Evolution of species ecological niche and geographical range

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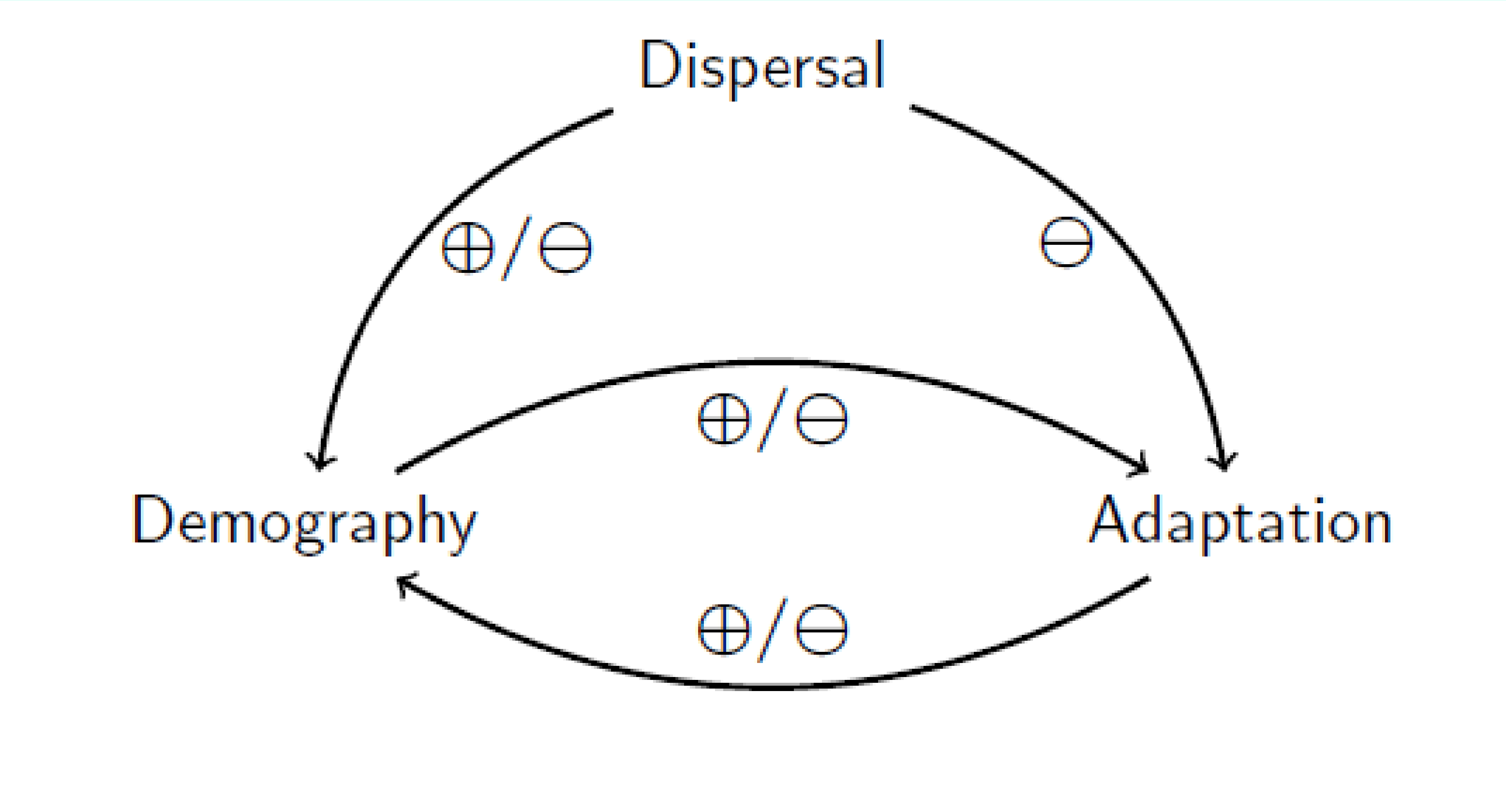


Dispersal
⊕/⊖
⊖
⊕/⊖
Demography
Adaptation
⊕/⊖

Fundamental niche

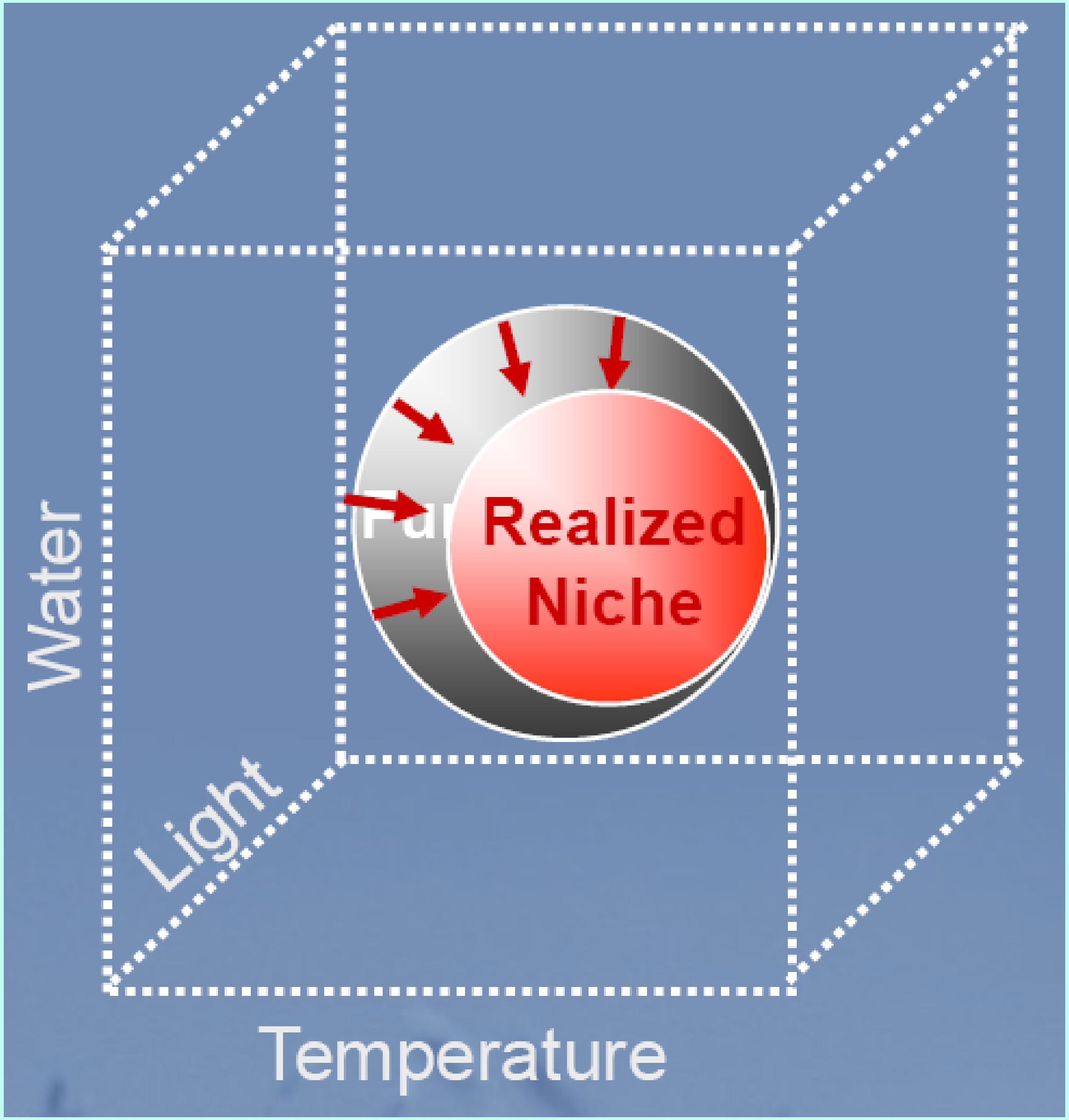
Hutchinson 1957 : the set of environmental conditions where the species can persist

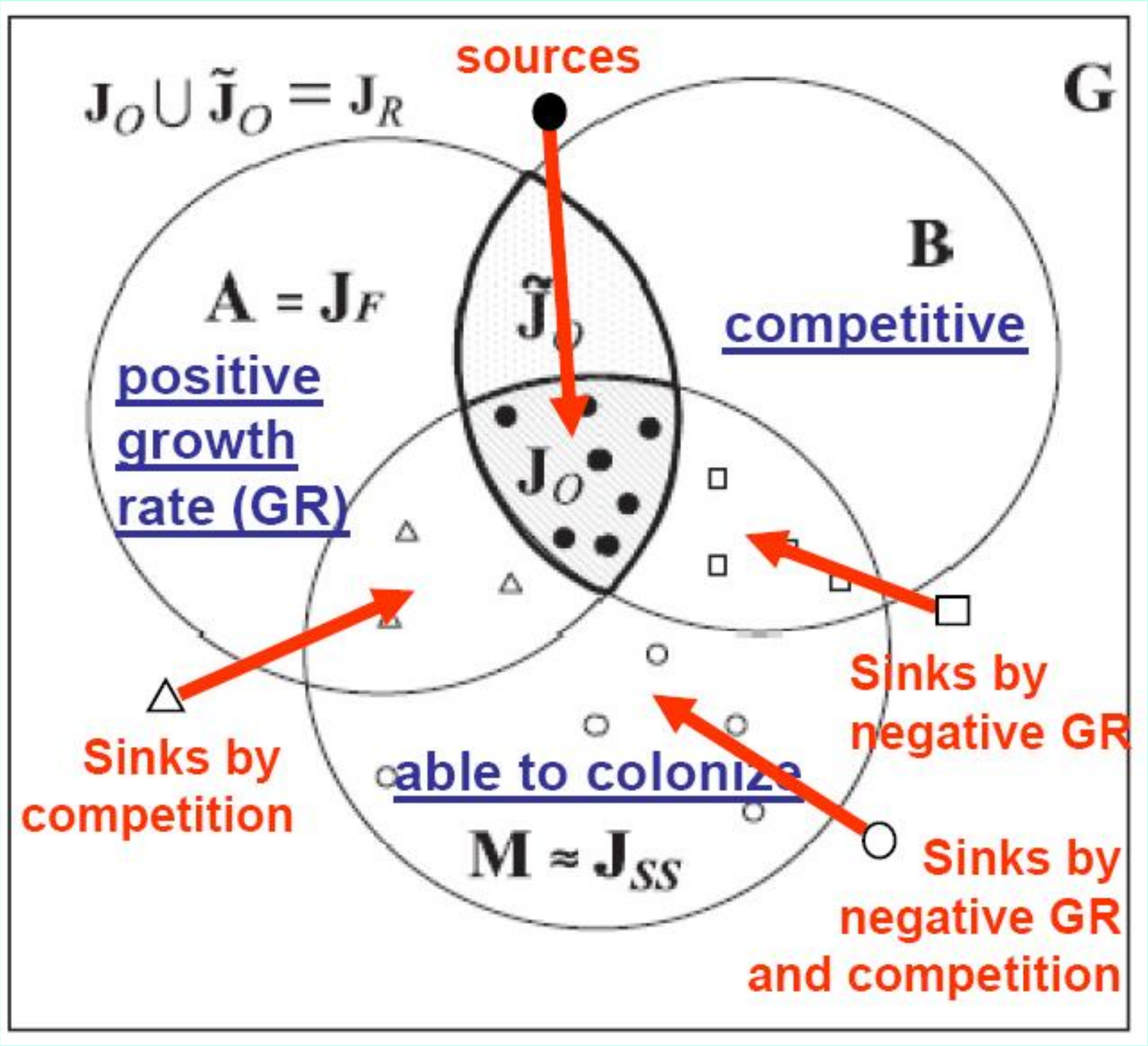
Realized niche:

Hutchinson 1957 : the set of environmental conditions where the species is found.

Geographical range:

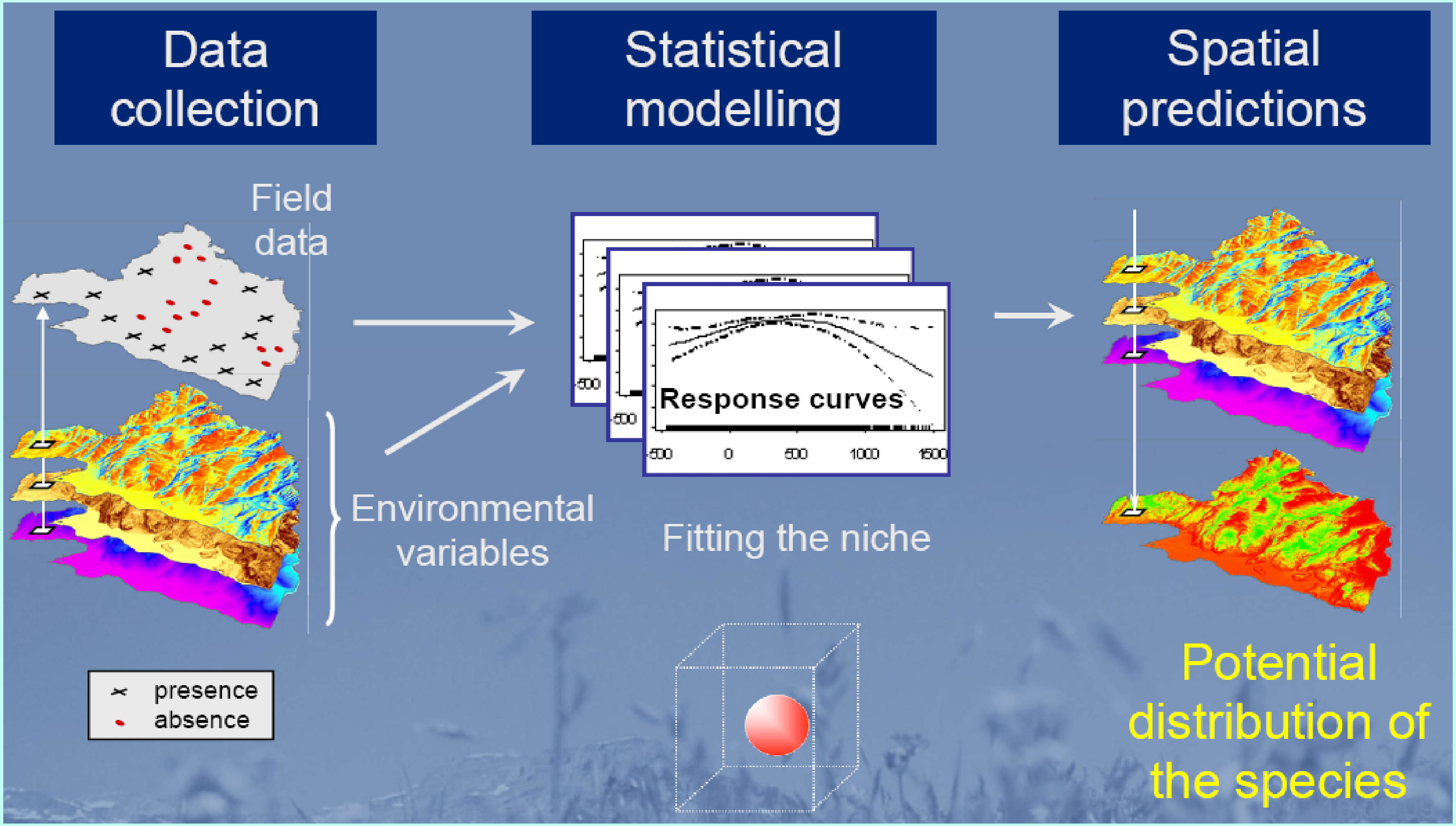
The set of geographical localities where the species is found


Water
Light
Temperature
Realized
Niche



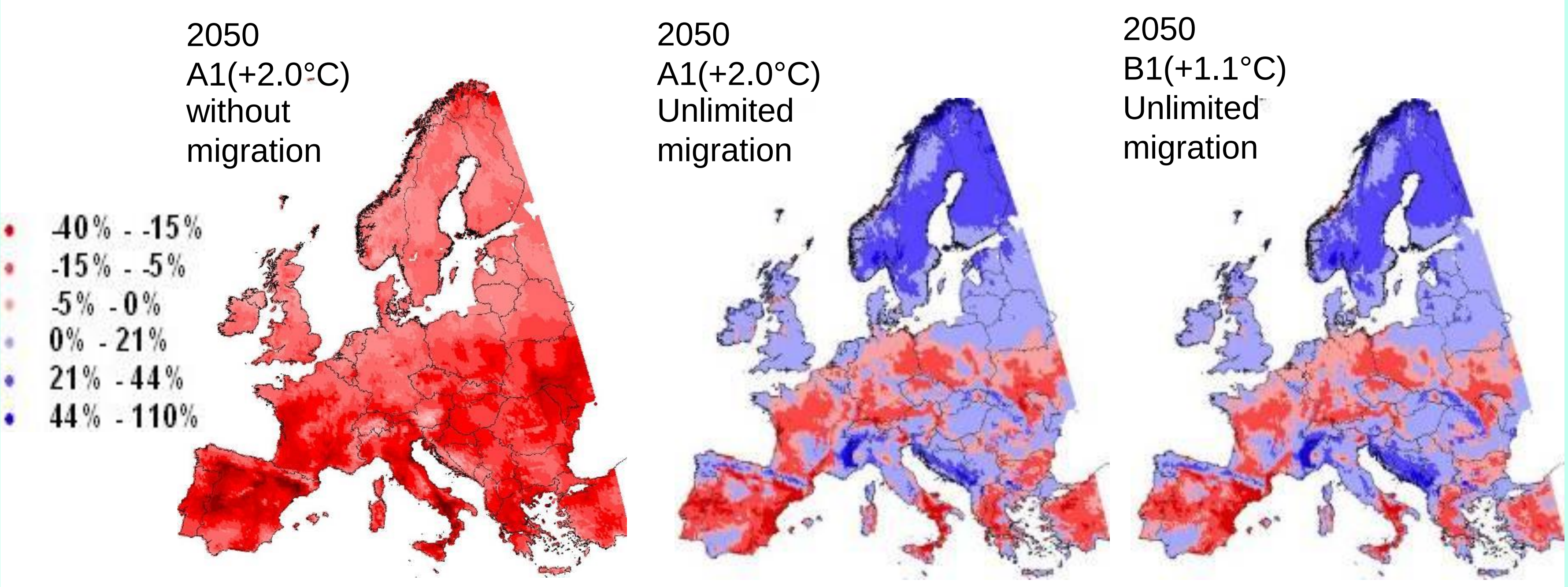
Soberon 2007 *Ecol. Lett.*

Species Distribution Models (SDM)



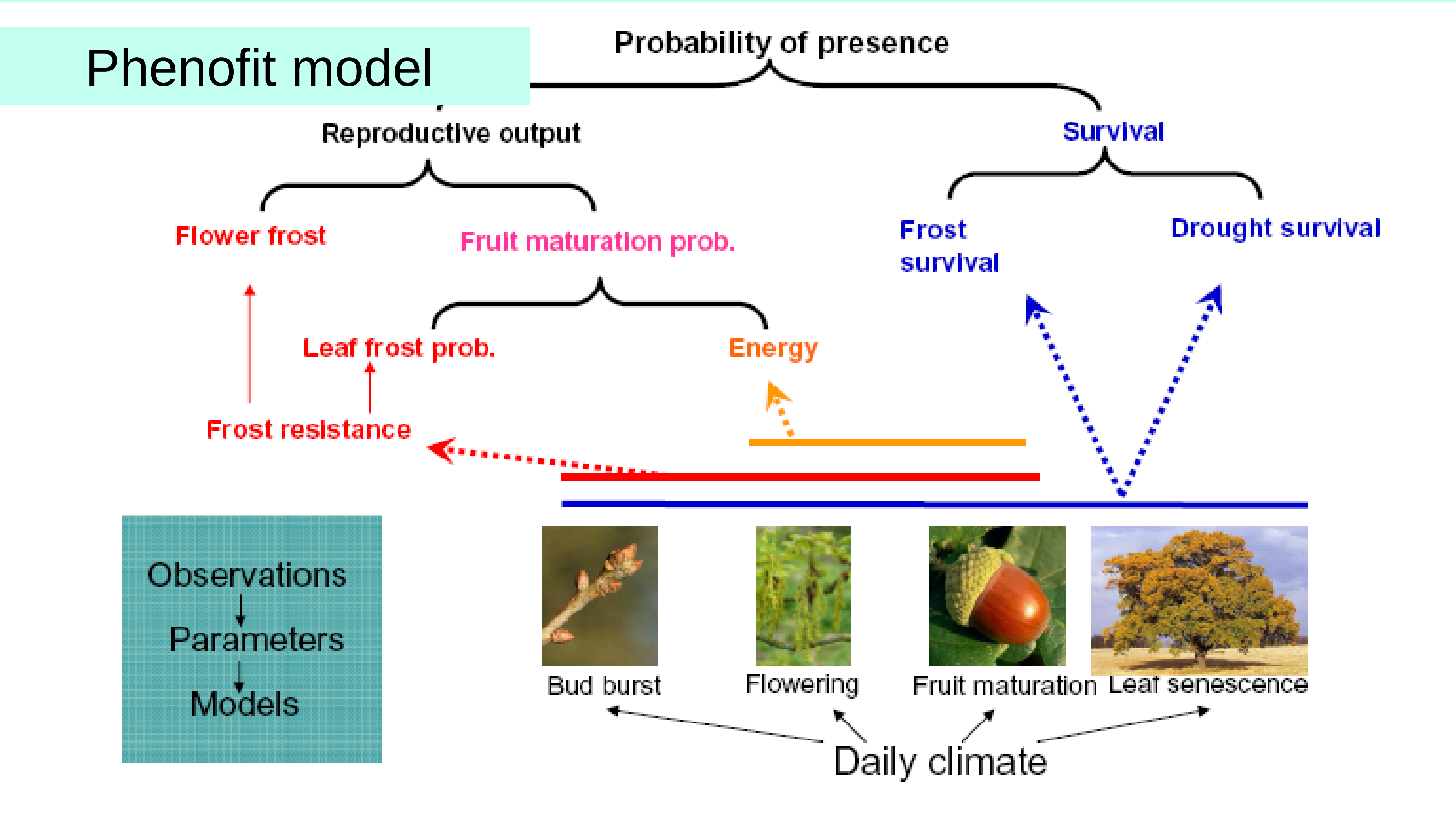
Scenarios for future biodiversity under climate change

- Forecasted biodiversity loss for Europe in 2050



Thuiller et al. 2004

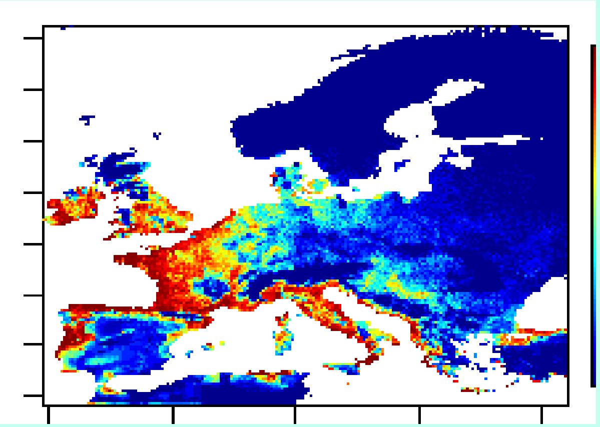
Phenology as a major determinant of species range



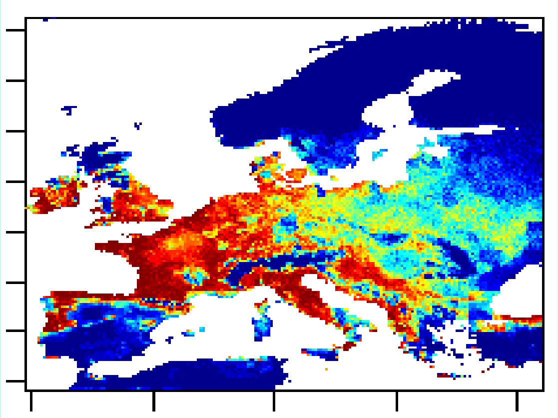
Phenology as a major determinant of species range

Phenofit model

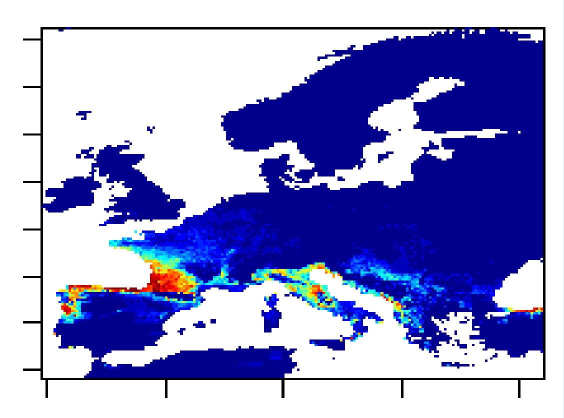
We fix bud burst date and compute average reproductive success in each location



60 days



100 days

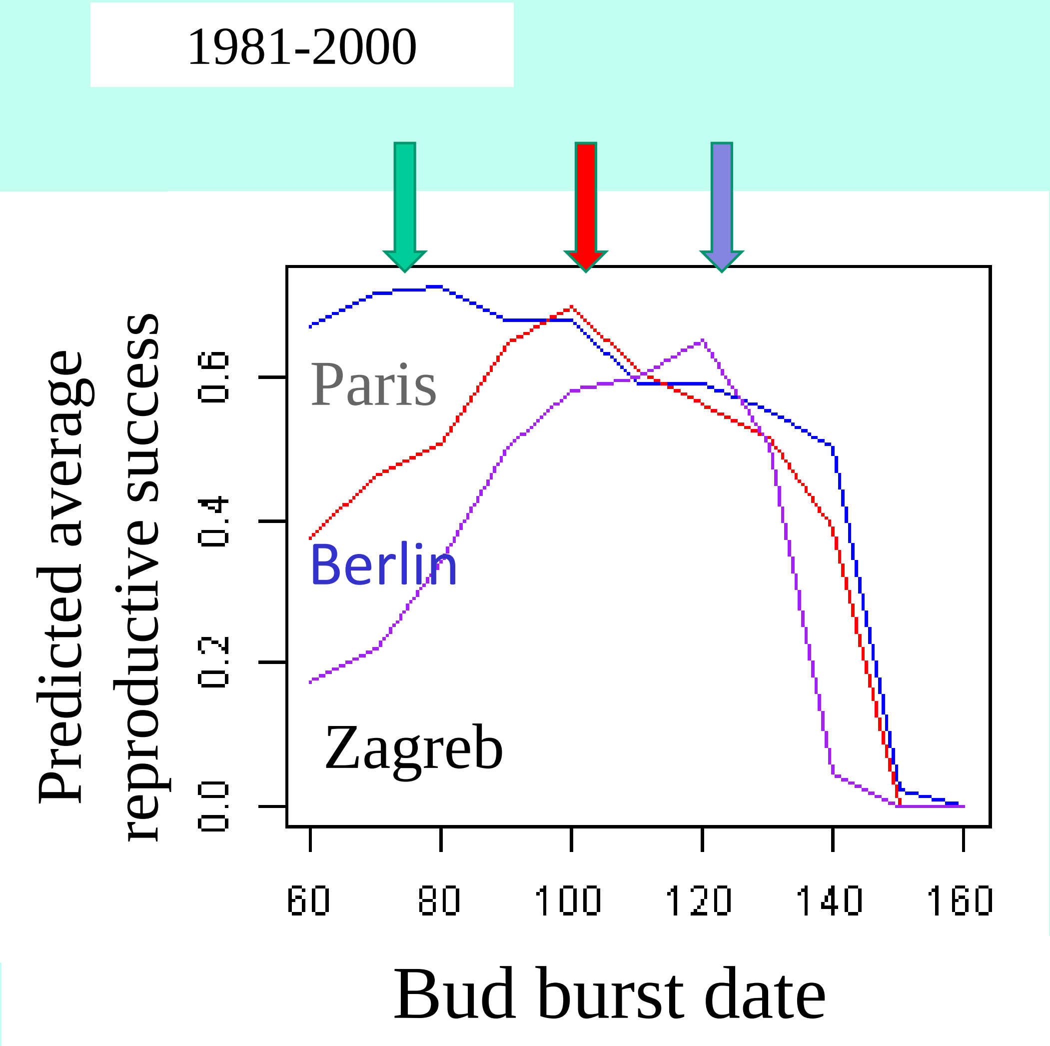


150 days

1981-2000

Quercus petraea

Selection on phenology

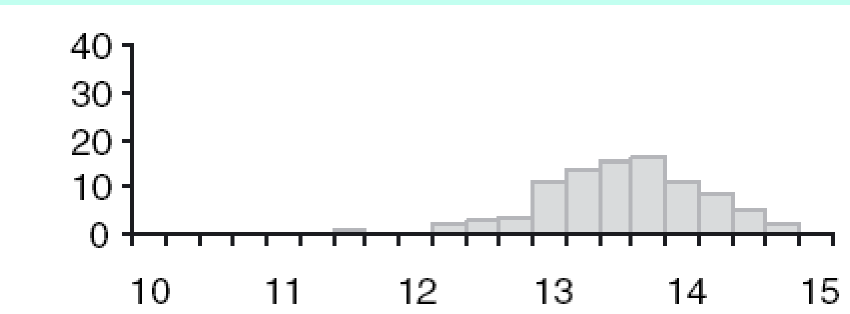


Quercus petraea

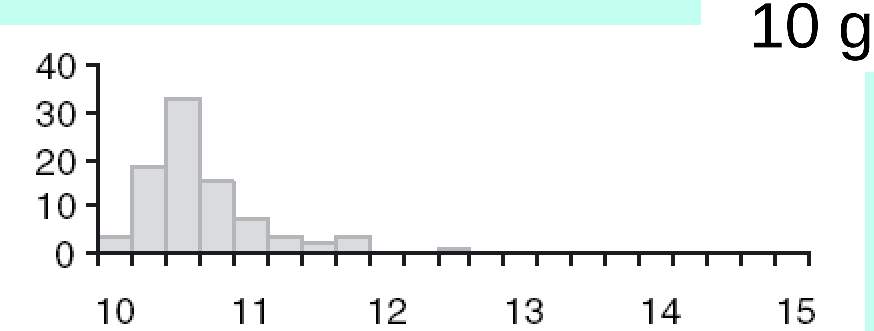
Phenology can evolve fast

Artificial selection

Van Dijk & Hautekee 2007



10 generations



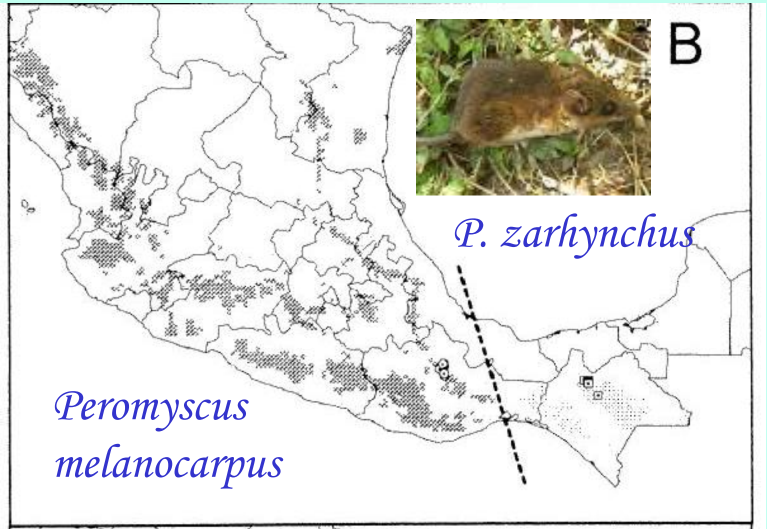
Number of daylight hours necessary to trigger flowering

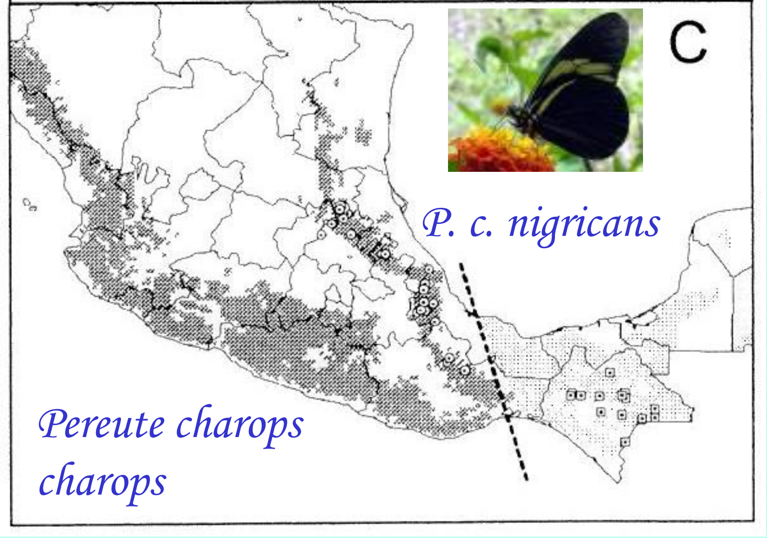
$$h^2 = \frac{\sigma_g^2}{\sigma_p^2} = 0.56$$

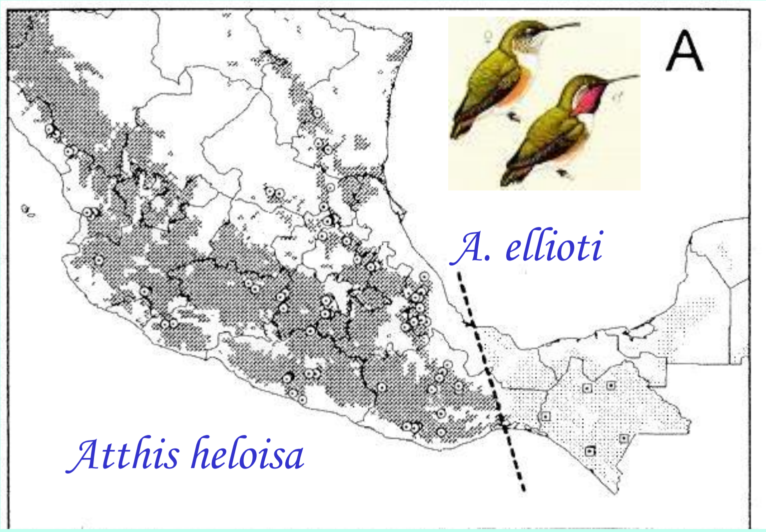
Evidence for niche conservatism

Peterson et al. 2002

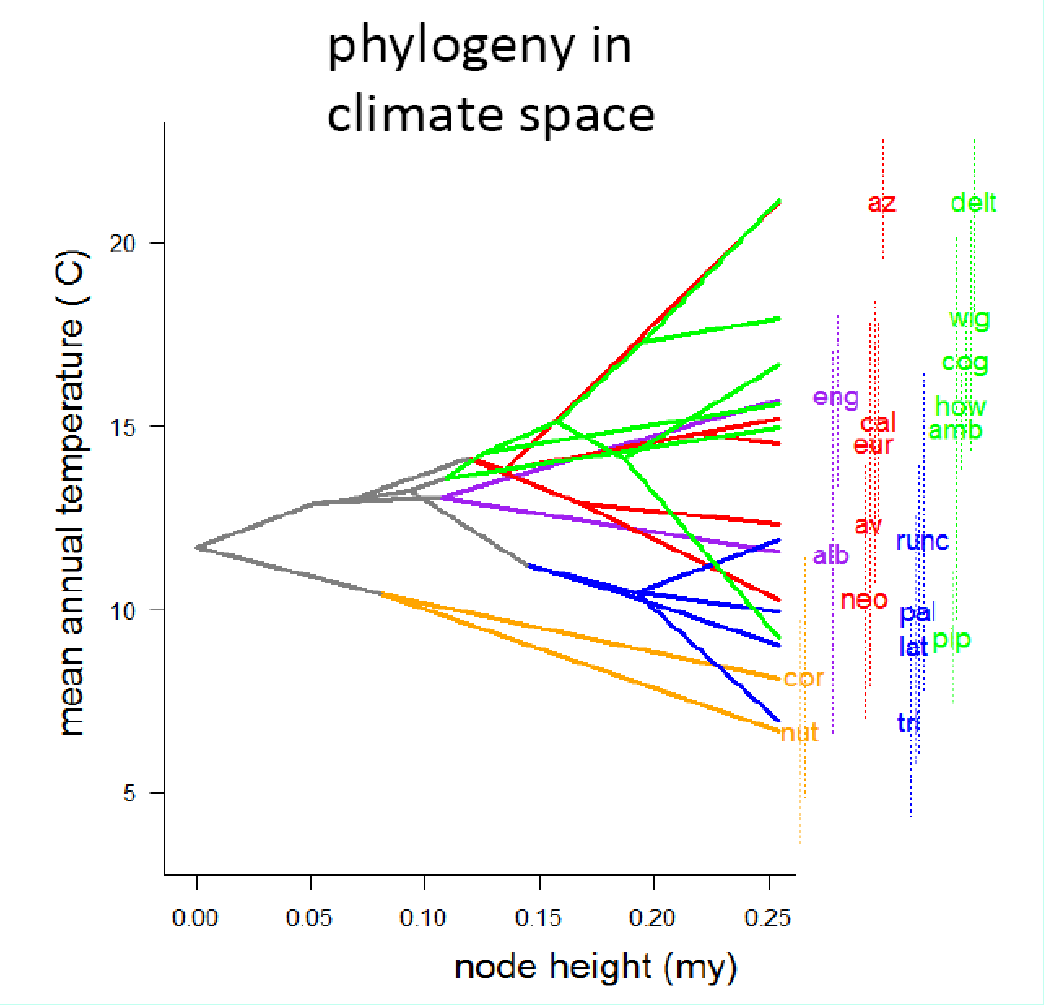
37 pairs of sister species having diverged for 2-10 millions years on each side of Tehuantepec isthma, Mexico

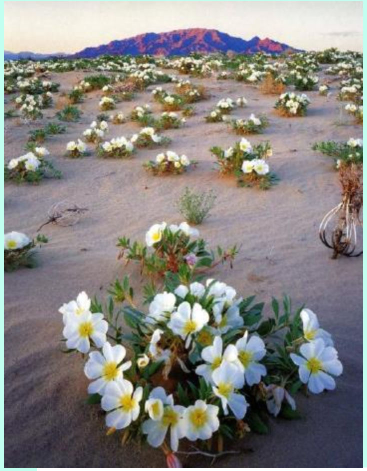






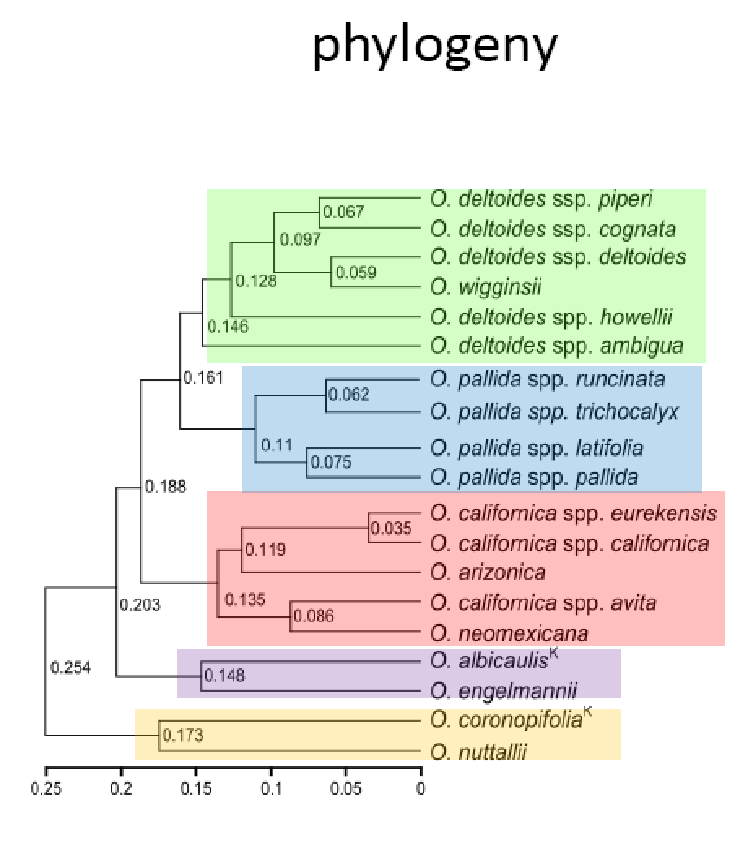
Niche evolution





Oenothera

19 taxa, Western North America



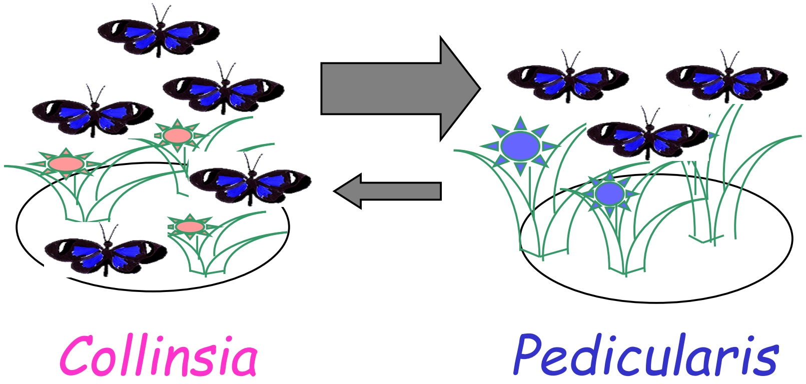
Rapid shifts in host use and source-sink dynamics

Euphydryas editha

Singer and Thomas 1996,

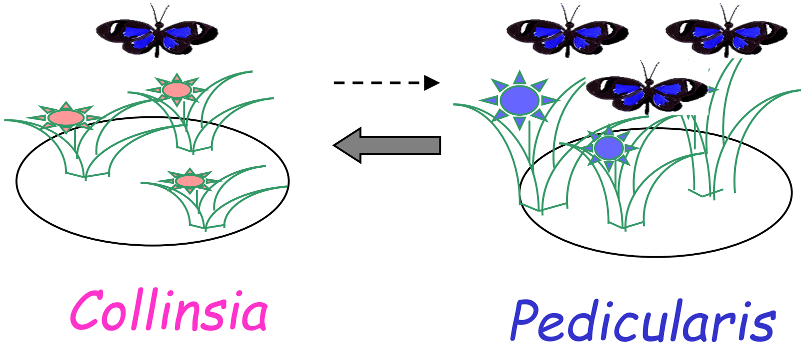
Boughton 1999

1979-1989:



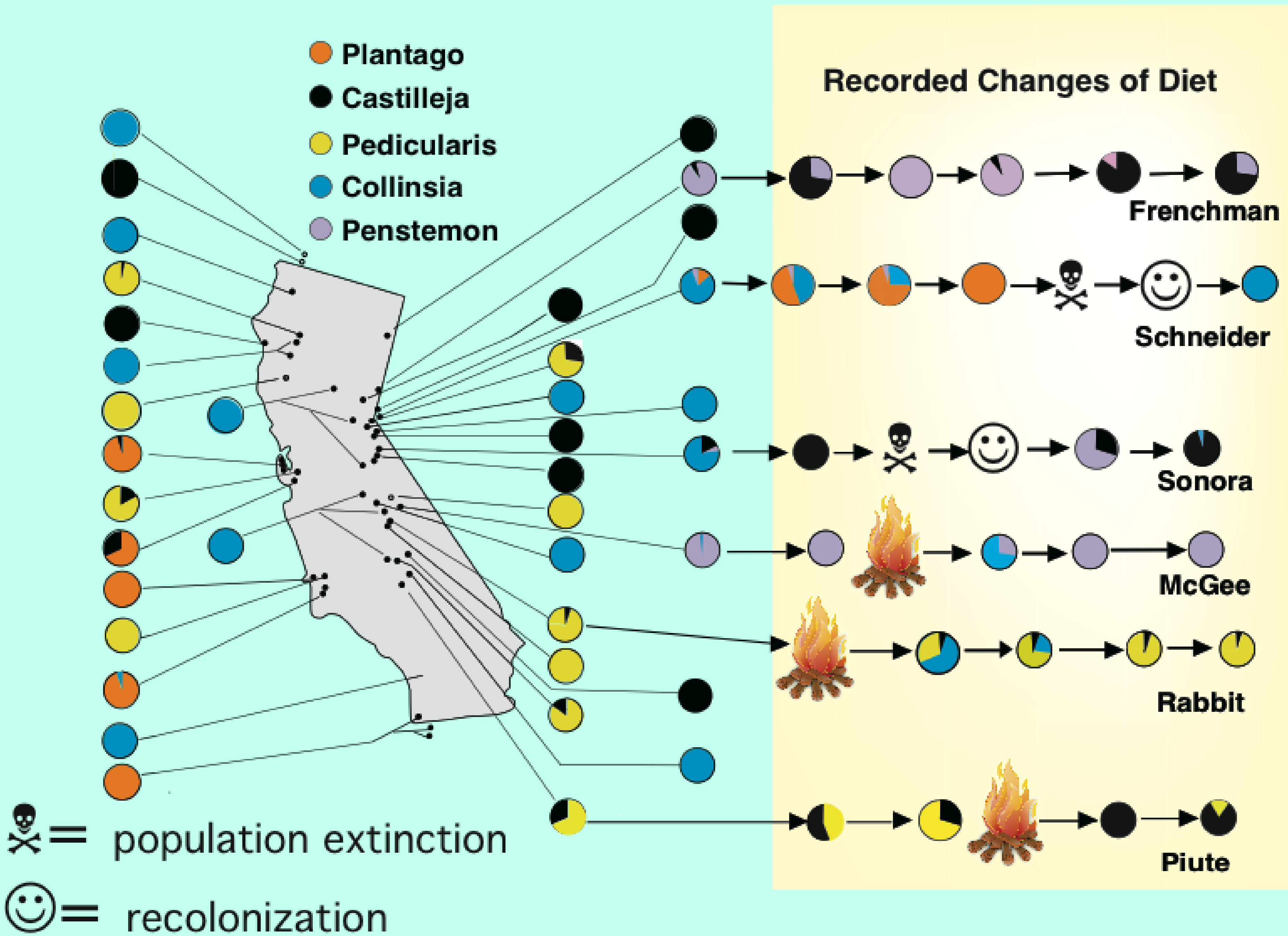
1989-1992: extinction on *Collinsia*

1992-1997:



Rapid shifts in host use

Mike C. Singer


Plantago
Castilleja
Pedicularis
Collinsia
Penstemon
Recorded Changes of Diet
Frenchman
Schneider
Sonora
McGee
Rabbit
Piute
= population extinction
= recolonization

Theoretical questions

What rules the evolution of ecological specialization/ ecological niche?

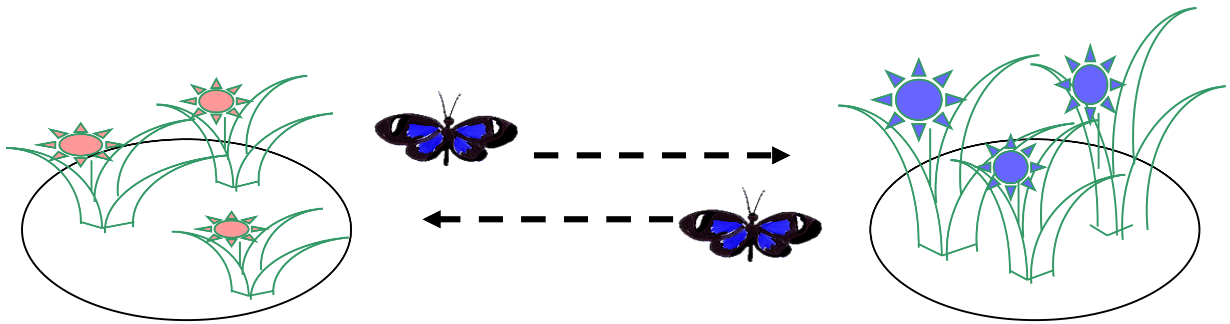
When can we expect shifts in source-sink dynamics?

What are the evolutionary consequences of such shifts?

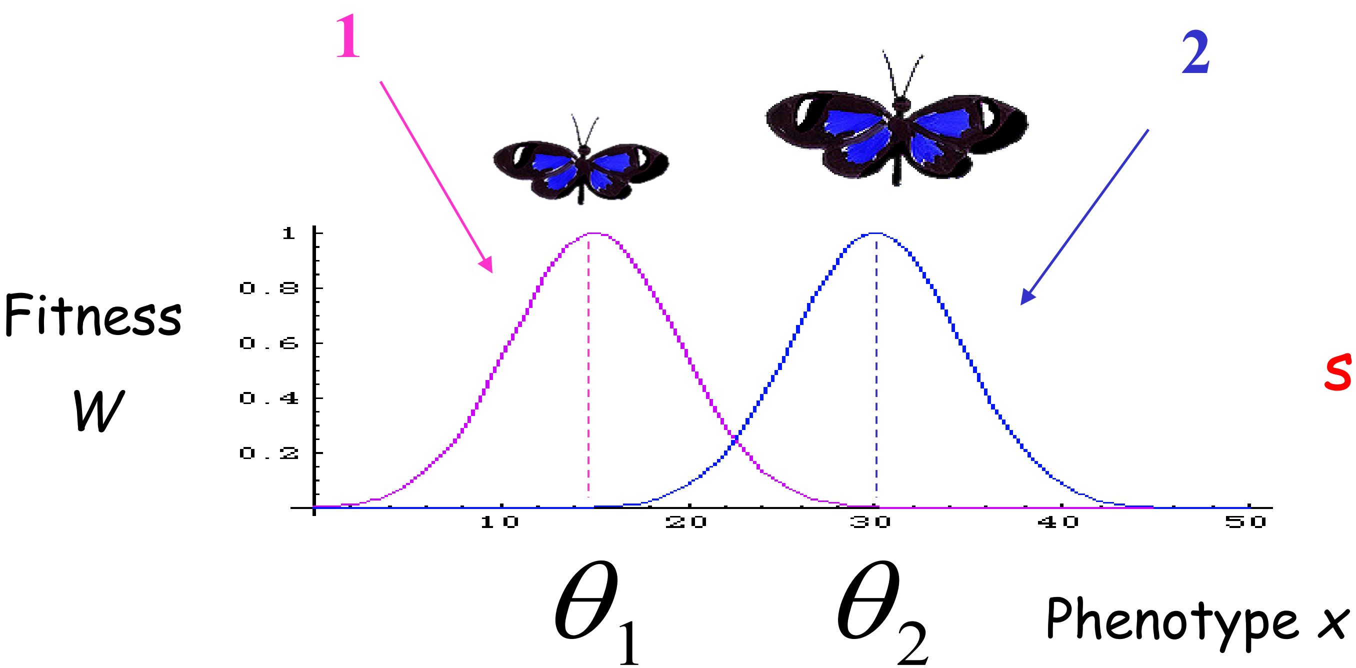
Migrational meltdown in an heterogeneous environment

Ronce and Kirkpatrick, Evolution 2000

A quantitative genetics model



Symmetric movement rates between host plants



Stabilizing selection within host plants

Assumptions of the quantitative genetic model

Constant genetic variance

Gaussian distribution of phenotypes

/ *Hypergeometric model*

n equivalent loci

Selection after recombination

The dynamical variables:

Density N_1

optimum ↓ mean phenotype ↙

Maladaptation $$Z_1 = \frac{\theta_1 - \bar{x}_1}{\sigma_g}$$

genetic standard deviation ← σ_g

The parameters:

Habitat heterogeneity $$\boldsymbol{H} = \frac{\theta_1 - \theta_2}{\sigma_g}$$

Movement rate $\boldsymbol{M}$

Intensity of stabilizing selection $\boldsymbol{\Gamma}$

Feed-backs between demography and adaptation

1) Population growth depends on maladaptation

$$\frac{dN_1}{dT} = M(N_2 - N_1) + \left(1 - N_1 - \frac{\Gamma}{2} Z_1^{\,2}\right) N_1$$

migration local growth

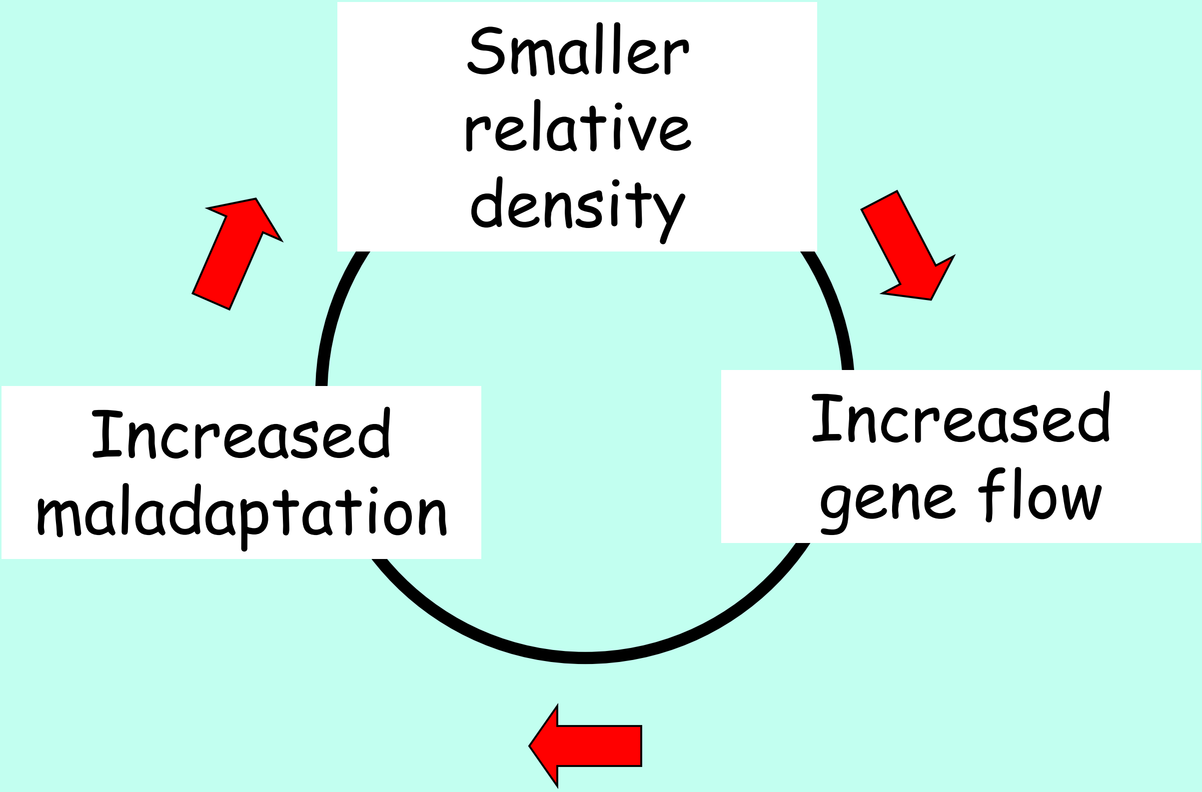
2) Gene flow depends on relative population sizes

$$\frac{dZ_1}{dT} = M\frac{N_2}{N_1}(H + Z_2 - Z_1) - \Gamma Z_1$$

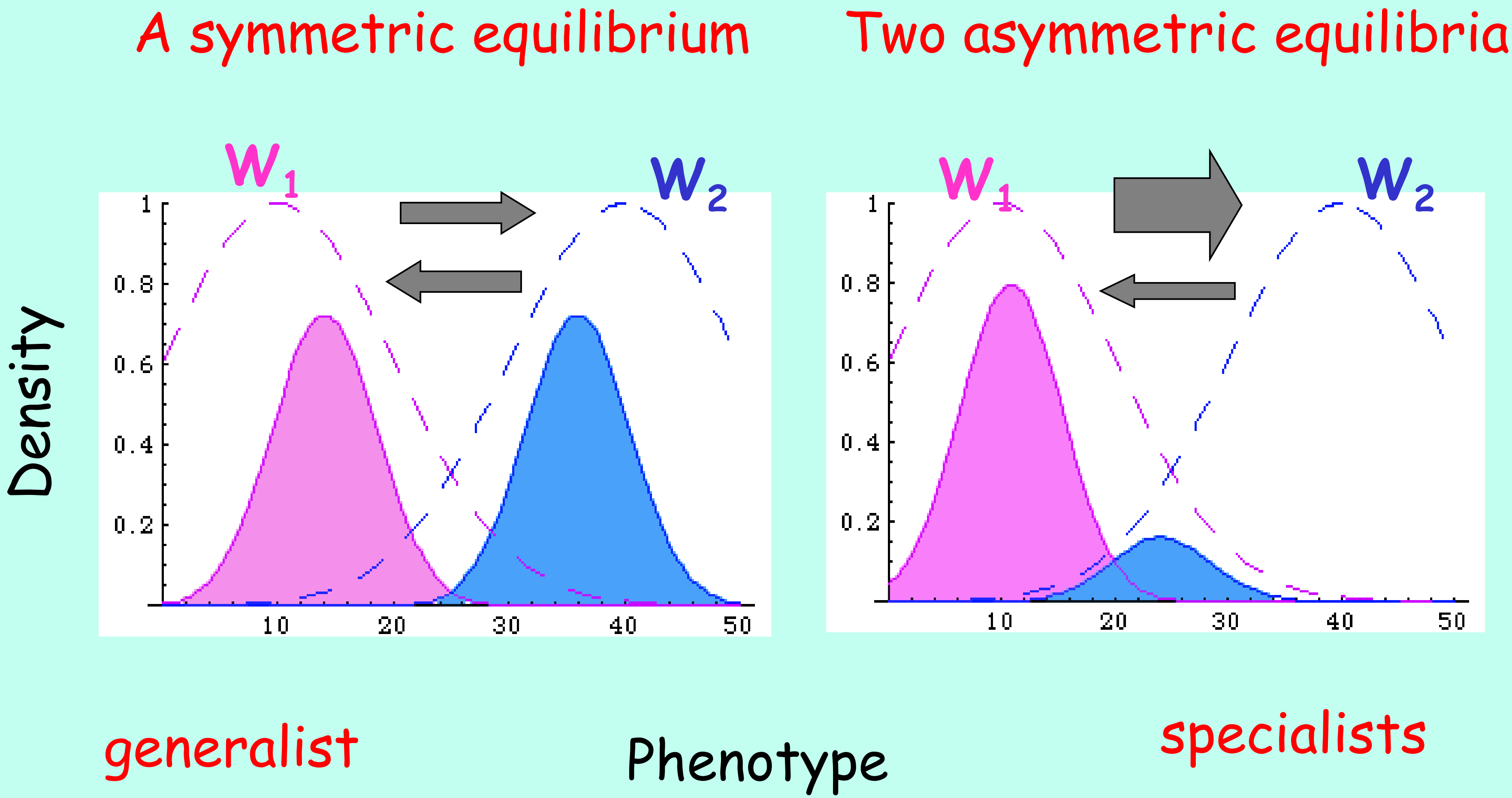
migration local selection

Feed-backs between demography and adaptation

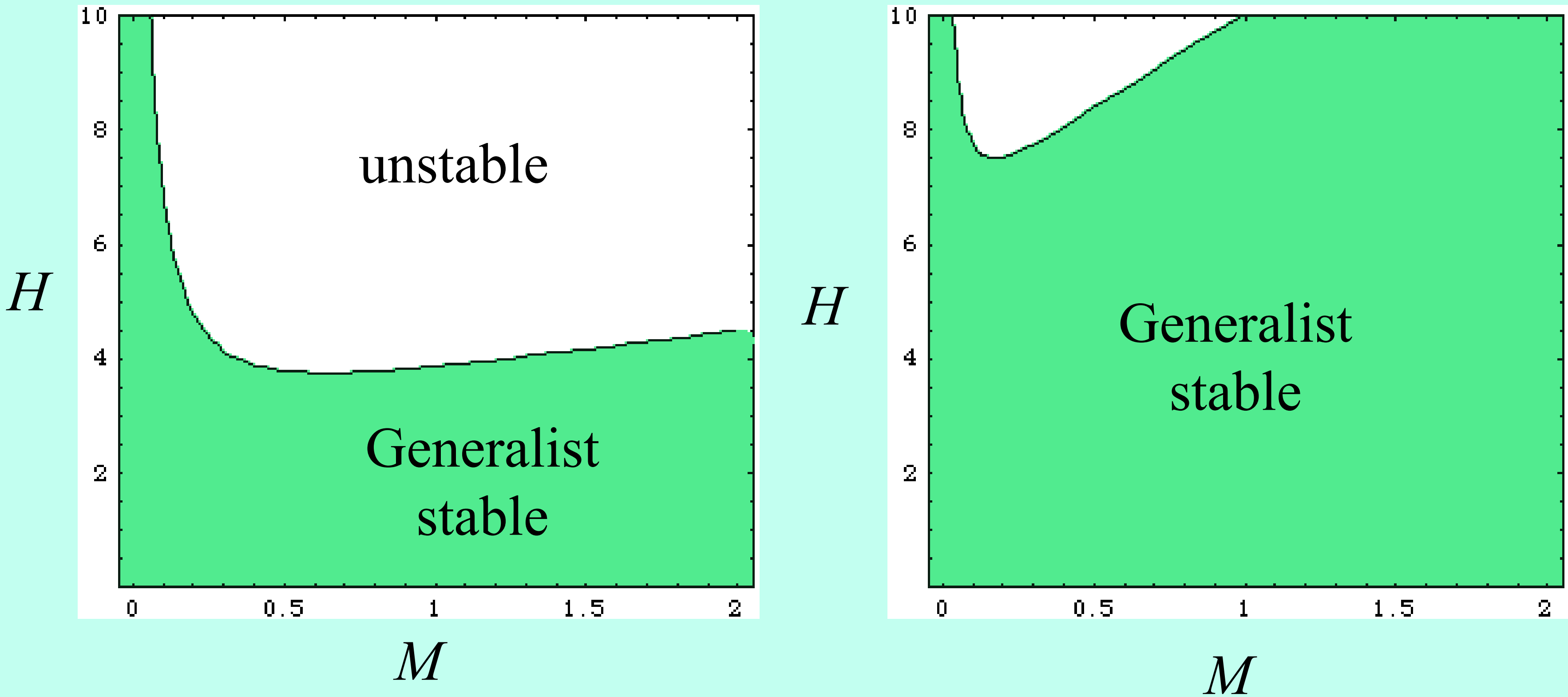
An evolutionary trap for smaller populations



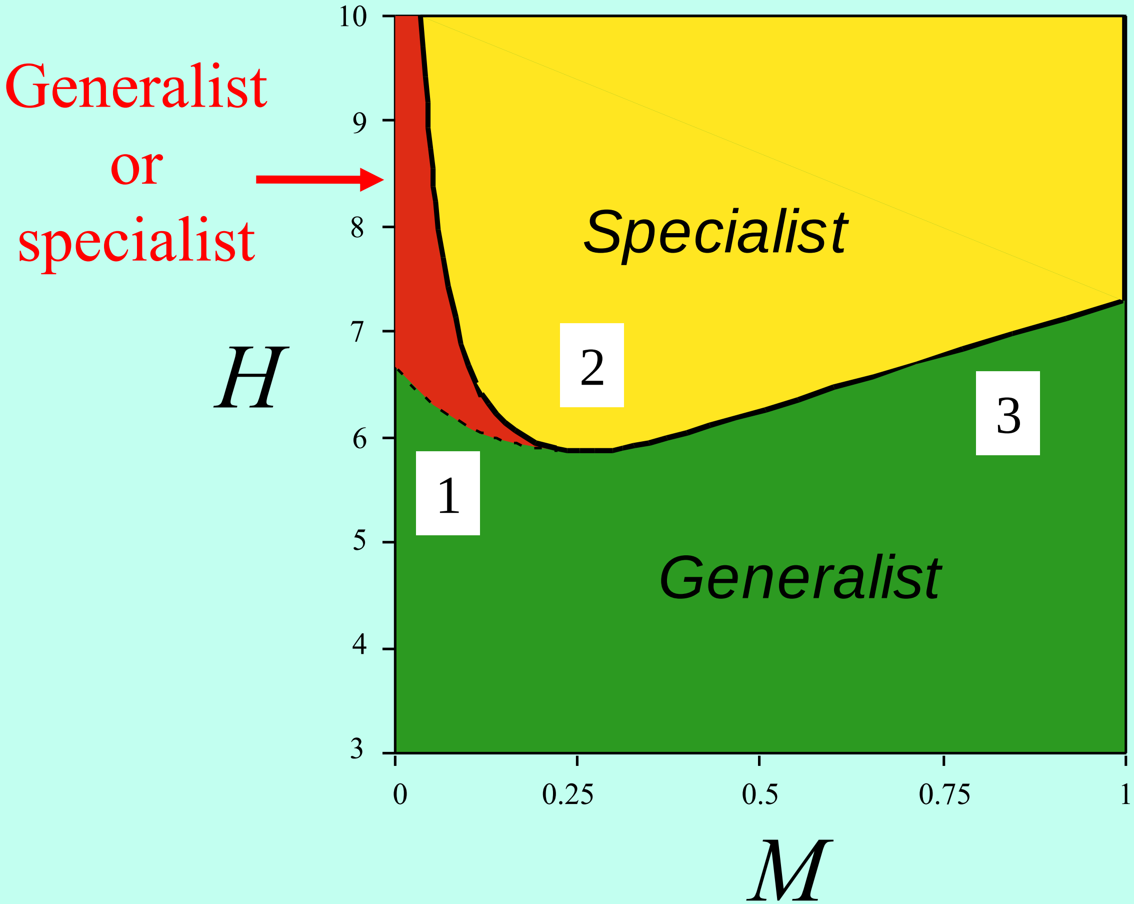
Several outcomes for the joint evolution of maladaptation and population size



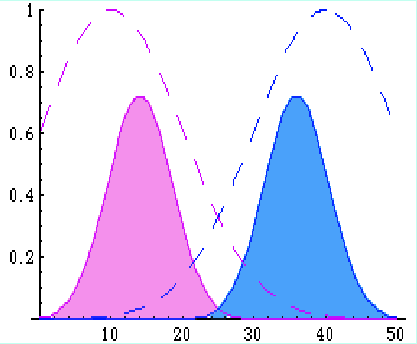
$\Gamma = 0.5$ $\Gamma = 0.05$



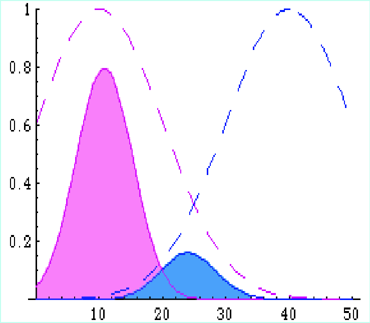
Stability of the different equilibria



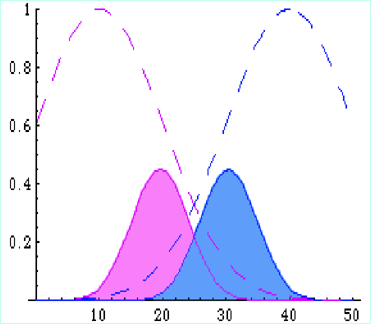
1



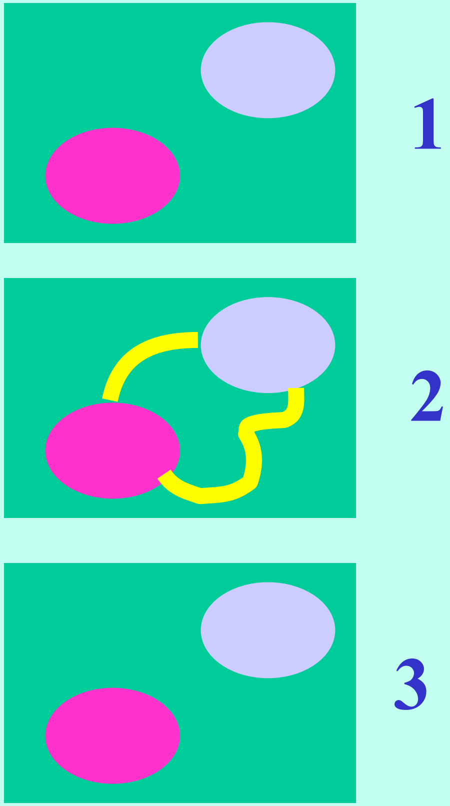
2

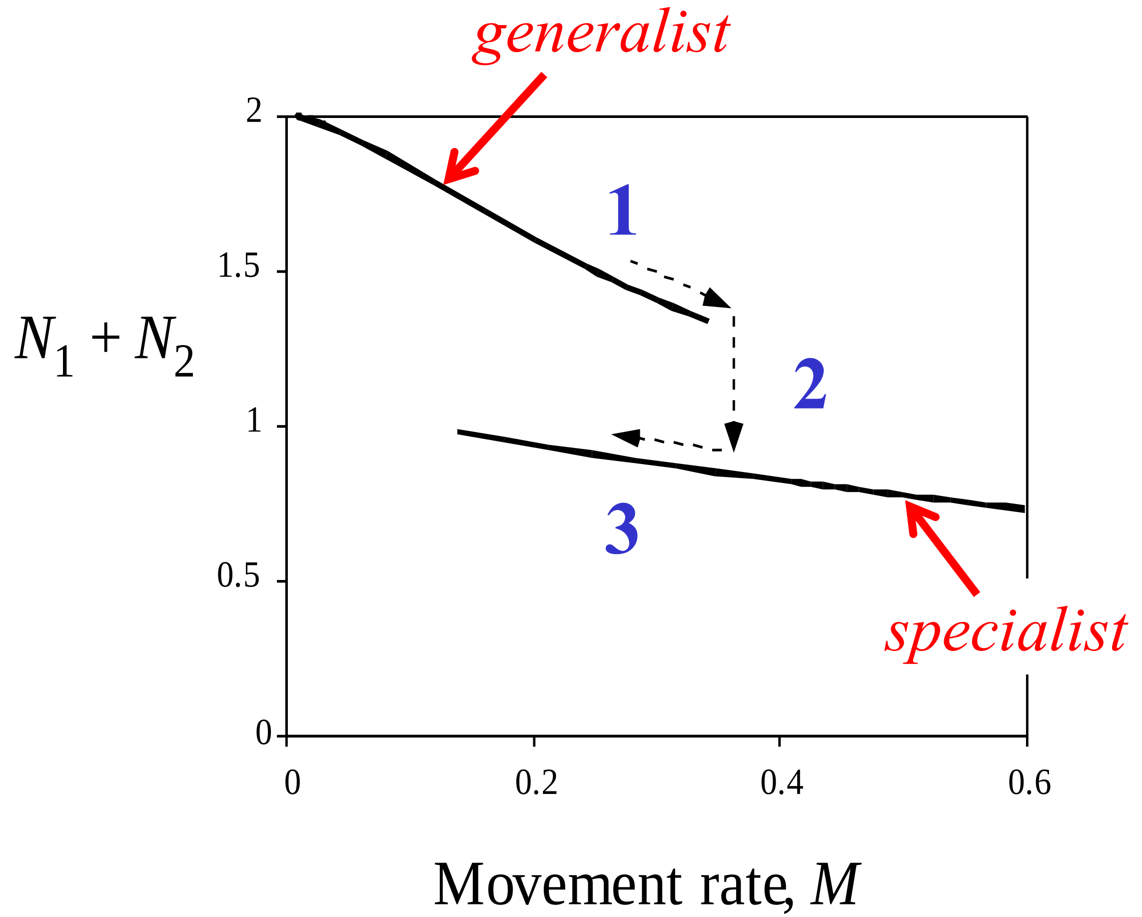


3

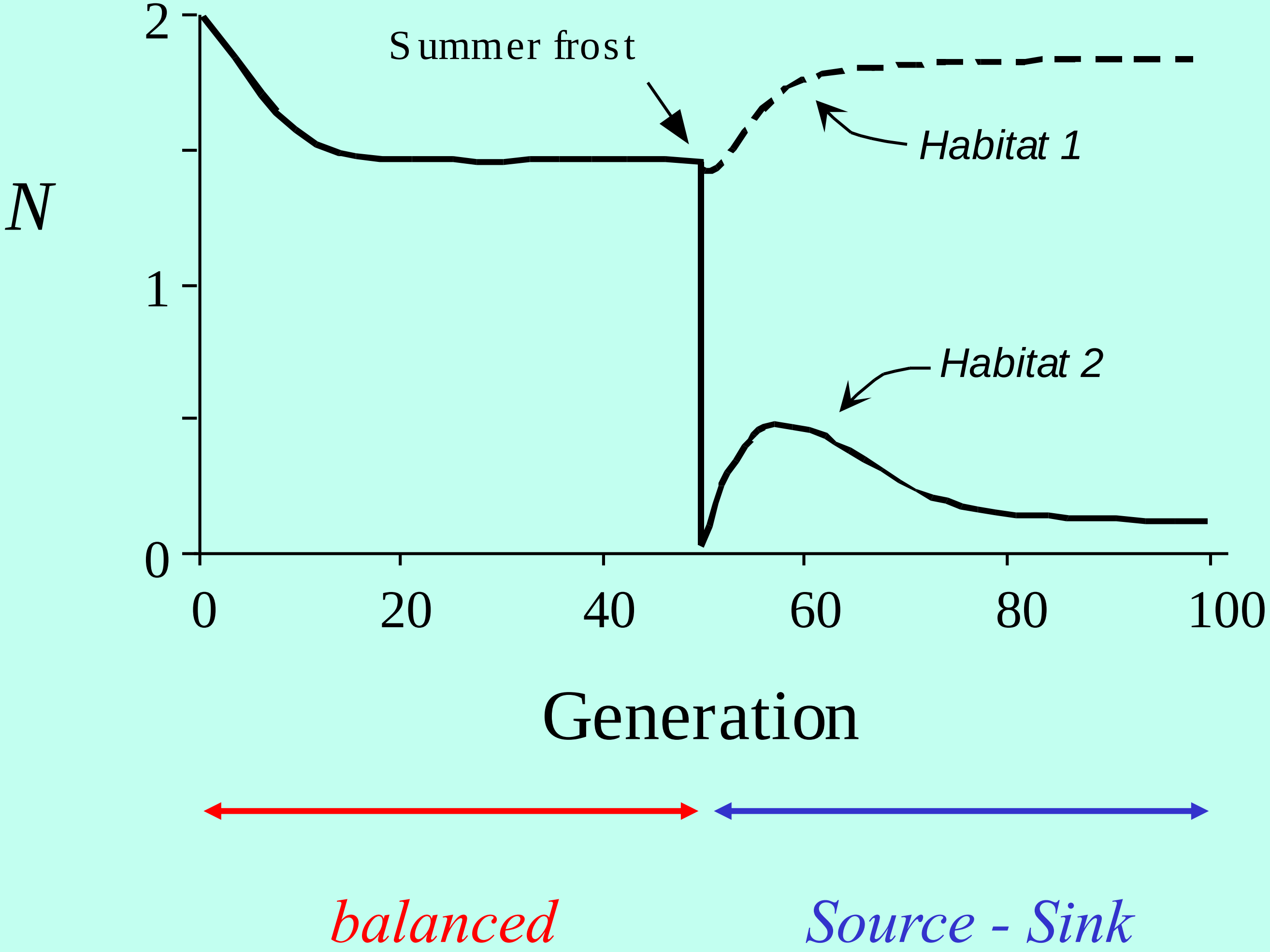


Irreversible consequences of transient changes in the landscape

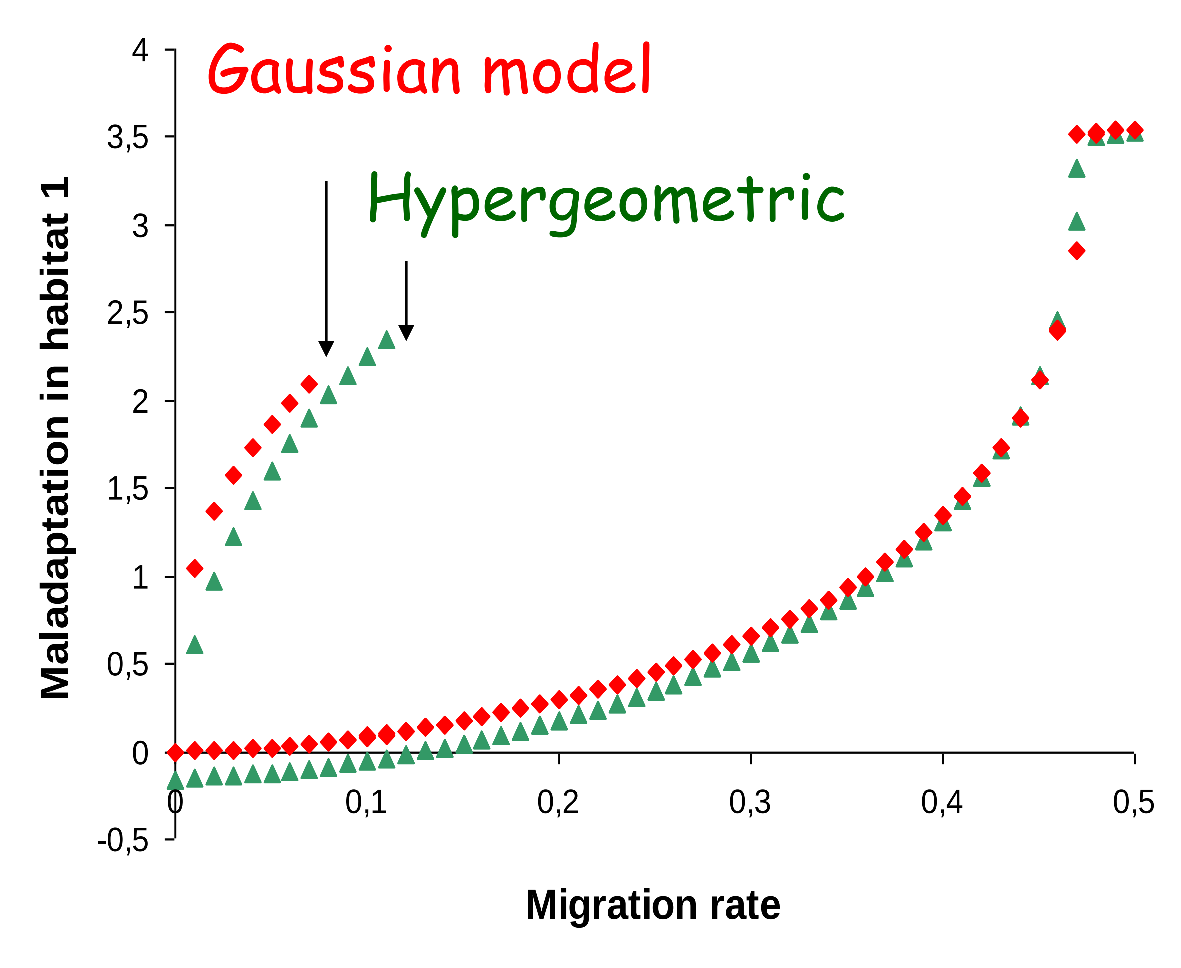




Effect of demographic disturbances



Checking on our assumptions



30 equivalent loci

Free recombination

Selection after recombination

Conclusions

Generalist :

Low habitat heterogeneity

Weak selection

Low or high movement rates

Specialist :

Strong habitat heterogeneity

Strong selection

Intermediate movement rates

Kawecki 2000 (single locus)

Meszéna et al. 1997 (clonal)

Conclusions

When is specialization a labile trait?

Multiple equilibria

↓

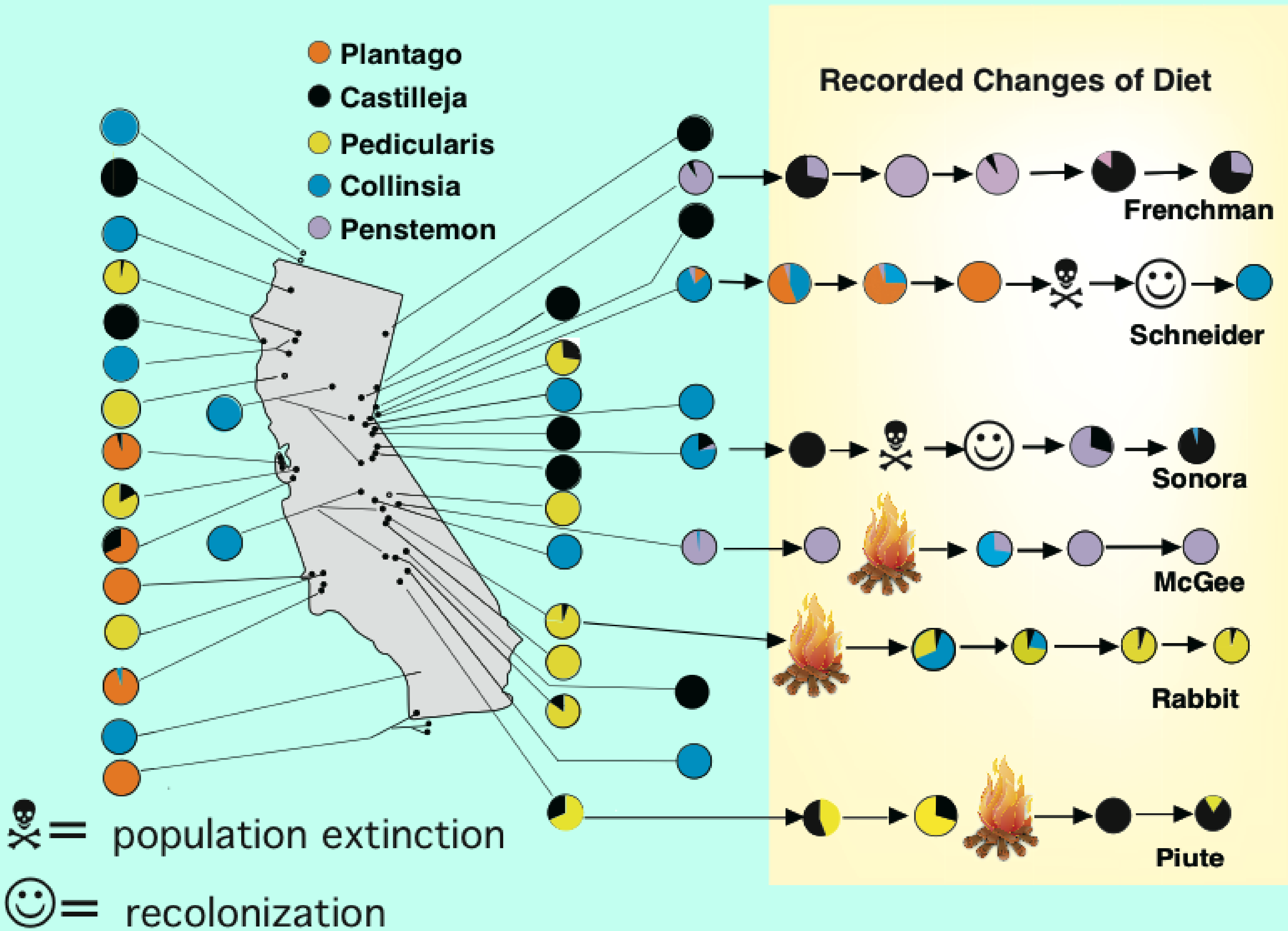
Historical factors

& Disturbances

↓

Geographical variation in host use

Temporal variation in host use



Plantago
Castilleja
Pedicularis
Collinsia
Penstemon
Recorded Changes of Diet
Frenchman
Schneider
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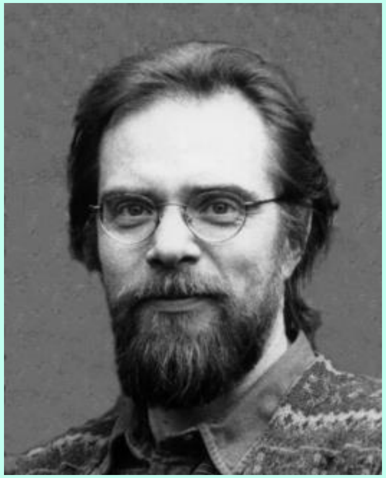
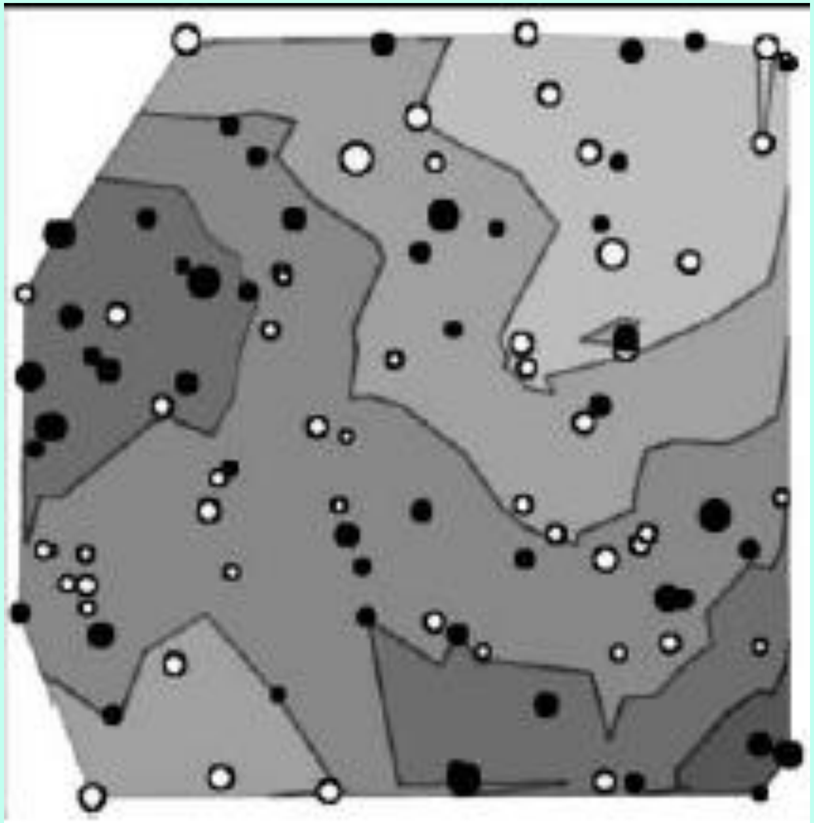
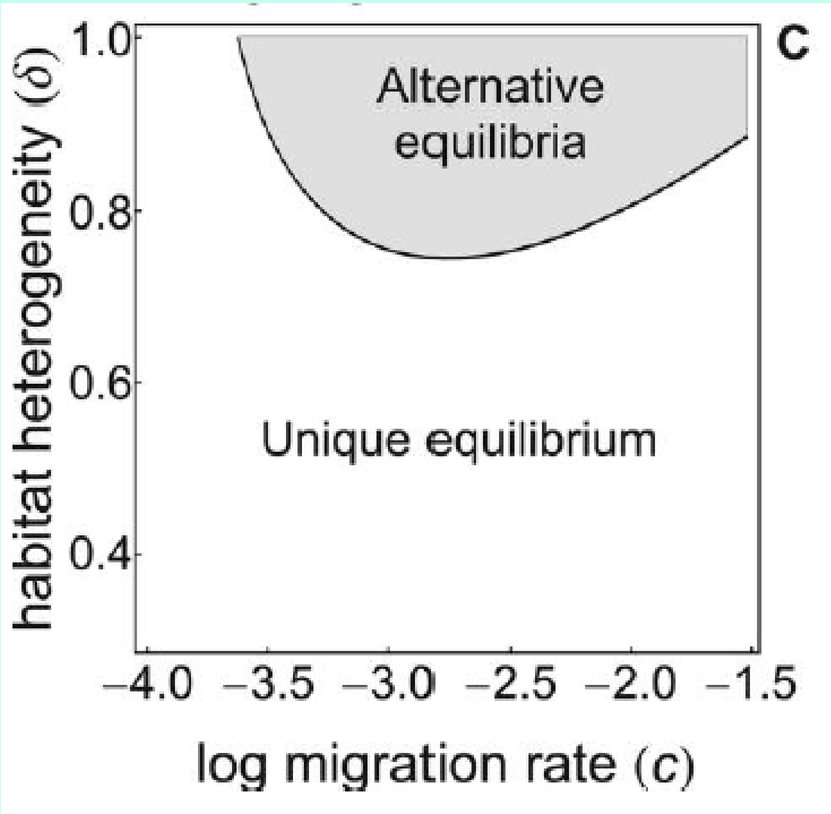
McGee
Rabbit
Piute
= population extinction
= recolonization

A **spatially realistic** model of niche evolution

Hanski et al. 2011



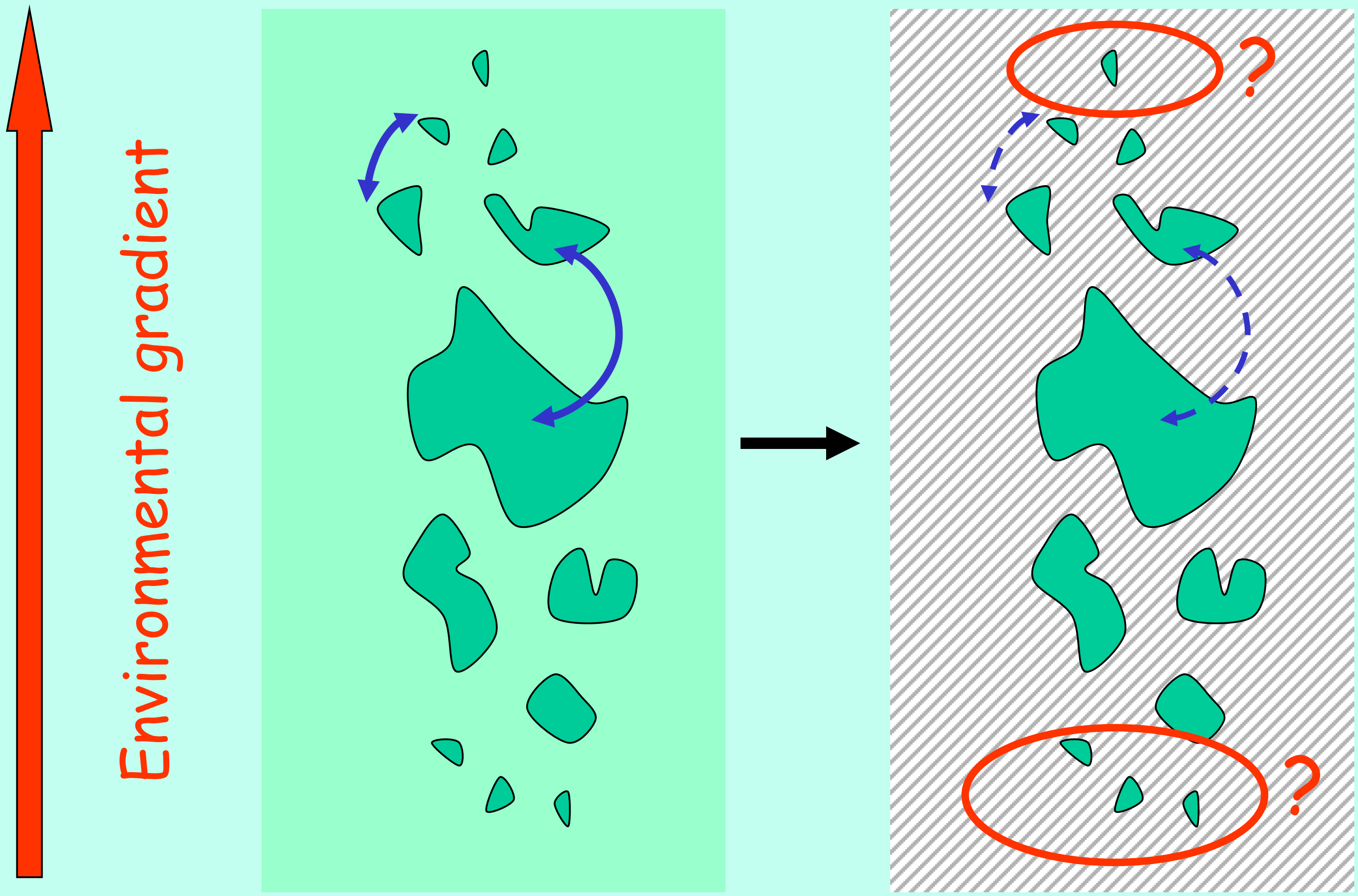




Is migration always constraining adaptation?

Alleaume et al. 2006

The scenario



Previous theoretical predictions

Garcia-Ramos and Kirkpatrick 1997

Disrupted migration → Increased adaptation in peripheral populations !

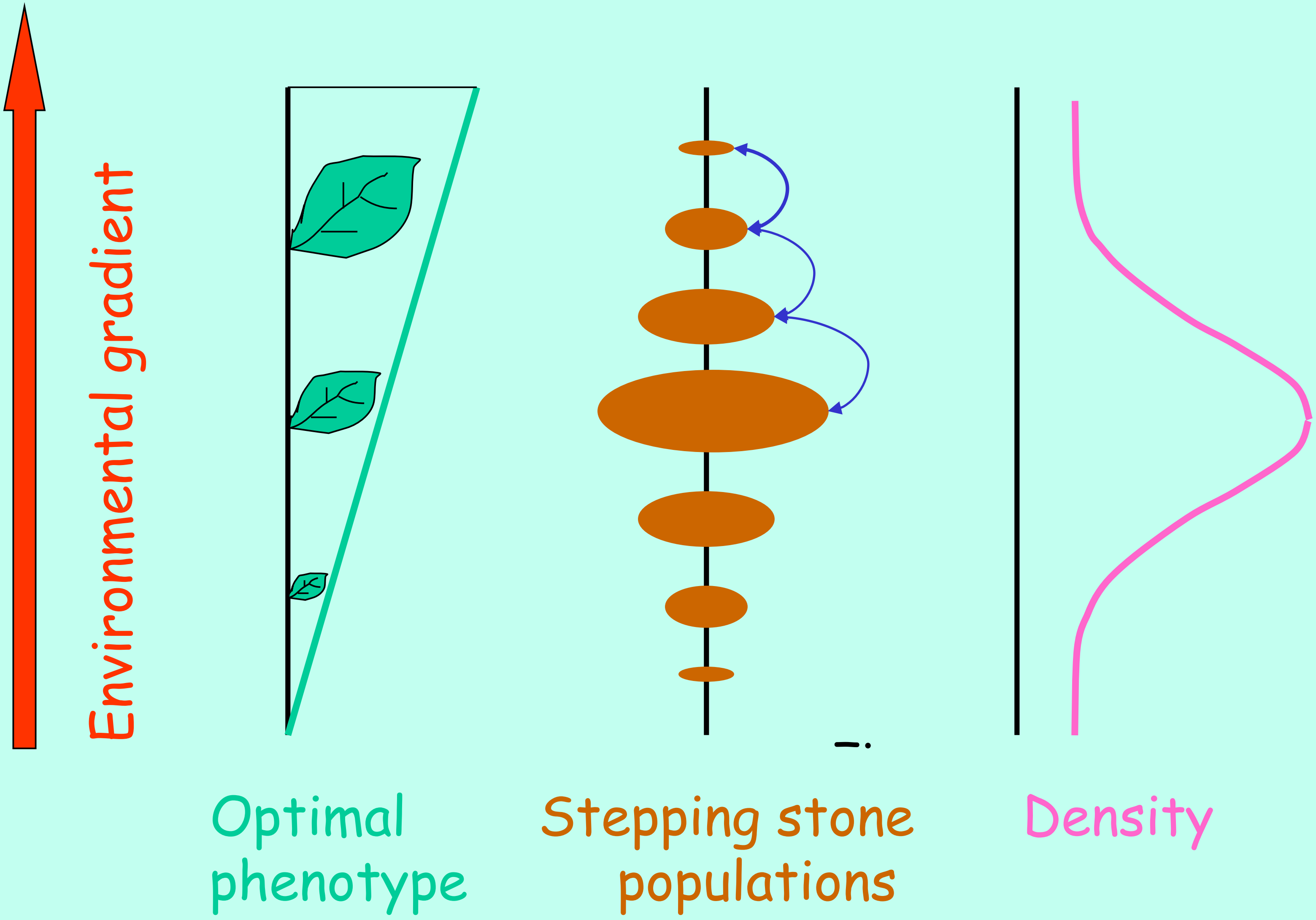
Because...

Gene flow opposes local selection

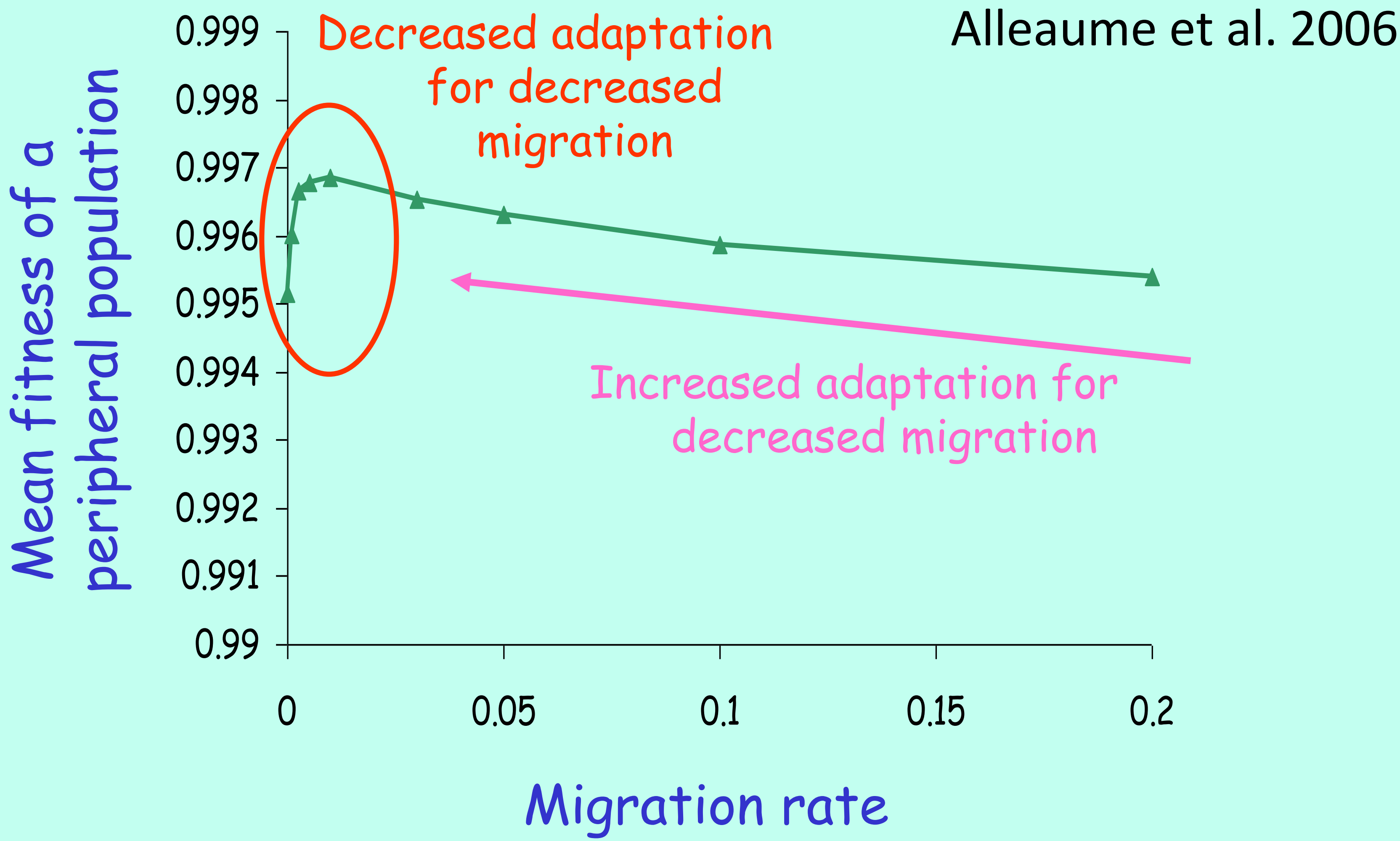
Gene flow is asymmetric

What about drift?

The model


Environmental gradient
Optimal phenotype
Stepping stone populations
Density

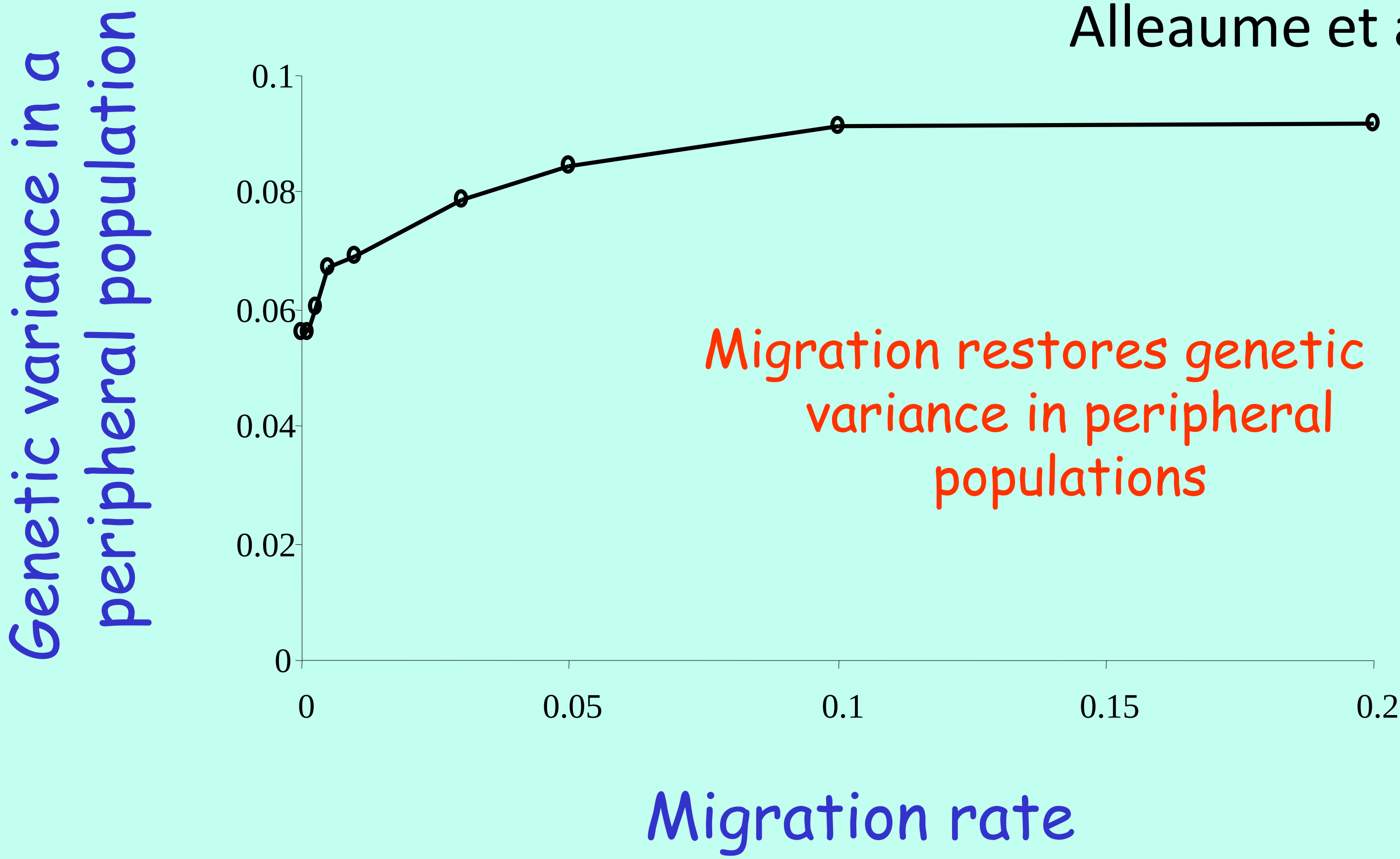
Results



Alleaume et al. 2006
Decreased adaptation for decreased migration
Increased adaptation for decreased migration
Mean fitness of a peripheral population
0.999
0.998
0.997
0.996
0.995
0.994
0.993
0.992
0.991
0.99
0
0.05
0.1
0.15
0.2
Migration rate

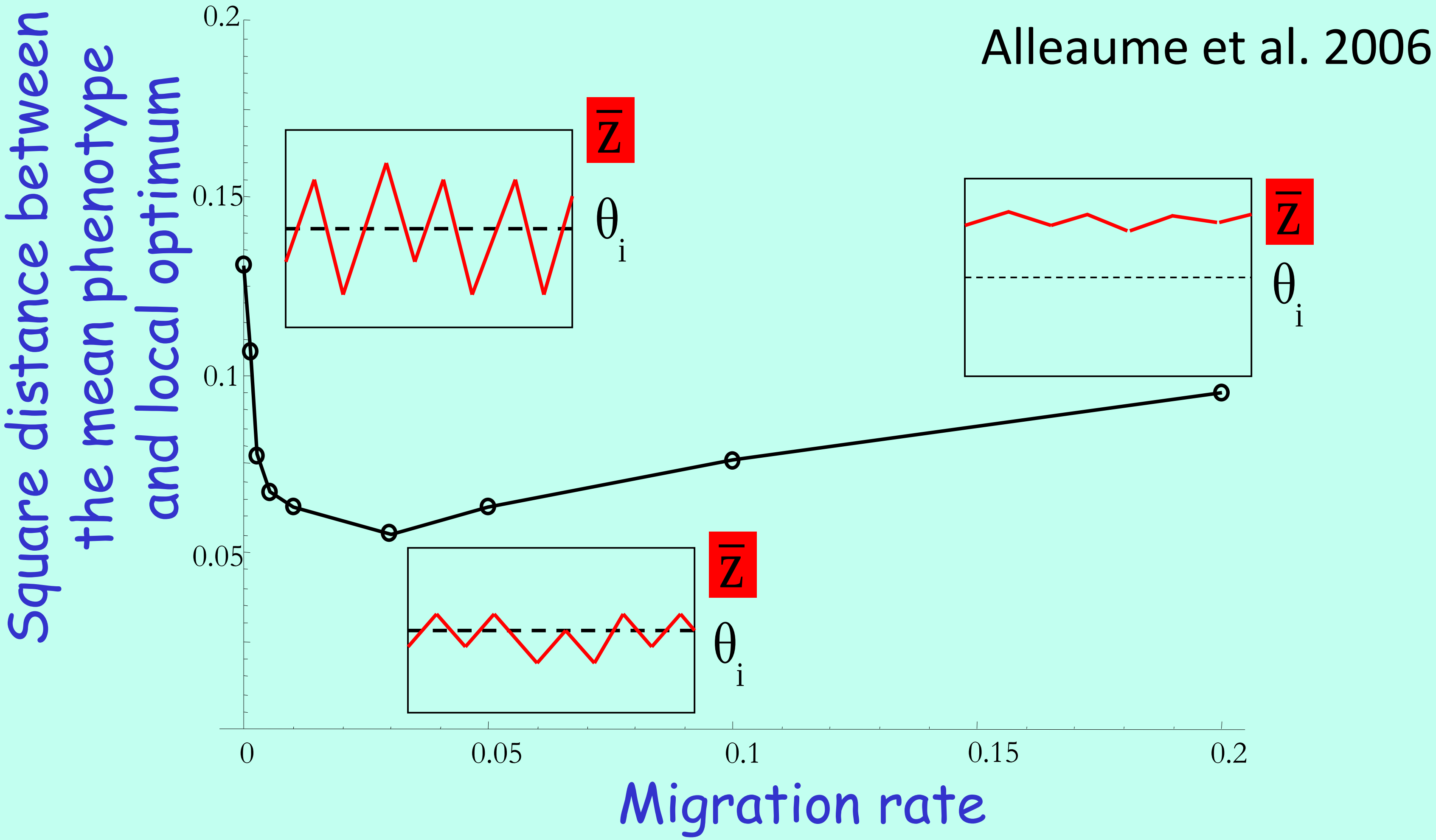
Results

Alleaume et al. 2006



Migration restores genetic variance in peripheral populations

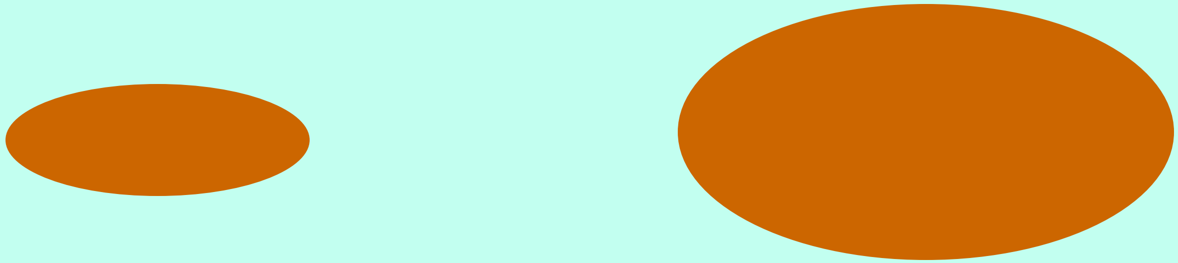
Results



Alleaume et al. 2006
Square distance between the mean phenotype and local optimum
0.2
0.15
0.1
0.05
0
0.05
0.1
0.15
0.2
Migration rate
$\bar{z}$
θ_i
$\bar{z}$
θ_i
$\bar{z}$
θ_i

Interpretation

1) No migration: drift-selection balance



Strong drift

Low genetic variance

Selection inefficient

Deleterious mutations fixed

Weaker drift

Higher genetic variance

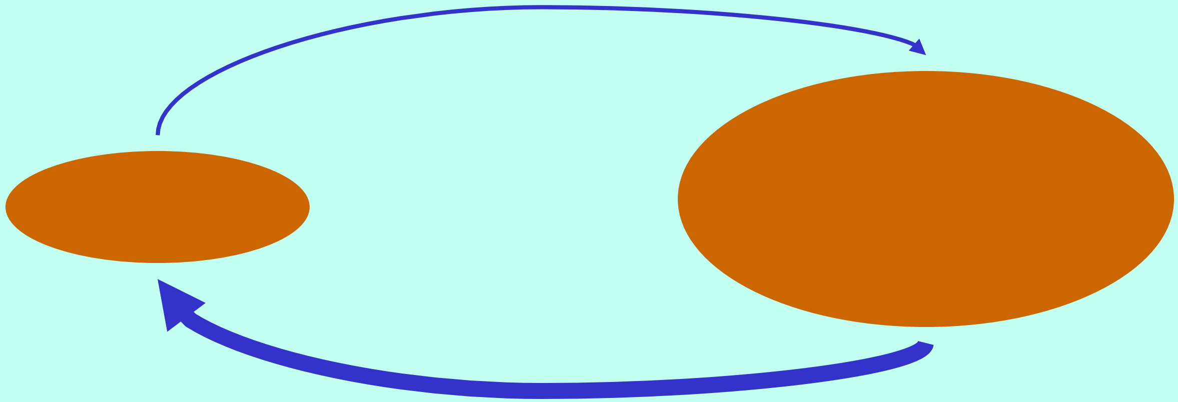
Efficient selection

Mean phenotype close to the local optimum

Leimu & Fischer 2008

Interpretation

2) Low migration



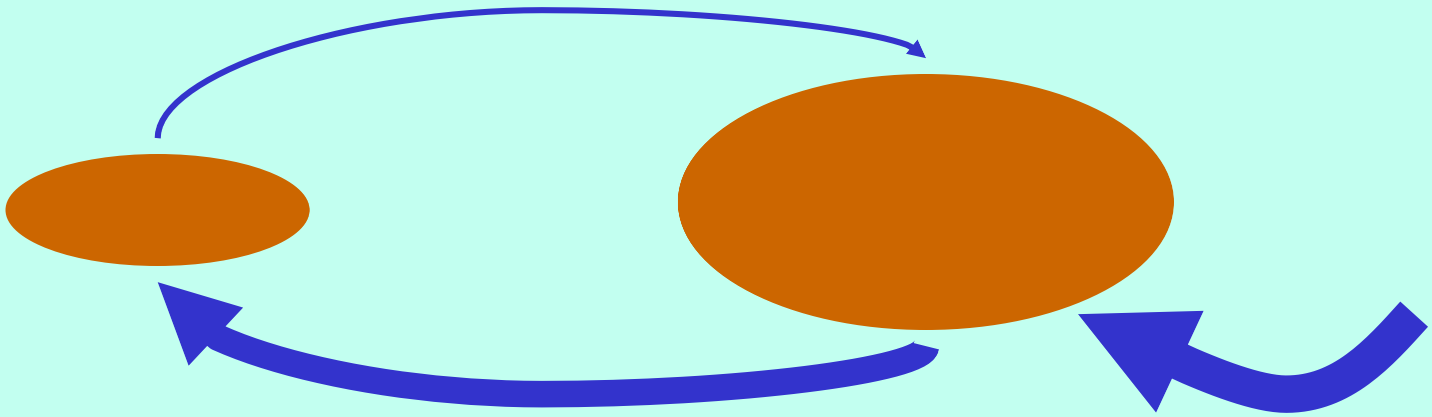
Immigration from larger adjacent populations…

…restores genetic variance

…introduces better adapted genotypes

Interpretation

2) High migration: migration-selection balance

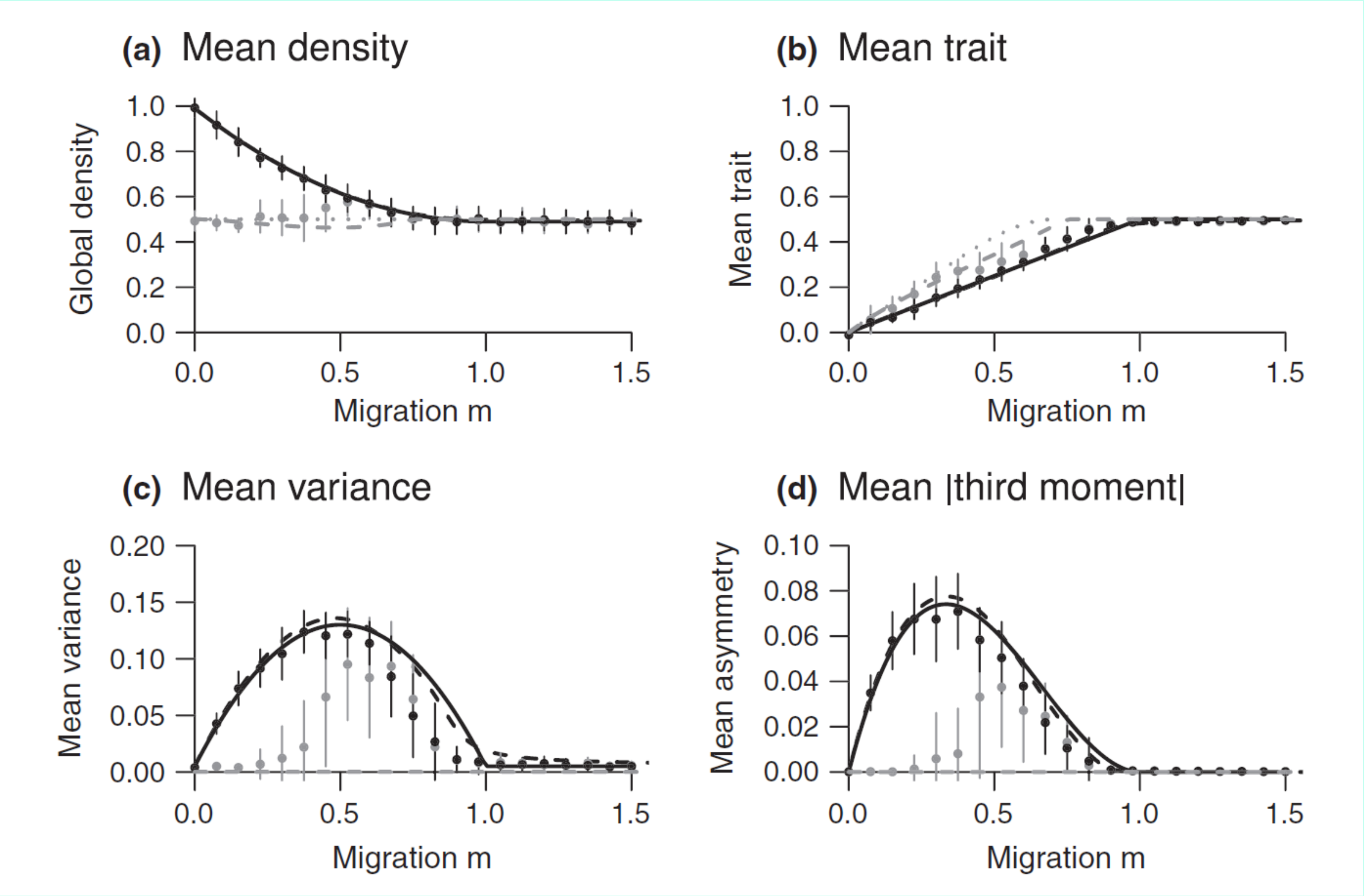


Gene swamping

Maladapted adjacent populations

Mean phenotype close to the central population optimum

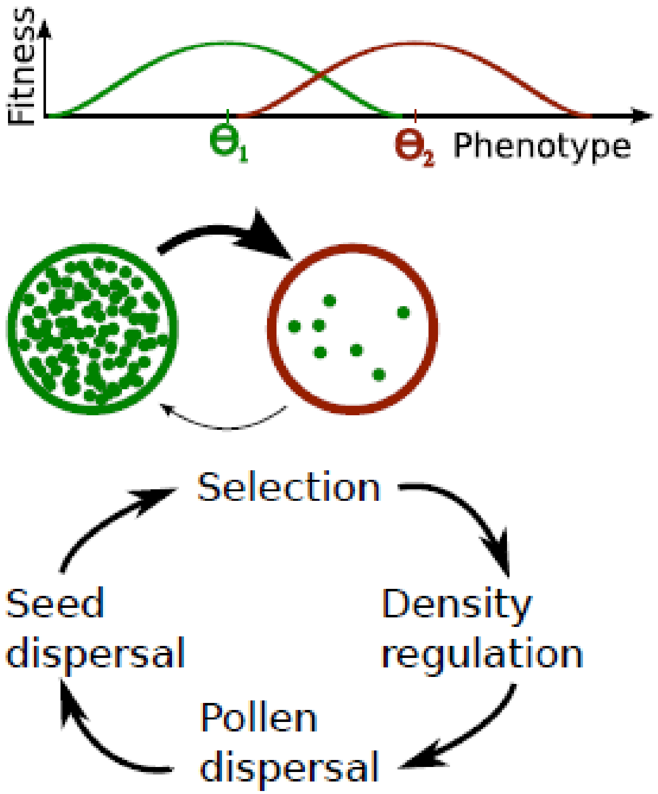
What me normal?



Débarre et al. 2013; Yeaman & Guillaume 2009; Huismann &Tufto 2012

Models of niche expansion with pollen dispersal

- 2 habitats, 2 optimal phenotypes
- Initial state: source-sink
- Discrete time, non-overlapping generations

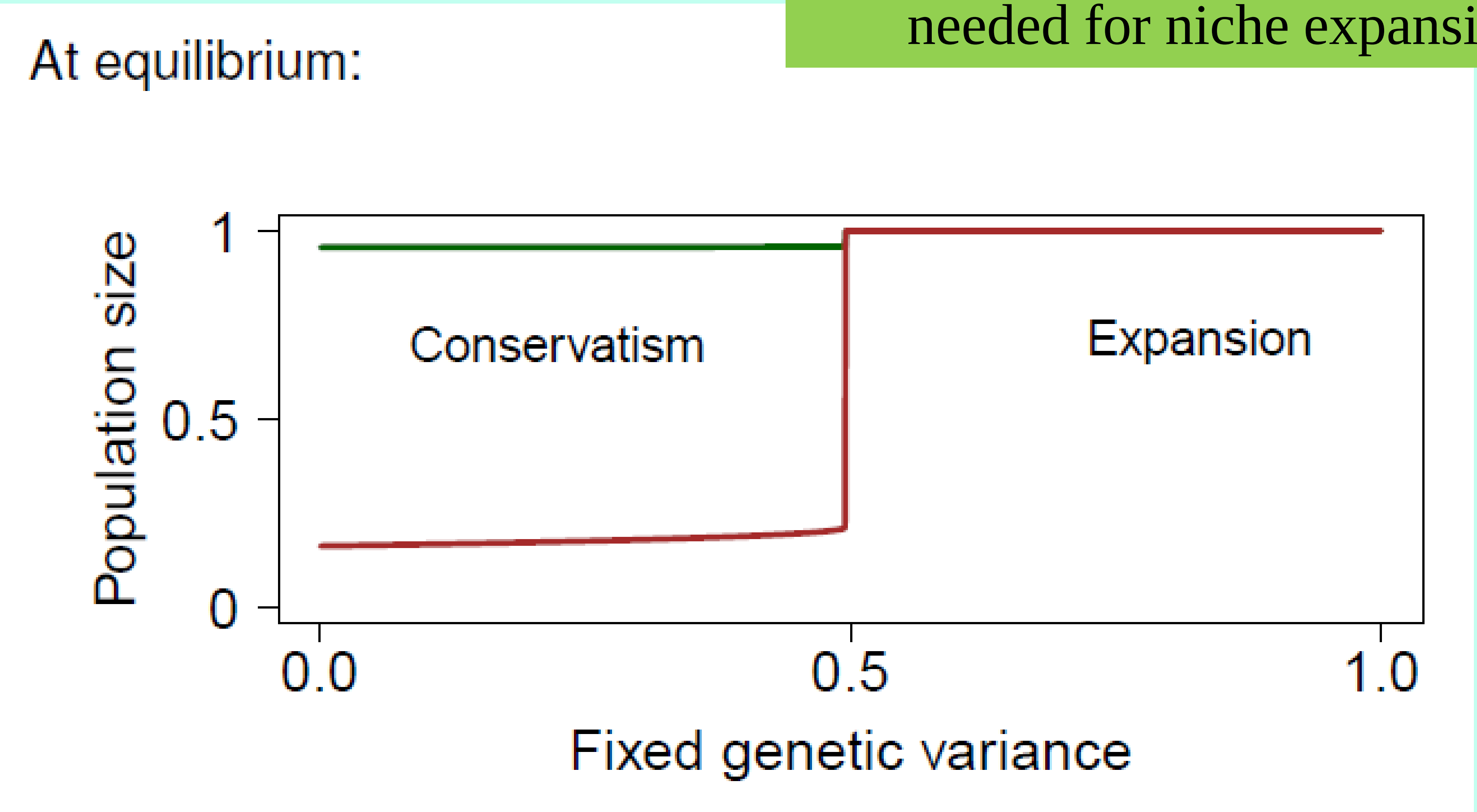


Analytical model: fixed genetic variance
Simulation model: evolving genetic variance

Aguilée et al. 2012 Evolution

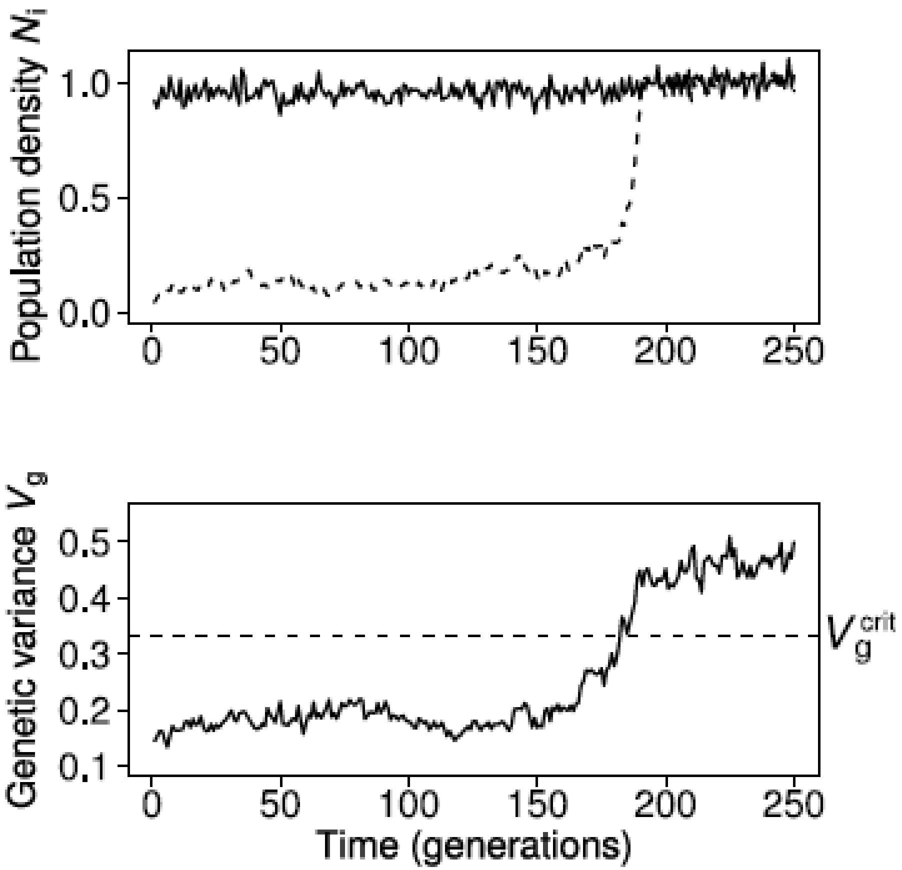
Models of niche expansion with pollen dispersal

Critical genetic variance needed for niche expansion

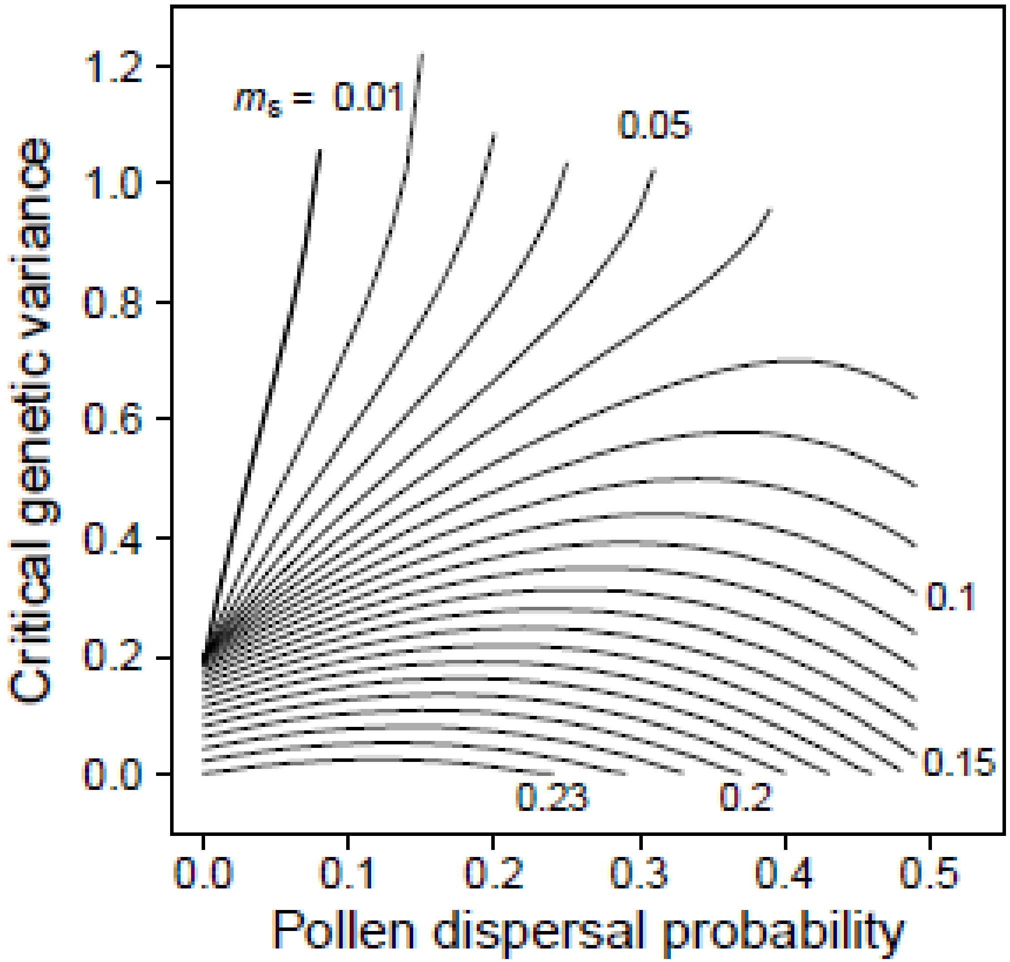


Critical genetic variance reached: niche expansion

(simulation model, **evolving** genetic variance)



Models of niche expansion with pollen dispersal

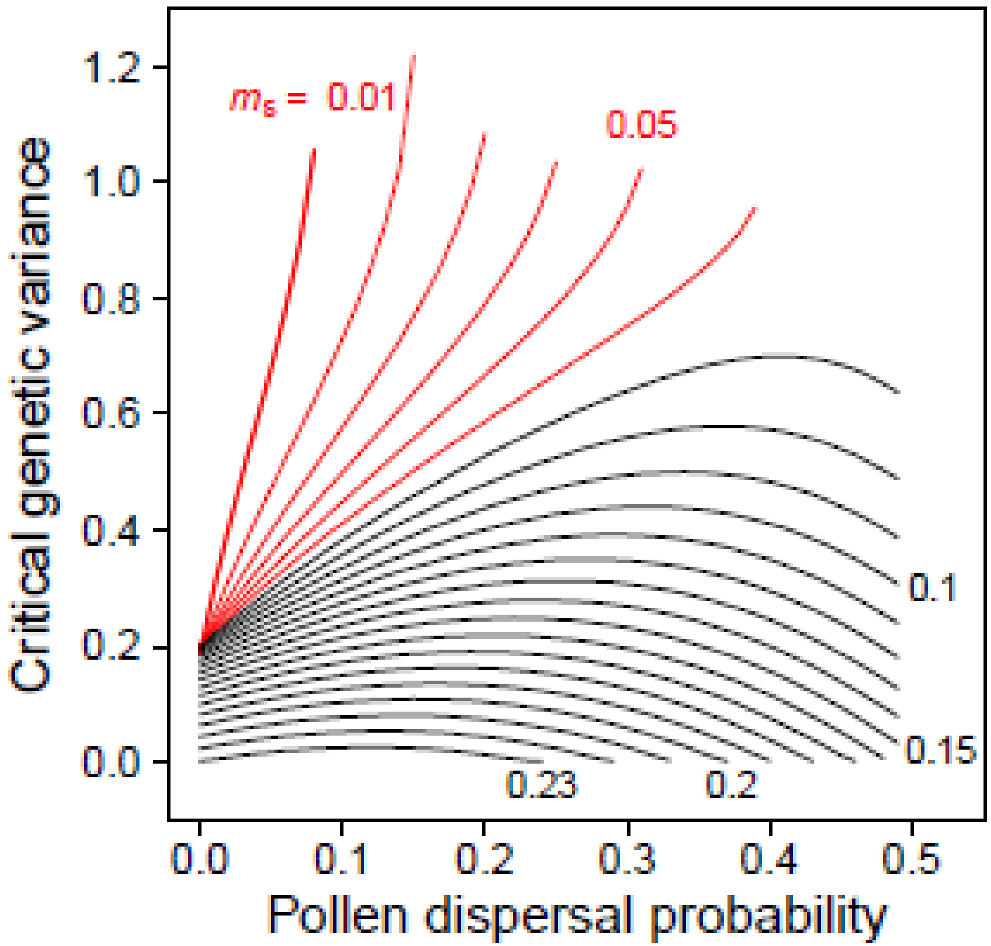


Critical genetic variance decreases with higher seed dispersal

Seed dispersal:

- demographic effect: easier niche expansion

Models of niche expansion with pollen dispersal



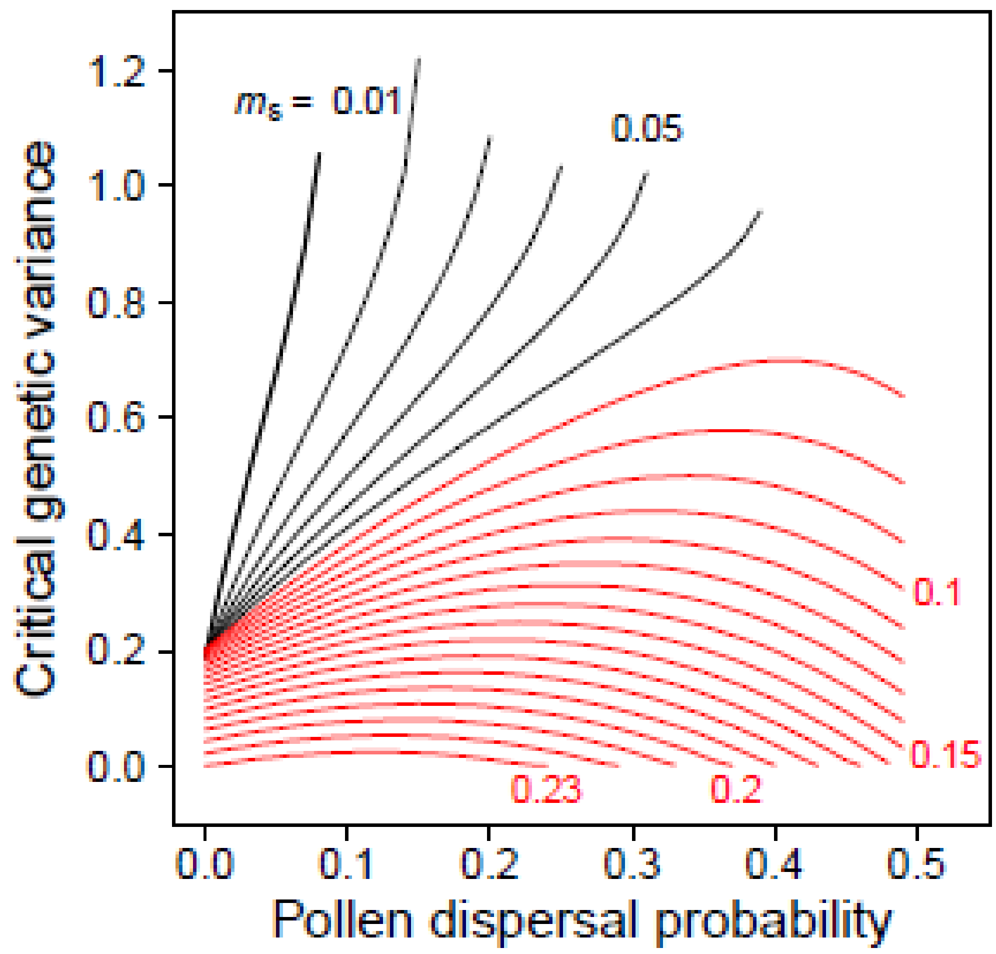
When seed dispersal is low

Critical genetic variance increases with higher pollen dispersal

Pollen dispersal:

- genetic effect:
  harder niche expansion
- indirect genetic effect:
  maladapted source,
  easier niche expansion

Models of niche expansion with pollen dispersal



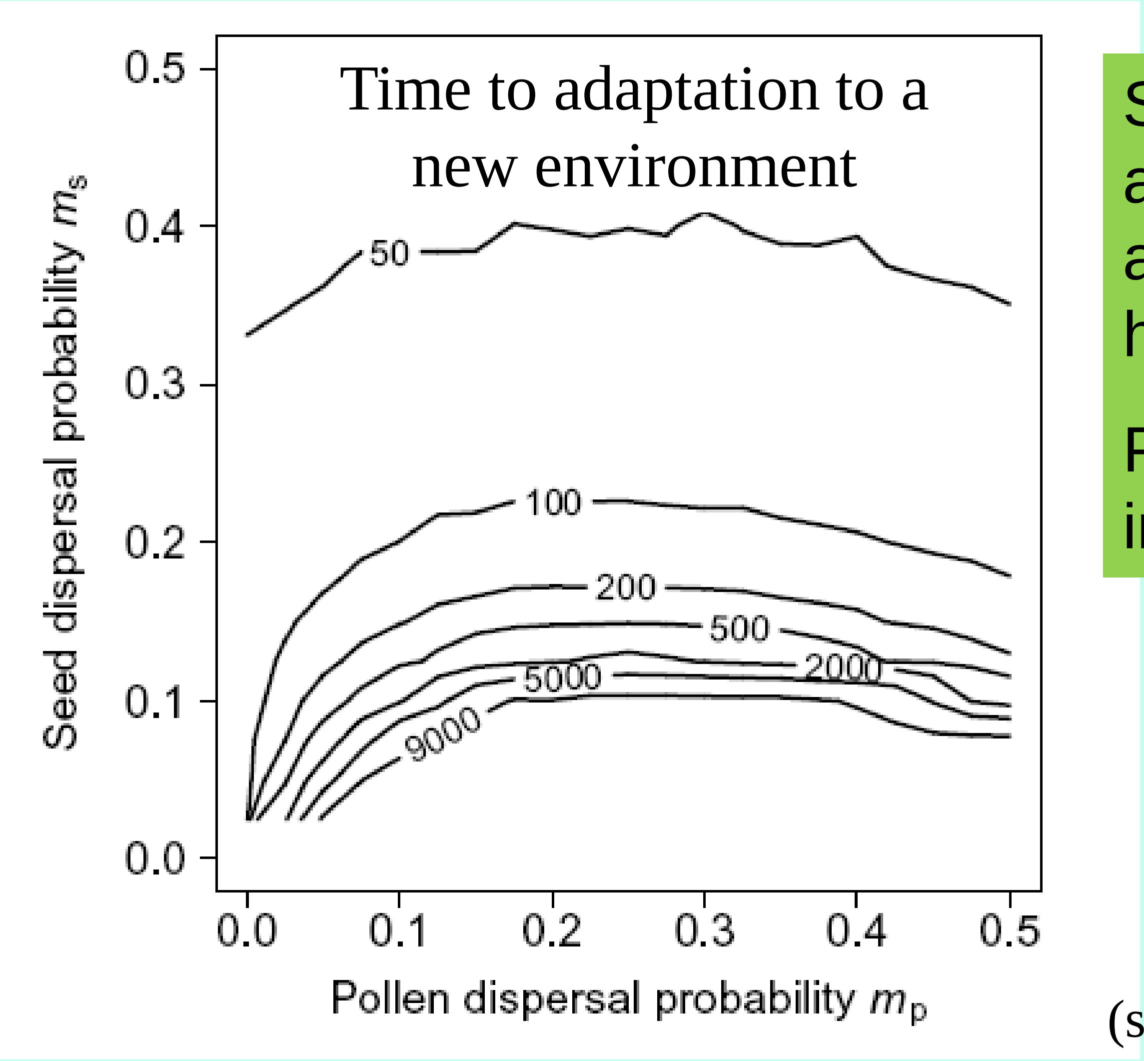
When seed dispersal is high

Non monotonic effect of pollen dispersal

Pollen dispersal:

- genetic effect: harder niche expansion
- indirect genetic effect: maladapted source, easier niche expansion

Models of niche expansion with pollen dispersal

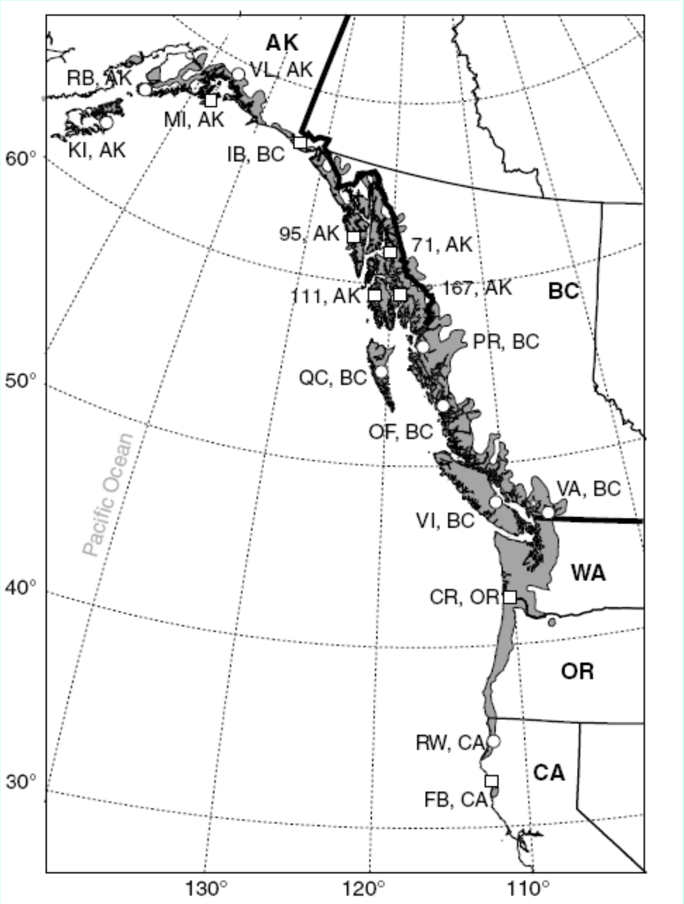


Seed dispersal accelerates adaptation to a new habitat

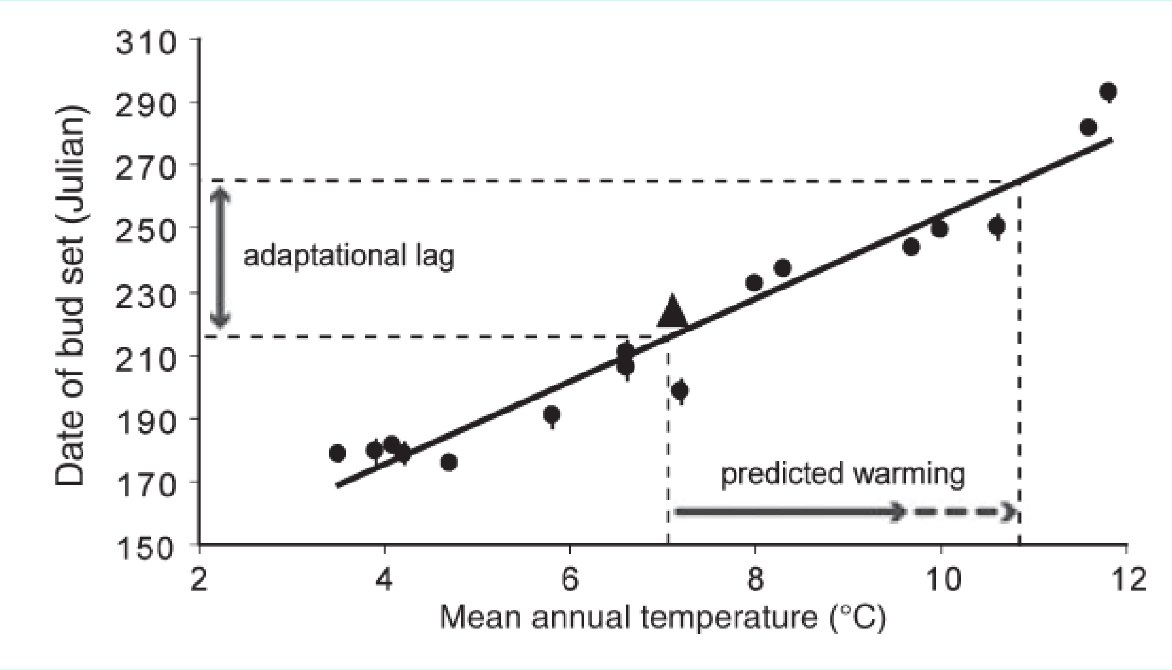
Pollen dispersal impedes it

(simulations)

Continuous environmental gradients



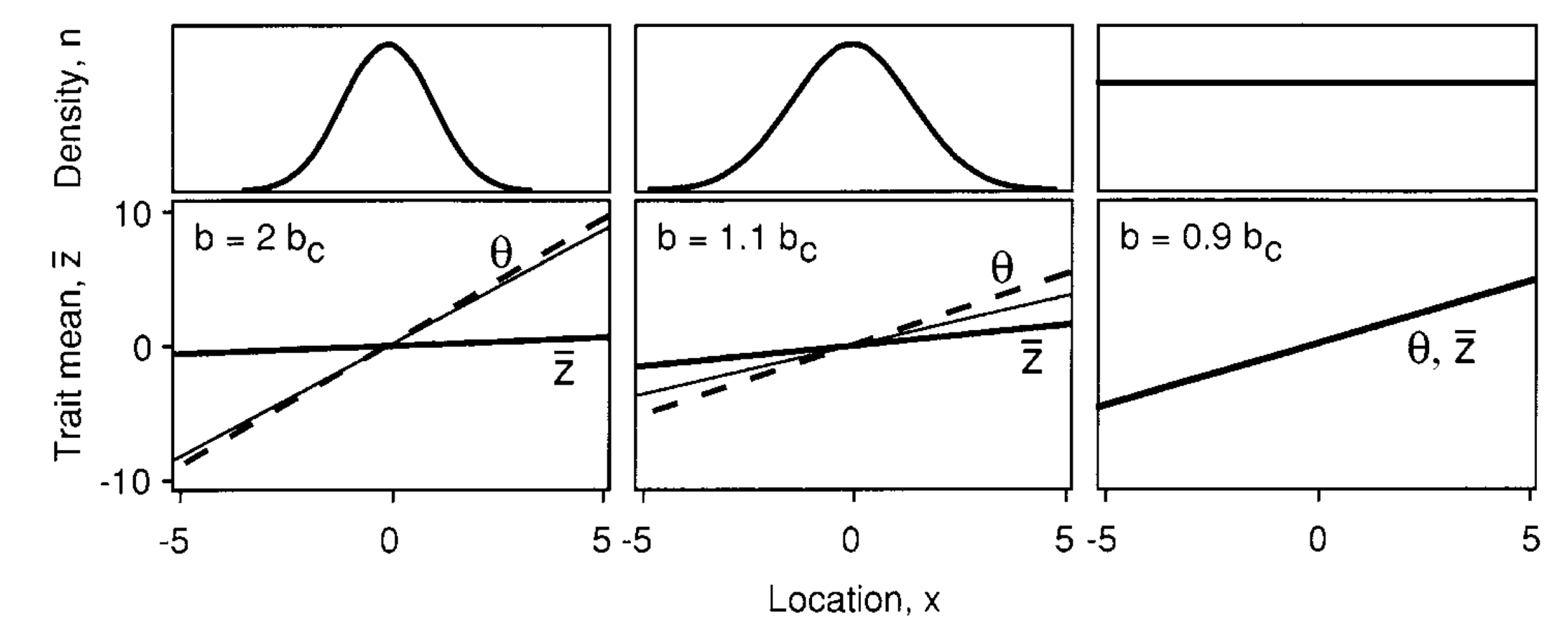
Sitka spruce



Mimura & Aitken 2007; Aitken et al. 2008

A quantitative genetics model for species range evolution

Kirkpatrick & Barton 1997

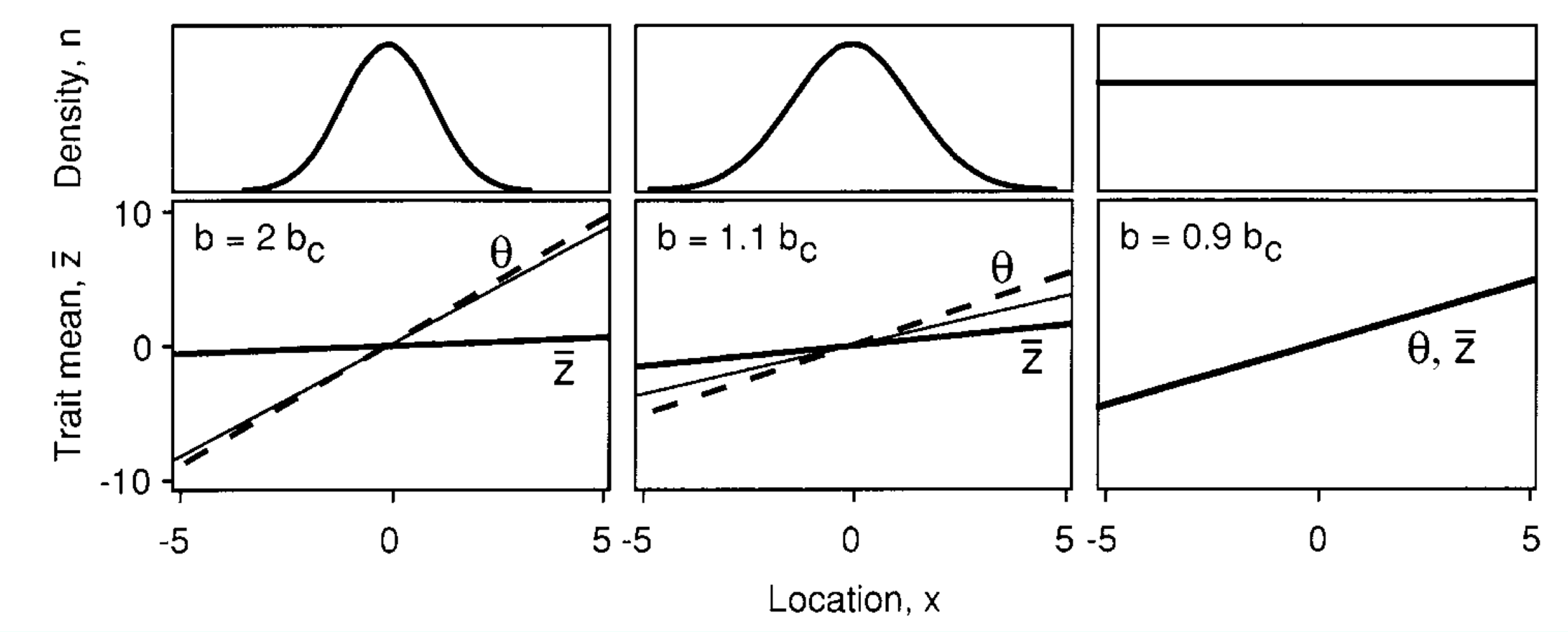


Maladaptation at the margins
Less phenotypic divergence than optimal
Limited range

Perfect adaptation everywhere
Infinite range

A quantitative genetics model for species range evolution

Kirkpatrick & Barton 1997



Spatial gradient above a critical value

Spatial gradient below a critical value

Are marginal populations maladapted?

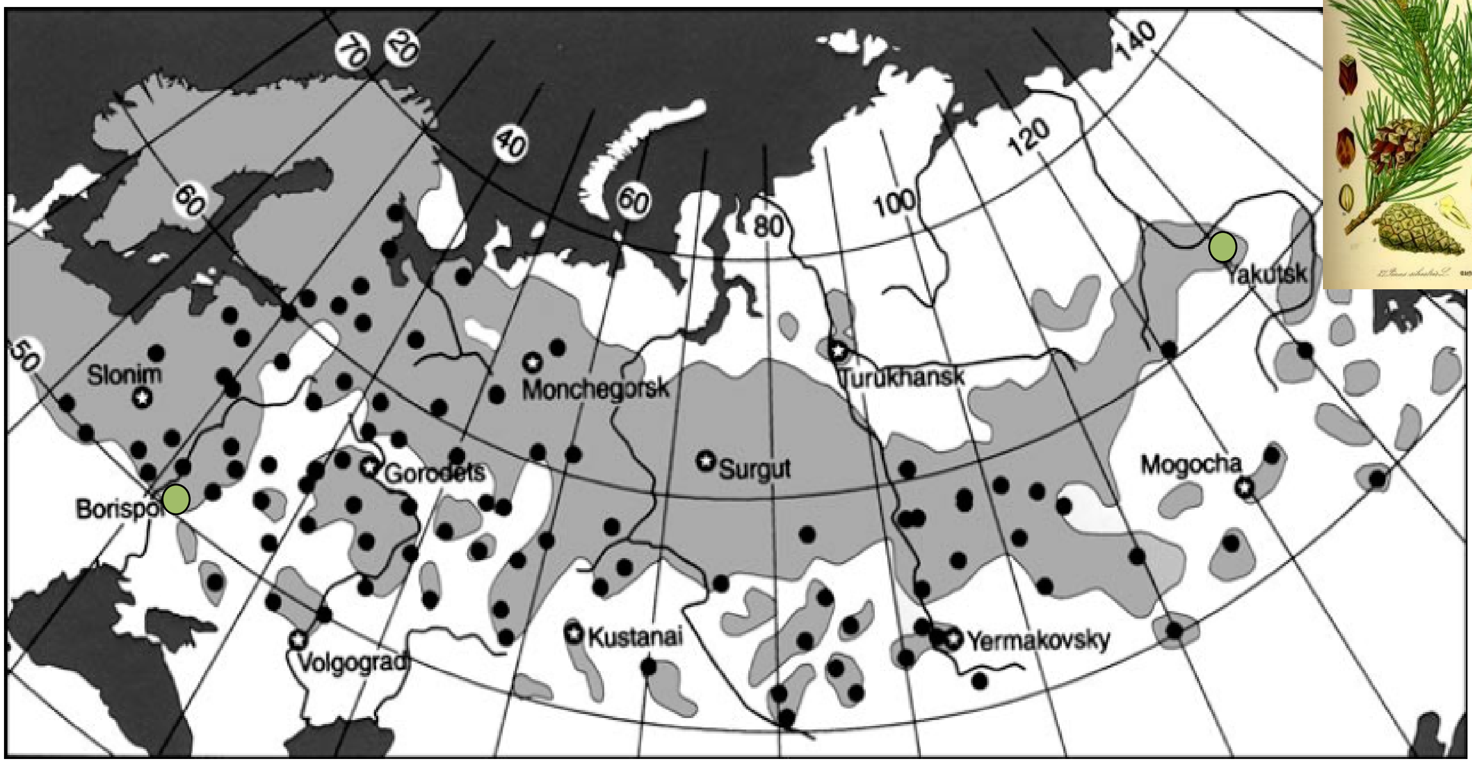
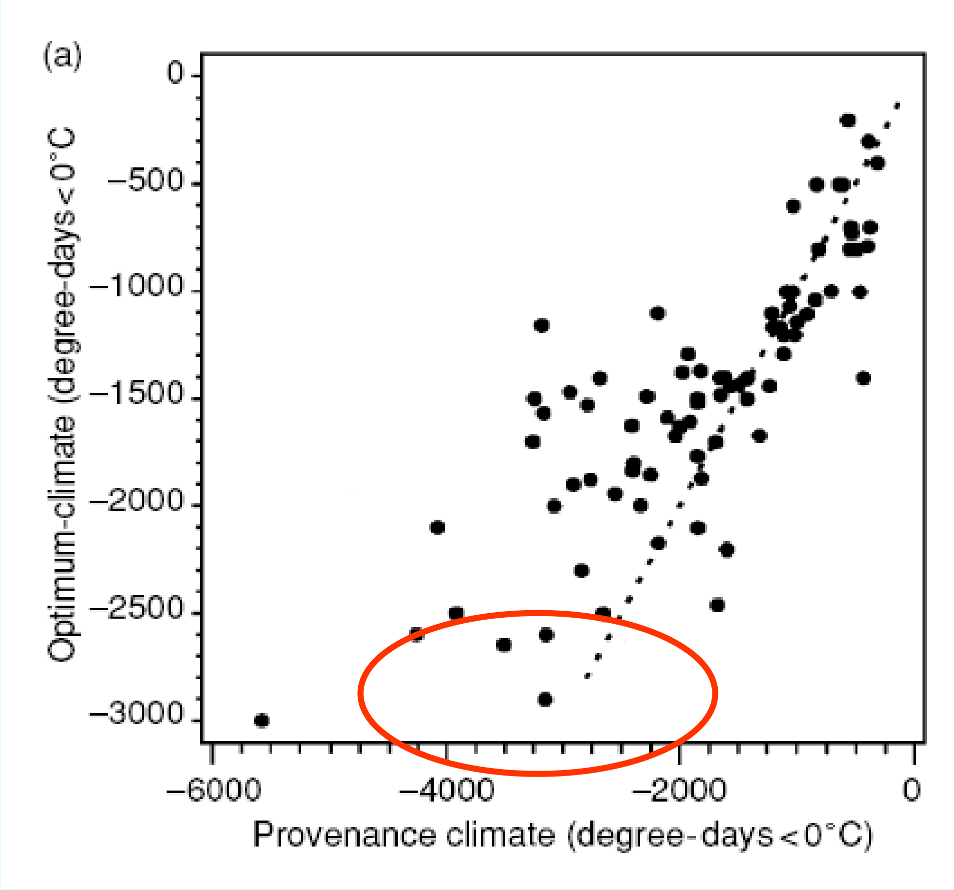
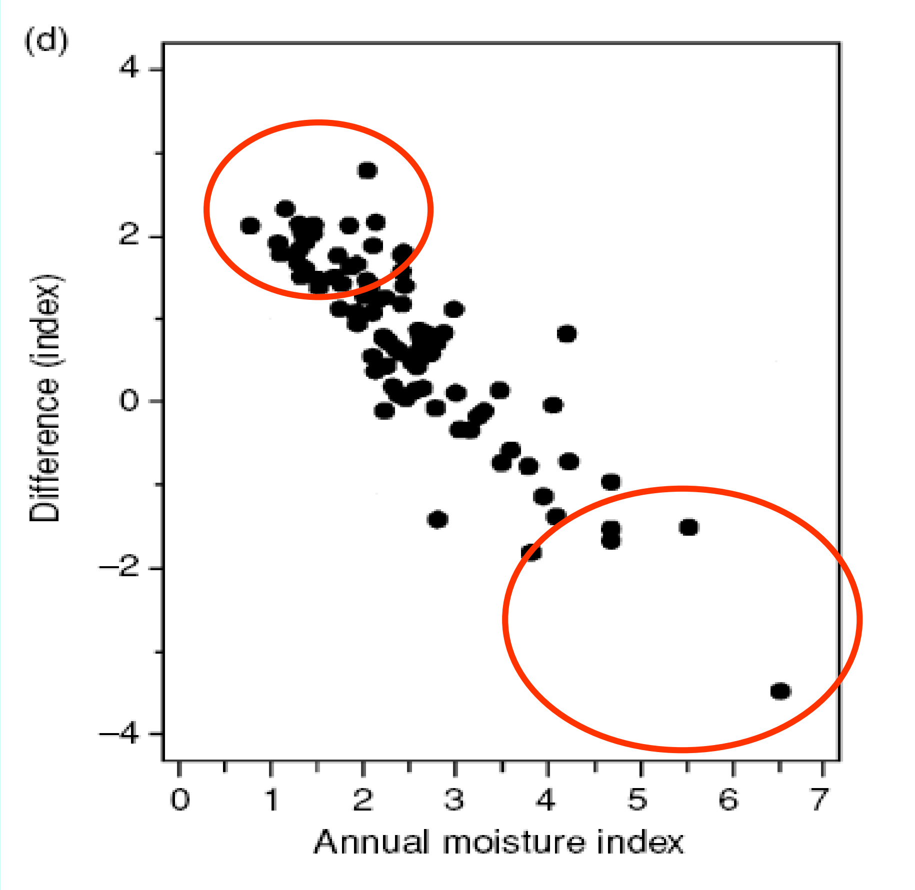


Fig. 1 Distribution (shading) of *P. sylvestris* (after Critchfield & Little, 1966) and location of populations (dots) sampled. Locations that are named are used throughout the paper to illustrate geographical effects.

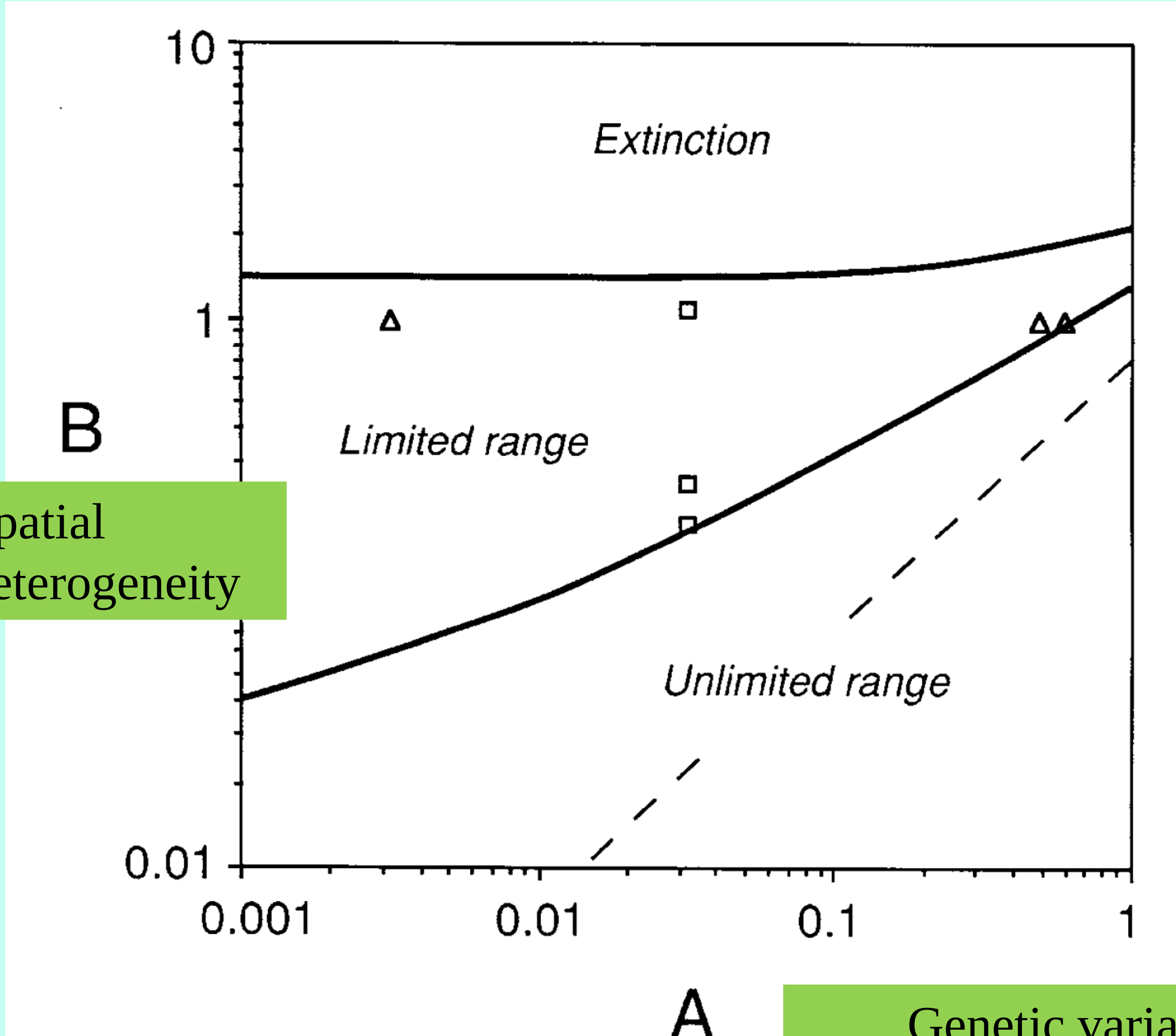
Pinus sylvestris

Are marginal populations maladapted?





Rehfeldt et al. 1999, 2002



Spatial heterogeneity

Genetic variance

Deriving K&B1997 model from structured models

Raoul 2017

Diffusion across space

Selection

Competition (local in space non local in phenotype)

$$\partial_t n(t,x,y) = \Delta_x n(t,x,y) + \left(1 + \frac{A}{2} - \frac{1}{2}(y - y_{opt}(t,x))^2 - \int n(t,x,z)\,dz\right) n(t,x,y)$$
$$+ \gamma \left(\int\int \Gamma_{A/2}\left(y - \frac{y_* + y'_*}{2}\right) \frac{n(t,x,y_*)n(t,x,y'_*)}{\int n(t,x,z)\,dz}\,dy_*\,dy'_* - n(t,x,y)\right),$$

Reproduction (Infinitesimal model of trait inheritance)

$$\Gamma_{A/2}(y) := \frac{1}{\sqrt{2\pi A}} e^{\frac{-|y|^2}{A}}.$$

if $\gamma > 0$ is large

$$n(t,x,y) \sim N(t,x)\Gamma_A\left(y - Z(t,x)\right)$$

Relaxing the hypothesis of constant variance

Barton 2001

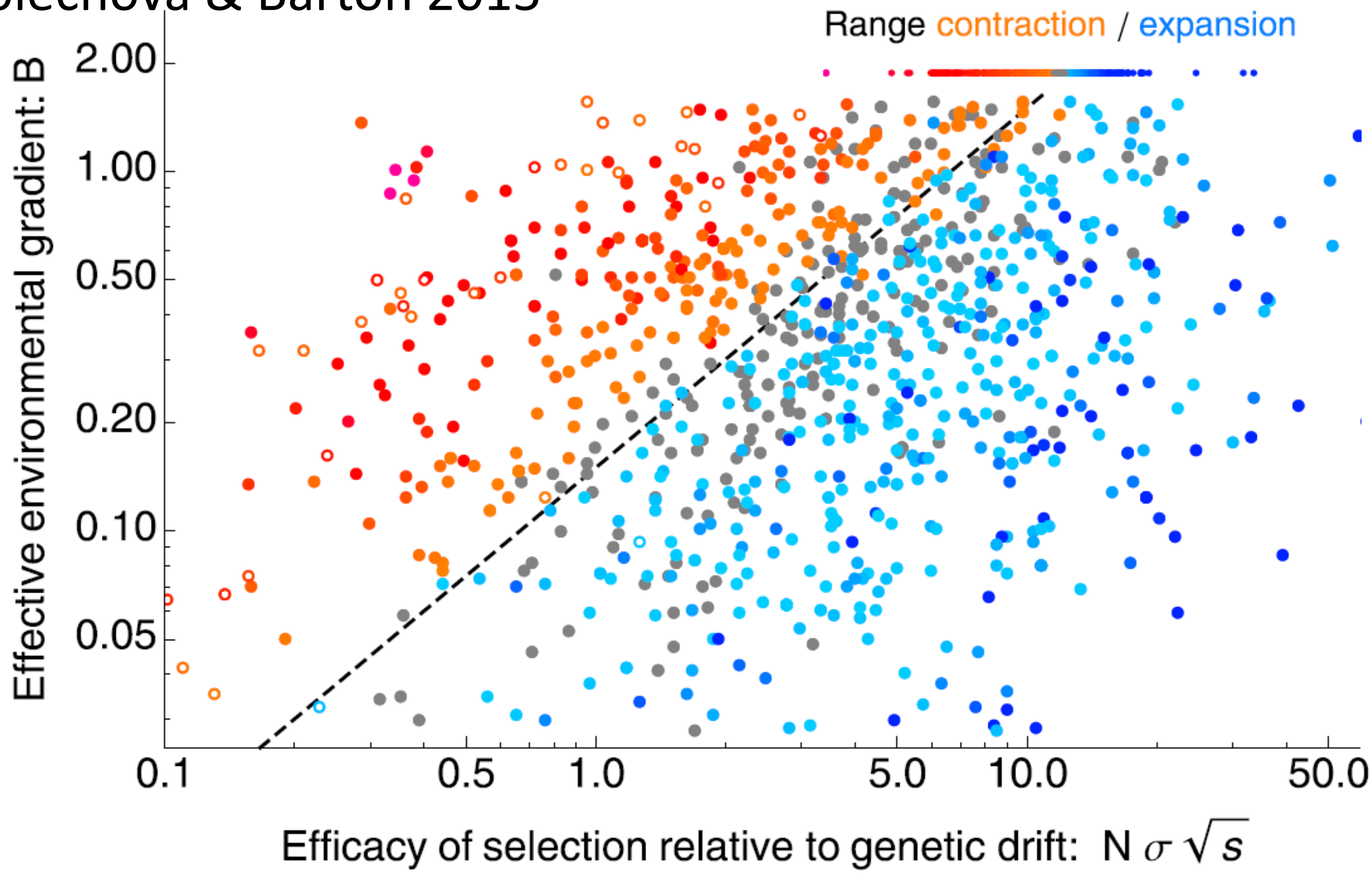
Gene flow across a phenotypic cline maintained by the environment can generate much more genetic variance than would mutation alone

Rise of genetic variance allow species to adapt to steep environmental gradients

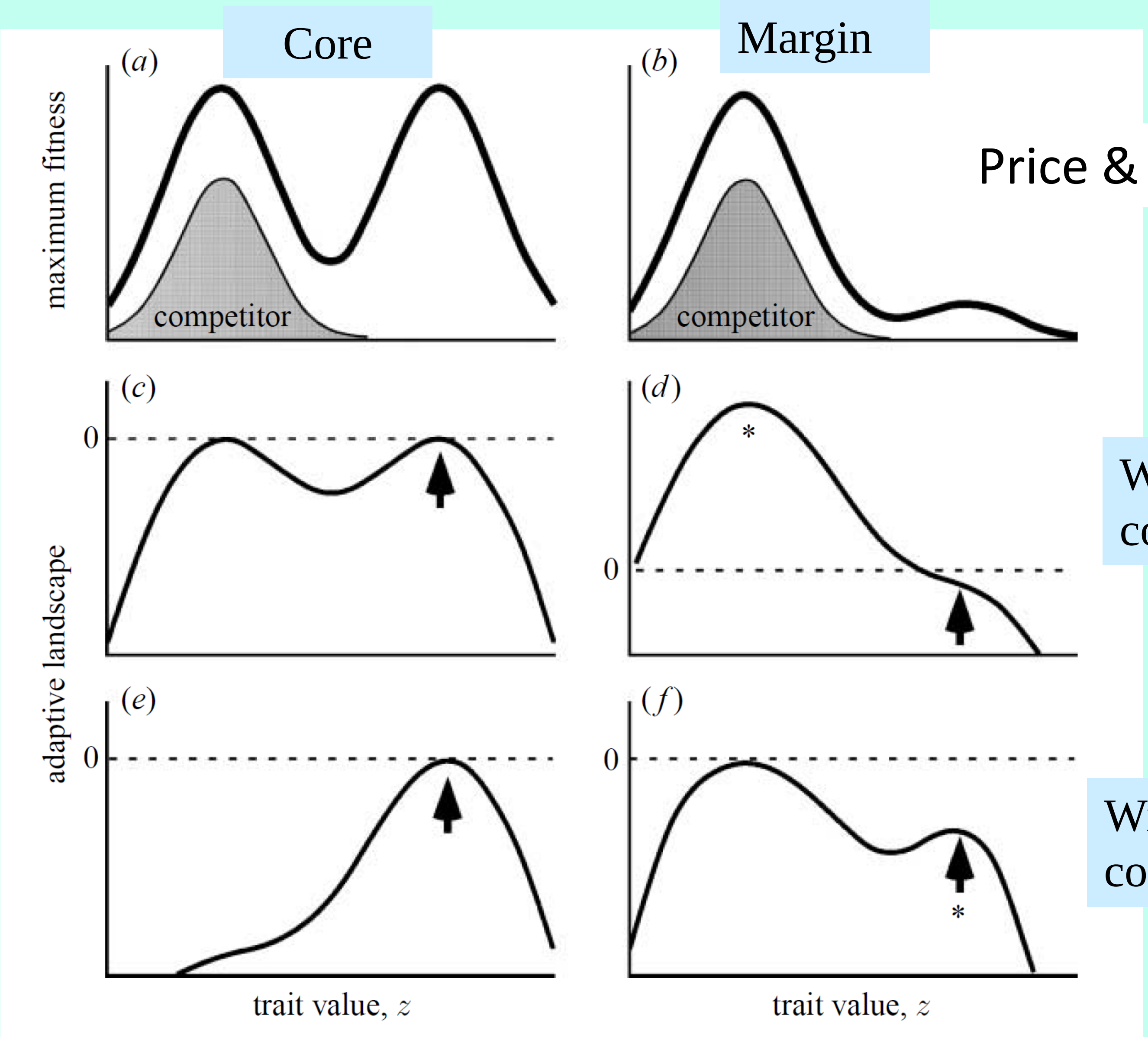
No limited range!

Relaxing the hypothesis of large population size

Polechova & Barton 2015



Evolutionarily stable range limits set by competition

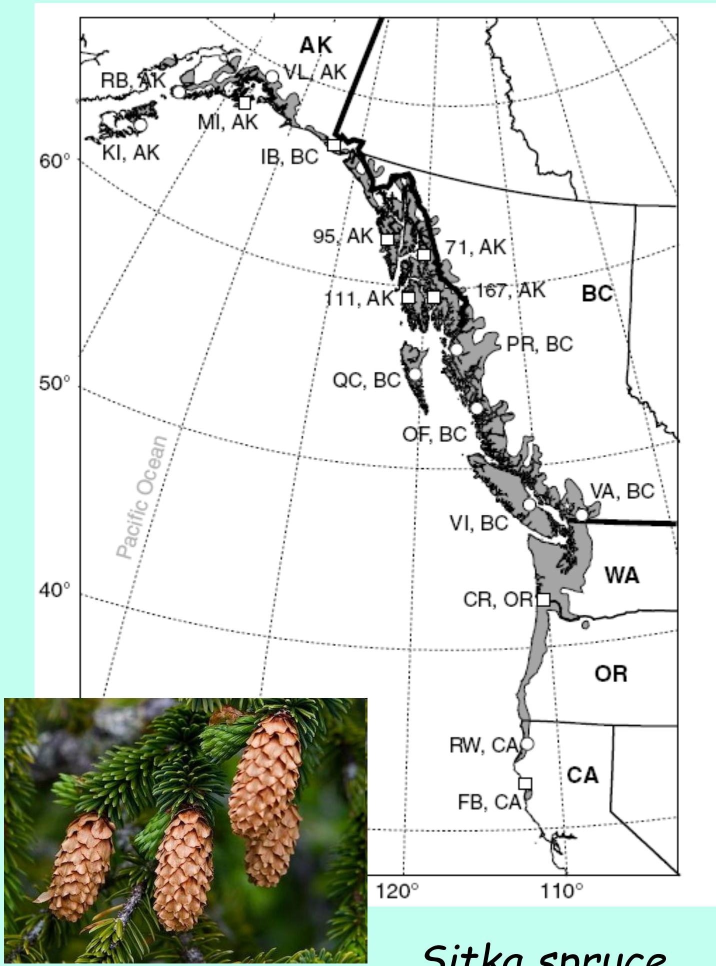


Price & Kirkpatrick 2009

Without competitor

With competitor

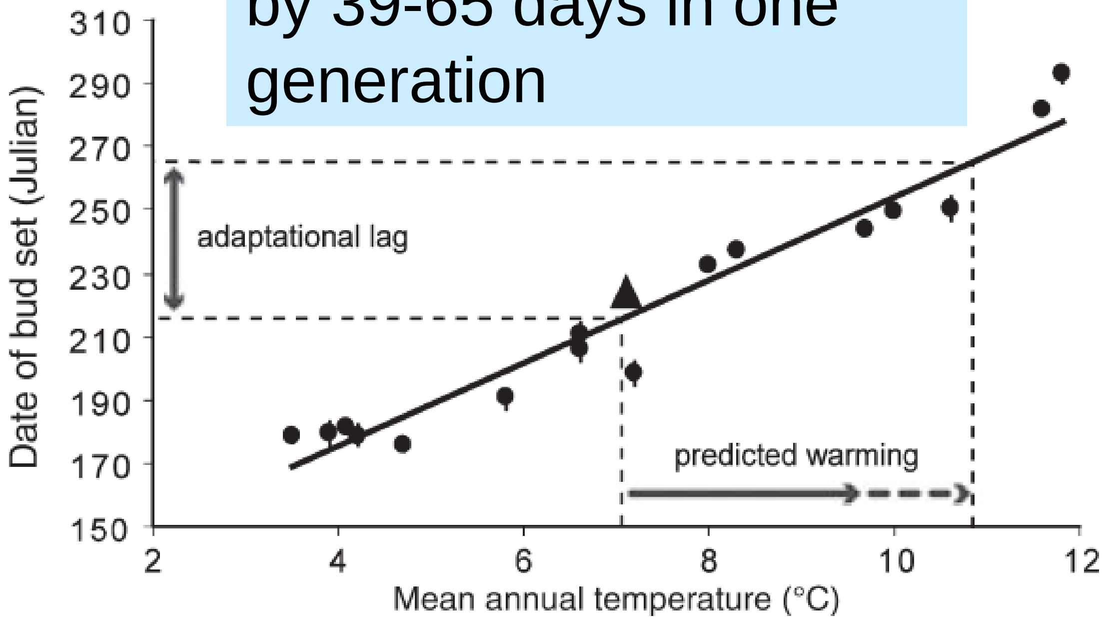
Adaptative challenges due to climate change



Sitka spruce

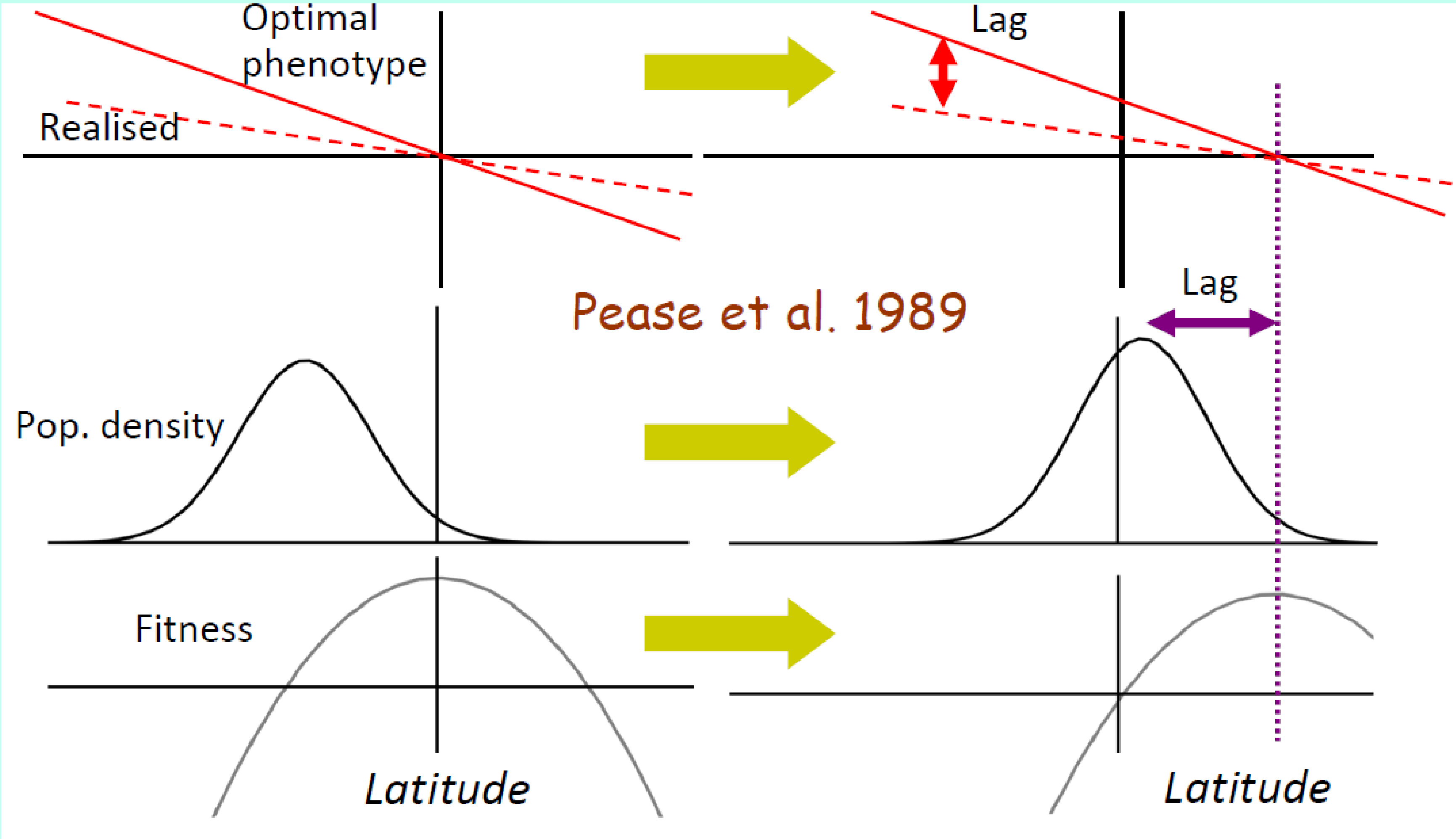
Mimura & Aitken 2007; Aitken et al. 2008

Bud set date should shift by 39-65 days in one generation

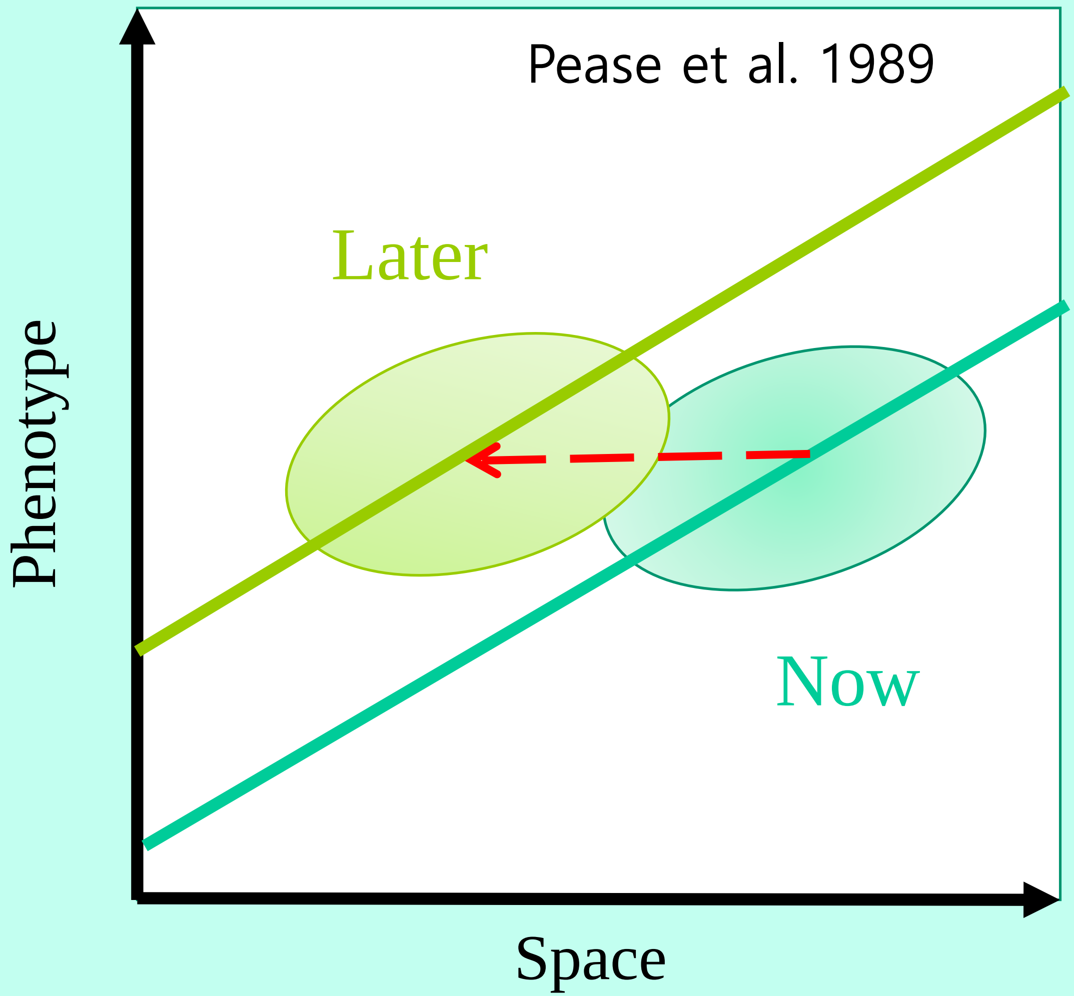


N Latitude S

Migration and adaptation can help tracking the climate



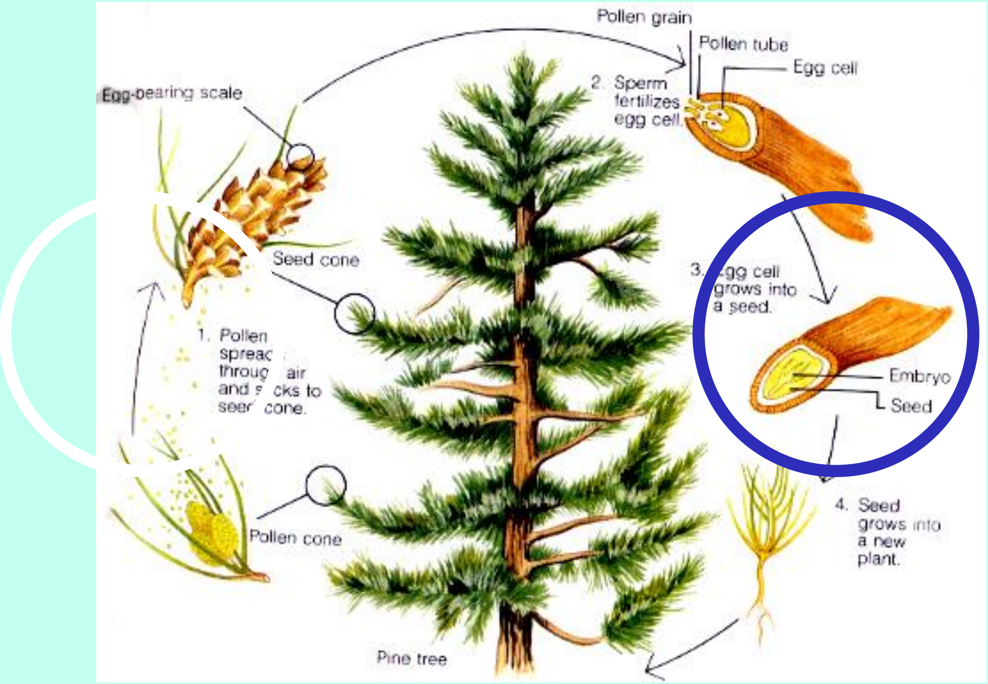
Migration and adaptation can help tracking the climate



Surviving species move at the same speed as climate

Niche conservatism!

Seed and pollen dispersal in a changing climate

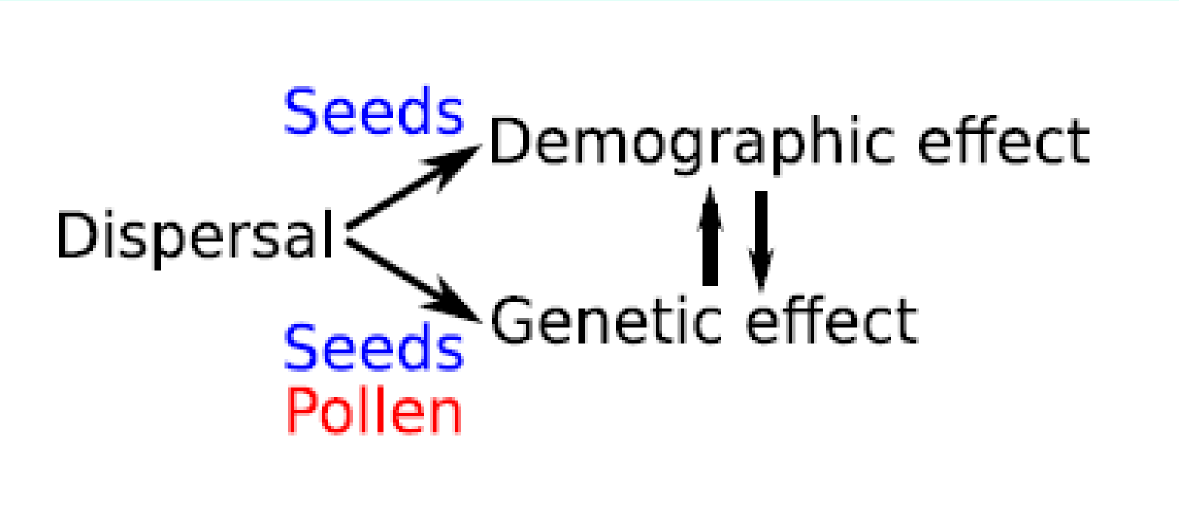


Kremer et al. 2013 Eco. Let.

Maximal pollen dispersal distance up to thousands of km

Maximal seed dispersal distance up to tens km

Effect of pollen on niche and range evolution under a changing climate



Robin Aguilée

A model of range and niche evolution with pollen dispersal

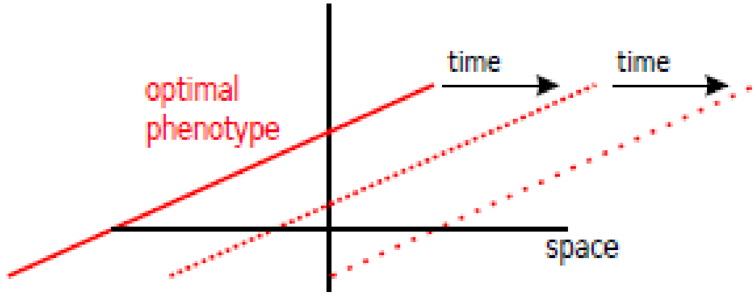
Aguilée et al. 2016 PNAS

Gaël Raoul François Rousset

Models of range evolution with pollen

A quantitative genetic model for population size $n(x, t)$ and mean phenotype $\bar{z}(x, t)$ with:

- A linear spatial gradient shifting in time at constant speed



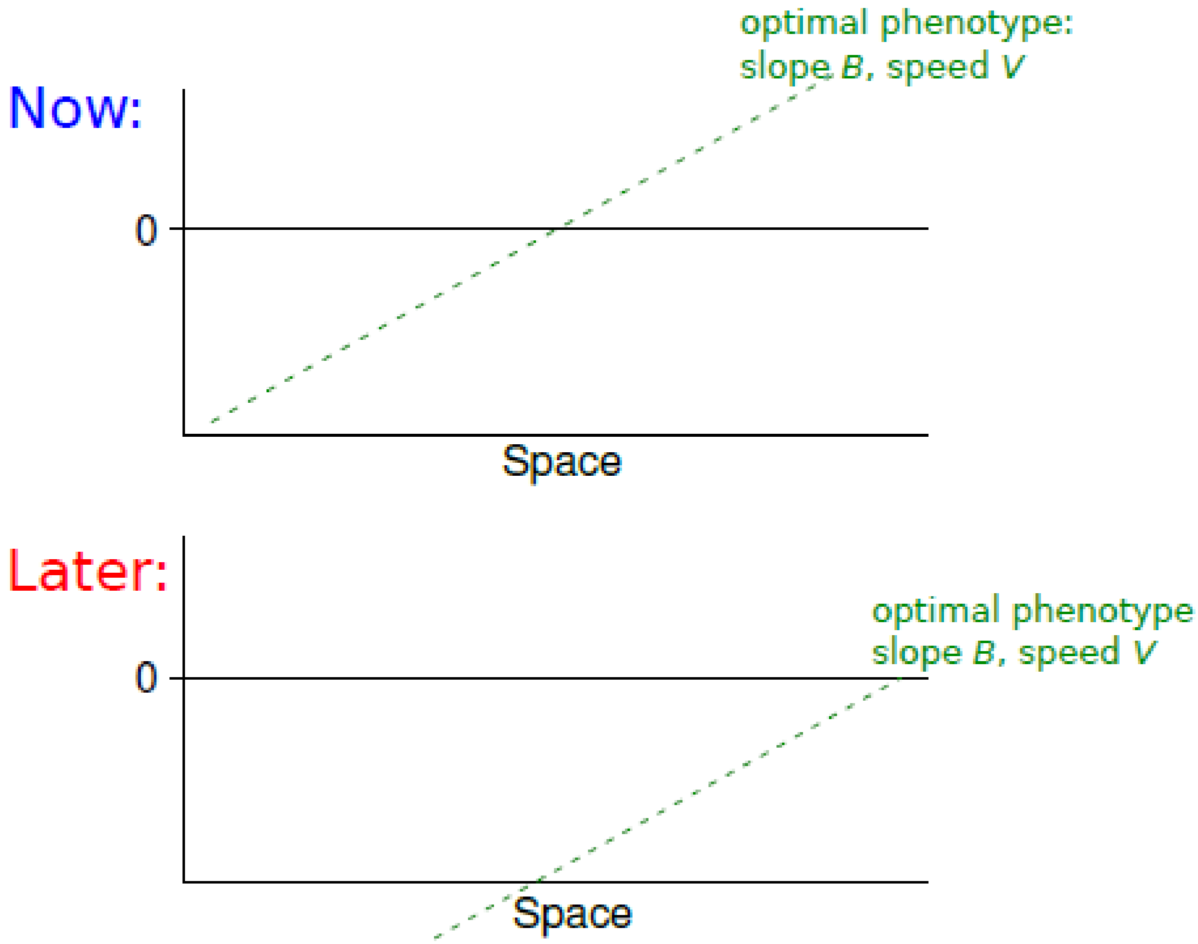
- Seed and pollen dispersal (diffusion, Gaussian dispersal kernel)
- Feedbacks between demography and adaptation

Two strong assumptions:

- Global density dependence
- Constant genetic variance

Relaxed without altering qualitative conclusions about the effect of pollen dispersal

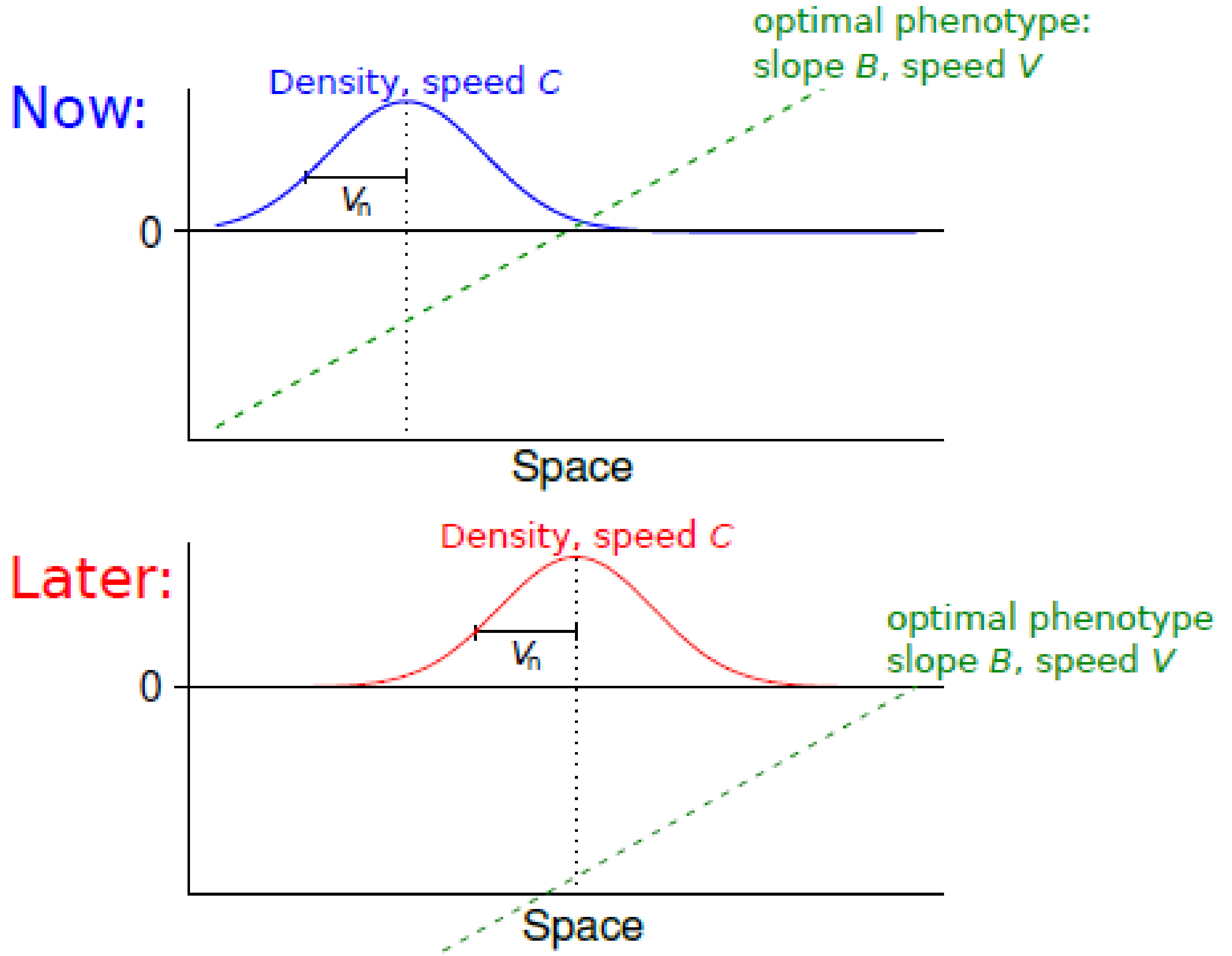
Models of range evolution with pollen



With pollen dispersal: spatial range shift **and** climatic niche shift

V_n = size of the range

C = speed of spatial range shift: slower than climate

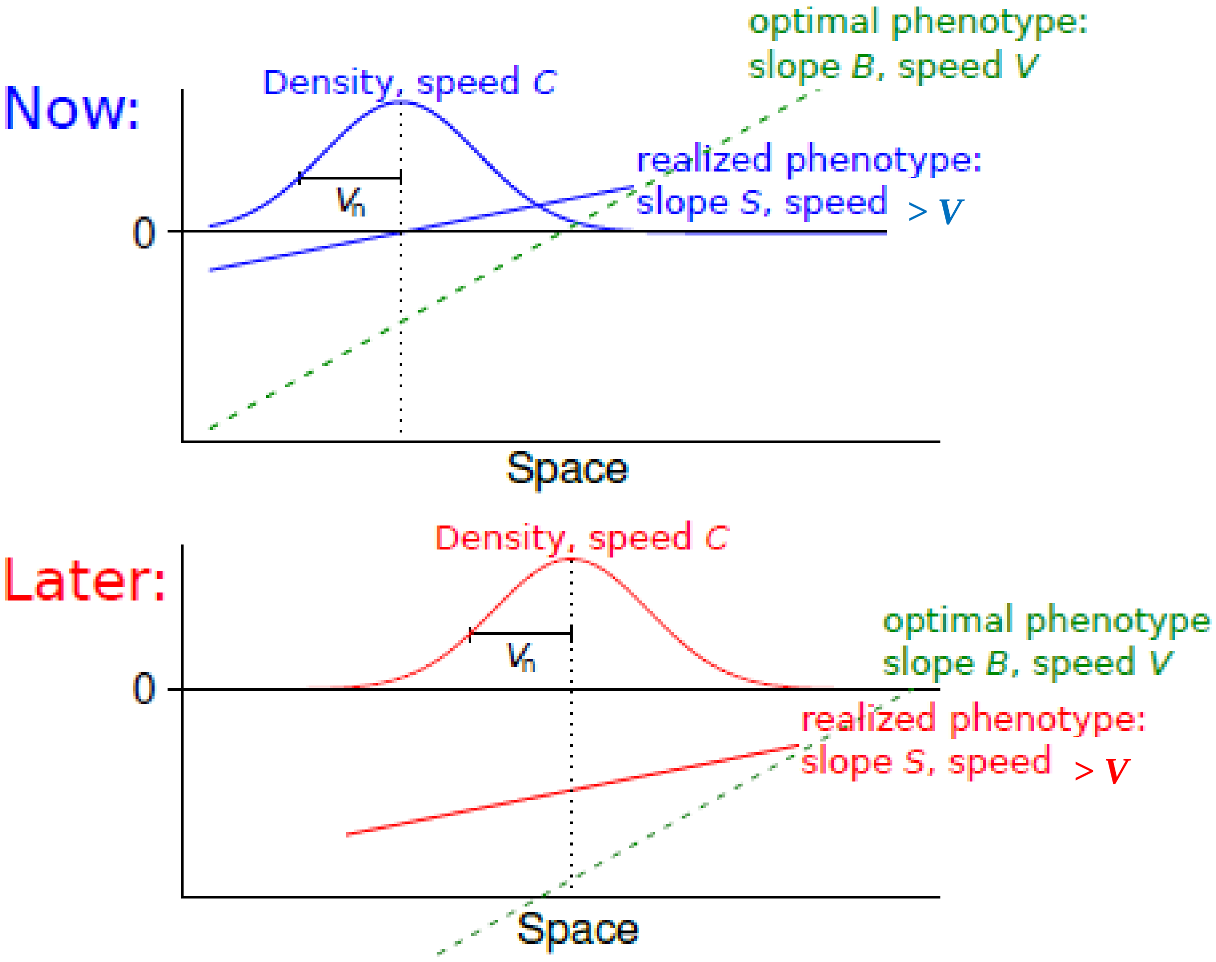


With pollen dispersal: spatial range shift **and** climatic niche shift

V_n = size of the range

C = speed of spatial range shift: slower than climate

S = slope of the realized phenotype



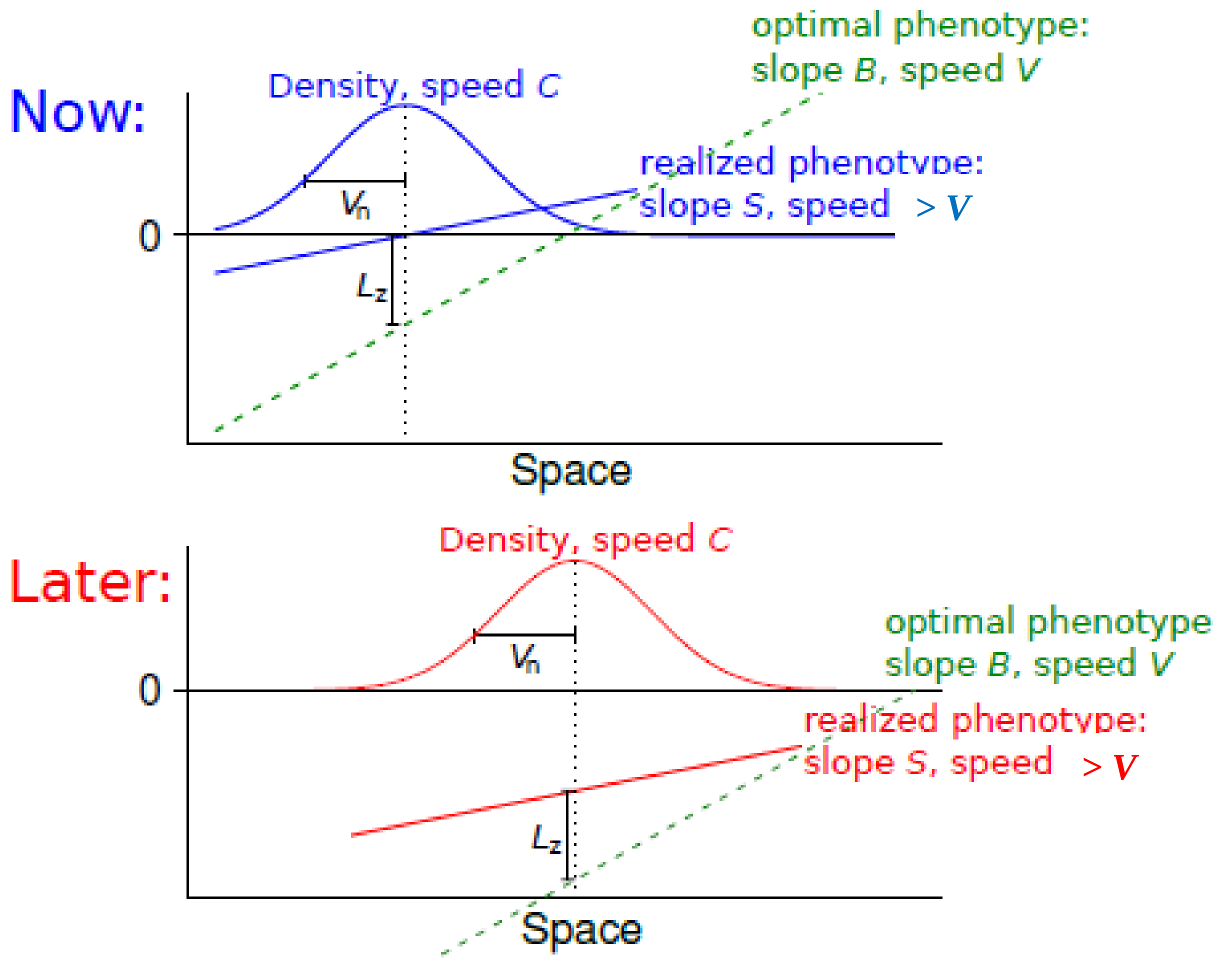
With pollen dispersal: spatial range shift **and** climatic niche shift

$V_{\rm n}$ = size of the range

C = speed of spatial range shift: slower than climate

S = slope of the realized phenotype

$L_{\rm z}$ = maladaptation at the core of the range



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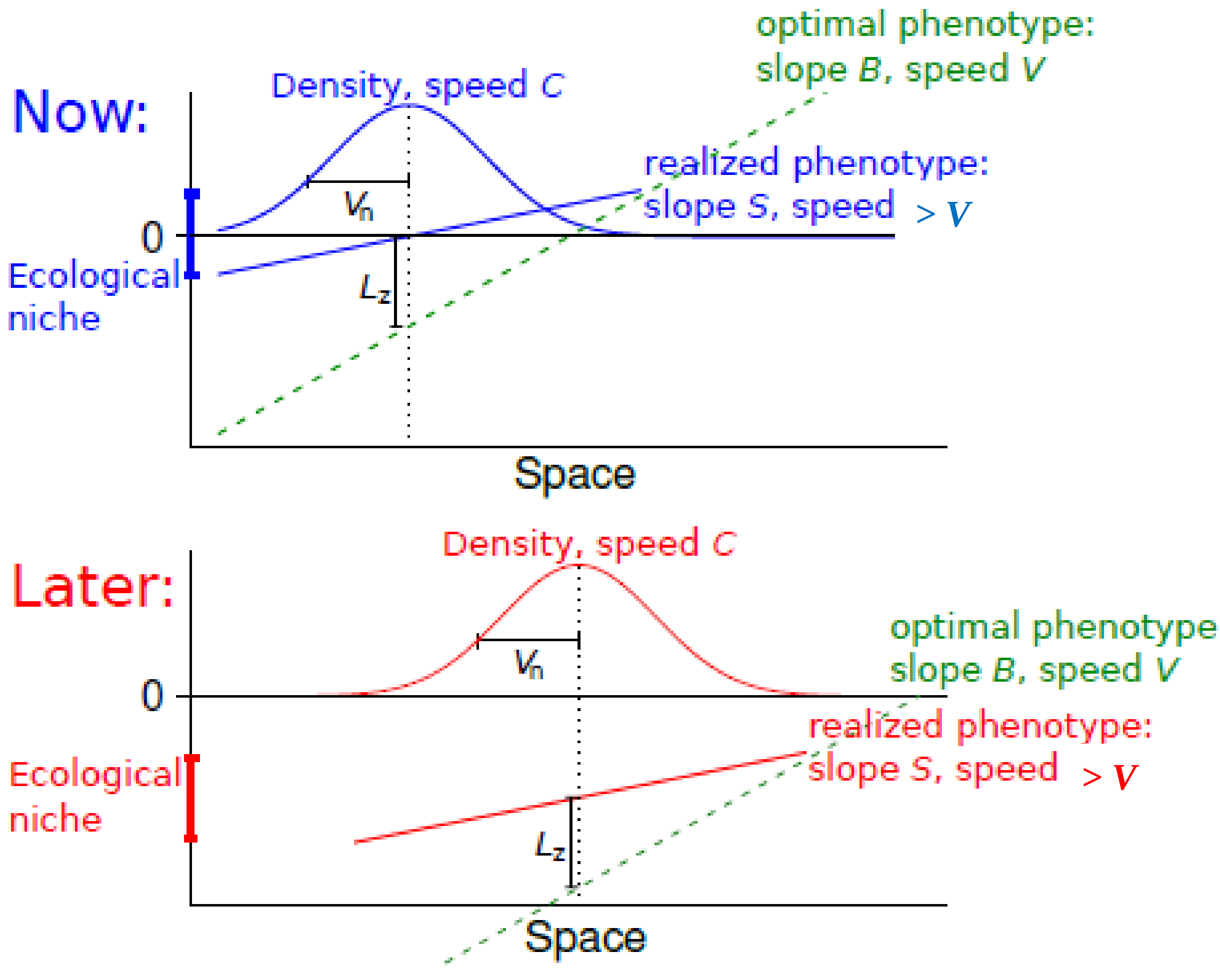
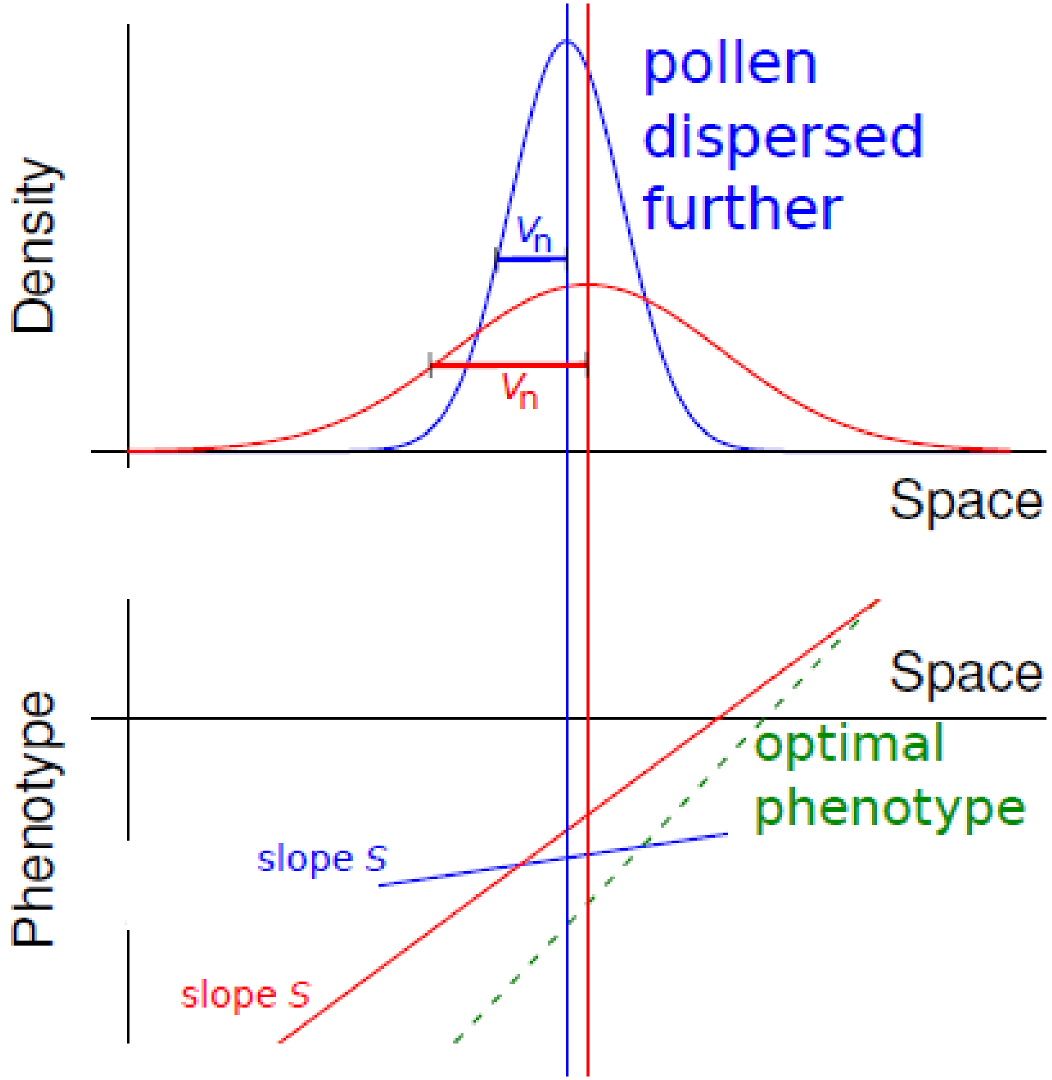


Models of range evolution with pollen

Blue = pollen dispersed further

- Flatter phenotypic cline ($|S|$)
- Narrower range (V_n)



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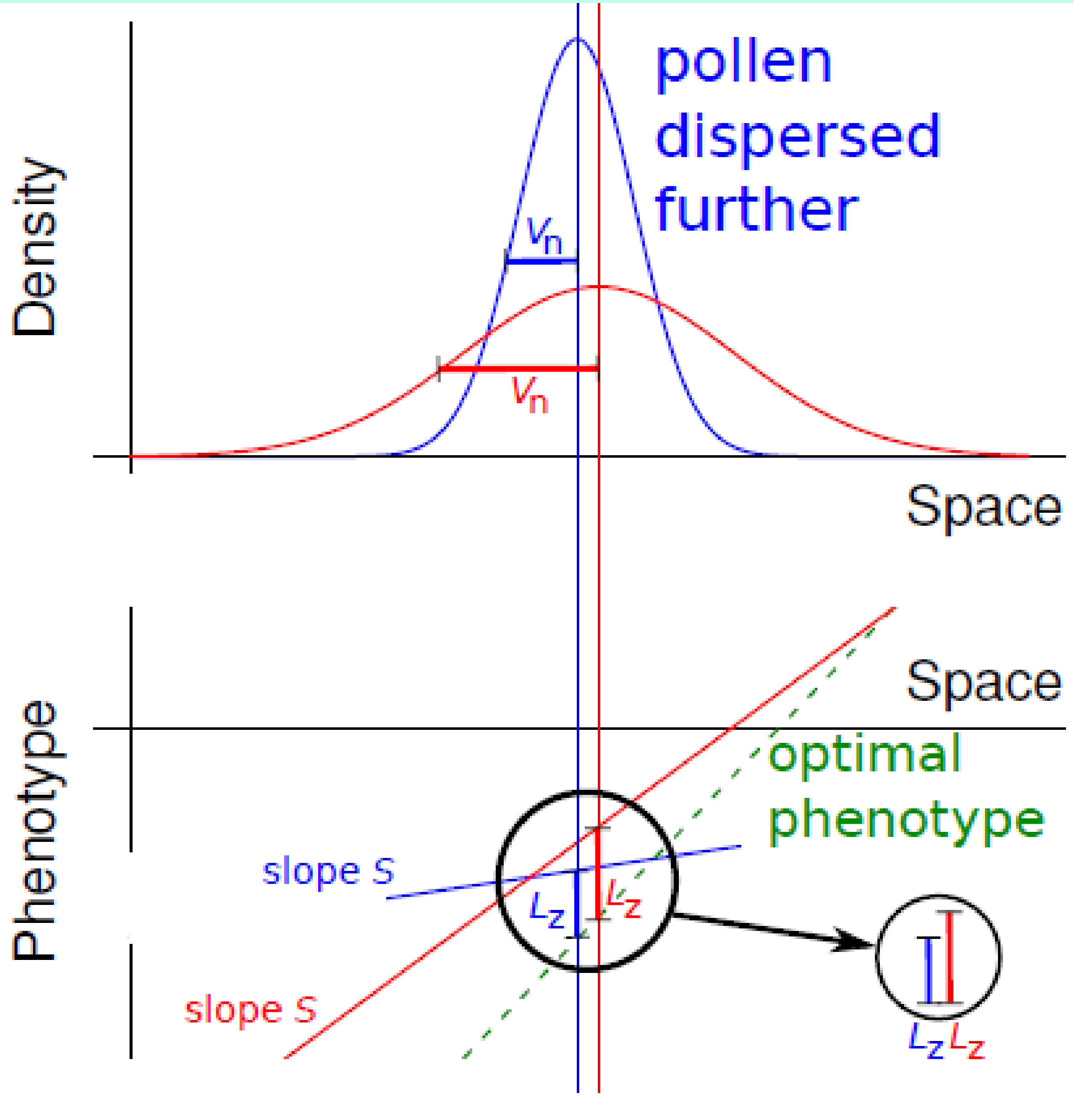
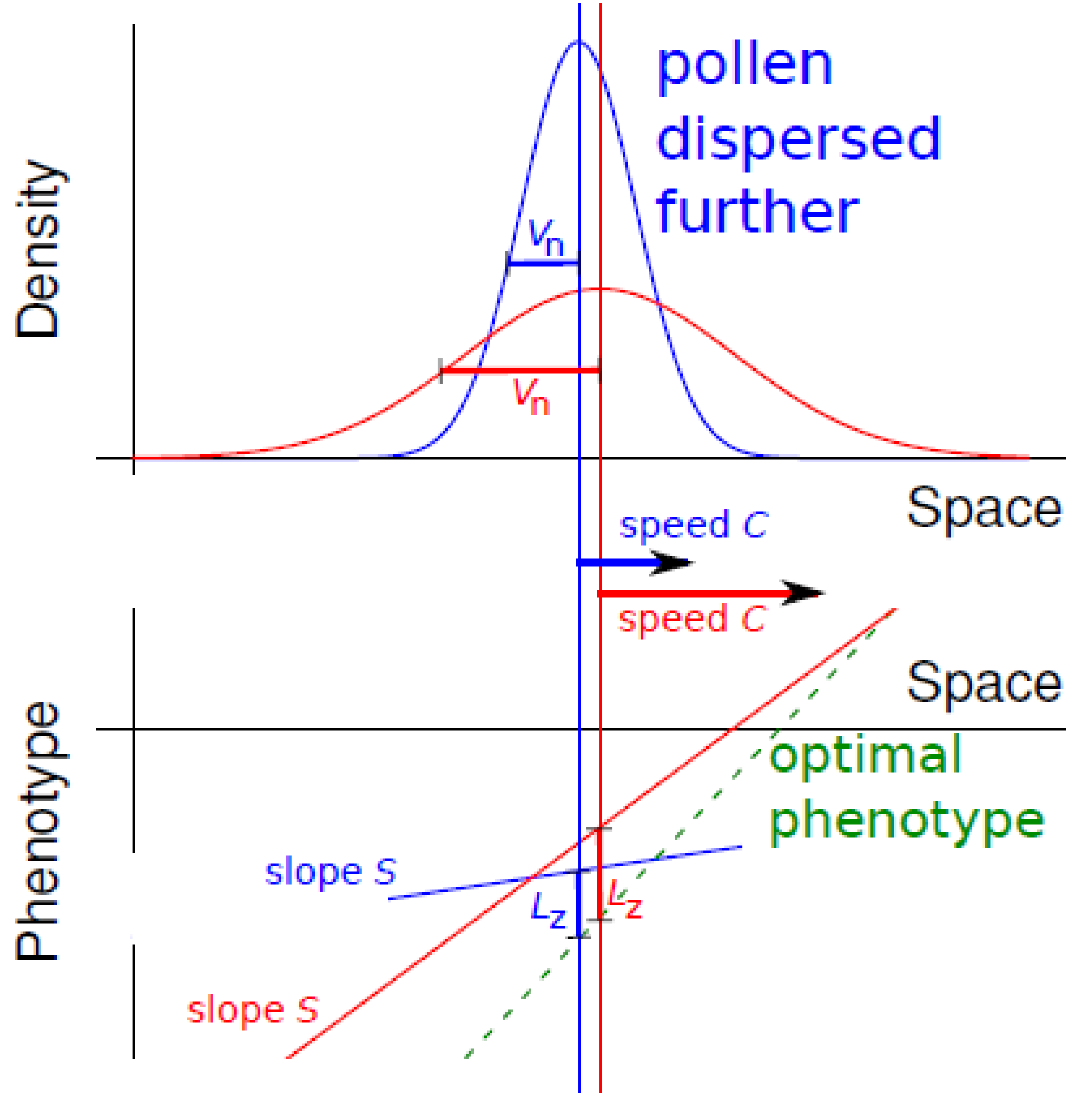


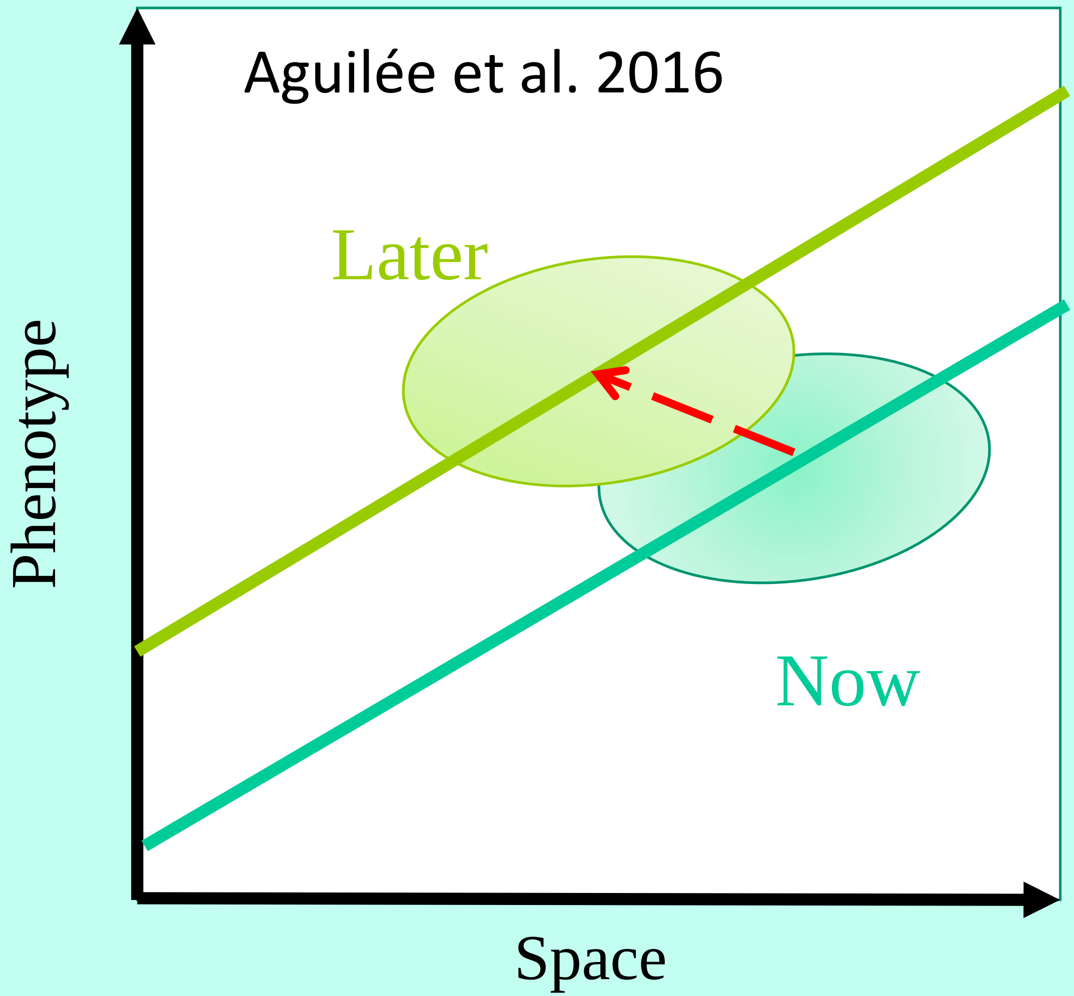
Models of range evolution with pollen

Blue = pollen dispersed further

- Flatter phenotypic cline ($|S|$)
- Narrower range (V_n)
- Better adaptation at the core ($|L_z|$)
- Slower wave (C)



Migration and adaptation can help tracking the climate

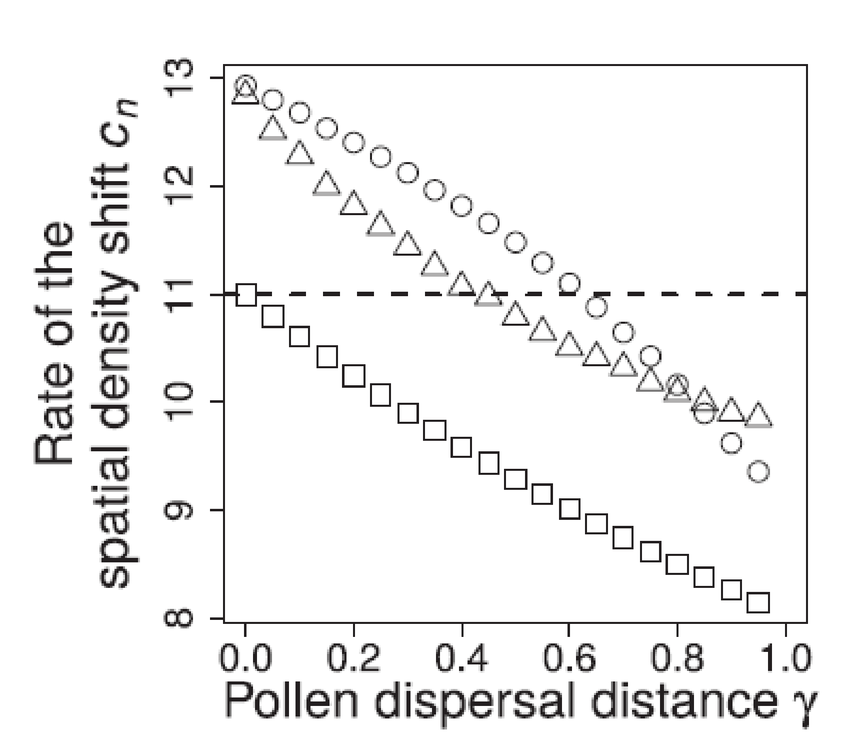


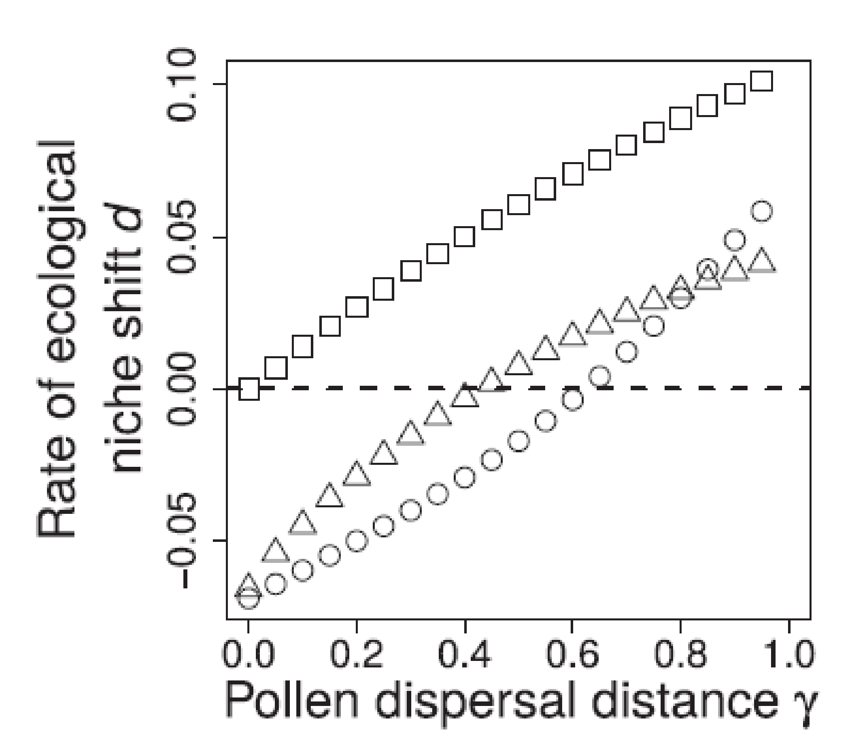
Long distance pollen dispersal slows down climate tracking through space

Long distance pollen dispersal results in niche shift and adaptation to warmer climate!

Effect of pollen on niche and range evolution under a changing climate

Parametrizing the model for Sitka Spruce and relaxing strong assumptions

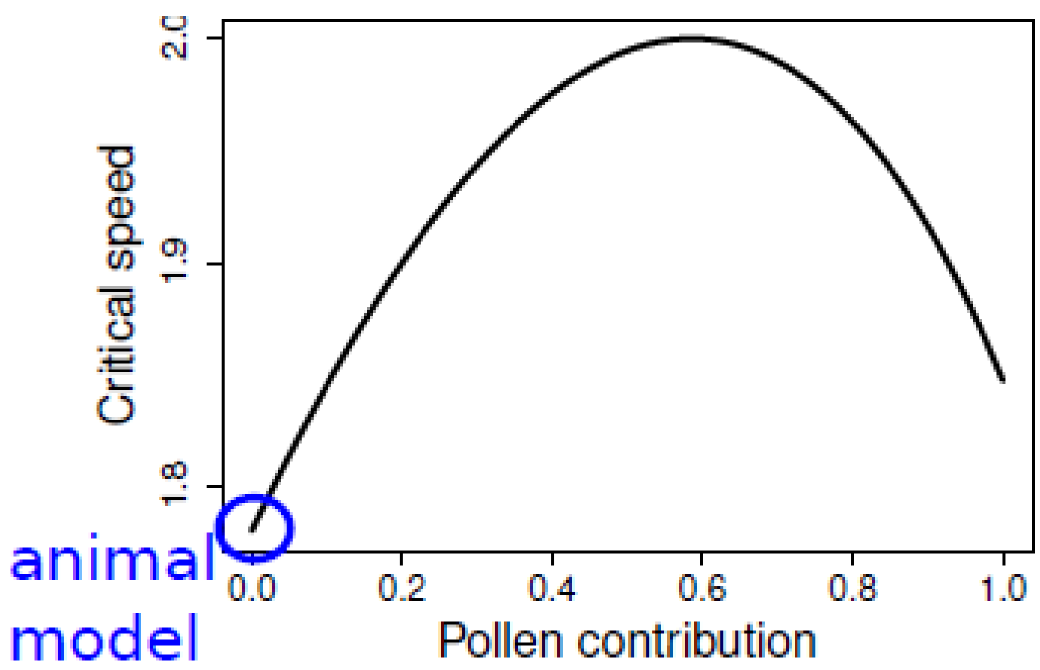




Pollen dispersal can help persisting under faster climate change

Extinction of the species will occur if climate change is too fast

Aguilée et al. 2016

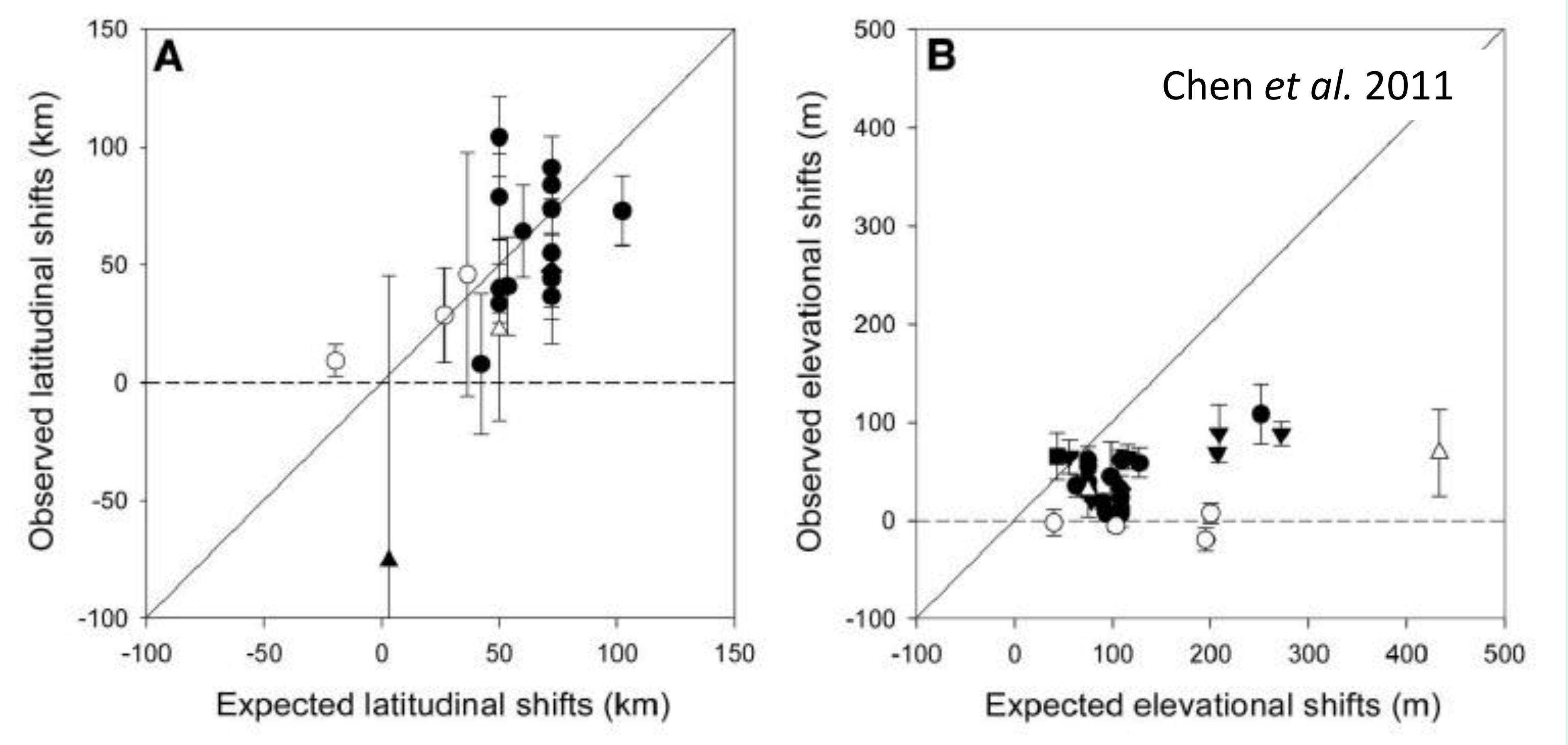


Long distance pollen dispersal can allow persistence under faster climate change

Conclusions

- Pollen dispersal worsens maladapation at the margins but improves adaptation at the core
- Pollen dispersal slows spatial range shifts, which is compensated by climatic niche shift
- For shallow/moderate gradients: pollen dispersal allows tracking faster climate changes

Species have shifted on average by 11m in altitude and 17km in latitude per decade



Interested in models of adaptation to changing environment?

PhD position available in our lab, Montpellier, starting **September 2018**

Co-supervized by Ophélie Ronce (biology) and Matthieu Alfaro (mathematics)