Models of metapopulation and metacommunity dynamics

Toward incorporating environmental filtering and biotic interactions

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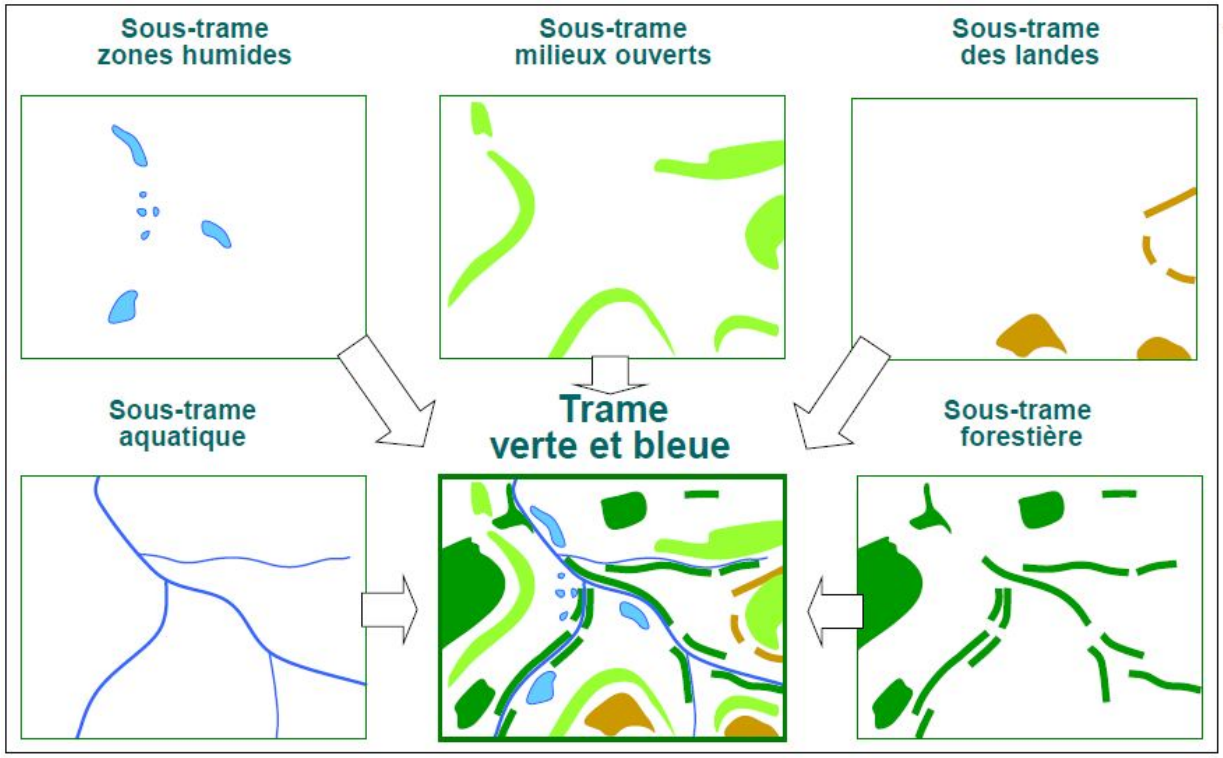
02/12/2022

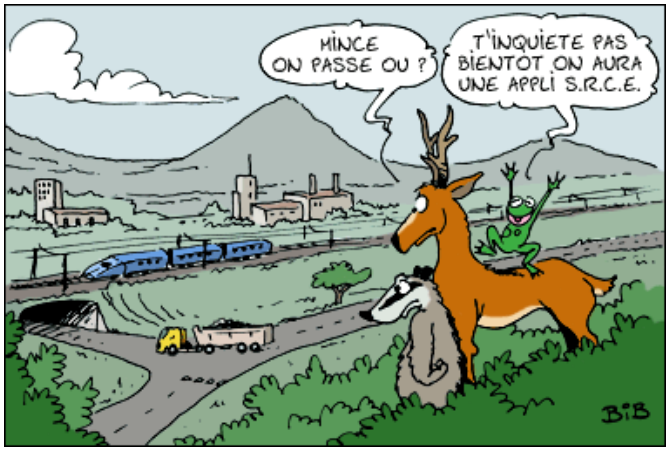
EverEvol – Population dynamics: from rare events to evolution

Life in a fragmented world

Local populations occupy localized separate habitat patches

- Example: « Green and Blue Network » (Trame Verte et Bleue)

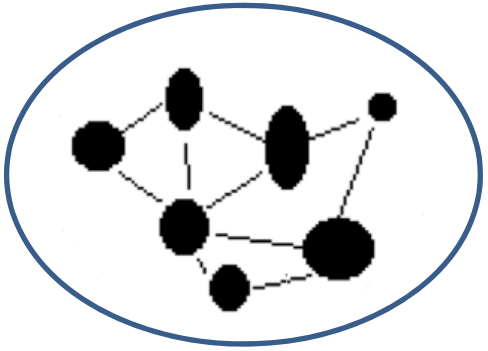




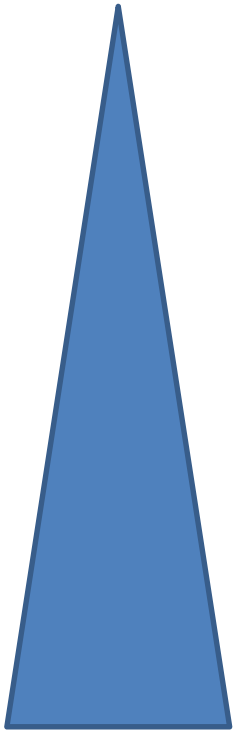
(source: IRSTEA)

Understanding and predicting biodiversity dynamics in spatially and temporally changing environments

Community dynamics



Metapopulation and metacommunity dynamics



Fine

Spatial and temporal scale

Broad

Understanding and predicting biodiversity dynamics in spatially and temporally changing environments

How do biotic interactions determine species diversity?

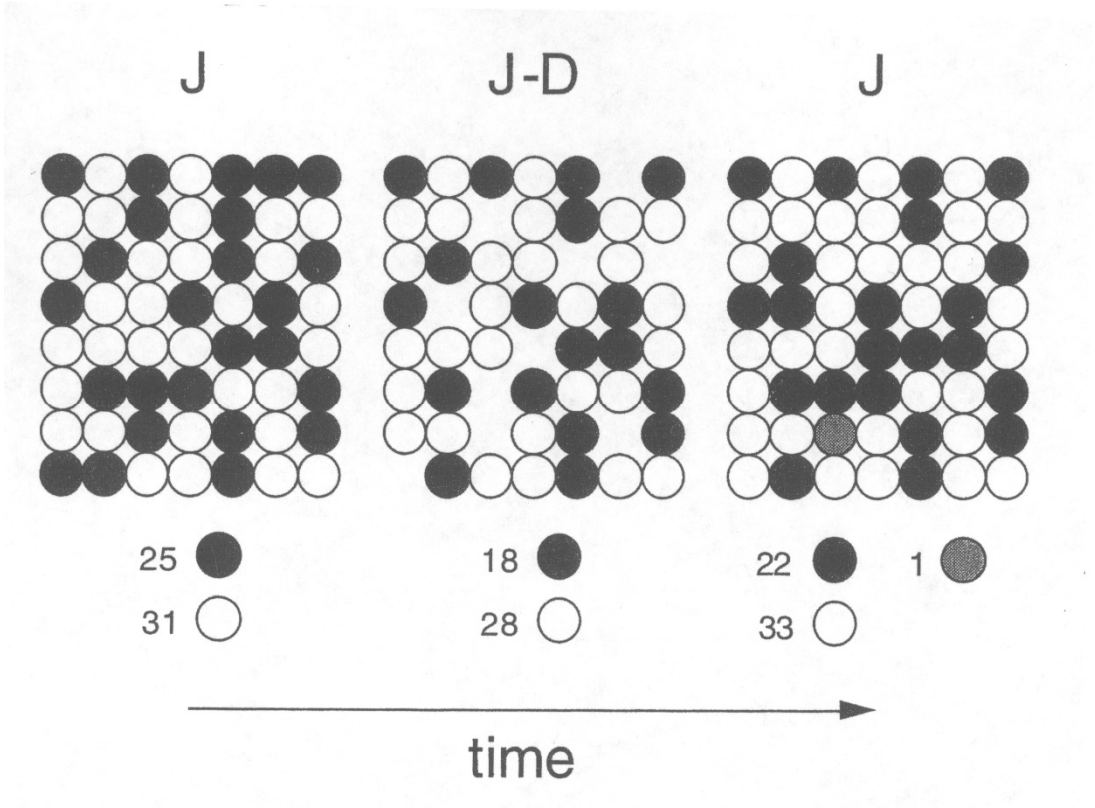
How do temporally fluctuating environment shape functional composition?

How does habitat fragmentation affect long-term dynamics of local populations?

Community

Niche-based dynamics

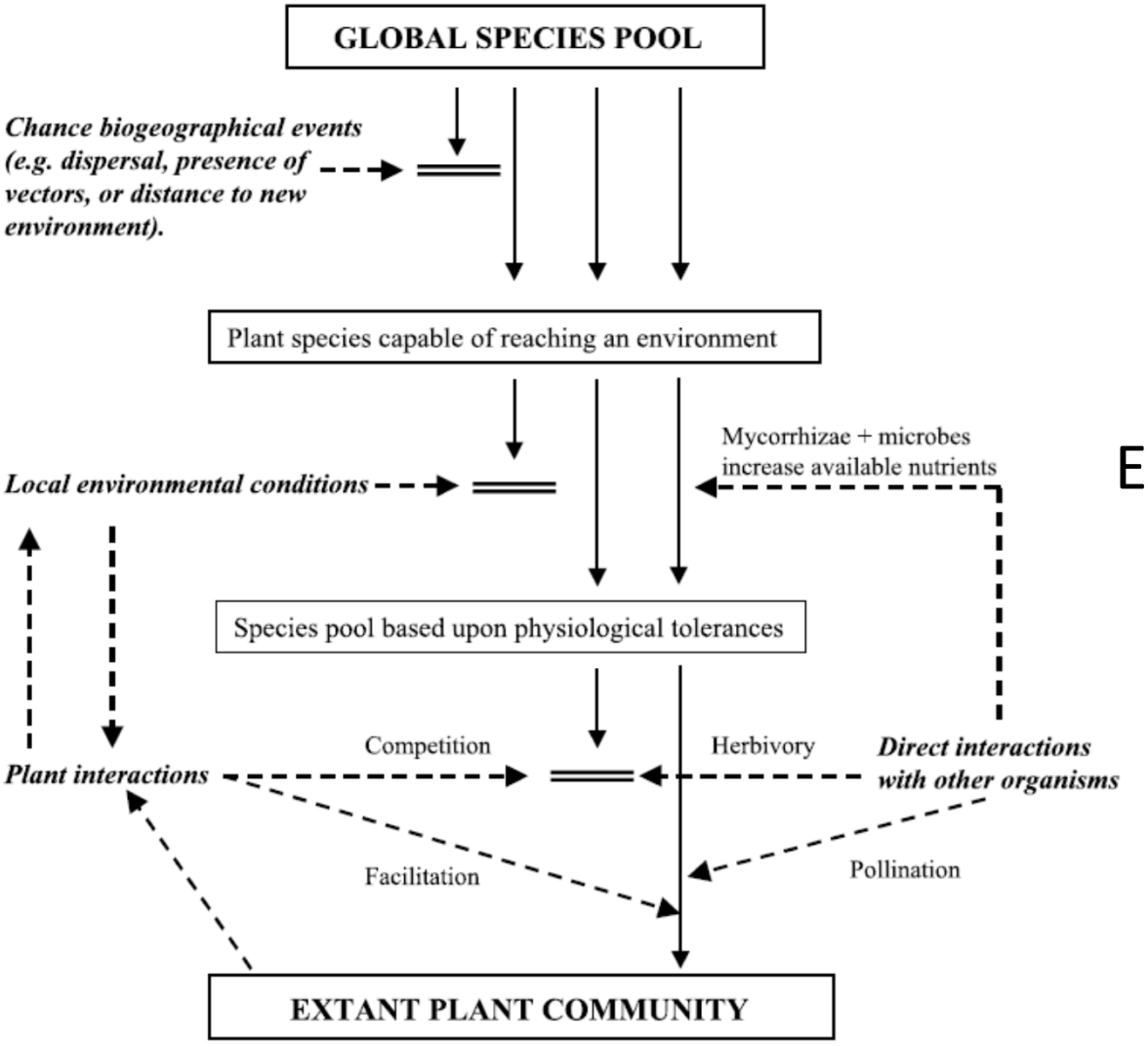
Zero-sum stochastic community dynamics



- Nombre fixé d'individus (J)
- Mortalité (D) et remplacement
- Possibilité de remplacement par migrant

Community

Niche-based dynamics



Environmental filtering

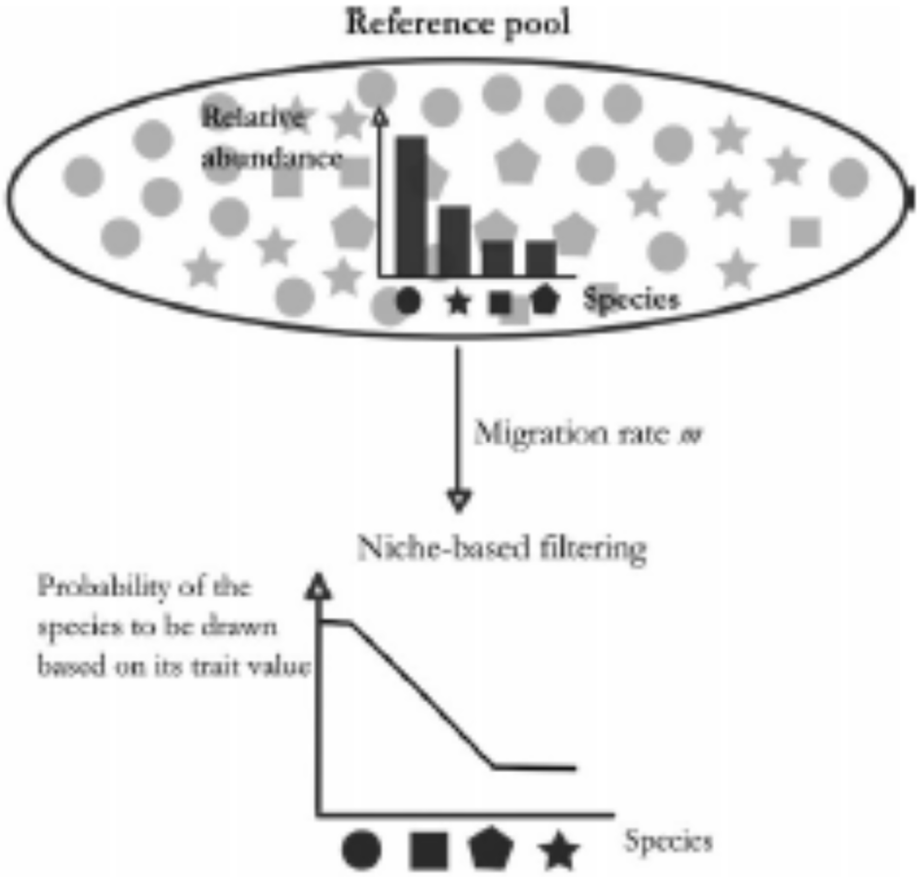
Biotic interactions

(Lortie et al. 2004)

Community

Niche-based dynamics

- The case of environmental filtering

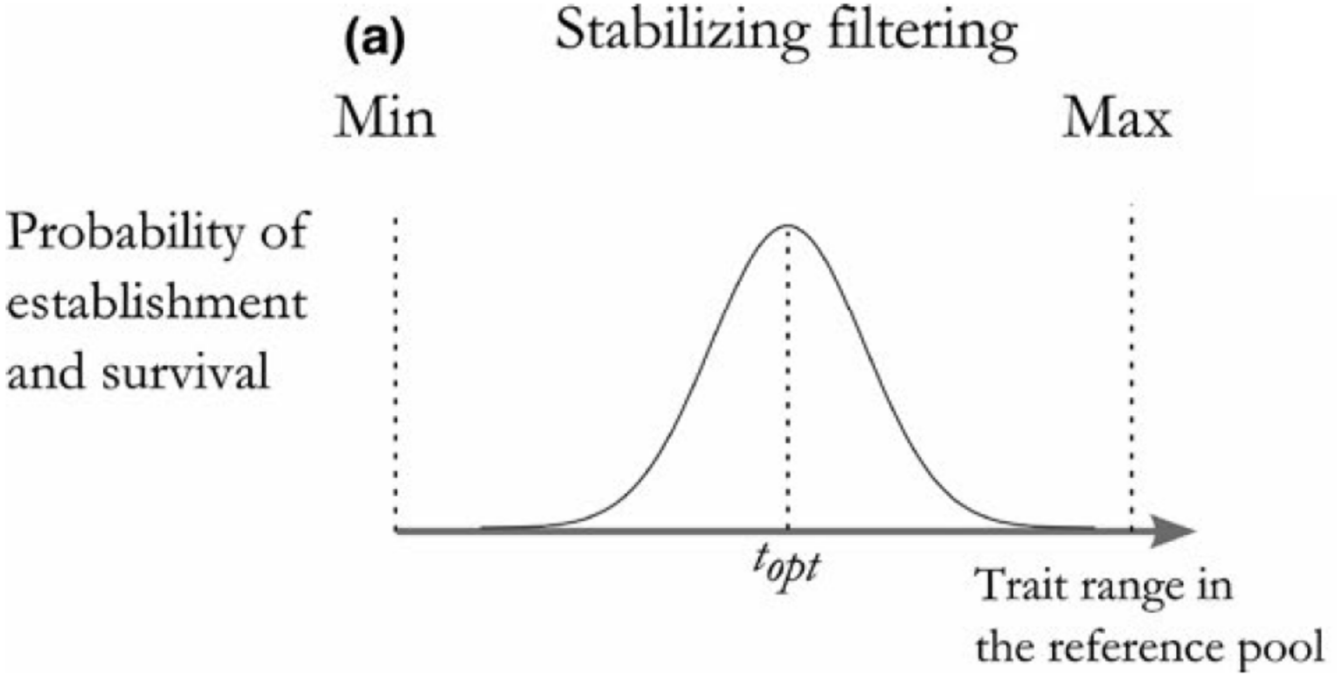


(Munoz et al. 2018)

Community

Niche-based dynamics

- The case of environmental filtering
  - ➢ Hypothesis of local functional optimum

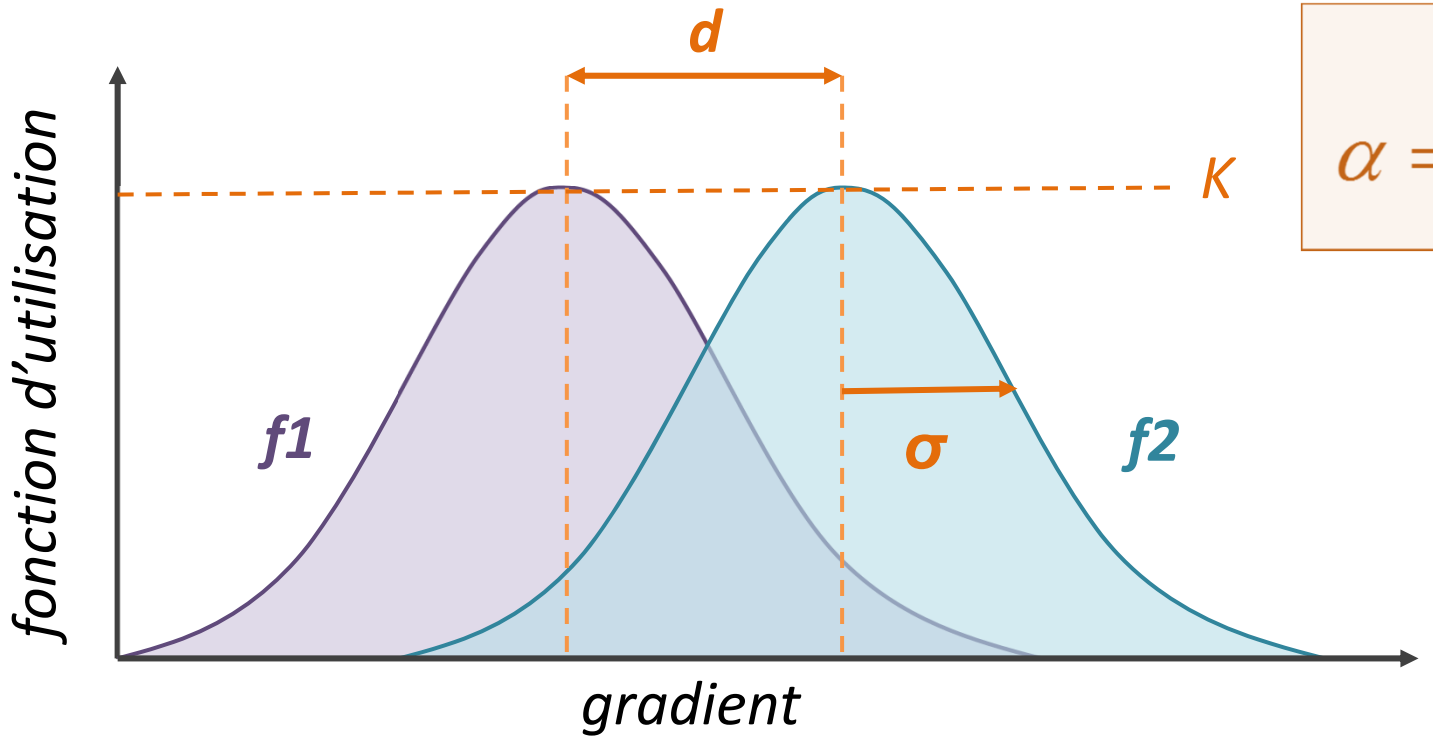


(Munoz et al. 2018)

Community

Niche-based dynamics

- The case of biotic interactions
  - ➢ Competition due to niche overlap



$$\alpha = e^{\frac{-d^2}{4\sigma^2}}$$

Community

Niche-based dynamics

- The case of biotic interactions
  - ➢ Competition due to niche overlap

- Alternative expected outcomes
  - ➢ Dominance of more fit species
  - ➢ Coexistence of species with different traits

Community

Niche-based dynamics

Simulation of community dynamics

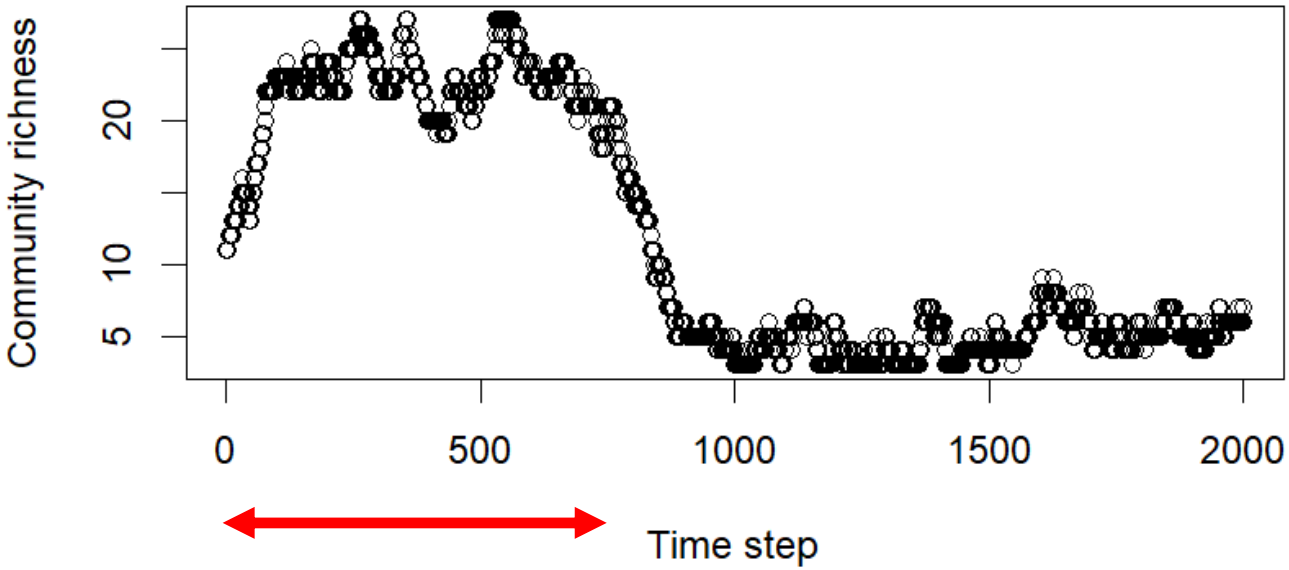
- Individuals die depending on how close they are to a local functional optimum (**environmental filtering**)
- Replacement by migrants with probability m, by local offspring with probability (1-m)
- Selection of estalished individuals
  - weighted by how close thy are to local functional optimum (**environmental filtering**)
  - Weighted depending on distance to other residents (**limiting similarity**)

forward function of package *ecolottery*

Limiting similarity

Simulation of community dynamics

- With limiting similarity, without environmental filtering



Transient coexistence of many species

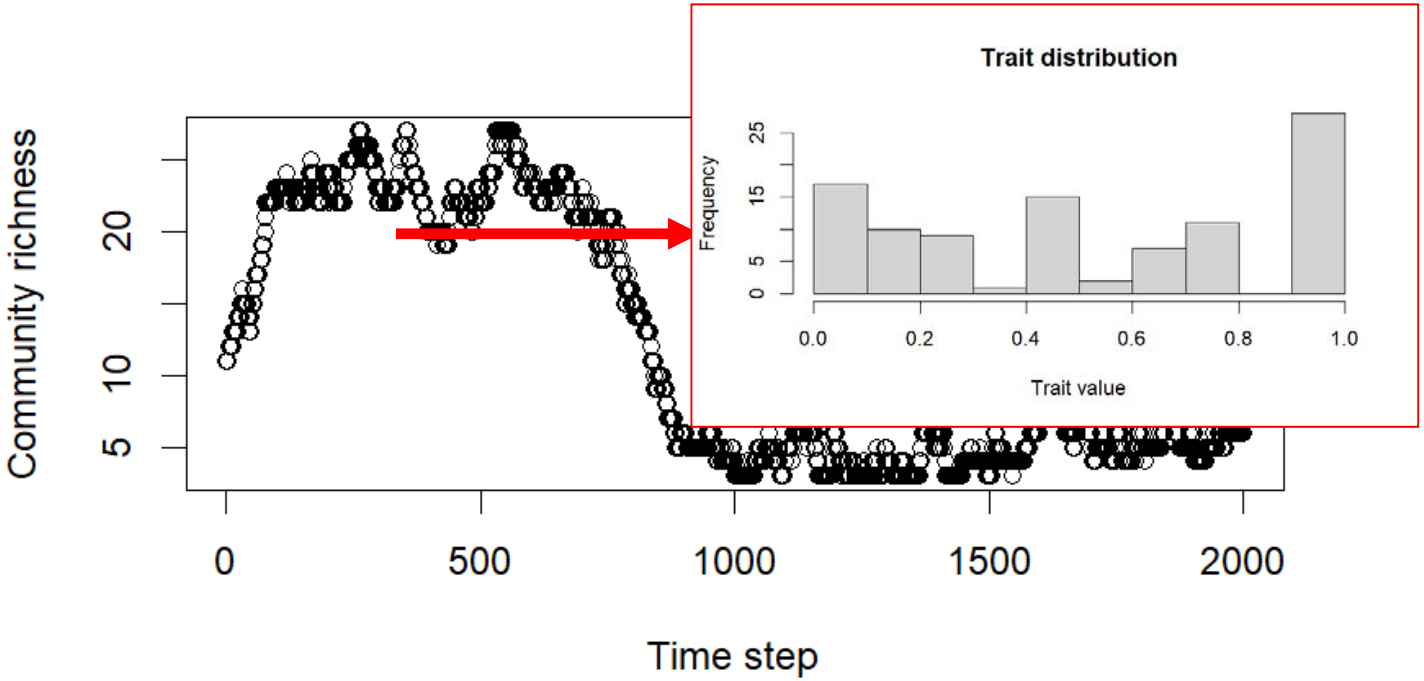
m = 0,1

Community

Limiting similarity

Simulation of community dynamics

- With limiting similarity, without environmental filtering



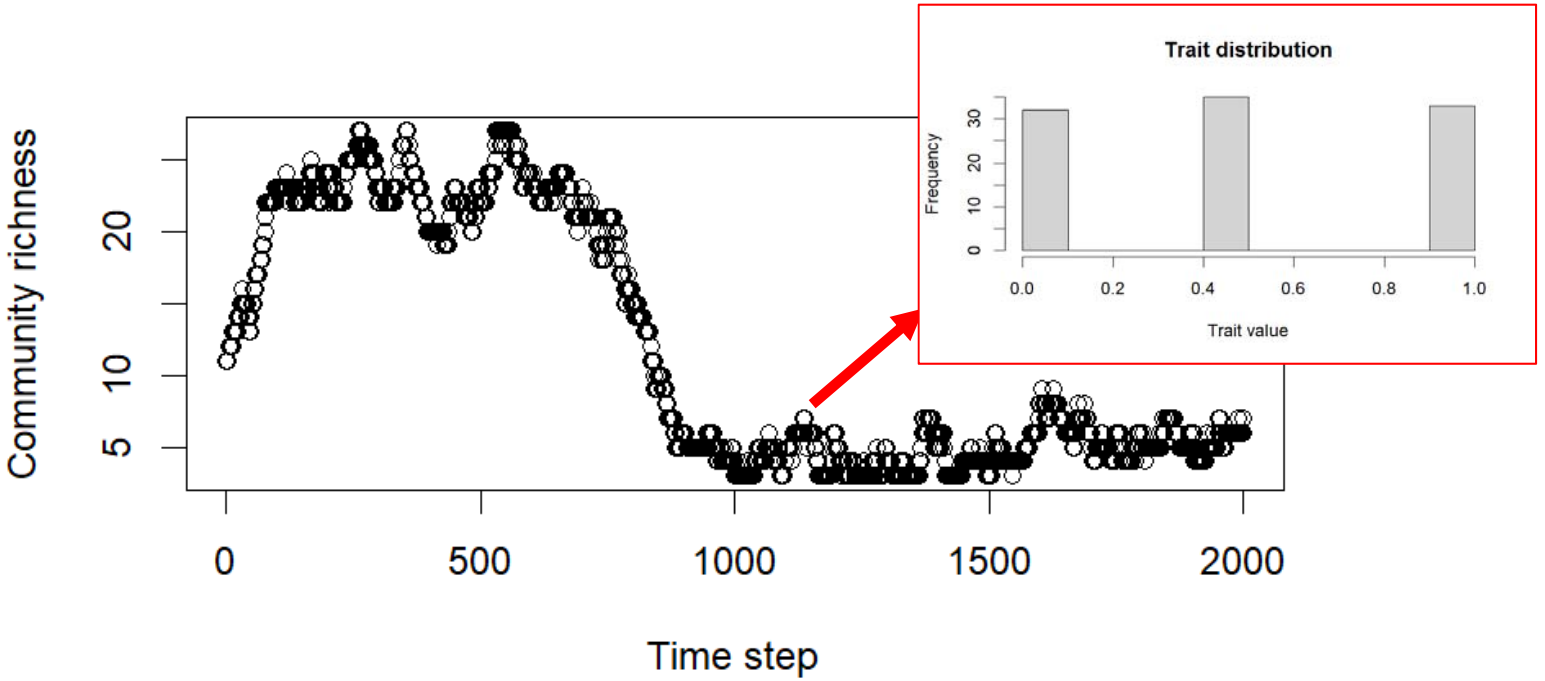
m = 0,1

Community

Limiting similarity

Simulation of community dynamics

- With limiting similarity, without environmental filtering



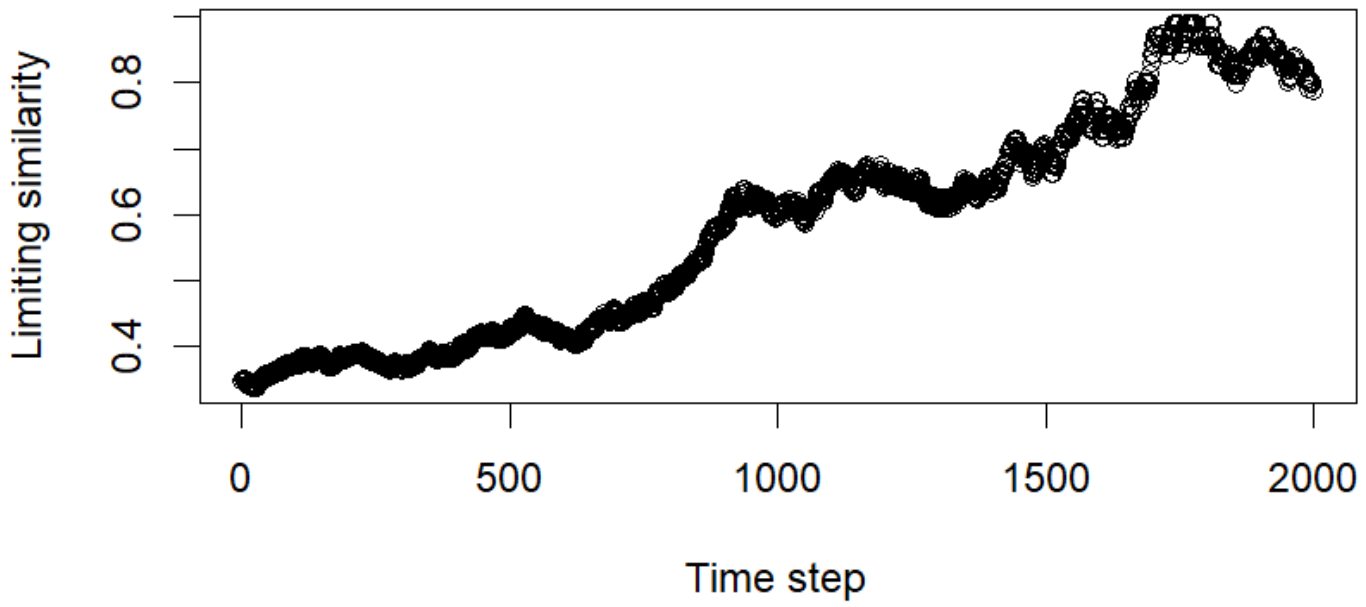
m = 0,1

Community

Limiting similarity

Simulation of community dynamics

- With limiting similarity, without environmental filtering



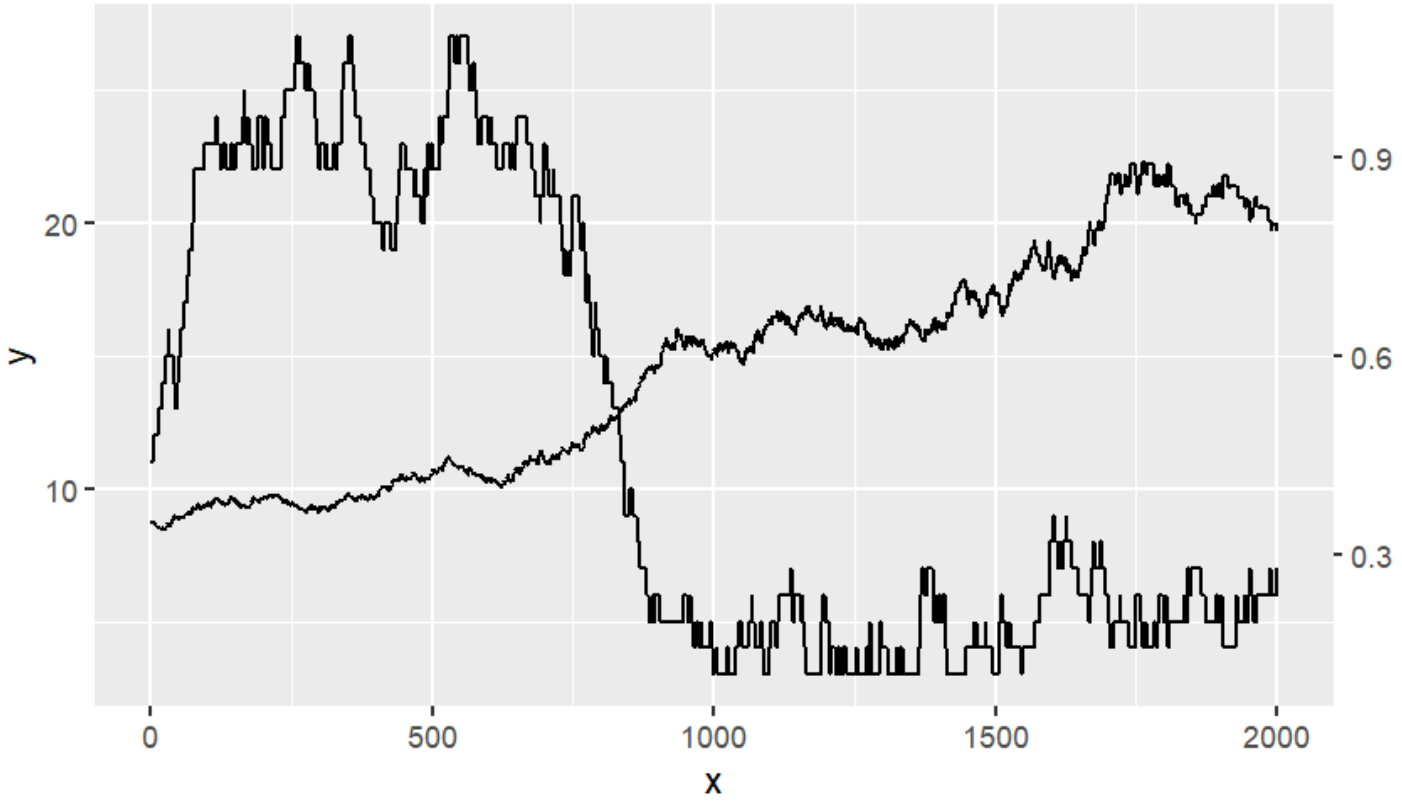
m = 0,1

Community

Limiting similarity

Simulation of community dynamics

- With limiting similarity, without environmental filtering



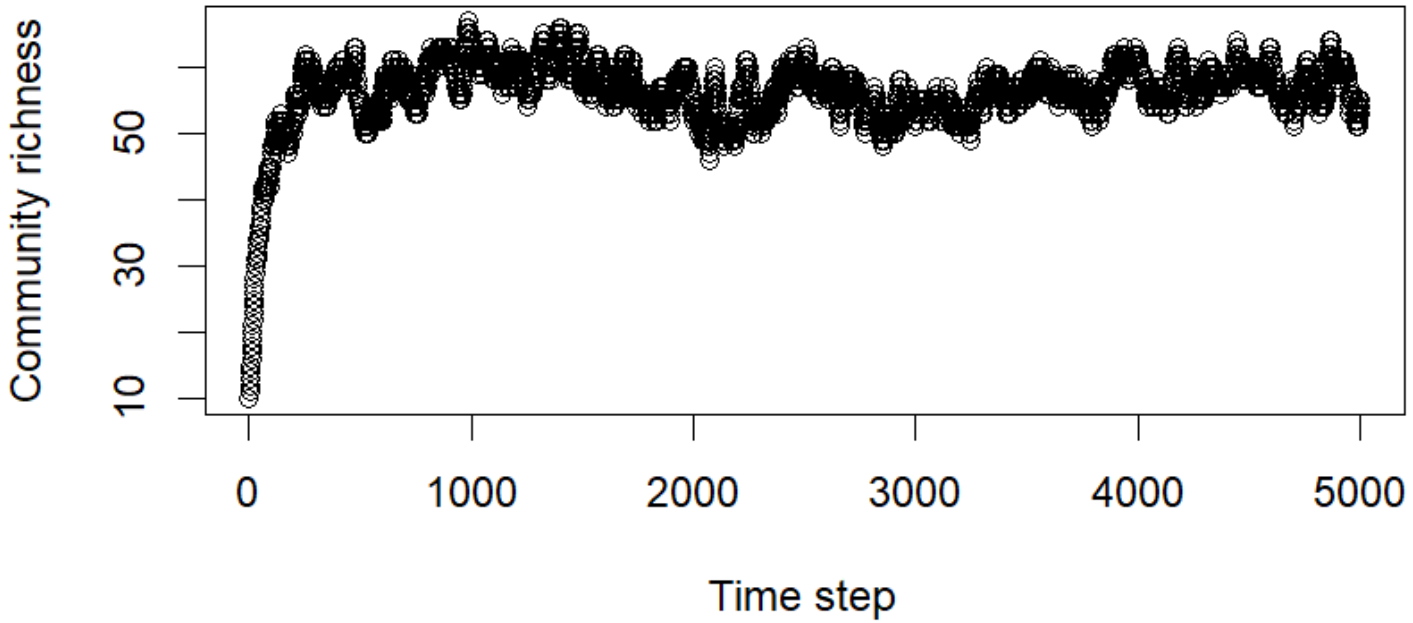
m = 0,1

Community

Limiting similarity

Simulation of community dynamics

- With limiting similarity, without environmental filtering
- **High migration rate**



Source-sink dynamics

m = 0,7

Community

Limiting similarity

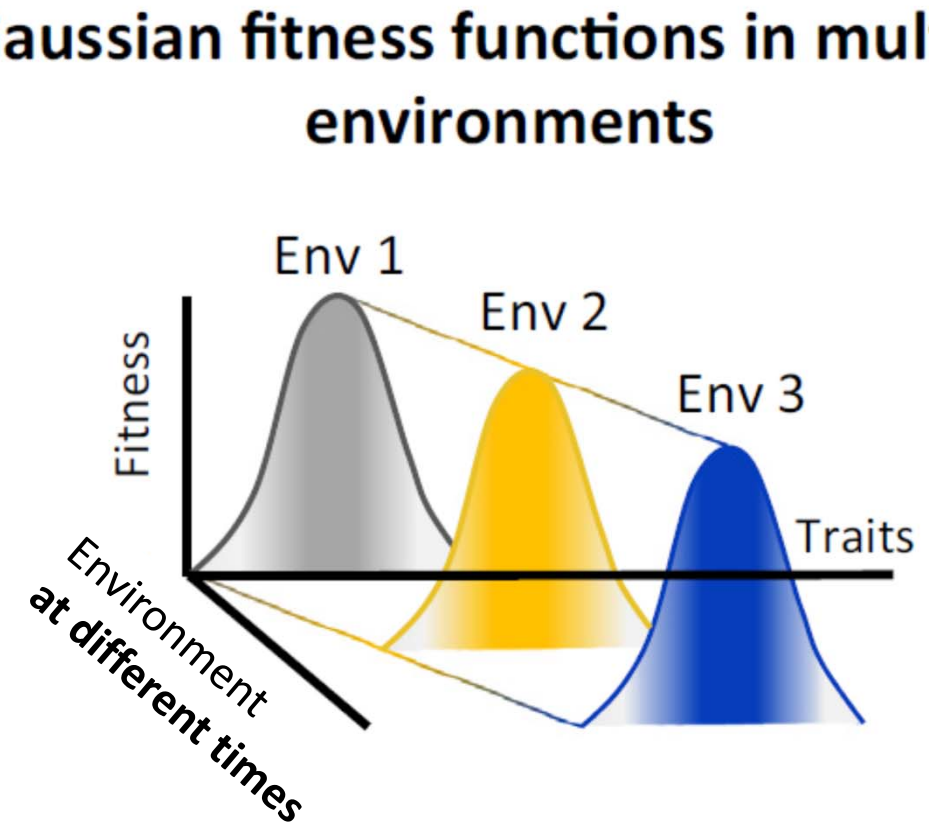
Ecological insights

- Species-rich communities can persist long time although competition plays
- Transient dynamics and collapse of local richness in the case of biological invasion

Community

Fluctuating environmental filtering

Temporal fluctuation of environment



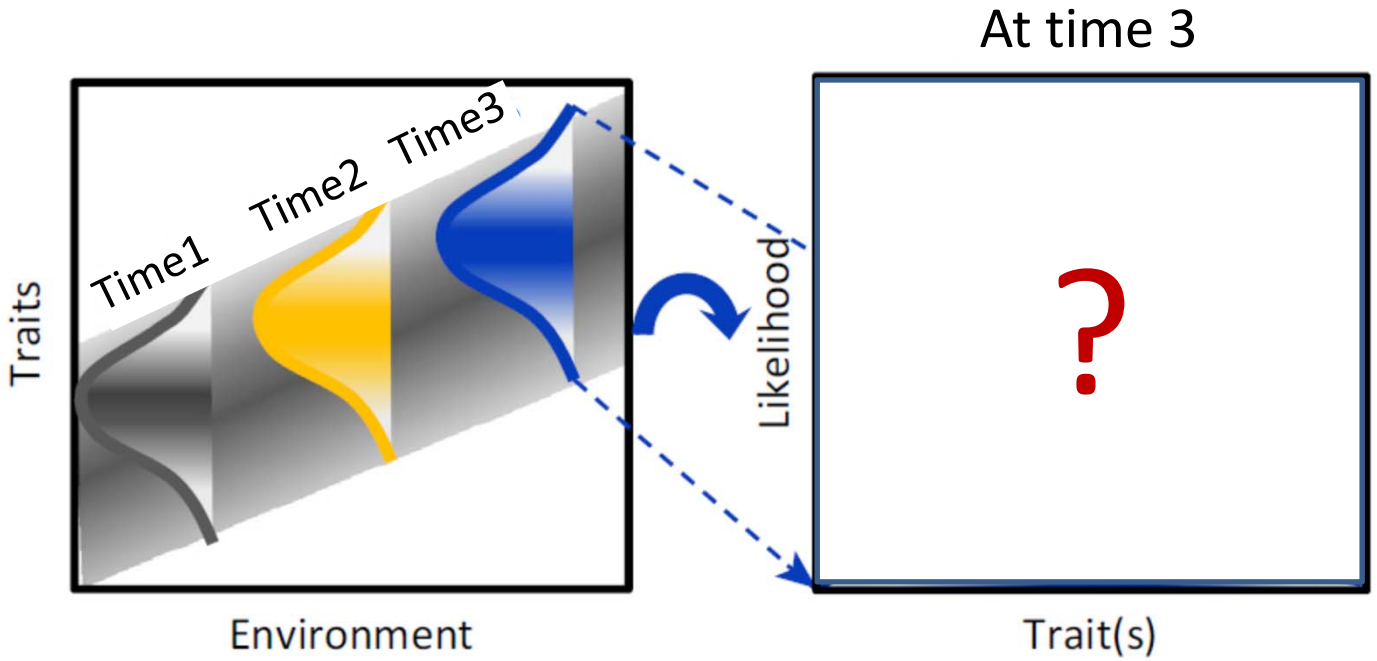
(Laughlin and Messier 2015)

Community

Fluctuating environmental filtering

Temporal fluctuation of environment

- How will the trait distribution be affected by the temporal variation of environmental filtering?

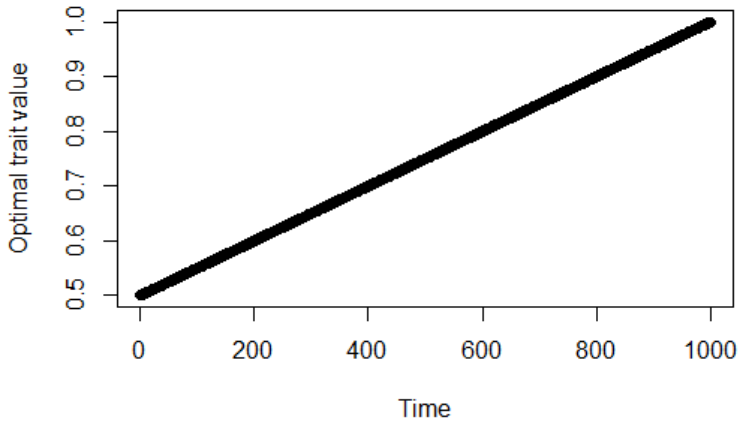


(modified from Laughlin and Messier 2015)

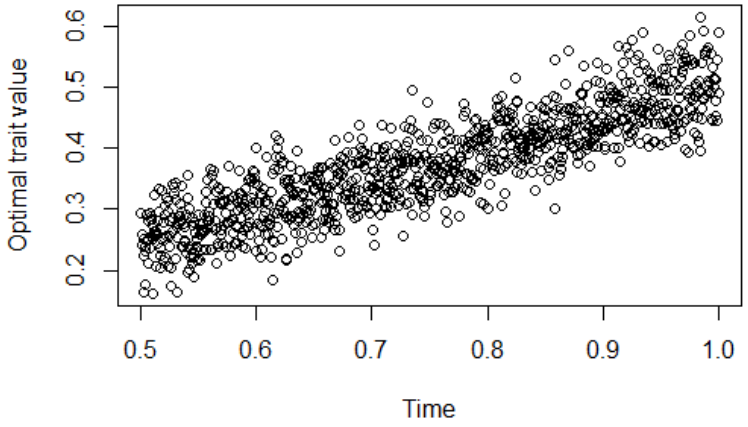
Community

Fluctuating environmental filtering

- **Expectation**: equilibrium distribution of trait values depends on the direction and on the amplitude of stochastic variation around the direction



Strictly directional

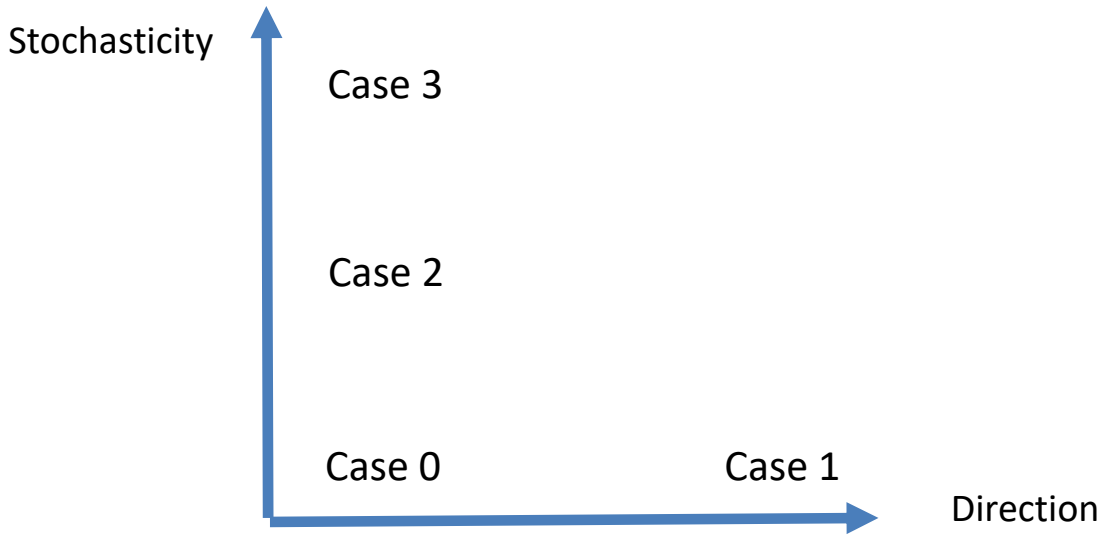


Directional with stochasticity

Community

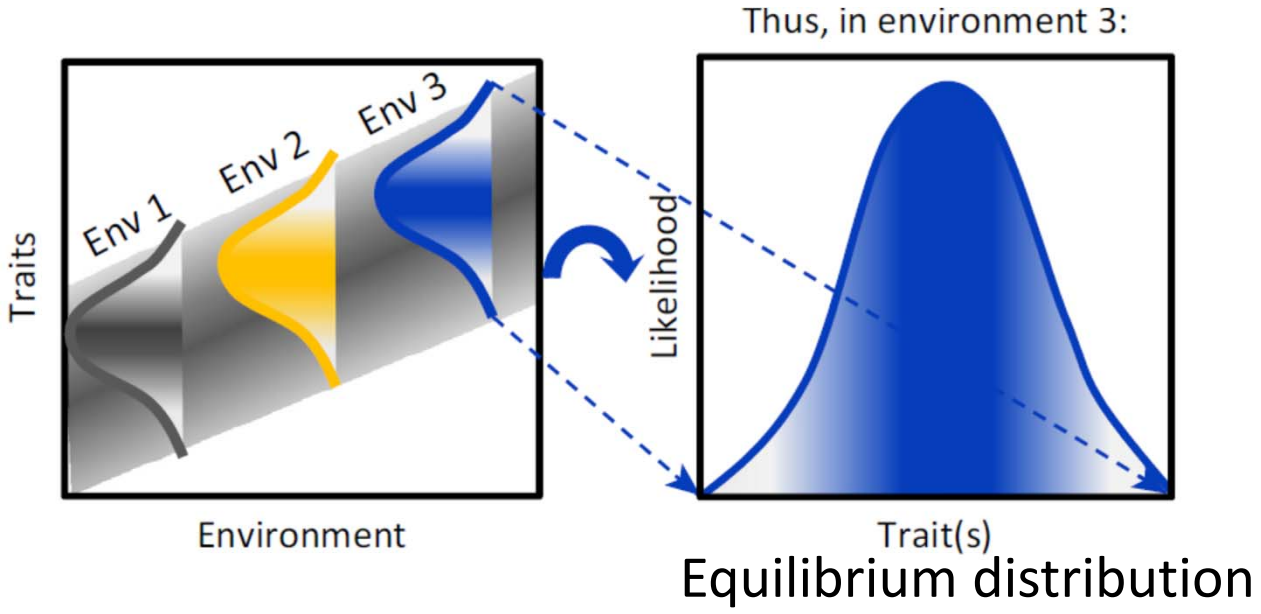
Fluctuating environmental filtering

- **Objective** : to characterize basic kinds of trait distributions for varying values of directionnality and stochastic variation



Fluctuating environmental filtering

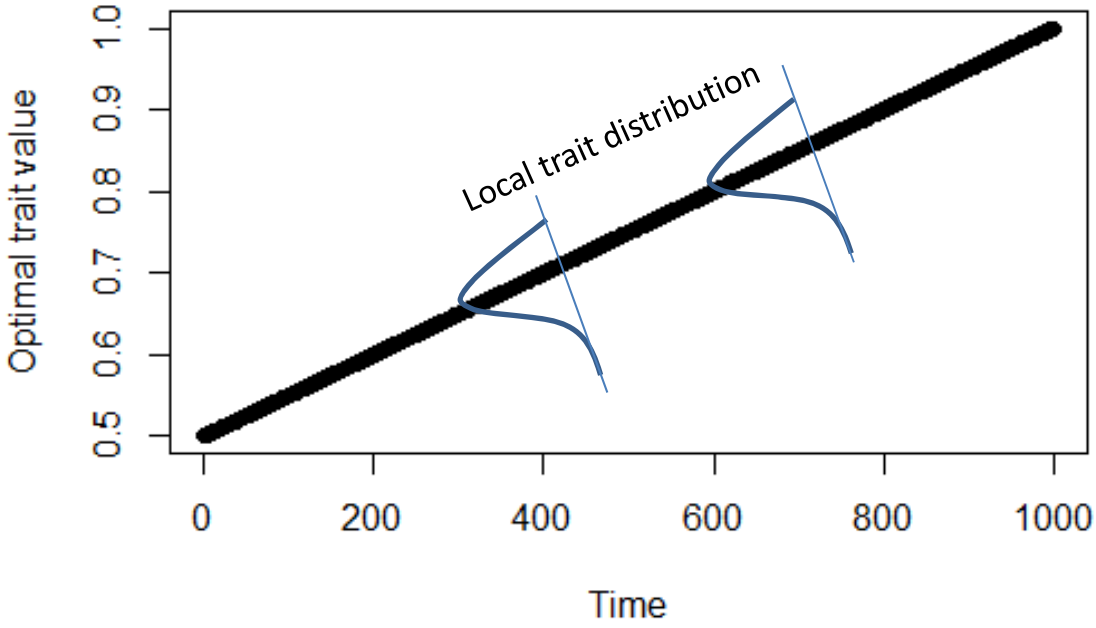
- **Case 0 - Stable environment**: We expect that functional trait convergence in a community mirrors the influence of environmental filtering

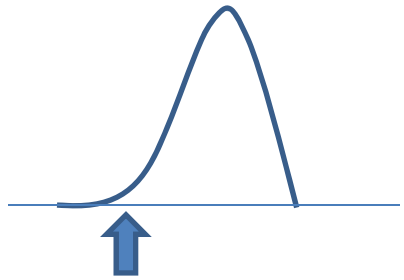


Community

Fluctuating environmental filtering

- **Case 1-directional environmental change**: depending on the speed of environmental change, maladapted phenotypes can persist over time





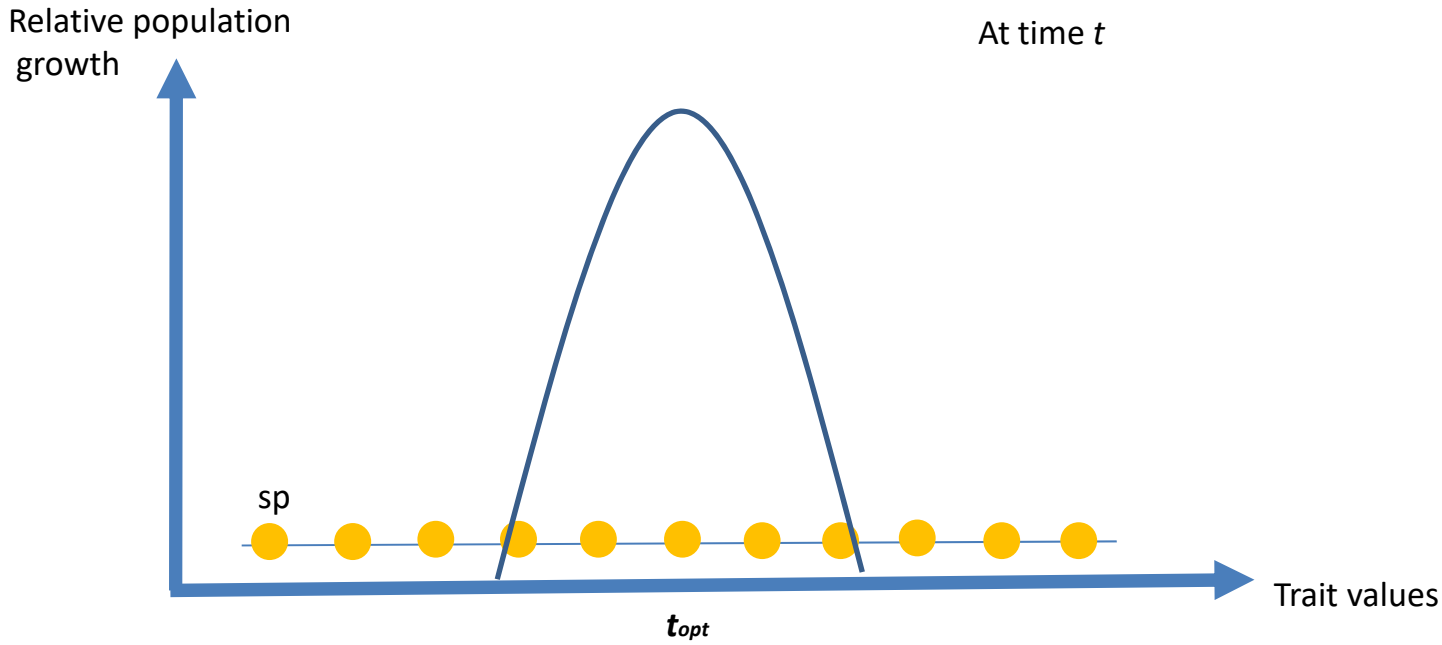
Distinctive species
Skewed distribution

(Enquist et al. 2015)

Community

Fluctuating environmental filtering

- **Case 2 - moderate environmental fluctuation** : Temporal variation in the success of phenotypes around some focal value



Community

Fluctuating environmental filtering

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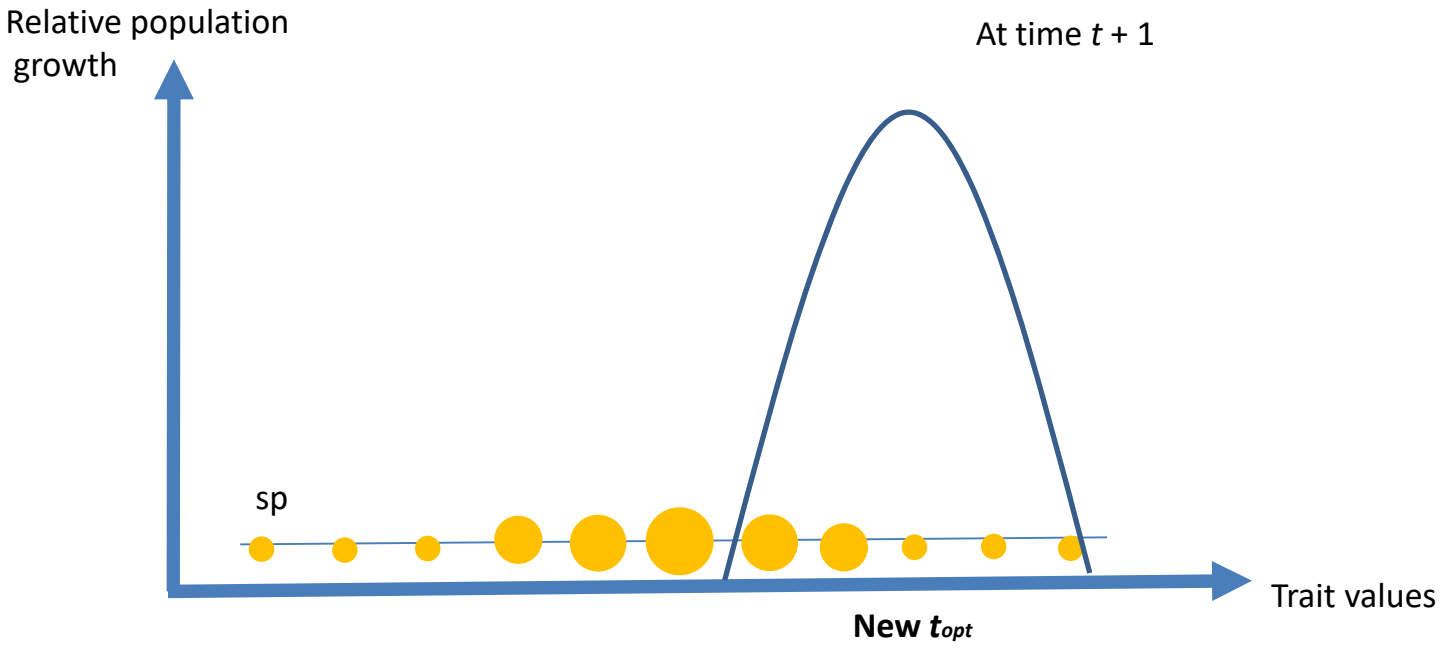
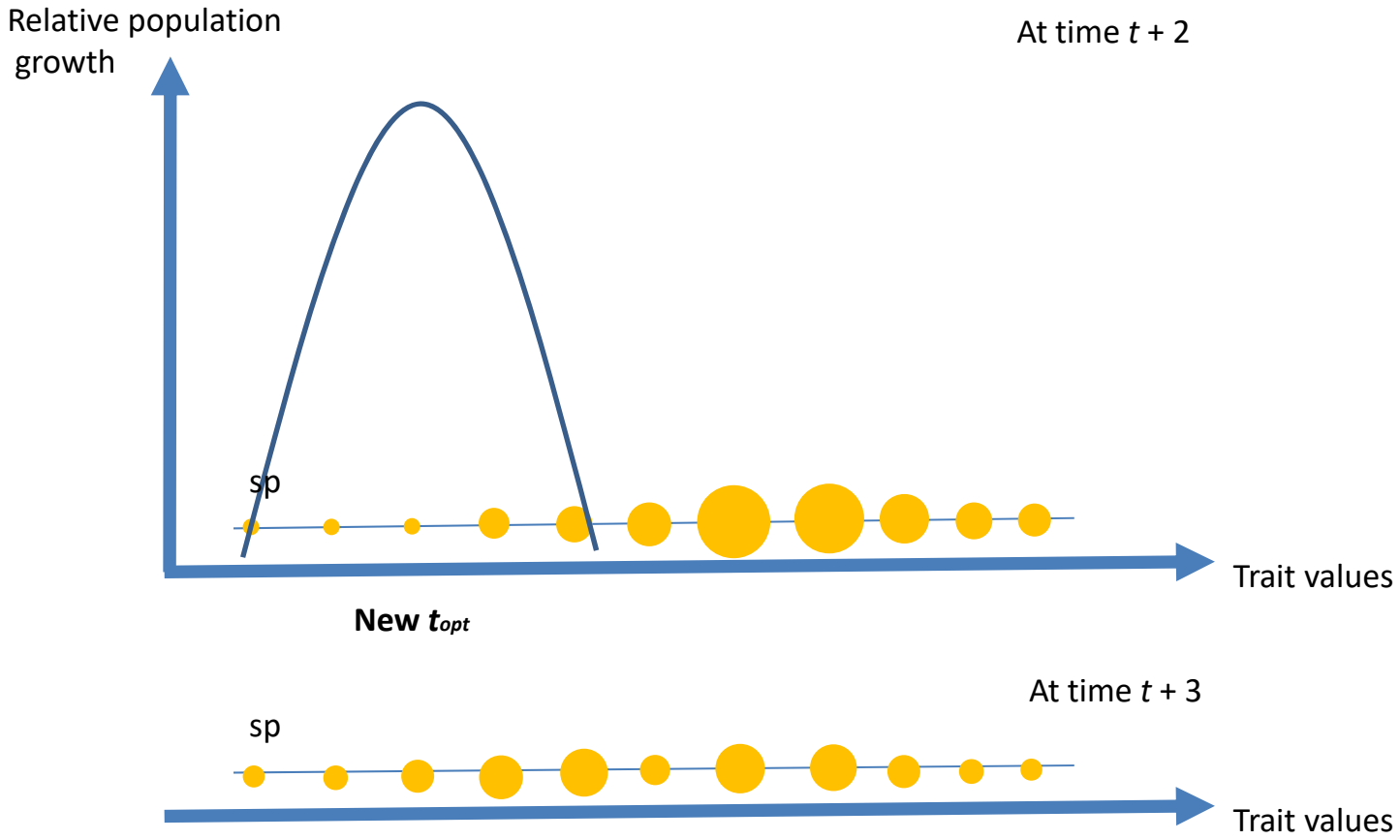


Community

Fluctuating environmental filtering

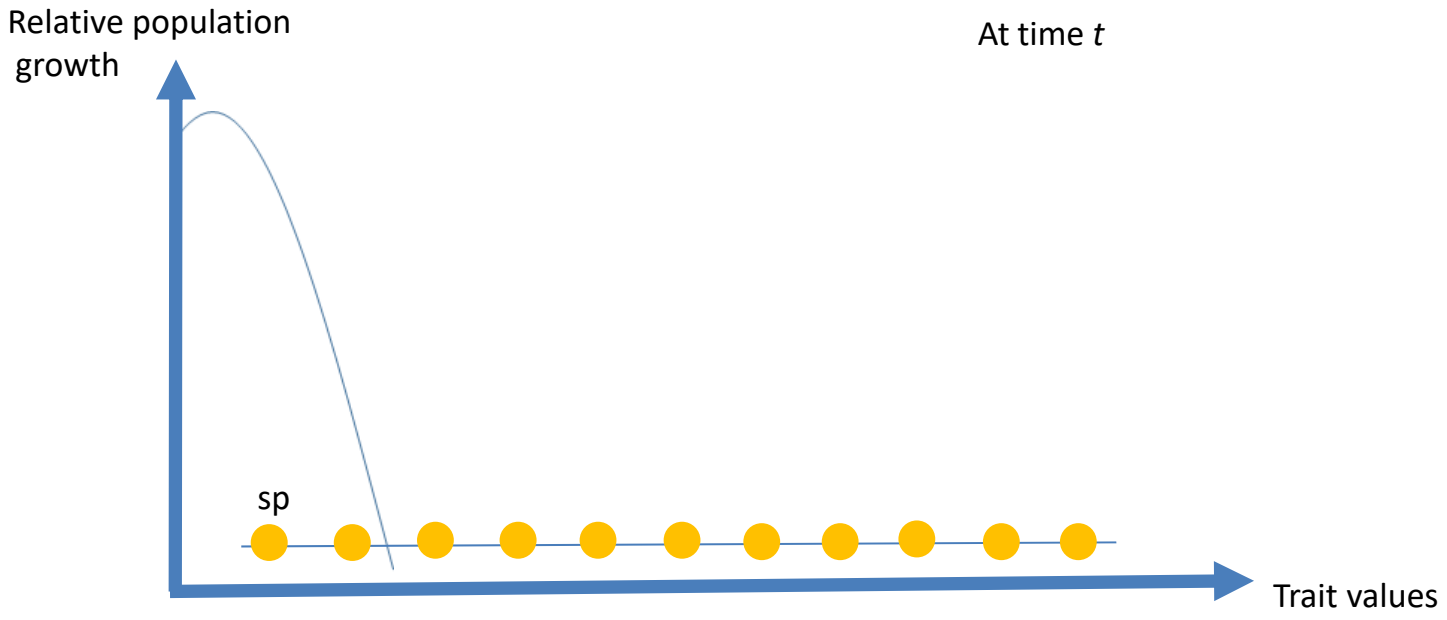
- **Case 2 - moderate environmental fluctuation**



Community

Fluctuating environmental filtering

- **Case 3 - large environmental fluctuation:** Extreme environmental conditions select traits at the extreme of phenotypic space



Community

Fluctuating environmental filtering

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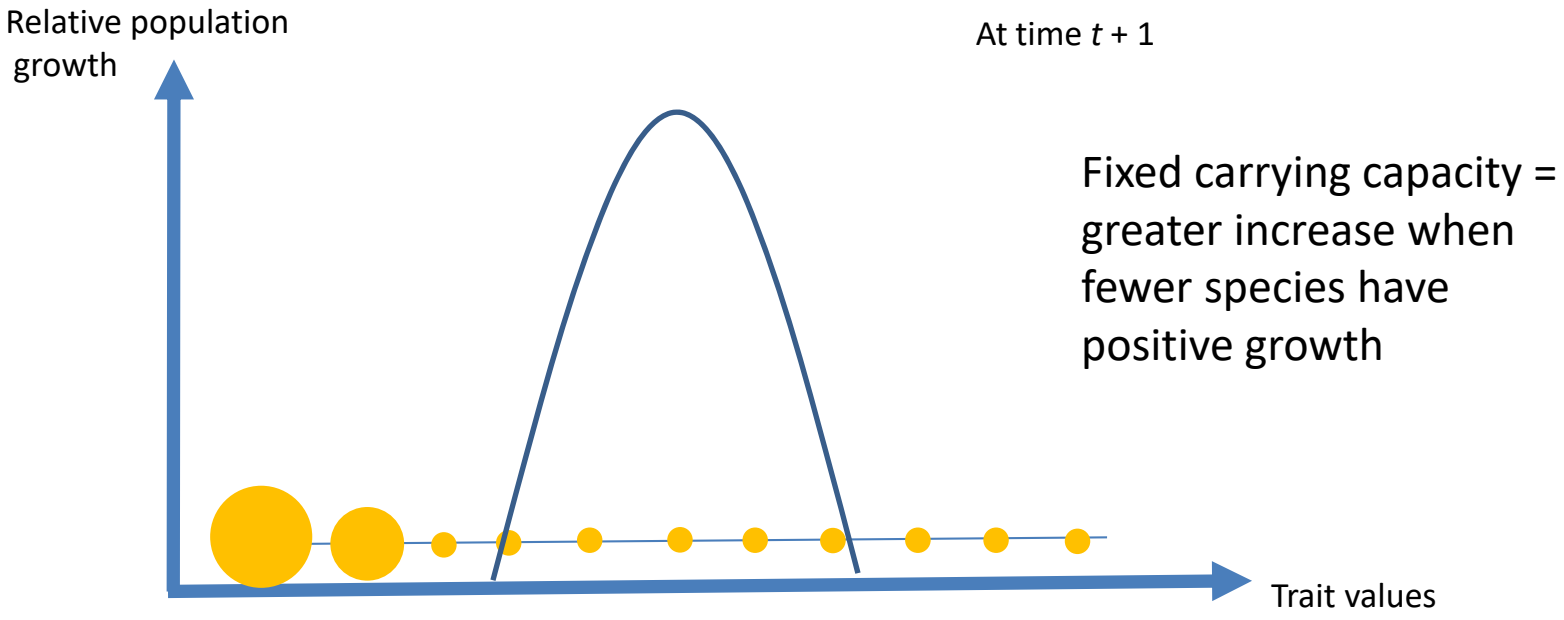

Community

Fluctuating environmental filtering

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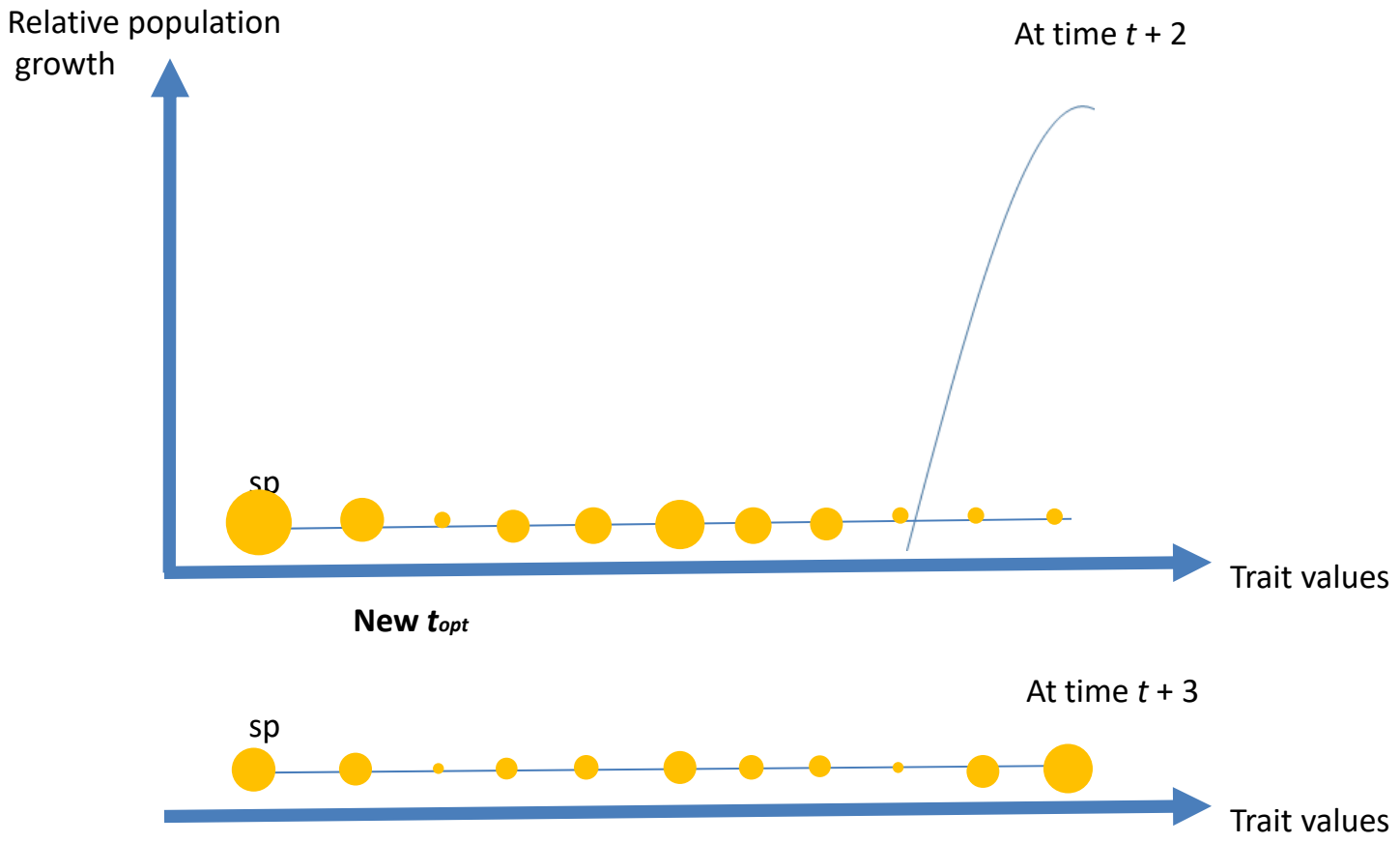

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Fluctuating environmental filtering

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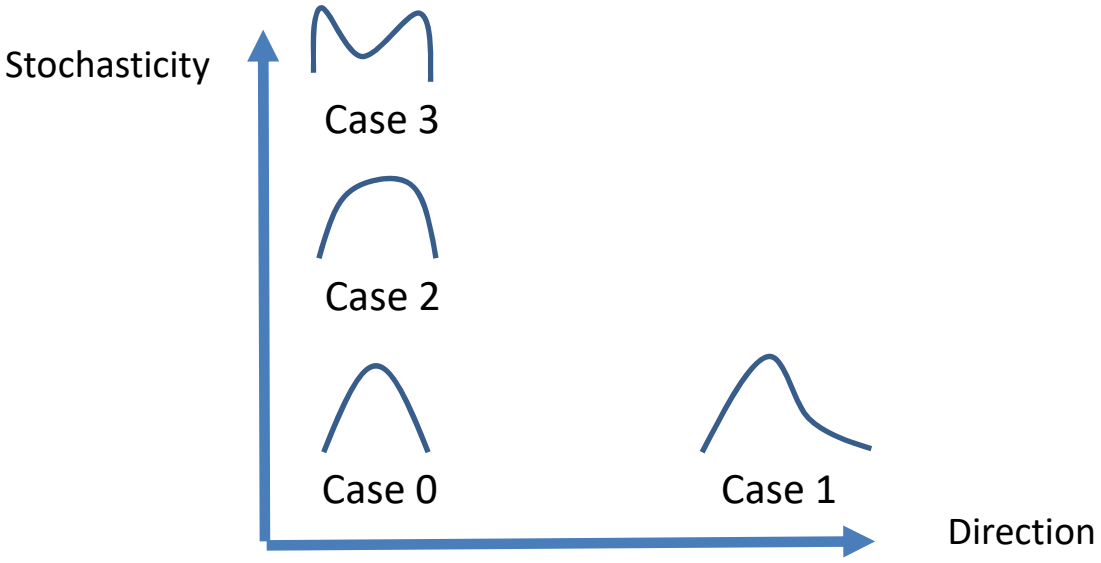
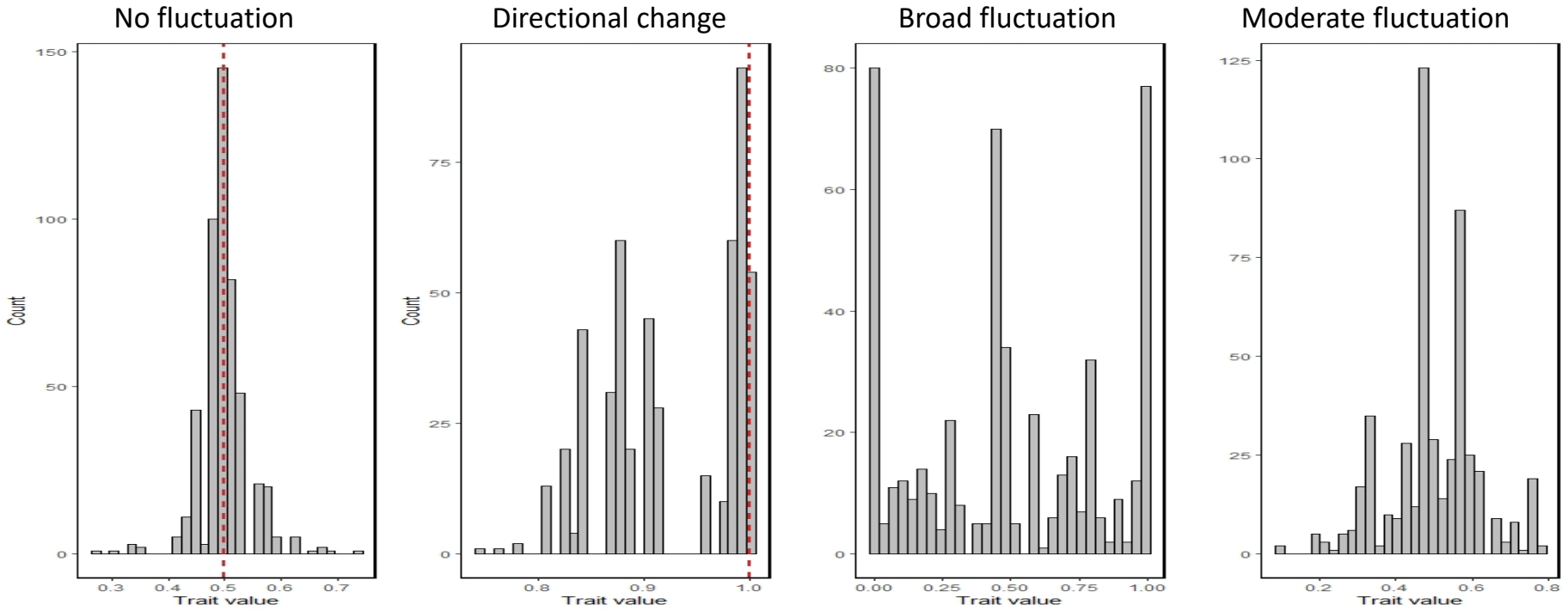


Different expectations in terms of distinctiveness,
But also other moments: variance, skewness, kurtosis

Community

Fluctuating environmental filtering

- **Simulation outcomes**: distinctiveness is highest with broad fluctuation, lowest with steady filtering



Community

Fluctuating environmental filtering

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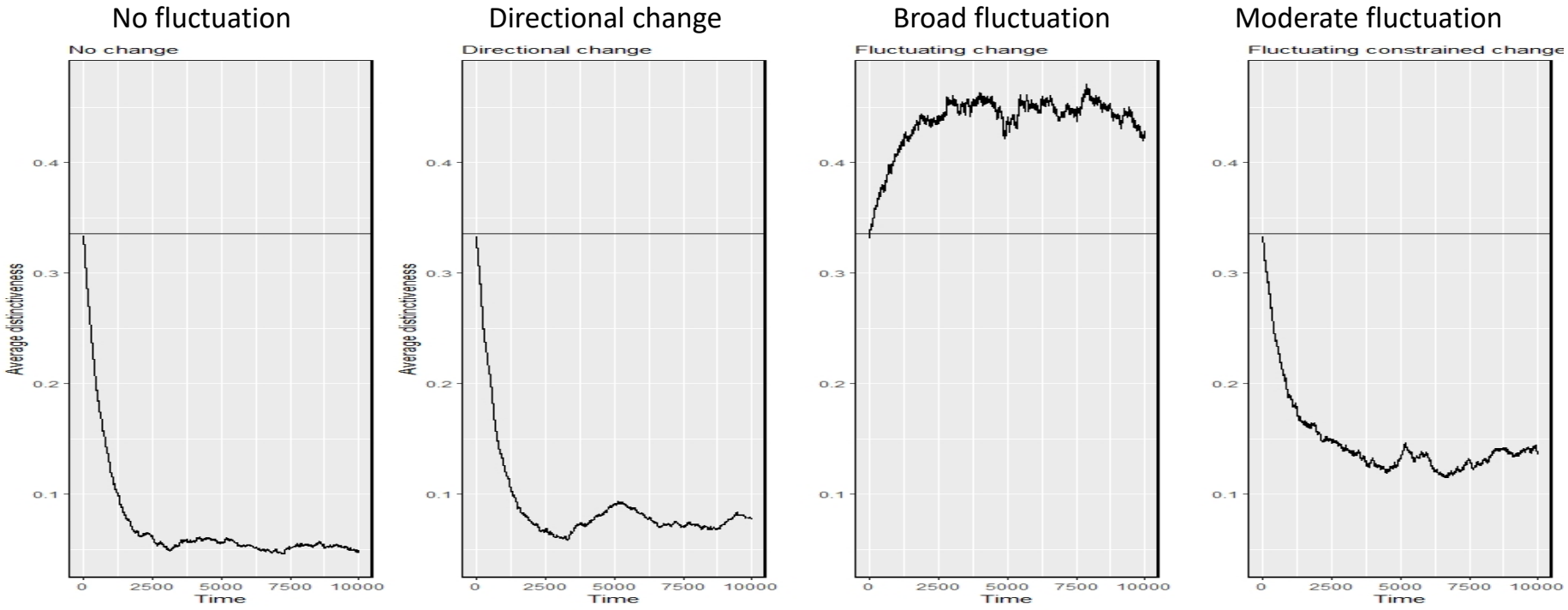


Community

Fluctuating environmental filtering

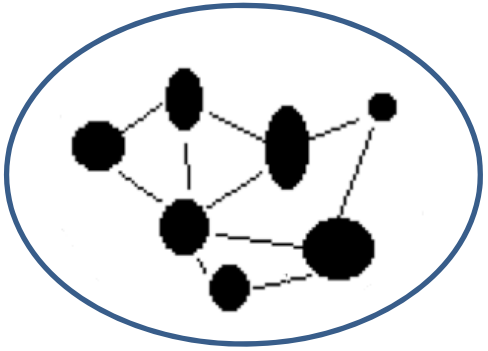
Ecological insights

- Mechanism of balancing selection considered in ecological context

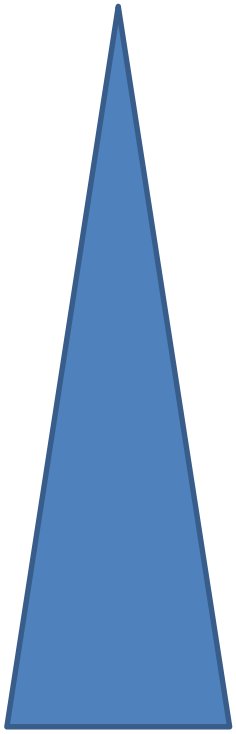
- Maintenance of functional diversity and distinctiveness under variable environmental conditions

Understanding and predicting biodiversity dynamics in spatially and temporally changing environments

Community dynamics



Metapopulation and metacommunity dynamics

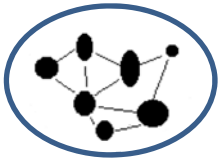


Fine

Spatial and temporal scale

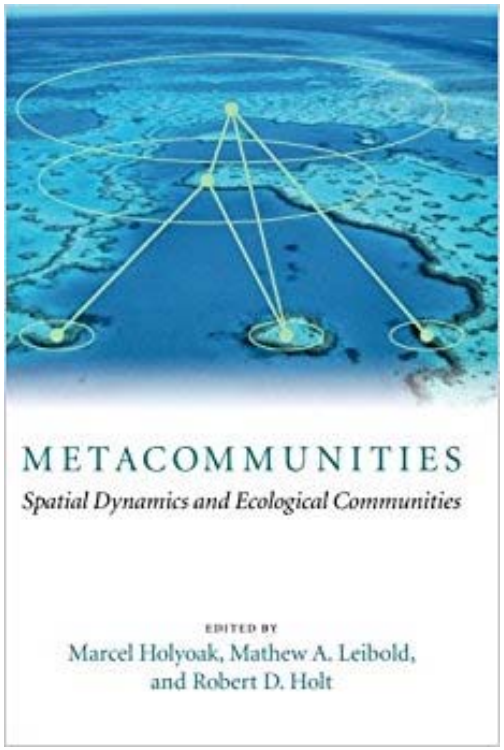
Broad

Metapopulation



Spatial ecological networks

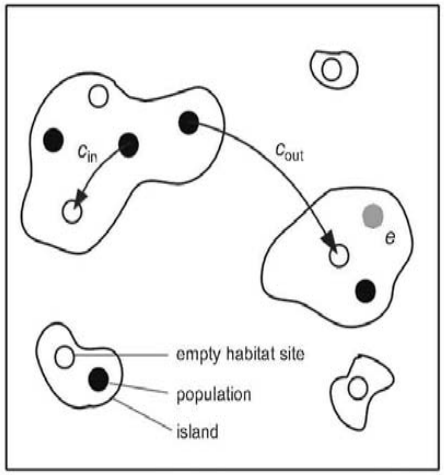
Influence of environmental spatial heterogeneity



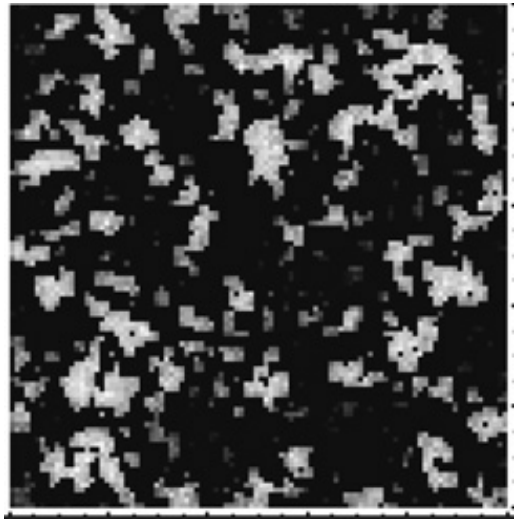
Colonisation-extinction dynamics

→ Modeling population persistence, density and spatial arrangement

→ Predicting local to regional biodiversity patterns



(Huth et al., AmNat 2015)



Densité de populations dans habitat fragmenté (Munoz et al. 2007)

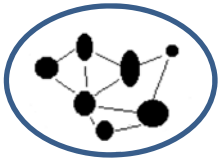
Impact of fragmentation

Variation in patch geometry

fragmentation

↘ Patch area

↗ Patch number
Rapport périmètre/surface des îles
Distance entre îles



Impact of fragmentation

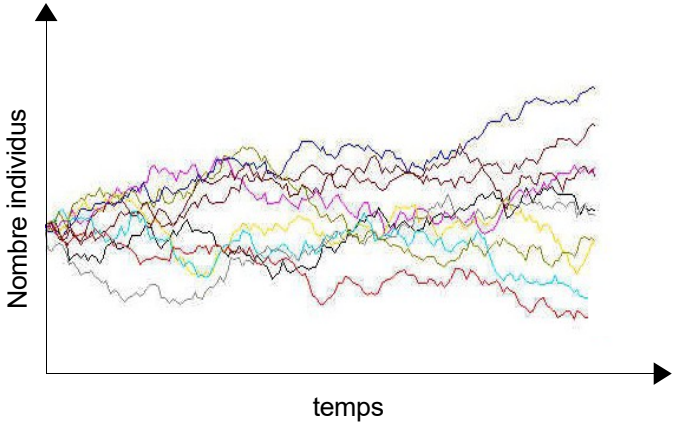
At patch level

Tailles des îles

Variations stochastiques de la taille des populations

↓

Extinction stochastique

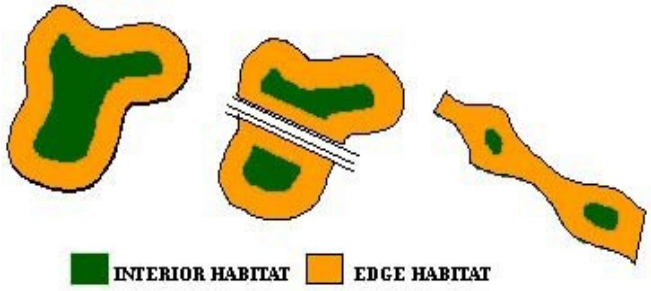


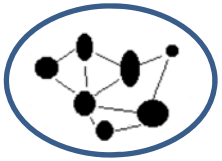
Quantité de lisières

Lisière : Changements biotiques et abiotiques

↓

Effets négatifs ou positifs





Impact of fragmentation

At the level of spatial habitat network

→ Comment la matrice entre îles facilite ou empêche les mouvements entre îles ?

Connectivité structurale
Habitat
=
Indépendante des espèces

Connectivité fonctionnelle
Dispersion
=
Perception des contraintes de l'habitat par les espèces

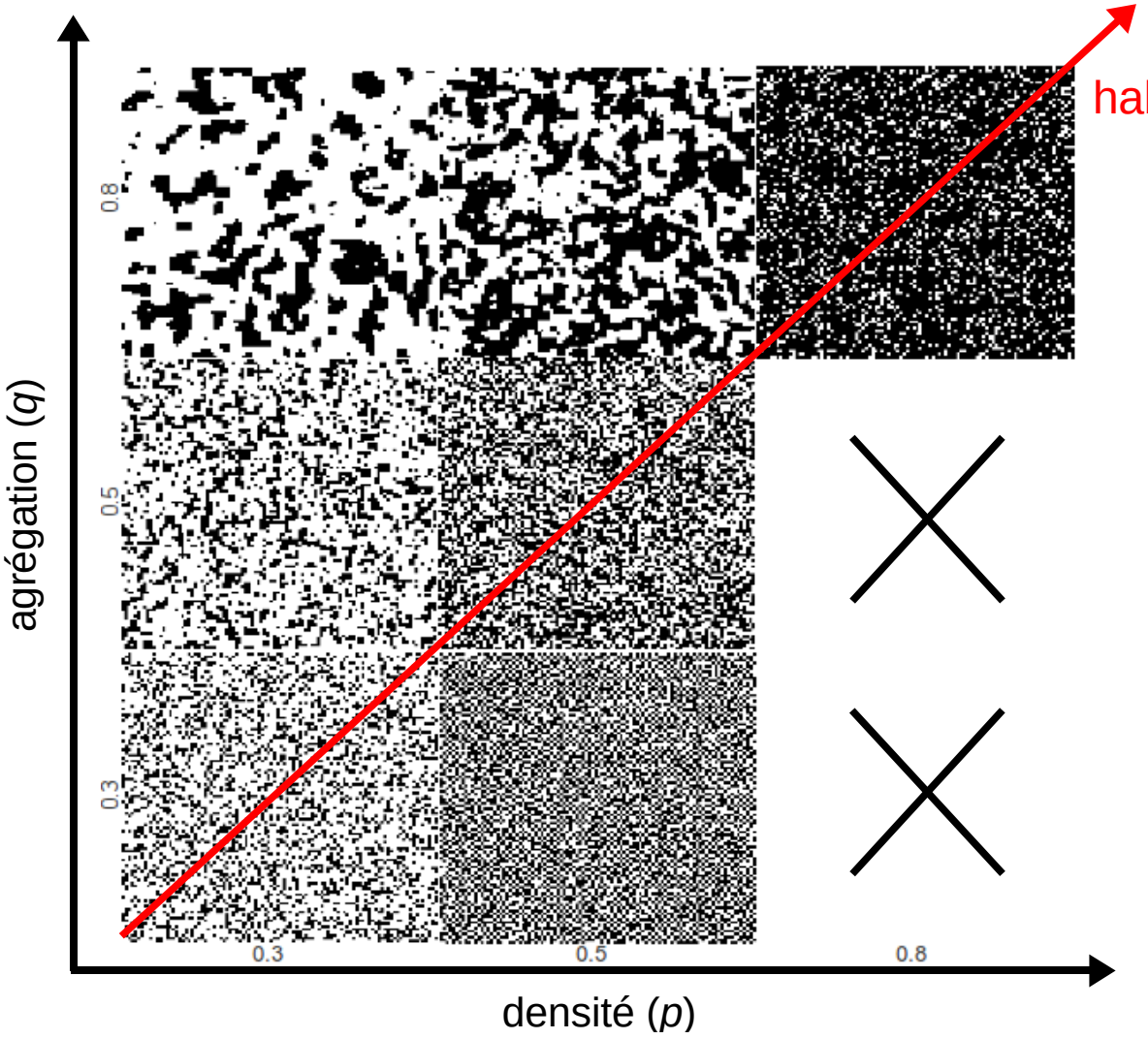
➢ **Dispersion** = mouvements conduisant potentiellement à des flux de gènes

- **Distances de dispersion = limitées dans l'espace**
  → **rôle structure de l'habitat**

- **Dispersion à longue distance = rare + peu prévisible**

Impact of fragmentation

Connectivité structurale et percolation



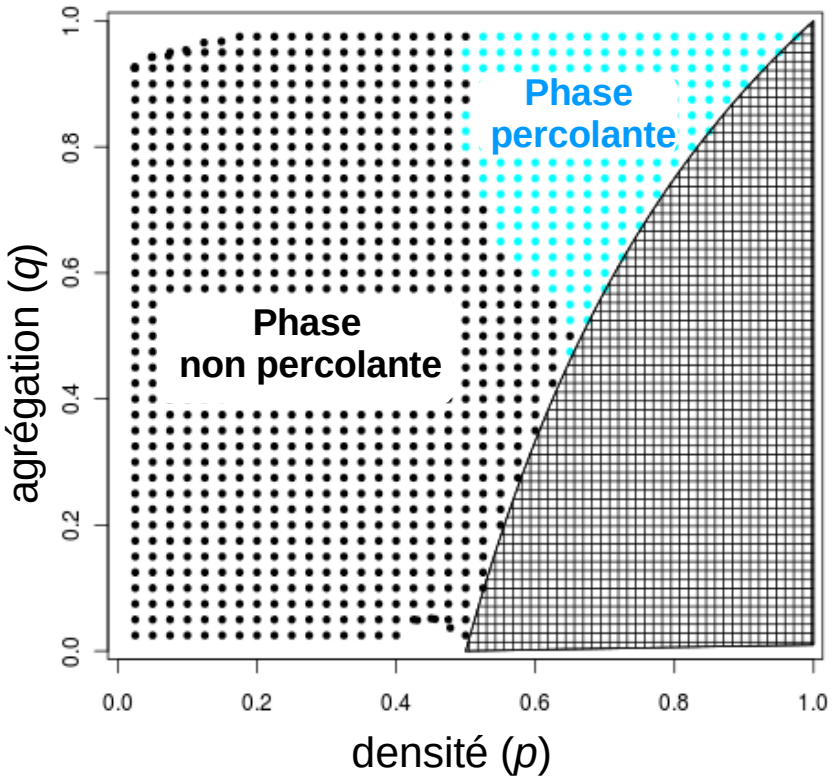
- **2 paramètres** :
- - densité d'habitat = ***p***
- - agrégation locale = ***q***

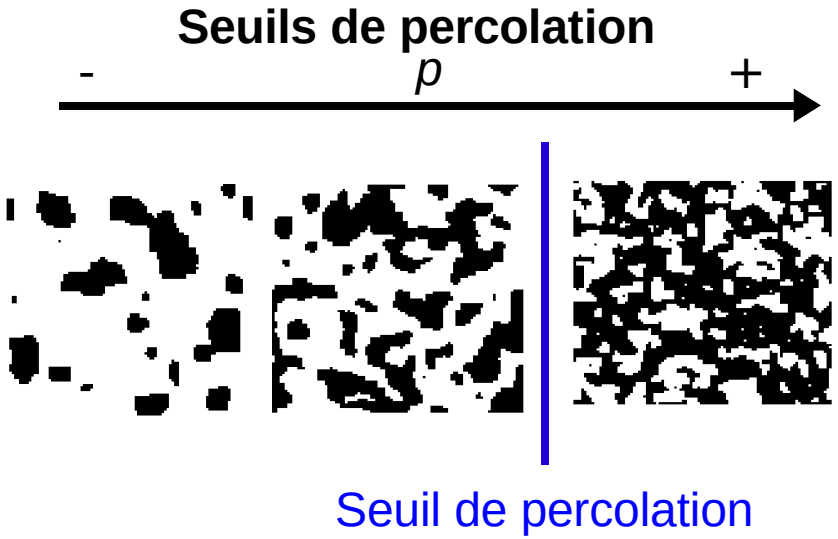
■ habitat favorable

Impact de la fragmentation

Connectivité structurale et percolation

Diagramme de phase





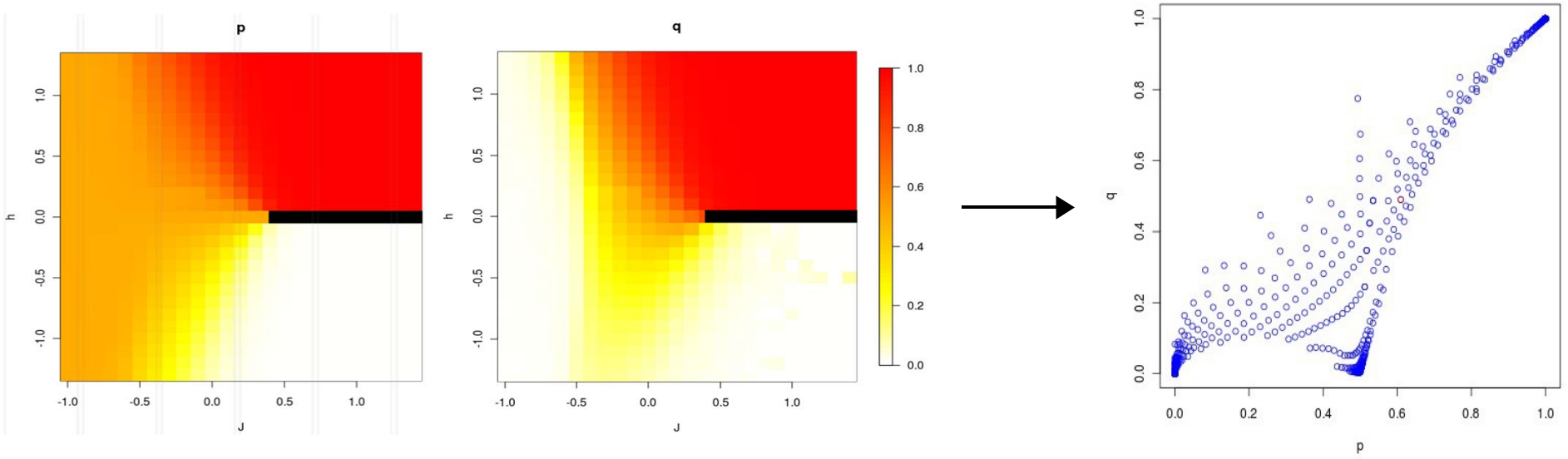
(Huth et al. 2014)

Impact de la fragmentation

Connectivité structurale et percolation

Lien avec modèle d'Ising

→ Interactions locales entre particules → deux paramètres *J* et *h*
→ Correspondance avec les paramètres *p* et *q*



→ Modèle d'Ising = paysages moins riches

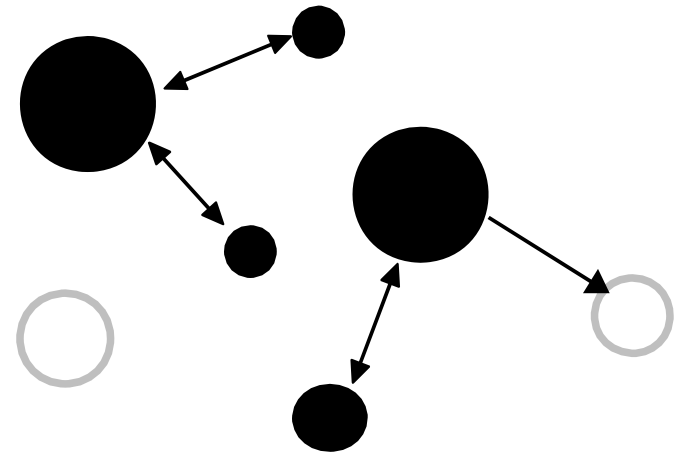
(Huth et al. 2014)

Métapopulation

Réseaux écologiques spatiaux

Dynamique d'un organisme dans un habitat: notion de métapopulation

{ } de populations connectées par des flux de dispersion



Colonisation = Dispersion + Établissement

Extinction = disparition d'une population

Métapopulation

Réseaux écologiques spatiaux

Modèle spatialement implicite: néglige la structure spatiale de l'habitat

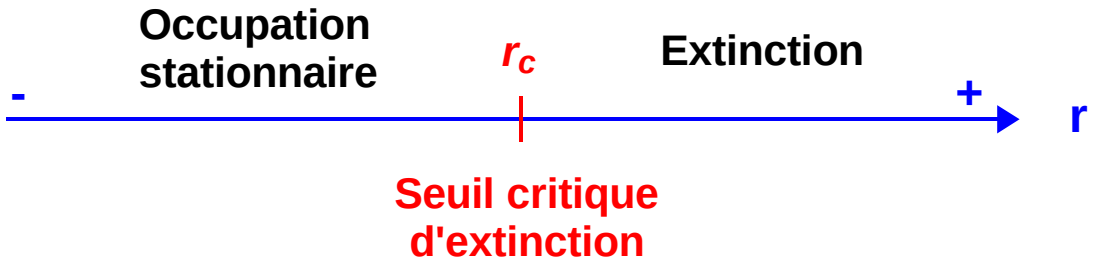
Variation densité sites occupés

$$\frac{d\rho}{dt} = \underbrace{c \cdot \rho \cdot (1 - \rho)}_{\text{colonisation}} - \underbrace{e \cdot \rho}_{\text{extinction}}$$

c = colonisation
e = extinction

$$r = e/c$$

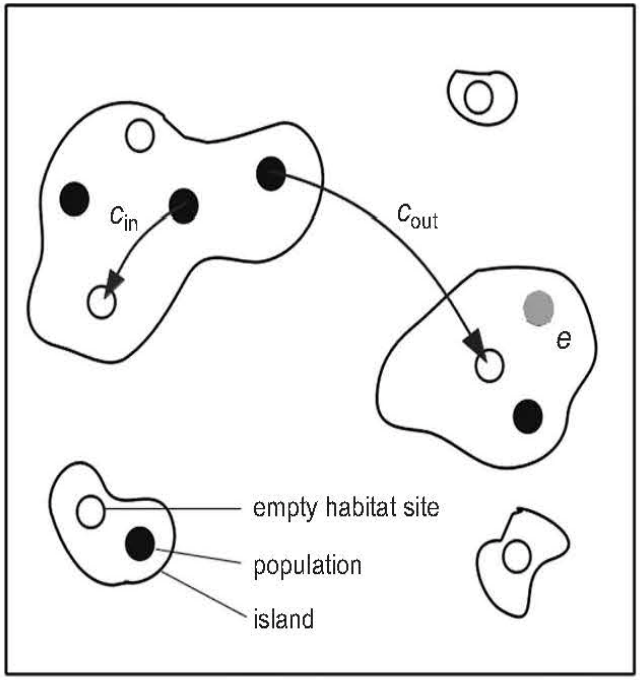
→ **États d'équilibre de l'occupation:**



Métapopulation

Réseaux écologiques spatiaux

Influence de l'hétérogénéité spatiale de l'environnement



At a given time, each habitat site is either occupied by a population or empty. We denote by $p_k^{(n)}$ the probability that k sites are occupied in an island of size n. Hence, the average fraction $f^{(n)}$ of occupied sites in islands of size n is given by

$$f^{(n)} = \sum_{k=1}^{n} \frac{k}{n} p_k^{(n)}, \tag{1}$$

and the average fraction f of occupied sites in the regional metapopulation is given by

$$f = \sum_n \frac{nP(n)}{\sum_m mP(m)} f^{(n)} = \sum_n \frac{nP(n)}{\bar{n}} f^{(n)}. \tag{2}$$

$$k \to k+1 \quad \text{with rate} \quad \lambda_k = c_{in} \frac{k}{n}(n-k) + c_{out} f(n-k),$$

$$k \to k-1 \quad \text{with rate} \quad \mu_k = ek.$$

(Huth et al., AmNat 2015)

Métapopulation

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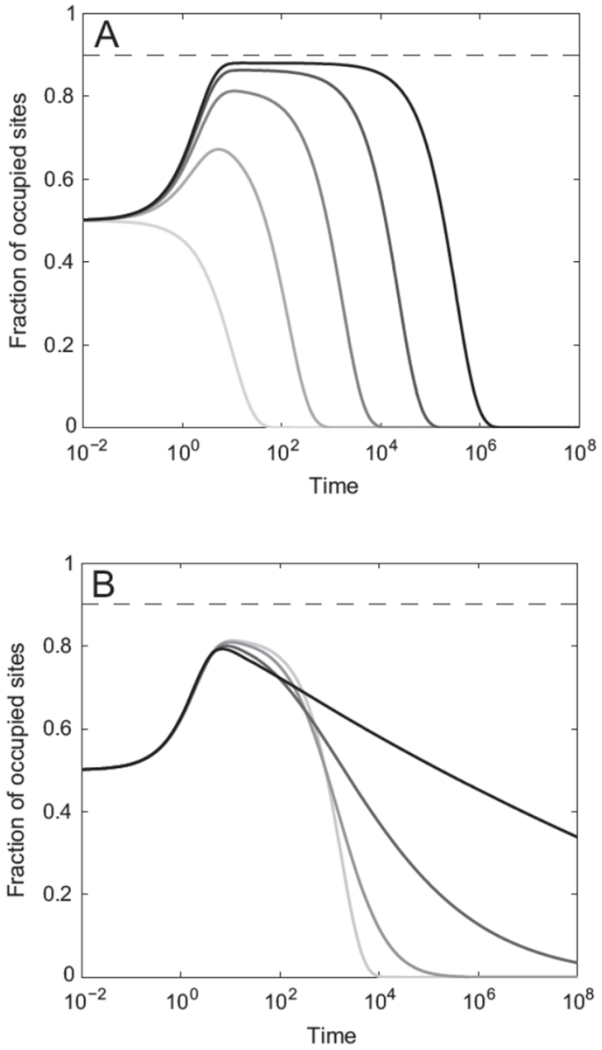
Influence de l'hétérogénéité spatiale de l'environnement

$$\frac{dp_k^{(n)}}{dt} = \lambda_{k-1}p_{k-1}^{(n)} + \mu_{k+1}p_{k+1}^{(n)} - \lambda_k p_k^{(n)} - \mu_k p_k^{(n)}.$$

$$\frac{df^{(n)}}{dt} = \left(c_{\text{in}}\, f^{(n)} + c_{\text{out}}\, f\right)\left(1 - f^{(n)}\right) - e f^{(n)}$$

Figure 2: Dynamics of regional occupancy f without colonization between islands ($c_{\text{out}} = 0$). *A*, Homogeneous island size distributions (ISDs; i.e., all islands have the same size). The darker the curve, the larger the island ($n = 1, 3, 5, 7, 9$). *B*, Heterogeneous ISDs with mean island size $\bar{n} = 5$ and different variances σ^2. The darker the curve, the larger the ISD variance. Explicit ISDs are given in appendix A. For both panels, parameter values are $c_{\text{in}} = 1.0$ and $e = 0.1$. The equilibrium occupancy of the corresponding Levins model is given by $1 - e/c_{\text{in}} = 0.9$ (horizontal dashed line). As initial conditions, habitat sites are filled randomly with probability 0.5.



(Huth et al., AmNat 2015)

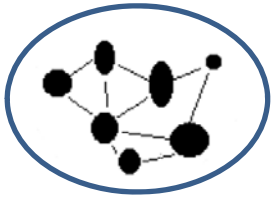
Understanding and predicting biodiversity dynamics in spatially and temporally changing environments

How do biotic interactions determine species diversity?

Transient species-rich communities

How do temporally fluctuating environment shape functional composition?

Maintenance of functional diversity



How does habitat fragmentation affect long-term dynamics of local populations?

Slow extinction dynamics

Models of metapopulation and metacommunity dynamics

Toward incorporating environmental filtering and biotic interactions

François Munoz

02/12/2022

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