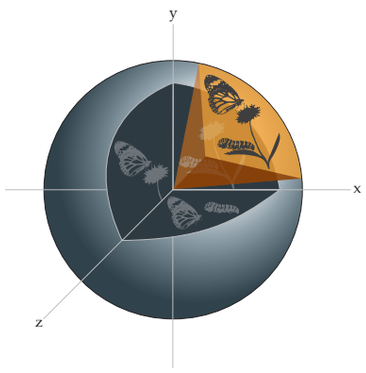
A structural stability approach to understand species coexistence

Chuliang Song

Department of Civil and Environmental Engineering, MIT

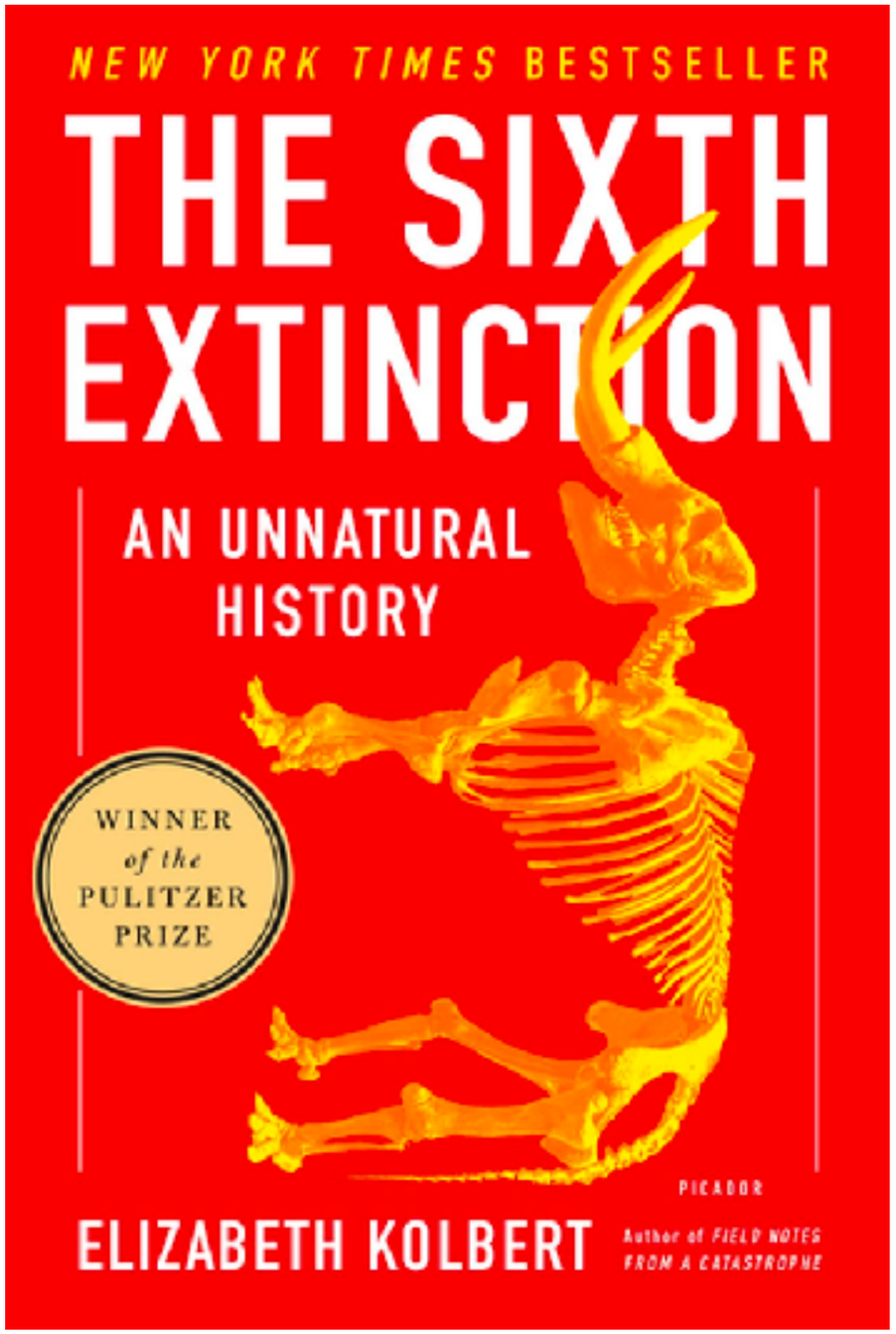


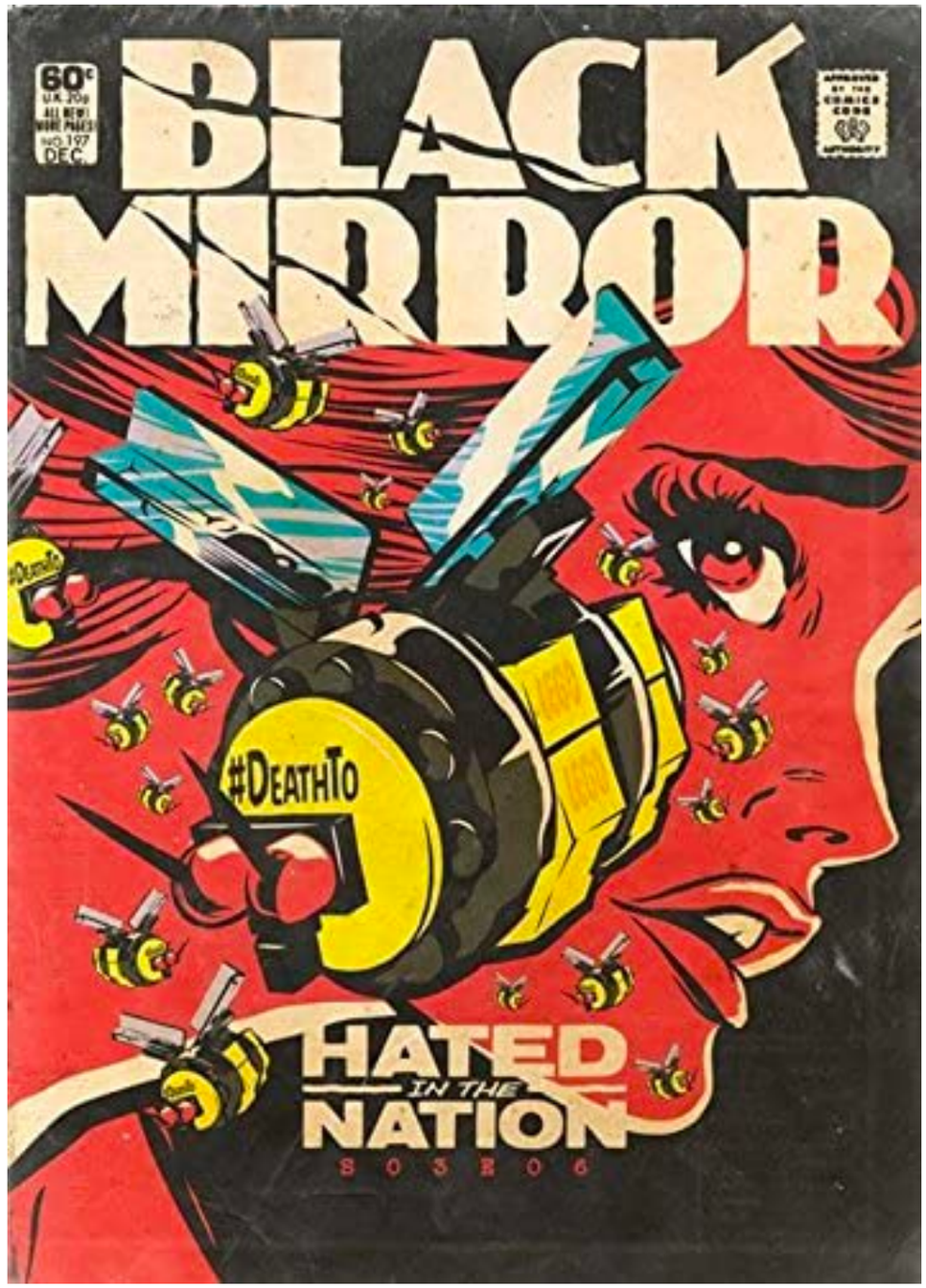
STRUCTURAL ECOLOGY

CForBio讲坛 06/18/2020

Biodiversity is under threat

Biodiversity loss triggers the domino effects

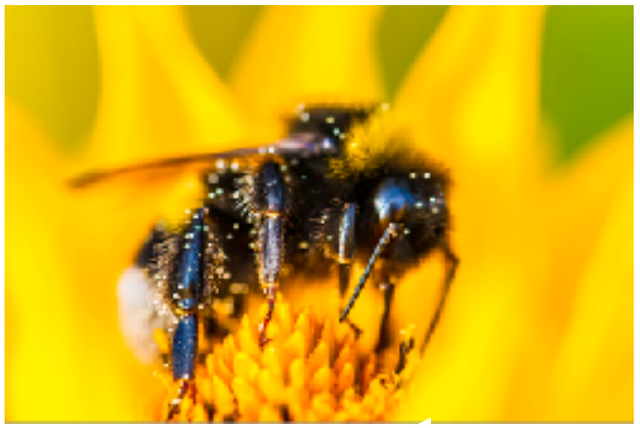




No species is an island

Competitive

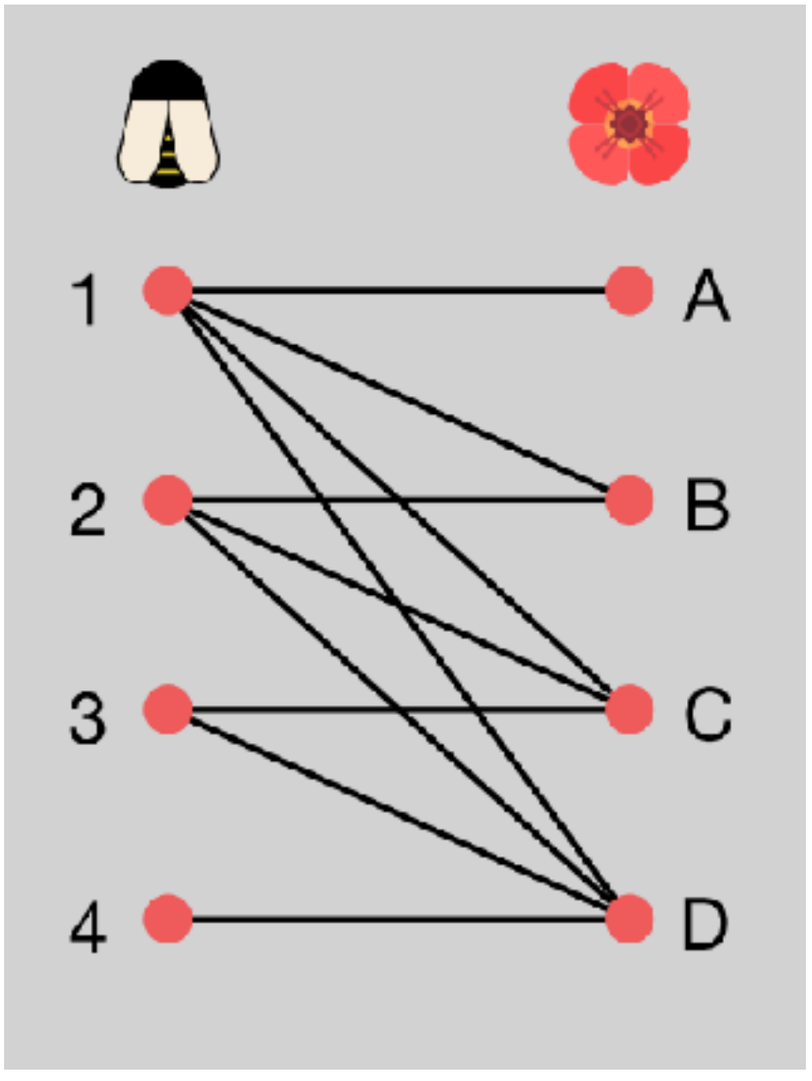
Antagonistic



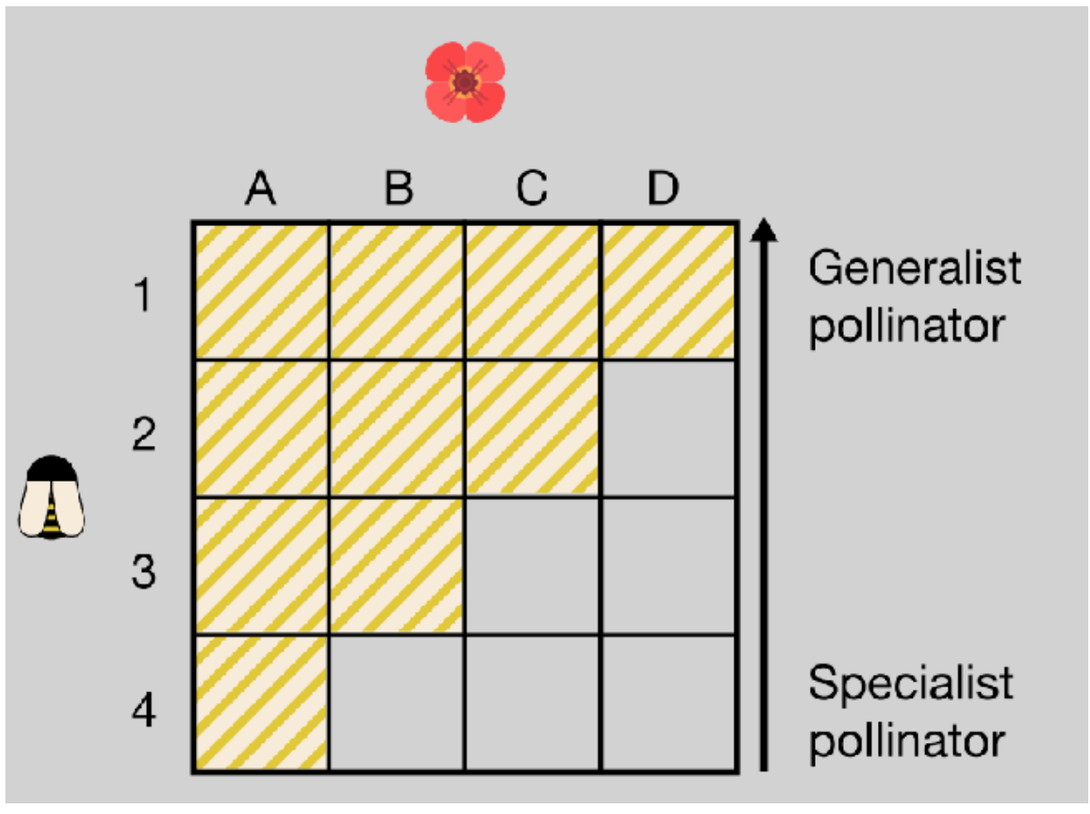
Mutualistic

Ecological network structure =
The organization of species interactions

Graph representation



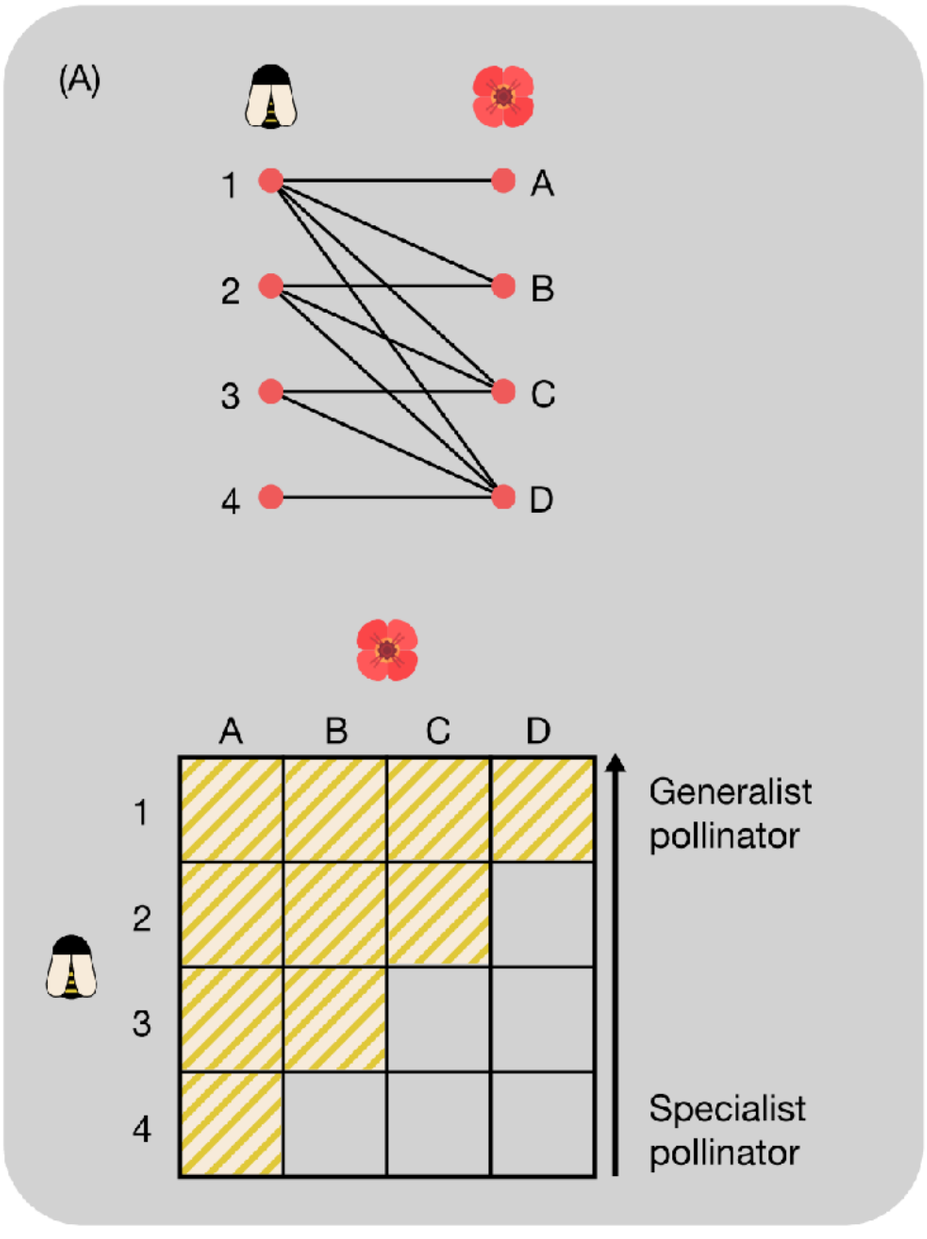
Matrix representation



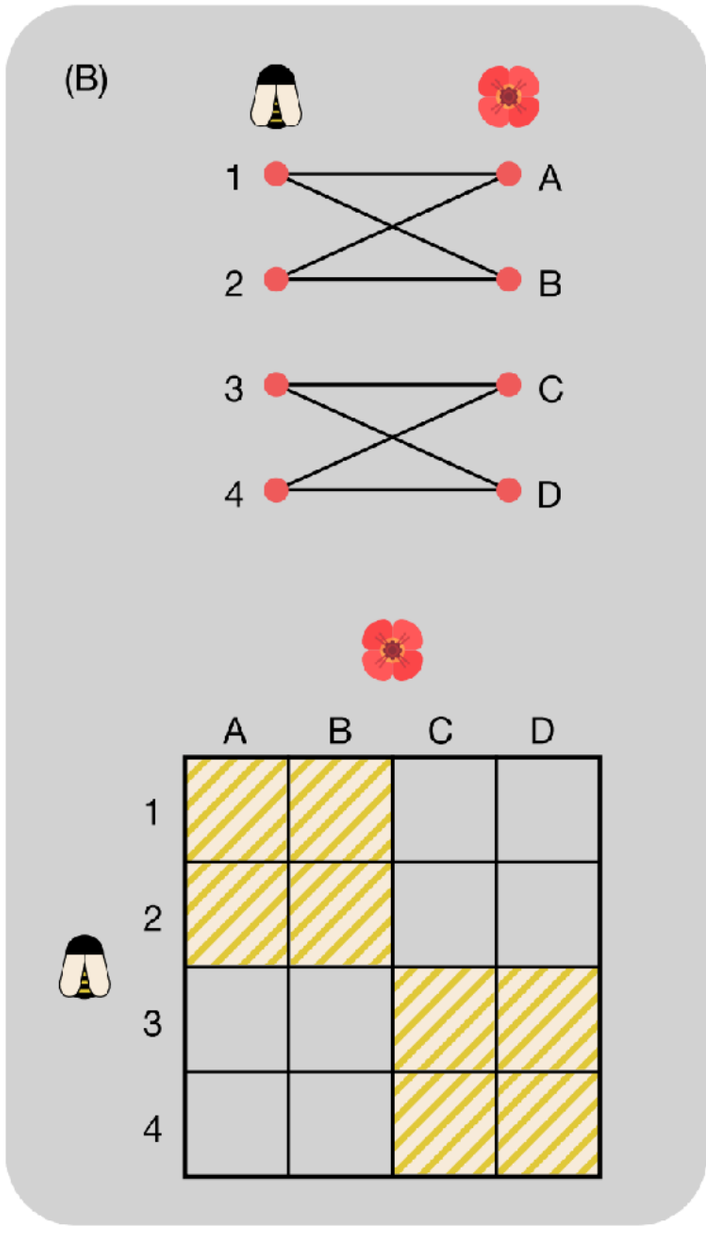
Besson et al., (2019)

Examples of ecological network structures

Nested



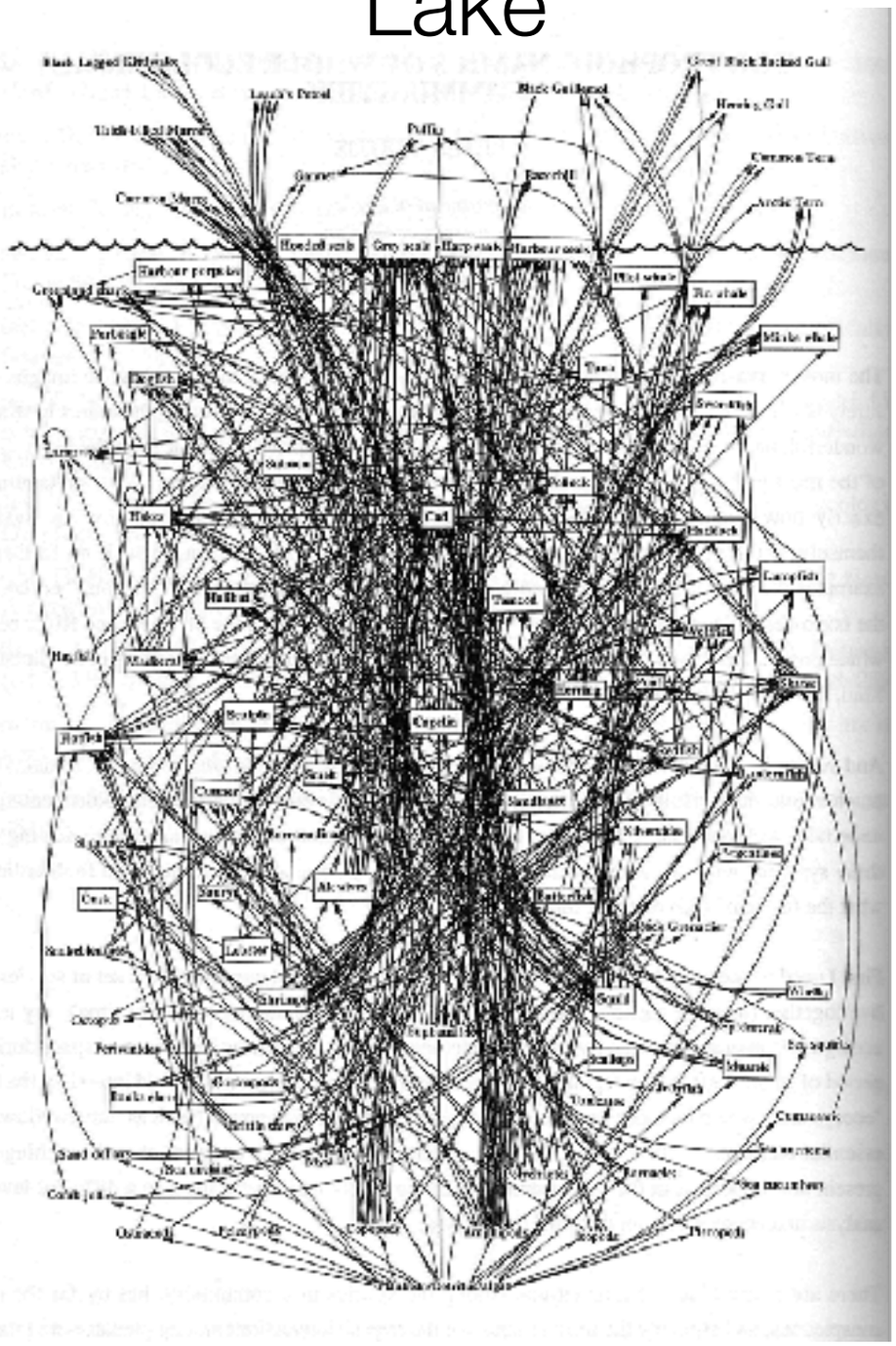
Modular



Besson et al., (2019)

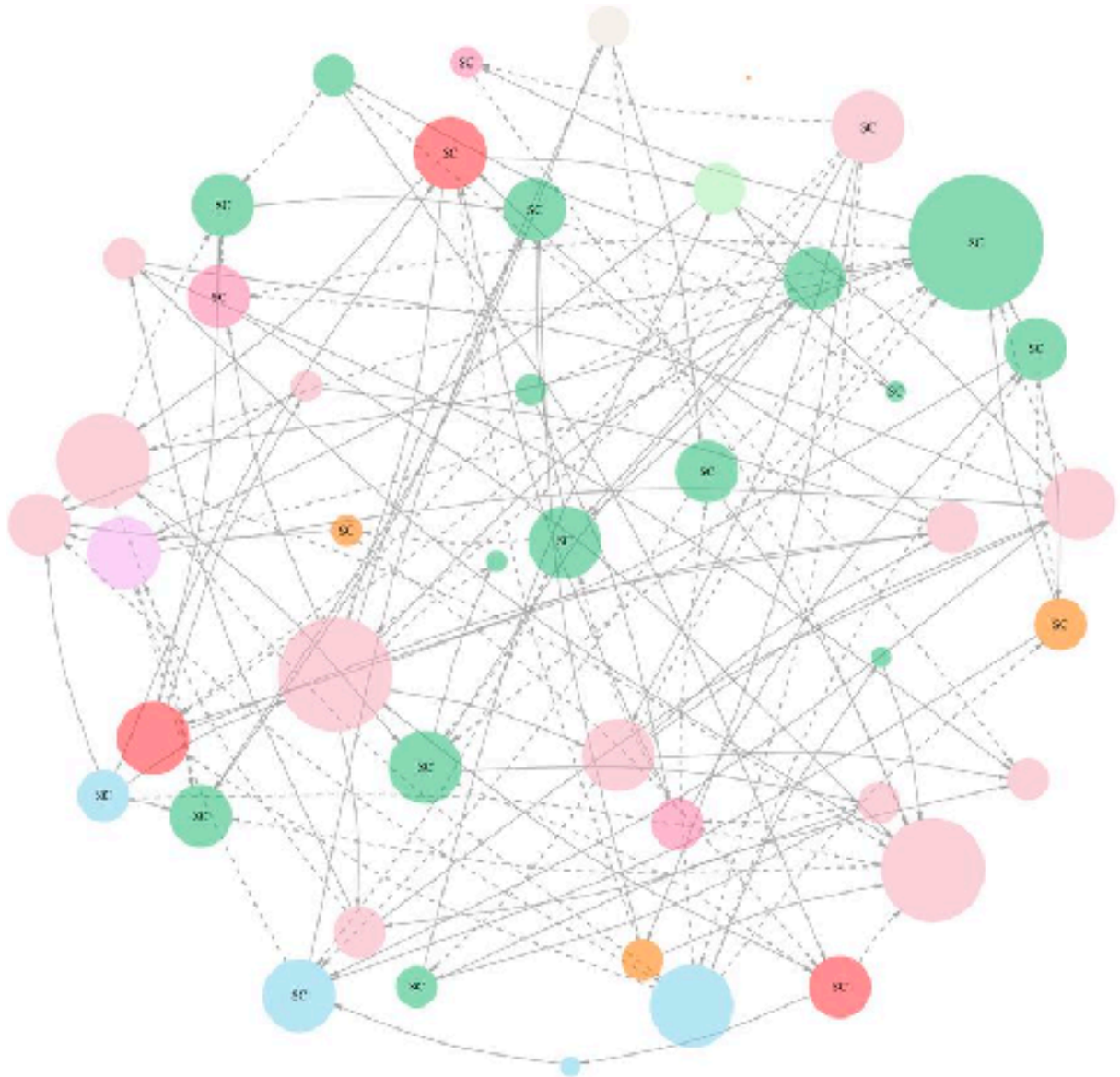
Complexity of ecological network structures

Lake



Elser & Hessen (2007)

Microbiome



Björk et al. (2018)

A central research line in community ecology to understand biodiversity

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Network structure

(The organization of species interactions)

Ecological dynamics

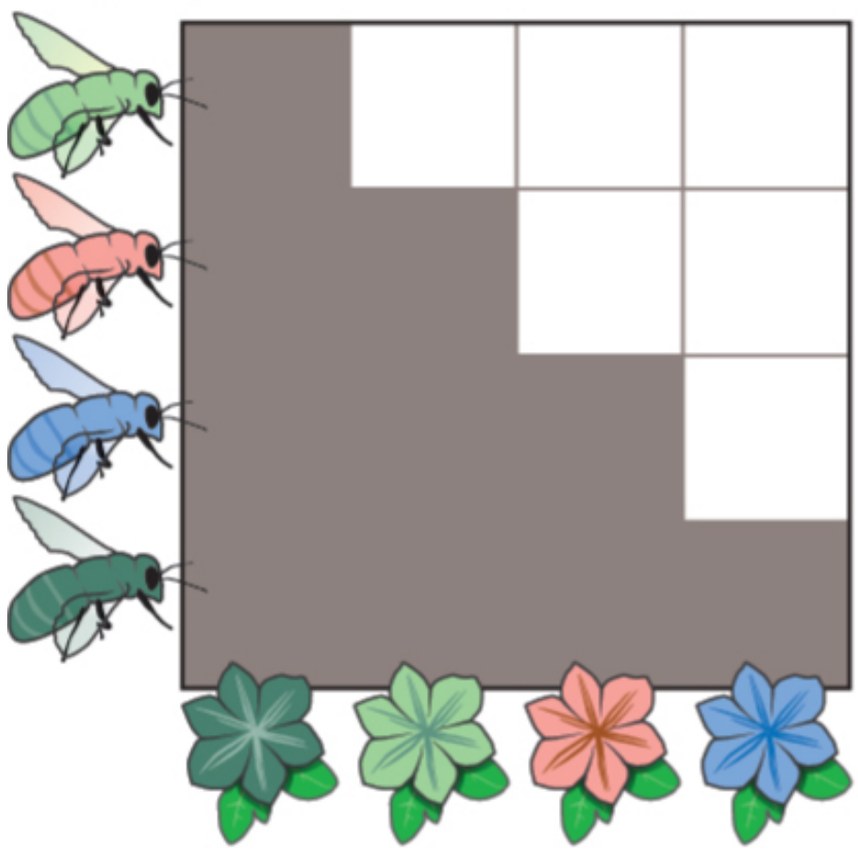
Persistence

(All species coexist without extinctions)

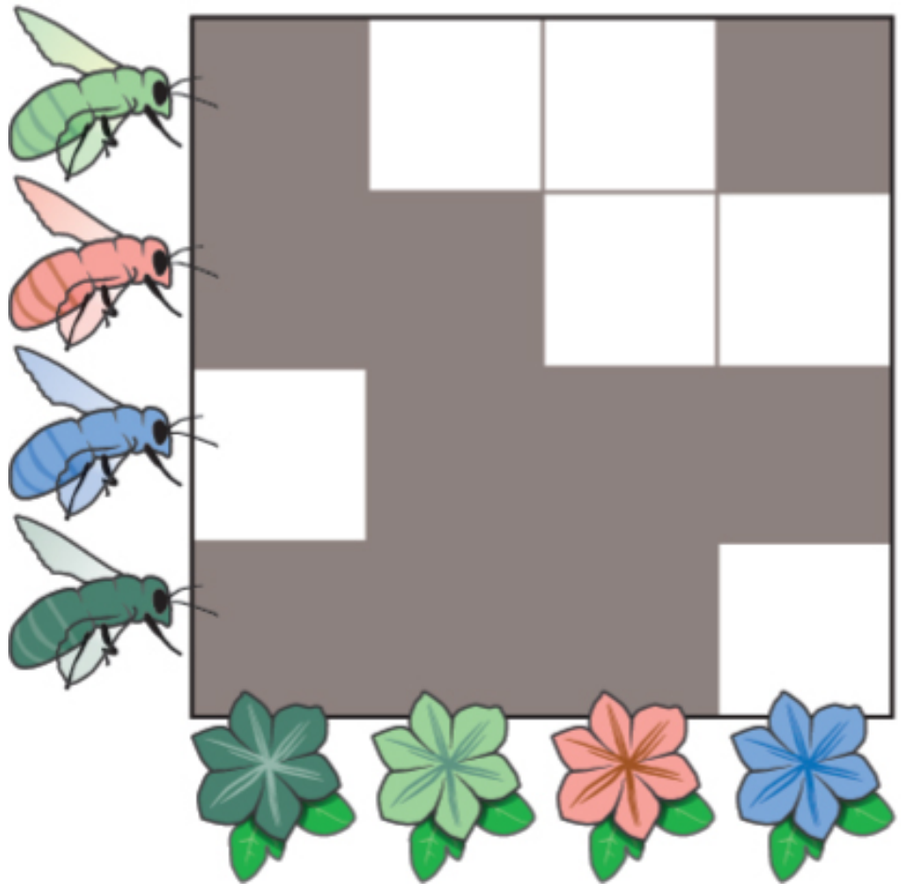
Emerging debates on this research line

Nested pattern in mutualistic community

Perfectly nested



Random



Pawar, *Science* (2014)

One school of thought:
Eureka! Nestedness is so important.

Nestedness

↓

Persistence

REPORT

Stability of Ecological Communities and the Architecture of Mutualistic and Trophic Networks

Elisa Thébault[1,2,*], Colin Fontaine[1,3,*]
+ See all authors and affiliations

Science
Vol. 329,
DOI: 10.1

Letter | Published: 21 August 2013

Emergence of structural and dynamical properties of ecological mutualistic networks

Samir Suweis, Filippo Simini, Jayanth R. Banavar & Amos Maritan

Letter | Published: 23 April 2009

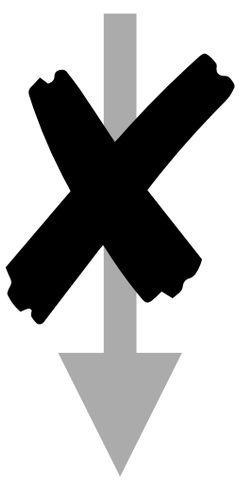
The architecture of mutualistic networks minimizes competition and increases biodiversity

Ugo Bastolla, Miguel A. Fortuna, Alberto Pascual-García, Antonio Ferrera, Bartolo Luque & Jordi Bascompte

Nature **458**, 1018–1020(2009) | Cite this article

Another school of thought:
Nestedness has nothing to do with persistence

Nestedness



Persistence

Review And Synthesis | Free Access

Mutualistic networks: moving closer to a predictive theory

Fernanda S. Valdovinos

First published: 26 June 2019 | https://doi.org/10.1111/ele.13270

Letter | Published: 20 June 2012

Disentangling nestedness from models of ecological complexity

Alex James, Jonathan W. Pitchford & Michael J. Plank

Nature **487**, 227–230(2012) | Cite this article

The Effect of Intra- and Interspecific Competition on Coexistence in Multispecies Communities

György Barabás,[1,*] Matthew J. Michalska-Smith,[1] and Stefano Allesina[1,2,†]

And another school of thought:
NO strong evidence for nestedness!

Article | Published: 22 January 2013

The ghost of nestedness in ecological networks

Phillip P. A. Staniczenko, Jason C. Kopp & Stefano Allesina

Nature Communications **4**, Article number: 1391 (2013) | Download Citation

Breaking the Spell of Nestedness: The Nestedness in Mutualistic Systems

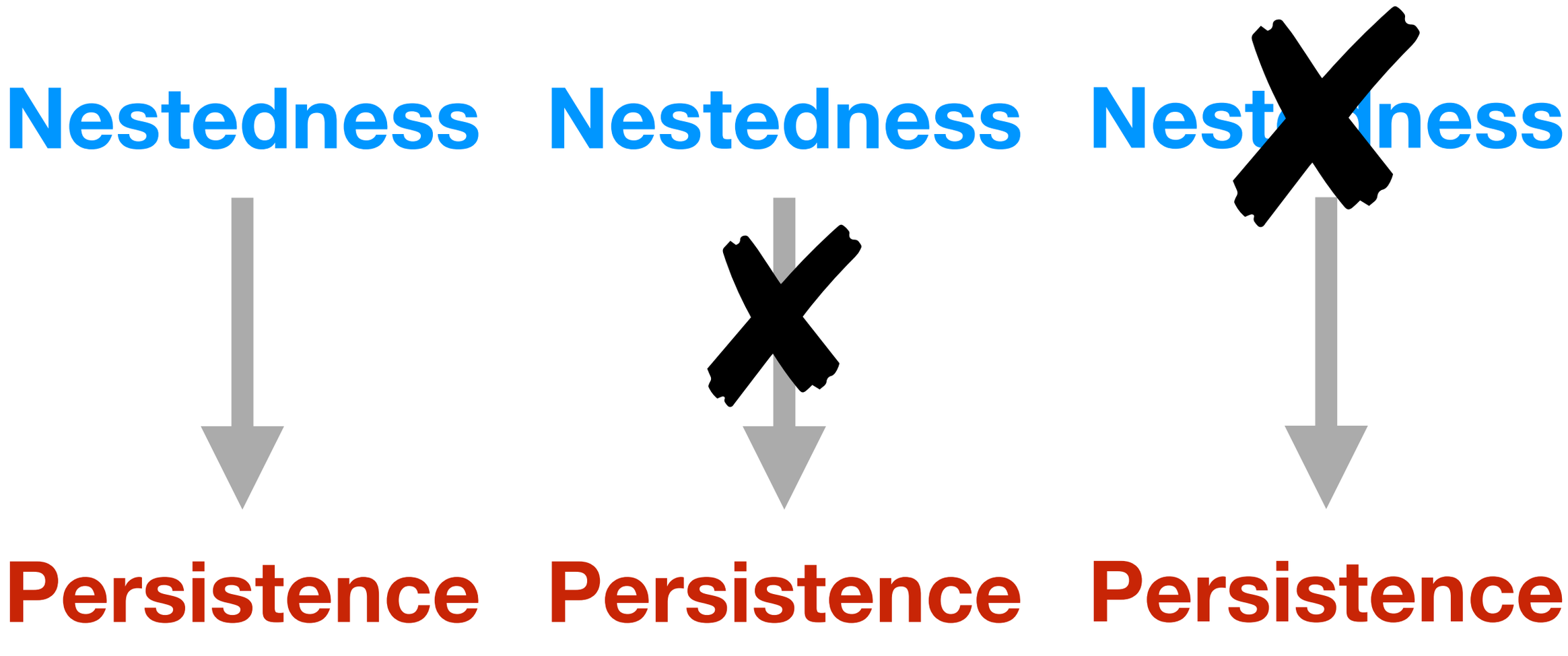
Clàudia Payrató-Borràs, Laura Hernández, and Yamir Moreno
Phys. Rev. X **9**, 031024 – Published 13 August 2019

PERSPECTIVE

Telling ecological networks apart by their structure: A computational challenge

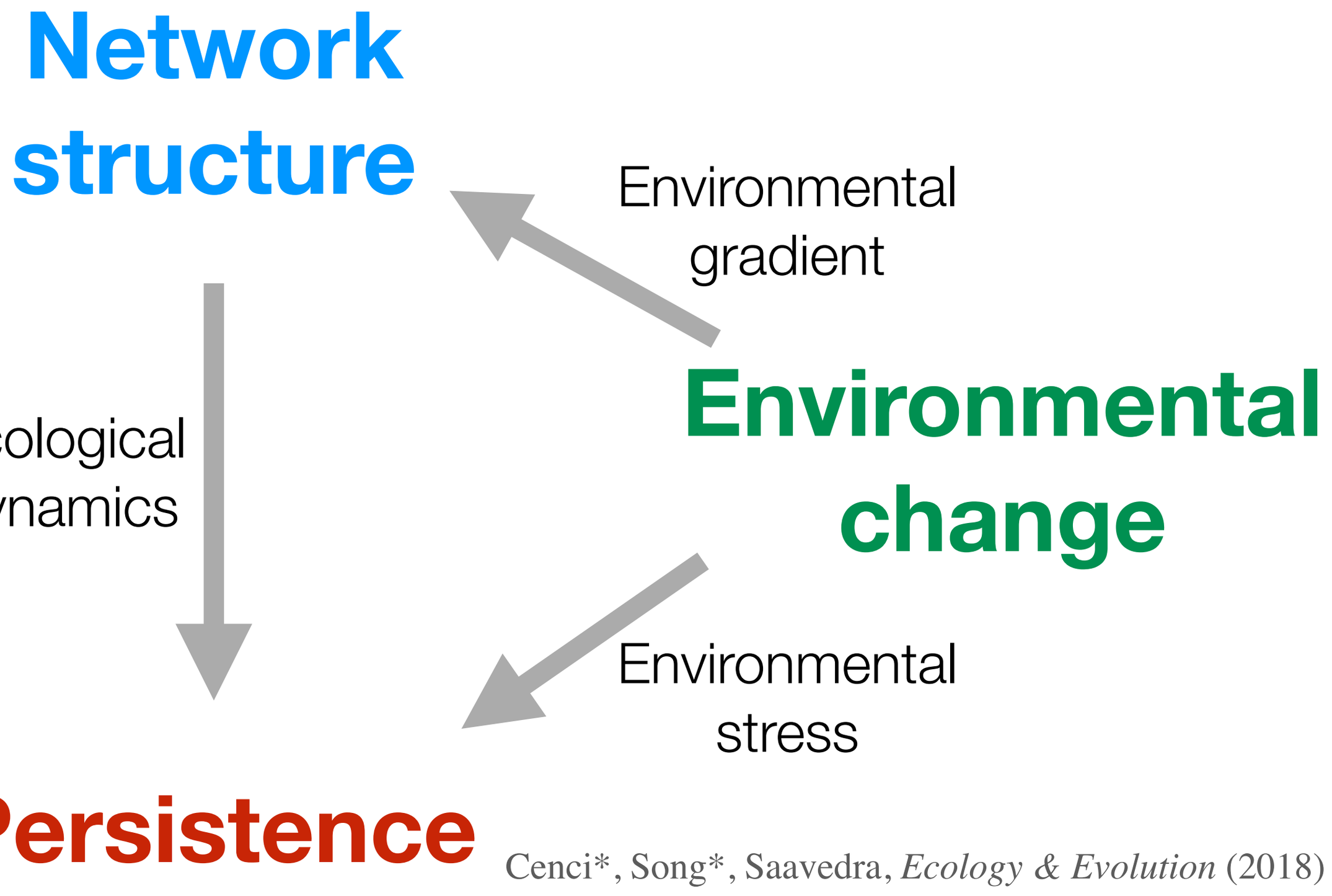
Matthew J. Michalska-Smith[1]*, Stefano Allesina[1,2]

Contrasting schools of thought



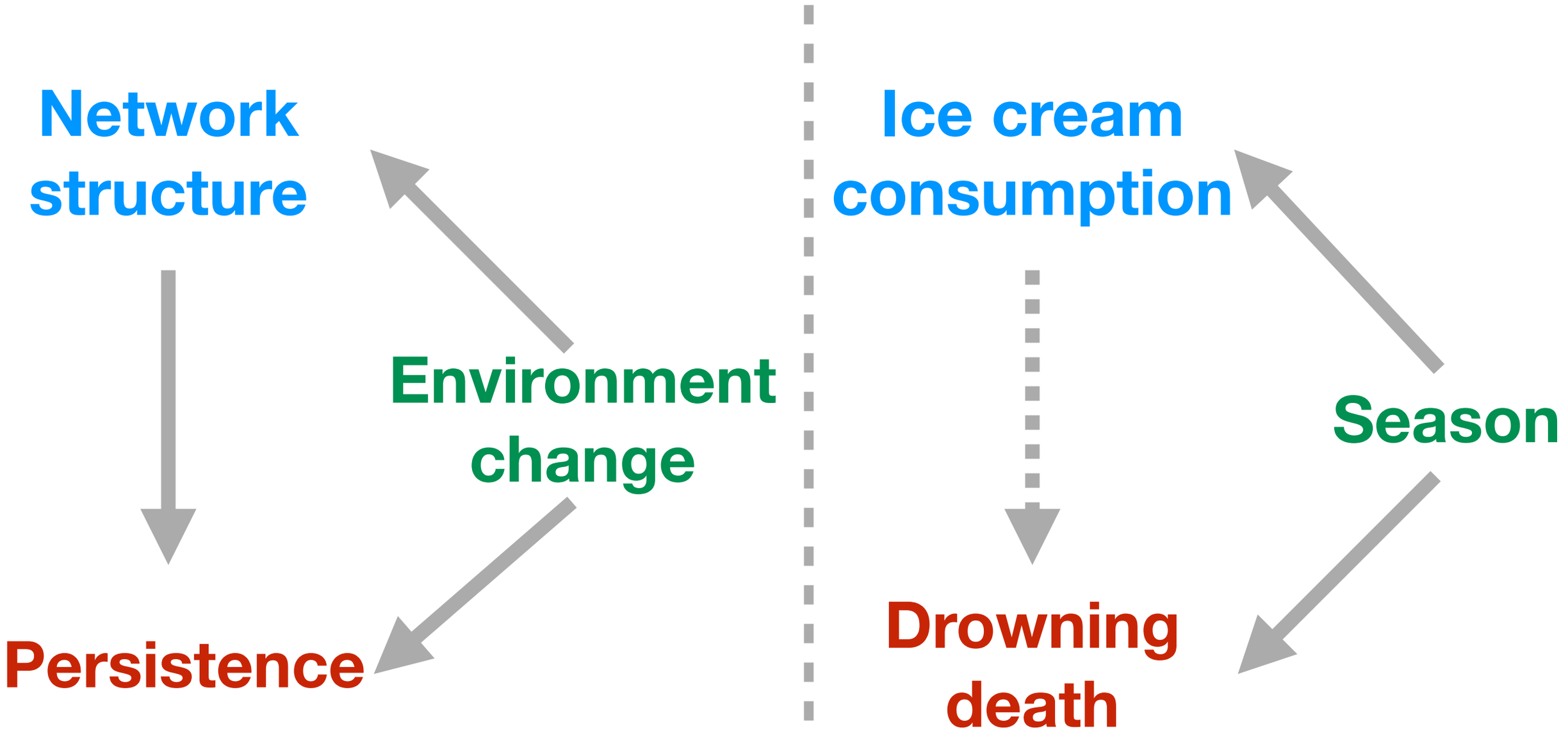
Add a missing link into this research line

Environmental change is often missing

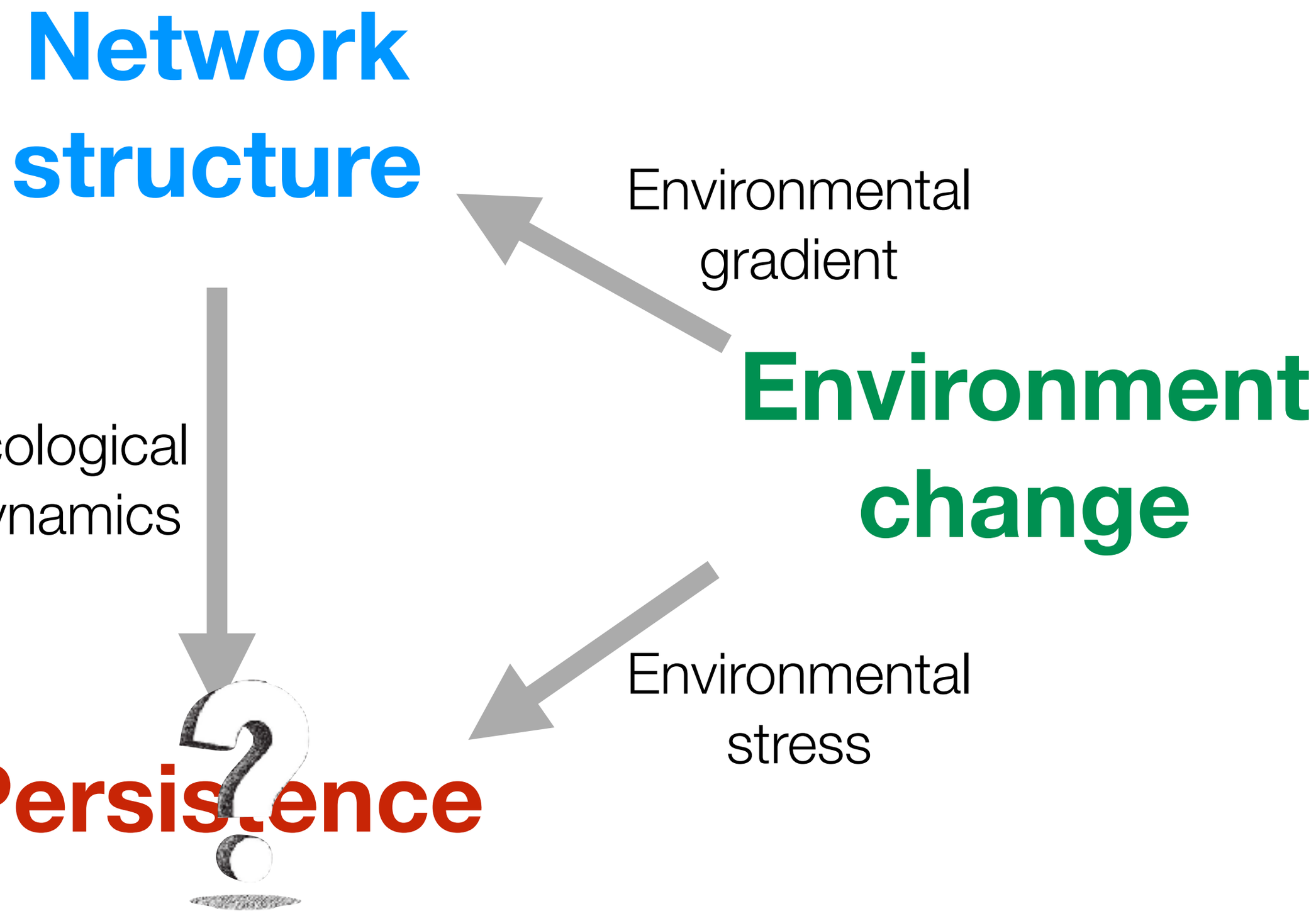


Cenci*, Song*, Saavedra, *Ecology & Evolution* (2018)

Environmental change is a confounder

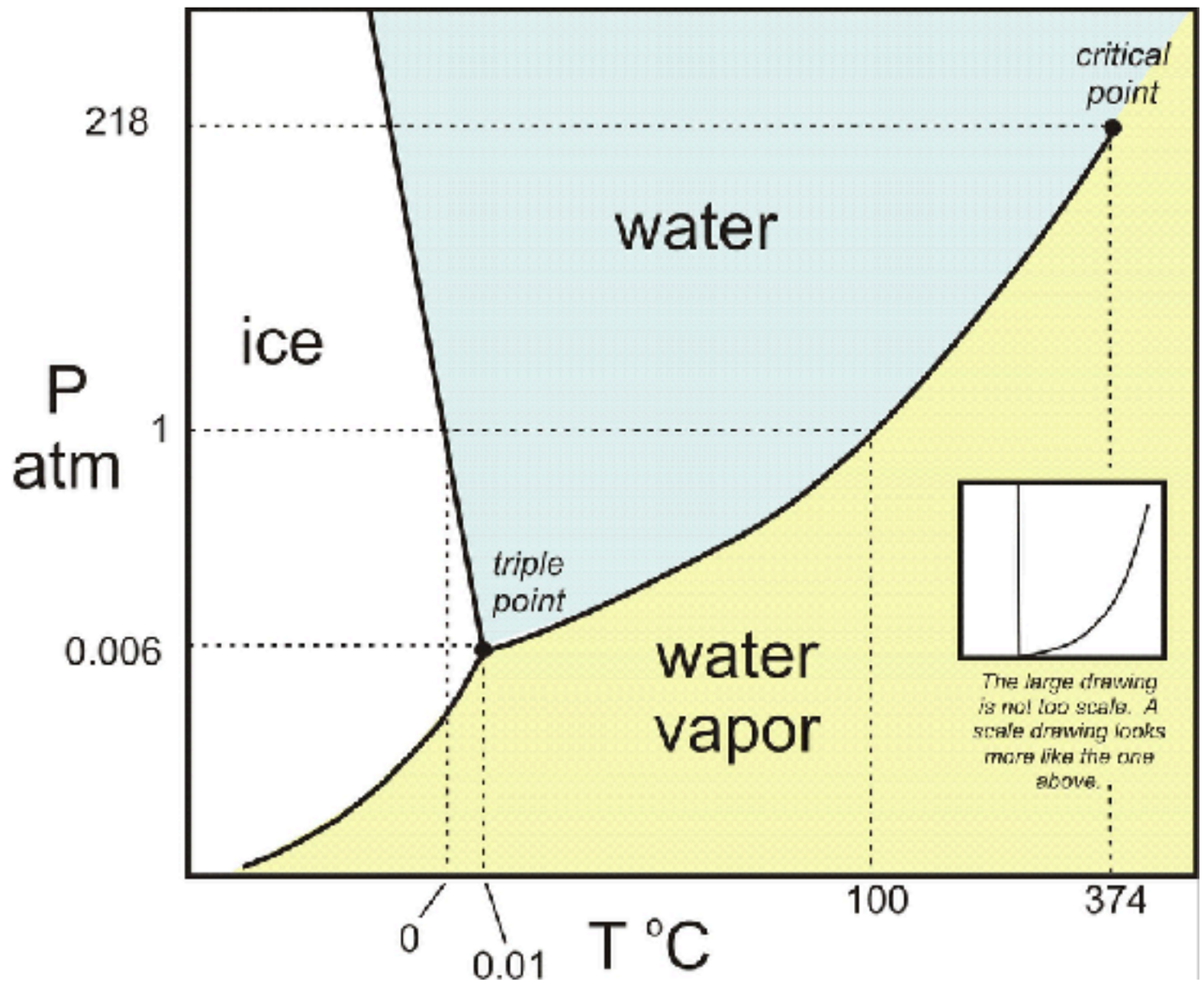


How to quantify Persistence with Network structure and Environmental change



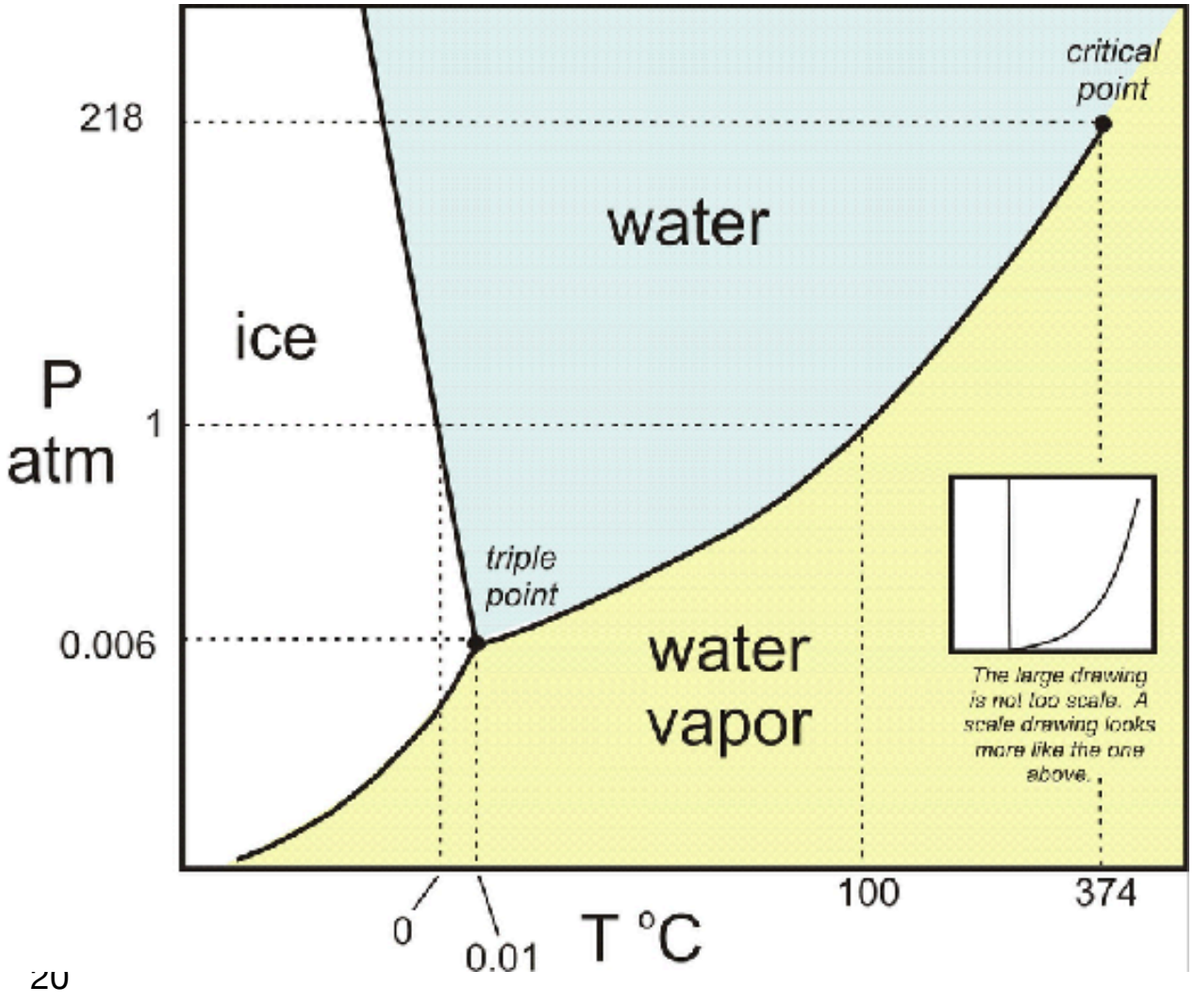
What is structural stability?

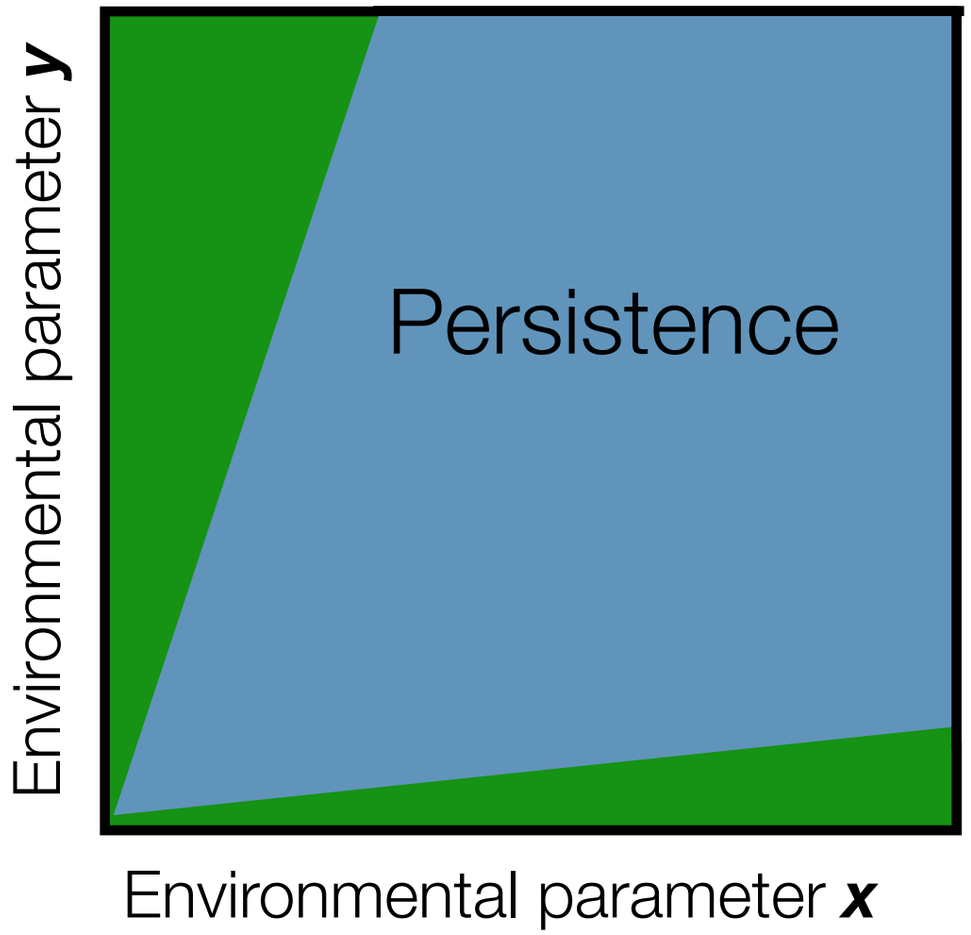
The full range of parameters compatible with some qualitative dynamical behavior



Structural stability in ecological contexts

The full range of **environmental conditions** (parameters) compatible with the **persistence** (qualitative dynamical behavior) of an ecological community



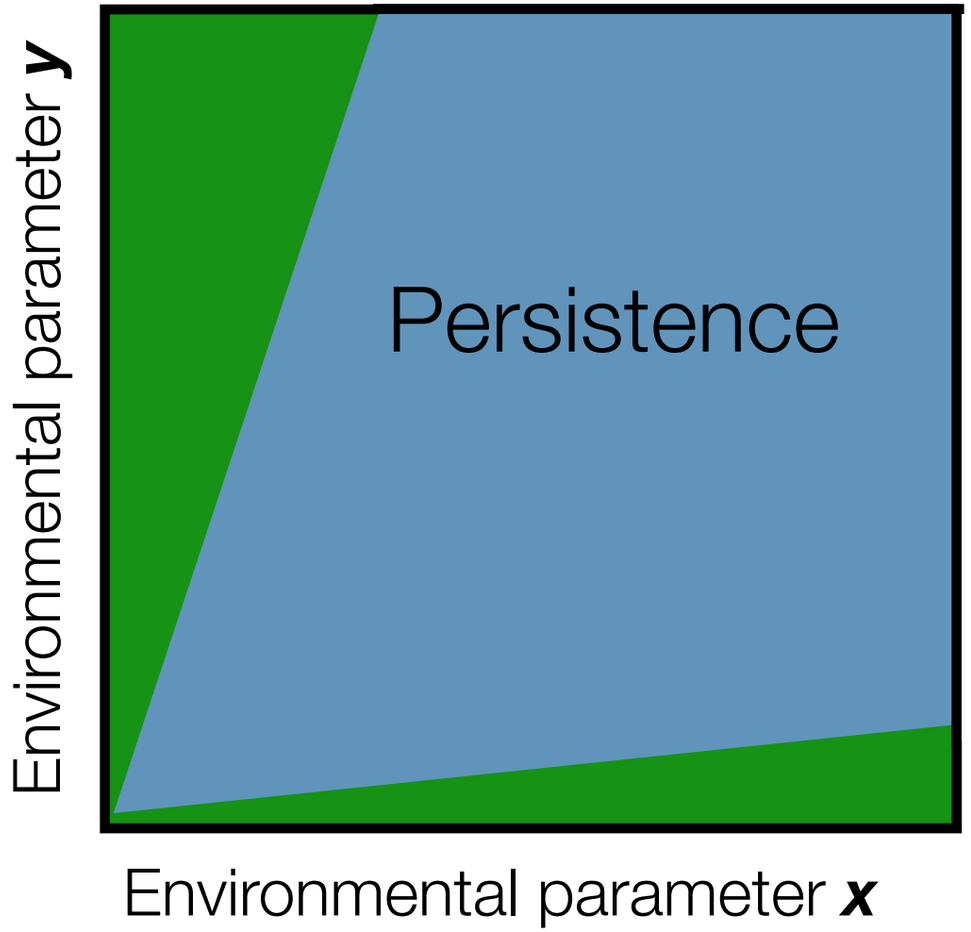


Structural stability in ecological contexts

The full range of **environmental conditions** (parameters) compatible with the **persistence** (qualitative dynamical behavior) of an ecological community

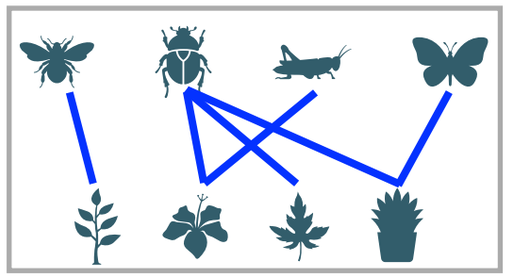
Structural stability :=

$$\frac{\textbf{Persistence domain}\ \text{(determined by the network structure)}}{\textbf{Environment domain}\ \text{(determined by the environmental change)}}$$



Probabilistic measure of Persistence under given Network structure and Environmental change

Song, *J. Theo. Bio.* (2018)



$$\frac{dN_i}{dt} = N_i(r_i + \sum_{j=1}^{S} a_{ij}N_j)$$

Ecological dynamics

Network structure

Environmental gradient

Environmental change

Environmental stress

Persistence

Persistence domain
(determined by the network structure)

Environment domain
(determined by the environmental change)

$$\frac{2}{(2\pi)^{S/2}\sqrt{|\det(A^TA)|}}$$

$$\int \dots \int_{\boldsymbol{N}\geq 0} e^{-\frac{1}{2}\boldsymbol{N}^T(A^TA)^{-1}\boldsymbol{N}} d\boldsymbol{N}$$

Understanding network structures through the lens of environment

Network structure

Q1: Is there any pattern of network structure along an **environmental gradient**?

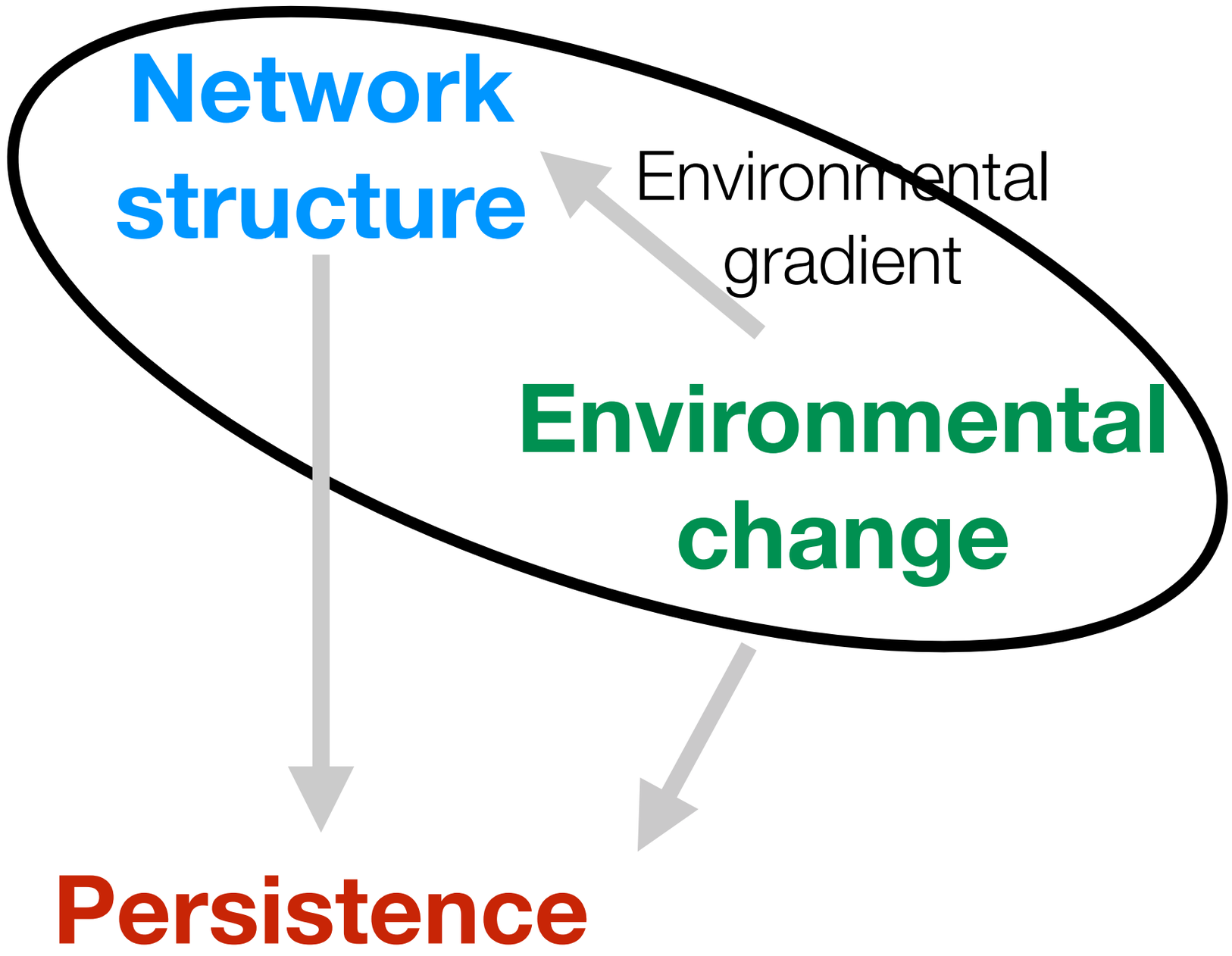
Q2: Does network structure contribute to persistence?

Environmental change

Q3: Can we disentangle the effects of **environmental stress** on persistence?

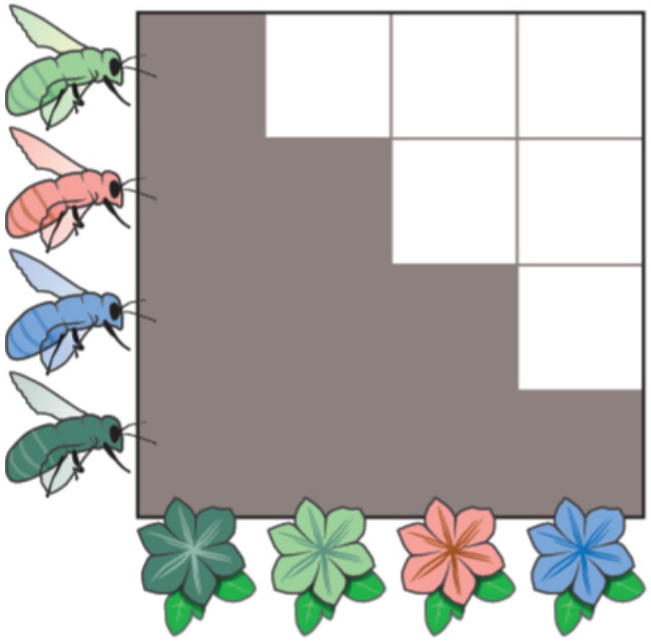
Persistence

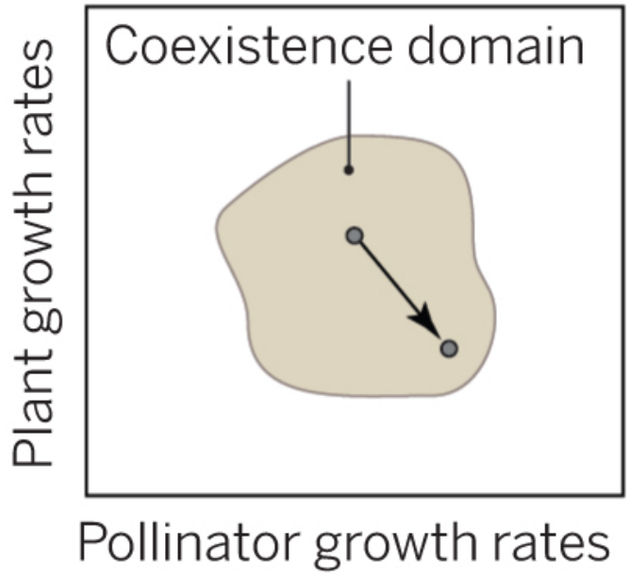
Q1: Is there any pattern of network structure along an environmental gradient?



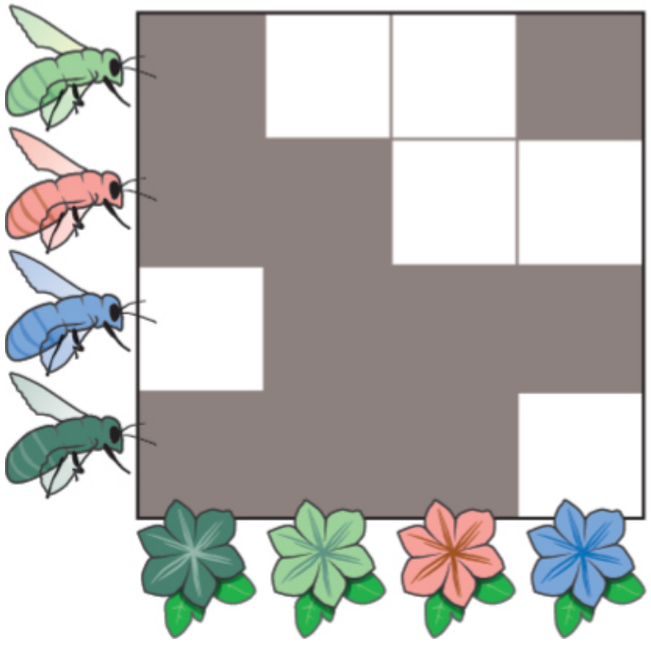
More nested structure = higher structural stability

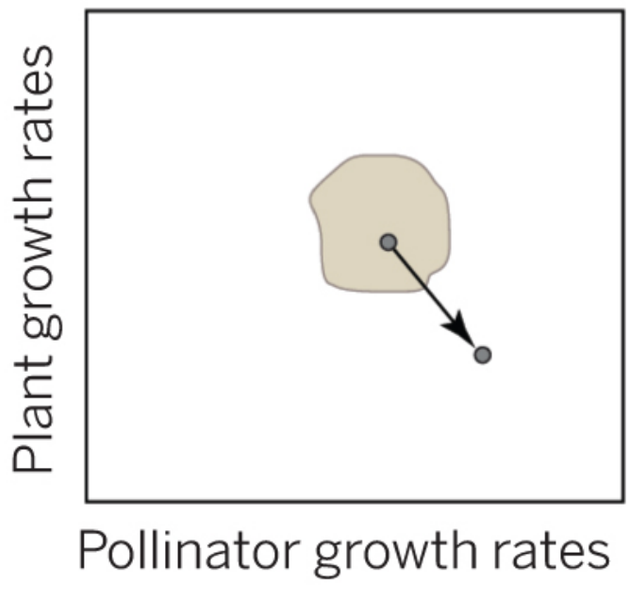
Highly nested network = high structural stability





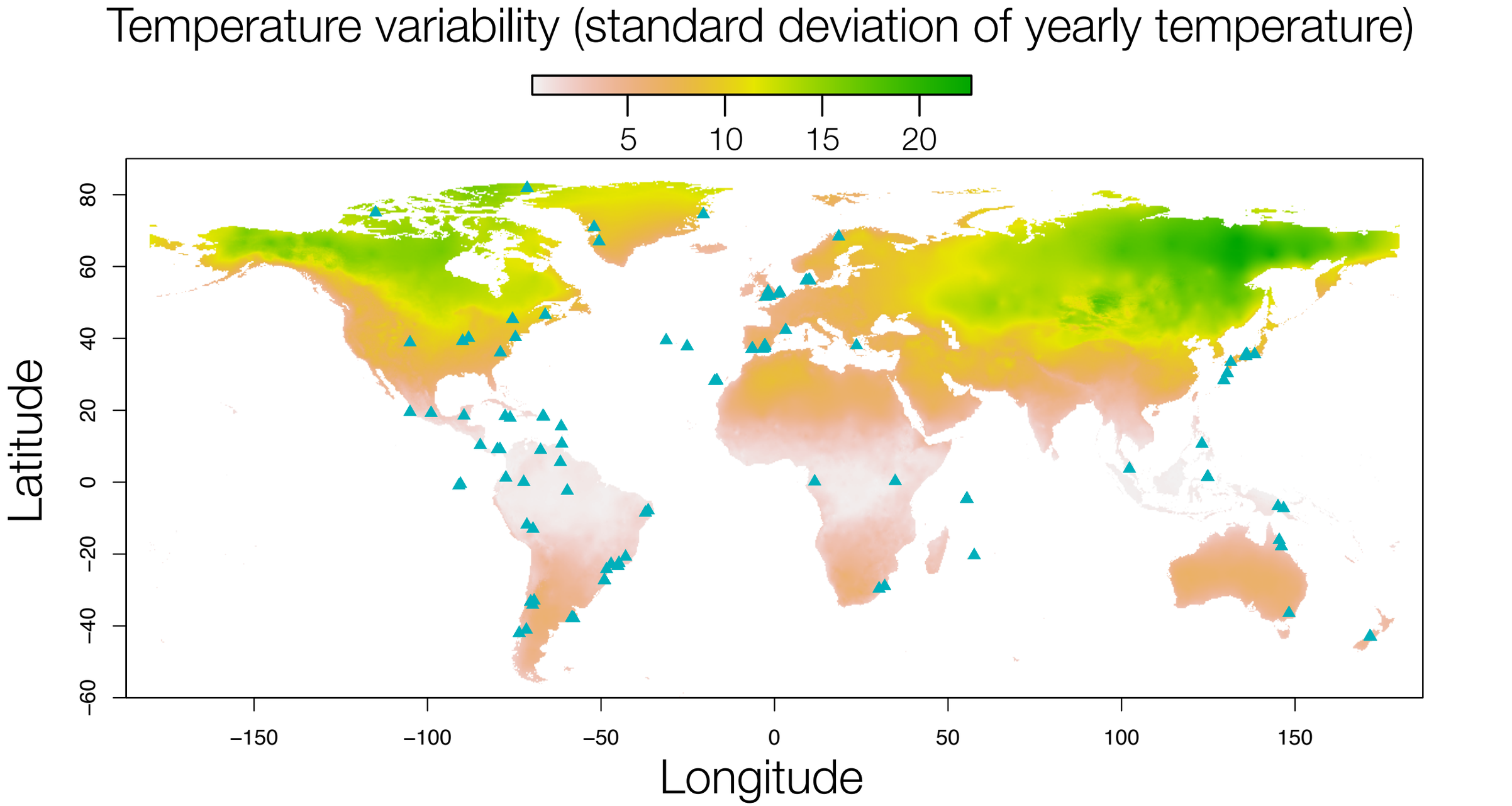
Less nested network = low structural stability





Rohr et al., *Science* (2014)
Pawar, *Science* (2014)

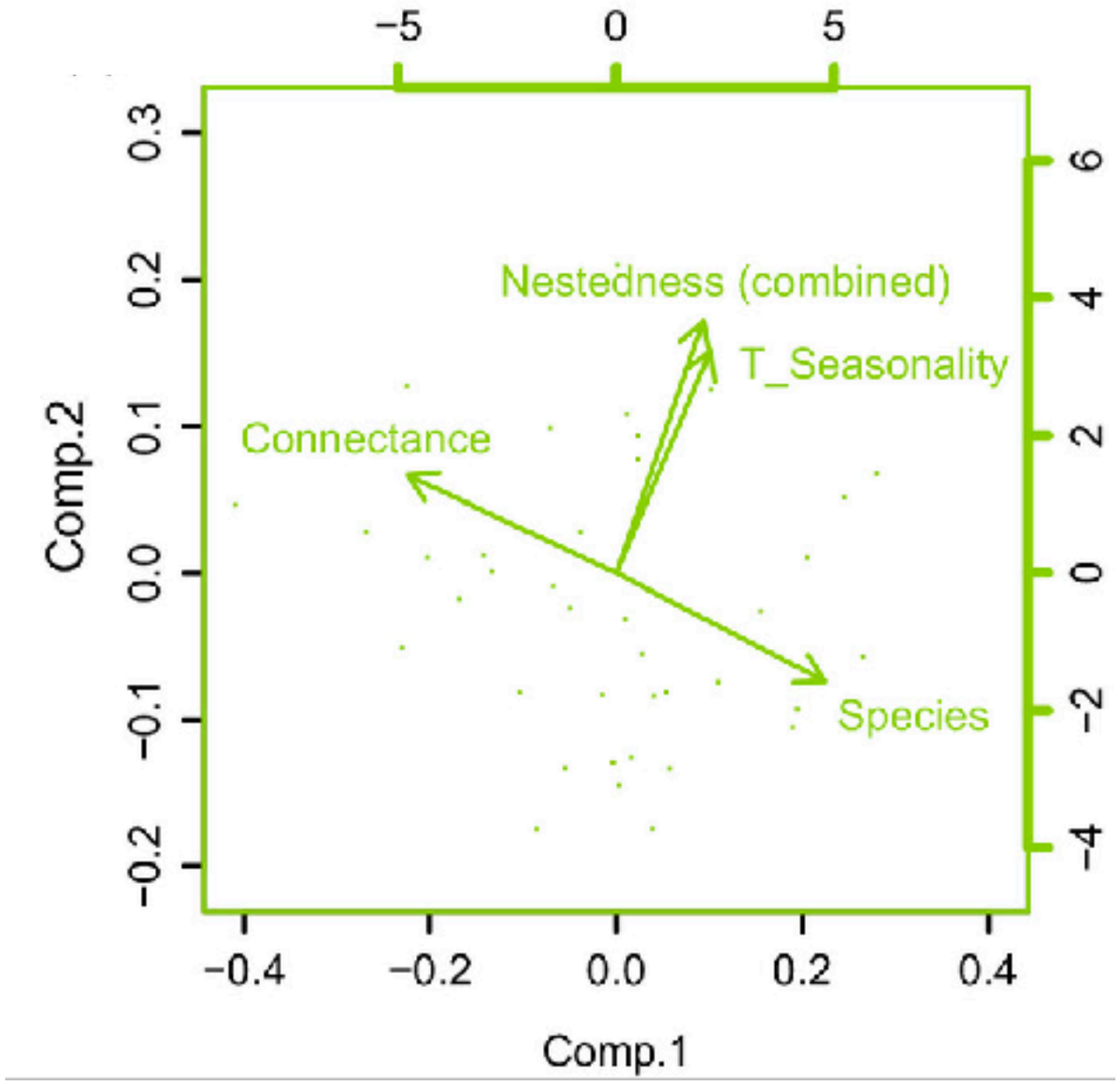
Mutualistic networks across the globe with local temperature variability

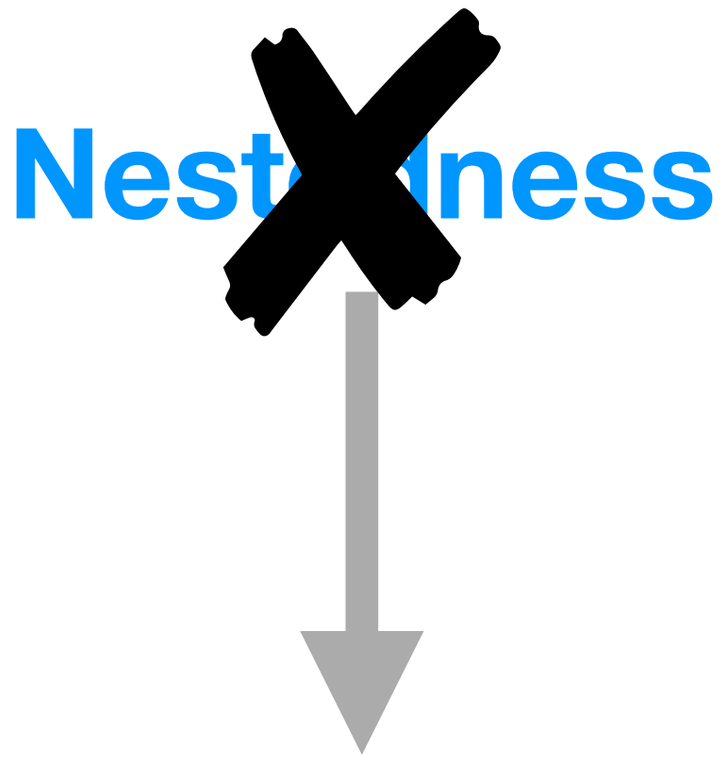


Source: www.web-of-life.es

Song & Saavedra, *PLOS Comp. Bio.* (2020)

Nestedness is strongly associated with temperature variability



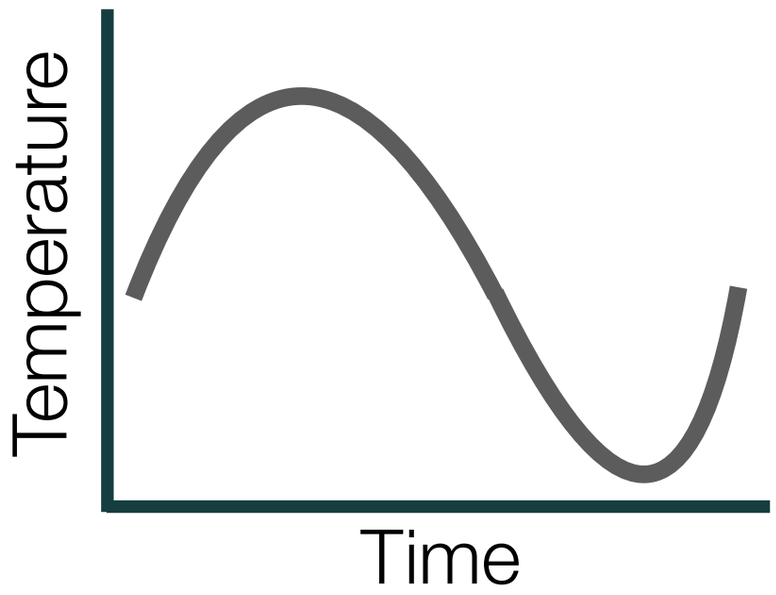


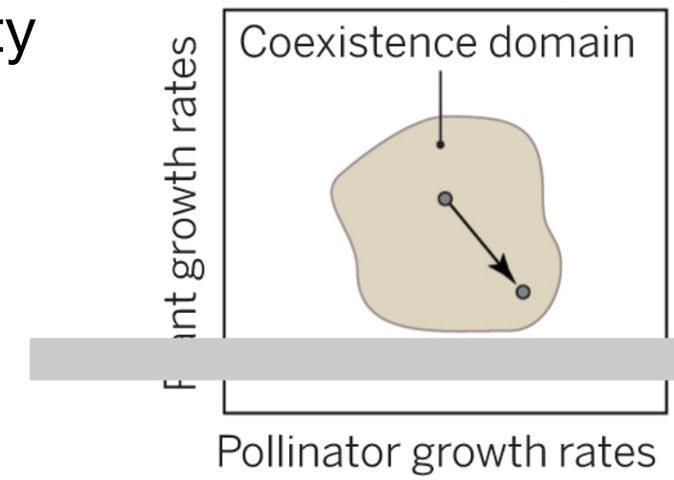
Song et al., *J. Animal Ecology* (2017)
Song et al., *J. Animal Ecology* (2019)

A1: Consistent pattern of network structure along an environmental gradient

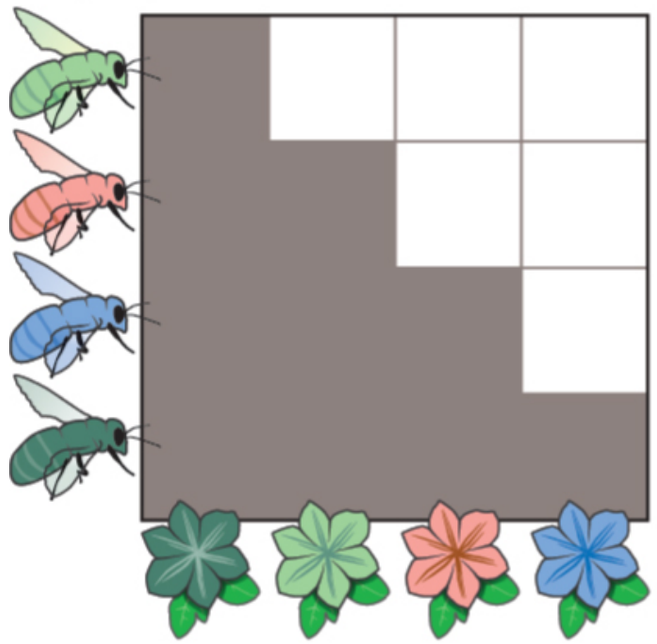
Environmental gradient

High temperature variability

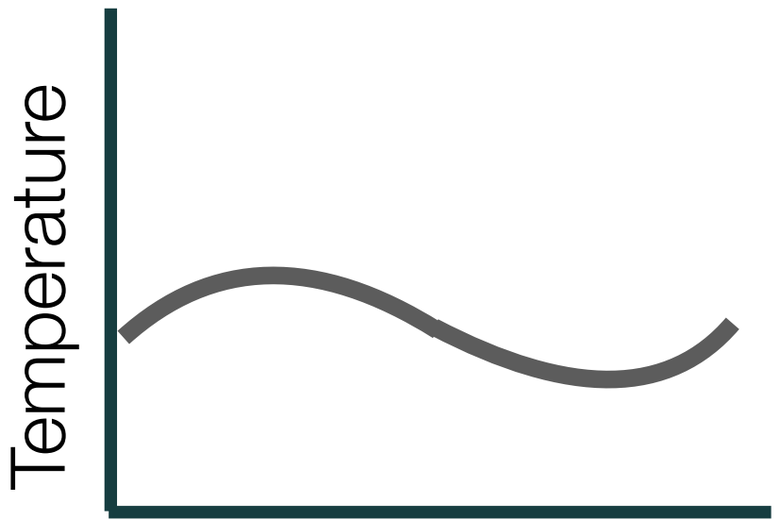


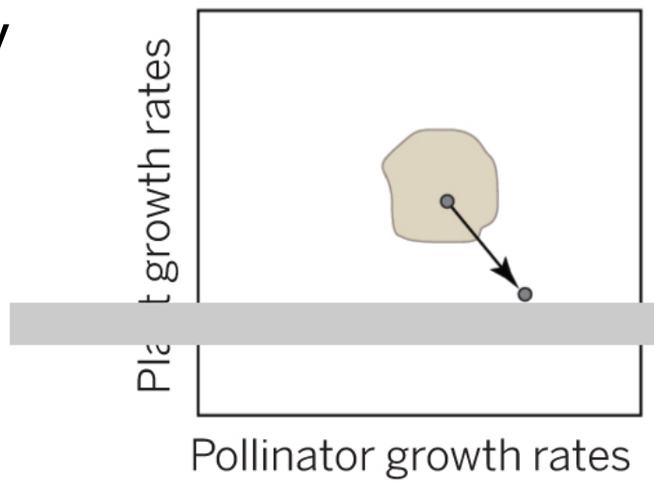


More nested structure

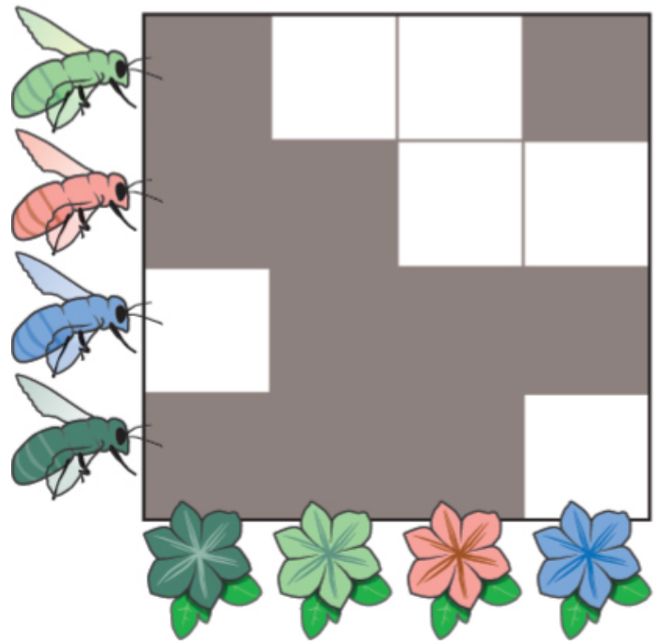


Low temperature variability

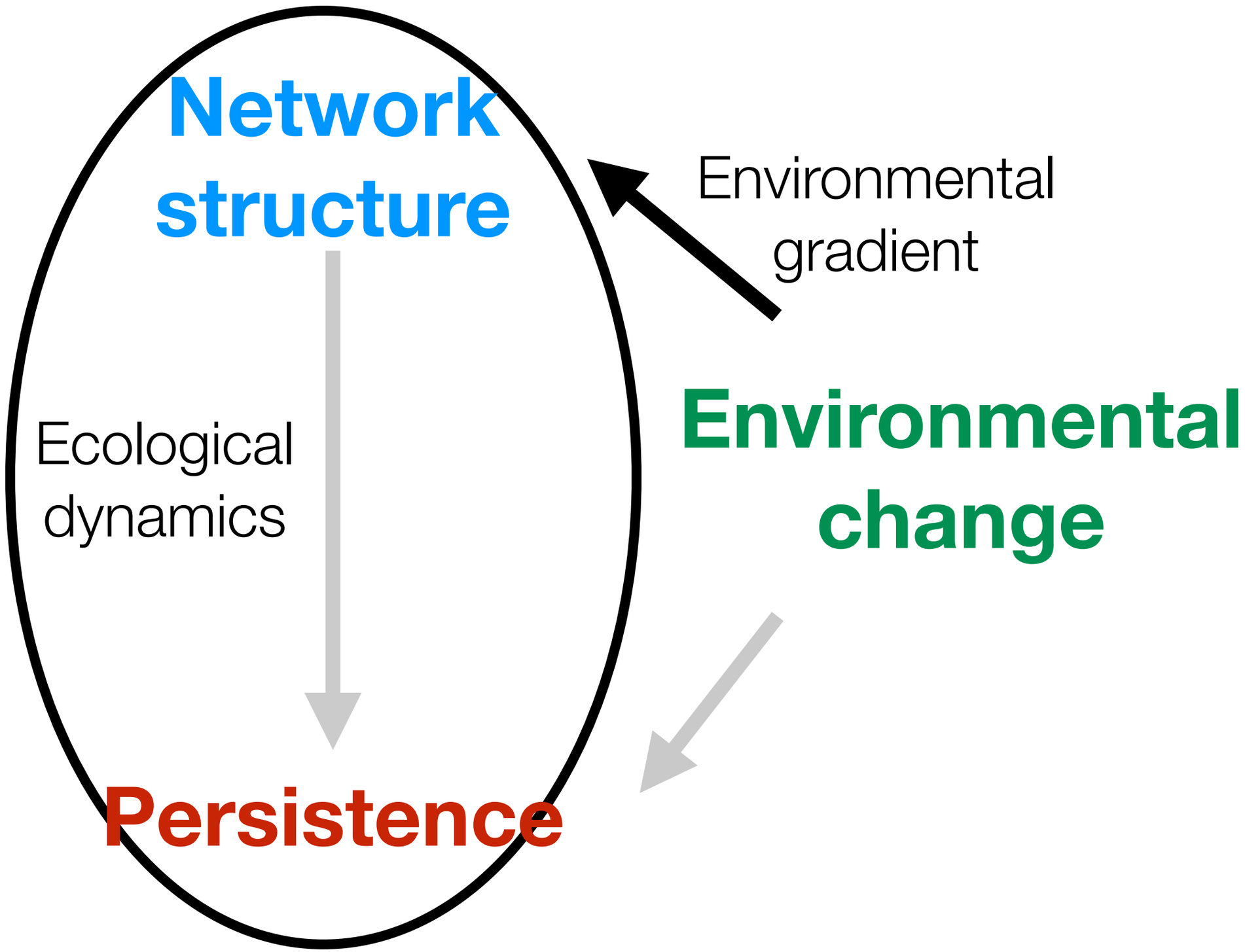




Less nested structure



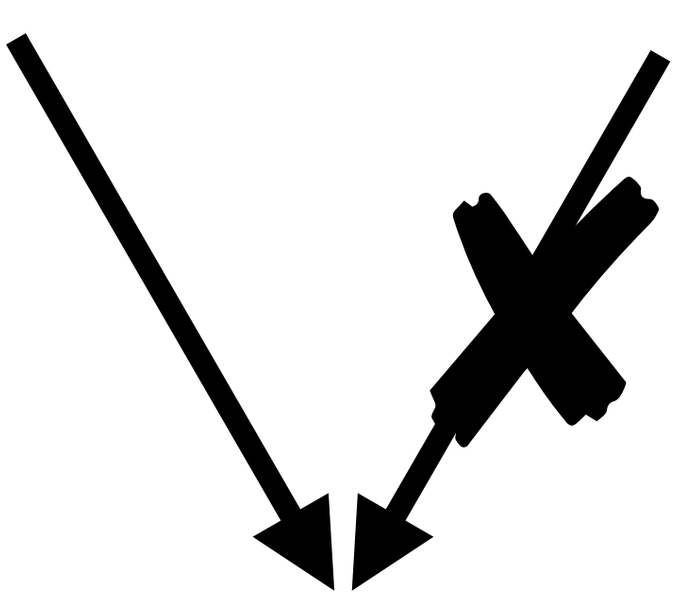
Q2: Does network structure contribute to persistence?



Hypothesis: Mutualistic/Antagonistic dynamics leaves some unique fingerprints on the structures

Mutualistic dynamics

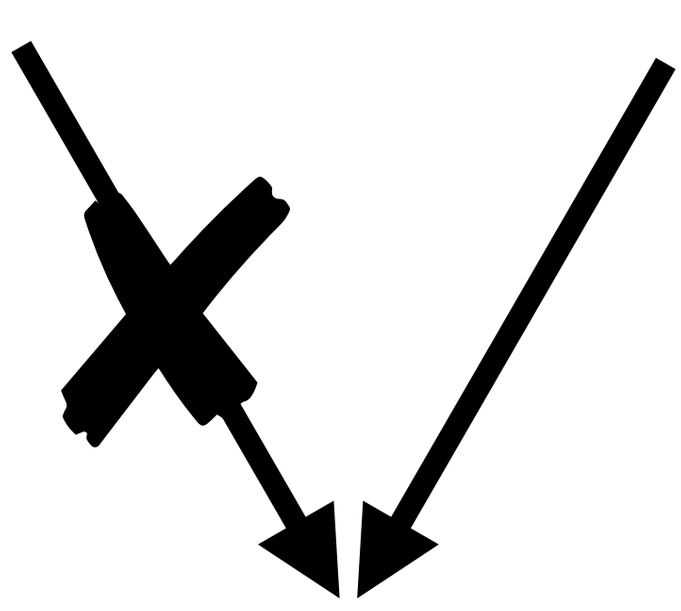
Nestedness **Modularity**



Persistence

Antagonistic dynamics

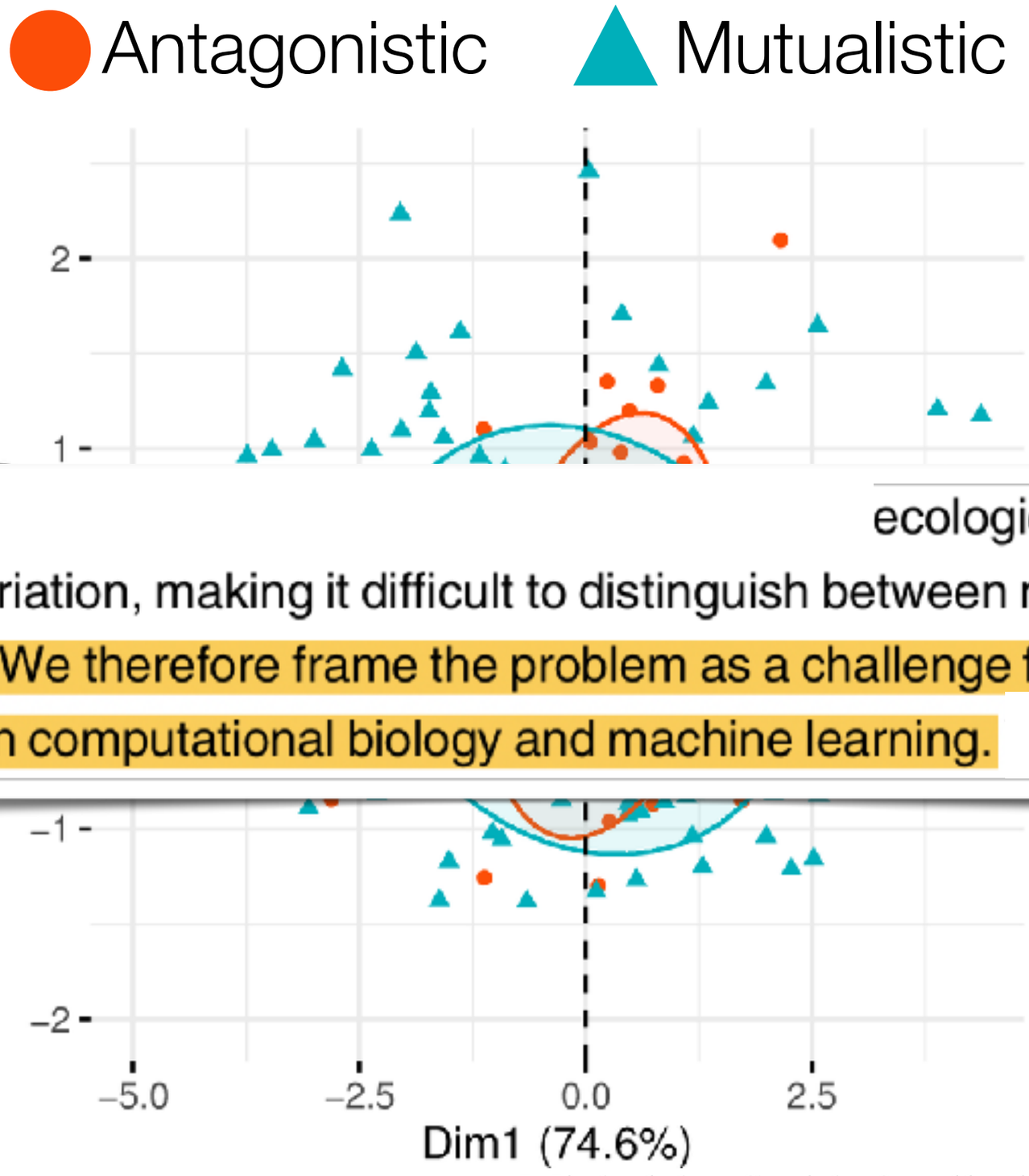
Nestedness **Modularity**



Persistence

Thébault & Fontaine, *Science* (2010)

NO empirical evidence that network structure differs between antagonistic and mutualistic networks



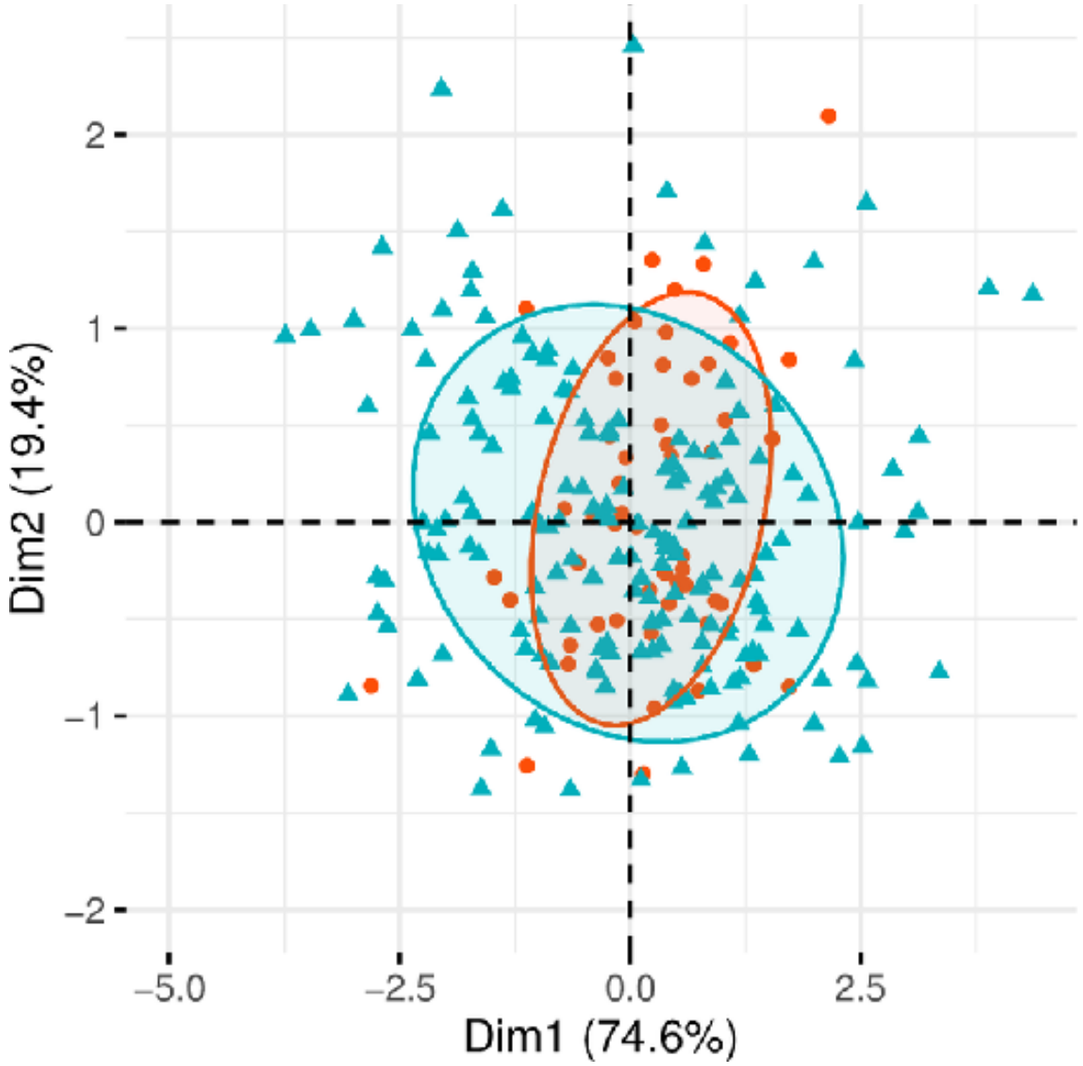
ecological networks display much structural variation, making it difficult to distinguish between mutualistic and antagonistic interactions. We therefore frame the problem as a challenge for the community of scientists interested in computational biology and machine learning.

Michalska-Smith & Allesina, *PLoS Comp. Bio.* (2019)

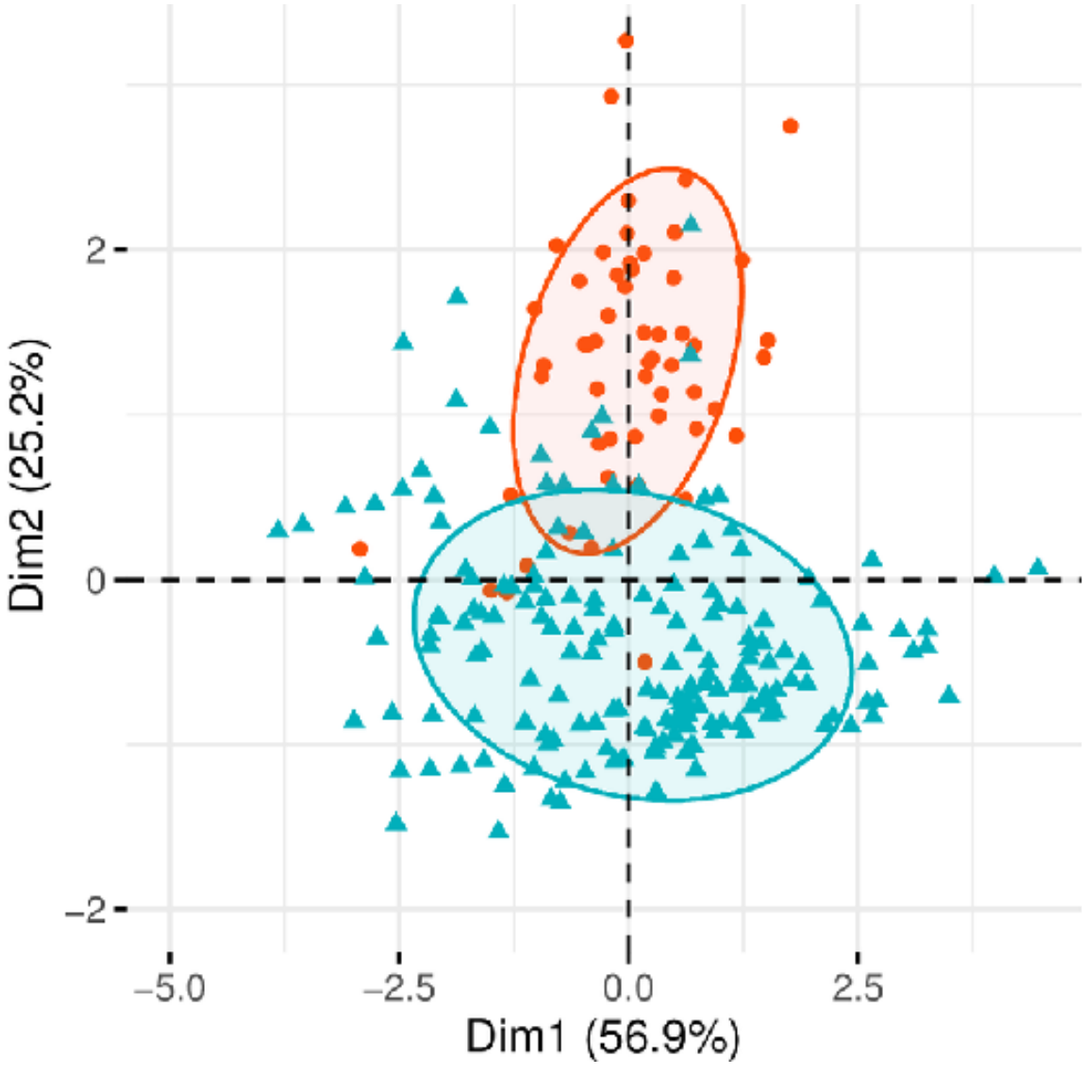
Network structures differ when the environment is controlled

Antagonistic Mutualistic

Without environmental information

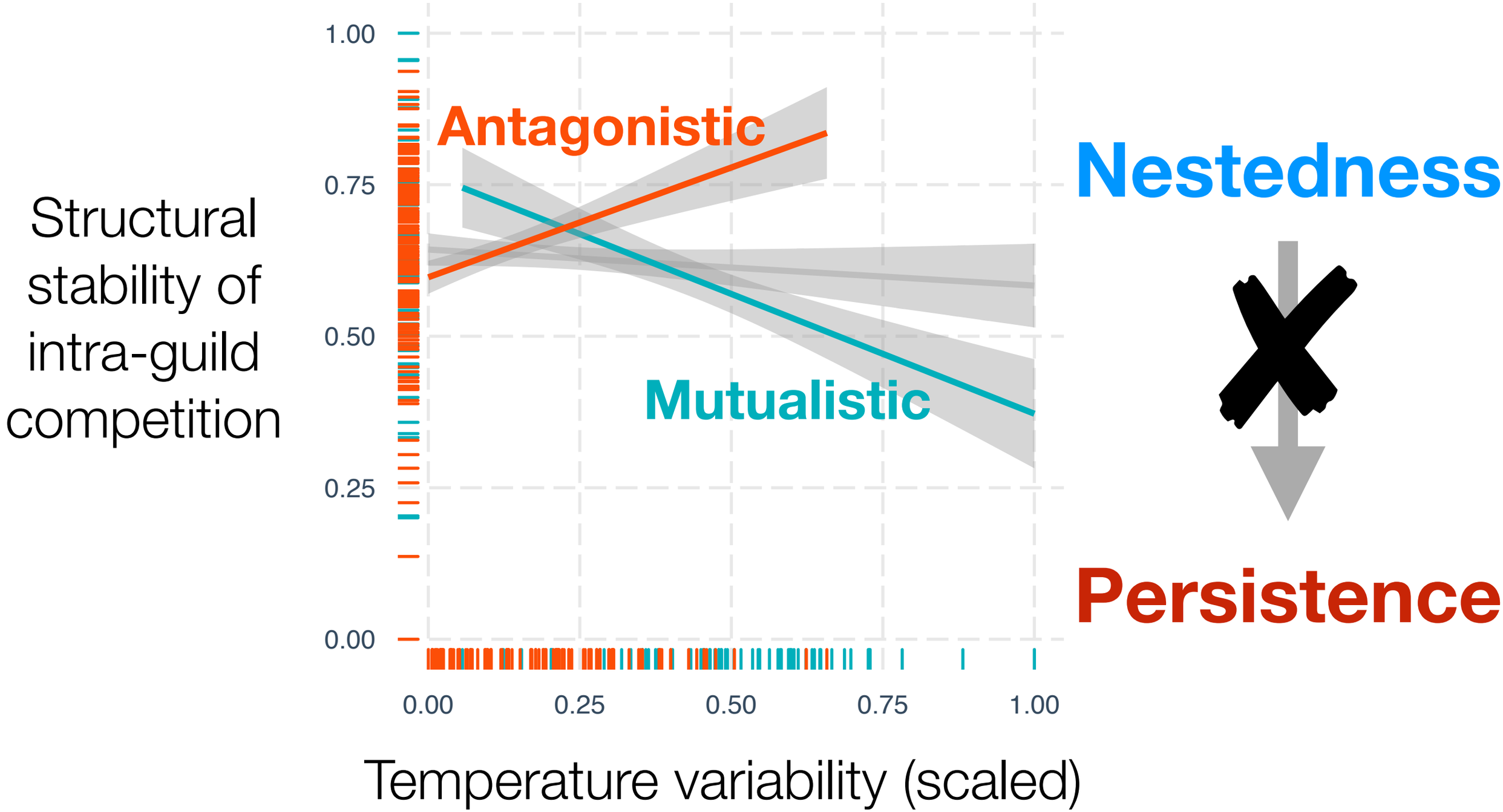


With environmental information



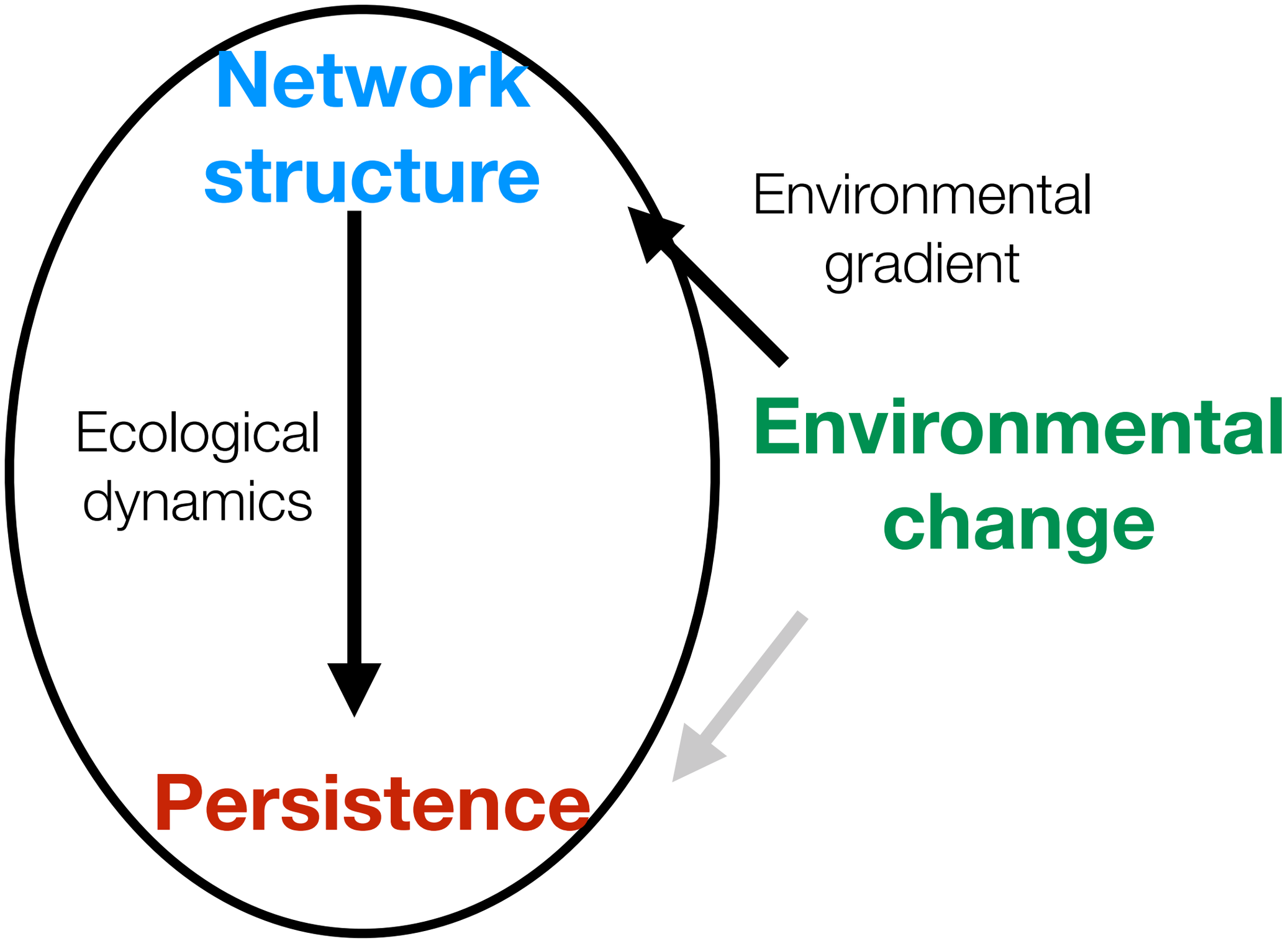
Song & Saavedra, *PLOS Comp. Bio.* (2020)

Opposing and predictable patterns of network structures along environmental gradients

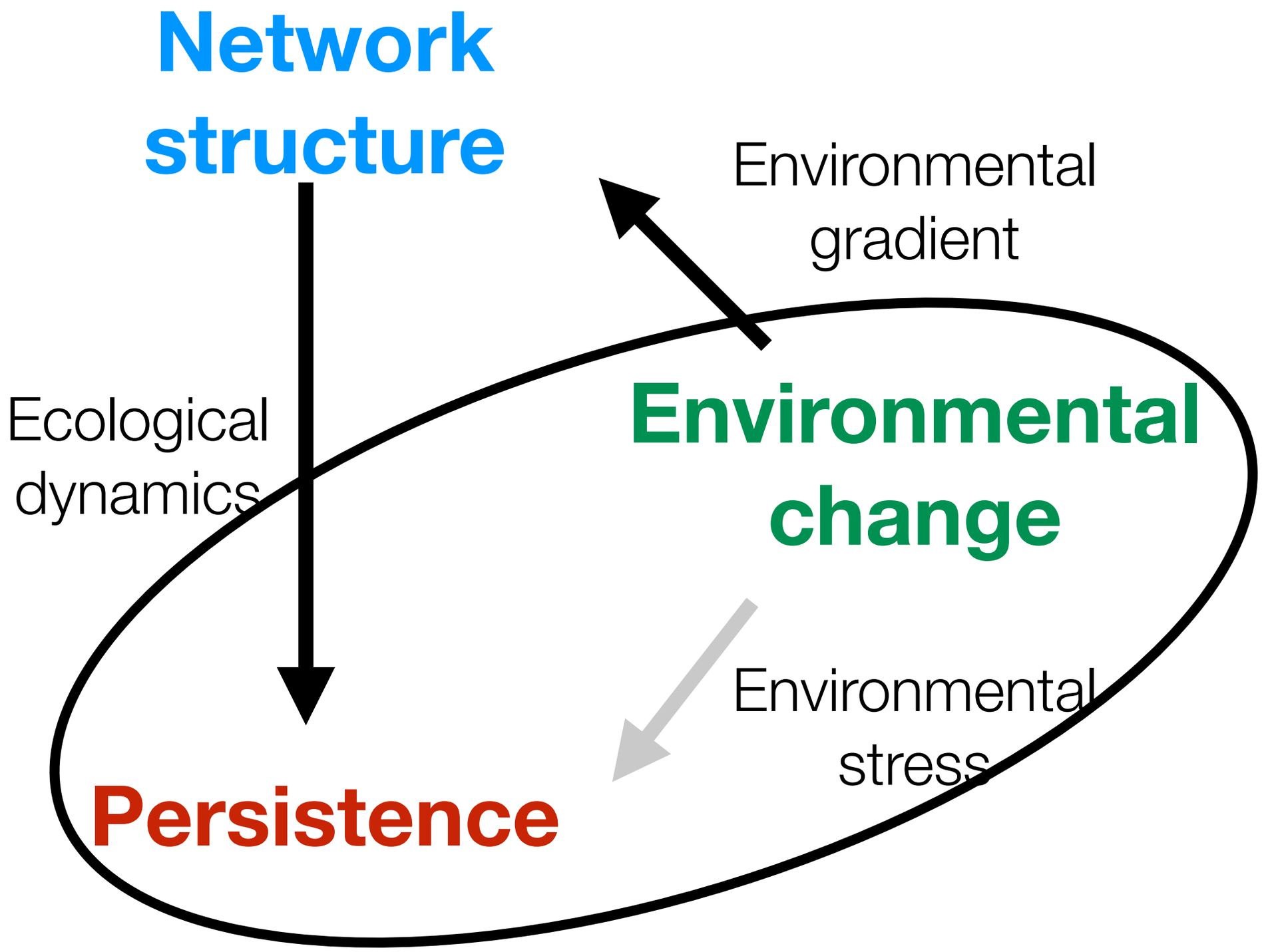


Song & Saavedra, *PLOS Comp. Bio.* (2020)

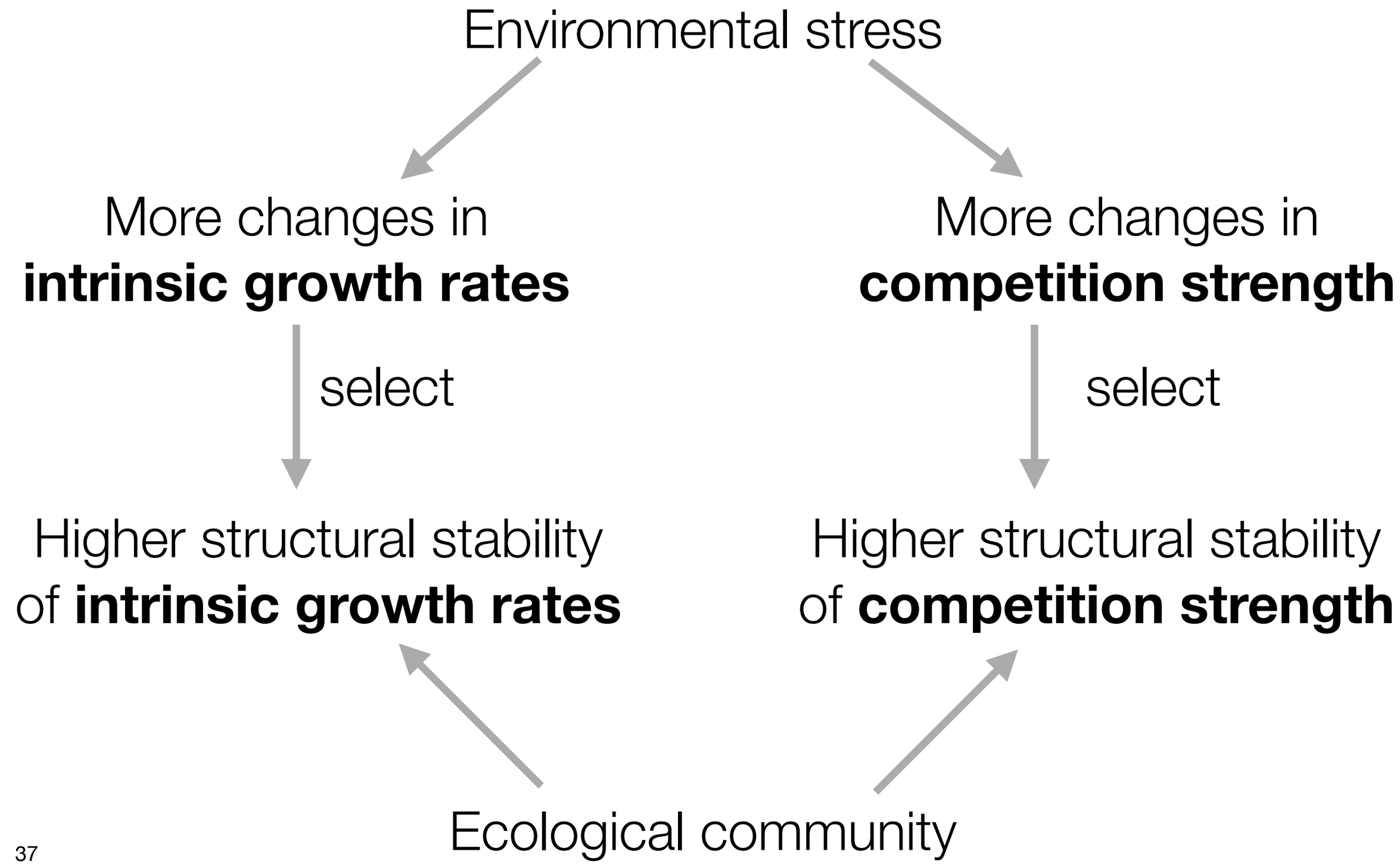
A2: Network structure contributes to persistence



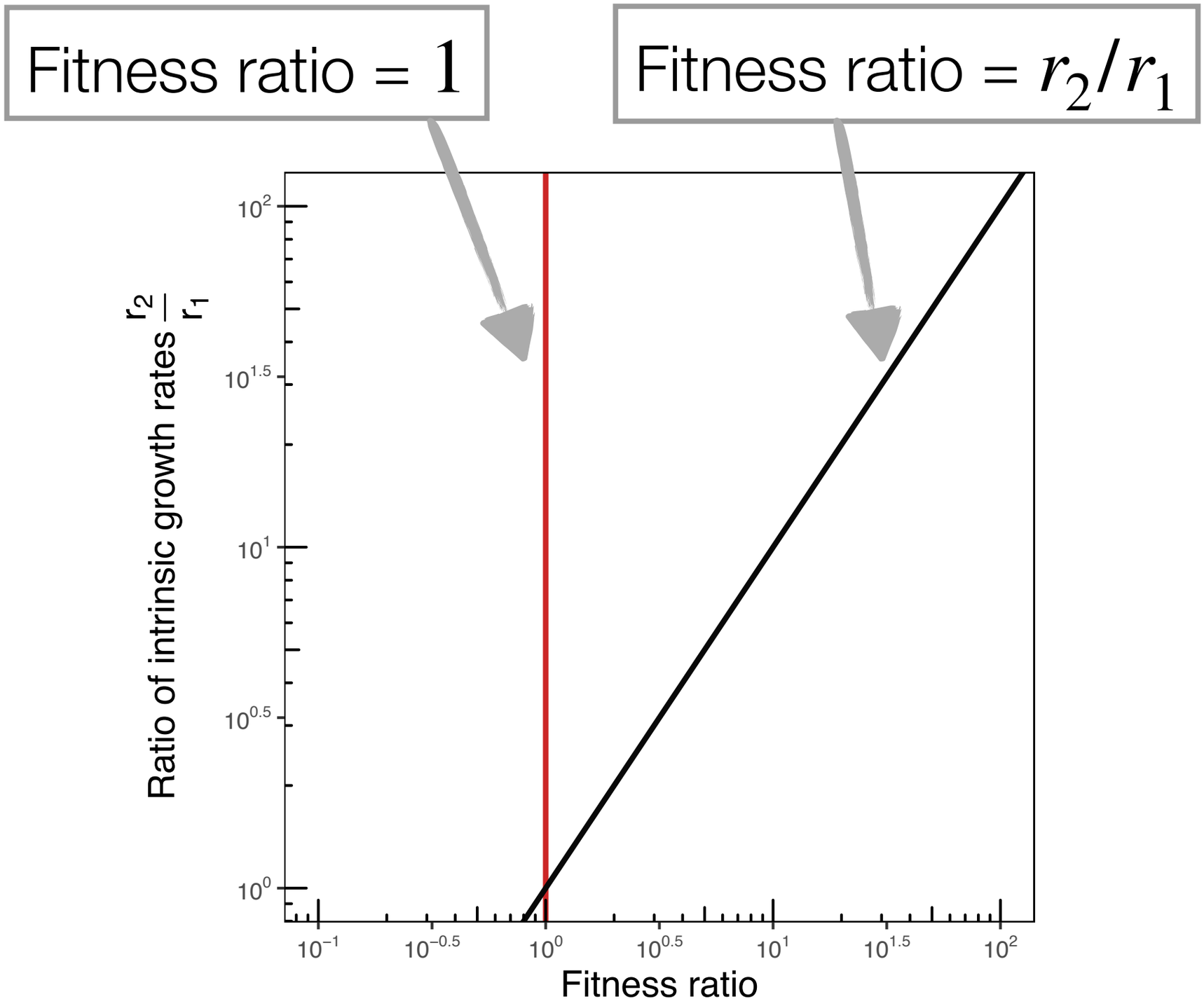
Q3: Can we disentangle the effects of environmental stress on persistence?



The scheme of disentangling the effects of environmental stress

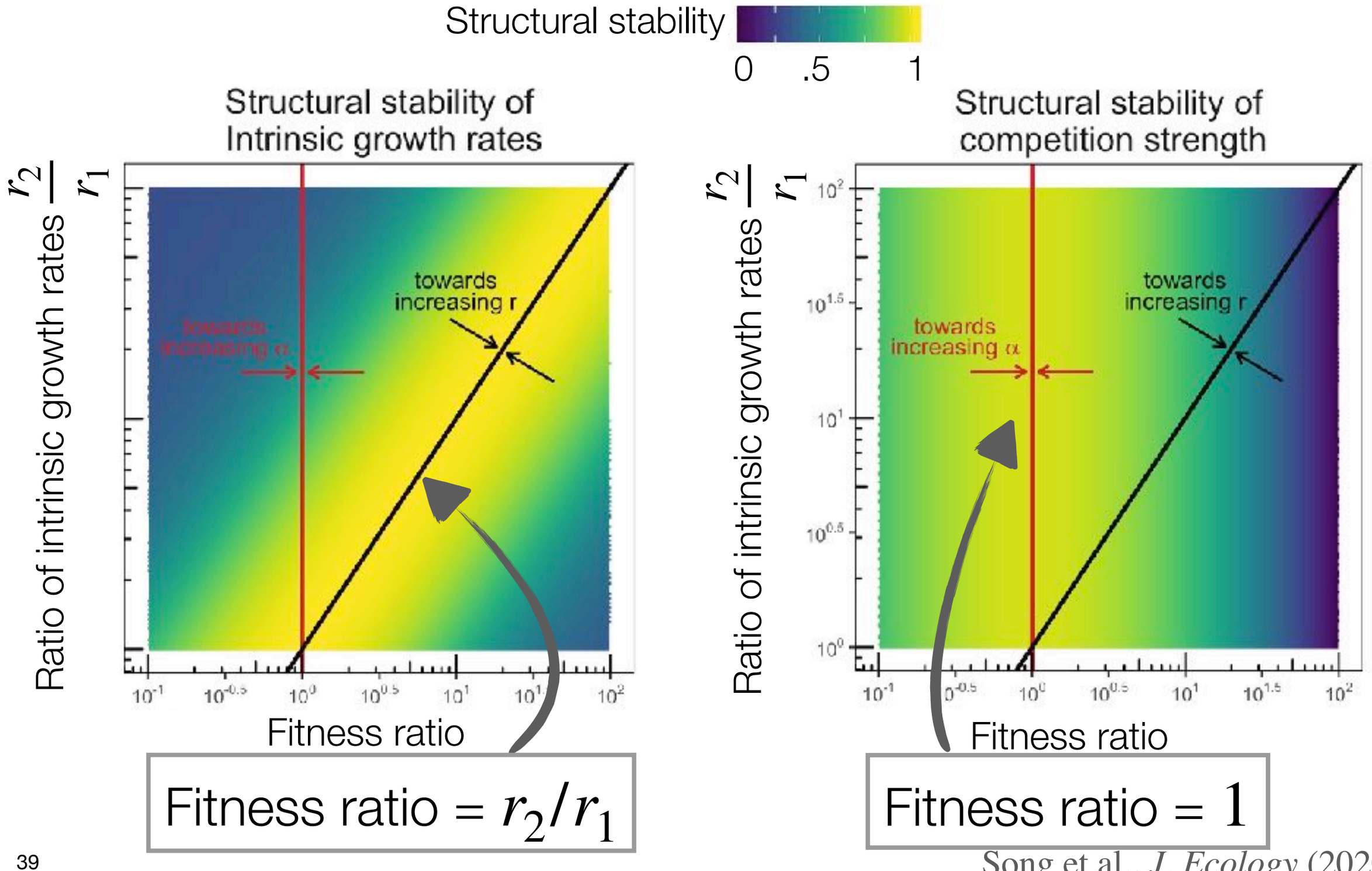


Generic trade-off between structural stability of competition strength and intrinsic growth rates



Song et al., *J. Ecology* (2020)

Generic trade-off between structural stability of competition strength and intrinsic growth rates



Fitness ratio = r_2/r_1

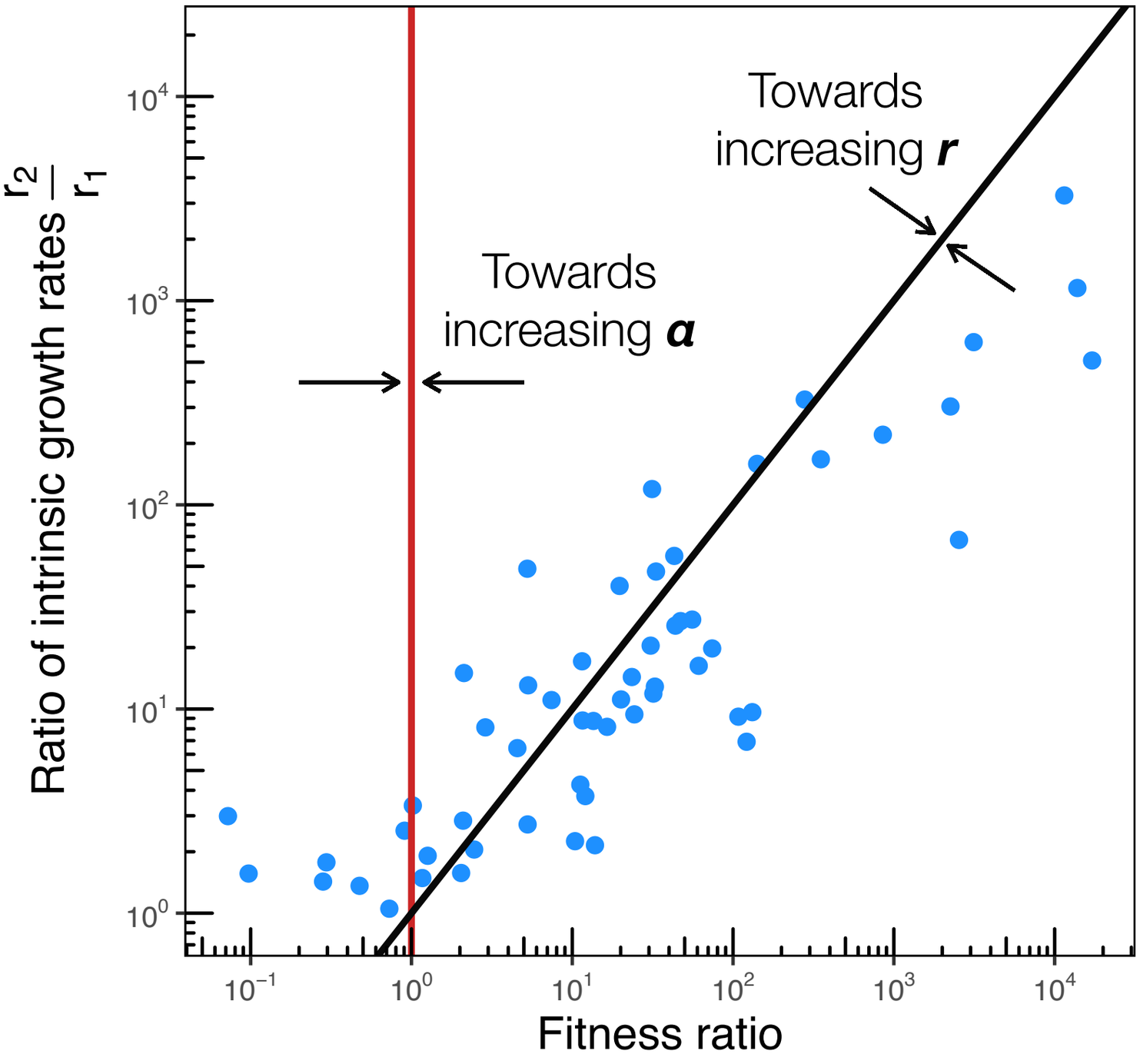
Fitness ratio = 1

Song et al., *J. Ecology* (2020)

Experiments of annual plant competition

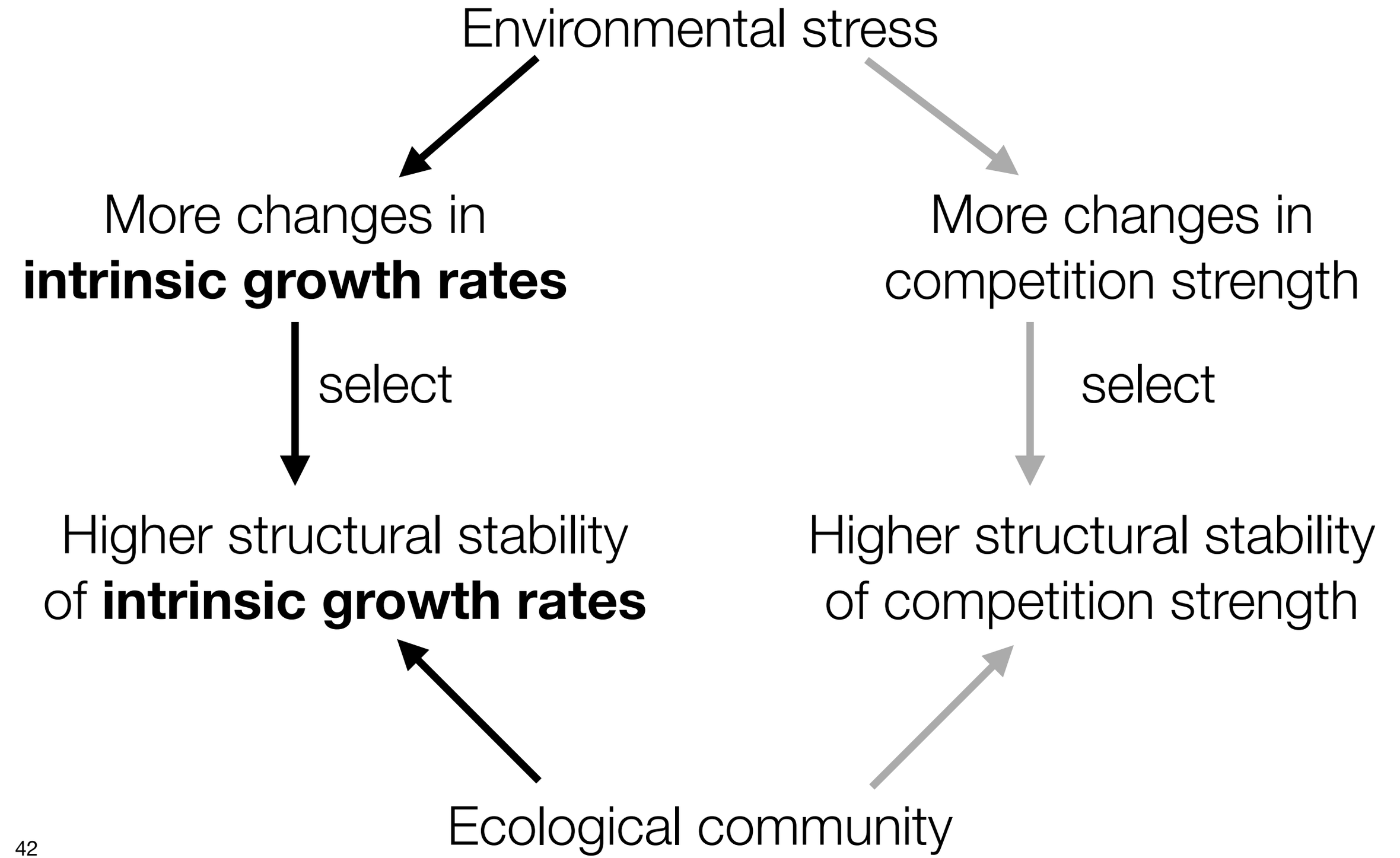
Kraft et al., *PNAS* (2015)

Annual plants exhibit a preference to maximize structural stability of intrinsic growth rates

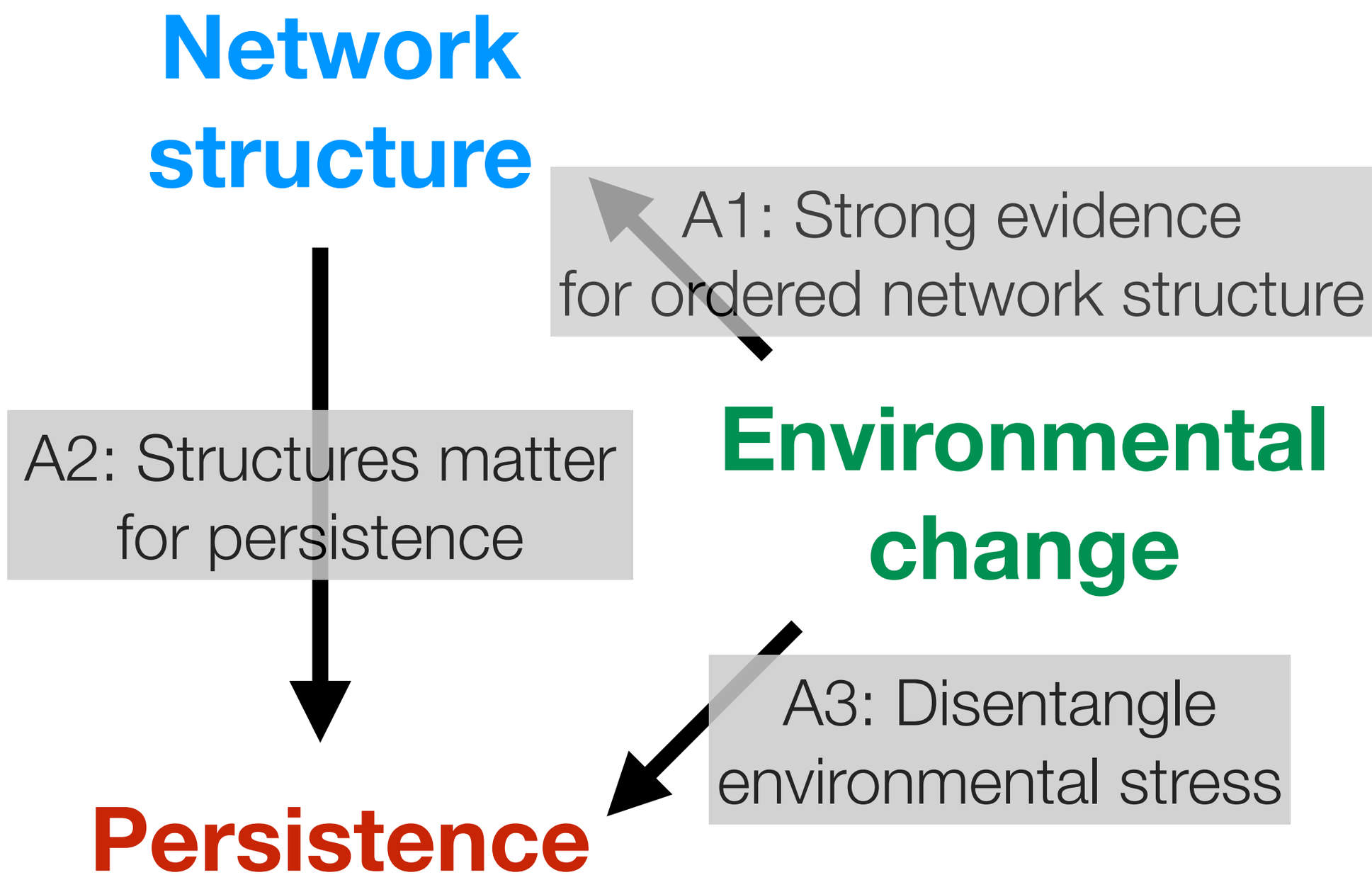


Song et al., *J. Ecology* (2020)

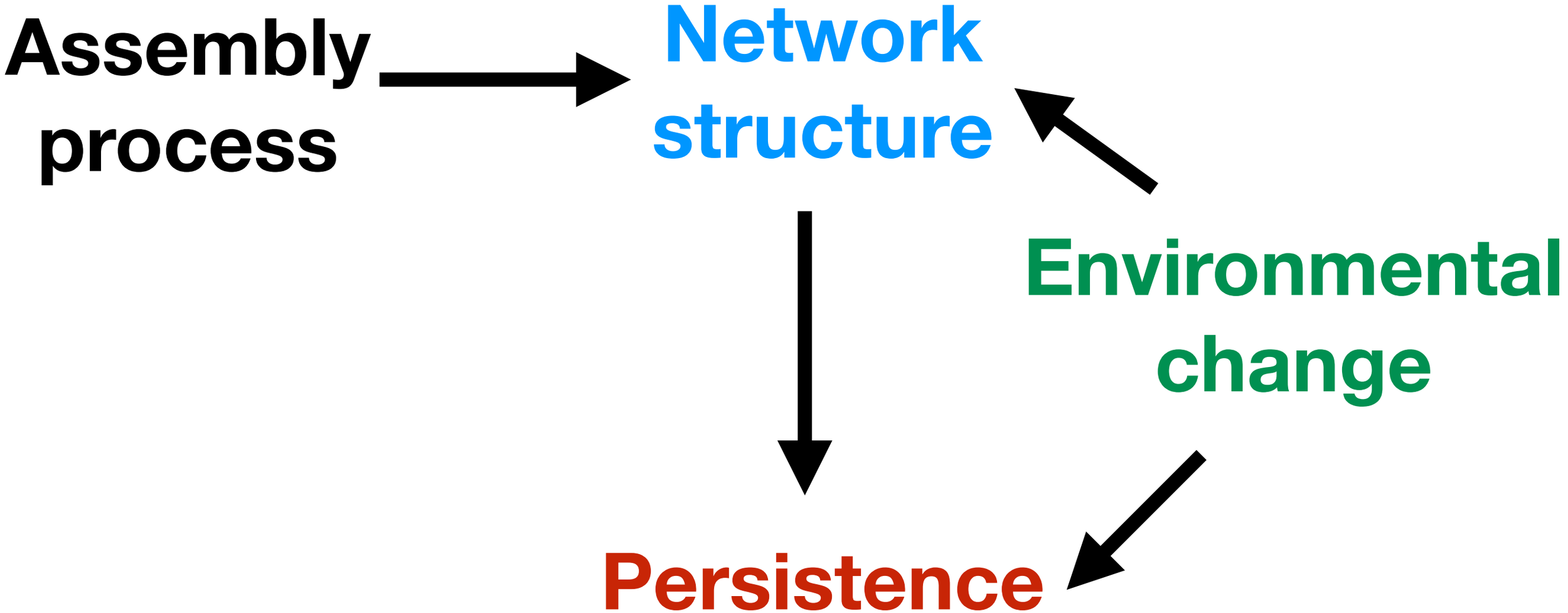
A3: The effects of environmental stress on persistence can be disentangled



Moving towards an environment-dependent understanding of network structures

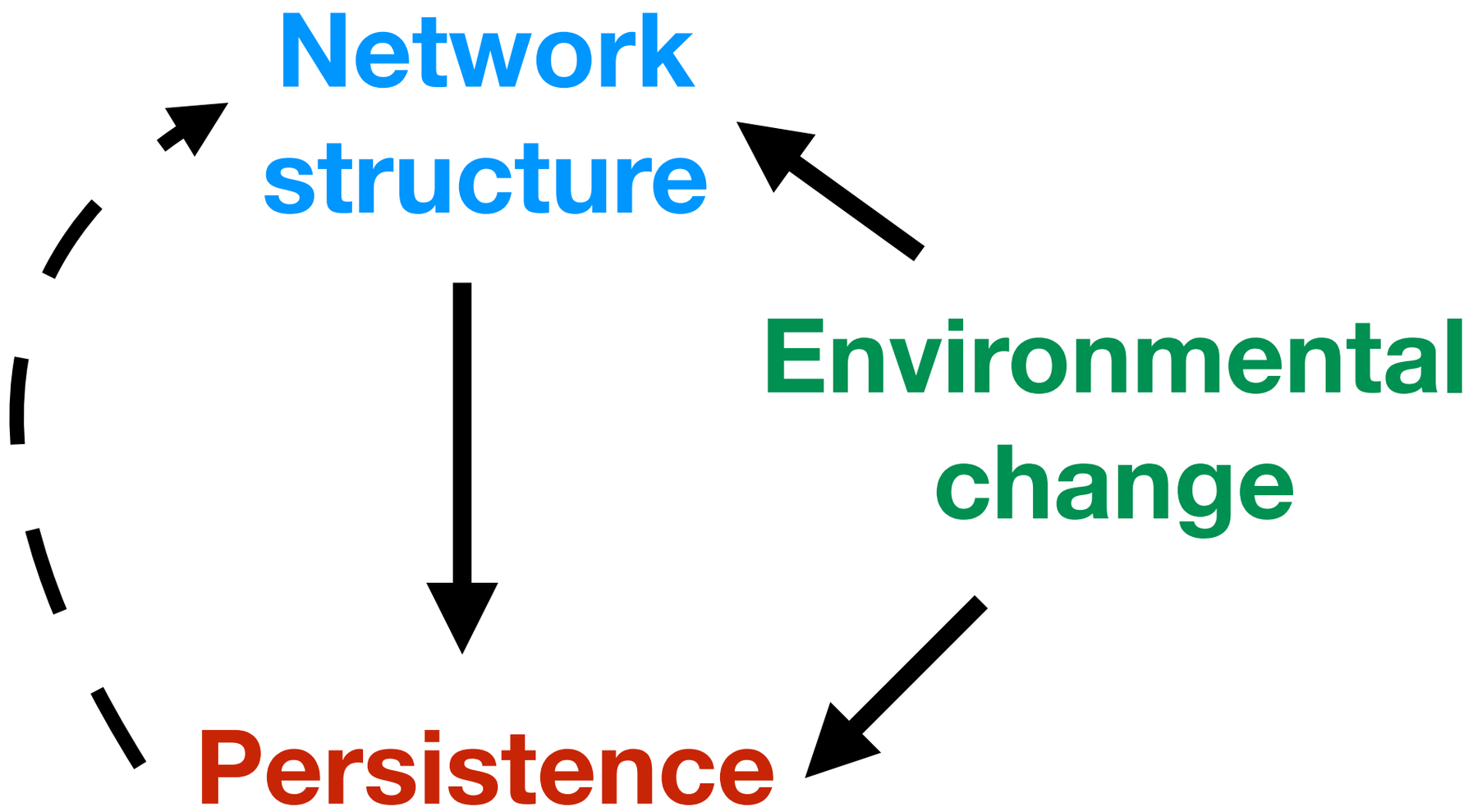


Many potential applications of the framework
- Elucidating the assembly rules of ecological communities



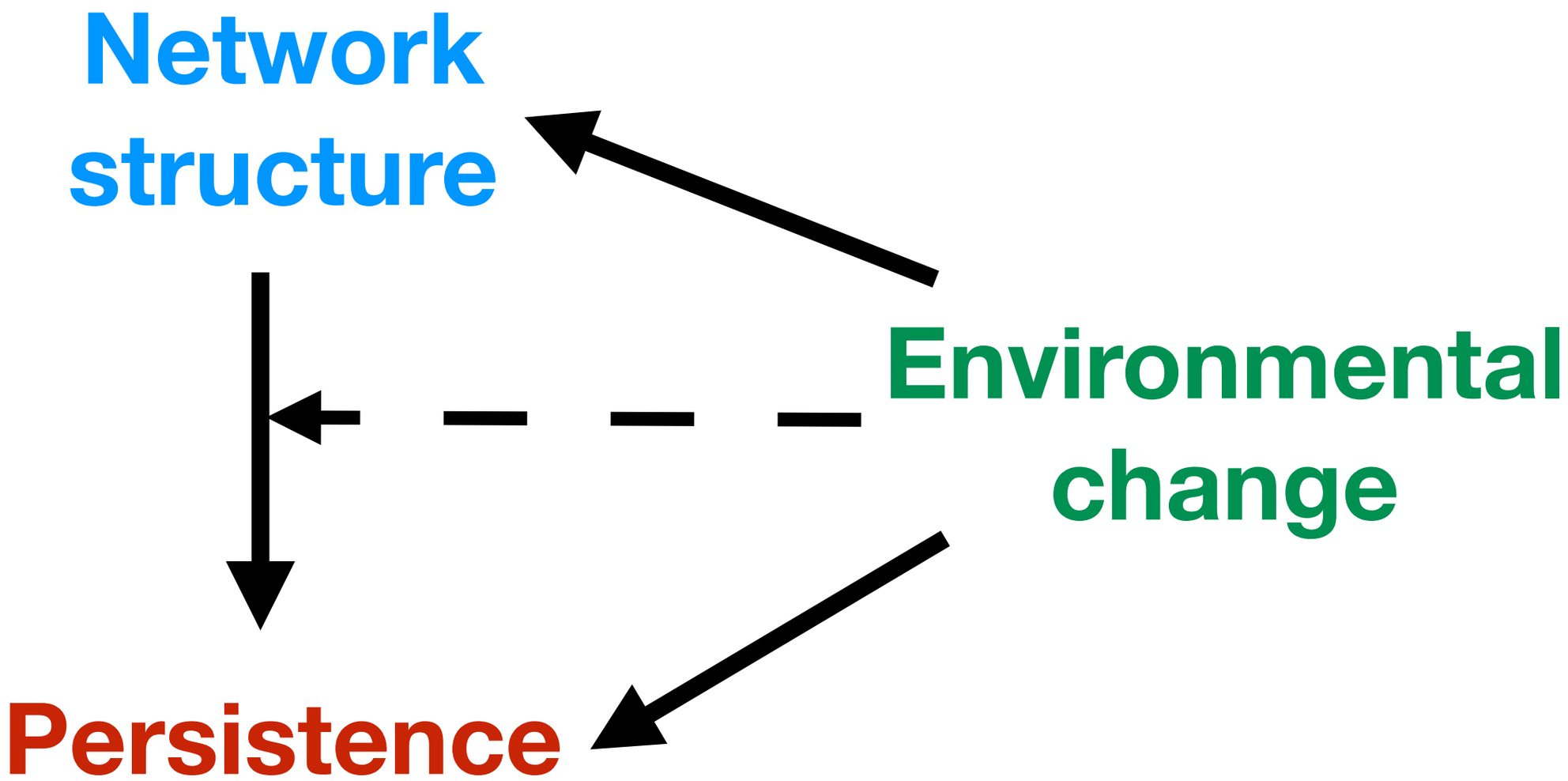
Song *et al*., *Ecology Letters* (2018)

Many potential applications of the framework
- Understanding phenological events



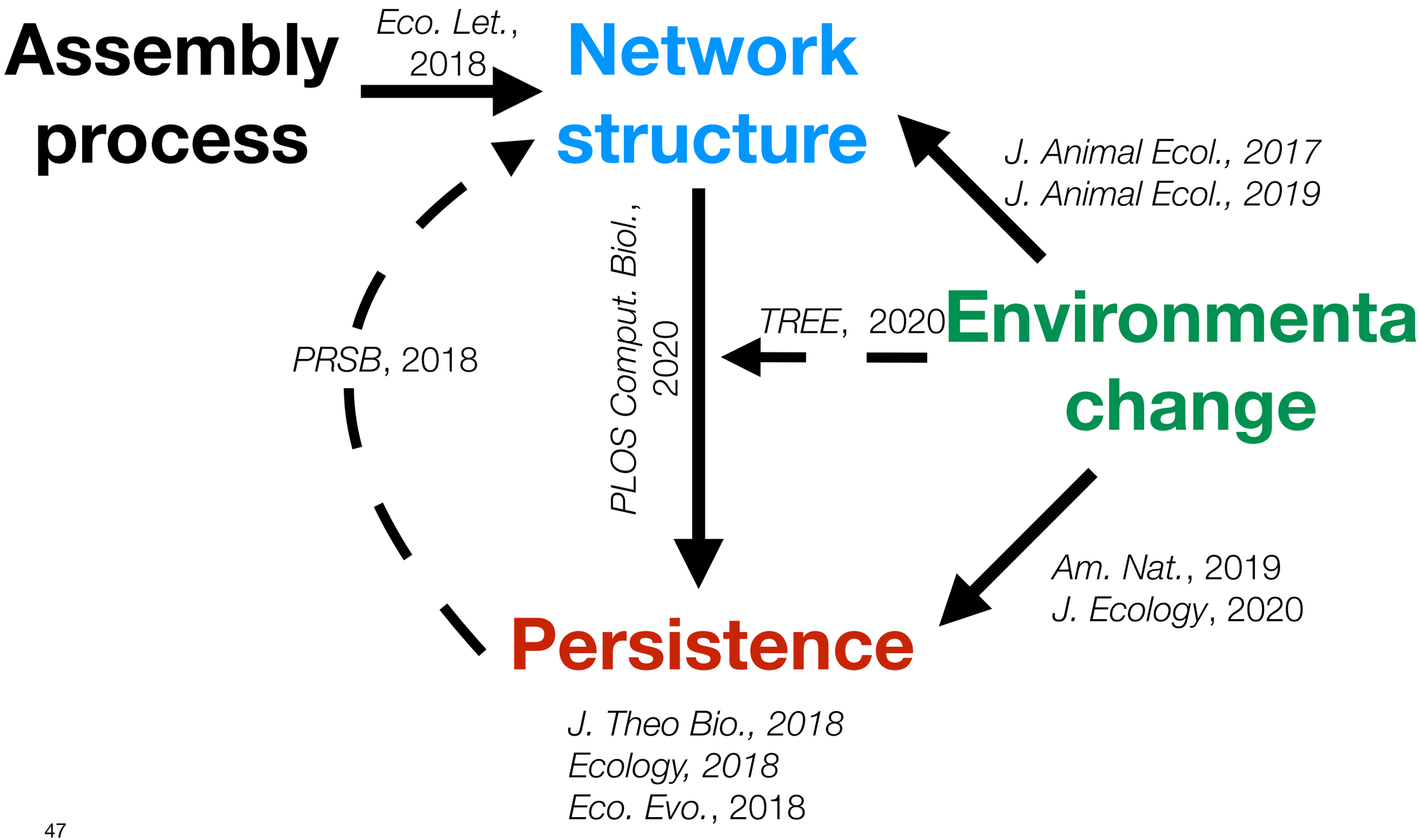
Song *et al.*, *PRSB* (2018)

Many potential applications of the framework
- Understanding the switch of species interaction types



Song *et al*., *TREE* (2020)

Summary of the environment-dependent framework



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