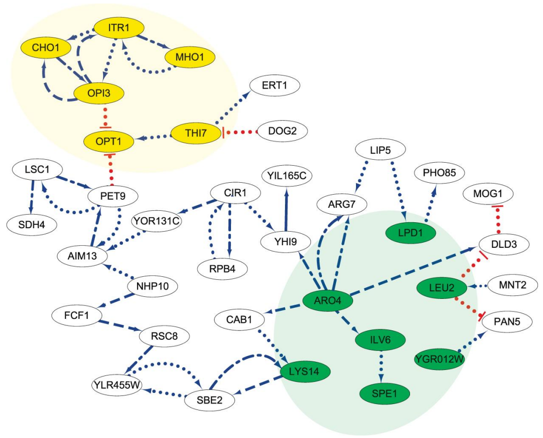
Evolution of Networks: From Ecology to Proteins

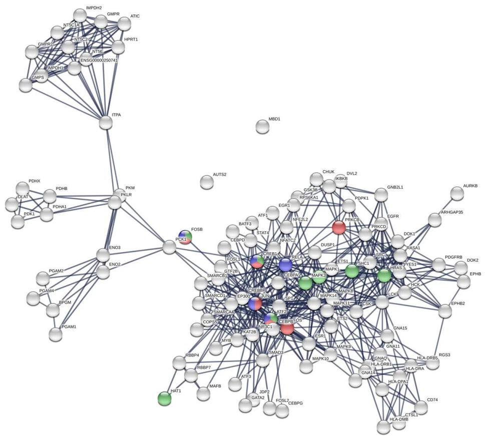
2025.03.28

Jiaqi Xu

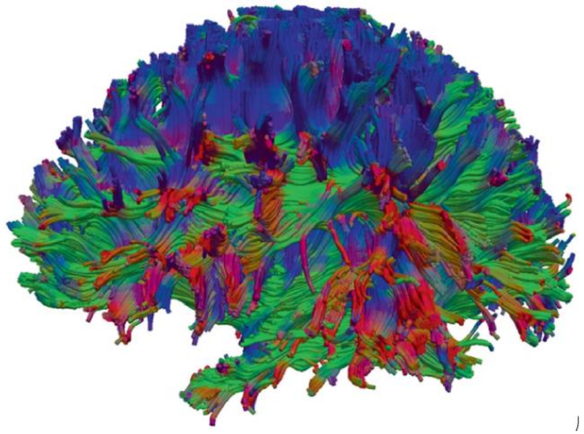
Network perspective on life systems



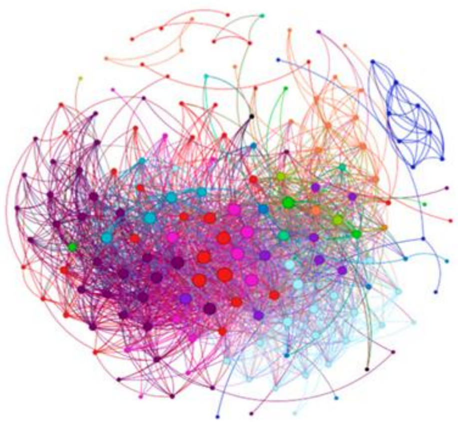
Gene regulatory network



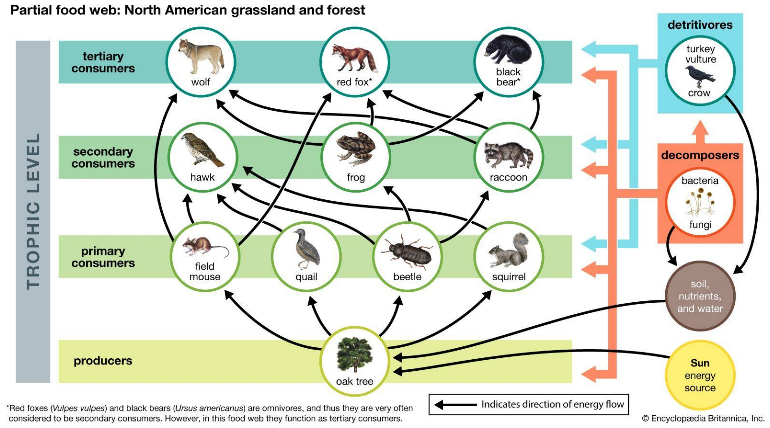
Protein–protein interaction network



Brian neural network

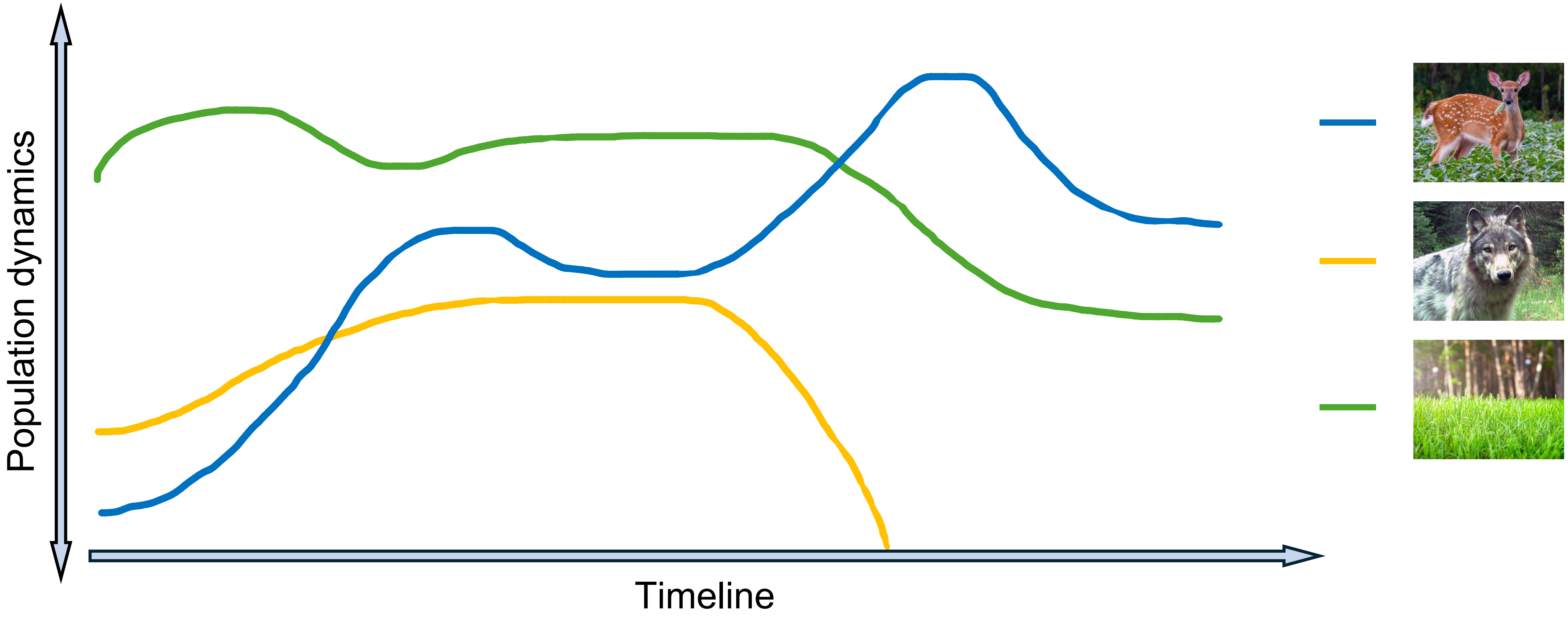


Microbial co-occurrence network



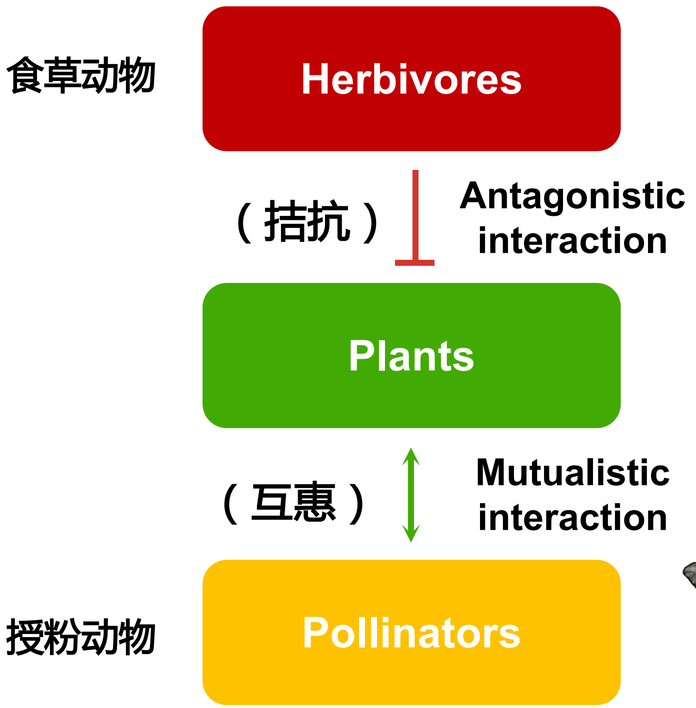
Ecological interaction network

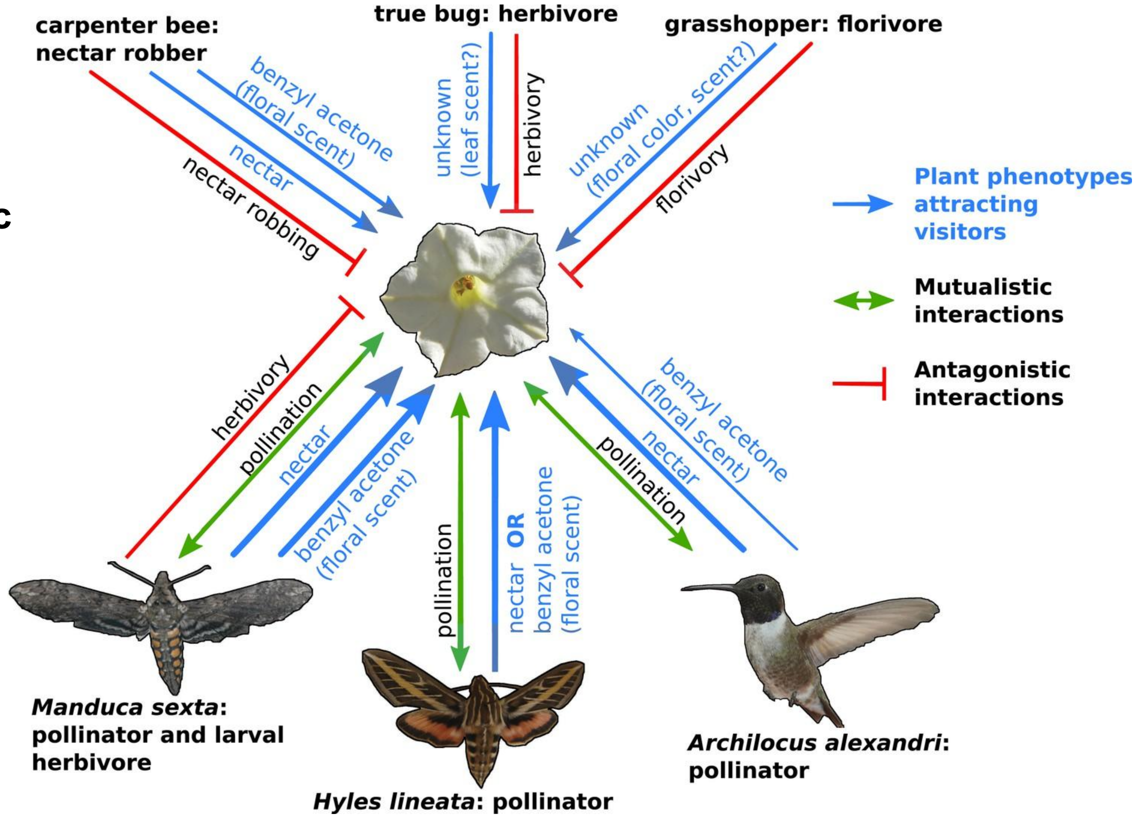
Network perspective on life systems



A holistic network approach is essential for analyzing ecosystem dynamics

Three-guild herbivore-plant-pollinator network





➢ Mutualistic and antagonistic interactions can regulate biomass balance within the network and maintain ecosystem stability.

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Adaptive rewiring shapes structure and stability in a three-guild herbivore-plant-pollinator network

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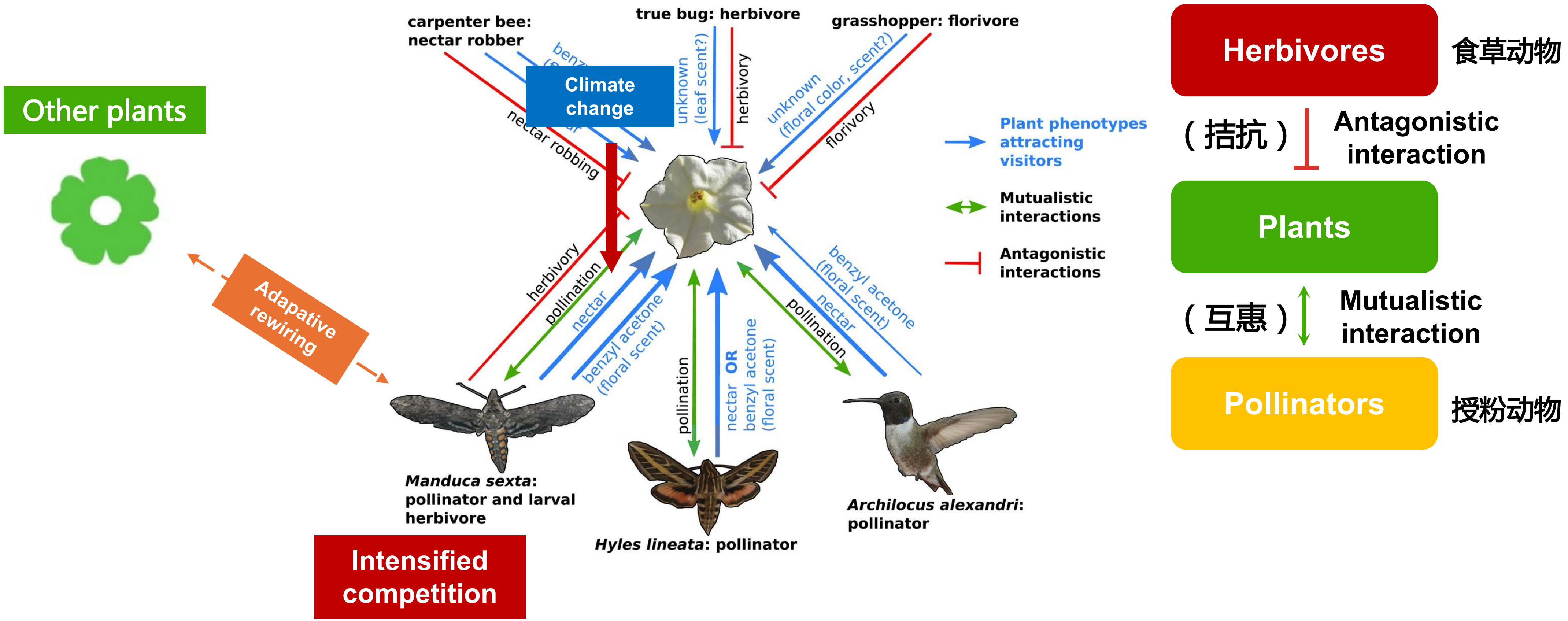
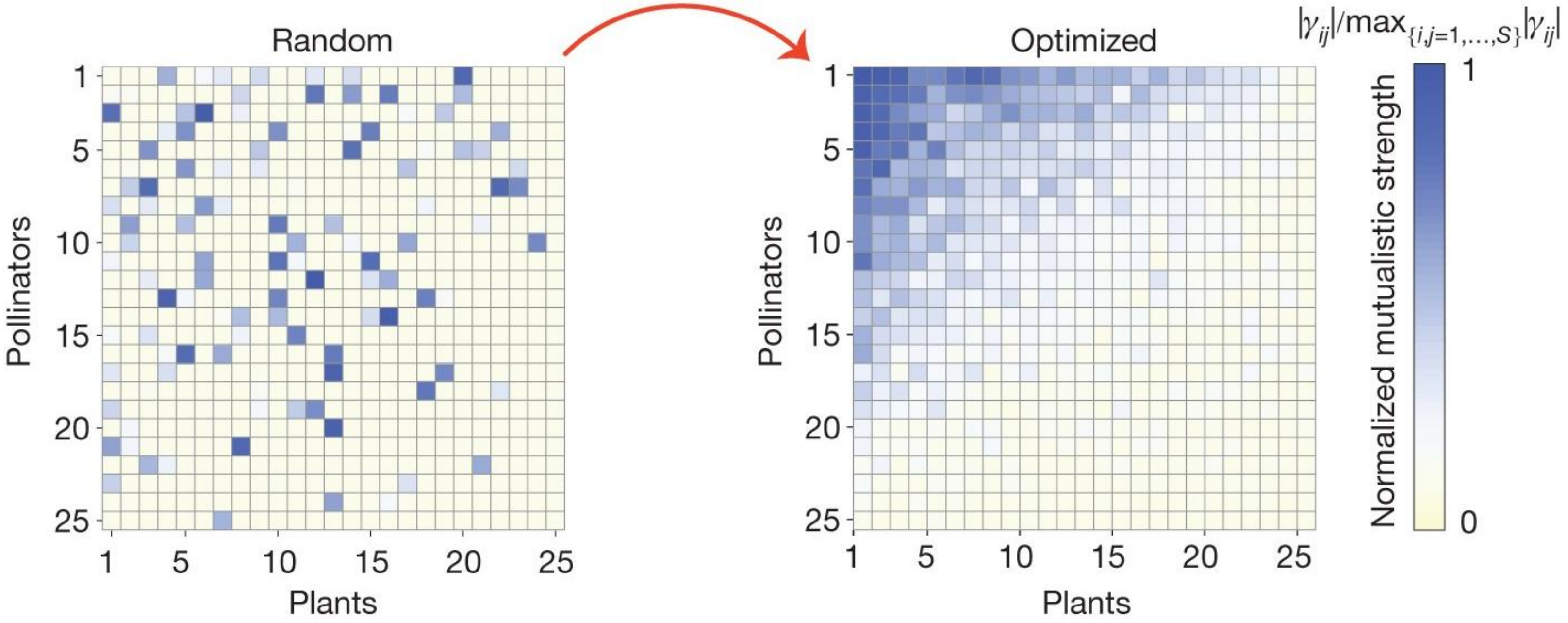
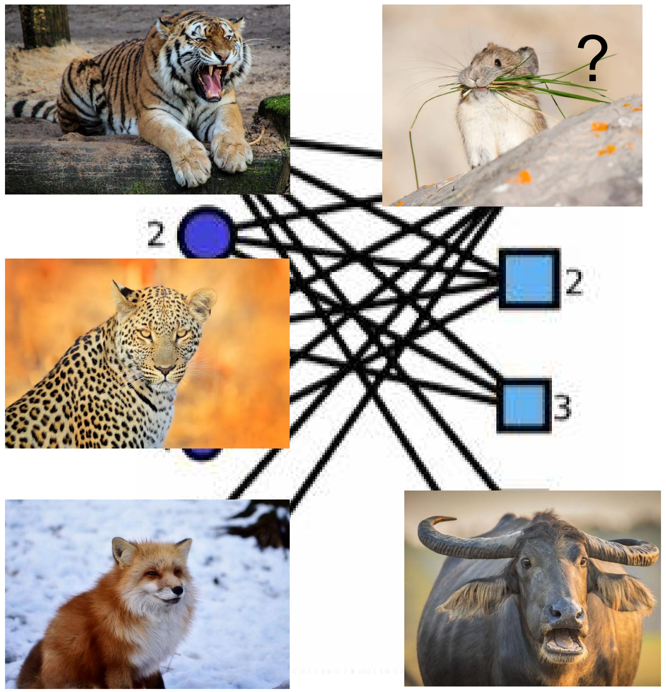
Adaptive rewiring



Adaptive rewiring helps species enhance the efficiency of resource utilization

Adaptive rewiring enhances the nestedness

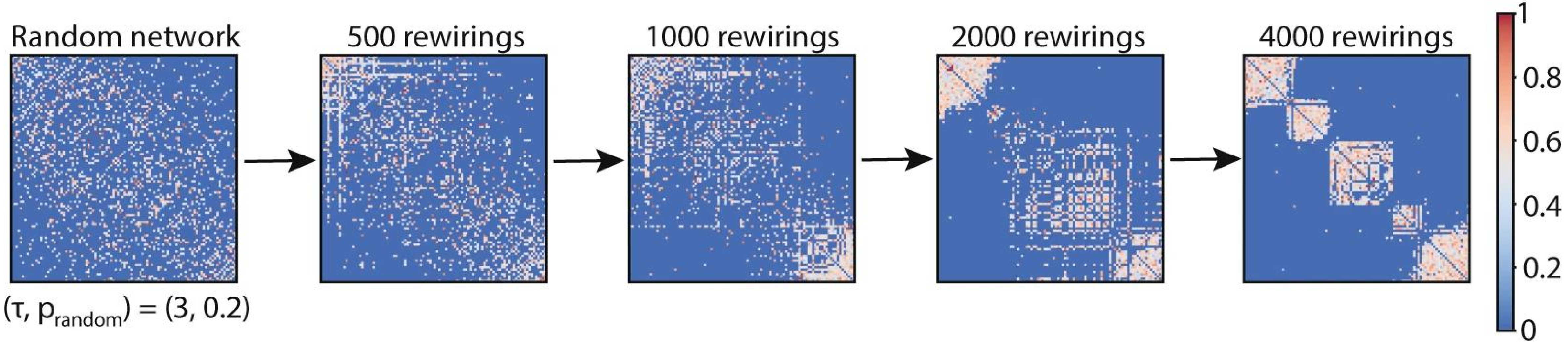




➢ Nestedness enhances network stability by ensuring species persistence through remaining interactions, even when some species are eliminated.

Nestedness (嵌套性): the interactions of specialized units are always encompassed within generalized units；

Adaptive rewiring enhances the modularity

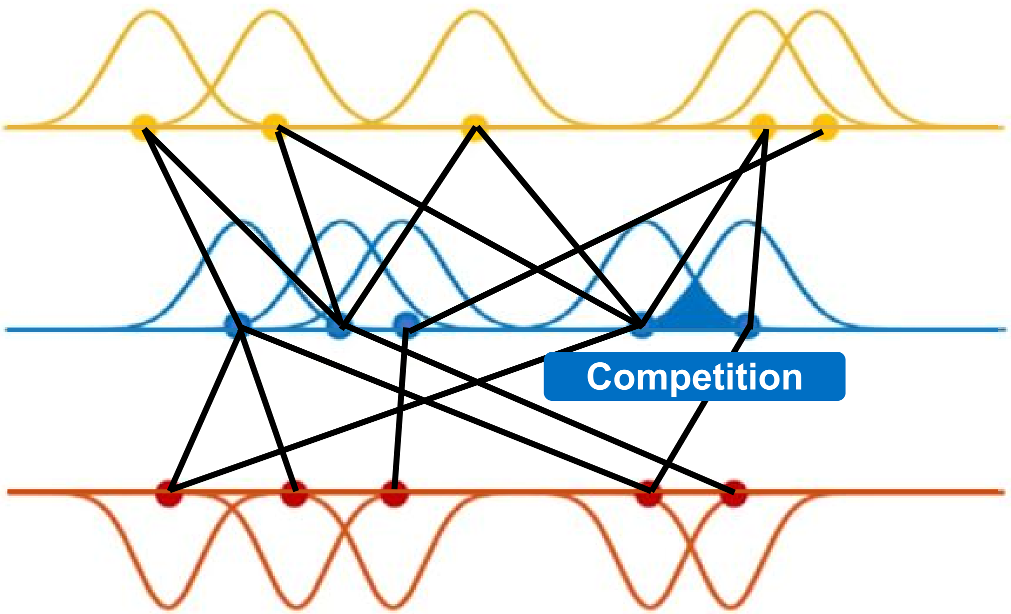


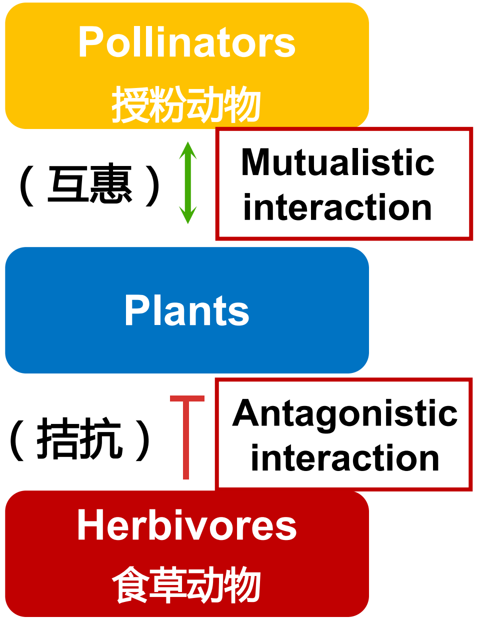
- Highly modularity enhance system stability by limiting local disturbance propagation through autonomous functional units.

Modularity (模块化): Species within the network can be partitioned into distinct modules or subgroups, where intra-modular connections exhibit dense linkage patterns while inter-modular interactions remain relatively sparse.

Network construction from adaptive niche-based interactions

Step1: Network initialization





Fixed parameters

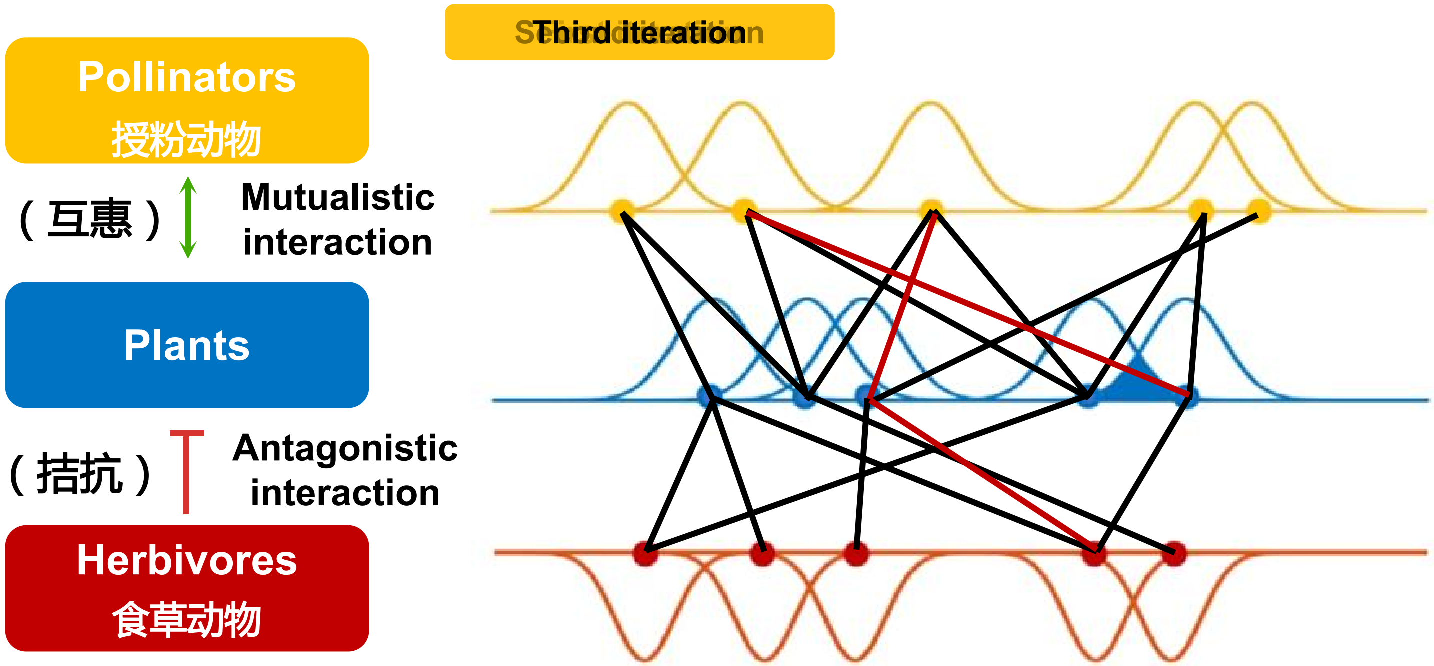
1. Species numbers;
2. Niche breadth;
3. Species' intrinsic growth rates;
4. Background interaction strengths;

Random parameters

1. Niche distribution;
2. Initial interactions;
3. Biomass;

Network construction from adaptive niche-based interactions

Step2: Adaptive interaction rewiring



Lotka-Volterra model governing the dynamics of the 3-guild network

$$\frac{dM_i}{dt} = \text{Biomass} \times (\text{Intrinsic growth} - \text{Competition} + \text{Mutualistic})$$

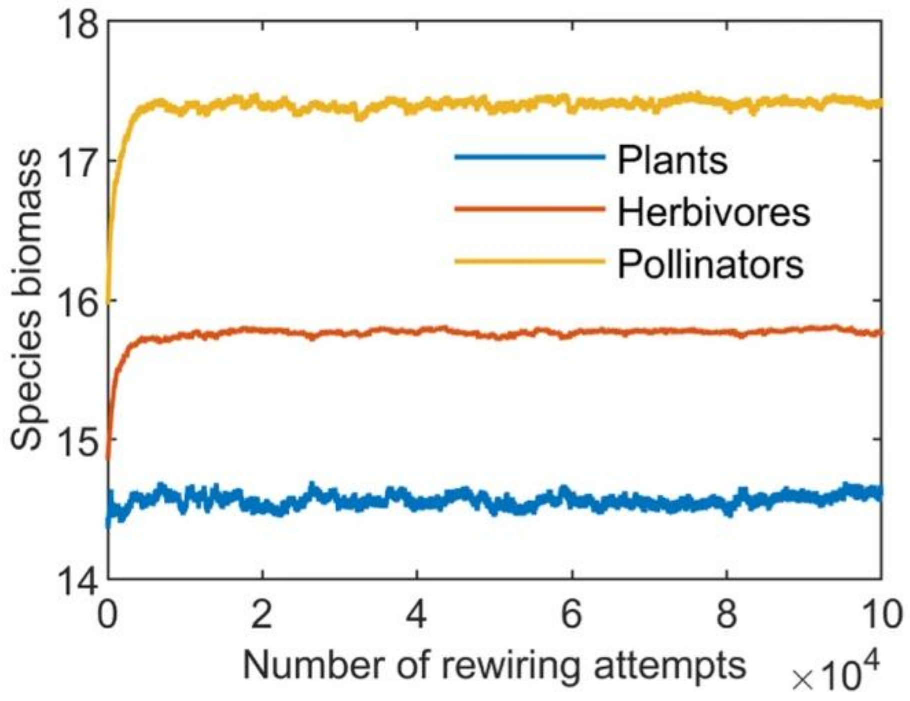
$$\frac{dP_i}{dt} = \text{Biomass} \times (\text{Intrinsic growth} - \text{Competition} - \text{Antagonism} + \text{Mutualism})$$

$$\frac{dH_i}{dt} = \text{Biomass} \times (\text{Intrinsic growth} - \text{Competition} + \text{Antagonism})$$

- In each iteration, a random interaction is changed with the probability $p_{ij} = 1 - \psi^{-1}$, where ψ represents the number of partners a plant has in the same guild as the selected animal species;
- Interactions are more likely to be lost by species that interact with many other species;
- After reestablishing interactions, species' biomass is updated.

Network construction from adaptive niche-based interactions

Step3: Reaching dynamic equilibrium



Lotka-Volterra model governing the dynamics of the 3-guild network

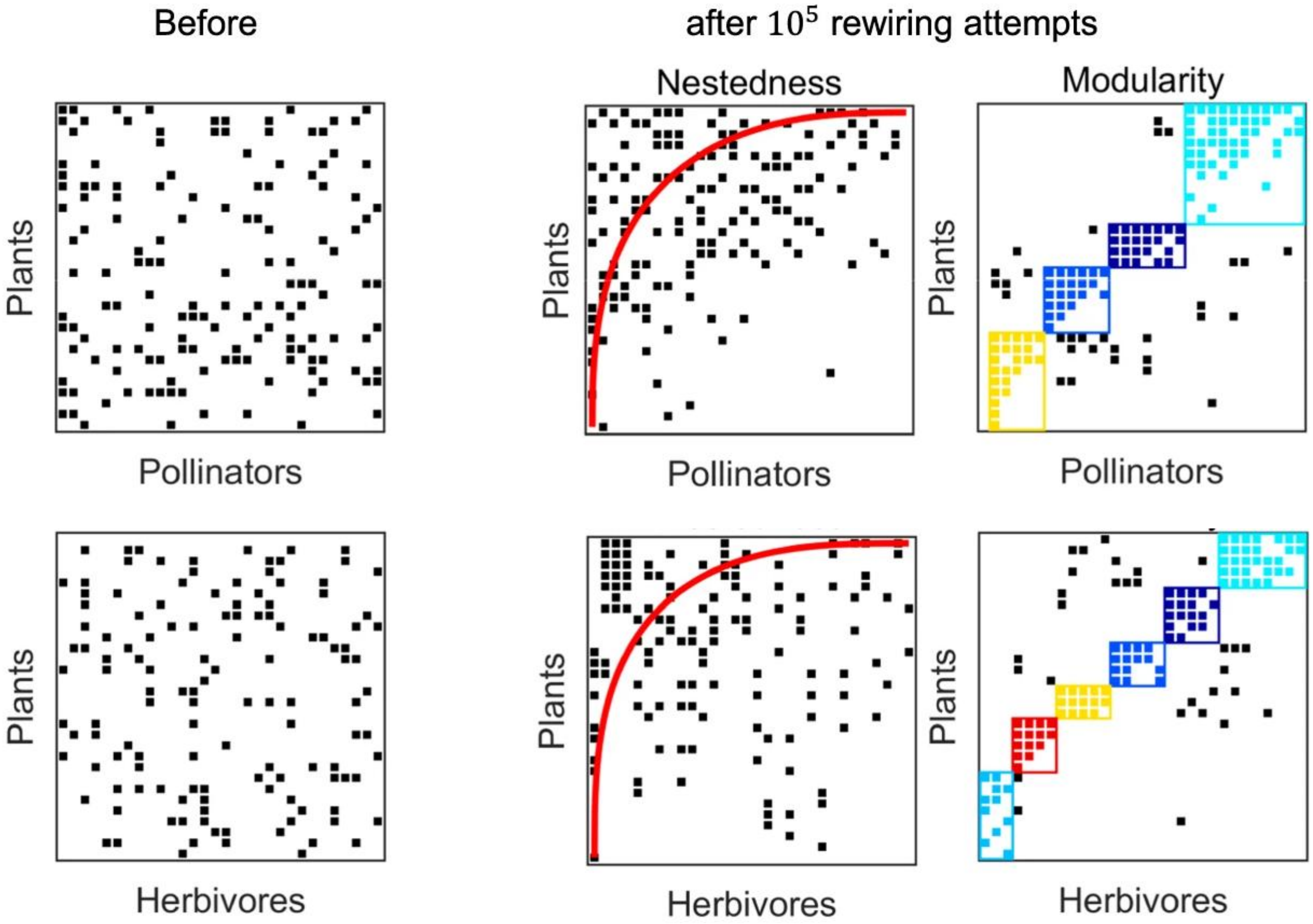
$\frac{dM_i}{dt}$ = Biomass × (Intrinsic growth – Competition + Mutualistic) — **Pollinators 授粉动物**

$\frac{dP_i}{dt}$ = Biomass × (Intrinsic growth – Competition - Antagonism + Mutualism) — **Plants**

$\frac{dH_i}{dt}$ = Biomass × (Intrinsic growth – Competition + Antagonism) — **Herbivores 食草动物**

- Biomass is used to determine if the three-guild network is stable;
- But no specific criteria for this judgment are provided;

The structure of network after rewiring iteration



Stability response to interaction strengths

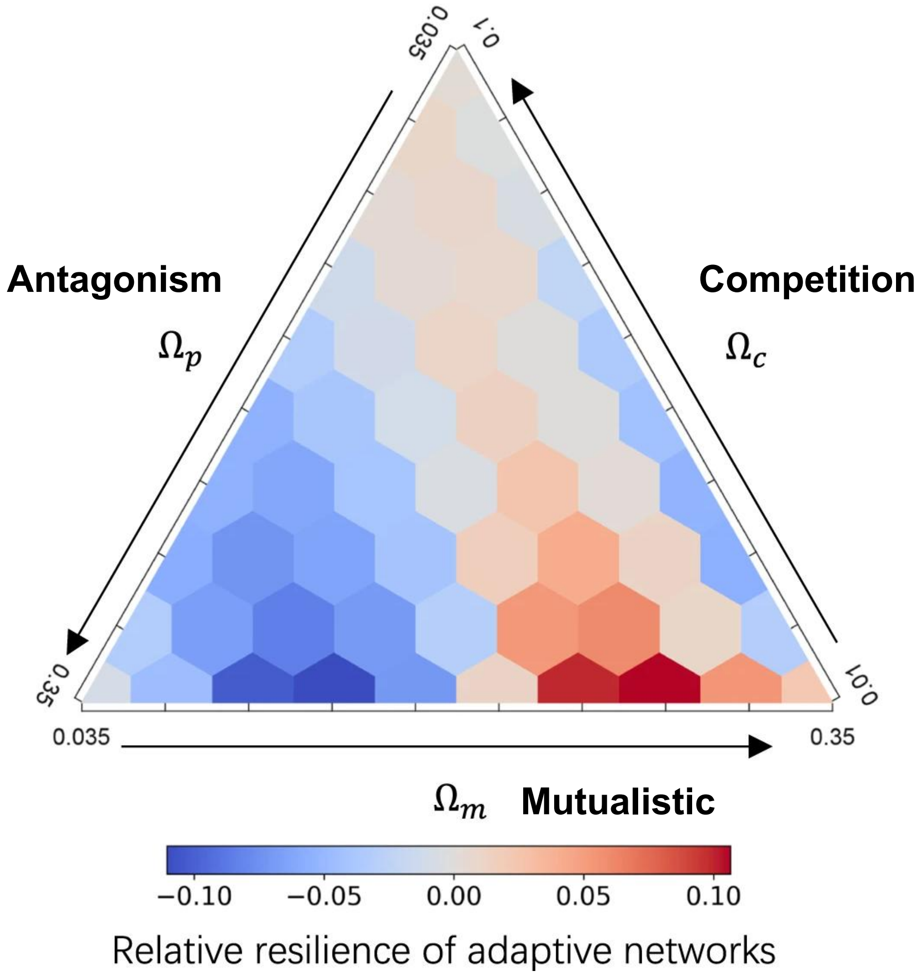
- **Resilience**: The capacity of ecological networks to regain equilibrium following minor perturbations, reflecting system stability when facing perturbations such as species extinction and environmental changes.

Lotka-Volterra model governing the dynamics of the 3-guild network

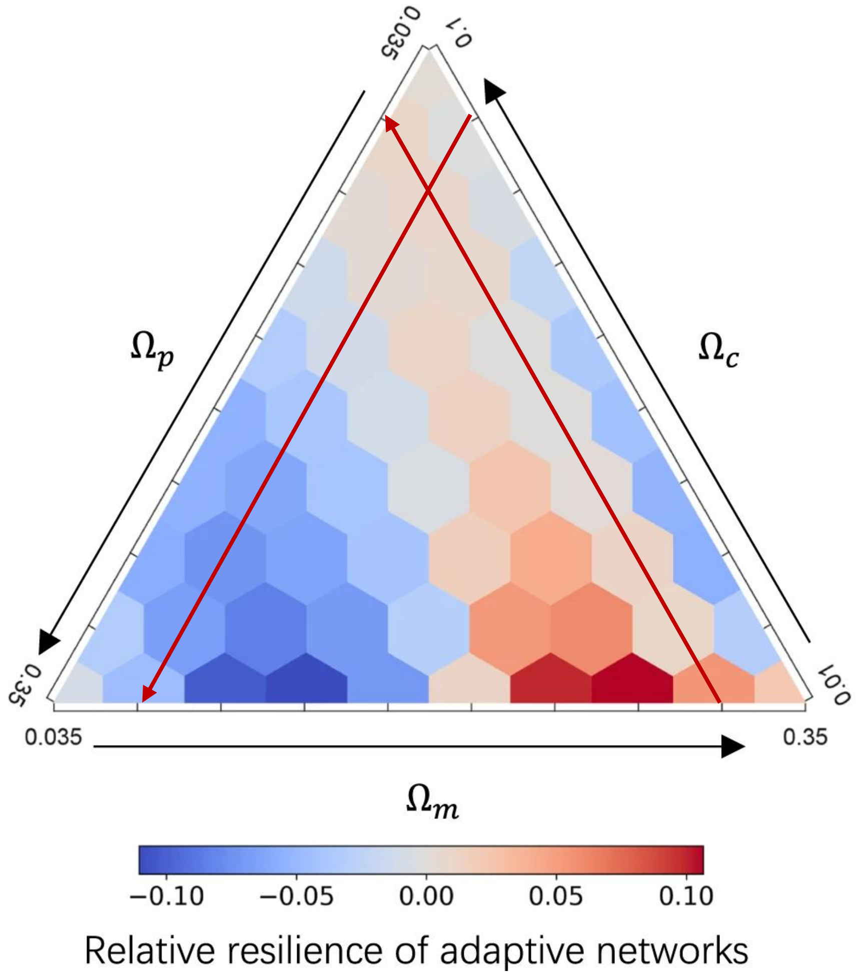
$\frac{dM_i}{dt} =$ Biomass × (Intrinsic growth – Competition + Mutualistic)

$\frac{dP_i}{dt} =$ Biomass × (Intrinsic growth – Competition - Antagonism + Mutualism)

$\frac{dH_i}{dt} =$ Biomass × (Intrinsic growth – Competition + Antagonism)



Stability response to interaction strengths



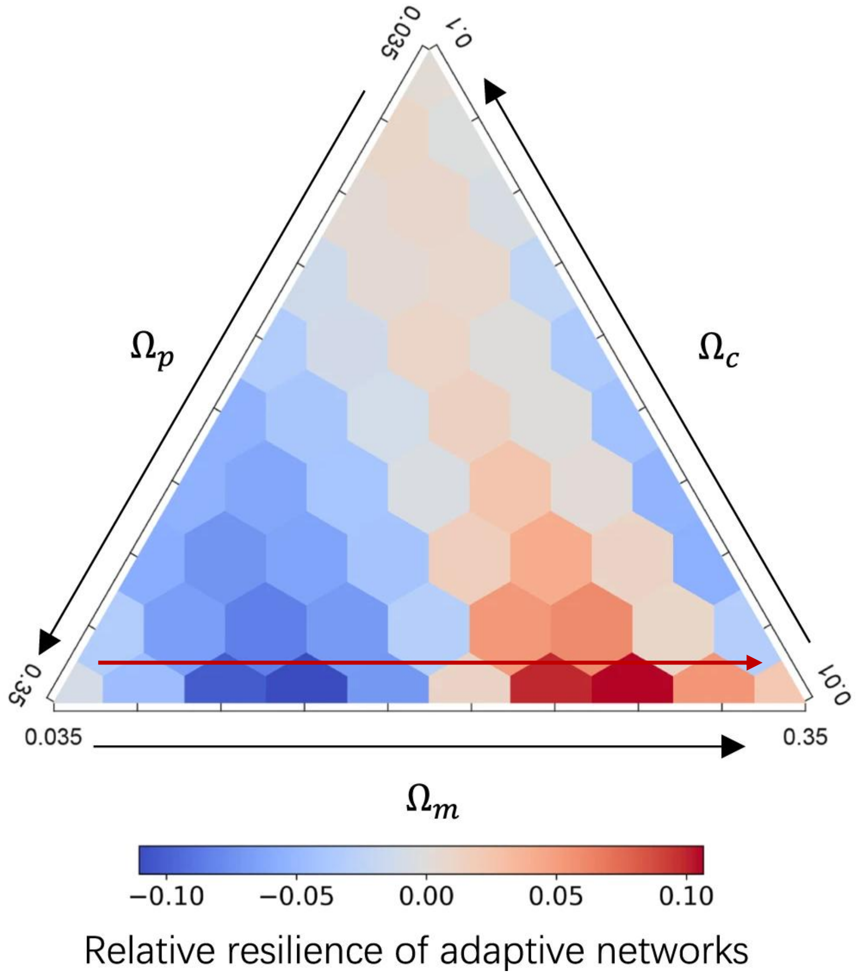
Competition (Ω_c):

- Changes in competition have a relatively small impact on network resilience;
- However, under different levels of competition intensity, alterations in the other two types of interactions (mutualism and antagonism) can significantly affect network resilience.

Antagonism (Ω_p):

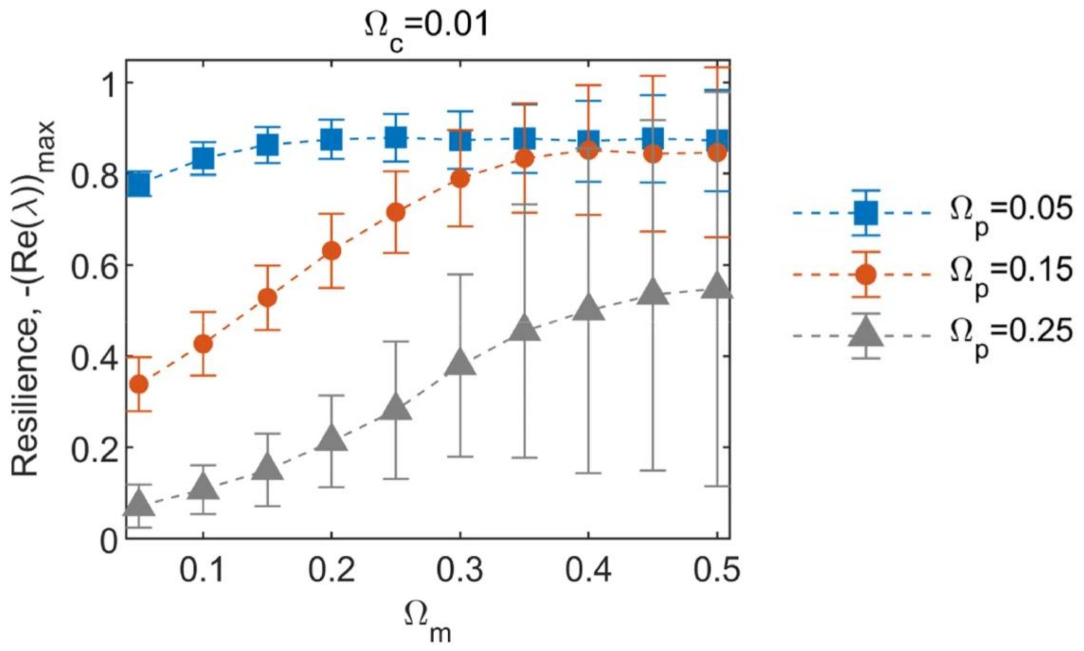
- An increase in antagonism reduces network resilience.

Stability response to interaction strengths

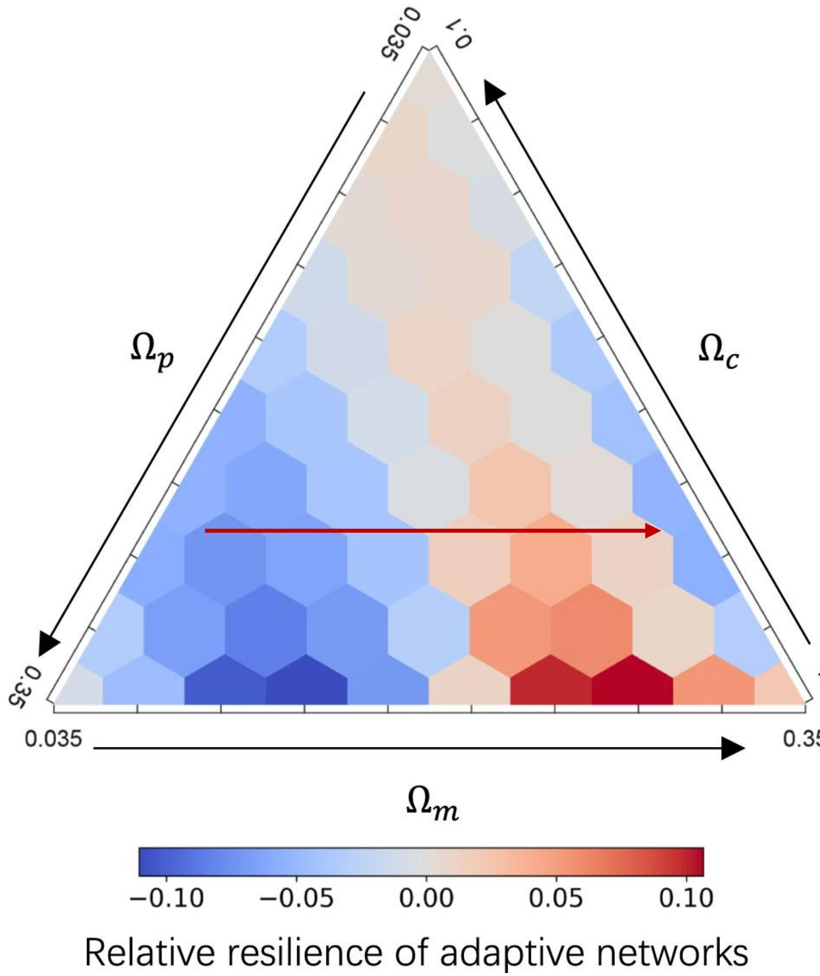


Mutualism (Ω_m):

➢ Under low competition intensity, increased mutualistic strength enhanced resilience of network;

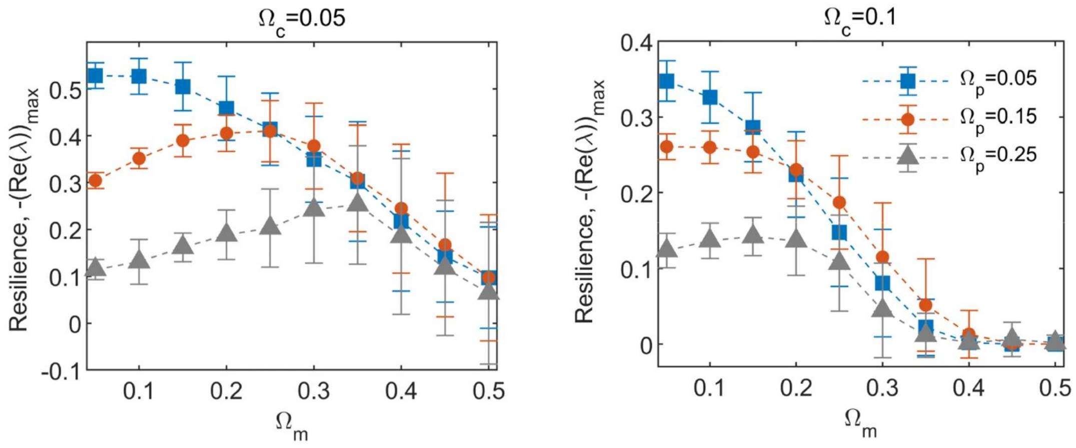


Stability response to interaction strengths



Mutualism (Ω_m):

- Under low competition intensity, increased mutualistic strength enhanced resilience of netwirk;
- Under moderate-to-high competition intensity, elevated mutualistic interaction strength reduce the network's resilience

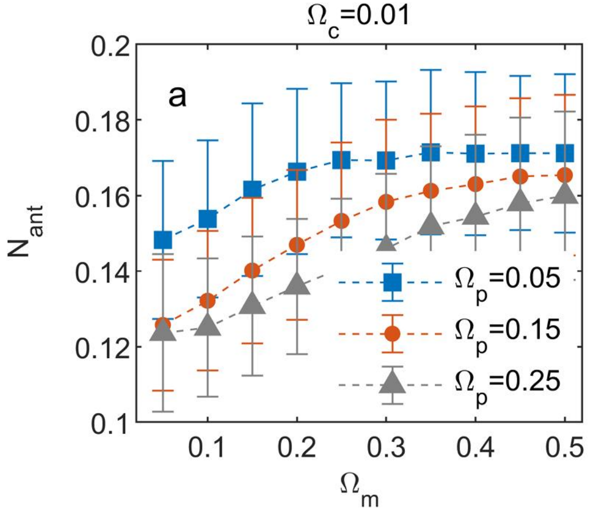


The balance of multiple interactions can exert selective forces that go beyond the direct additivity of different interactions

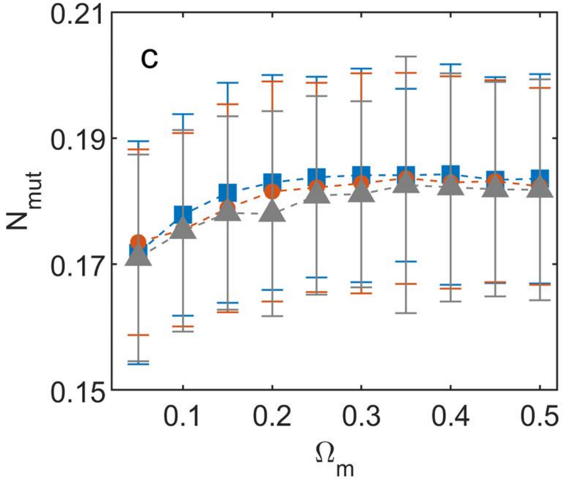
Response of nestedness to interaction strengths

Sub-network of mutualism

Nestedness increasing



Sub-network of mutualism



Sub-network of antagonism

Sub-network of antagonism

Low competition strength:

- Increasing mutualism strength enhances network nestedness;
- Increasing antagonistic strength reduces network nestedness；

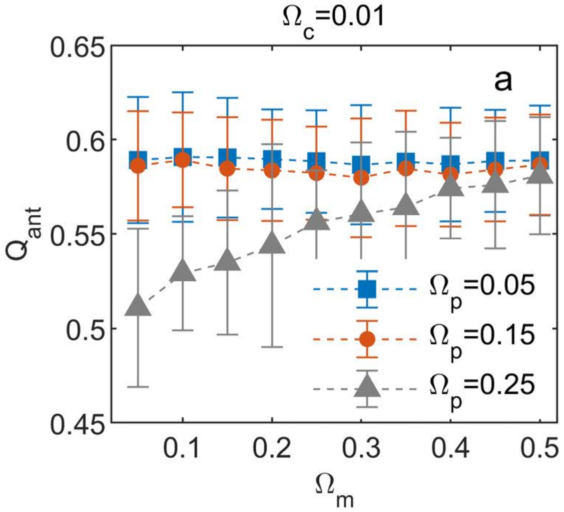
High competition strength:

- Higher competition strength increases network nestedness；
- Elevated mutualism strength reduces nestedness；

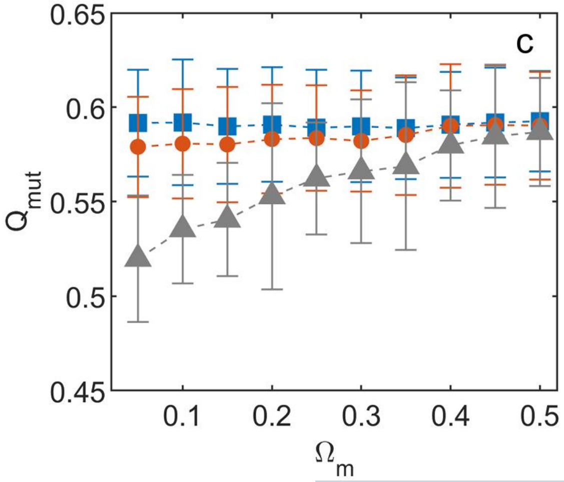
Response of modularity to interaction strengths

Sub-network of mutualism

Modularity increasing



Sub-network of mutualism



Sub-network of antagonism

Sub-network of antagonism

Low competition strength:

- Under low antagonistic strength, modularity remains stable;
- Under high antagonistic strength, low mutualistic strength reduces modularity;

High competition strength:

- Increased competition strength does not affect overall modularity;
- Increased mutualistic and antagonistic strengths decrease modularity.

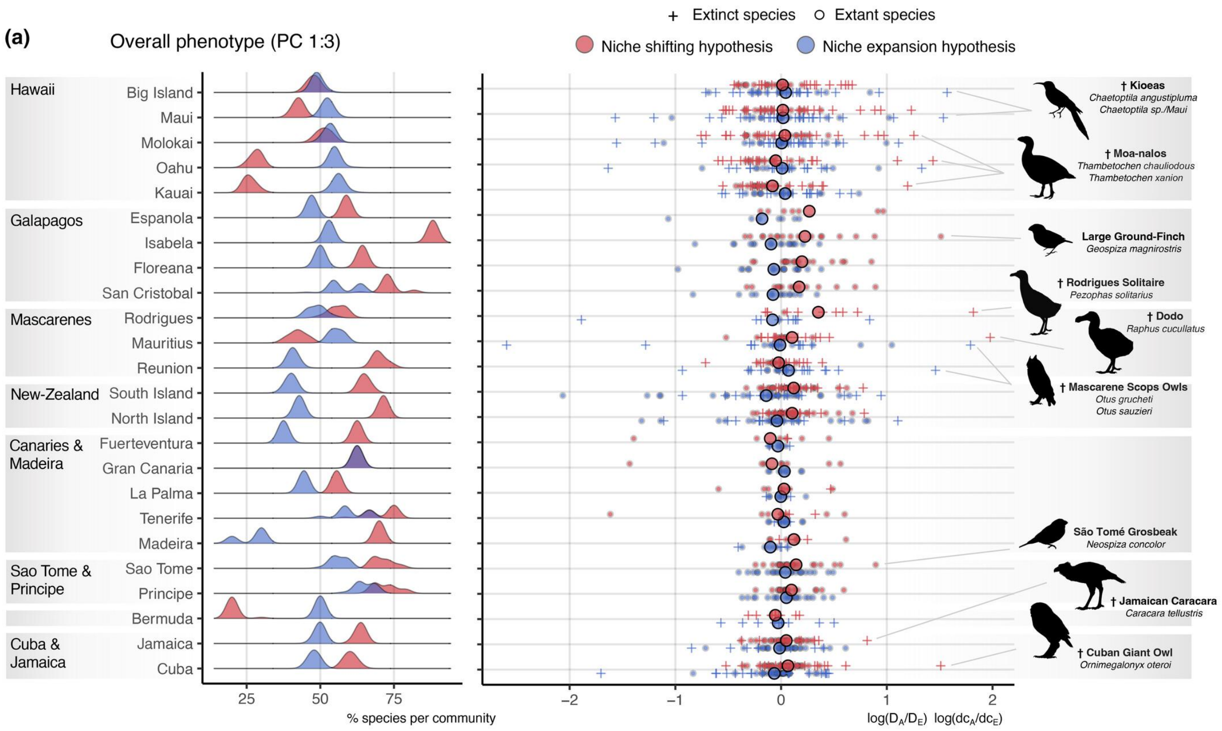
Conclusions & Adavantages

- This study simulated the adaptive rewiring process in a three-guild herbivore-plant-pollinator network through modeling;
- Adaptive rewiring drives the evolution of sub-network structures, with the nestedness and modularity significantly increased;
- Network stability is governed by the dynamic balance of interaction strengths:
  - ✓ The optimal ratio of mutualism (Ω ↑) to competition (Ωc↓) determining system resilience;
  - ✓ The link between structural complexity (nestedness/modularity) and stability requires multidimensional analysis.
- Theoretical innovations offer insights for empirical research:
  - ✓ Highlight the necessity of integrating adaptive behaviors and interaction strength dynamics in understanding ecological network persistence.

Problems

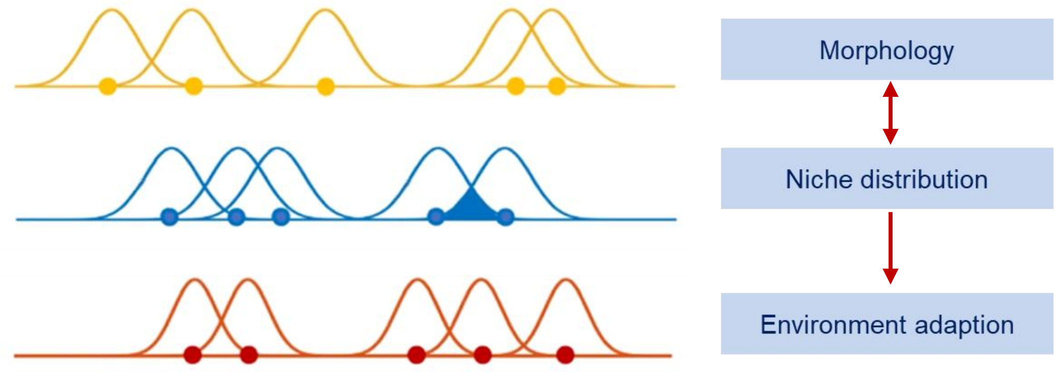
- **Over-simplification of ecological mechanisms**
  - ✓ The study assumes symmetrical niche distribution, such as equal network size and connectance, and simplifies species interaction rules, like competition strength and resource allocation patterns. This may cause the model to fail to capture non-linear dynamics in real ecosystems.
- **Limitations in combining theory with empirical evidence**
  - ✓ Although the model shows that network structure and stability are regulated by the intensity balance of multiple types of interactions, it does not compare results with field observations or experimental data, such as actual food web structures and community stability thresholds.
- **Insufficient breadth and depth in discussion**
  - ✓ There is not enough comparison with similar studies, like multi-trophic level network models and mutualism-antagonism trade-off theories, and the application potential of the conclusions under climate change or human disturbance is not discussed.

Prospects



- Left: the percentages of species per community that follow each of the two hypotheses (niche shifting or niche expansion).
- Right: the position of each endemic species according to its distinctiveness or distance to centroid values, compared to the values of their ancestor.

- **Niche shifting hypothesis**: evolve towards filling a functional gap (more distinct);
- **Niche expansion hypothesis**: evolve towards common morphological traits (more similar);



Species tend to develop divergent trait values rather than converge toward intermediate traits

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