Invasion and robustness in ecological meta-community models

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Ecological models: overview

We may be familiar with two-species predator-prey models:

Predator-prey model with logistic growth and Lotka-Volterra FR

$$\frac{\mathrm{d}x}{\mathrm{d}t} = rx(1-x) - cxy, \qquad \frac{\mathrm{d}y}{\mathrm{d}t} = \lambda cxy - dy$$

Generalising these relationships:

- **Community (foodweb) model:** multiple interacting species. Food chains; specialists vs. generalists.
- **Meta-population model:** single species, multiple patches. Environmental heterogeneity; dispersal.
- **Meta-community model:** multiple species, multiple patches.

Meta-community eco-evolutionary models

Considerations for models of ecosystem development:

- How to define species (one vs. multiple traits)?
- How to specify the feeding relationships?
- Is network structure of the spatial landscape (regular, fractal, small worlds or large worlds) important?
- Can foodweb structure be generated by simple evolutionary rules with ecological feedback (**eco-evolutionary dynamics**)?

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. Simulation occurs in nested loops:

- **Evolutionary loop:** select 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 select feeding strategies.

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

Ecological loop (feeding, reproduction, death, dispersal)

During ecological timestep t, population dynamics of species i in patch (x, y) updated:

$$N_{i,x,y}^{t} \mapsto N_{i,x,y}^{t} + \Delta\left(-2s_i^{-0.25}N_{i,x,y}^{t} + \lambda s_i^{-1}N_{i,x,y}^{t}\sum_{j=0}^{n} g_{i,j}s_j - \sum_{k=1}^{n} N_{k,x,y}^{t}g_{k,i}\right)$$

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 functional response on j

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Subsequently, migration to and from neighbouring patches:

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

Dispersal rate μ increases in patches where population is declining.

Foraging loop

Between updating population sizes, the local population of species i in patch (x, y) iterates feeding strategies in two stages:

- Update feeding efforts distributed across prey j:

$$f_{i,j,x,y} = \frac{g_{i,j,x,y}}{\sum_{k \in K_i} g_{i,k,x,y}}$$

- Update ratio-dependent functional responses:

$$g_{i,j,x,y} = \frac{S_{i,j} f_{i,j,x,y} N_{j,x,y}}{0.005 N_{j,x,y} + \sum_{k \in P_j} \alpha_{i,k} S_{k,j} f_{k,j,x,y} N_{k,x,y}}$$

K_i is the set of possible prey of i; P_j is the set of possible predators of j;
$S_{i,j}$ is trait-dependent feeding score of i on j;
$\alpha_{i,k}$ controls competition based on level of similarity.

Example ensembles

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

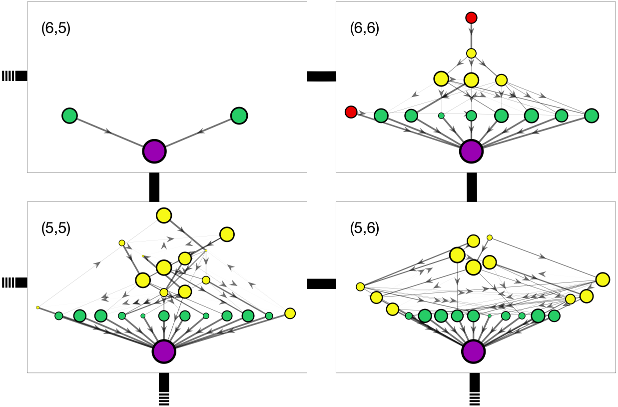
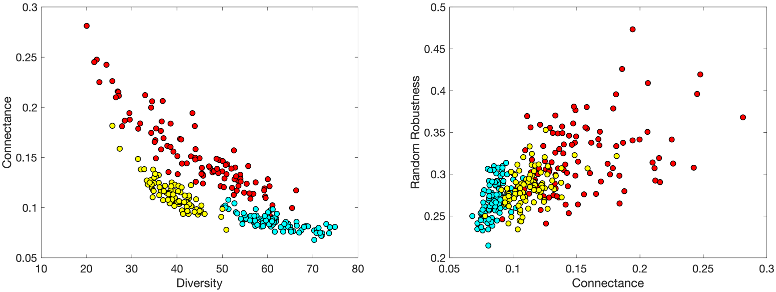


Figure 1: Foodwebs in 6×6 spatial network (colours denote trophic role)

Foodweb structure and stability



(a) Structure (b) Robustness

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

- Scaling of number of feeding links L with number of species S.
- Connectance $(L/(S(S-1))$ decreases with diversity.
- Community robustness increases with connectance.

Invasion of patches in the meta-community

Practical stability: **robustness** of existing ecosystems to species invasion.

Each species is deleted, (max loss 2.1%) then re-introduced to *all* patches (max loss 12%).

Number of patches invaded is increased by:

- Co-evolved traits.
- Larger bodysizes.

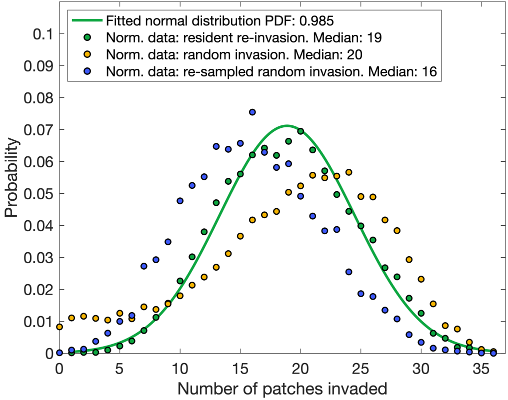
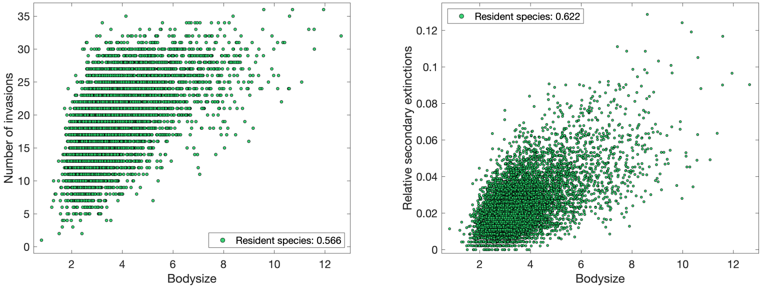


Figure 3: Probability of patch invasion

Invasion - role of bodysize



(a) Patch invasions

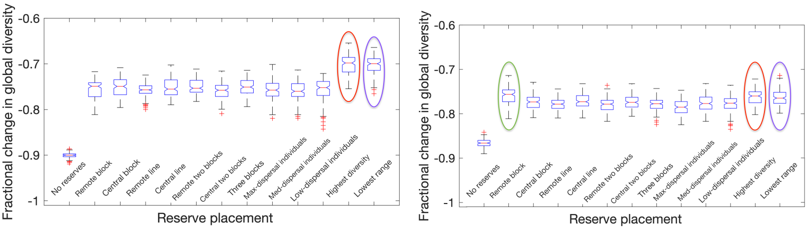
(b) Secondary extinctions

Figure 4: Bodysize correlations with invasion and secondary extinctions

- Larger-bodysize species prefer to predate at higher trophic levels, avoiding strong competition to feed on resources.
- Benefit more from uniform-population re-introduction.

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 5: 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 greater stability.
- Can be used to determine principles for which sites and species are most vulnerable to perturbation, and hence inform environmental efforts.

Challenges:

- Empirical data limited for validation.
- Abstract models hard to apply to specific ecosystems - focus on simpler, bespoke models?
- Exact mechanisms not easily identifiable in complex systems.

References

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