# Stability in ecological meta-community models

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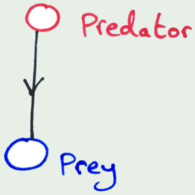
# Ecological models: overview

We may be familiar with two-species models in population dynamics:

**Predator-prey model**

$$\text{Prey:} \quad \frac{\mathrm{d}x}{\mathrm{d}t} = f(x)x - g(x,y)y$$

$$\text{Predator:} \quad \frac{\mathrm{d}y}{\mathrm{d}t} = \lambda g(x,y)y - dy$$



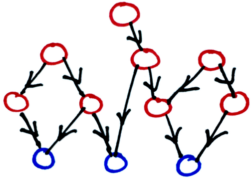

e.g. with logistic prey growth and Lotka-Volterra predation...

$$\text{Prey:} \quad \frac{\mathrm{d}x}{\mathrm{d}t} = rx(1-x) - cxy$$

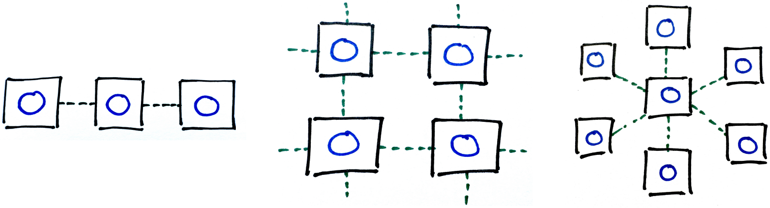
$$\text{Predator:} \quad \frac{\mathrm{d}y}{\mathrm{d}t} = \lambda cxy - dy$$

# Ecological models: overview

- **Community (foodweb) model:** multiple interacting species.

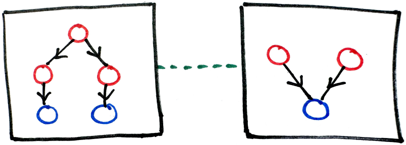


- **Meta-population model:** single species, multiple patches.

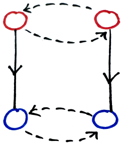


# Ecological models: overview

- **Meta-community model:** multiple species, multiple patches.



- **Eco-evolutionary model:** mutation/speciation, adaptive dynamics.



- **Community assembly model:** multiple species, new species invade from pre-existing pool.

# Eco-evolutionary meta-community models

**Combine all three features:**

- Mutation and evolutionary effects
- Space
- Multiple species

**Conceptual challenges:**

- How to define species (one vs. multiple traits)?
- Dynamically determine feeding relationships (based on traits)?
- Network structure of the spatial landscape?
- Dispersal mechanism (diffusion, probabilistic, adaptive)?
- Population dynamics (reproduction, functional response)?
- Does the ruleset result in plausible foodweb structures?

# An eco-evolutionary meta-community model

Species are defined by a bodysize and discrete set of traits that score against other traits. Begin with one species, and resources in each patch on a square $N \times N$ lattice. Simulation occurs in nested loops:

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- **Evolutionary loop:** choose a parent species and introduce mutant (with 9/10 of parent's traits and similar bodysize).
  - **Ecological loop:** feeding, reproduction, death, dispersal.
    - **Foraging loop:** local populations adaptively decide feeding strategies (avoid competition, prefer populous prey).

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Developed from the Webworld foodweb model (*Drossel et al* 2001).

# Ecological loop (feeding, reproduction, death, dispersal)

At time $t$, population dynamics of species $i$ in patch $(x, y)$ obeys:

$$N_{i,x,y}^{t} \mapsto N_{i,x,y}^{t} + \Delta\left(-d_0 s_i^{-0.25} N_{i,x,y}^{t} + \lambda s_i^{-1} N_{i,x,y}^{t} \sum_{j=0}^{n} g_{i,j} s_j - \sum_{k=1}^{n} N_{k,x,y}^{t} g_{k,i}\right)$$

Loss due to mortality. Gains due to feeding. Loss due to predation.

$s_i$ is bodysize; $\lambda = 0.3$ is ecological efficiency; $g_{i,j}$ is ratio-dependent response on $j$.

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Subsequently, migration from and to neighbouring patches:

$$N_{i,x,y}^{t} \mapsto N_{i,x,y}^{t} + \Delta\left(N_{i,x,y}^{t} + \sum_{j=1}^{x_{max}} \sum_{k=1}^{y_{max}} \mu_{i,j,k,x,y} N_{i,j,k}^{t} - \sum_{j=1}^{x_{max}} \sum_{k=1}^{y_{max}} \mu_{i,x,y,j,k} N_{i,x,y}^{t}\right)$$

Dispersal rate $\mu$ increases in patches where population is declining.

# Example ensembles

Simulation generates a meta-community of co-evolved species.

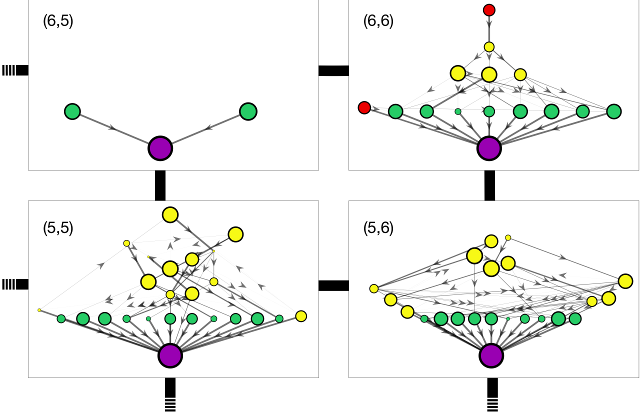
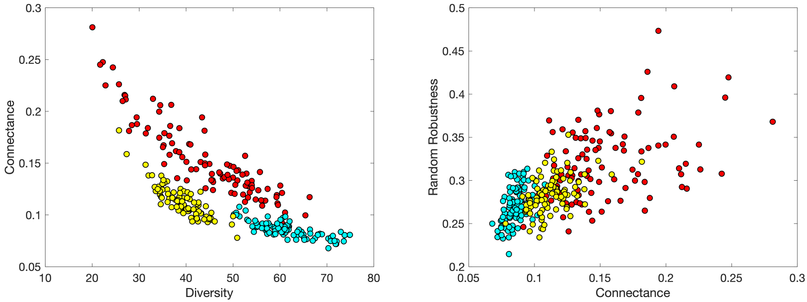



Figure 1: Foodwebs in $6 \times 6$ spatial network (colours denote trophic role)

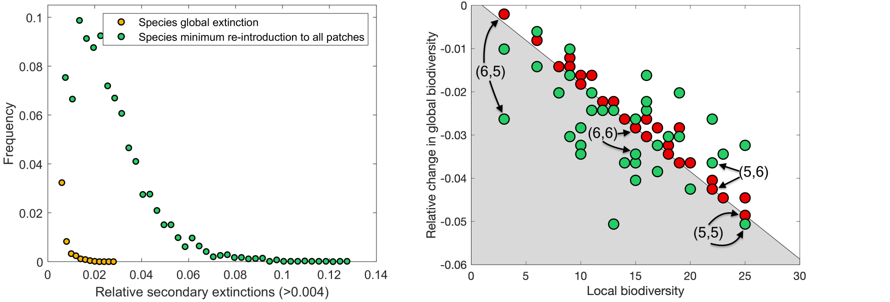
# Foodweb structure and stability




(a) Structure (b) Robustness

Figure 2: Local foodweb properties (colours relate to model configuration)

- How does the number of realised feeding links $L$ depend on diversity $S$? Connectance $(L/(S(S-1))$ decreases with diversity.
- **Stability:** Community robustness increases with connectance.



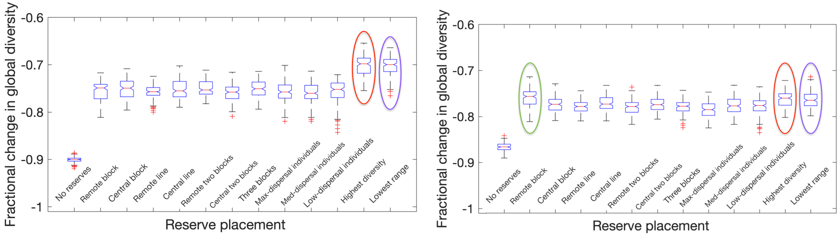

(a) Frequency distribution (b) Displacement vs. elimination

Figure 3: Effects of extinction, invasion and displacement

- Each species is deleted, (max loss 2.1%) then re-introduced to *all* patches (max loss 12%).
- Displacement to neighbouring patches can be more damaging than extinction.

# Habitat loss and nature reserves

Patches are subjected to repeated random disturbances, except for 6 (of 36) designated as nature reserves. What is the best choice?




(a) Elimination (b) Displacement

Figure 4: Biodiversity loss due to perturbation of random patch sequences

- Reliable to select patches with the greatest biodiversity or to protect the rarest species.
- If disturbed populations are displaced (rather than eliminated), isolating large, remote areas *from invasion* also effective.

# Outlook

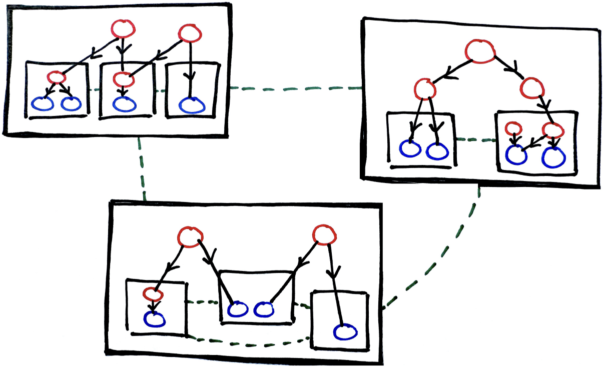
**Summary:**

- Models with simple evolutionary rules re-create complex network structure with improved stability.
- Can inform environmental efforts by determine principles for which sites and species are most vulnerable to perturbation.

**Challenges:**

- Validation from empirical data?
- Species-area curve and mixed range of species (neither spatially-homogeneous, nor total species-sorting).
- Limited conclusions from abstract models for specific ecosystems.

# Future work: strand I



- Simplified trait-space with explicit specialist-generalist trade-off;
- Multi-scale species perceptions of habitat;
- Role of scaling patterns in habitat structure and its removal.

# Future work: strand II

Application to management of water vole, mink and otter meta-communities in South Yorkshire:

- Collaboration with Sheffield Hallam University and the Sheffield and Rotherham Wildlife Trust;
- Simplified community model - three-species population dynamics;
- Highly-resolved spatial network from GIS data;
- Application to predicted impact of habitat perturbation.

# References


- **Original model:** Drossel, B., Higgs, P. G., & McKane, A. J. (2001). The influence of predator–prey population dynamics on the long-term evolution of food web structure. *Journal of Theoretical Biology*, 208(1), 91-107.
- Abernethy, G. M. (2020). Allometry in an eco-evolutionary network model. *Ecological Modelling*, 427, 109090.
- Abernethy, G. M. (2021). Sequences of patch disturbance in a spatial eco-evolutionary model. *Communications in Nonlinear Science and Numerical Simulation*, 97, 105746.
- **Review:** Gross et al. (2020). Modern models of trophic meta-communities. *Philosophical transactions of the Royal Society B*, 375: 20190455.