Structure et dynamique des communautés écologiques

(iii)

Stability of ecological communities

Colin Fontaine

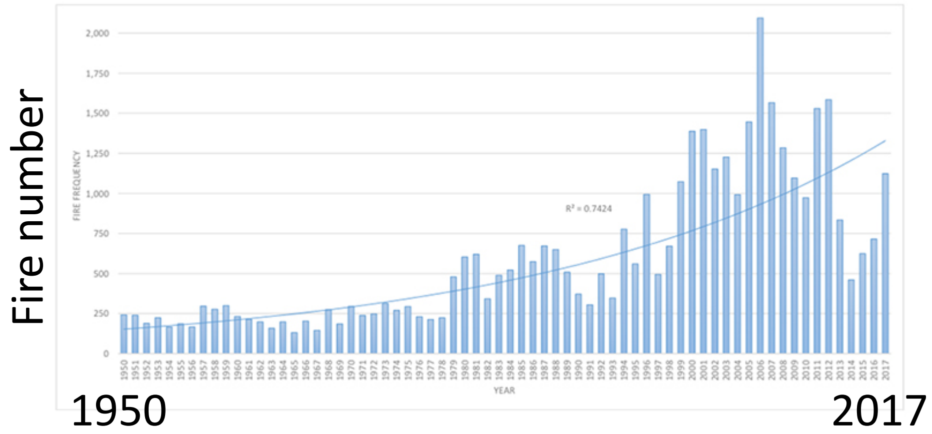
Aussois 2021

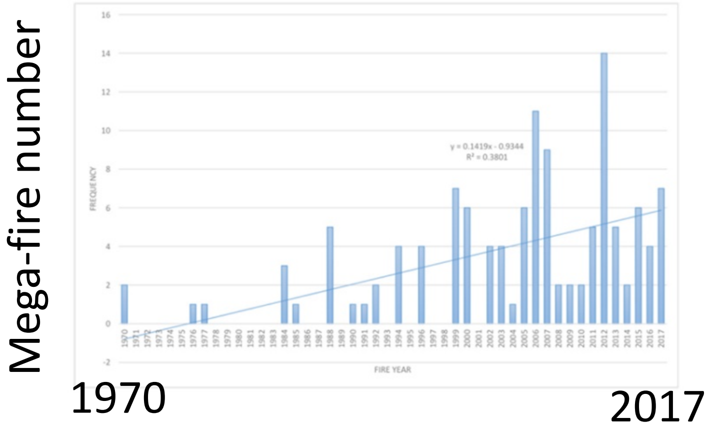
Stability of ecosystems

- Most ecologists describe ecosystem stability as the ability of an ecosystem to **maintain its structure and function** over long period of time and **despite disturbances**

- Natural ecosystems experience regular punctual environmental changes, or disturbances
  - Fire; flooding; storm; Insect outbreak…

- The Anthropocene is characterized by
  - An increase in the frequency and amplitude of **pulse perturbations**





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- The Anthropocene is characterized by
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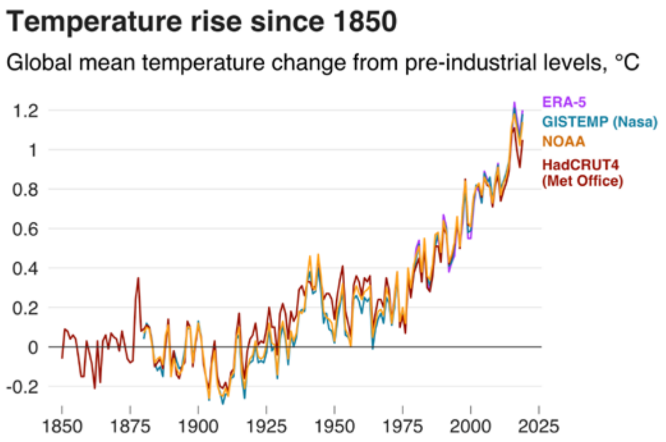
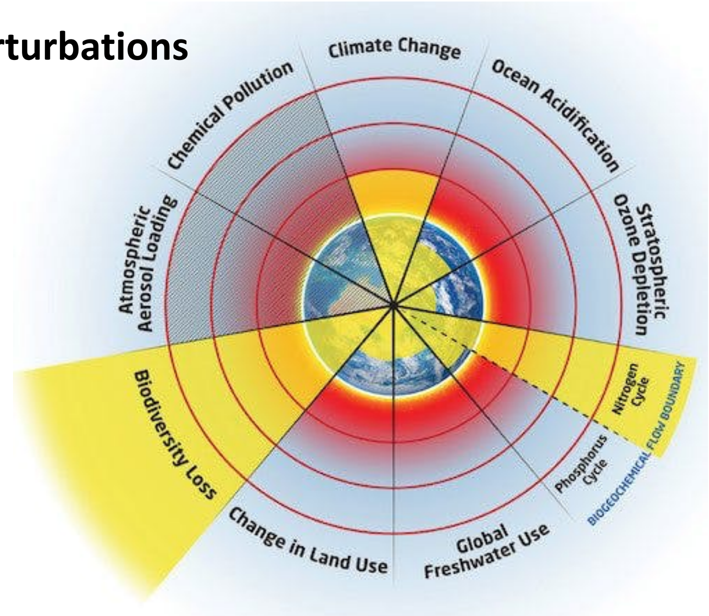
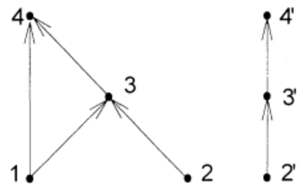
  - An increase of system forcing/**press perturbations**





Complexity stability relashionship

- Original idea:
  - Theoretical and experimental evidence that simple model ecosystems are inherently unstable
  - Observations suggest that diversity of species and interactions among them favor community stability

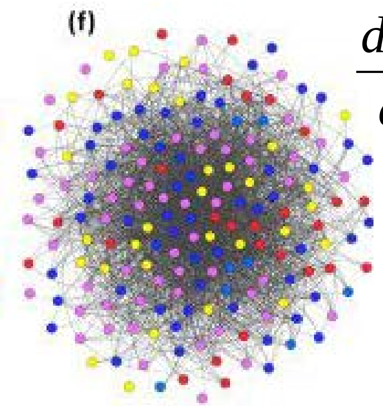


Odum E. 1950

Elton C. S. 1958

MacArthur R. 1955

- Challenged by theory

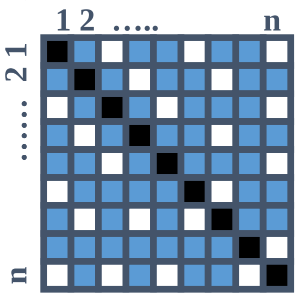


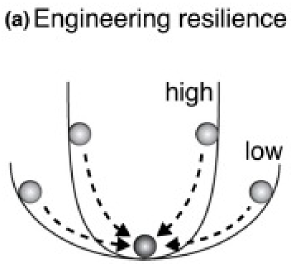
$$\frac{dN_i}{dt} = F_i(N_1, \ldots, N_k)$$

A = matrice de communauté

a_{ij} = force d'interaction

$$a_{ij} = \left(\frac{\partial F_i}{\partial N_j}\right)_{eq}$$



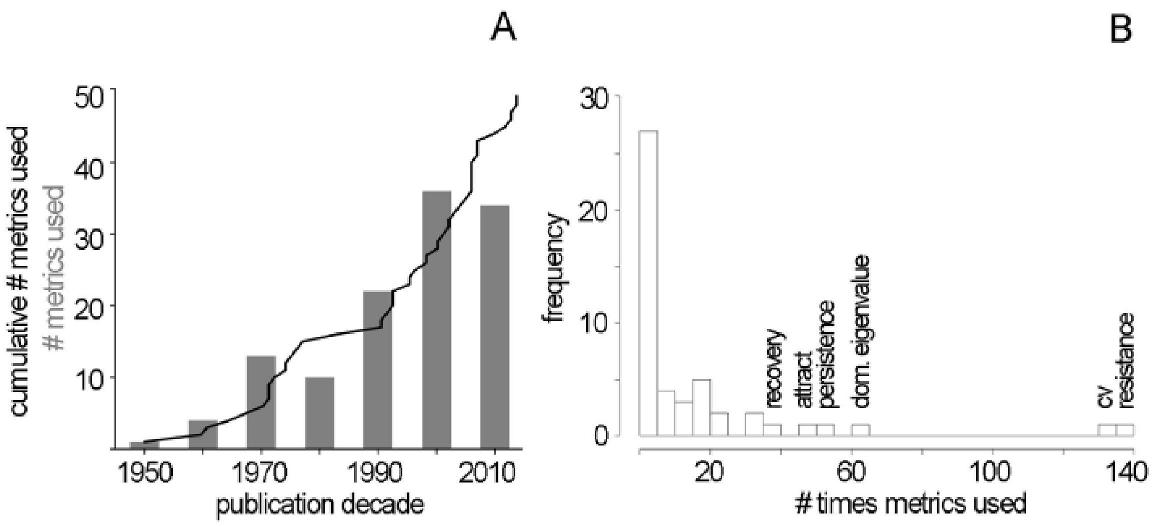


$$i\sqrt{SC} \leq 1$$

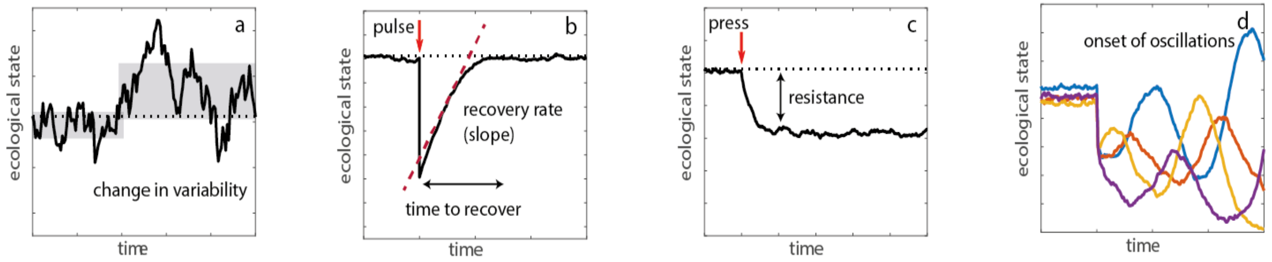
Mean interaction strength | Species number | Proportion of realised interactions

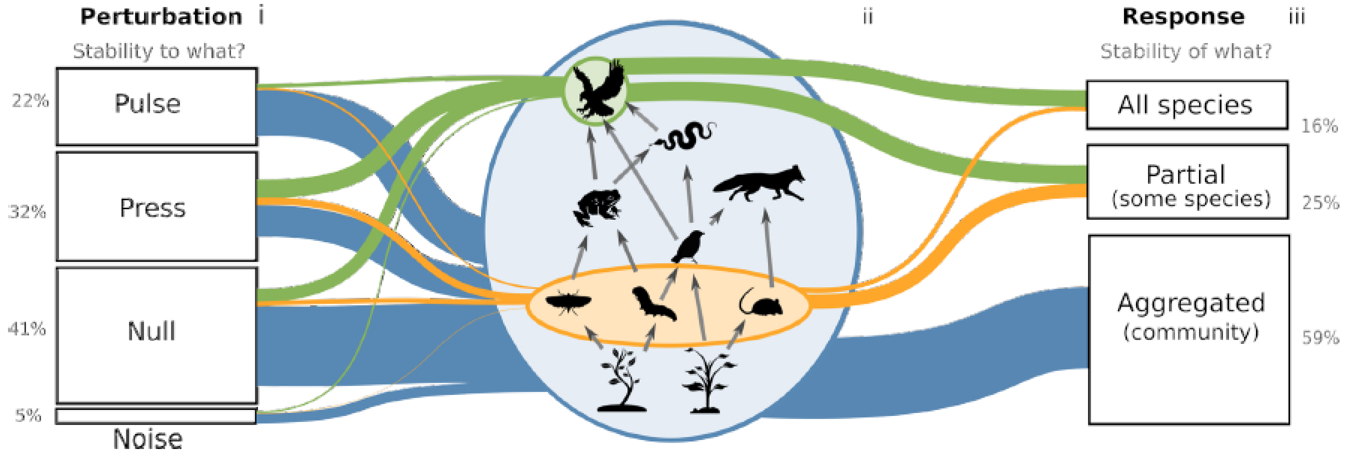
May R. 1971

Ecological stability: an expending (messy) field



	Constancy	Recovery	Resistance	Dynamical Attractors
defintion	variability (or lack thereof) of the dynamics of composition or structure of the system over time or space	whether and how fast the system recovers after a perturbation	how much the system changes after a perturbation	existence or changes between attractors/dynamical states (alternative stable states or stable to unstable/oscillation)
metric (example)	variability (cv, std) persistence permanence	engineering resilience recovery back to predisturbed state	resistance (eg deviation from reference) robustness	attractor type trends in variance/autocorrelation





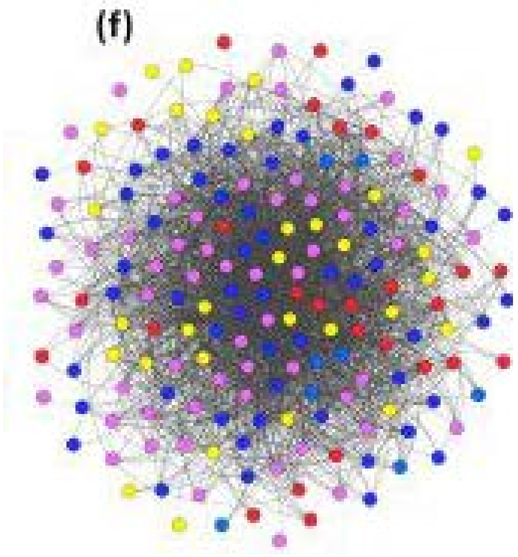
Kéfi et al. 2020

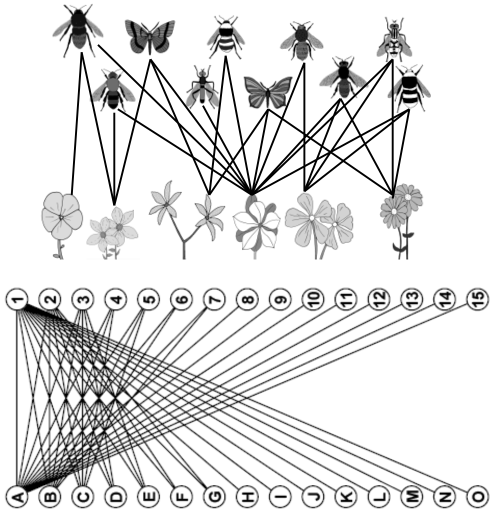
- How to reconcile May’s results with the idea that complexity favors stability?

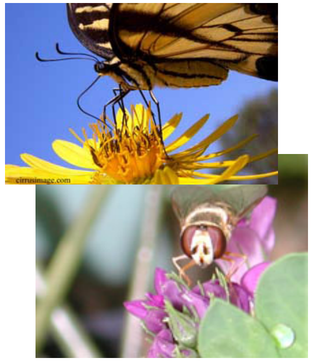
- Empirical approches to ecological stability

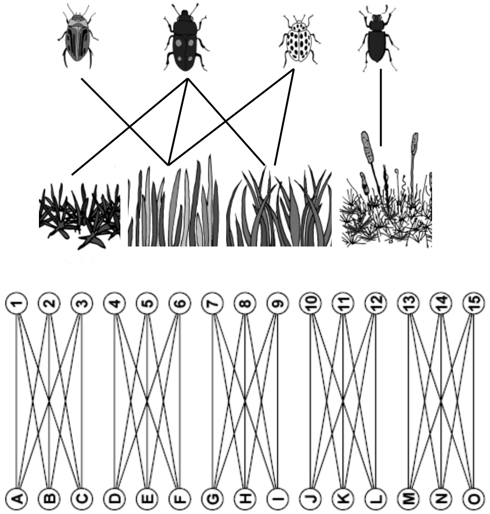
- The dimensionality of ecological stability

Ecological interaction networks are not random

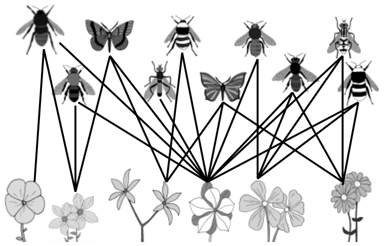








Network structure and community dynamic



Mutualistic

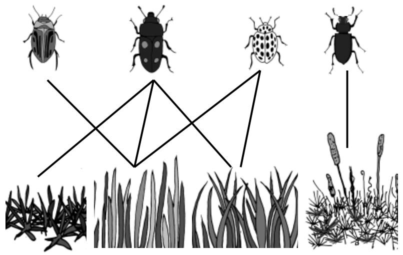
$$\frac{dA_i}{dt} = r_{Ai}A_i - I_{Ai}A_i^2 + \sum_{j=1}^{Np} \frac{c_{ji}A_iP_j}{\alpha_{ji}^{-1} + \sum_{Pk \in mut(Ai)} P_k}$$

$$\frac{dP_i}{dt} = r_{Pi}P_i - I_{Pi}P_i^2 + \sum_{j=1}^{Na} \frac{c_{ij}A_jP_i}{\alpha_{ij}^{-1} + \sum_{Ak \in mut(Pi)} A_k}$$

-intrinsic growth rates
r_P and $r_A < 0$ ➔ obligate mutualism

-density dependence term

-interaction term
saturates with mutualistic partner densities



Trophic

$$\frac{dA_i}{dt} = r_{Ai}A_i - I_{Ai}A_i^2 + \sum_{j=1}^{Np} \frac{c_{ji}A_iP_j}{\alpha_{ji}^{-1} + \sum_{Pk \in prey(Ai)} P_k}$$

$$\frac{dP_i}{dt} = r_{Pi}P_i - I_{Pi}P_i^2 - \sum_{j=1}^{Na} \frac{c_{ij}A_jP_i}{\alpha_{ij}^{-1} + \sum_{Pk \in prey(Aj)} P_k}$$

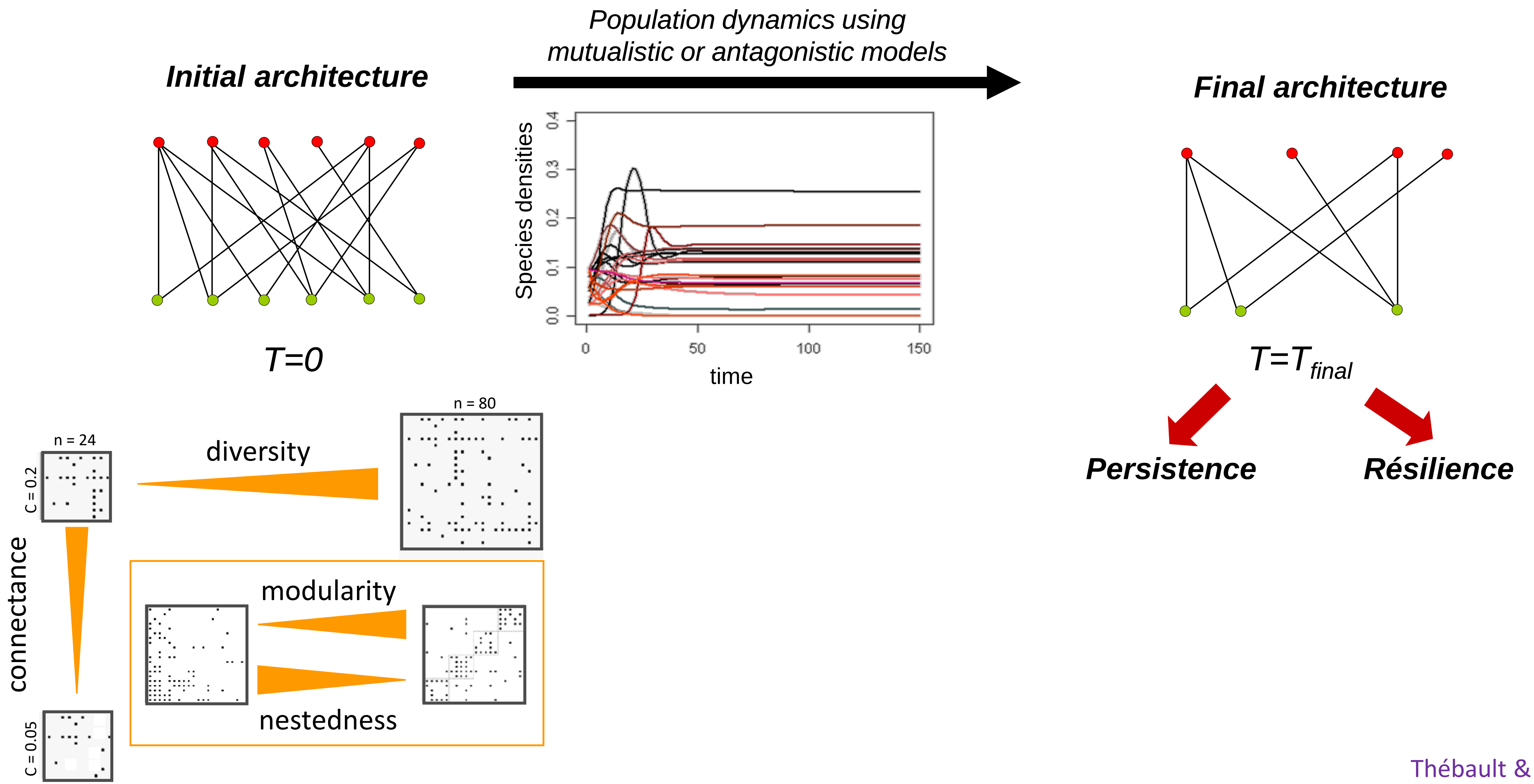
-intrinsic growth rates
$r_P > 0$ and $r_A < 0$

-density dependence term

-interaction term
saturates with prey densities

Thébault & Fontaine 2010

Network structure and community dynamic



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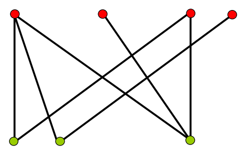
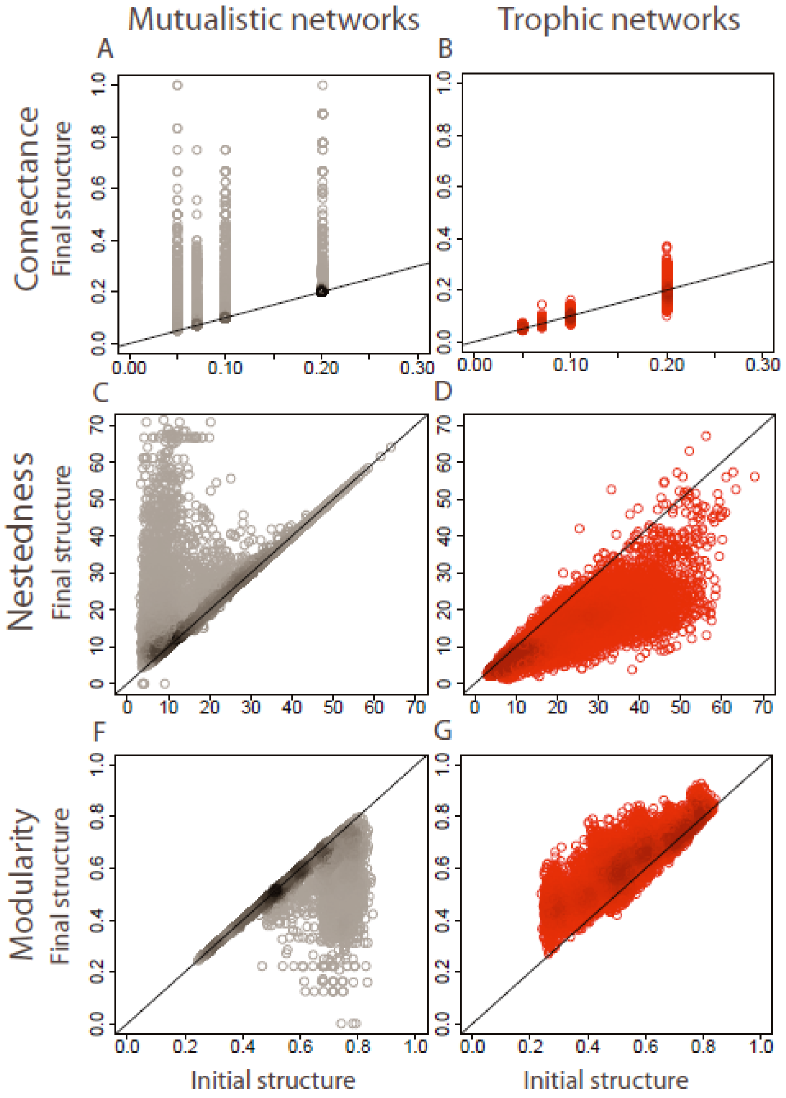
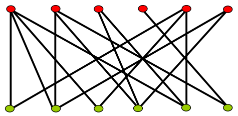






Persistence

	réseau mutualiste	réseau trophique
diversité	+	-
connectance	+	-
emboitement		-
compartimentalisation	-	

Résilience

	réseau mutualiste	réseau trophique
diversité	+	-
connectance	+	-
emboitement	+	
compartimentalisation		+

Thébault & Fontaine 2010

Considering effects of foraging adaptation

Metabolic rate

Foraging efficiency

Attack rate

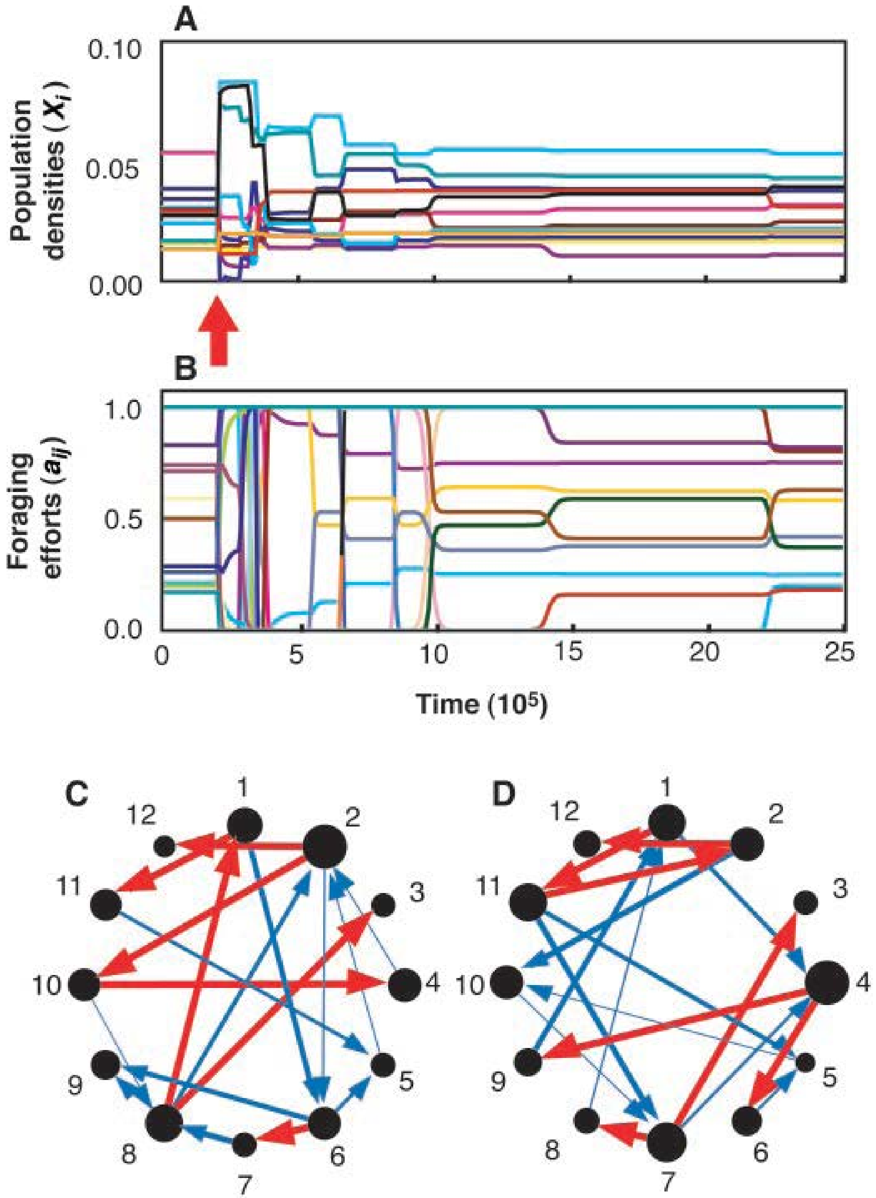
$$\frac{dX_i}{dt} = X_i\left(r_i - s_iX_i + \sum_{j \in resources} e_{ij} f_{ij} a_{ij} X_j - \sum_{j \in consumers} f_{ji} a_{ji} X_j\right) \qquad (1)$$

$$\frac{da_{ij}}{dt} = G_i a_{ij}\left(e_{ij} f_{ij} X_j - \sum_{k \in resources} a_{ik} e_{ik} f_{ik} X_k\right) \qquad (2)$$

Profitability of other resources

Profitability of resource *j*

Adaptation rate



Kondoh 2003

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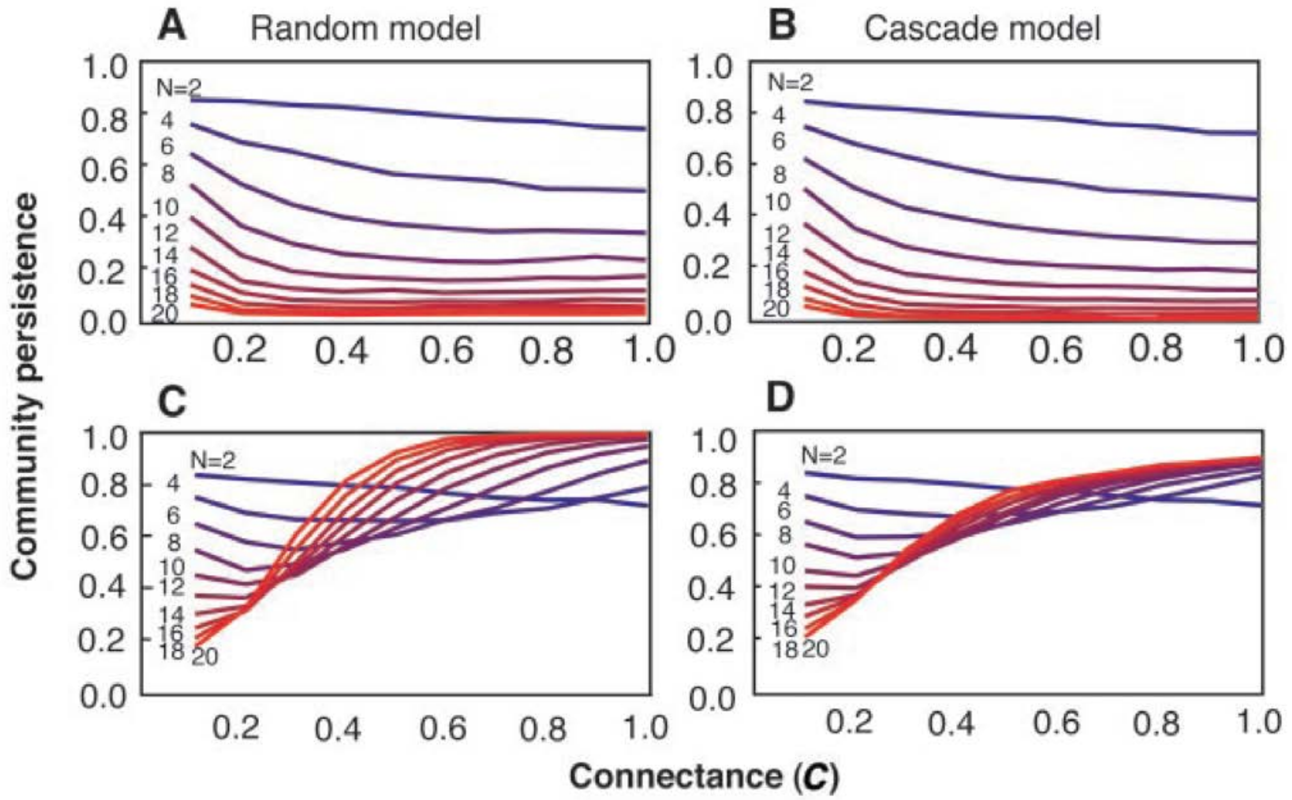
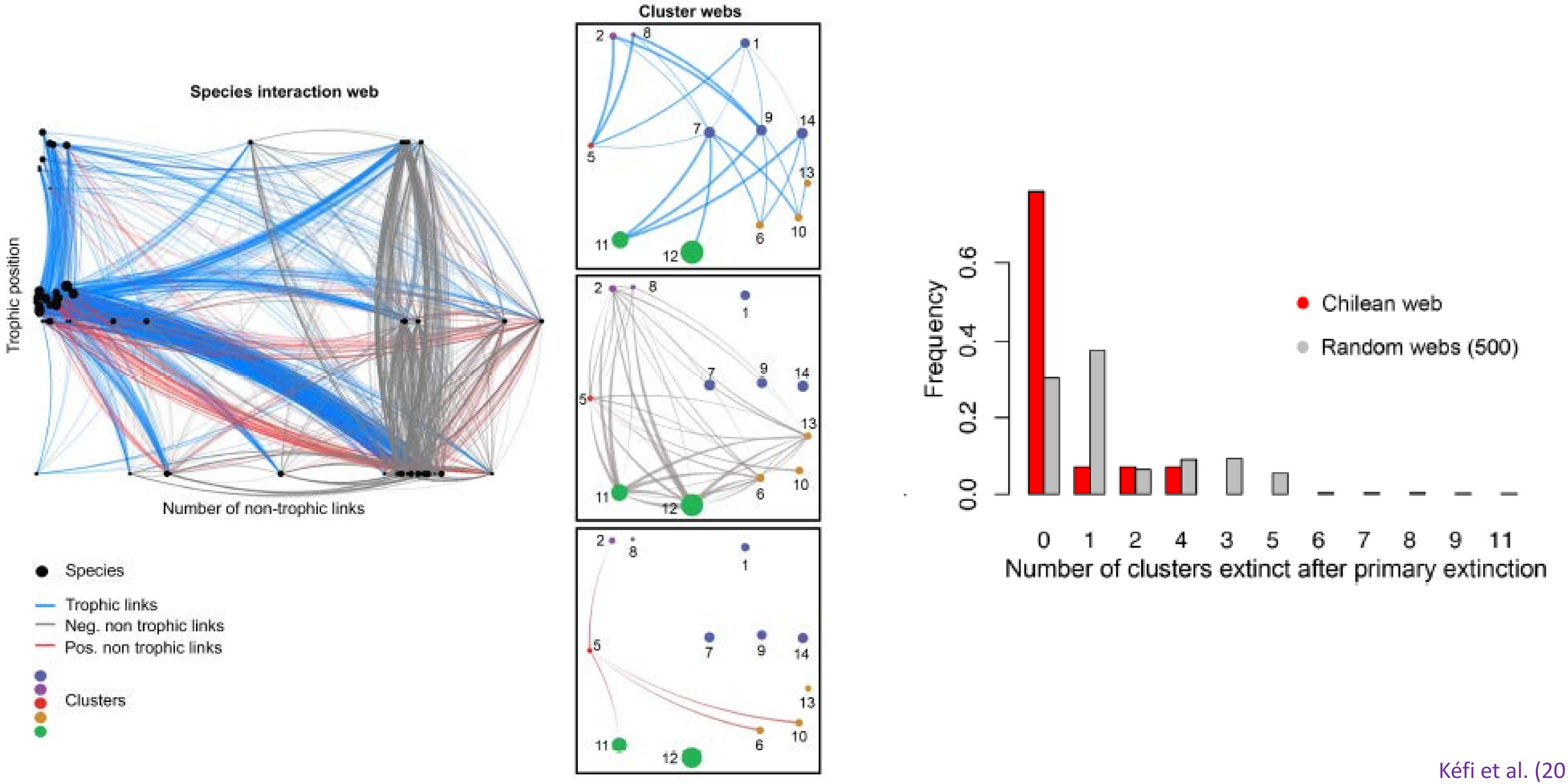


Kondoh 2003

Stabilty of networks integrating different interaction types



Kéfi et al. (2016)

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The relationship between diversity and temporal stability of communities

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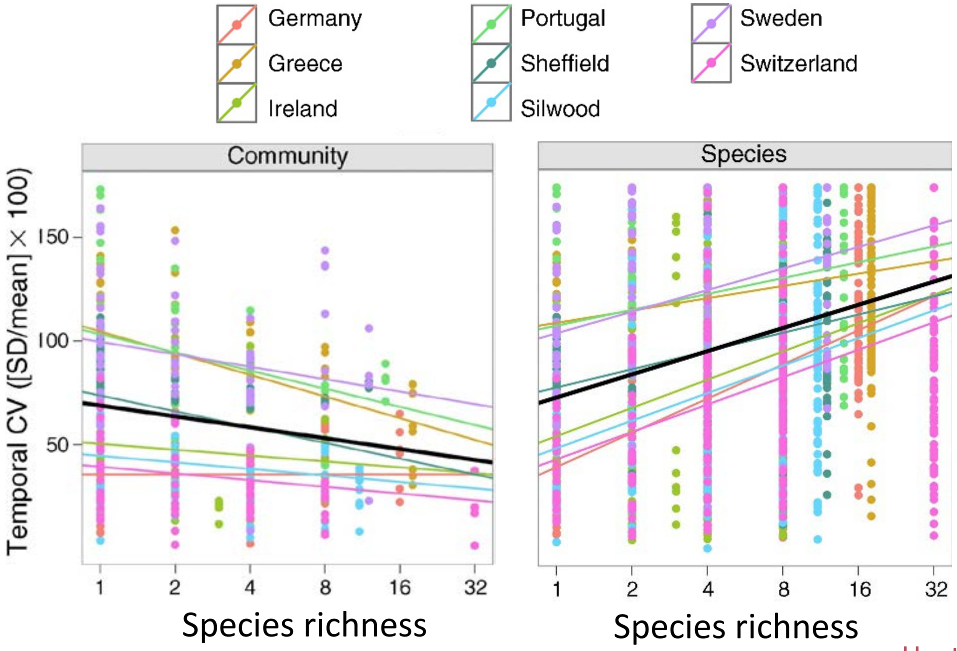
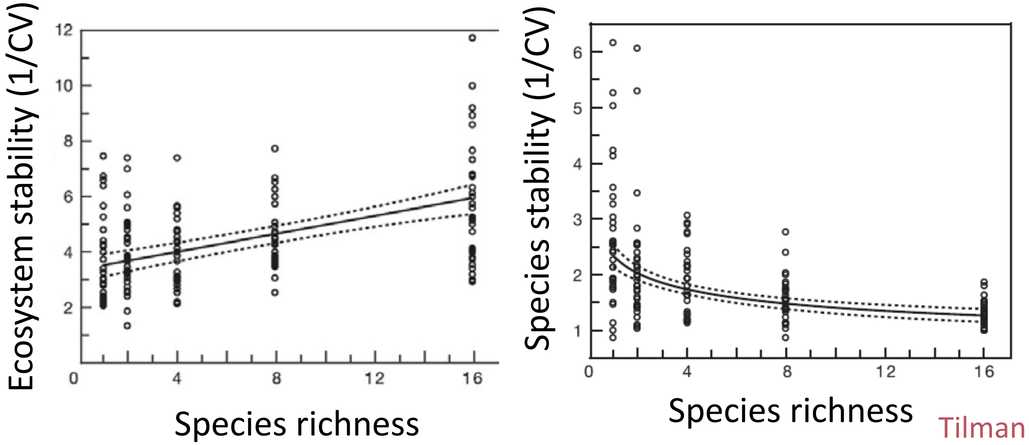


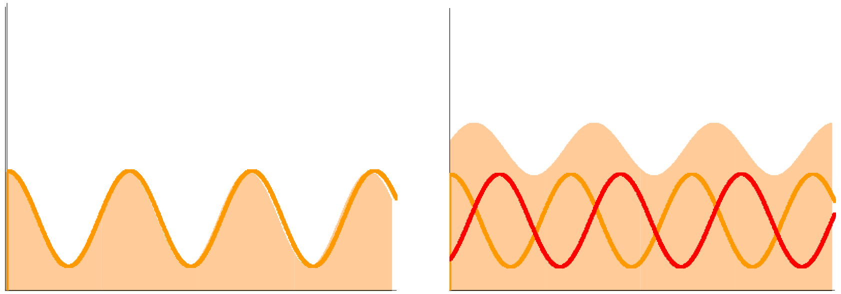
Hector et al. (2010)



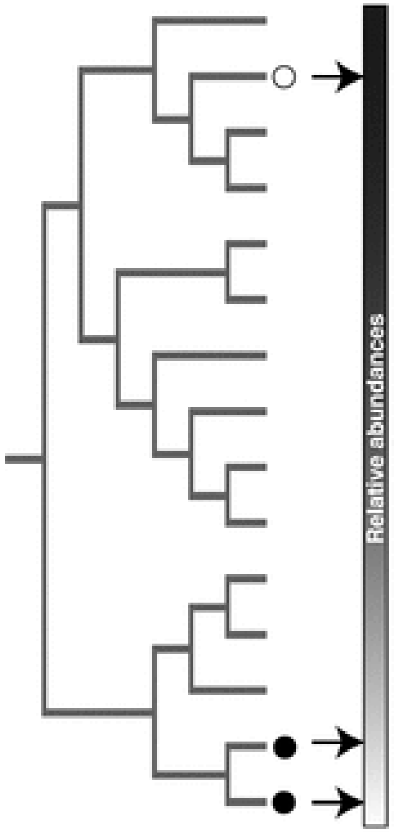
Tilman et al. (2006)

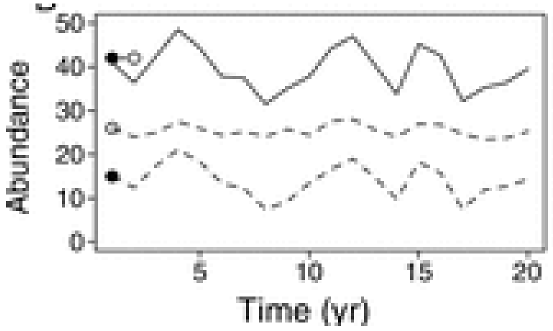
Diversity decreases variability of ecosystem properties through:

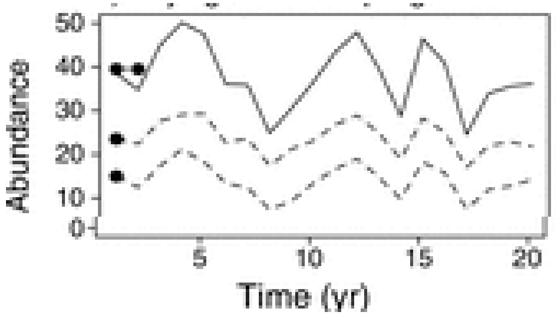
- Asynchronous responses of species to environmental perturbation

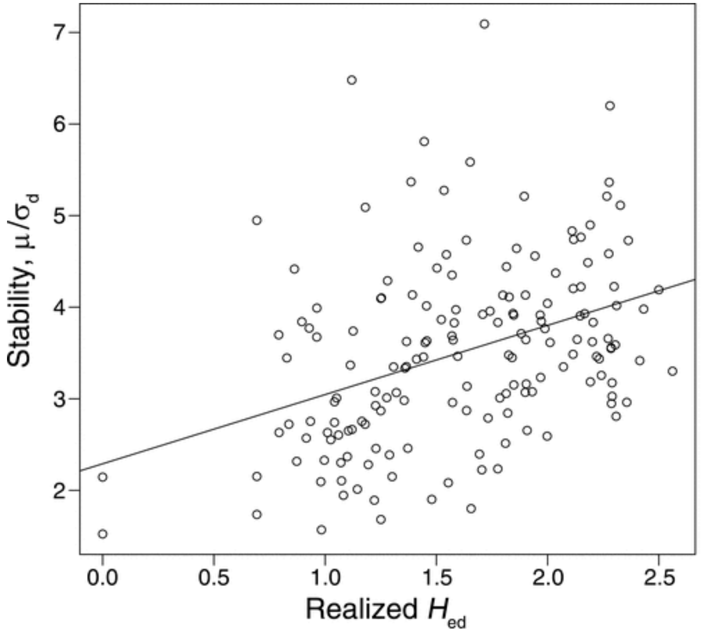


Evolutionary history of species and the temporal stability of biomass production



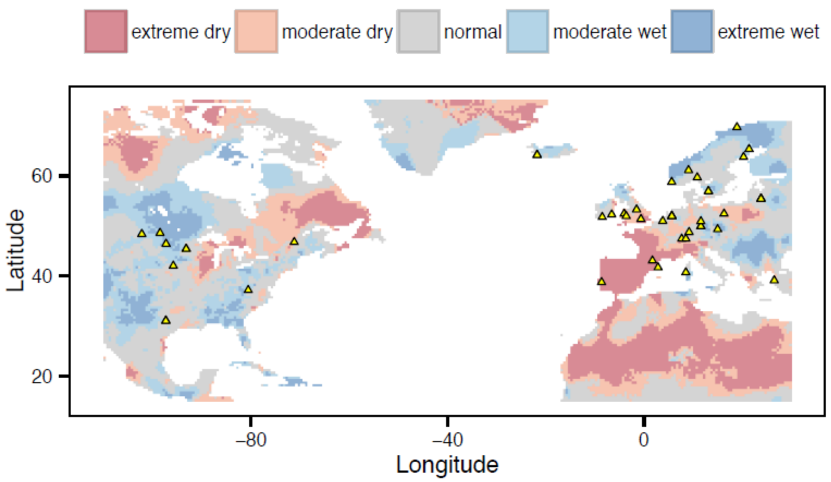




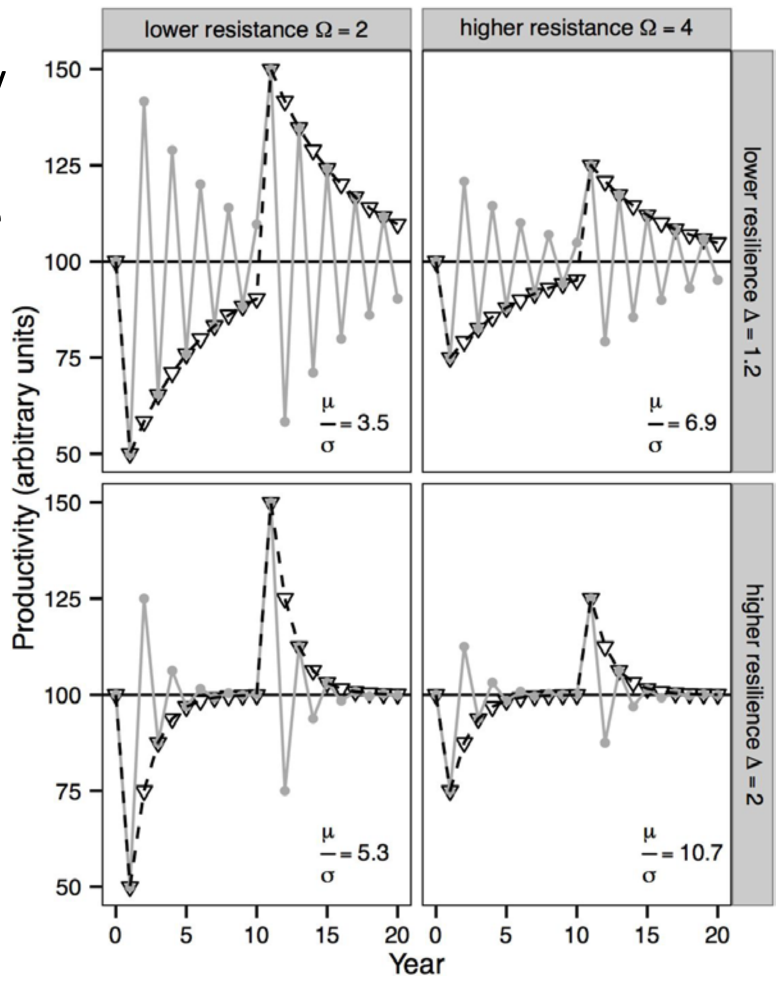


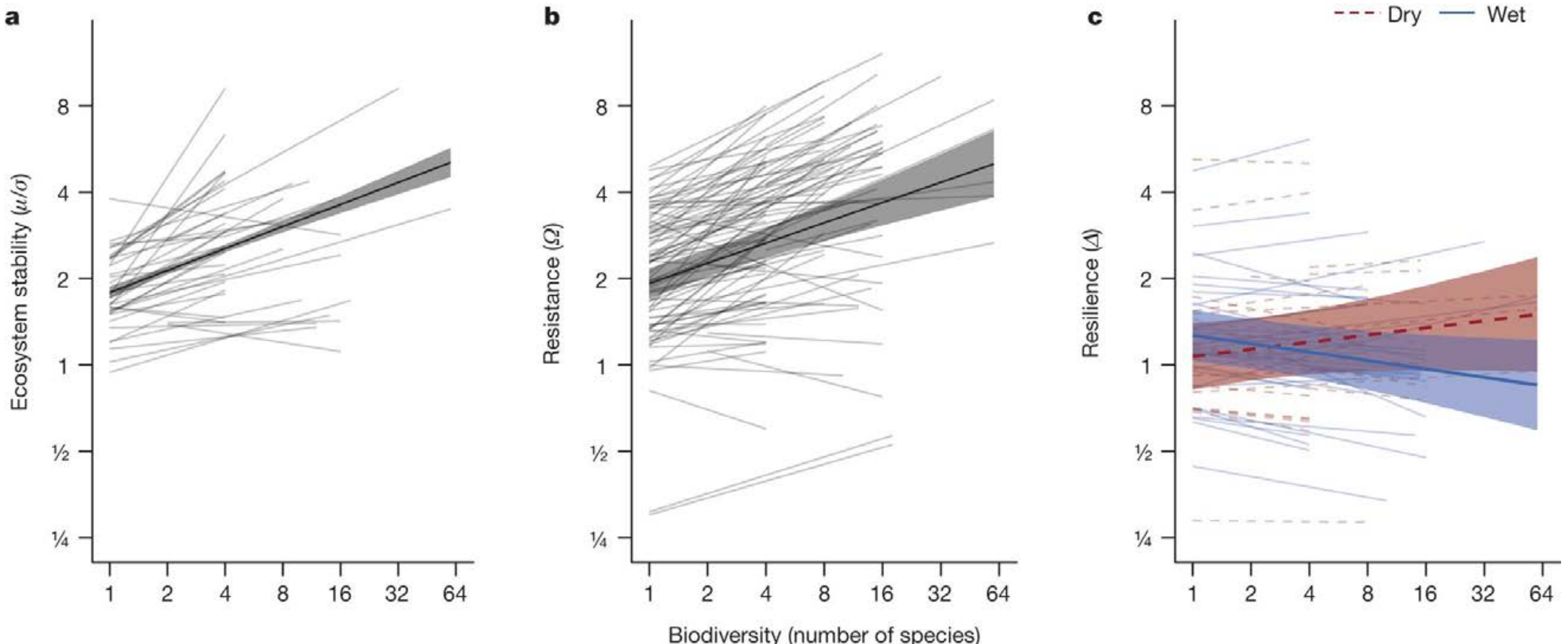
Cadotte et al. 2012

Resitance, resilience and variability of primary production to climatic extrems



- In addition to warming, current climat change lead to a increase in the frequency of extrem climatic events
- Both resitance and resilence can affect the variability of primary production
- Plant diversity mainly affects resistance





Isbell et al. 2015

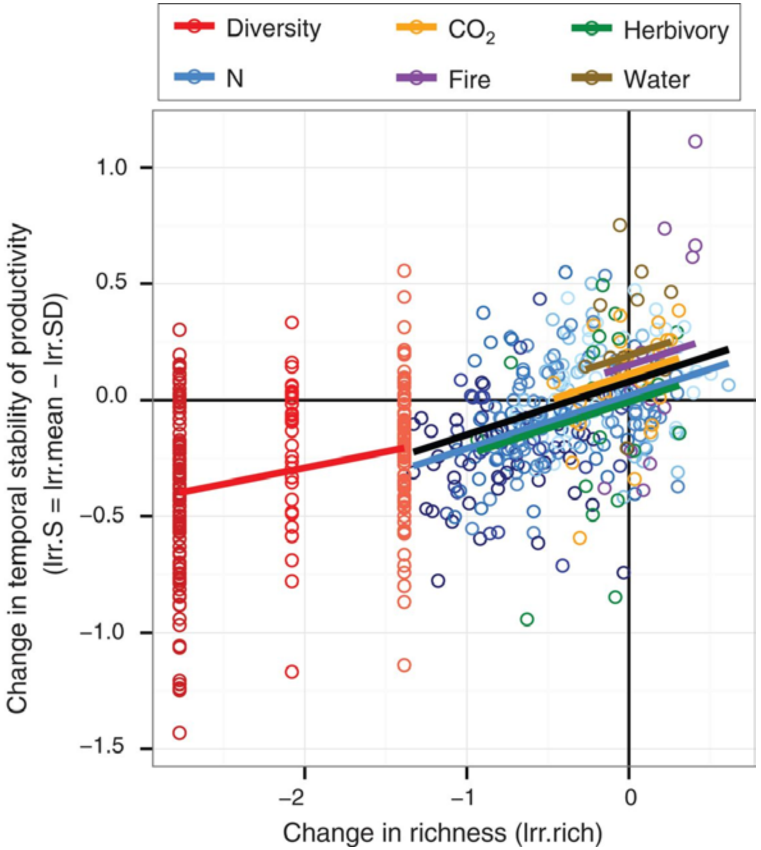
The relationship between diversity and temporal stability of communities: Limits of existing empirical studies

- Mostly comes from plant experimental communities
  - diversity - stability relationship for other taxa?
  - Effects of non-random species loss?

- Effects of anthropogenic perturbations other than species loss on community and ecosystem stability?

Perturbations → diversity loss → lower stability

?



Hautier et al. (2015)

Data from citizen science programs to investigate the links between land uses, species diversity and community stability

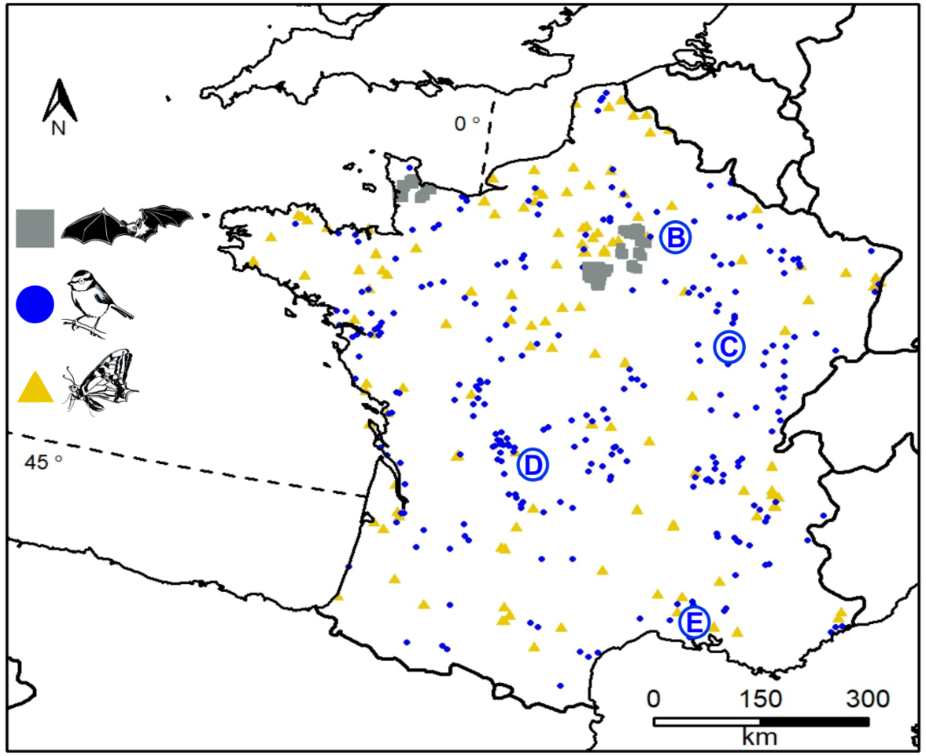
Muséum national d'Histoire naturelle

VIGIENATURE

Vigie-Chiro
Suivi des chauves-souris

STOC
SUIVI TEMPOREL DES OISEAUX COMMUNS

Observatoire de la Biodiversité des Jardins
OPÉRATION PAPILLONS



Annual abundances of communities:
161 bat communities for 4 year
269 bird communities for 8 years
130 butterfly communities for 7 years

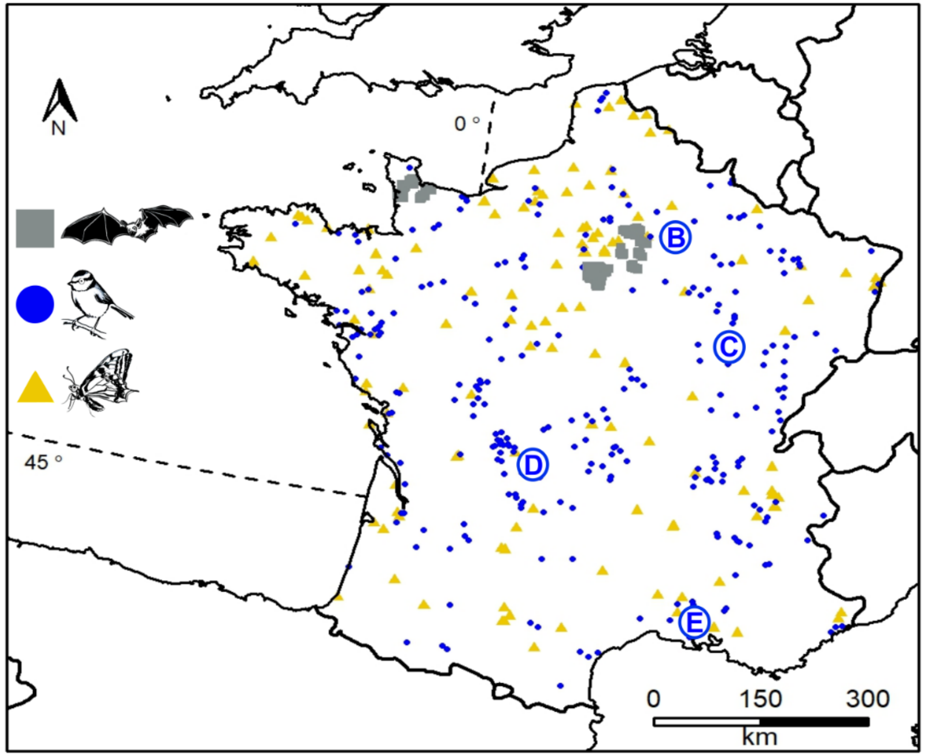
Standardized protocols in fixed sites

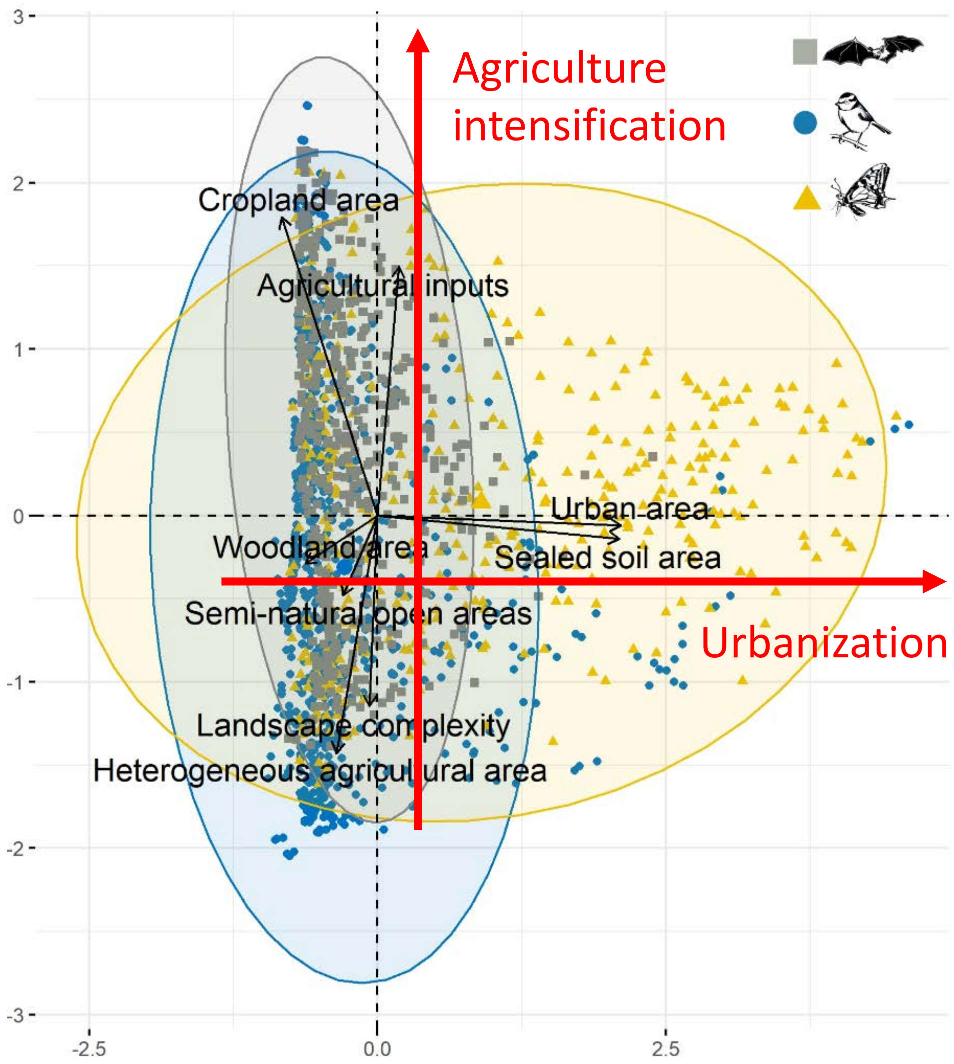
Non-lethal monitoring

Olivier et al. 2020

Assessing the links among: land uses, species diversity and community stability

- 8 landscape variables





Olivier et al. 2020

Assessing the links among:
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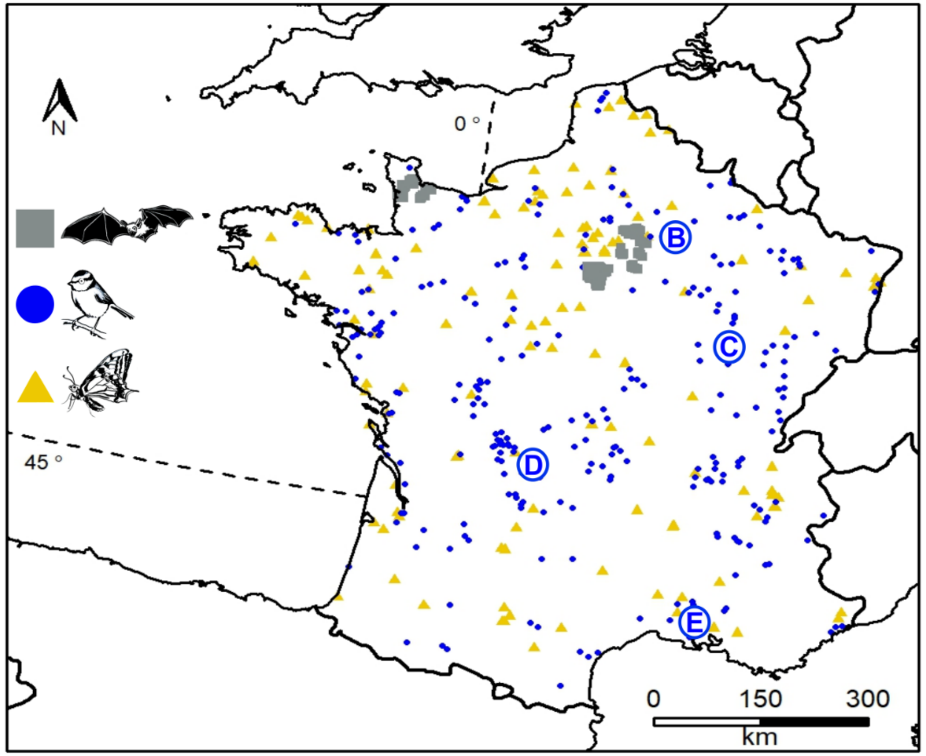
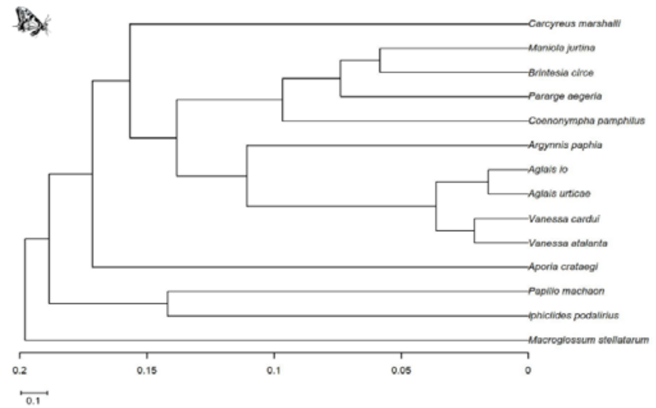
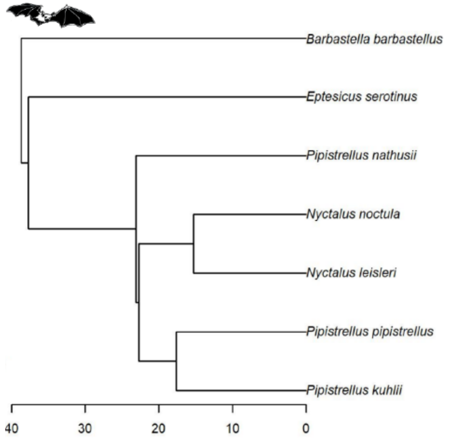
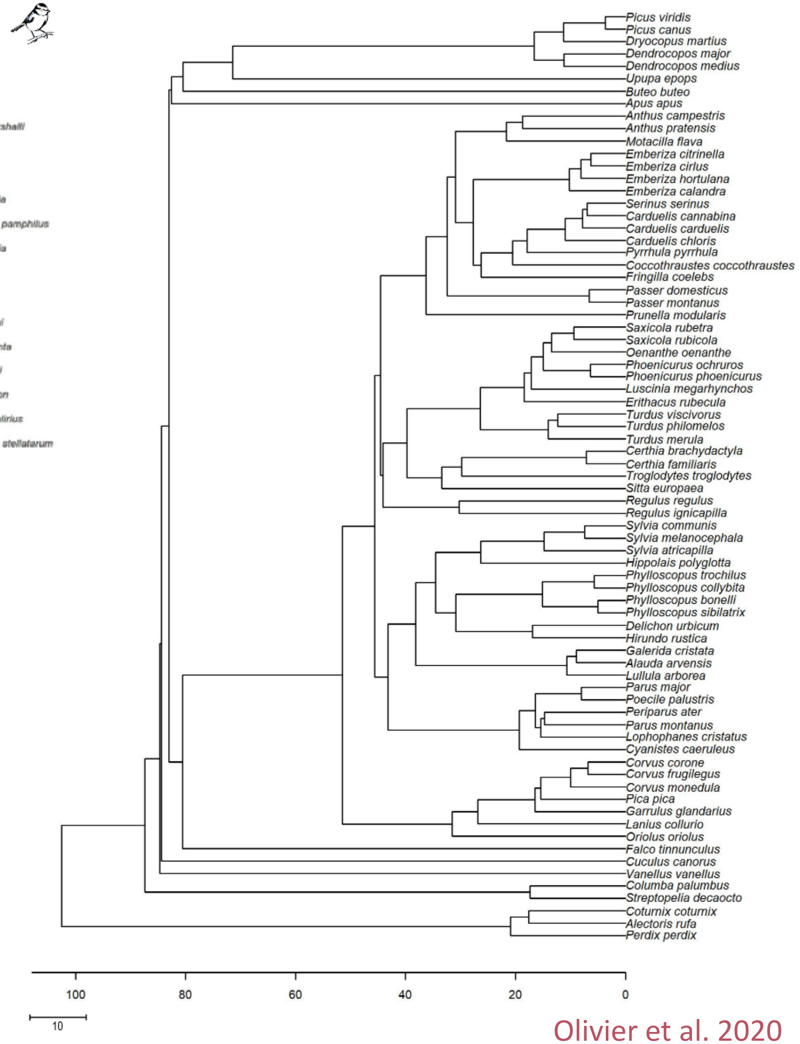
- Species richness and phylogenetic diversity





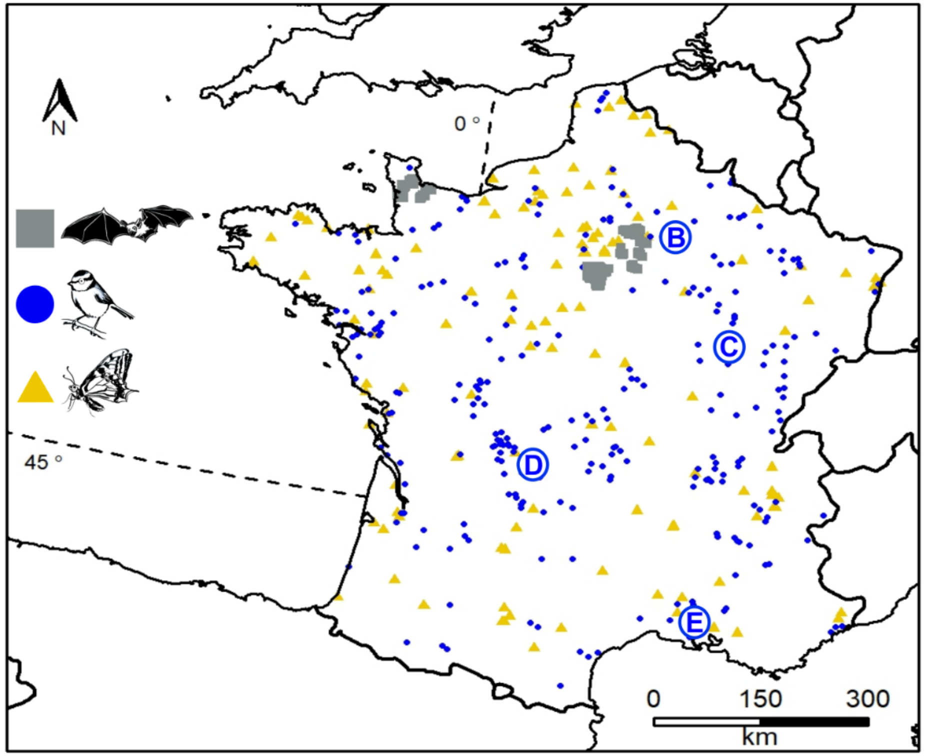


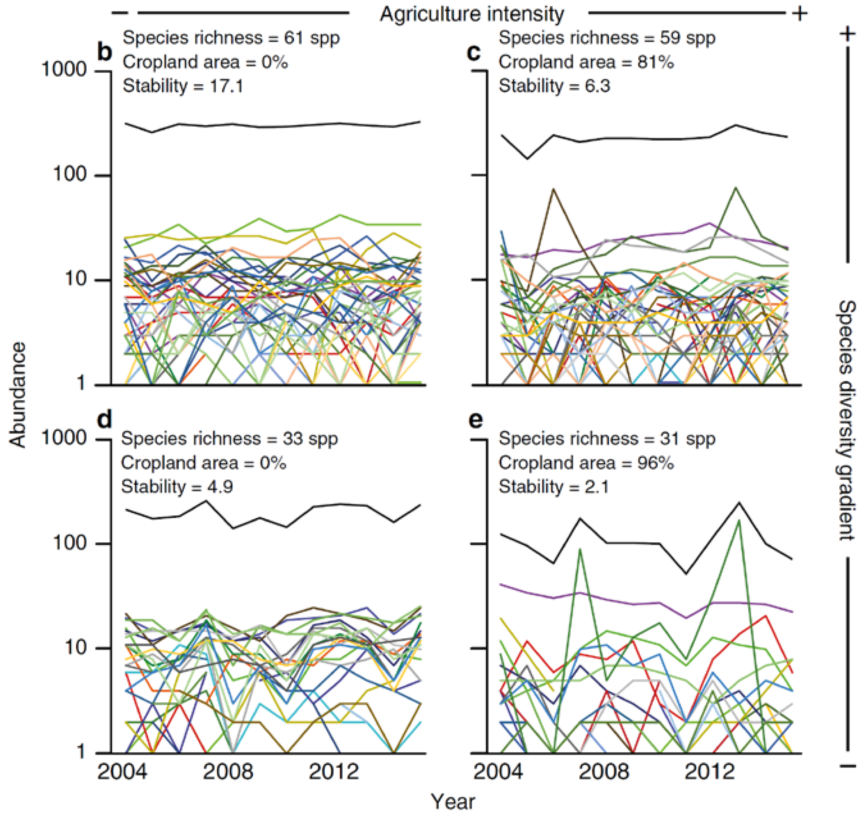


Olivier et al. 2020

Assessing the links among:
land uses, species diversity and community stability

- 8 landscape variables
- Species richness and phylogenetic diversity
- Community stability/variability as a function of population stability/variability and asynchrony





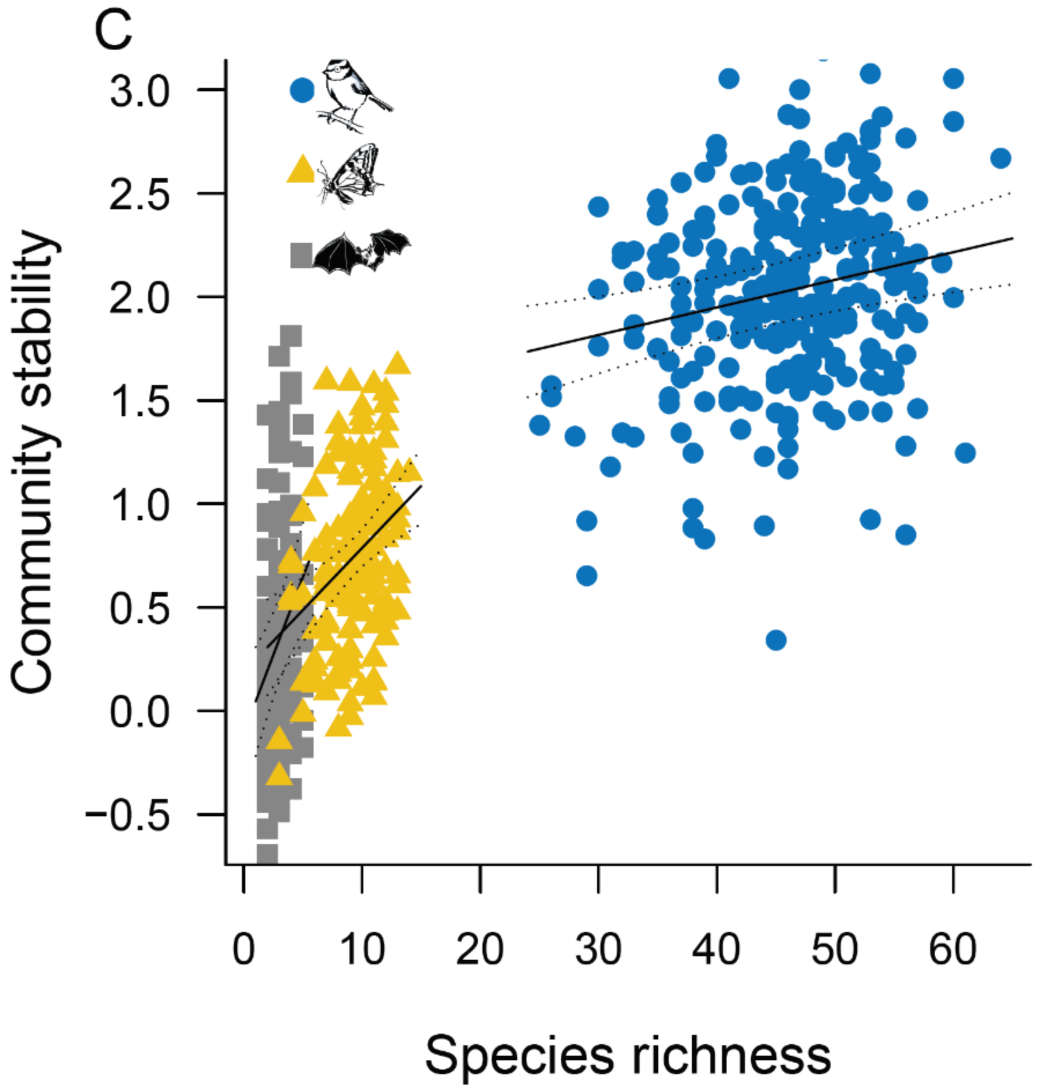
$$CV = \sqrt{\varphi}\,\overline{CV_w}$$ with $$\varphi = \frac{\sigma^2}{\left(\sum_i \sigma_i\right)^2}$$ and $$\overline{CV_W} = \sum_i \frac{\mu_i}{\mu} \, x \, \frac{\sigma_i}{\mu_i} = \frac{\sum_i \sigma_i}{\mu}$$

community variability — synchrony — weighted mean population variability

Loreau & de Mazancourt (2008)

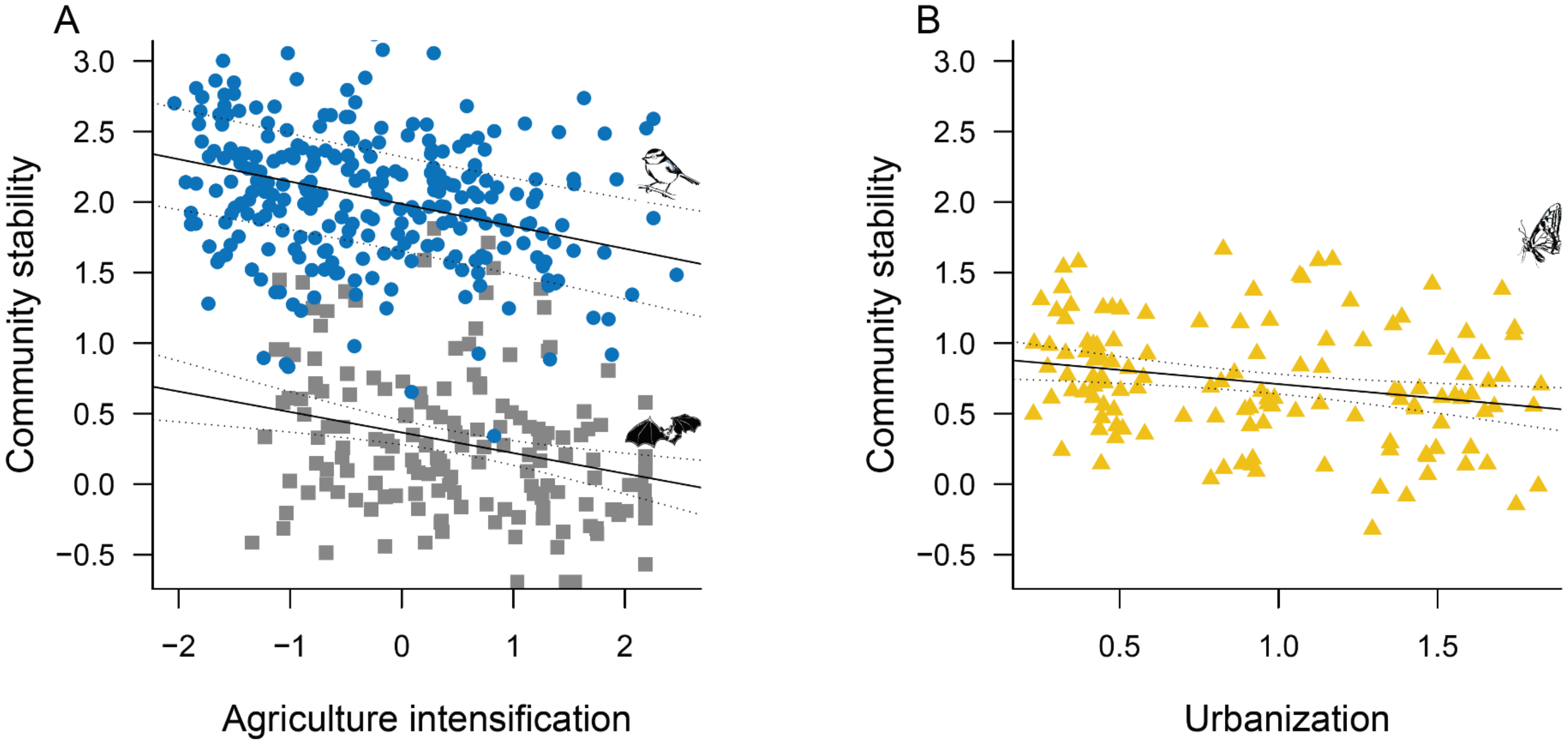
Thibaut & Connolly et al. (2013)

Results: relation between diversity and community stability



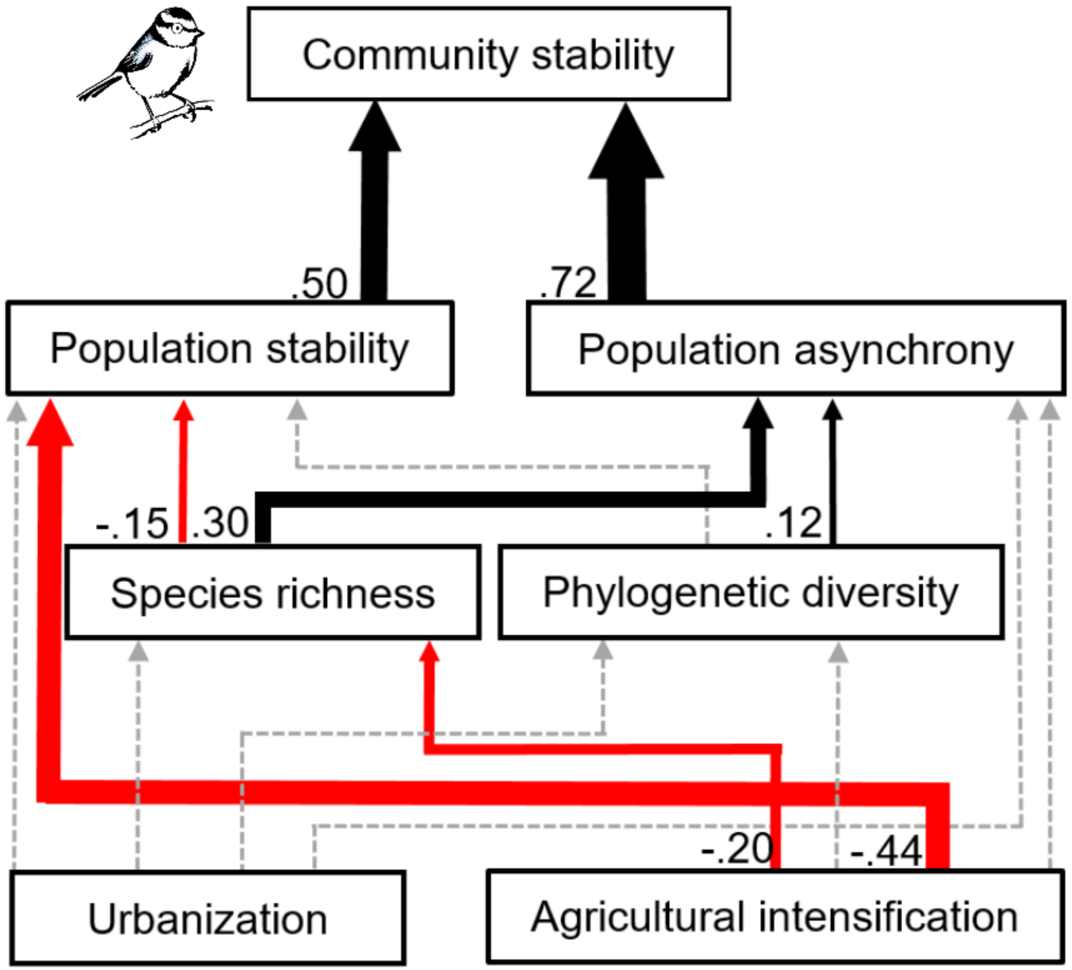
Olivier et al. 2020

Results: relation between land use and community stability



Olivier et al. 2020

Results: disentangling the effects of land use and diversity on community stability



Olivier et al. 2020

Results: disentangling the effects of land use and diversity on community stability

Effects on community stability			
Diversity:			
Total effects	0.433	0.224	0.513
Richness effects	0.195	0.139	0.347
Phylogenetic diversity effects	0.238	0.085	0.166
Effects via population stability	NS	-0.076	0.172
Effects via population asynchrony	0.433	0.299	0.341

Negative effects of diversity loss on community stability mainly mediated through decreased population asynchrony

Olivier et al. 2020

Effects of habitat degradation and diversity loss on community stability
Conclusion

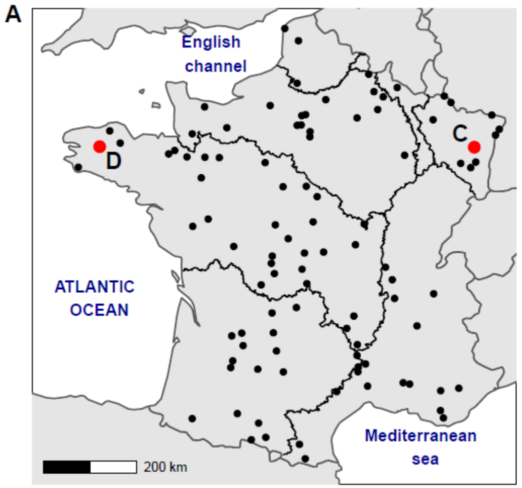
- Anthropogenic habitat degradation and species diversity loss have both destabilizing effects at community level

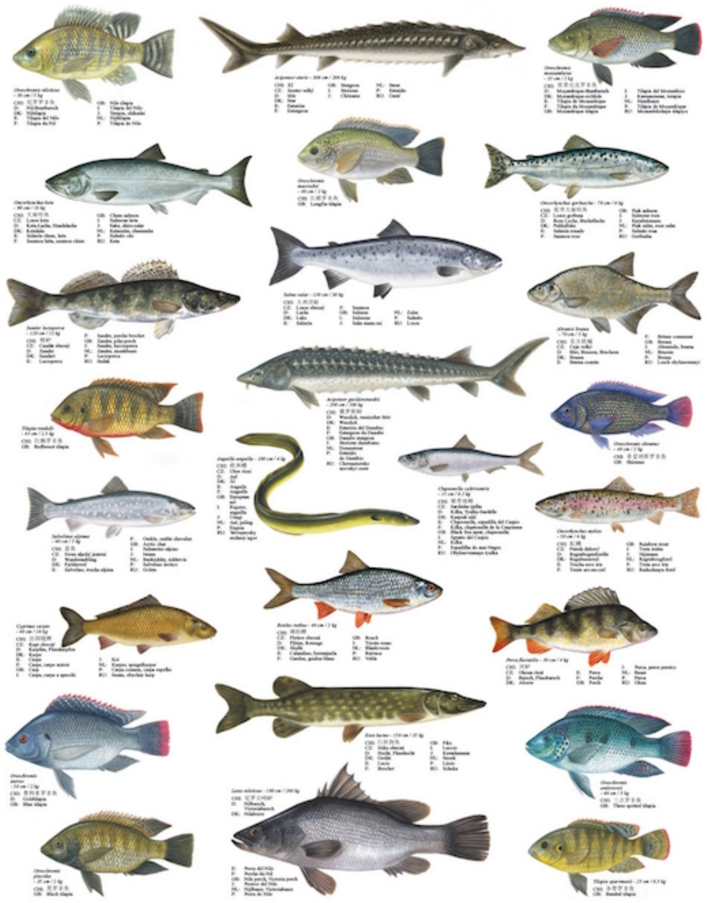
- While the stabilizing effects of diversity are mediated by greater population asynchrony, the destabilizing effects of habitat degradation are mainly channeled by lower population stability

- These results suggest that classical studies on the diversity-stability relationship might miss a critical determinant of natural community stability by not including perturbations into the framework

Stability of empirical multitrophic communities

- Standardized monitoring of river fish communities (ONEMA/OFB)





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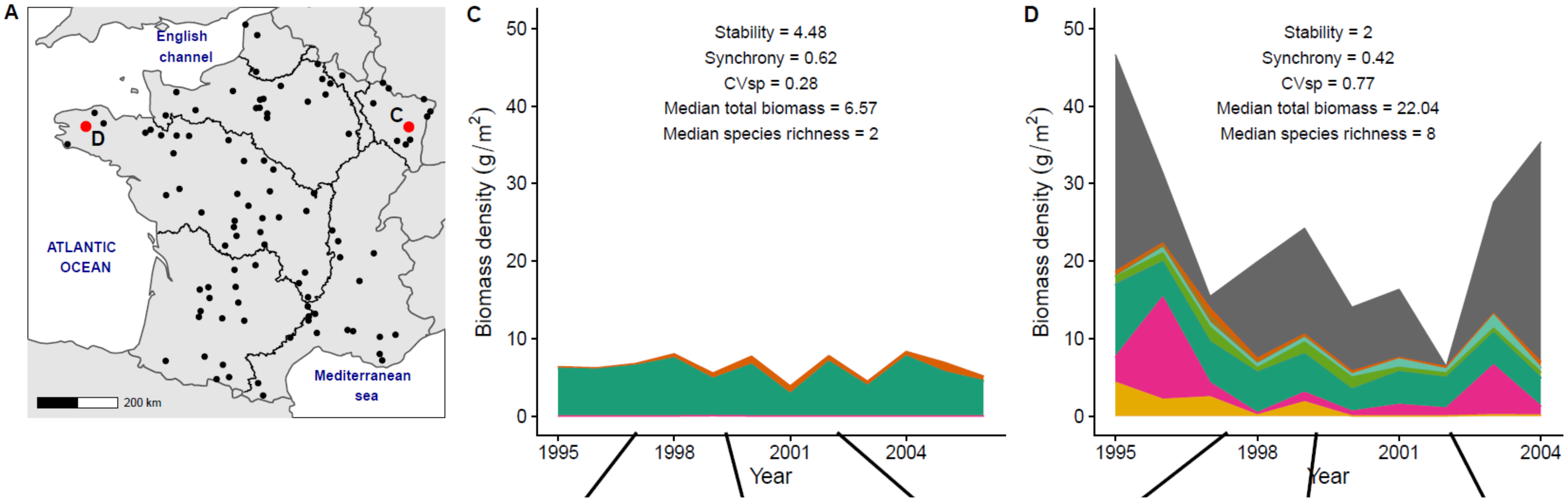

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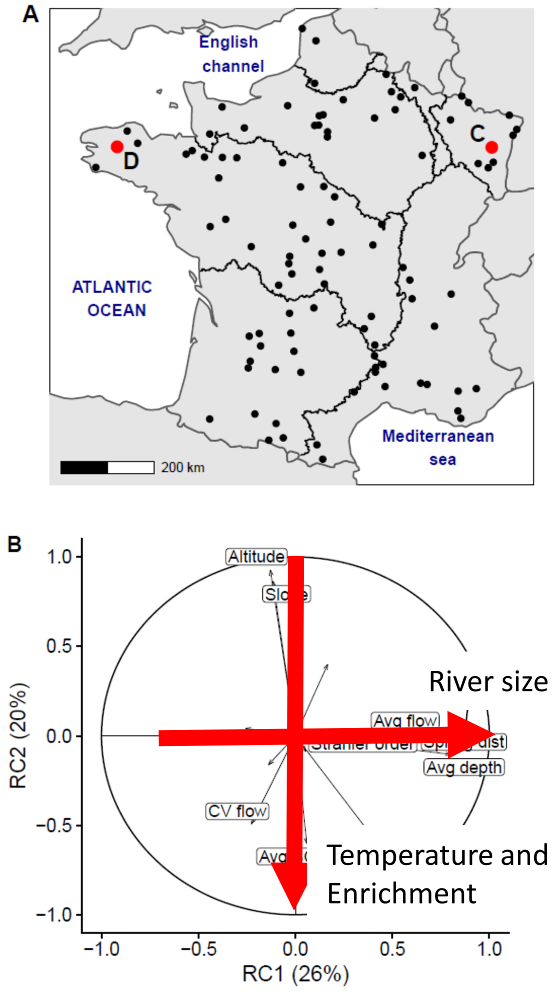
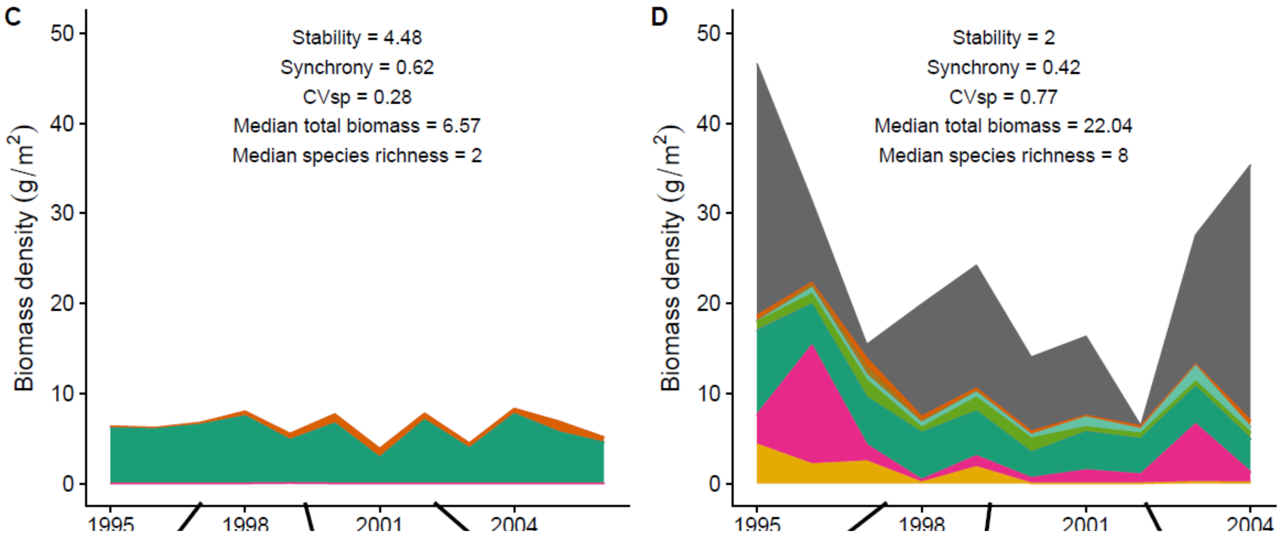
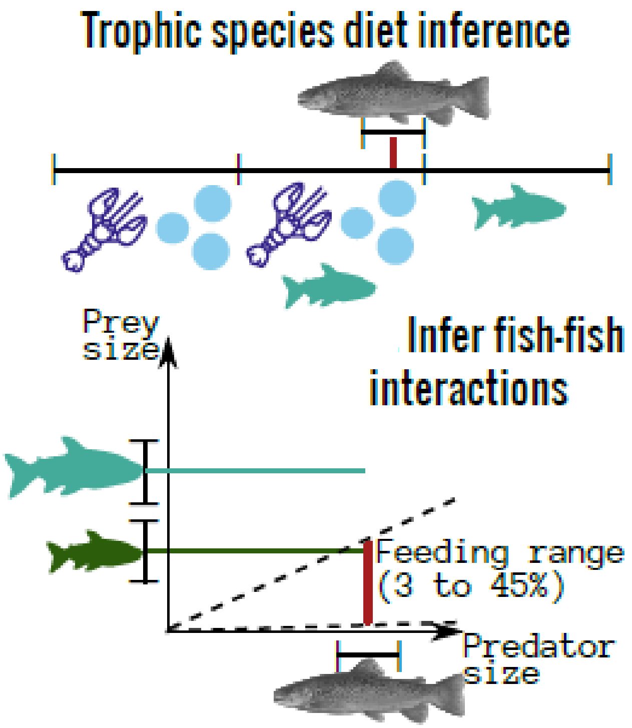
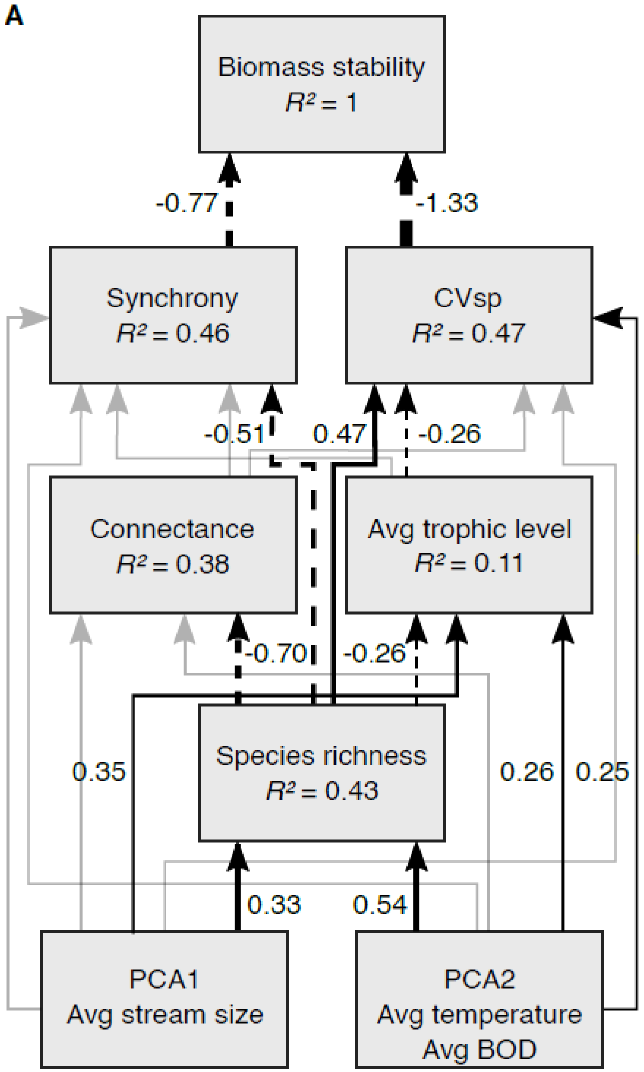






Stability of empirical multitrophic communities



Variable	Direct	Indirect effects via Species richness	Connectance	Avg trophic level	CVsp	Synchrony	Total effect
PCA1 Avg stream size	NA	-0.10	0.00	0.12	0.00	0.00	0.02
PCA2 Avg temperature & Avg BOD	NA	-0.17	0.00	0.09	-0.33	0.00	-0.41
Species richness	NA	NA	0.00	-0.09	-0.62	0.40	-0.31
Connectance	NA	NA	NA	NA	0.00	0.00	0.00
Avg trophic level	NA	NA	NA	NA	0.35	0.00	0.35

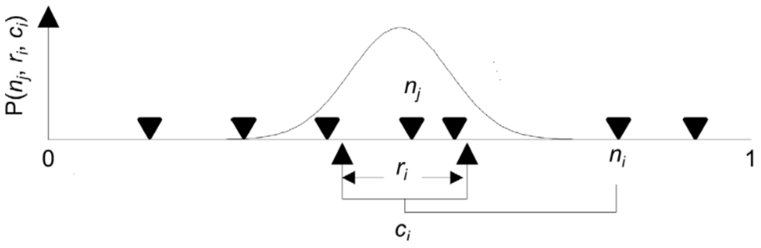
- How to reconcile May’s results with the idea that complexity favors stability?

- Empirical approches to ecological stability

- The dimensionality of ecological stability

What is the dimensionality of ecological stability?

Niche model to define network structure



Bioenergetic model to simulate population dynamics

Conversion efficiency

Metabolic demand

Death rate

$$\frac{dB_i}{dt} = r_i G_i B_i + B_i \sum_{j \in prey} e_{0j} F_{ij} - \sum_{k \in pred} B_k F_{ki} - x_i B_i - d_i B_i$$

$$G_i = (1 - \frac{B_i}{K_i})$$

Logistic groth rate

$$F_{ij} = \frac{w_i a_{ij} B_j^{1+q}}{m_i (1 + w_i \sum_{k \in prey} a_{ik} h_{ik} B_k^{1+q})}$$

Holling-type functional response

Three type of perturbations:

- pulse (e.g. mortality events)
- press (e.g. increased mortality rate, extinctions)
- environmental stochasticity (e.g. white noise)

Twenty seven stability metrics

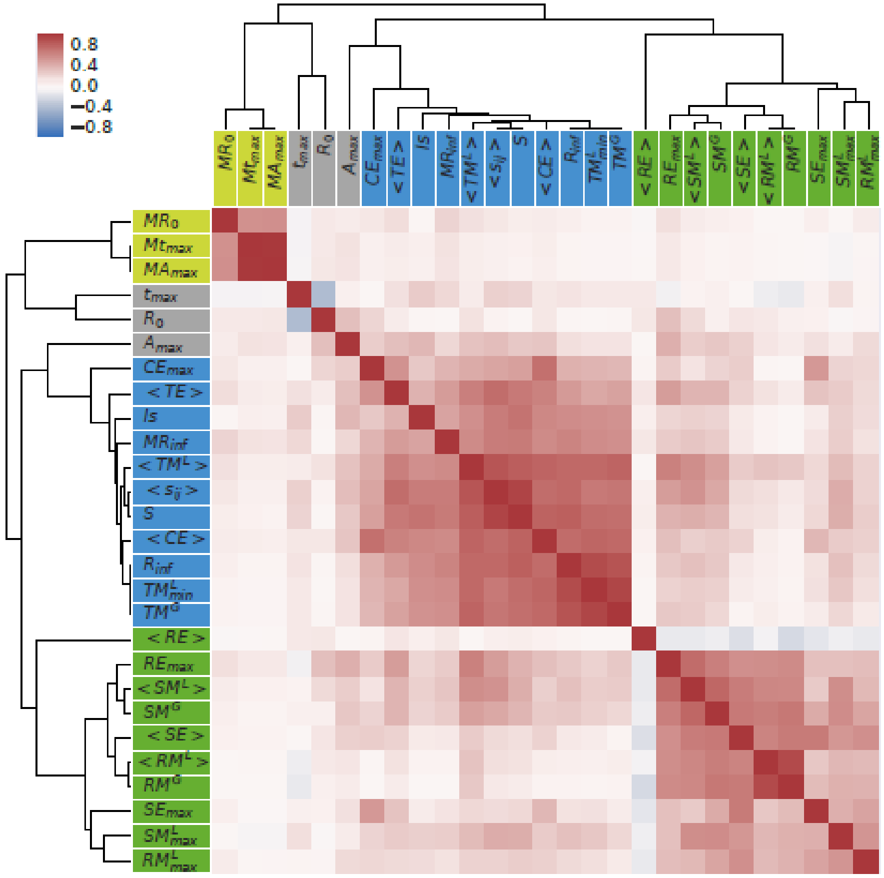
Name (time scale)	Acronym [equation in SI Appendix, section 10]
Reactivity (initial)	R_0 [6], MR_0 [11]
Maximum amplification (transient)	A_{max} [9], MA_{max} [12]
Time to maximum amplification (transient)	t_{max}, Mt_{max}
Resilience (long-term)	$R_{\inf}$ [10], $MR_{\inf}$ [13]
Stochastic invariability (long-term)	I_s [14]
Sensitivity matrix (long-term)	$< s_{ij} >$ [16], S [15]
Tolerance (long-term): To mortality	TM^G [17]
	$< TM^L >$, TM^L_{min}
To extinctions	$< TE >$

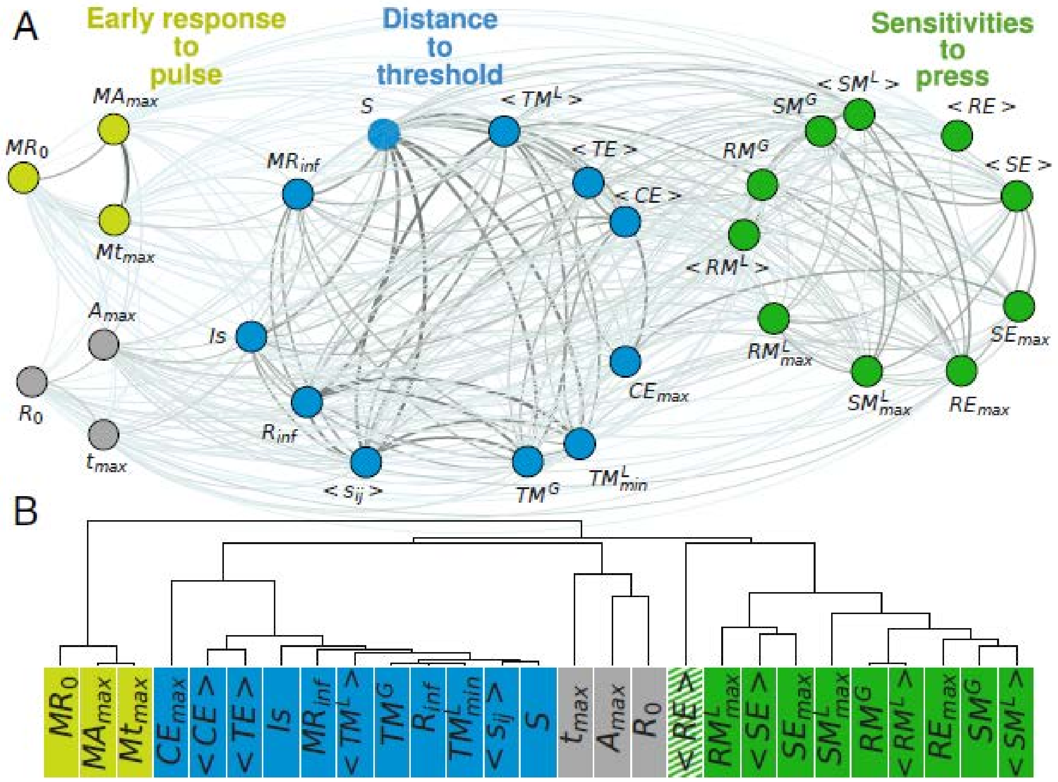
Name (time scale)	Acronym [equation in SI Appendix, section 10]
Resistance of total biomass (long-term): To mortality	RM^G [18]
	$< RM^L >$, RM^L_{max}
To extinctions	$< RE >$ [20], RE_{max}
Cascading extinctions (long-term)	$< CE >$, CE_{max}
Sensitivity of species' biomass (long-term): To mortality	SM^G [19]
	$< SM^L >$, SM^L_{max}
To extinctions	$< SE >$ [21], SE_{max}

Domingues-Garcia et al. 2019

What is the dimensionality of ecological stability?

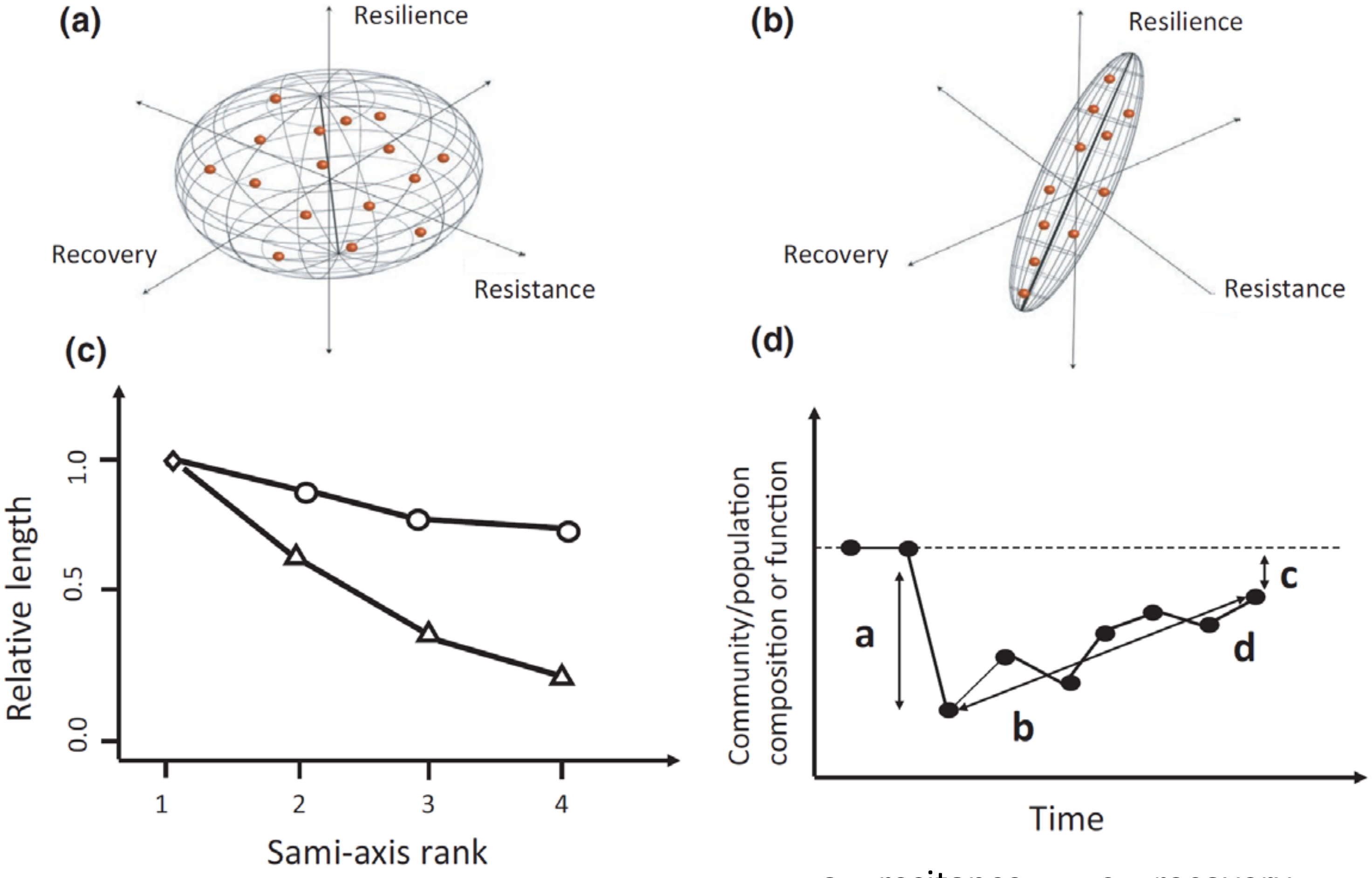
Modularity analysis on the spearman correlation coefficients among stability metrics





Domingues-Garcia et al. 2019

Effect of perturbations on the dimensionality of stability

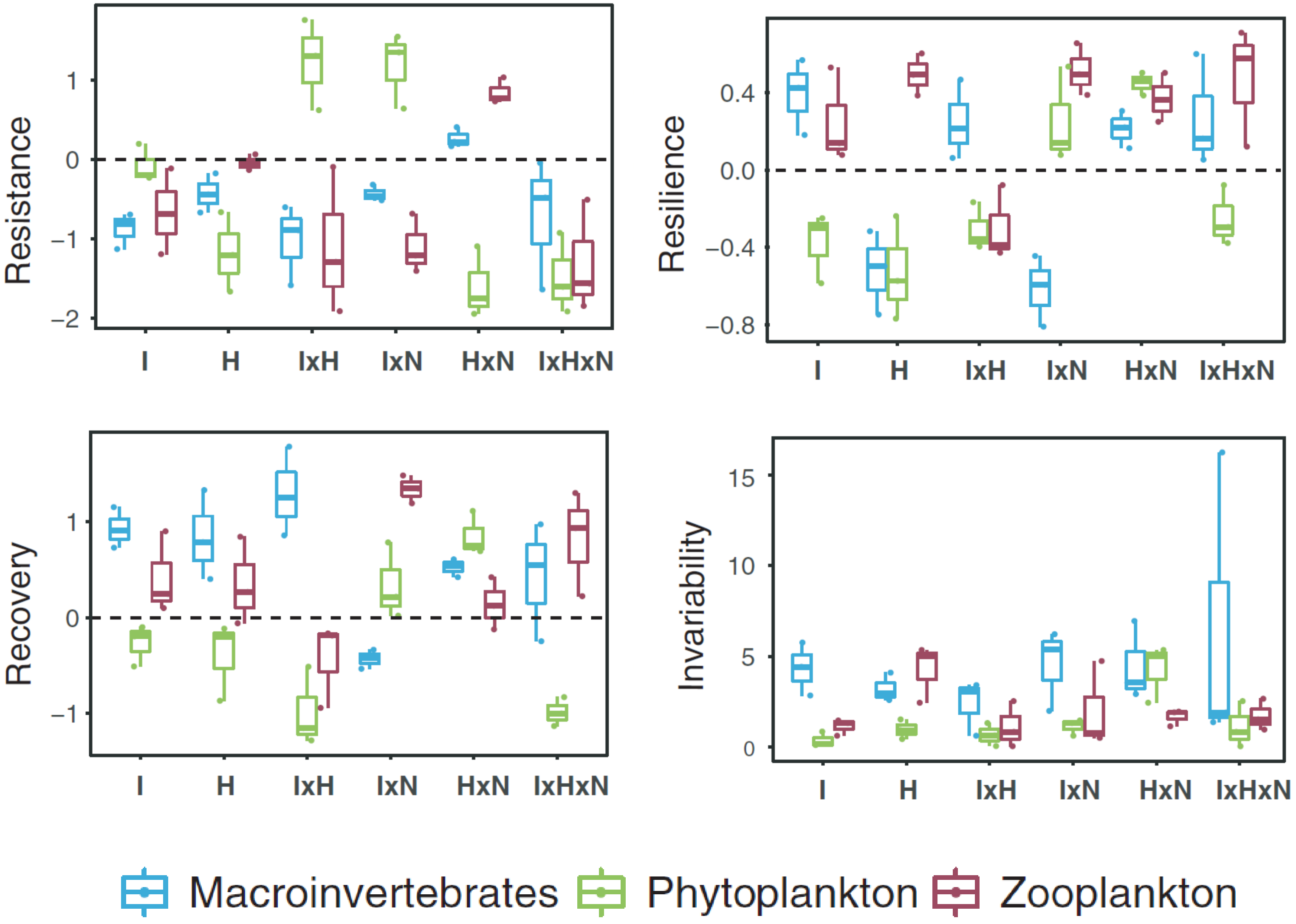


a = resitance
b = resilience
c = recovery
b = invariability

Perturbation treatments:
Insecticide x Herbicide x nutrients

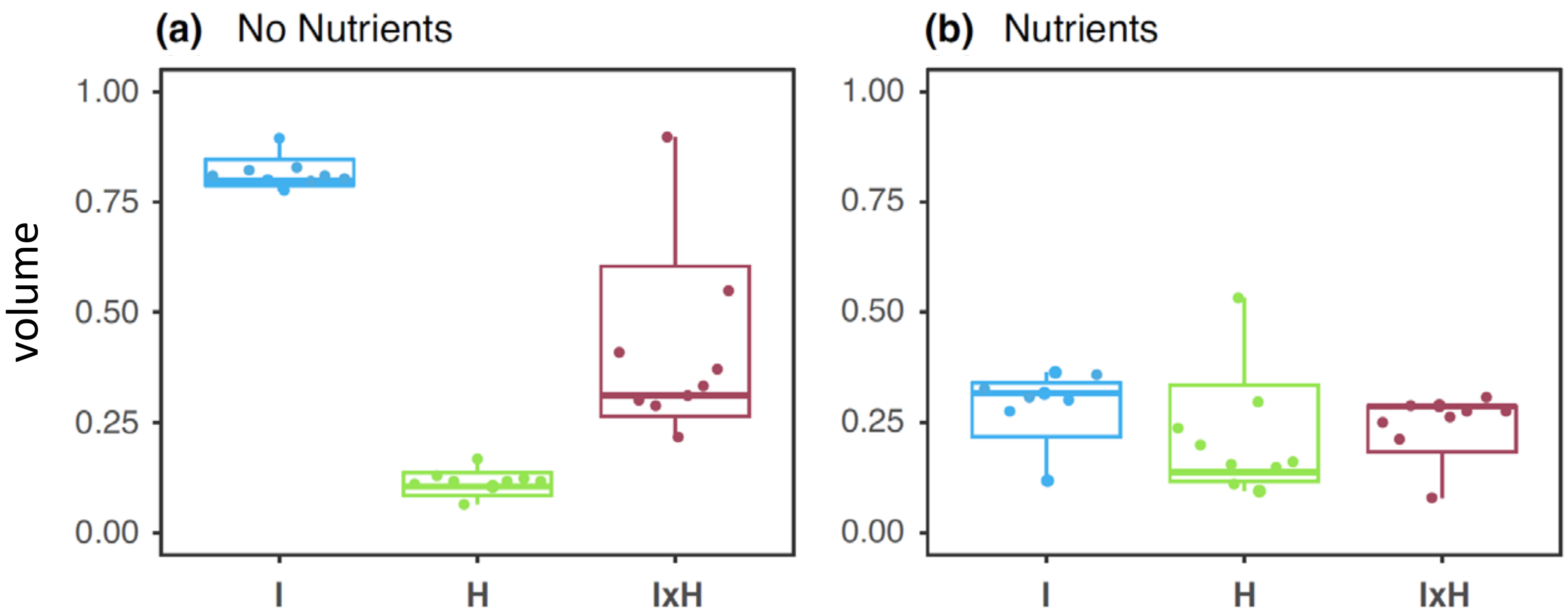
Pollazo et al. 2021

Effect of perturbations on the dimensionality of stability



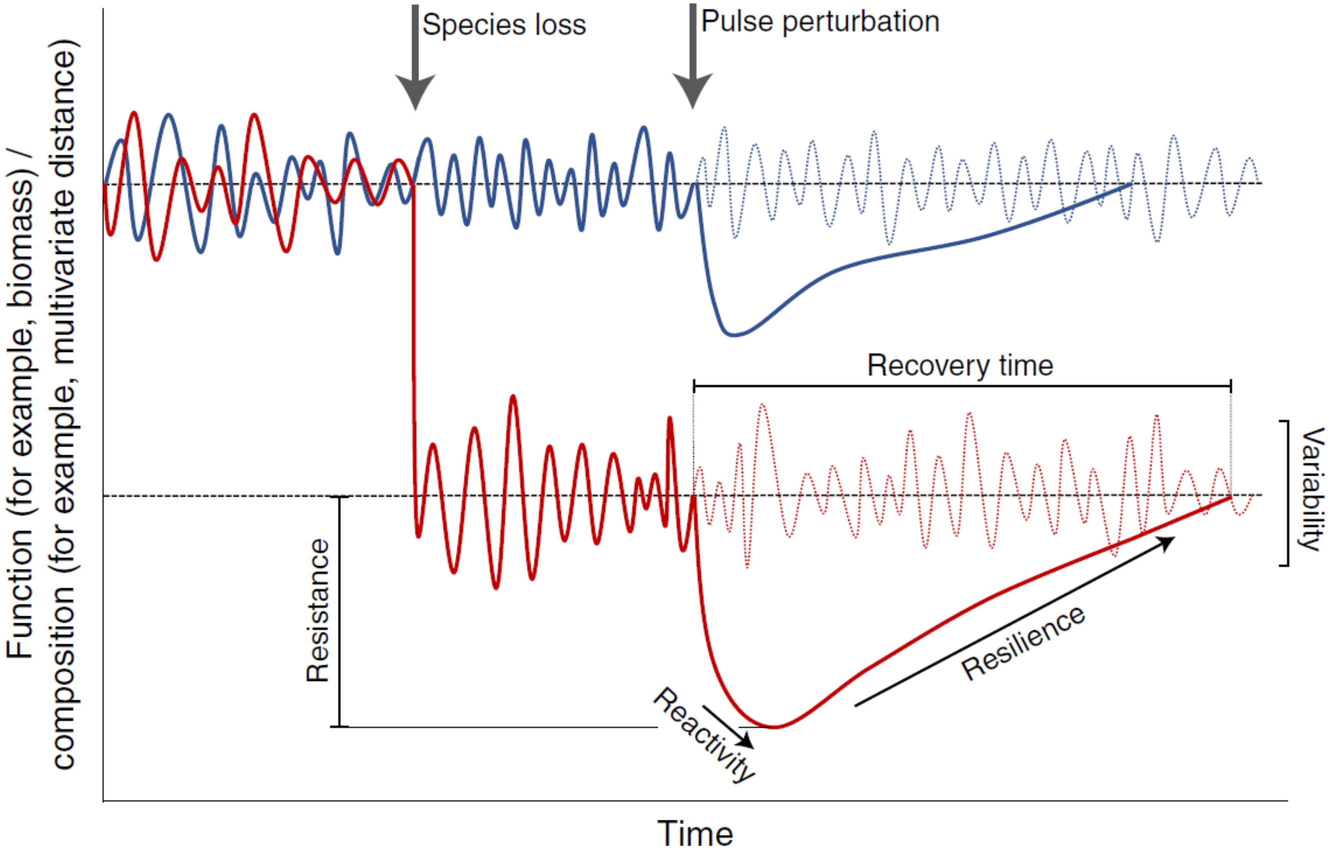
Pollazo et al. 2021

Effect of perturbations on the dimensionality of stability



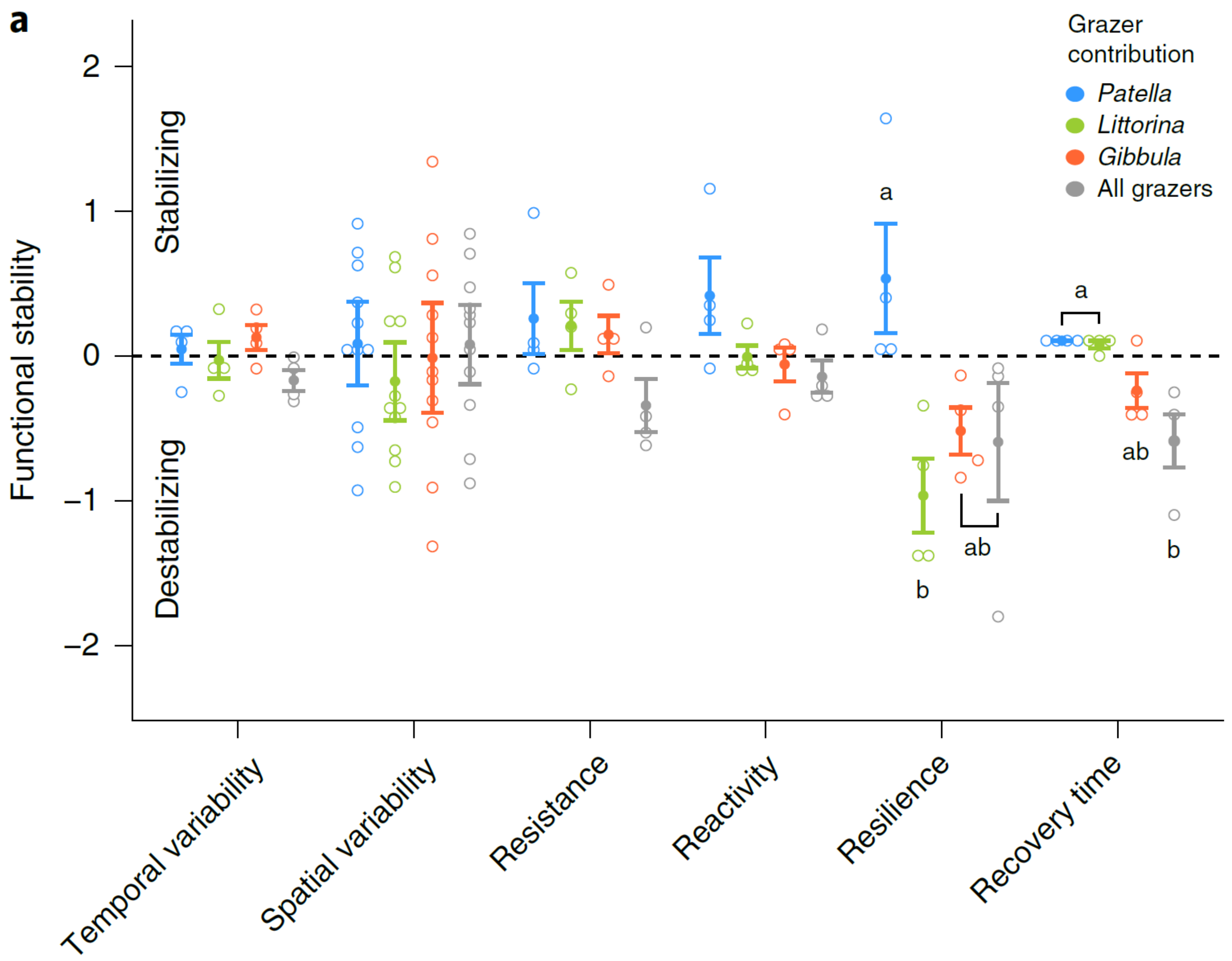
Pollazo et al. 2021

Species contribution to different components of stability



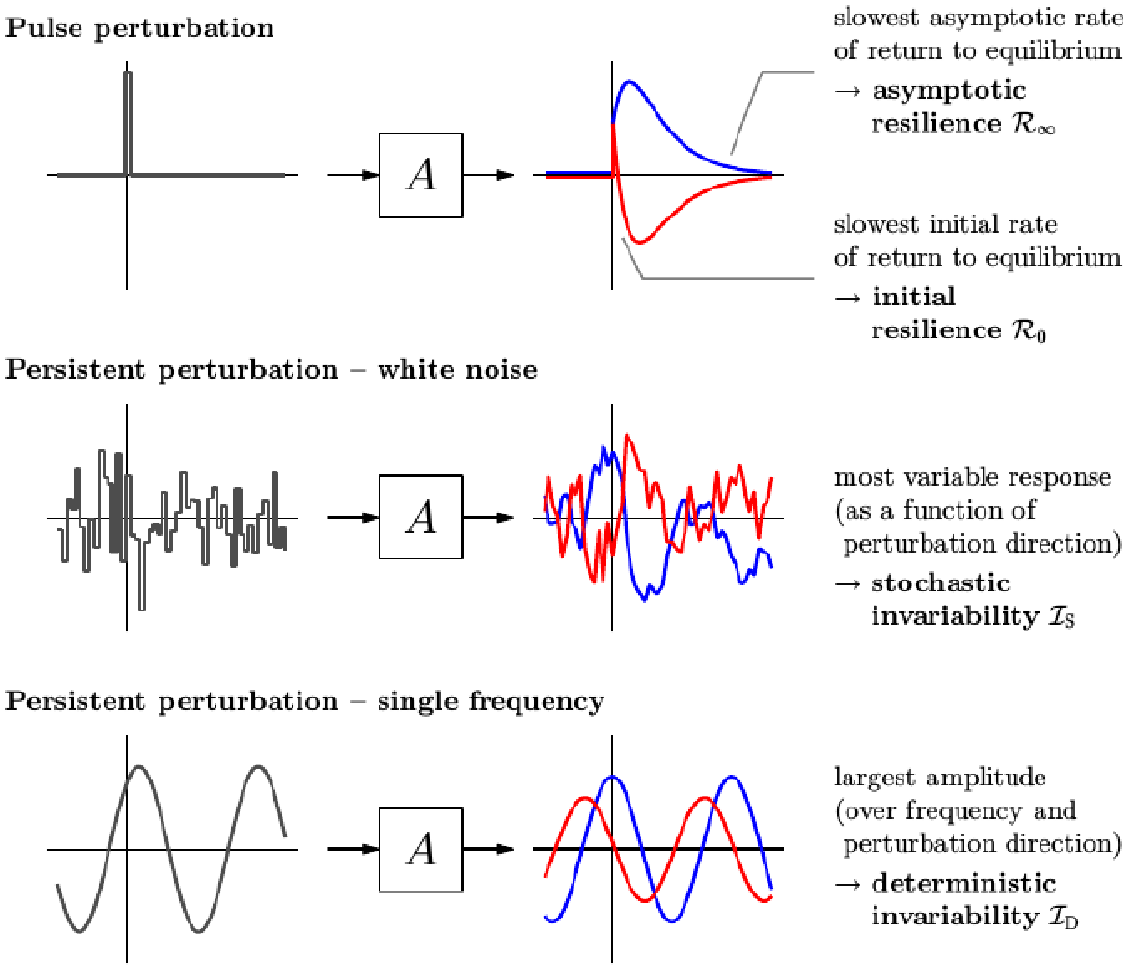
White et al. (2020)

Species contribution to different components of stability



White et al. (2020)

Mathematical relationship among stability new metrics



Stability measure	Interpretation	Formula
Asymptotic resilience	Slowest asympt. rate of return to equilibrium after a shock.	$\mathcal{R}_\infty = -\Re(\lambda_{\mathrm{dom}}(A))$ [a]
Deterministic invariability	Inverse of maximal response amplitude to periodic forcing.	$\mathcal{I}_D = (\sup_\omega \lvert\lvert(i\omega - A)^{-1}\rvert\rvert)^{-1}$ [b]
Stochastic invariability	Inverse of maximal response variance to white-noise.	$\mathcal{I}_S = \frac{1}{2}\lvert\lvert - \hat{A}^{-1}\rvert\rvert^{-1}$ [c]
Initial resilience	Slowest initial rate of return to equilibrium after a shock.	$\mathcal{R}_0 = -\frac{1}{2}\lambda_{\mathrm{dom}}(A + A^\top)$ [d]

[a] λ_{dom} is the eigenvalue of community matrix A with maximal real part $\Re(\lambda_{\mathrm{dom}})$.

[b] i is the imaginary unit and $\omega \geq 0$. $\lvert\lvert \cdot \rvert\rvert$ is the spectral norm of matrices.

[c] $\hat{A} = A \otimes \mathbb{I} + \mathbb{I} \otimes A$ where $\mathbb{I}$ is the identity matrix; $\otimes$ is the Kronecker product.

[d] $A^\top$ is the transpose of A.

$$\mathcal{R}_0 \leq \mathcal{I}_S \leq \mathcal{I}_D \leq \mathcal{R}_\infty$$

Arnoldi et al. 2016