Consequences of network structure on ecosystem functioning

Elisa Thébault

FRB FONDATION POUR LA RECHERCHE SUR LA BIODIVERSITÉ

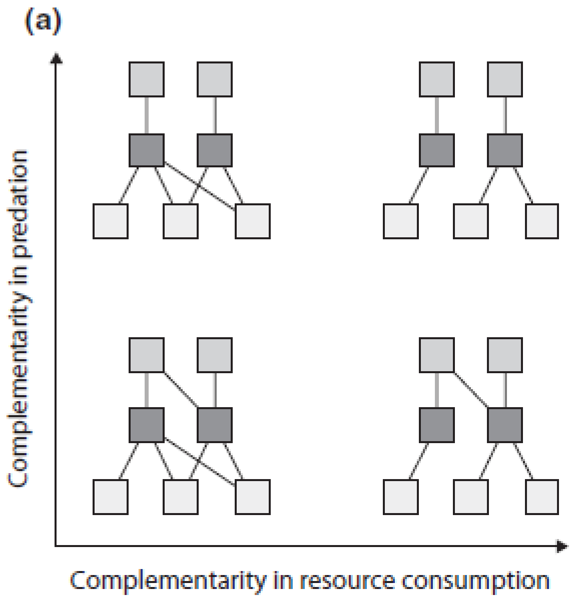
CESAB CENTRE FOR THE SYNTHESIS AND ANALYSIS OF BIODIVERSITY

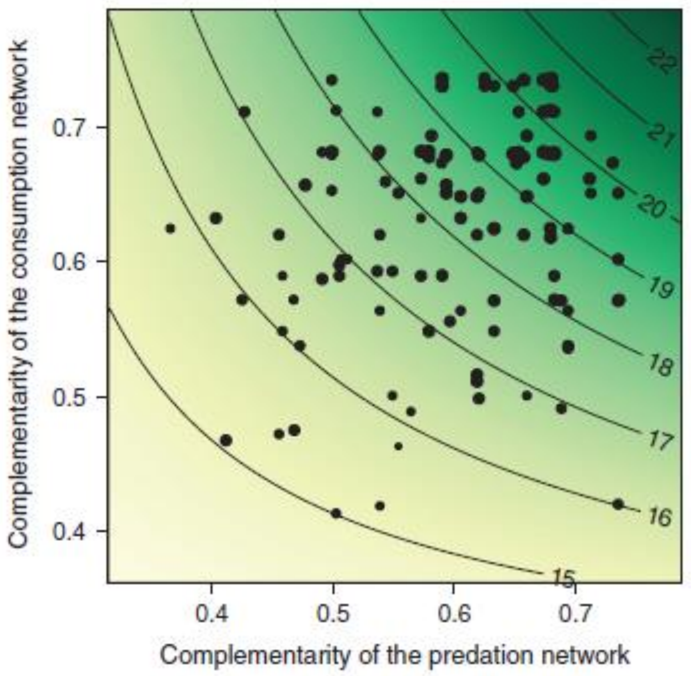
Diversity and ecosystem functioning

Tilman et al. (2006)

Hector et al. (2010)

Diversity and ecosystem functioning in ecological networks





Poisot et al. 2013

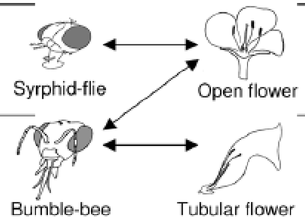
Diversity of pollinators and functioning

PLOS BIOLOGY January 2006 | Volume 4 | Issue 1 | e1

Functional Diversity of Plant–Pollinator Interaction Webs Enhances the Persistence of Plant Communities

Colin Fontaine[1,2*], Isabelle Dajoz[1,2], Jacques Meriguet[1,2], Michel Loreau[2,3]

Pollinators species and groups	Mouthpart length (mm ± S.E.)	Theoretical pollination network	Plants species and groups	Accessibility pollen	Accessibility nectar
Sphaerophoria sp.	2.66 ± 0.35		*M. officinalis*	easy	easy
E. balteatus	2.3 ± 0.20		*E. cicutarium*	easy	easy
E. tenax	5.47 ± 0.29		*R. raphanistrum*	easy	difficult
B. terrestris	9.02 ± 0.19		*M. guttatus*	easy	difficult
B. hortorum	9.21 ± 1.02		*M. sativa*	difficult	difficult
B. lapidarius	8.10 ± 0.86		*L. corniculatus*	difficult	difficult



Diversity of pollinators and functioning

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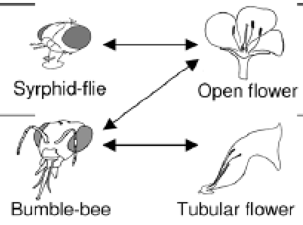
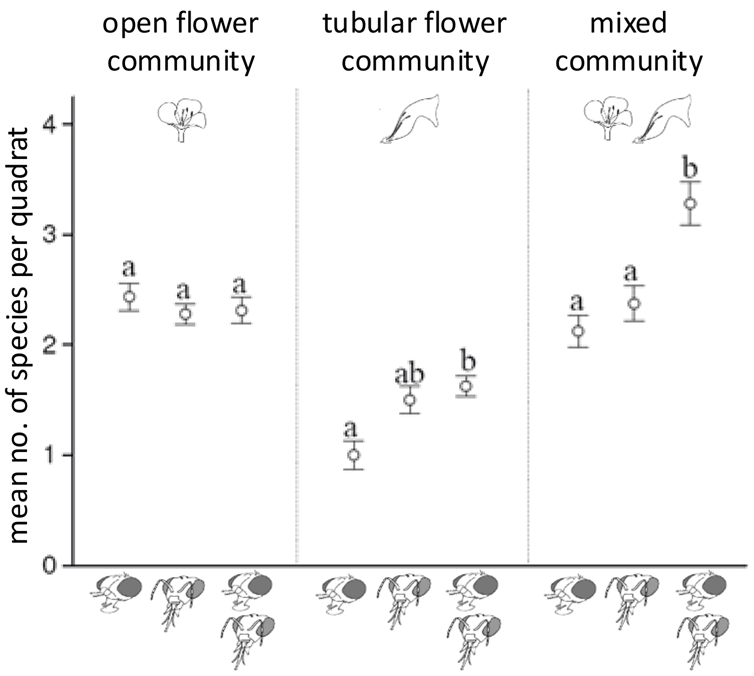
E. balteatus	2.3 ± 0.20	Syrphid-flie / Open flower	*E. cicutarium*	easy	easy
E. tenax	5.47 ± 0.29		*R. raphanistrum*	easy	difficult
B. terrestris	9.02 ± 0.19		*M. guttatus*	easy	difficult
B. hortorum	9.21 ± 1.02		*M. sativa*	difficult	difficult
B. lapidarius	8.10 ± 0.86	Bumble-bee / Tubular flower	*L. corniculatus*	difficult	difficult





Diversity of pollinators and functioning

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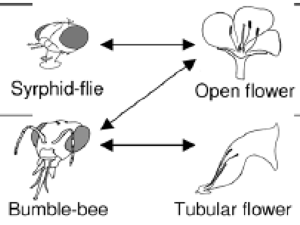
Sphaerophoria sp.	2.66 ± 0.35		*M. officinalis*	easy	easy
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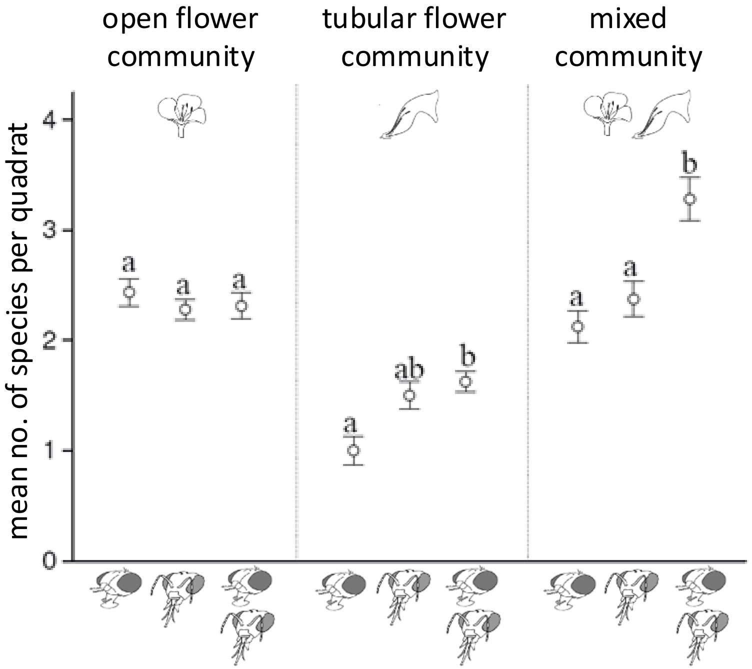
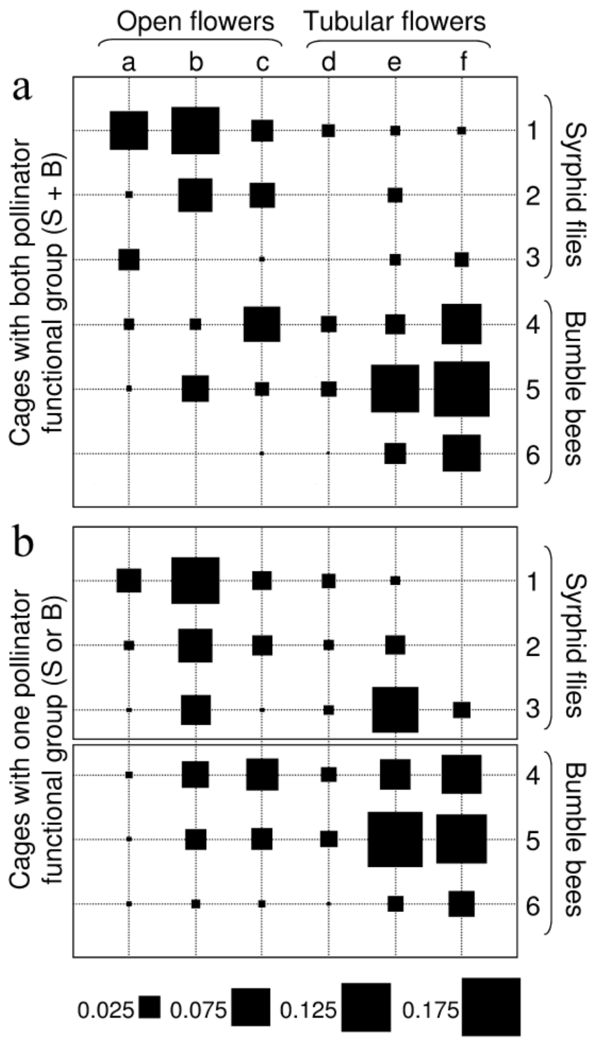
B. lapidarius	8.10 ± 0.86		*L. corniculatus*	difficult	difficult



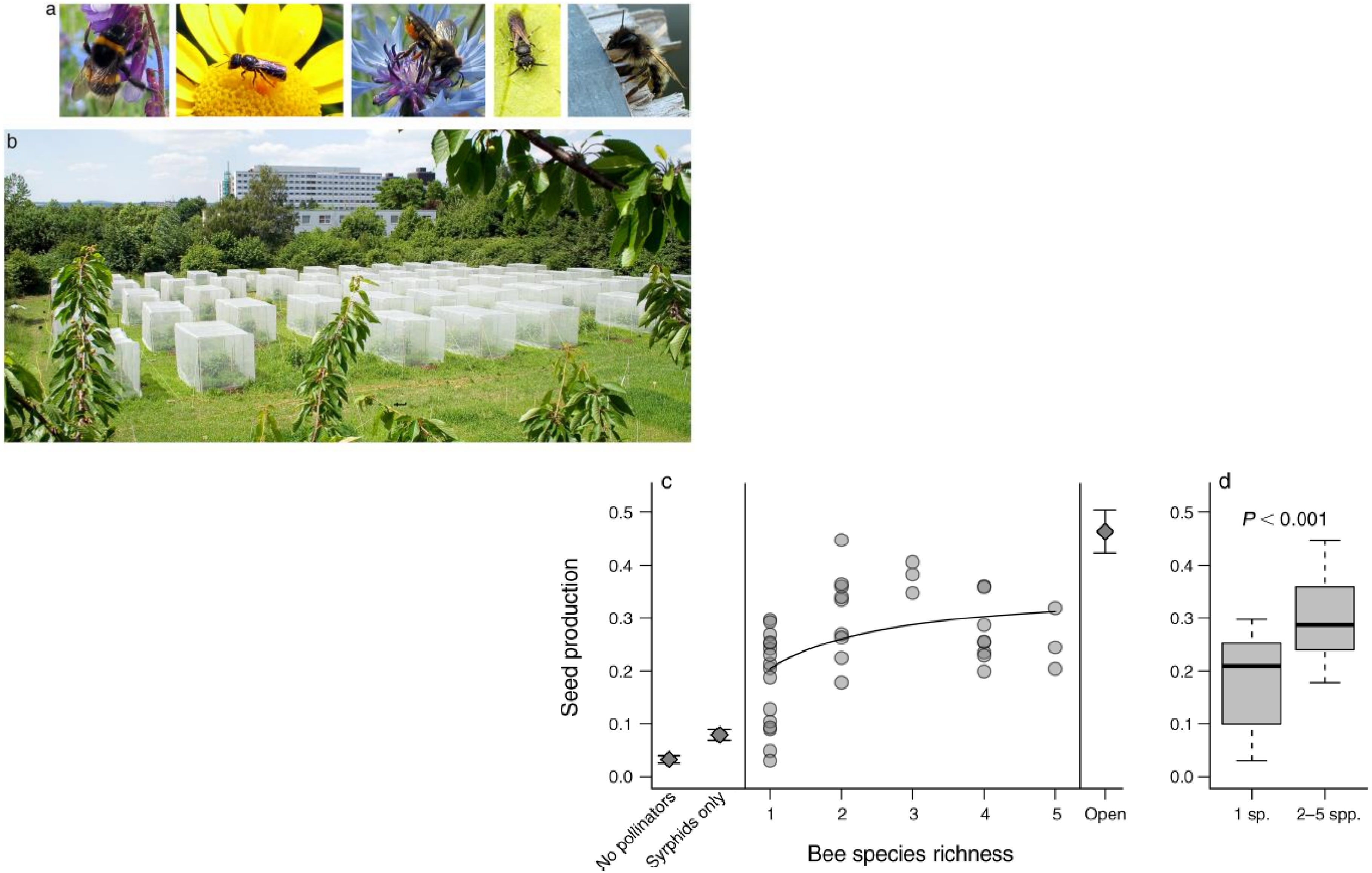


Diversity of pollinators and functioning

Bee diversity effects on pollination depend on functional complementarity and niche shifts

Jochen Fründ,[1,5] Carsten F. Dormann,[2,3] Andrea Holzschuh,[1,4] and Teja Tscharntke[1]

Ecology, 94(9), 2013, pp. 2042–2054



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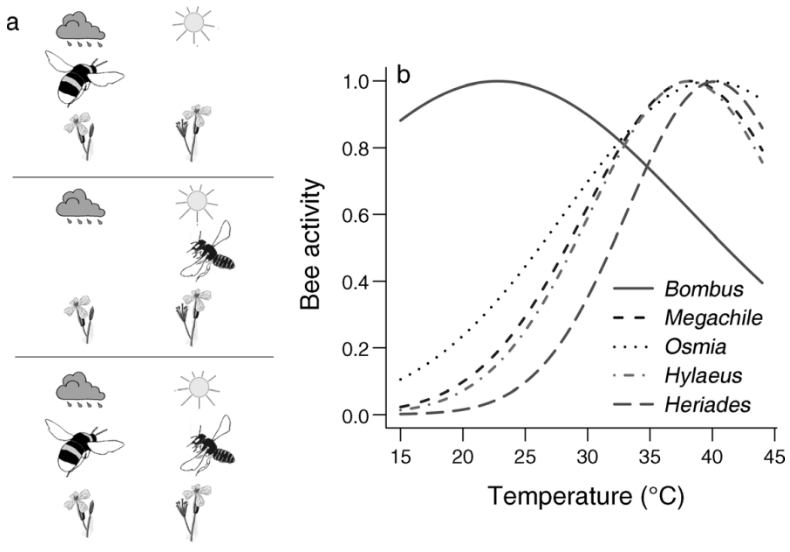
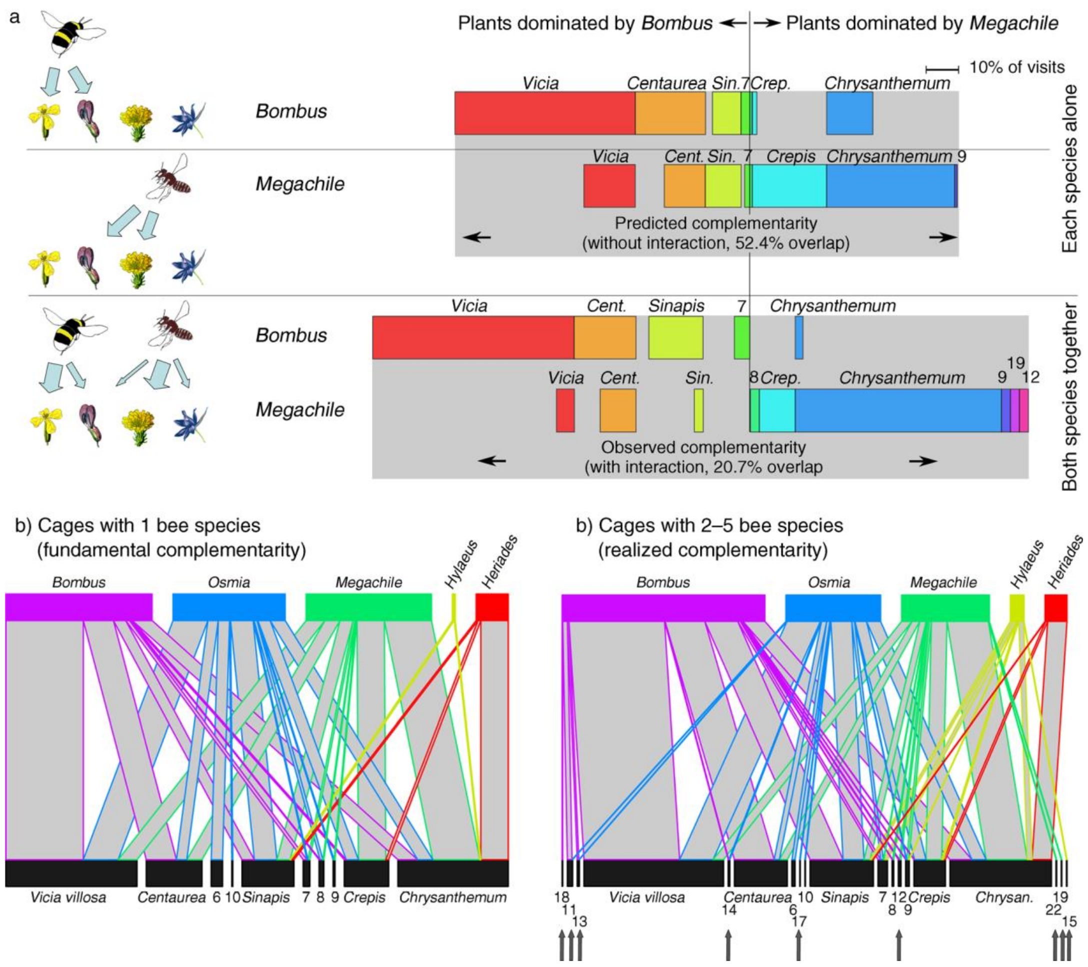


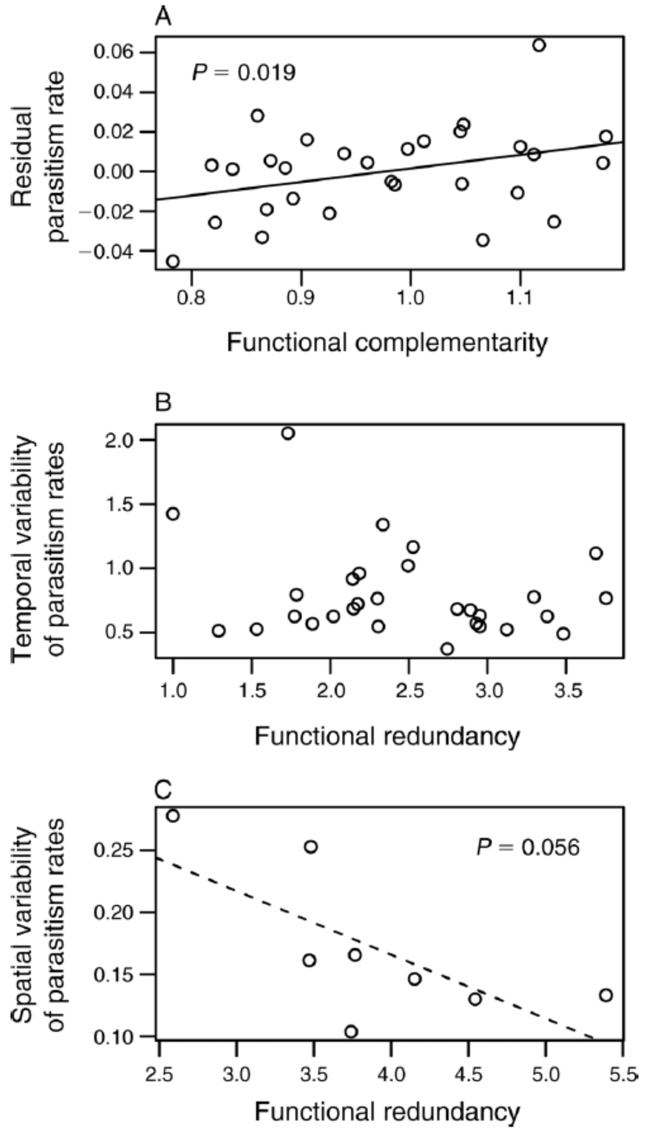


The structure of host-parasitoid networks and functioning

Complementarity and redundancy of interactions enhance attack rates and spatial stability in host–parasitoid food webs

Guadalupe Peralta,[1,6] Carol M. Frost,[1] Tatyana A. Rand,[2] Raphael K. Didham,[3,4] and Jason M. Tylianakis[1,5]

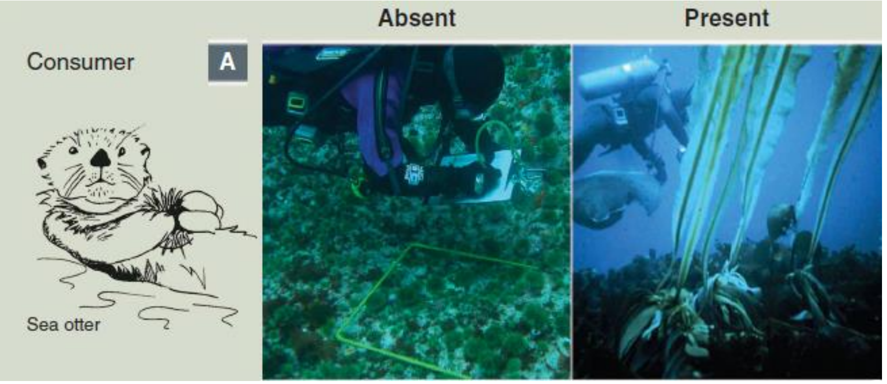
Peralta et al. 2014



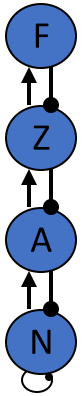
Network structure allows to describe complementarity and redundancy among species

→ **Direct links with the study of ecosystem functions and stability**

Cascading effects in networks?
Network structure and indirect interactions



Estes et al. (2011)

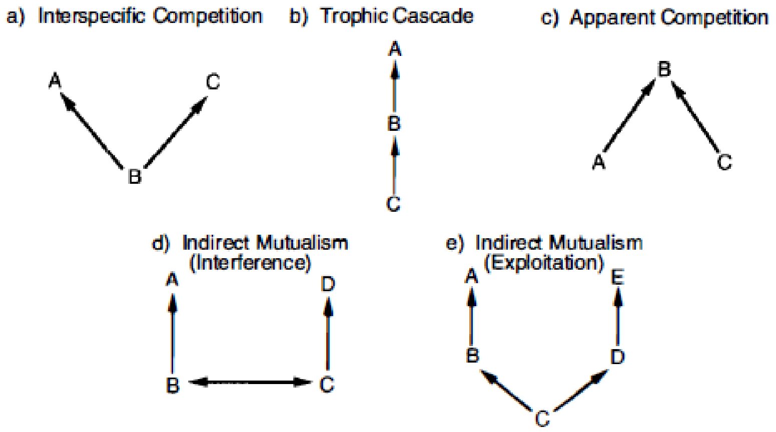


Understanding indirect effects: a central issue in ecological networks

Annu. Rev. Ecol. Syst. 1994. 25:443–66

THE NATURE AND CONSEQUENCES OF INDIRECT EFFECTS IN ECOLOGICAL COMMUNITIES

J. Timothy Wootton



Ecology, 90(9), 2009, pp. 2426–2433

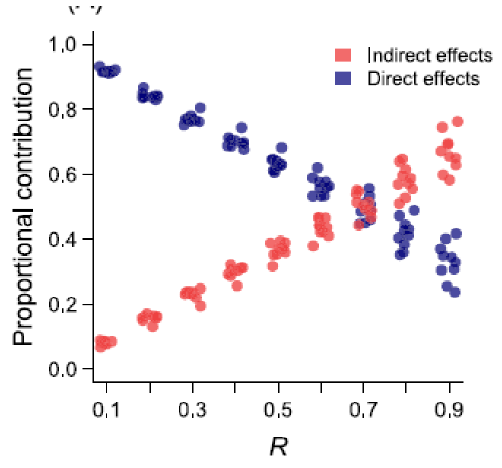
Press perturbations and indirect effects in real food webs

José M. Montoya,[1,2,6] Guy Woodward,[2] Mark C. Emmerson,[3,4] and Ricard V. Solé[5]

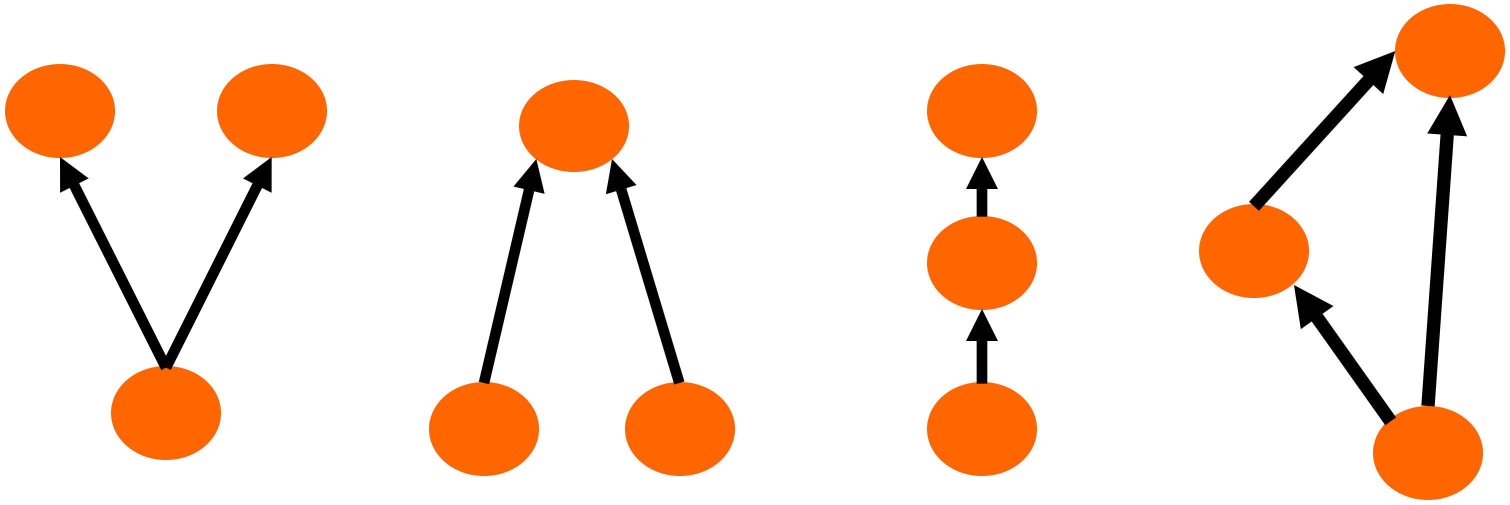
Ecology, 101(7), 2020, e03080

The indirect paths to cascading effects of extinctions in mutualistic networks

Mathias M. Pires,[1,11] James L. O'Donnell,[2] Laura A. Burkle,[3] Cecilia Díaz-Castelazo,[4] David H. Hembry,[5,6] Justin D. Yeakel,[7] Erica A. Newman,[6] Lucas P. Medeiros,[8] Marcus A. M. de Aguiar,[9] and Paulo R. Guimarães Jr.[10]



Understanding direct and indirect effects: studies on network motifs



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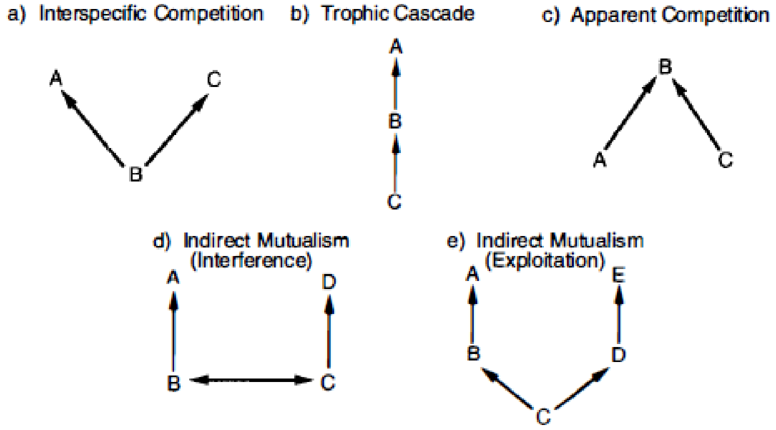

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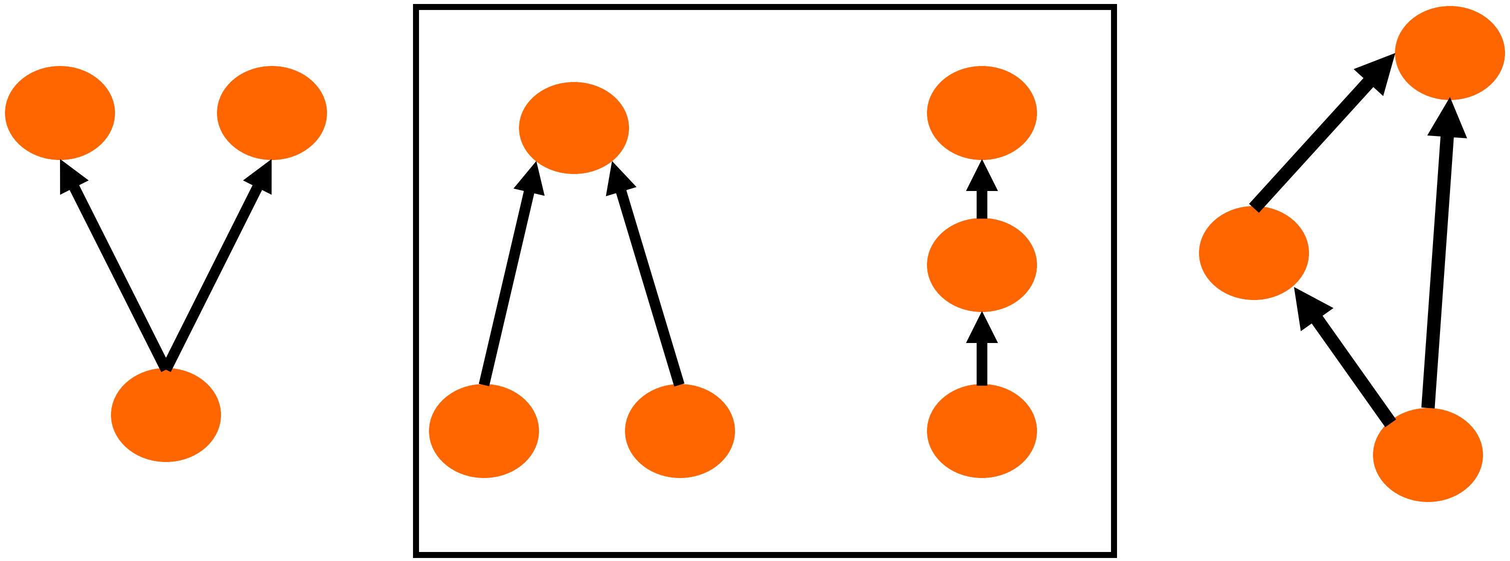

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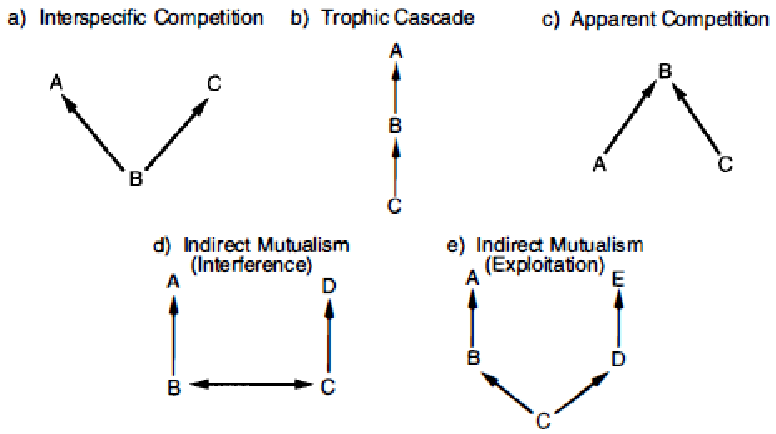


Effects can differ from predictions

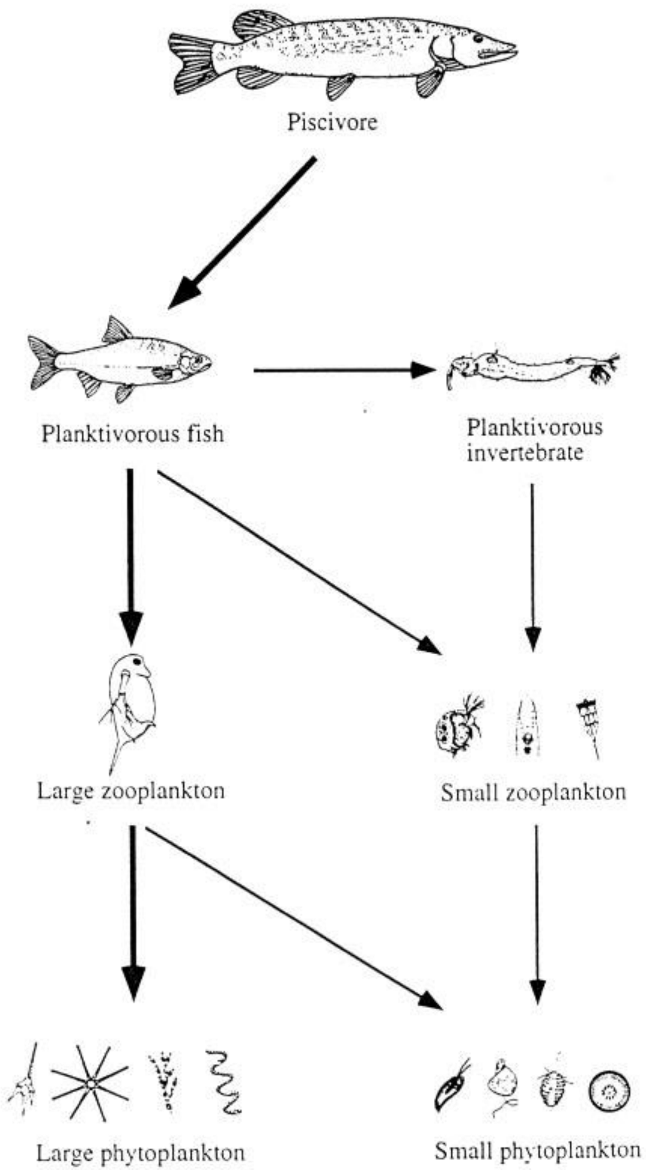
Table 1 Qualitative effects of nutrient enrichment as predicted by two linear food-chain models and corresponding experimental results in mesocosms

	Model predictions		Experimental results	
	Prey dependence	Ratio dependence	Without fish	With fish
Carnivores	+	+	–	§
Herbivores	0	+	ns	ns
Autotrophs	+	+	ns	ns
Phosphorus	0	+	ns	+

Qualitative effects are indicated by their sign: +, 0 and – denote a positive effect, no effect and a negative effect, respectively, of nutrient enrichment on density. Experimental results: + and – denote a significant positive effect and a significant negative effect, respectively ($P \leq 0.05$); brackets, marginally significant effect ($0.05 < P \leq 0.10$); ns, nonsignificant effect ($P > 0.10$); §, no test possible because the sum of invertebrate carnivores density and fish biomass is senseless.

Hulot et al. Nature 2000

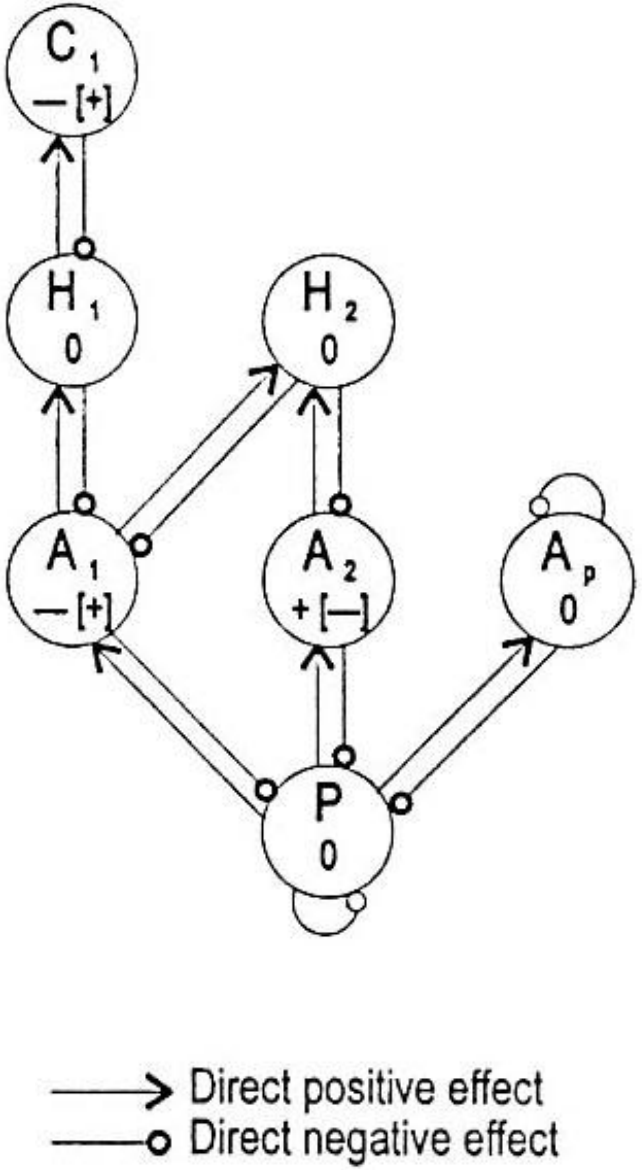
Need to consider food web structure



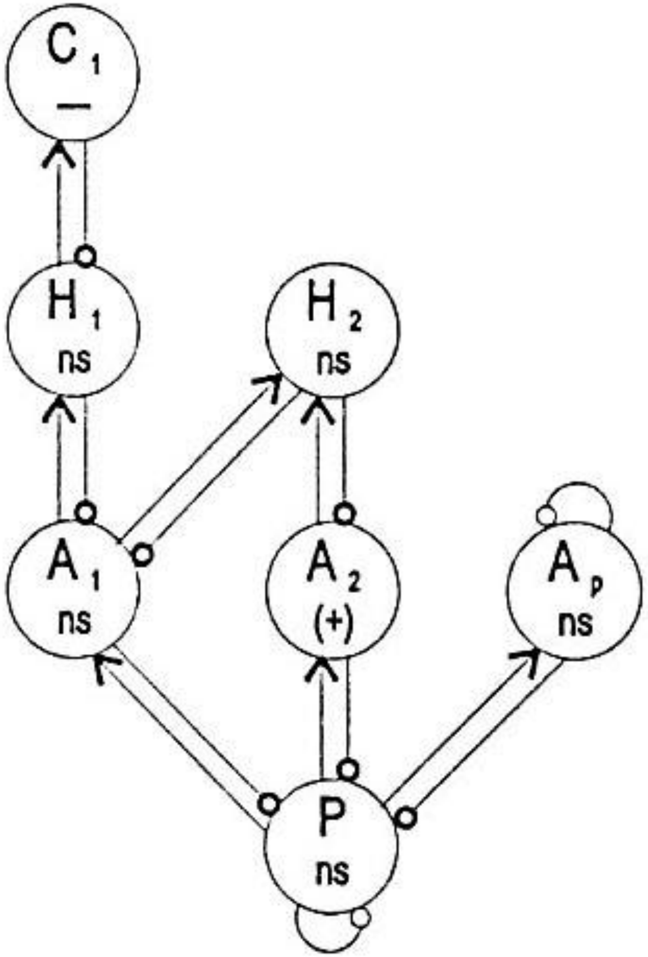
Simplified pelagic food web

(from Carpenter et Kitchell, 1993,
The trophic cascade in lakes,
Cambridge University Press).

Model

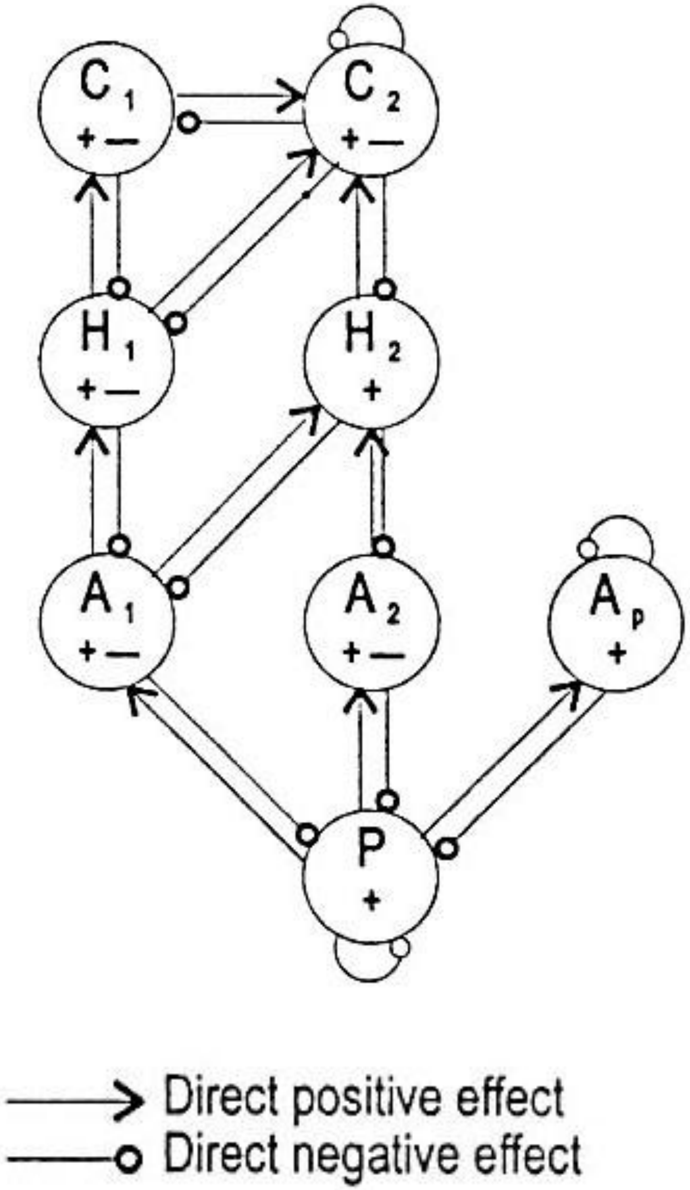


Experimental results



Hulot et al. Nature 2000

Model



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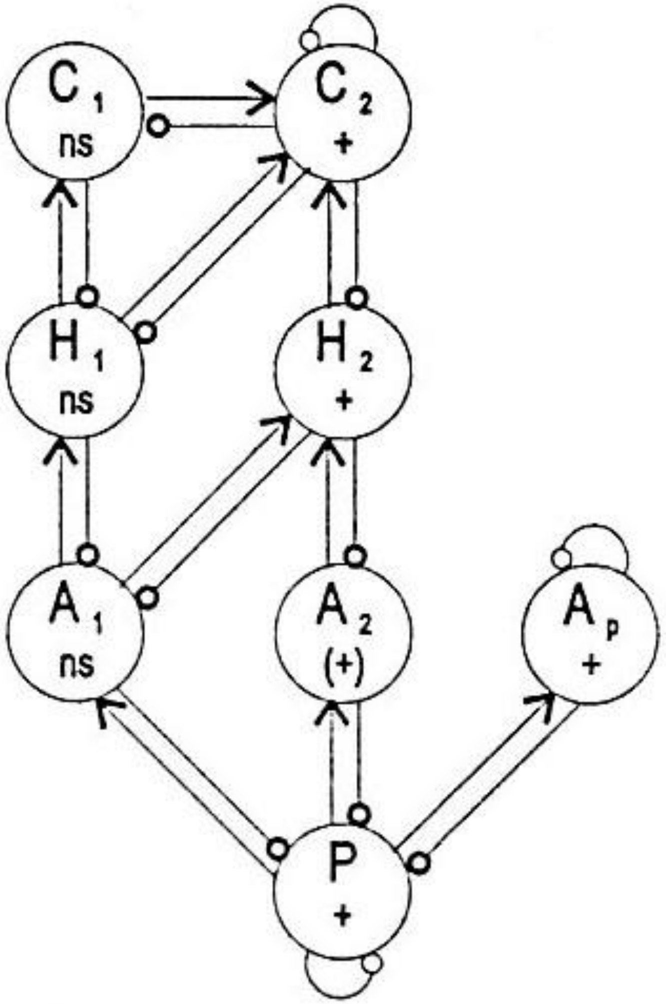

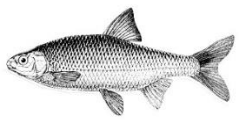

Hulot et al. Nature 2000

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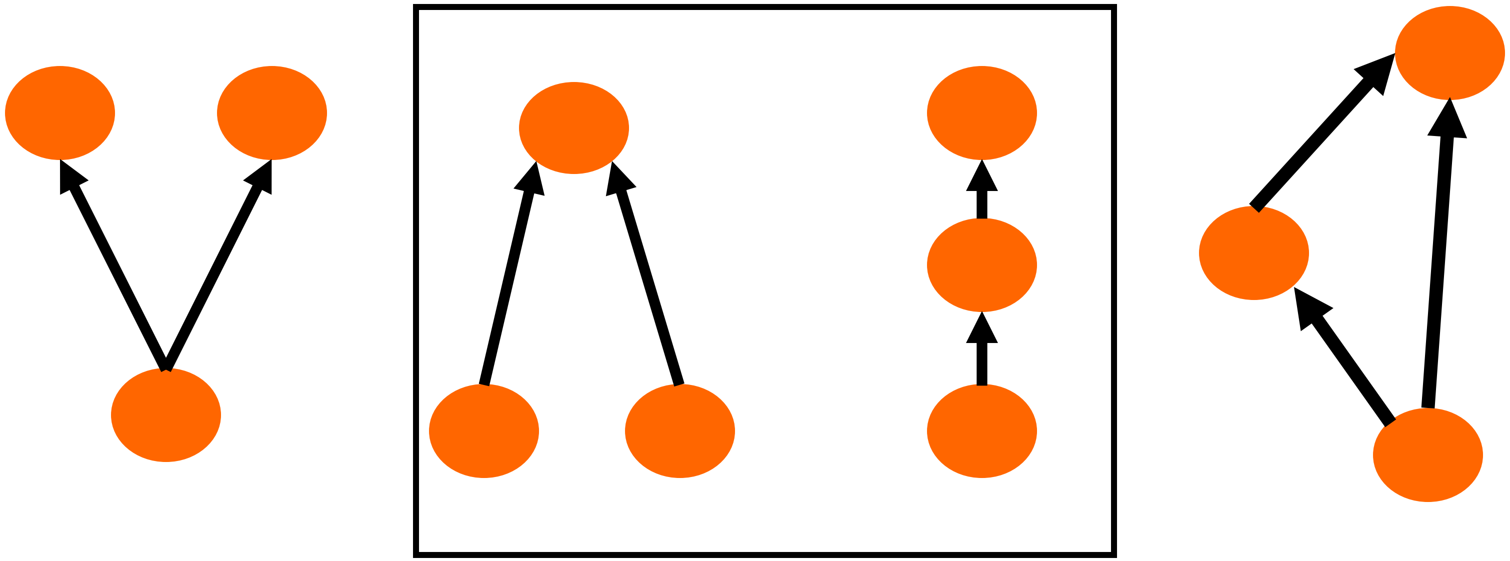

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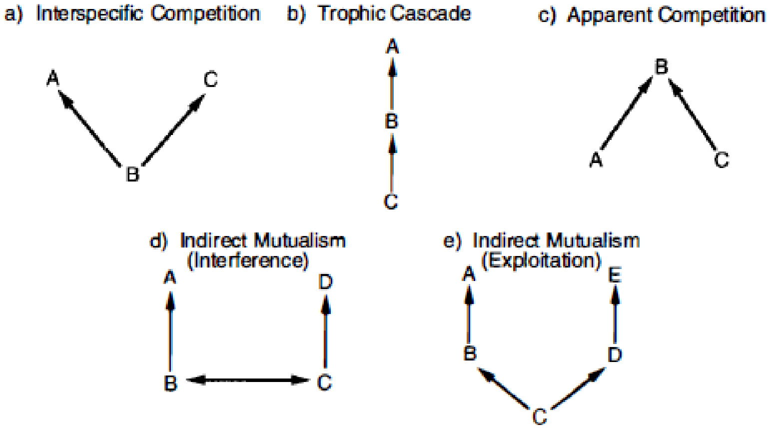
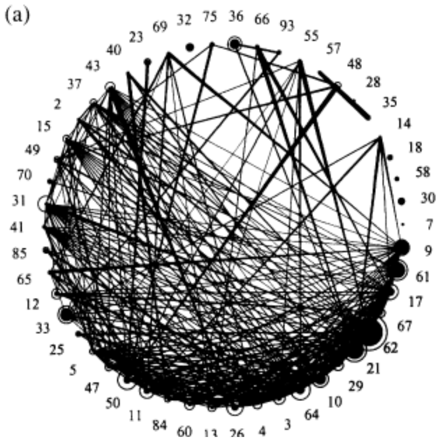
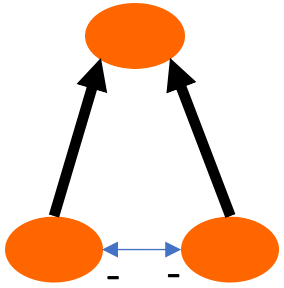
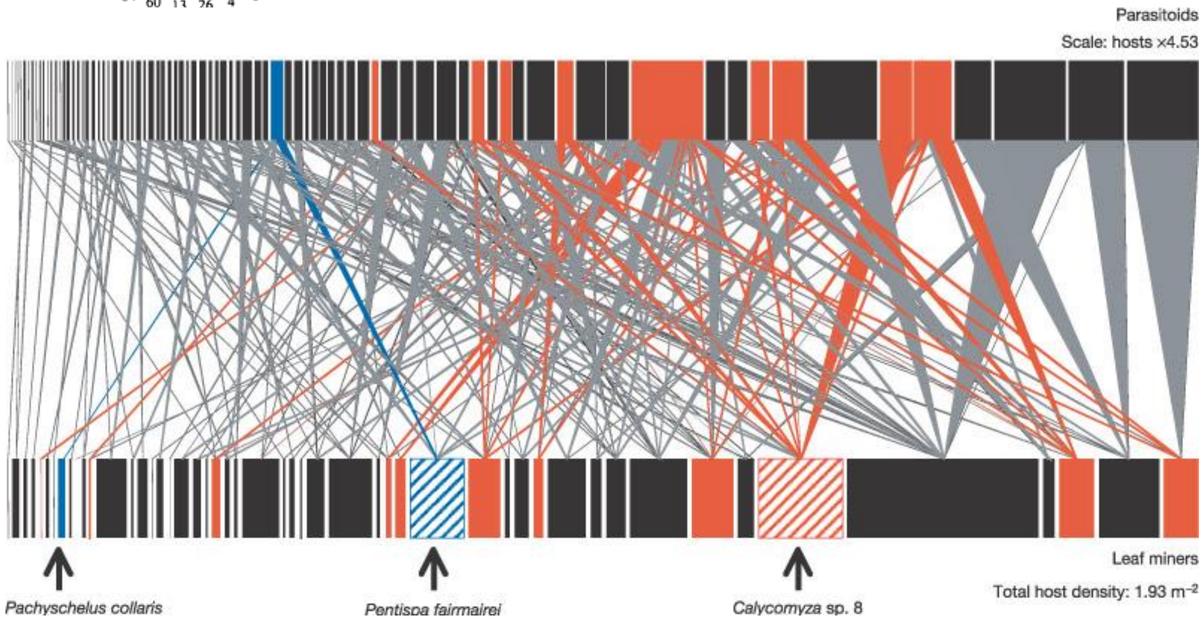


Understanding direct and indirect effects
apparent competition







Morris et al. 2004

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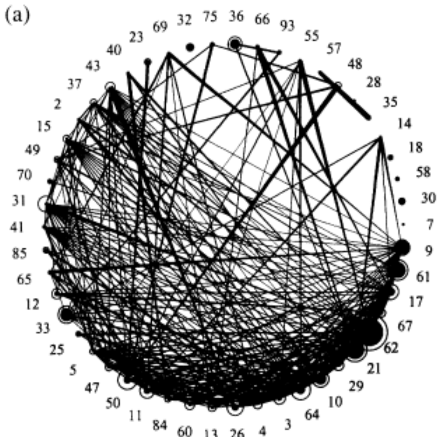
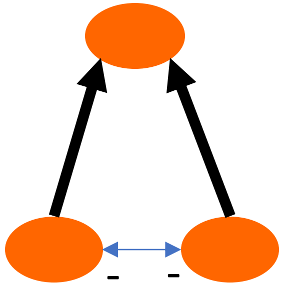
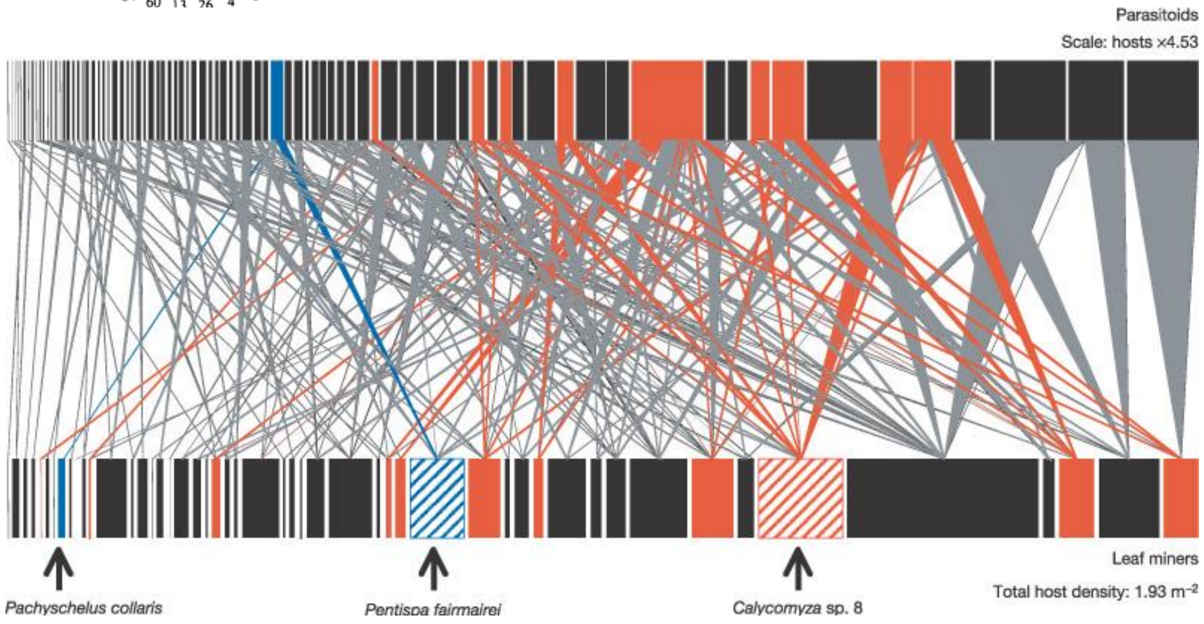
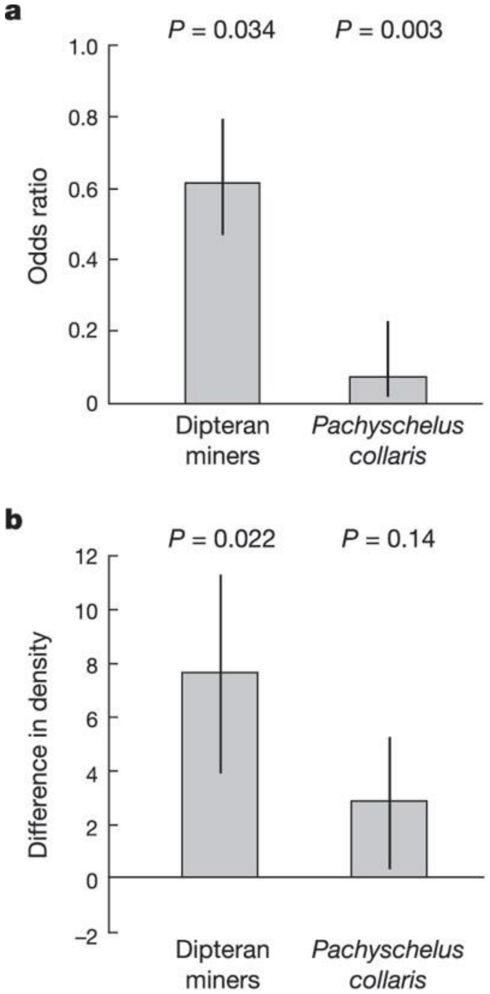
apparent competition





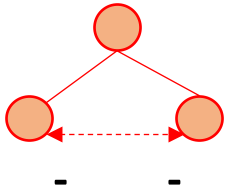




Morris et al. 2004

Important applications for management

Available online at www.sciencedirect.com
SCIENCE DIRECT
Agriculture, Ecosystems and Environment 102 (2004) 205–212
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee



Enhancing parasitism of wheat aphids through apparent competition: a tool for biological control

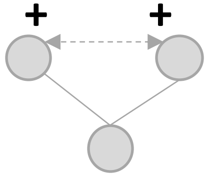
Alain Langer[1], Thierry Hance*

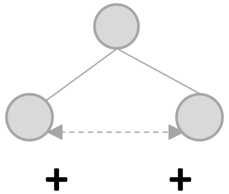
Ecology Letters, (2008) **11**: 690–700 doi: 10.1111/j.1461-0248.2008.01184.x

LETTER

Apparent competition can compromise the safety of highly specific biocontrol agents

Carvalheiro et al. (2008)





ECOLOGY LETTERS
Ecology Letters, (2014) **17**: 1389–1399 doi:10.1111/ele.12342

LETTER

The potential for indirect effects between co-flowering plants via shared pollinators depends on resource abundance, accessibility and relatedness

Carvalheiro et al. (2014)

ELSEVIER
GfÖ
GfÖ Ecological Society of Germany, Austria and Switzerland
Basic and Applied Ecology 63 (2022) 36–48
Basic and Applied Ecology
www.elsevier.com/locate/baae

RESEARCH PAPER

Co-flowering plants support diverse pollinator populations and facilitate pollinator visitation to sweet cherry crops

Amy-Marie Gilpin[a,*], Corey O'Brien[a], Conrad Kobel[b], Laura E. Brettell[a,c], James M. Cook[a], Sally A. Power[a]

Estimating potential indirect competition among prey the Muller's index

The Structure of an Aphid-Parasitoid Community

C. B. Muller; I. C. T. Adriaanse; R. Belshaw; H. C. J. Godfray

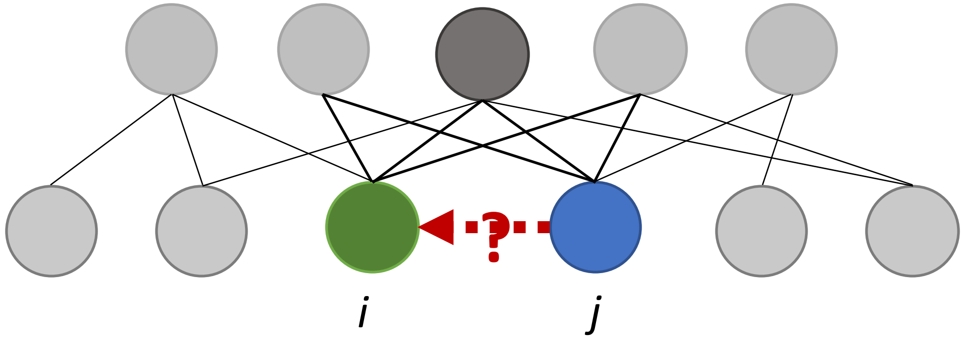
The Journal of Animal Ecology, Vol. 68, No. 2 (Mar., 1999), 346-370.

Indirect effect of species *j* on species *i*:

$$d_{ij} =$$

Predators or parasitoids

Prey



Estimating potential indirect competition among prey
the Muller's index

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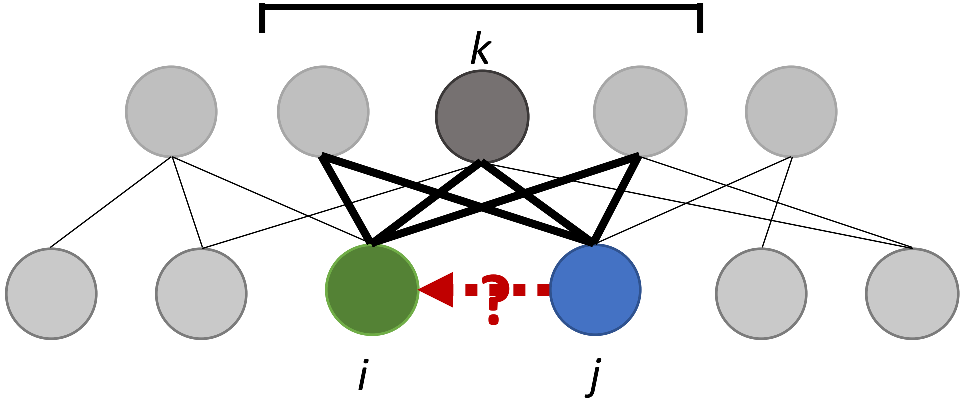
$$d_{ij} = \sum_{k} \left(\qquad \qquad \right)$$

Sum over all shared predators

Predators or parasitoids

Prey



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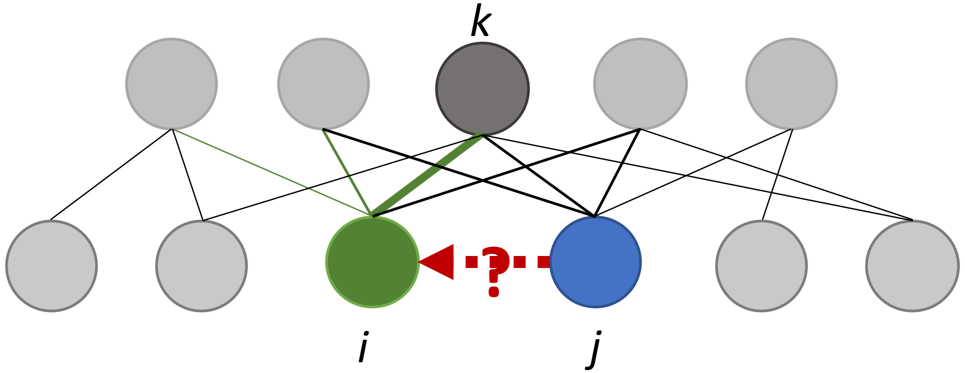
$$d_{ij} = \sum_k \left(\boxed{\frac{\alpha_{ik}}{\sum_l \alpha_{il}}} \times \qquad \right)$$

Fraction of predators of species *i* that belong to predator species *k*

Predators or parasitoids

Prey



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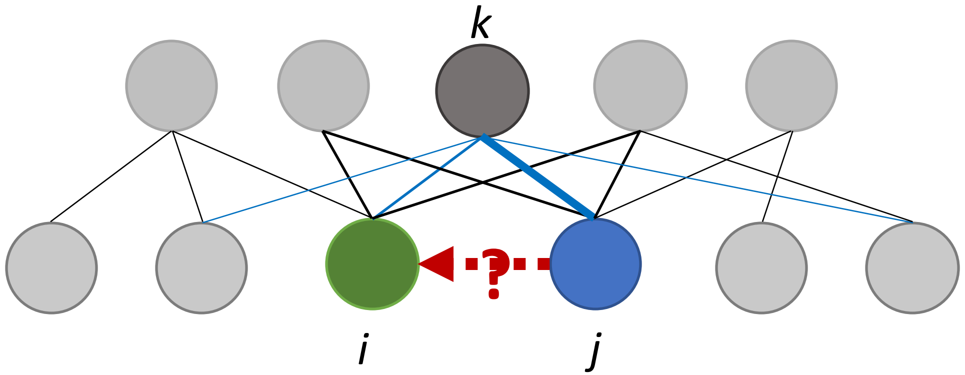
$$d_{ij} = \sum_k \left(\boxed{\frac{\alpha_{ik}}{\sum_l \alpha_{il}}} \times \boxed{\frac{\alpha_{jk}}{\sum_m \alpha_{mk}}} \right)$$

Fraction of predators of species *i* that belong to predator species *k*

Fraction of predator species *k* attacking species *j*

Predators or parasitoids

Prey



Estimating potential indirect competition among prey
the Muller's index

Indirect effect of species *j* on species *i*:

$$d_{ij} = \sum_k \left(\frac{\alpha_{ik}}{\sum_l \alpha_{il}} \times \frac{\alpha_{jk}}{\sum_m \alpha_{mk}} \right)$$

$$d_{ji} \neq d_{ij}$$

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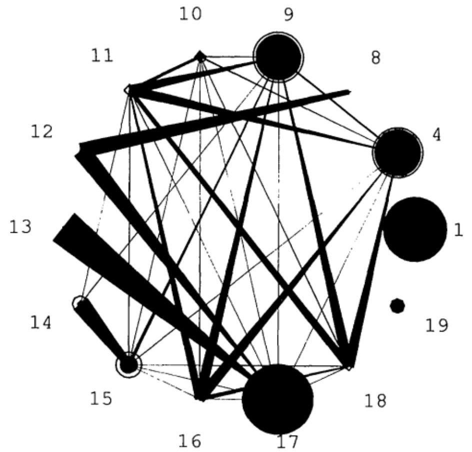

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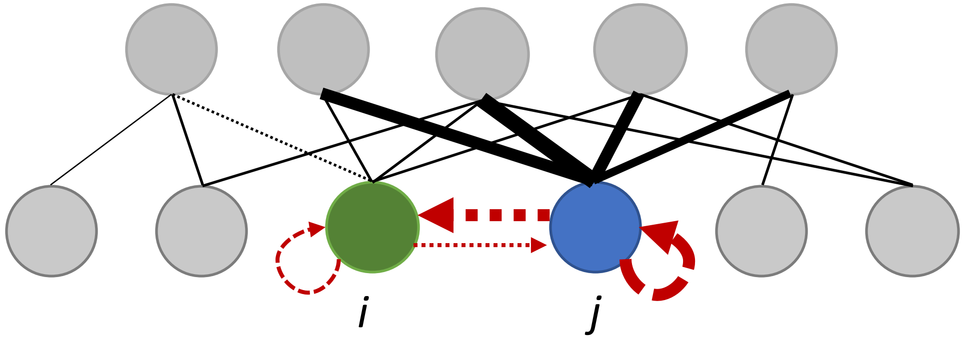
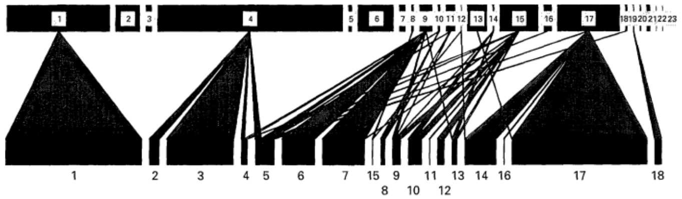


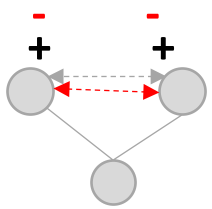


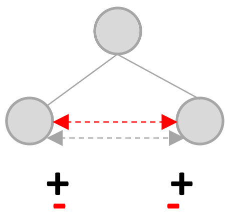
Primary parasitoids (scale: aphids × 58)

Competition or facilitation in plant-pollinator networks?

- Complex indirect interactions among plants and among pollinators, importance of the balance between mutualism and competition

Bastolla et al. (2009)   Valdovinos et al. (2016)





Competition or facilitation in plant-pollinator networks?

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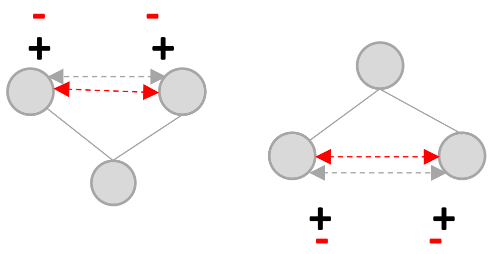

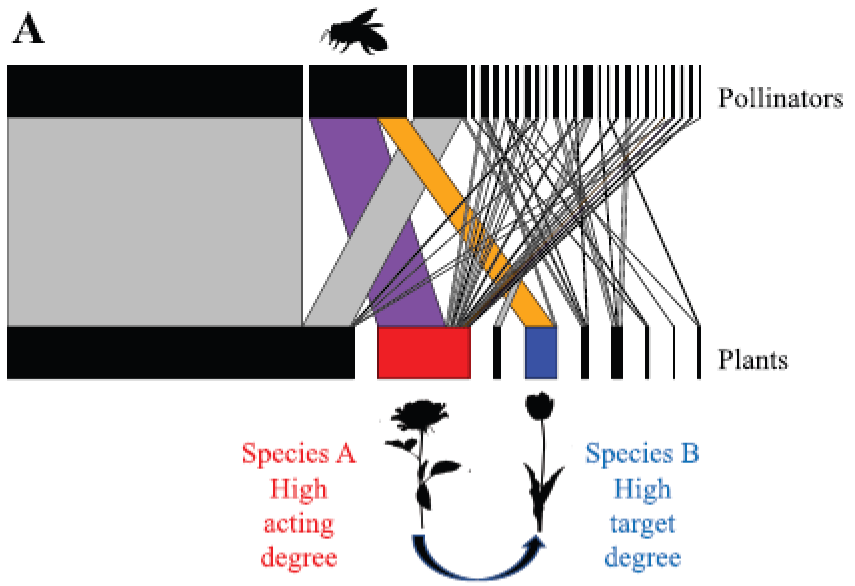

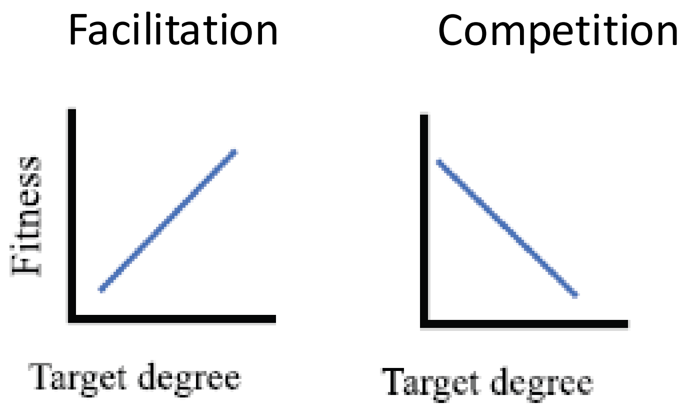

Bergamo et al. 2021

Competition or facilitation in plant-pollinator networks?

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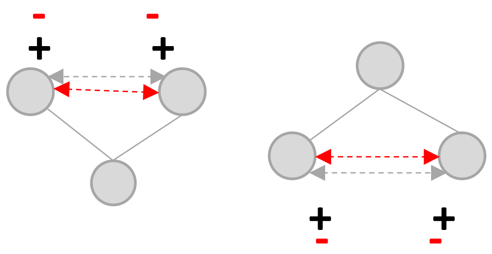
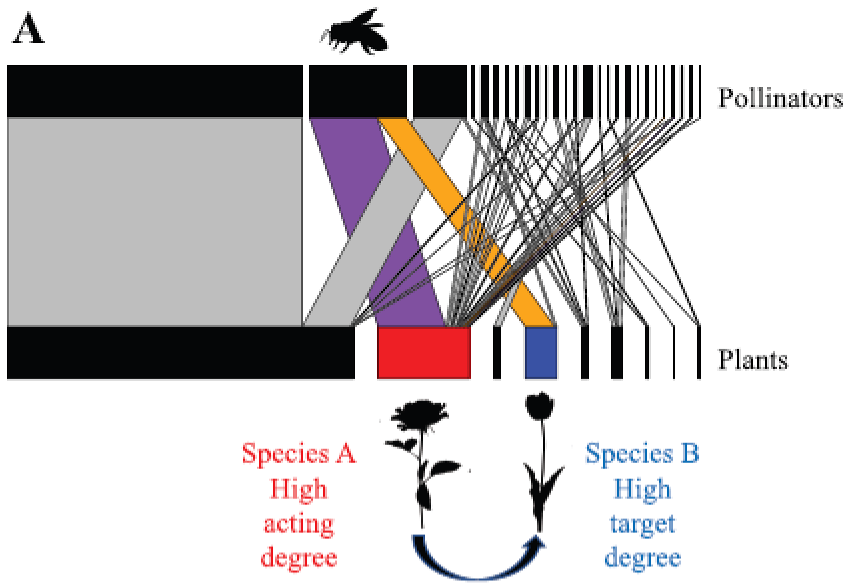
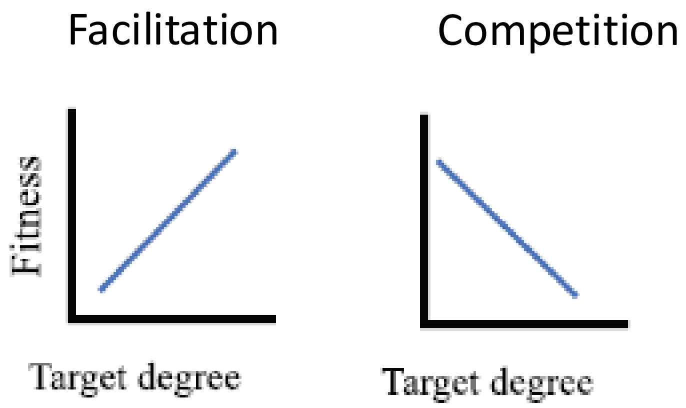
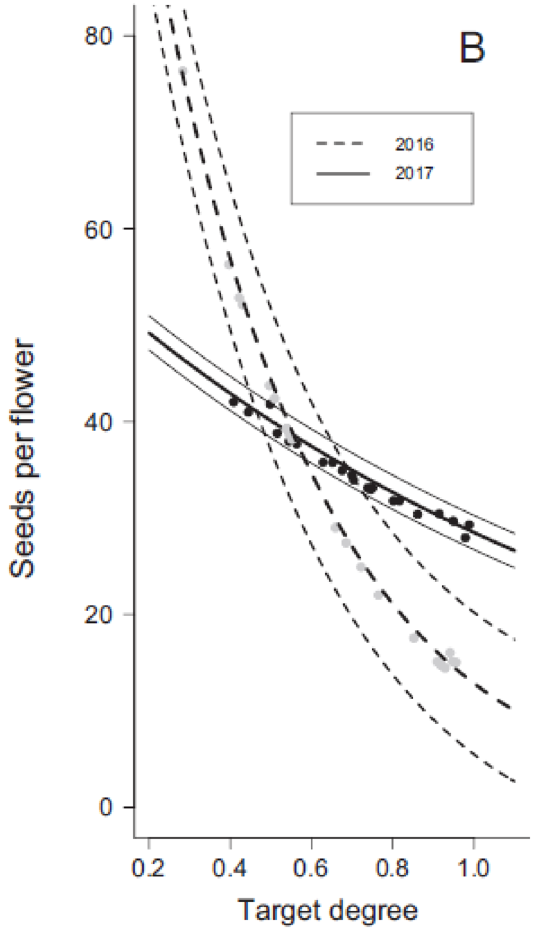


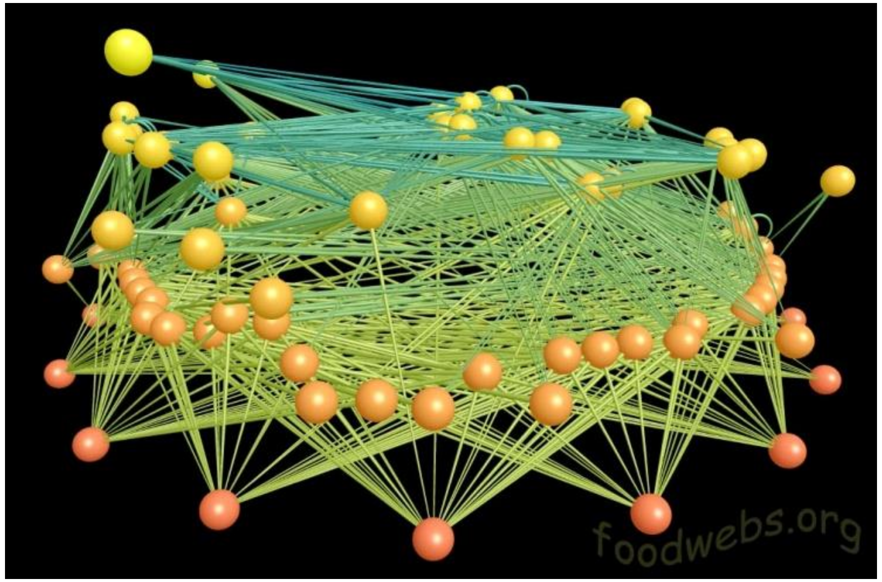


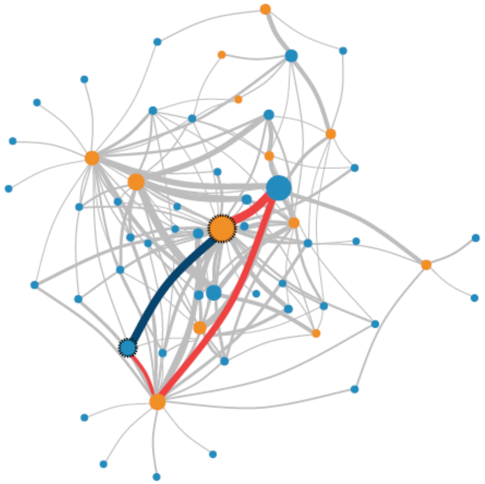




Bergamo et al. 2021

Predicting cascading effects in complex ecological networks?





Pires et al. (2020)

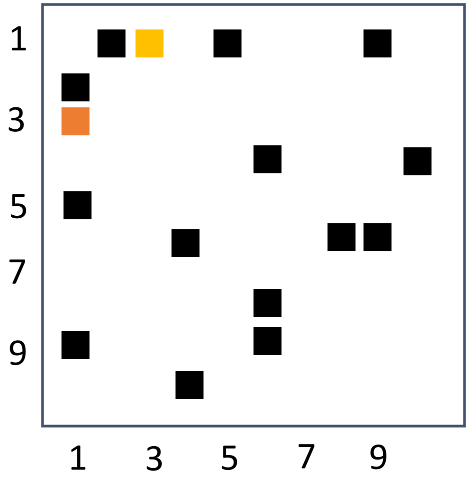
- ➢ Need for a dynamical perspective and accounting for long indirect pathways

Interaction coeff.

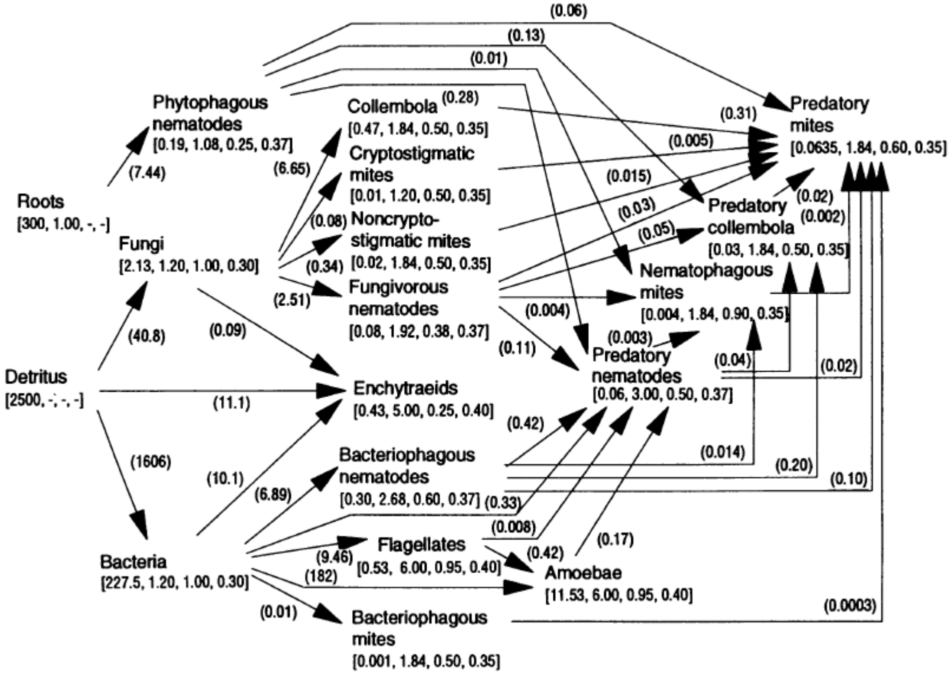
$$\frac{dB_i}{dt} = b_iB_i + \sum_{j=1}^{n} c_{ij}B_jB_i$$

$$\alpha_{ij} = \left(\frac{\partial \frac{dB_i}{dt}}{\partial B_j}\right)^*$$

Interaction strength



Terms of the Jacobian



$$\alpha_{ij} = c_{ij}B_i^*$$

Per capita effect of pred j on prey i

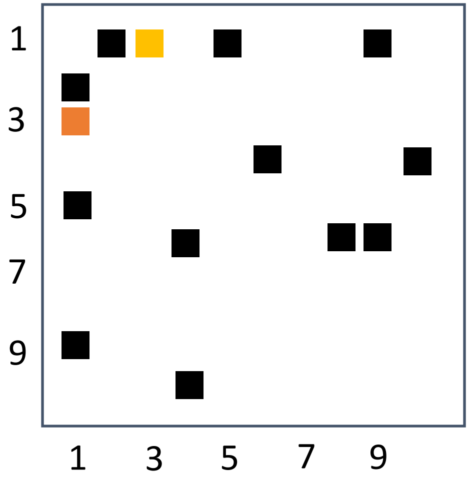
$$\alpha_{ji} = c_{ji}B_j^*$$

Per capita effect of prey i on pred j

De Ruiter et al. 1995 Science

Estimating direct and indirect effects in networks

Jacobian

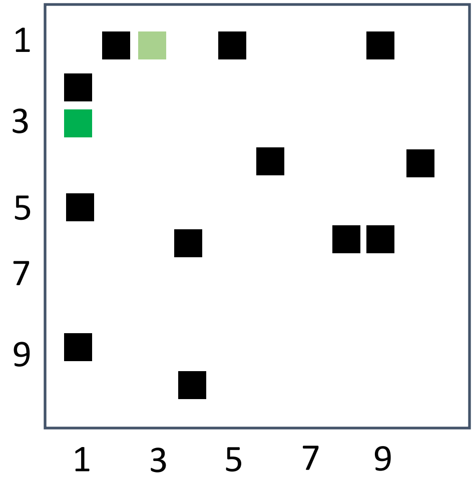


Per capita **direct** effect of pred j on prey i

Per capita **direct** effect of prey i on pred j

Inverse of the Jacobian

Sensitivity matrix = (Jacobian)$^{-1}$

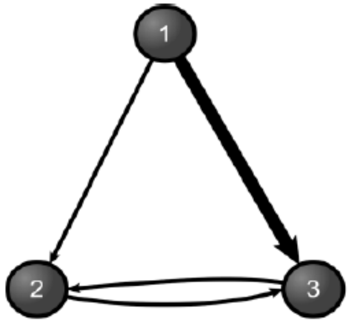


Net effect of pred j on prey i

Net effect of prey i on pred j

Nakajima and Higashi (1995)

« Diffuse effects in food webs »



$$\mathbf{C} = \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \left[\begin{array}{ccc} 0 & - & - \\ + & 0 & - \\ + & - & 0 \end{array}\right] \end{array} \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \qquad \mathbf{C}^{-1} = \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \left[\begin{array}{ccc} \ldots & - & + \\ \ldots & \ldots & - \\ \ldots & \ldots & \ldots \end{array}\right] \end{array} \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array}$$

Montoya et al. 2009

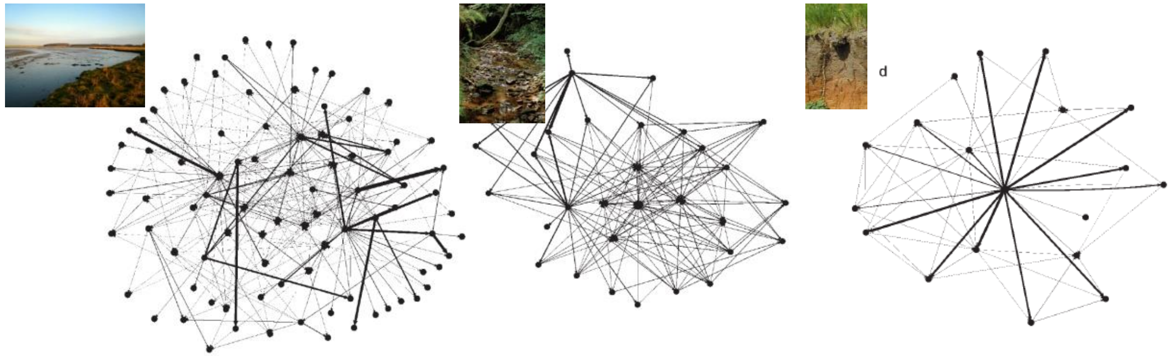


TABLE 3. Sign structure of the Jacobian matrix $\mathbf{C}$ and of its inverse $\mathbf{C}^{-1}$.

	Same sign		Different sign	
Food web	%	log mean $\lvert c_{ij} \rvert$	%	log mean $\lvert c_{ij} \rvert$
Ythan	54.4	−1.41***	45.6	−1.59***
Broadstone	54	0.16***	46	−0.28***
Soil 1	63.1	0.38	36.9	0.17
Soil 2	53.8	0.12***	46.2	0.46***
Soil 3	63.2	0.45***	36.8	0.3***
Soil 4	57.9	0.44	42.1	0.46
Soil 5	66.7	0.78***	33.3	0.55***
Soil 6	77.8	0.85***	22.2	−0.20***
Soil 7	57.5	0.13***	42.5	−0.04***
Mean	60.93		39.07	

Another approach: food web model based on allometric relations

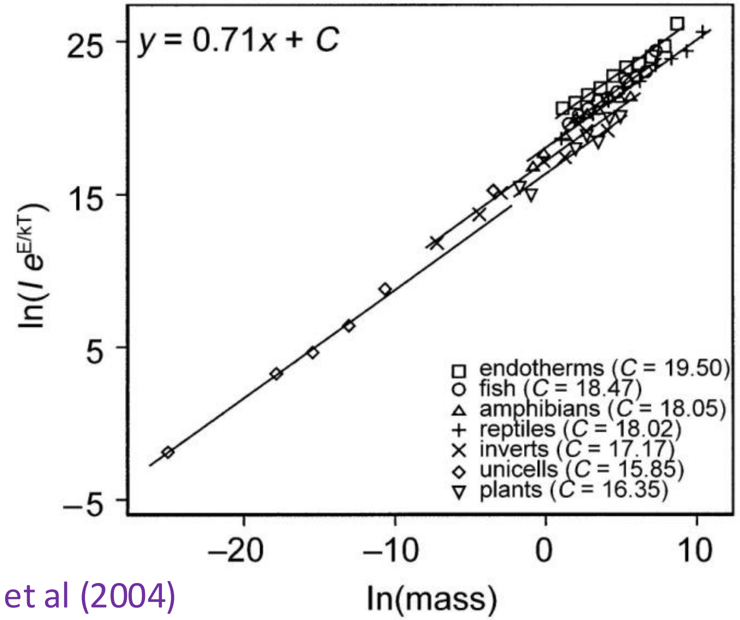
Bioenergetic model of Yodzis and Innes (1992)

$$\frac{dC}{dt} = C\left(-T + (1-\delta) J_{\max} \frac{R^n}{R^n + R_0^n} \right)$$

$$\frac{dR}{dt} = rR\left(1 - \frac{R}{K} \right) - C \frac{J_{\max}}{f_e} \frac{R^n}{R^n + R_0^n}$$

T = mass-specific respiration rate of the population (respiration per unit biomass)

$$T = a_T m_C^{-0.25}$$



Brown et al (2004)

Another approach: food web model based on allometric relations

Bioenergetic model of Yodzis and Innes (1992)

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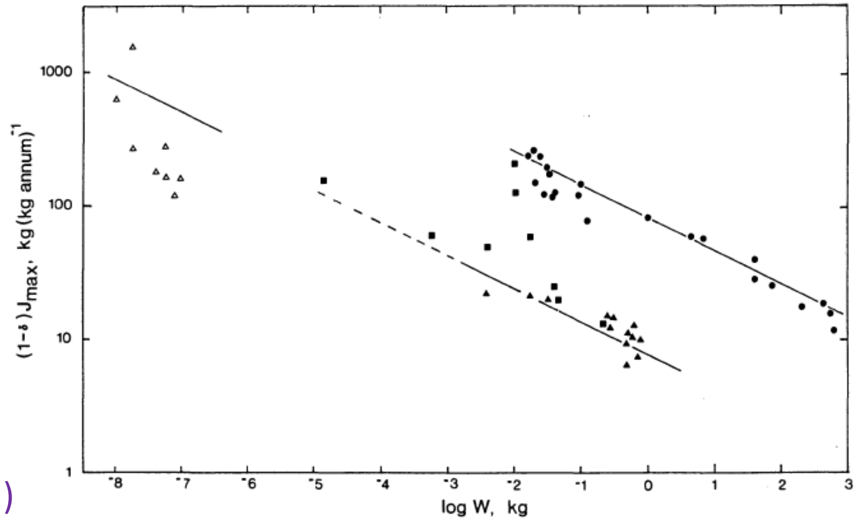
T = mass-specific respiration rate of the population (respiration per unit biomass)

J = mass-specific ingestion rate of the population

$$T = a_T m_C^{-0.25}$$

$$(1-\delta)J_{\max} = f_J a_J m_C^{-0.25}$$

Mass specific maximum feeding rates



Yodzis and Innes (1992)

Another approach: food web model based on allometric relations

Bioenergetic model of Yodzis and Innes (1992)

$$\frac{dC}{dt} = C\left(-T + (1-\delta)J_{\max}\frac{R^n}{R^n + R_0^n}\right)$$

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T = mass-specific respiration rate of the population (respiration per unit biomass)

J = mass-specific ingestion rate of the population

r = intrinsic production-biomass ratio

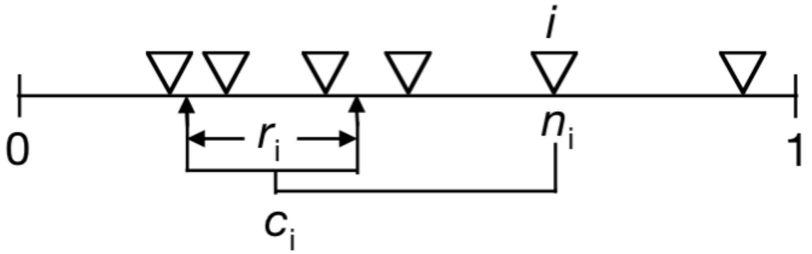
$$T = a_T m_C^{-0.25}$$

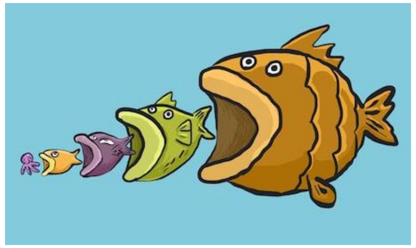
$$(1-\delta)J_{\max} = f_J a_J m_C^{-0.25}$$

$$r = f_r a_r m_R^{-0.25}$$

Another approach: food web model based on allometric relations

Trophic interactions based on the niche model



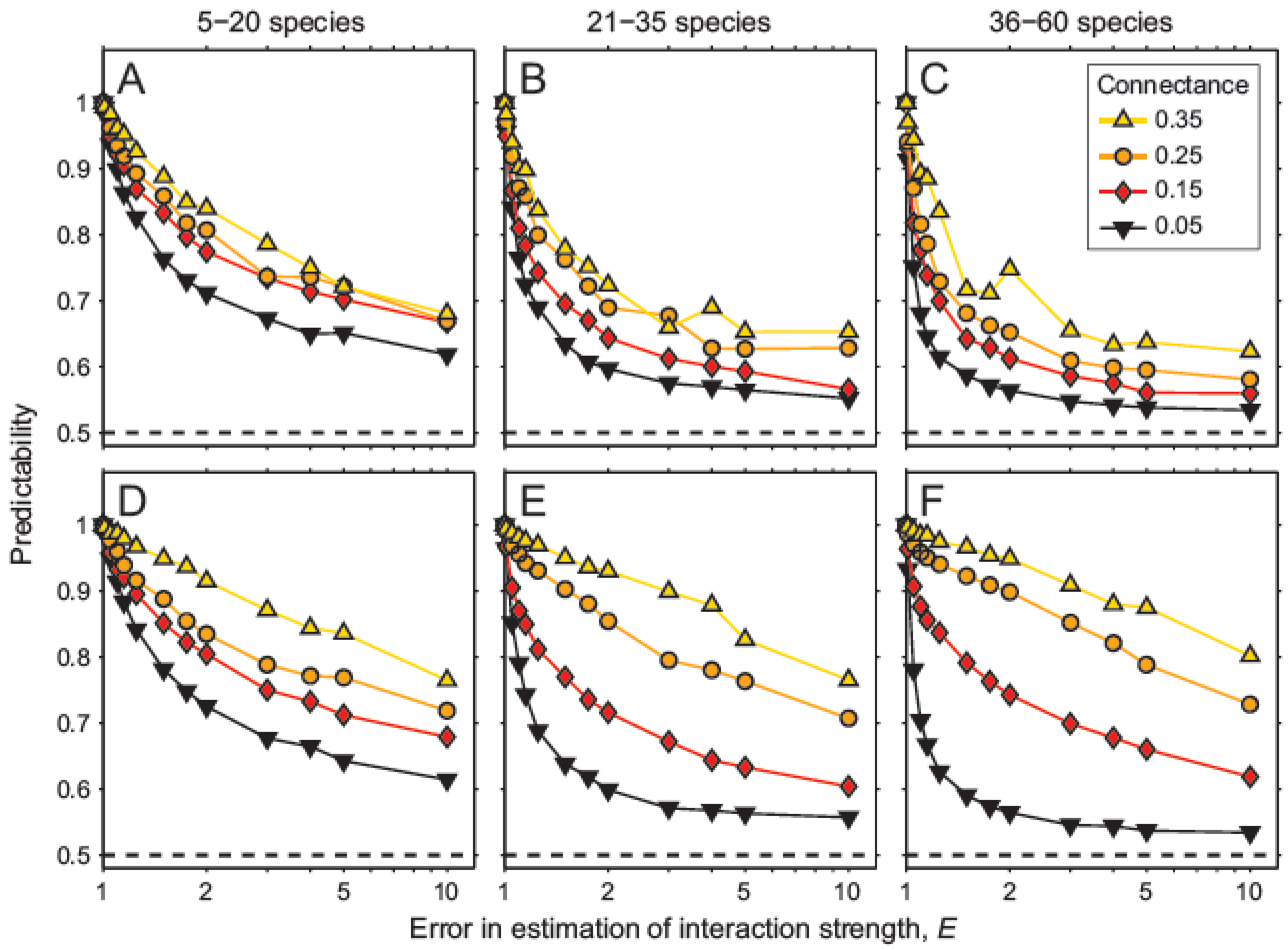


$$\frac{\mathrm{d}B_i}{\mathrm{d}t} = \overbrace{\sum_{j=1}^{n} x_i y B_i F_{ji}}^{\text{resource gain}} - \overbrace{\sum_{k=1}^{m} x_k \left(\frac{y}{e_i}\right) B_k F_{ik}}^{\text{consumer loss}} - \overbrace{x_i B_i}^{\text{metabolic loss}} \tag{2a}$$

$$\frac{\mathrm{d}B_i}{\mathrm{d}t} = \overbrace{\varepsilon x_i B_i G_i}^{\text{production gain}} - \overbrace{\sum_{k=1}^{m} x_k \left(\frac{y}{e_i}\right) B_k F_{ik}}^{\text{consumer loss}} - \overbrace{(1-\varepsilon) x_i B_i}^{\text{metabolic loss}} \tag{2b}$$

Brose et al. 2006 ; Iles & Novak 2016

Predicting cascading effects in complex food webs?



Iles & Novak 2016

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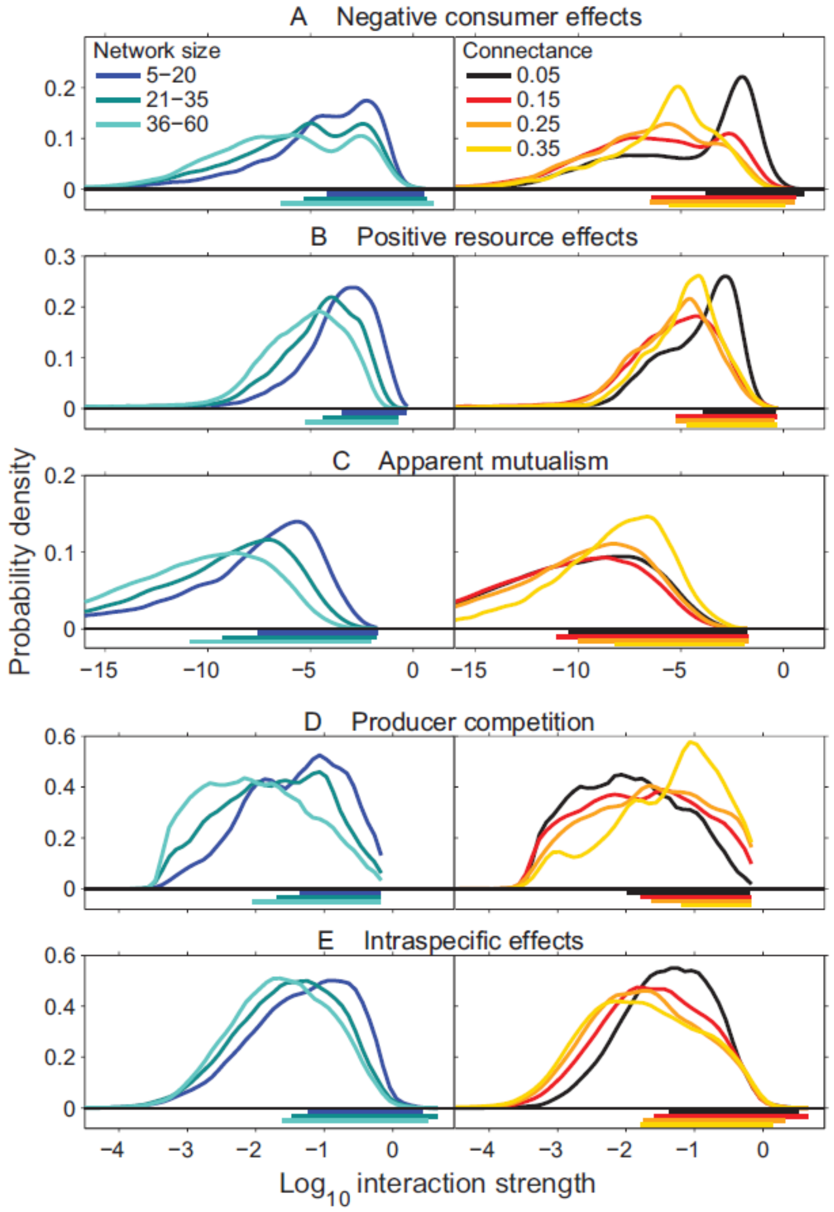

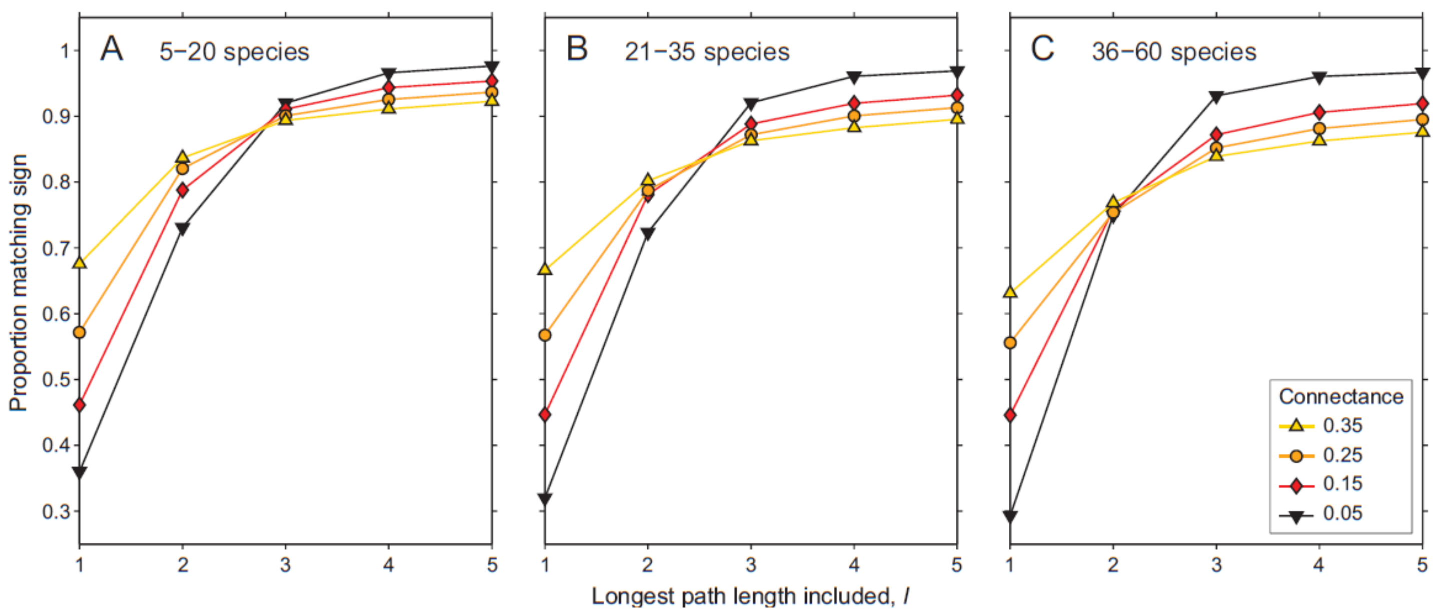

Iles & Novak 2016

Part III: Cascading effects in networks
Network structure and indirect interactions
Some conclusions and perspectives

- Importance of indirect interactions: network structure matters for understanding cascading effects in ecological communities

- Can we predict consequences of perturbations on ecological networks?

- Which network structures limit the spread of cascading effects?