·	·	·	·	·	2c	2c	2c	2c	·	·	·
14	·	·	·	·	1	·	·	·	1c	1c	1c	1c	2c	·	·	·	·	·	·	·	·	1c	2c	1c	2c	1c	1c	·
15	·	·	·	·	2c	·	·	·	1c	1c	1c	1c	2c	·	·	·	·	·	·	·	·	1c	1c	1c	2c	1c	1c	·
16	·	·	·	·	2c	·	·	·	1c	1c	1c	1c	2c	·	·	·	·	·	·	·	·	1c	1c	1c	2c	1c	1c	·
17	·	·	·	·	2c	·	·	·	1c	1c	1c	1c	2c	·	·	·	·	·	·	·	·	1c	2c	1c	2c	1c	1c	·
18	·	·	·	·	2c	·	·	·	1c	1c	1c	1c	2c	·	·	·	·	·	·	·	·	1c	2c	1c	2c	1c	1c	·
19	·	·	·	·	2c	·	·	·	1c	1c	1c	1c	2c	·	·	·	·	·	·	·	·	1c	2c	1c	2c	1c	1c	·
20	·	·	·	·	2c	·	·	·	1c	1c	1c	1	2c	·	·	·	·	·	·	·	·	1c	2c	1c	2c	1c	1c	·
22	·	·	·	·	·	·	·	·	2c	2c	2	2	1c	·	·	·	·	·	·	·	2c	2c	2c	2c	2c	2c	2c	·
23	·	·	·	·	·	·	·	·	1c	1c	1c	1c	1c	·	·	·	·	·	·	·	·	2c	2c	2c	2c	·	·	·
24	·	·	·	·	·	·	·	·	1c	1c	1c	1c	1c	·	·	·	·	·	·	·	·	2c	2c	2c	2c	·	·	·
25	·	·	·	·	·	·	·	·	1c	1c	1c	1c	1c	·	·	·	·	·	·	·	·	2c	2c	2c	2c	·	·	·
27	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	2c	·	·	·
28	·	·	·	·	·	·	·	·	1	1	1	1	2	·	·	·	·	·	·	·	2a	1	2	2	2	1	·	·
29	·	·	·	·	1	·	·	·	·	·	1	·	2	·	·	·	·	·	·	·	·	1	2	1	2	·	·	·
30	·	·	·	·	1	·	·	·	·	·	1	·	2	·	·	·	·	·	·	·	·	1a	2a	2a	2a	·	·	·

Warren 1989 Oikos

Consumer as adult

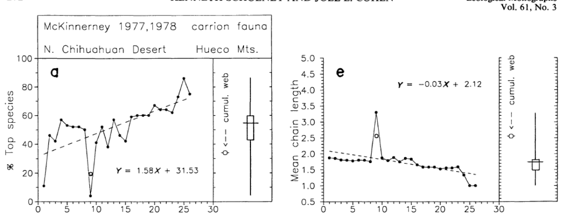
Consumer as larva

TEMPORAL VARIATION IN FOOD WEB STRUCTURE: 16 EMPIRICAL CASES[1]

KENNETH SCHOENLY AND JOEL E. COHEN
Rockefeller University, 1230 York Avenue, Box 20, New York, New York 10021-6399 USA

Used 16 webs from **published** data

1. Quantify 9 properties.
2. Compare aggregated to time-specific.
3. Remove rare species to detect their effects on aggregation.

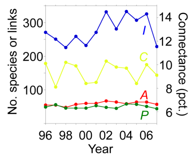


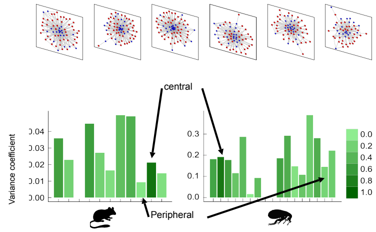
Temporal fluctuations in some properties but not others

No. links (L)			$S \times C\| = 2L/(S-1)$			
Range	Med.	Cum.	Range	Med.	Cum.	Reference(s)
3–92	36	195	2.0–8.06	4.4	8.48	McKinnerney (1977, 1978)
2–39	22	50	2.0–4.22	2.62	4.17	McKinnerney (1977, 1978)
3–9	7	11	2.0–3.0	2.8	3.14	Robinson (1953)
47–156	75	192	2.57–3.67	2.82	3.46	Savely (1939)
70–117	116	199	2.69–2.99	2.90	2.88	Savely (1939)

The aggregated network consistently:

- overestimates the number of species, edges and SxC
- underestimates %B



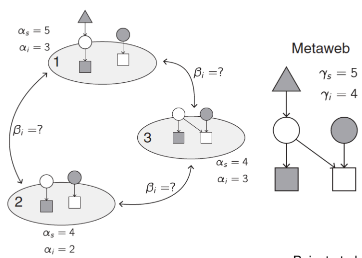


Olesen et al 2011, PLoS One

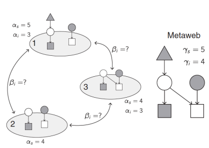
Pilosof et al 2013, J. Anim. Ecol.

Species and interaction turnover in space and time

Tim Poisot

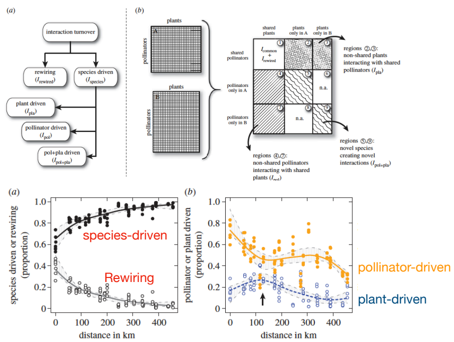


Poisot et al. 2012, Ecol. Lett.



Measure	Definition
β_S	Dissimilarity in the species composition of communities
β_{OS}	Dissimilarity of interactions established between species common to both realisations
β_{WN}	Dissimilarity of interactions
β_{ST}	Dissimilarity of interactions due to species turnover
β'_{OS}	Dissimilarity between a local network and its counterpart in the metaweb
β_{ST}/β_{WN}	Contribution of species dissimilarity to network dissimilarity

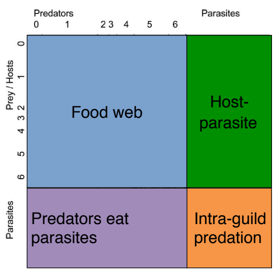
Poisot et al. 2012, Ecol. Lett.



Trøjelsgaard et al., 2015

Merging multiple kinds of interactions

Kevin Lafferty



Including parasites changes the structure of the food web

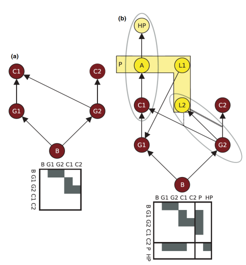
How to include parasites? Multiple life stages?

Lafferty, Dobson, Kuris. PNAS 2006

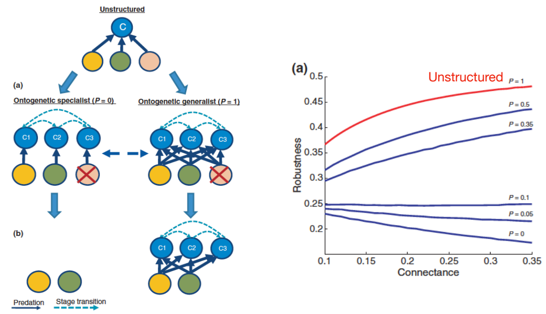
IDEA AND PERSPECTIVE

Parasites in food webs: the ultimate missing links

Kevin D. Lafferty,[1]* Stefano Allesina,[2] Matias Arim,[3,4] Cherie J. Briggs,[5] Giulio De Leo,[6] Andrew P. Dobson,[7] Jennifer A. Dunne,[8,9] Pieter T. J. Johnson,[10] Armand M. Kuris,[5] David J. Marcogliese,[11] Neo D. Martinez,[2,9] Jane Memmott,[12] Pablo A. Marquet,[4,13,14] John P. McLaughlin,[5] Erin A. Mordecai,[5] Mercedes Pascual,[14] Robert Poulin[15] and David W. Thieltges[15]



Ecology Letters 2008

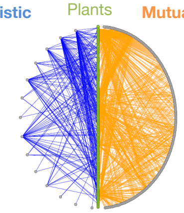


Rudolf and Lafferty 2011 Ecol. Lett

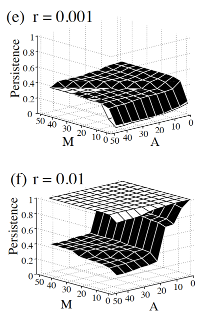
Jordi Bascompte

Oikos 118: 122–130, 2009
doi: 10.1111/j.1600-0706.2008.16751.x,
© 2008 The Authors. Journal compilation © 2008 Oikos
Subject Editor: Jonathan Shurin. Accepted 4 July 2008

Diversity in a complex ecological network with two interaction types

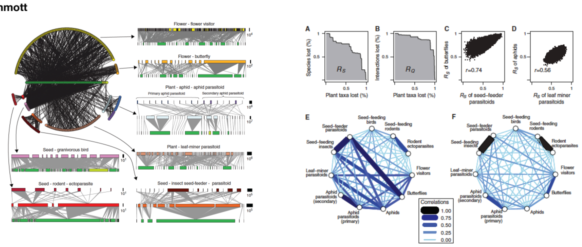


Doñana Biological Reserve, Spain



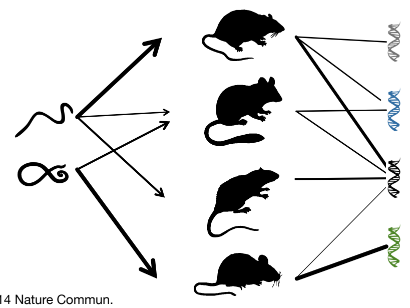
Multiple interaction types and network robustness

Jane Memmott

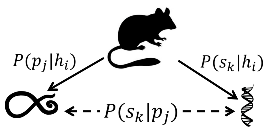


Pocock et al. 2012 Science

Ecological network **Immunogenetic network**



Pilosof et al. 2014 Nature Commun.

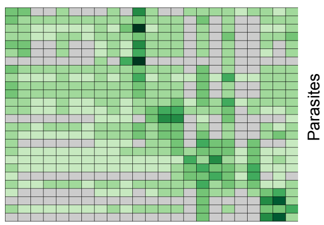


$$P(s = s_k \mid p = p_j) = \qquad (1)$$

$$\sum_{i \in H} P(s_k \mid h_i) \cdot P(h_i \mid p_j) = \qquad (2)$$

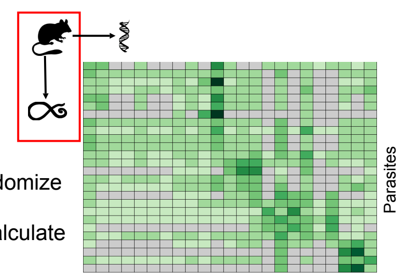
$$\sum_{i \in H} P(s_k \mid h_i) \cdot \frac{P(p_j \mid h_i) \cdot P(h_i)}{P(p_j)} = \qquad (3)$$

$$\sum_{i \in H} P(s_k \mid h_i) \cdot \frac{P(p_j \mid h_i) \cdot P(h_i)}{\sum_{i \in H} P(h_i) \cdot P(p_j \mid h_i)} \qquad (4)$$

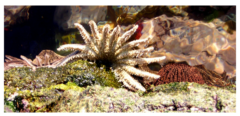


Pilosof et al. 2014 Nature Commun.

Does the ecological network determine supertype-parasite associations?



1. Randomize
2. Recalculate

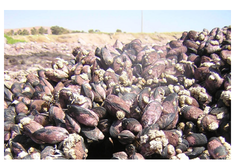


Trophic interactions

Negative non-trophic interactions

Positive non-trophic interactions

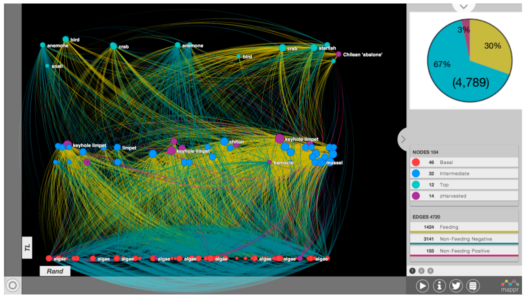
Slide courtesy Sonia Kéfi
Kéfi et al. 2015



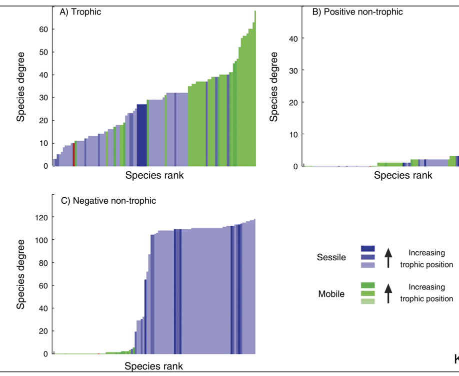
Positive non-trophic interactions

Trophic and non-trophic interactions

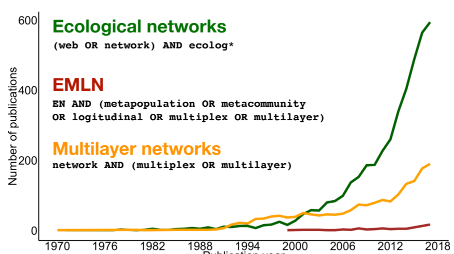
Sonia Kéfi



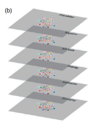
Kéfi et al. 2015 Ecology

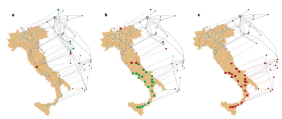


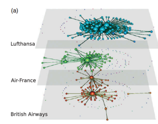
Kéfi et al. 2015 Ecology



Multilayer networks in the broader network science







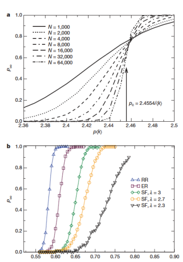
Roethlisberger & Dickson (1939)

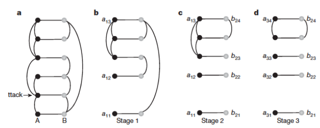
Buldyrev et al. (Nature, 2010)

Cardillo et al. (2013)

Catastrophic cascade of failures in interdependent networks

Sergey V. Buldyrev[1,2], Roni Parshani[3], Gerald Paul[2], H. Eugene Stanley[2] & Shlomo Havlin[3]

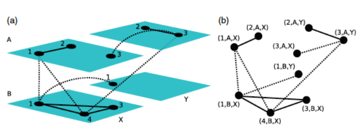


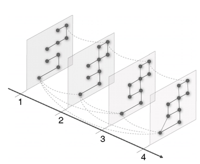


- Couple ER networks.
- Randomly remove nodes.
- Obtain giant mutually connected component.

Buldyrev et al. (Nature, 2010)

Mason Porter





General definitions for multilayer networks

Kivelä et al. (2014)

Development of new metrics

So so many…

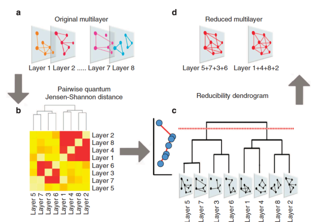
An example for a generalization to a multilayer metric: multilayer modularity function

$$Q_B = \frac{1}{2\mu} \sum_{ijsr} \Bigg[\underbrace{\boxed{\left(A_{ijs} - \gamma_s \frac{k_{is} d_{js}}{m_s}\right) \delta_{sr}}}_{\text{within-layer}} + \underbrace{\boxed{\delta_{ij} \omega_{jsr}}}_{\text{between-layer}} \Bigg] \delta(g_{is}, g_{jr})$$

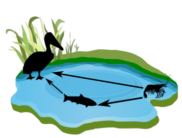
Mucha et al. 2010 Science

An example for a novel development of a multilayer metric: network reducibility

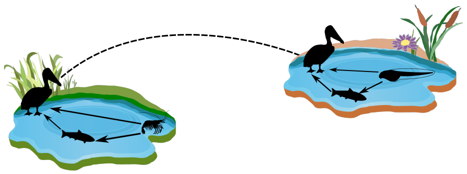
Manlio De Domenico
Alex Arenas



De Domenico et al. 2015 Nature Commun.

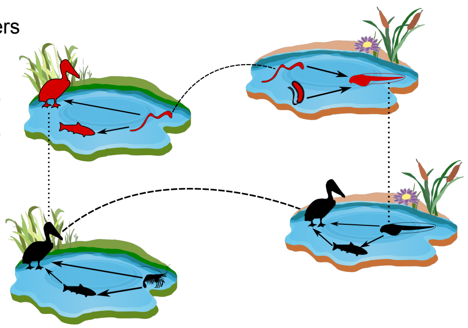


Pilosof et al. 2017 Nature Ecol. Evol.



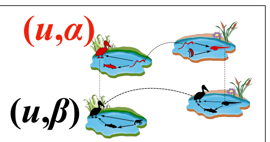
Pilosof et al. 2017 Nature Ecol. Evol.

- Dimensions, layers
- State nodes
- Intra-layer edges
- Inter-layer edges



Pilosof et al. 2017 Nature Ecol. Evol.

$$\mathbf{L} = \{L_a\}_{a=1}^{d}$$
$$V_M \subseteq V \times L_1 \times L_2 \cdots \times L_d$$
$$E_M \subseteq V_M \times V_M$$
$$M = (V_M, E_M, V, \mathbf{L})$$



Kivelä et al. 2014 J. Complex. Networks

$\mathbf{L} = \{L_a\}_{a=1}^{d}$

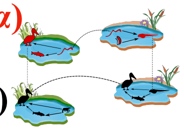
$V_M \subseteq V \times L_1 \times L_2 \cdots \times L_d$

$E_M \subseteq V_M \times V_M$

$M = (V_M, E_M, V, \mathbf{L})$

(u,α)

(u,β)



$$E_A = \{((u,\alpha),(v,\beta)) \in E_M | \alpha = \beta\}$$

$$E_C = E_M \setminus E_A$$

Kivelä et al. 2014 J. Complex. Networks

$\mathbf{L} = \{L_a\}_{a=1}^{d}$

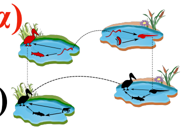
$V_M \subseteq V \times L_1 \times L_2 \cdots \times L_d$

$E_M \subseteq V_M \times V_M$

$M = (V_M, E_M, V, \mathbf{L})$

(u,α)

(u,β)



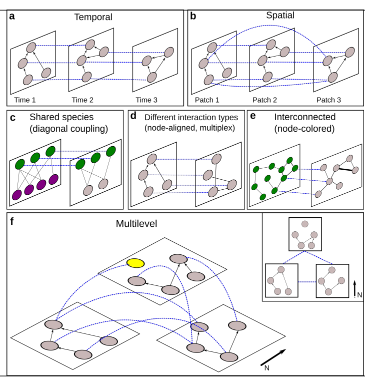
$$E_A = \{((u,\alpha),(v,\beta)) \in E_M | \alpha = \beta\}$$

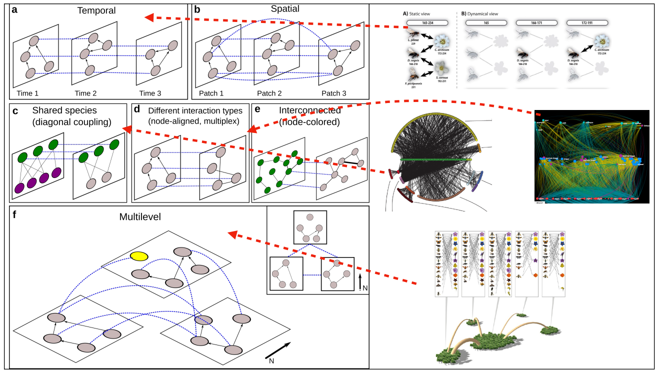
$$E_C = E_M \setminus E_A$$

$$E_T = \{((u,t),(v,t+\tau)) \in E_C\}$$

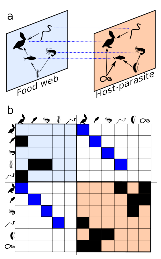
Temporal network

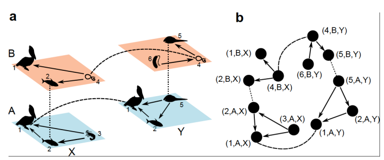
Kivelä et al. 2014 J. Complex. Networks



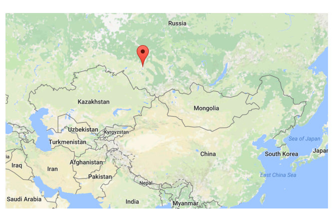


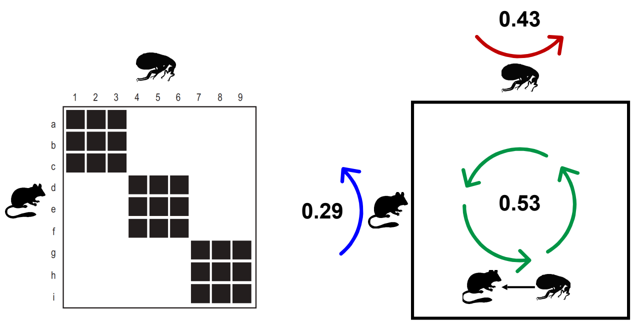
Multilayer networks can be represented as tensors (or supra-adjacency matrices)





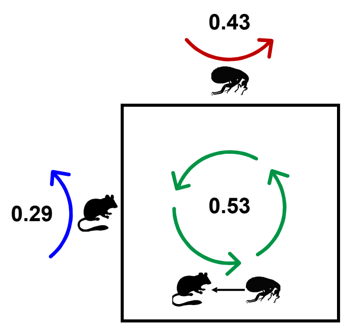
- 6 consecutive summers (1982-1987).
- 22 mammalian hosts.
- 56 ectoparasites (fleas and mites).



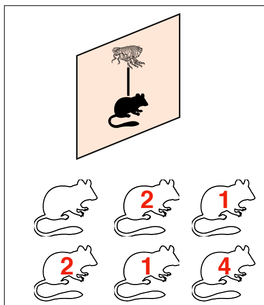


Pilosof et al. 2013, J. Anim Ecol.

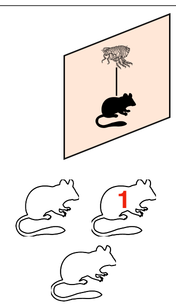
Does the structure of the host-parasite community evolve in time?



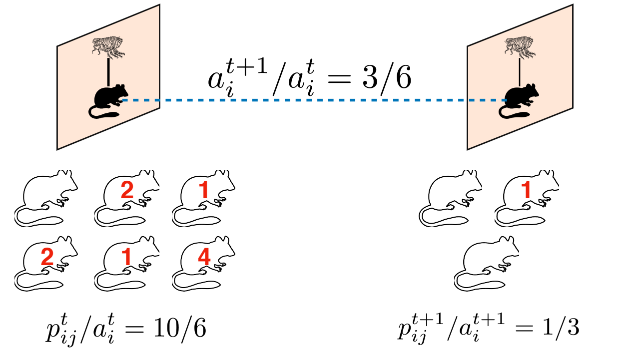
Pilosof et al. 2013, J. Anim Ecol.



$p_{ij}^{t}/a_i^{t} = 10/6$



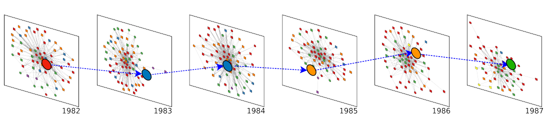
$p_{ij}^{t+1}/a_i^{t+1} = 1/3$



- **Intra-layer edges**: Incidence of parasite species in a host species.
  $m_{ij}^t = p_{ij}^t/a_i^t$
- **Inter-layer edges**: Relative change in abundance.
  $n_i^{t\to t+1} = a_i^{t+1}/a_i^t$
- The future infection of a host *i* with parasite *j:*

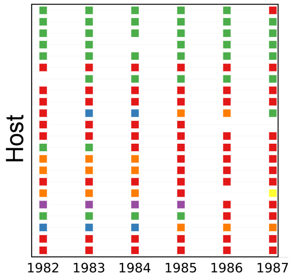
$$m_{ij}^{t,t+1} = \frac{p_{ij}^{t+1}}{a_i^{t+1}} = \frac{p_{ij}^{t+1}}{n_i^{t\to t+1}a_i^t} = \frac{n_j^{t\to t+1}p_j^t}{n_i^{t\to t+1}a_i^t}$$

Time-evolving structure of a host-parasite community



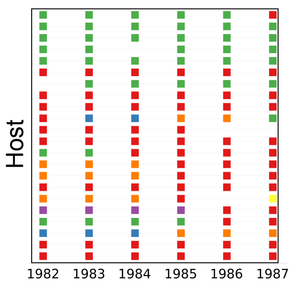
- ~6 modules with **non-random**, time-dependent structure.
- Species can change modules in time.

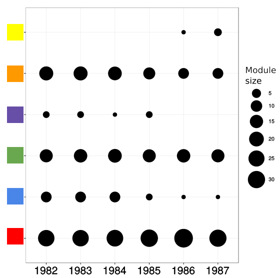
Network flexibility -- community structure evolves in time



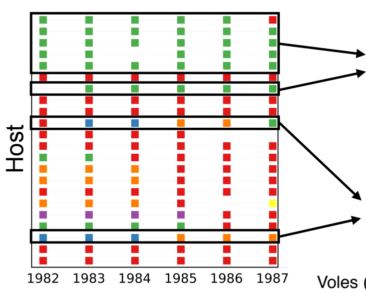
47% hosts and 35% parasites change modules at least once

Network flexibility -- community structure evolves in time





Network flexibility -- community structure evolves in time



Shrews (*Sorex spp.*)

Voles (*Myodes spp.*, *Arvicola spp.*)

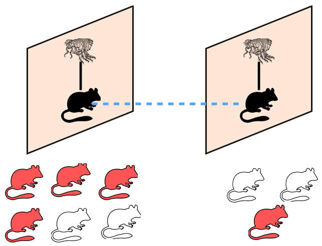
Non-flexible

- Support consistent parasite assemblages.

Flexible

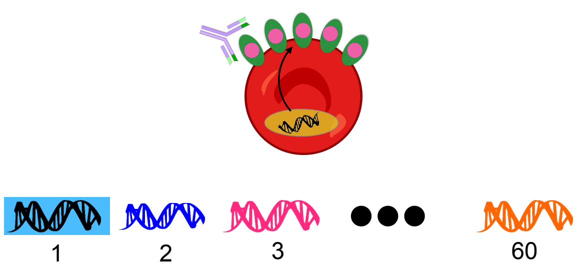
- Support variable parasite assemblages.
- Bridge infections between species and in time.

- Time-dependent distribution of parasites in hosts.
- The same species is functionally different at different times.

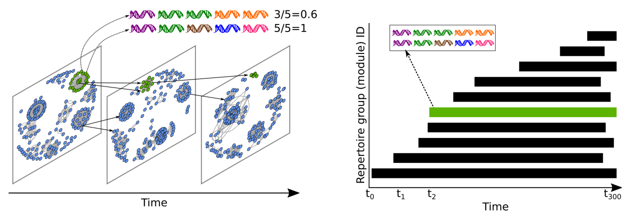


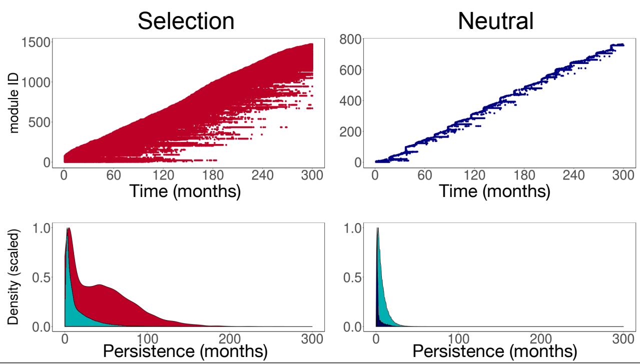
State nodes!

Revealing ecological niches using community detection



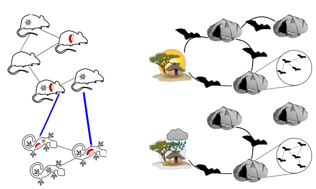
Revealing ecological niches using community detection





Applications

- Community ecology
- Biogeography
- Disease ecology
- Movement ecology
- Conservation biology



Key questions

- How do multiple interaction types affect the stability of communities?
- Will a multilayer approach change understanding of ecological concepts (e.g., “key-stone species”)?

Multilayer networks and global change ecology

- How does a focus on whole communities shift our understanding of ecosystem dynamics?
- How do interaction networks change across land-use gradients?
- How do dynamic processes spread across layers?
    - Disease
    - Extinctions and invasions

Hutchinson et al. (in prep)

Challenges

- Quantification of both intra- and inter-layer edges.
    - Common currency for multiple interactions/ processes.
- Large-scale data collection and curation.