Dynamique d'aires de répartition d'espèces

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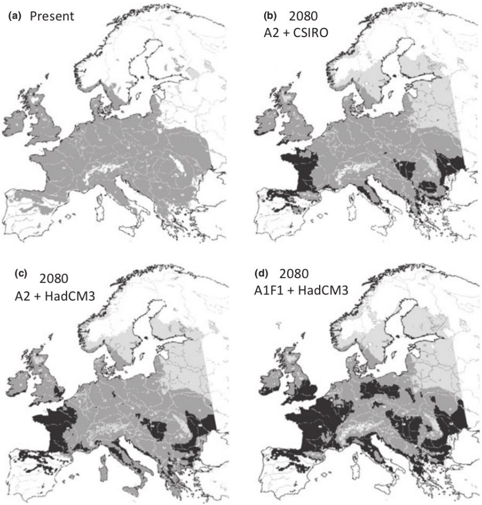
evolution of species' range



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1. Thuiller, Glob. Change Biol. 9 (2003).

Consequences for the forestry industry

We found that by 2100—depending on the interest rate and climate scenario applied—this loss varies between 14 and 50% (mean: 28% for an interest rate of 2%) of the present value of forest land in Europe, excluding Russia, and may total several hundred billion Euros. [2]

What should be done :

- Change the culture strategy ?
- Change the crop species ?
- How can micro-scale properties be taken into account ?
- ...

2. Hanewinkel et al, Nature climat change 3, 203–207 (2013).

SAFRAN data

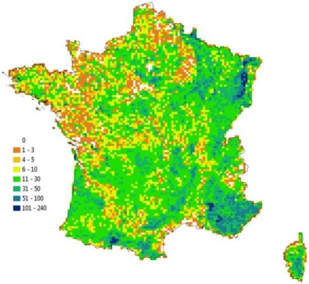


Figure 1.7 : Nombre de points IFN par maille SAFRAN

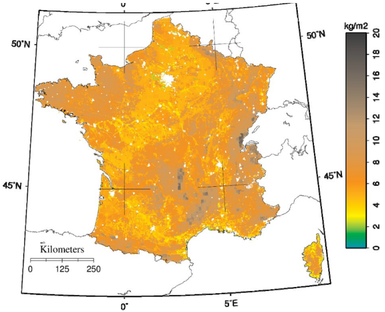


Figure 1.9 : Carte des stocks de carbone organique sur les premiers 30cm de sol. [3]

3. ONERC, Climat France XXI, Vol 4.

Climate predictions

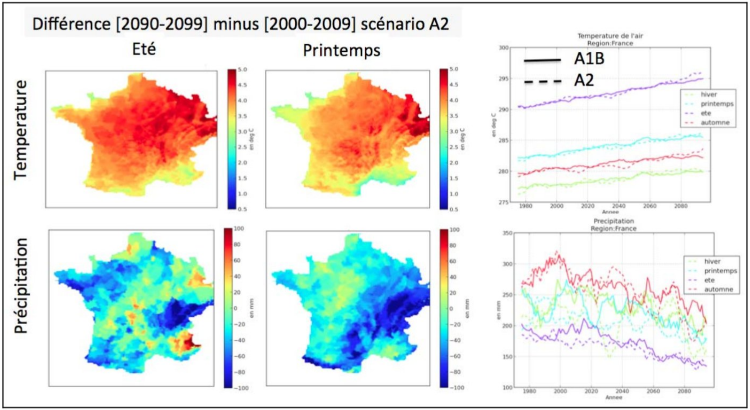


Figure 2.2 : Distribution spatiale des différences de température et de précipitations pour l'été (Juin, Juillet, Aout) et le printemps (Mars, avril, mai) entre la période 2090-2099 et la période 2000-2009. A gauche sont reporté les évolutions en moyenne sur la France des températures et précipitations pour les 4 saisons. [4]

4. ONERC, Climat France XXI, Vol 4.

On-going projects

- ANR project Evorange (Ophélie Ronce, ISEM) : try to improve field data and prediction models to assess the effect of climate change on species' range.
- Software PHENOFIT (Isabelle Chuine, CEFE) : a software to characterize the effect of environmental conditions on a species, and simulate the (quantitative) effect of a given climatic scenario. Theoretical tool : climate envelope modeling.
- GIS Climat Environnement Société

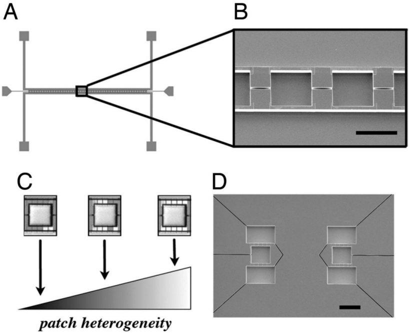
1. Asexual populations submitted to climate change

2. Sexual populations submitted to climate change

Collaborators

- Matthieu Alfaro (University of Montpellier),
- Henri Berestycki (EHESS),
- + Ophélie Ronce (ISEM, University of Montpellier) for biological aspects.

Experimental settings



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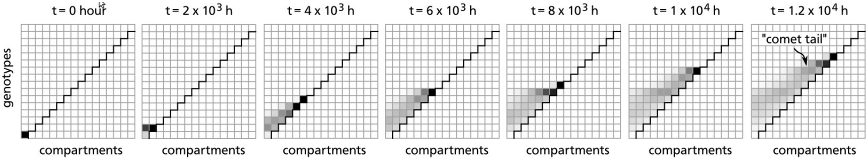

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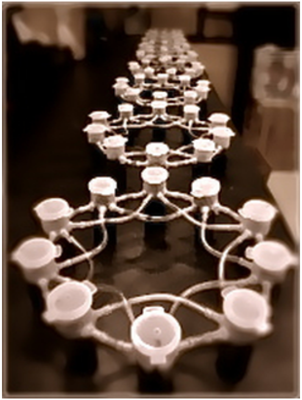
5. Keymer et al., PNAS, 2006.
6. Hermsen et al., PNAS, 2012.

Experimental settings

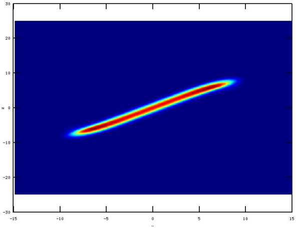
[7]

7. Andrew Gonzalez lab, Mc Gill University.

Model for asexual populations

We consider a population $n(t,x,y)$, where $t \geq 0$ is the time, $x \in \mathbb{R}$ is a space variable, and $y \in \mathbb{R}$ is a phenotypic trait (or breeding value). The evolution of n is given by the following model :

$$\partial_t n(t,x,y) \quad -\Delta_x n(t,x,y) - \Delta_y n(t,x,y) = \left(r(t,x,y) - \int_{\mathbb{R}} n(t,x,y')\,dy' \right) n(t,x,y).$$

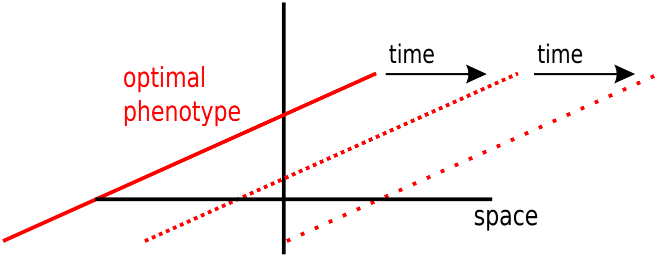


Climate change

We consider a climate change of (spatial) speed c :

$$\partial_t n(t,x,y) \quad -\Delta_x n(t,x,y) - \Delta_y n(t,x,y) = \left(r(x-ct,y) - \int_{\mathbb{R}} n(t,x,y')\,dy' \right) n(t,x,y).$$

A typical example would is $r(x-ct,y) = 1-(y-B(x-ct))^2 - \alpha y^2$, for some $\alpha > 0$.



Principal eigenvalue problem

we can define $\lambda_\infty \in \mathbb{R}$ and Γ_∞ as the solution of the principal eigenvalue problem

$$\begin{cases} -\partial_{xx}\Gamma_\infty(x,y) - \partial_{yy}\Gamma_\infty(x,y) - r(x,y)\Gamma_\infty(x,y) = \lambda_\infty\Gamma_\infty(x,y) \\ \Gamma_\infty(x,y) > 0, \quad \|\Gamma_\infty\|_\infty = 1. \end{cases}$$

In the example above, we can explicitly compute, when $\alpha = 0$:

$$\lambda_\infty = \sqrt{A(1+B^2)} - 1, \quad \Gamma_\infty = \exp\left(-\sqrt{\frac{A}{1+B^2}}(y - Bx)^2\right).$$

Extinction or survival

$$c^* := \begin{cases} 2\sqrt{-\lambda_\infty} & \text{if } \lambda_\infty < 0 \\ -\infty & \text{if } \lambda_\infty \geq 0 \end{cases}$$

Proposition

If $c^* < c$, *and* $\sup_{x\in\mathbb{R}} \int_{\mathbb{R}} n_0(x,y)\, dy < \infty$. *Then,*

$$\|n(t,\cdot,\cdot)\|_\infty \to_{t\to\infty} 0,$$

If $0 \leq c < c^*$, *then for any non-negative solution* $n \neq 0$, *there exists a non-negative function* $h \neq 0$ *such that*

$$n(t, x + ct, y) \geq h(x, y) \text{ for all } t \geq 1,\ x \in \mathbb{R},\ y \in \mathbb{R}.$$

Scheme of the proof 1 : Estimations on the tails

$$\partial_t n(t,x,y) \quad -\Delta_x n(t,x,y) - \Delta_y n(t,x,y) = \left(r(x-ct,y) - \int_{\mathbb{R}} n(t,x,y')\,dy' \right) n(t,x,y).$$

Lemma (Exponential decay of tails)

Assume that $r(x,y) \leq -\delta < 0$ for (x,y) large enough. If moreover $0 \leq n_0(x,y) \leq C_0 e^{-\mu_0(|x|+|y|)}$, then there exist $C>0$ and $\mu>0$ such that

$$0 \leq n(t,x,y) \leq Ce^{-\mu(|x-ct|+|y|)},$$

for all $t \geq 0$, $x \in \mathbb{R}$, $y \in \mathbb{R}$.

Scheme of the proof 2 : extinction case

n satisfies :

$$(\partial_t - \Delta_x - \Delta_y)\, n(t,x,y) \leq r(x-ct,y)n(t,x,y),$$

and then, with $\tilde{n} := e^{\frac{c(x+ct)}{2}} n(t,x+ct,y)$,

$$(\partial_t - \Delta_x - \Delta_y)\, \tilde{n}(t,x,y) \leq \left(r(x,y) - \frac{c^2}{4} \right) \tilde{n}(t,x,y),$$

We notice that $\bar{n}(t,x,y) := M e^{\left(-\lambda_\infty - \frac{c^2}{4}\right)t} \Gamma_\infty(x,y)$ is a solution of the above equation, which, combined to the tail estimates, provides the result (if n^0 is gentle enough).

We see here how $c^* = 2\sqrt{-\lambda_\infty}$ comes into play...

Scheme of the proof 3 : survival case

- We consider the problem on a compact set : n satisfies

$$(\partial_t - \Delta_x - \Delta_y)\, n(t,x,y) = \left(r(x-ct,y) - \int_{-R}^{R} n(t,x,y')\,dy' + o(R) \right) n(t,x,y),$$

for $t \geq 0$ and $(x-ct,y) \in B_R(0)$.

- We use the Harnack inequality to estimate the non-local term :

$$\sup_{(x-ct,y)\in B_R(0)} n(t,x,y) \leq C \inf_{(x-ct,y)\in B_R(0)} n(t+1,x,y),$$

and then,
$\max_{(x-ct)\in B_R(0)} \int_{-R}^{R} n(t+1,x,y')\,dy' \leq 2CRe^{\max r} n(t,x_0,y_0)$ for any $(x_0-ct,y_0) \in B_R(0)$.

Scheme of the proof 4 : survival case

- we have shown that n satisfies, for $t \geq 0$ and $(x - ct, y) \in B_R(0)$

$$(\partial_t - \Delta_x - \Delta_y)\, n = (r(x - ct, y) - Cn(t, x, y) + o(R))\, n.$$

- Just as in the extinction part, we introduce $\tilde{n} := e^{\frac{c(x+ct)}{2}} n(t, x + ct, y)$, that satisfies

$$(\partial_t - \Delta_x - \Delta_y)\, \tilde{n} = \left(r(x, y) - \frac{c^2}{4} - C\tilde{n}(t, x, y) + o(R) \right) \tilde{n}.$$

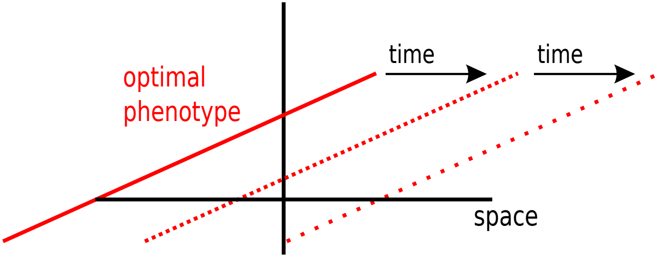
- We notice that $\bar{n}(t, x, y) := Me^{\left(-\lambda_\infty - \frac{c^2}{4}\right)t} \Gamma_R(x, y)$ is a sub-solution of the above equation provided $M > 0$ is chosen small enough. Thus, $\bar{n}(t, \cdot, \cdot) \leq \tilde{n}(t, \cdot, \cdot)$ for all $t \geq 0$, which proves the result.

Unconfined case

We consider a climate change of (spatial) speed c :

$$\partial_t n(t,x,y) \quad -\Delta_x n(t,x,y) - \Delta_y n(t,x,y) = \left(r(x-ct,y) - \int_{\mathbb{R}} n(t,x,y')\,dy' \right) n(t,x,y).$$

A second example is $r(x-ct,y) = 1 - (y - B(x-ct))^2 - \alpha y^2$, for $\alpha > 0$.



Unconfined case

Assume $r(x,y) = \tilde{r}(y - Bx)$.

$$c^{**} := \begin{cases} 2\sqrt{-\lambda_\infty \frac{1+B^2}{B^2}} & \text{if } \lambda_\infty < 0 \\ -\infty & \text{if } \lambda_\infty \geq 0 \end{cases}$$

Proposition

If $c^{**} < c$, and $\sup_{x\in\mathbb{R}} \int_{\mathbb{R}} n_0(x,y)\, dy < \infty$. Then,

$$\|n(t,\cdot,\cdot)\|_\infty \to_{t\to\infty} 0,$$

If $0 \leq c < c^*$, then the population propagates to the left at a speed ω_x^-, and to the right at a speed ω_x^+, where

$$\omega_x^\pm = \pm\sqrt{-\frac{4\lambda_\infty}{1+B^2} - \frac{B^2}{(1+B^2)^2}c^2} + \frac{B^2}{1+B^2}c.$$

Unconfined case

Remarks :

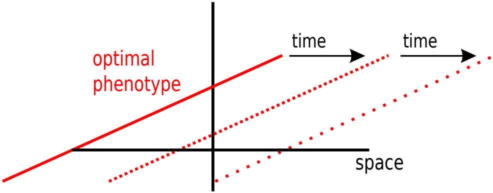
- $\omega_+ > 0$ can be less or greater than c, the speed of the climate.
- ω_- can be either positive or negative (linked to the survival of the population in one given location),
- the minimal trait present in the population decreases. The maximal trait can either increase or decrease.
- $c^* = 2\sqrt{-\lambda_\infty} < c^{**} = 2\sqrt{-\lambda_\infty \frac{1+B^2}{B^2}}$. Indeed, $c > c^*$ in the unconfined case is equivalent to $\omega_x^- < 0$.

Mixed case

We consider a climate change of (spatial) speed c :

$$\partial_t n(t,x,y) \quad -\Delta_x n(t,x,y) - \Delta_y n(t,x,y) = \left(r(x-ct,y) - \int_{\mathbb{R}} n(t,x,y')\,dy' \right) n(t,x,y).$$

A third (and last) example is
$r(x-ct,y) = 1 - A(y + B(x-ct))^2 1_{x-ct\leq 0} - Ay^2 1_{x-ct\geq 0} - \alpha y_+^2$, for $\alpha > 0$ small.



Mixed case

Our goals here :

- understand better the interplay between c^* and c^{**},
- investigate the robustness of the biological implications of the results above.

Assumption : $r(x,y)$ such that $r(x,y) = r_u(x,y)$ for $x < 0$, where r_u satisfies the conditions of the unconfined case, while for $x > 0$, $r(x,y)$ satisfies the conditions of the confined case.

Definition : c^* as before, and $\widetilde{c^{**}}$ as c^{**}, but defined with r_u.

Mixed case

Proposition

1. *if* $\max(c^*, \widetilde{c^{**}}) < c$, *then*

$$\sup_{x\in\mathbb{R}} \int_{\mathbb{R}} n(t,x,y)\, dy \to_{t\to\infty} 0.$$

2. *if* $\widetilde{c^{**}} < c < c^*$, *and* n_0 *is compactly supported, The population survives and follows the climate shift, but does not succeed to propagate.*
3. *if* $c^* < c < \widetilde{c^{**}}$, *then the population survives, but does not succeed to follow the climate*
4. *if* $c < \min(c^*, \widetilde{c^{**}})$, *then the population survives. It propagates at speed* c *to the right, and at speed* $\widetilde{\omega_x^-}$ *to the left.*

Mixed case

Given the dynamics of a population's range, is it possible to infer robustness of the population to an increase of the climate shift speed ?

- c^* is not necessarily smaller than $\widetilde{c^{**}}$: a species that succeed to follow the climate change is not necessary far from extinction.

  In the example : $c^* < \widetilde{c^{**}}$ if and only if $(1+B^2)^{3/2} - B^2 < \frac{1}{\sqrt{A}}$.
- A species with a range that increases in size (even rapidly) may not be far from extinction.

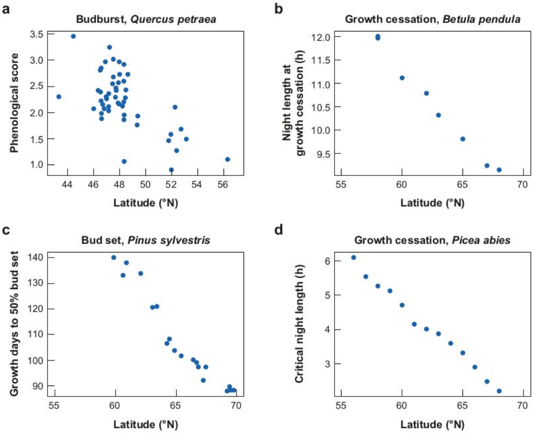
1. Asexual populations submitted to climate change

2. Sexual populations submitted to climate change

Collaborators

- Robin Aguilée (LEDB, University of Toulouse),
- Ophélie Ronce (ISEM, University of Montpellier),
- François Rousset (ISEM, University of Montpellier).

Phenotypic gradients



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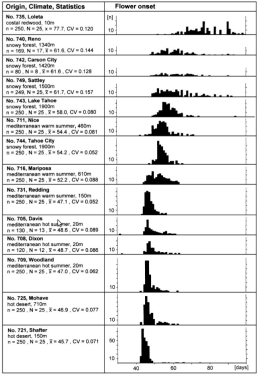

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8. O.Savolainen, T. Pyhajarvi, T. Knurr, Annu. Rev. Ecol. Evol. Syst. 2007.
9. Neuffer et al., Molecular Ecology, 1999.

Existing models

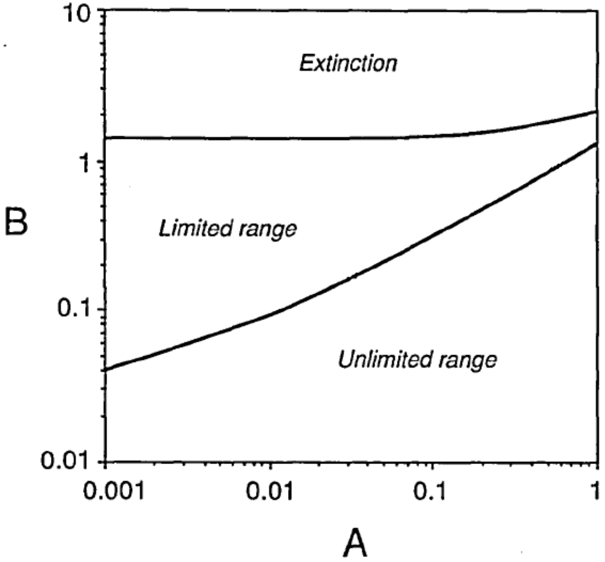
C.P. Pease, R. Lande, J.J. Bull, Ecology, 1989.
$N(t,x)$: population density, $Z(t,x)$: mean phenotypic trait.

$$\begin{cases} \partial_t N - \Delta_x N = \left(1 - \frac{1}{2}(y - Bx)^2 - \int N(t,y)\,dy\right) N, \\ \partial_t Z - \Delta_x Z = 2\frac{\partial_x N}{N}\partial_x Z + A(Bx - Z). \end{cases}$$

M. Kirkpatrick, N. Barton, American Naturalist, 1997.

$$\begin{cases} \partial_t N - \Delta_x N = \left(1 - \frac{1}{2}(y - Bx)^2 - N\right) N, \\ \partial_t Z - \Delta_x Z = 2\frac{\partial_x N}{N}\partial_x Z + A(Bx - Z). \end{cases}$$

Dynamics of the population



An infinitesimal model (see Sepideh Mirrahimi, G.R.)

We consider a population $n(t,x,y)$, where $t \geq 0$ is the time, $x \in \mathbb{R}$ is a space variable, and $y \in \mathbb{R}$ is a phenotypic trait (or breeding value). Then, the evolution of n is given by the following model :

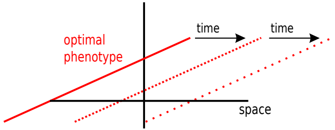
$$\partial_t n(t,x,y) - \Delta_x n(t,x,y)$$
$$= -\left[(C-(1+A/2)) + (y-Bx)^2 + \int n(t,x,y')\,dy'\right] n(t,x,y)$$
$$+C \int\int \frac{n(t,x,y_*)n(t,x,y_*')}{\int n(t,x,w)\,dw} K(y,y_*,y_*')\,dy_*\,dy_*',$$

Parameters : A, B, C. If C becomes large, we formally recover the model of Kirkpatrick and Barton.

Pollen + climate change

We want to investigate the effet of the pollen on a population facing a climate change :

- Climate change :



- Pollen : the male gametes disperse much more than the seeds.

Model

We consider a tree population $n(t,x,y)$, and the pollen population $p(t,x,y)$:

$$\partial_t n(t,x,y) - \frac{\sigma^2}{2}\Delta_x n(t,x,y)$$
$$= -\left[\eta + \frac{1}{2V_s}(y - b(x - vt))^2 + \frac{r_{max}}{K}\int n(t,x,y')\,dy'\right] n(t,x,y)$$
$$+(r_{max}+\eta)\int\int \frac{n(t,x,y_*)p(t,x,y'_*)}{\int n(t,x,w)\,dw} K(y,y_*,y'_*)\,dy_*\,dy'_*.$$

with $p(t,x,y) = K *_x n(t,x,y) \sim n(t,x,y) + \kappa\Delta n(t,x,y)$.

Moment equation

Then, with similar arguments as above, we get :

$$\partial_t N - \Delta_x N = \left[1 - \frac{1}{2}(Z - B(x - Vt))^2 - N\right] N,$$

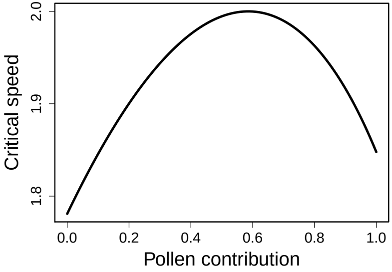
$$\partial_t Z - \frac{1}{1-\gamma}\Delta_x Z = \frac{2}{1-\gamma}\frac{\partial_x N}{N}\partial_x Z + A(B(x - Vt) - Z),$$

where $\gamma := \frac{\frac{1}{2}\sigma_p^2}{\sigma_t^2} \in (0,1)$ is the contribution of pollen to dispersal.

Consequence : Critical speed of climate change

Sustainable climate change if $1 - \frac{1}{V_n} - \frac{L_z^2}{2} > 0$, that is if the speed of the climate change is below :

$$V^{crit} = 2\left(1 + \frac{A}{|B|\sqrt{2}}\gamma\right)\sqrt{1 - \frac{|B|\sqrt{2}}{2} + \frac{A}{2}(1-\gamma)}.$$



Consequence : Optimal pollen dispersal

The optimal critical speed is obtained for $\gamma_{opt} = \frac{2}{3} - \frac{1}{A}\left(|B|\sqrt{2} - \frac{4}{3}\right)$. It is then best to :

- disperse pollen a lot when $|B| < \frac{4-A}{3\sqrt{2}}$,
- not disperse pollen when $|B| > \frac{\sqrt{2}}{3}(2+A)$,
- disperse at an intermediate rate for an intermediate gradient of the optimal phenotypic trait B.

Numerical simulations

These computation had to be checked numerically.

- Pease et al model : OK,
- Kirkpatrick Barton model : OK for a part of the parameter space,
- Individual-based simulations with explicit loci : would require too much time,
- Kinetic model : OK.

  Why is it interesting : The phenotypic variance is not fixed, the linkage equilibrium is not assumed.

Thank you for your attention !