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Modeling eco-evolutionary dynamics

Sylvie Oddou-Muratorio

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Contents

Part 2 : Modeling eco-evolutionary dynamics

- ✓ A synthesis study on demo-genetic models
- ✓ Two study cases:
 - Adaptation, persistence and management of Atlantic salmon in a metapopulation context
 - Vulnerability of forests in face of climate change: DG-ABMs to investigate adaptive management strategies in Cedar and Douglas stands

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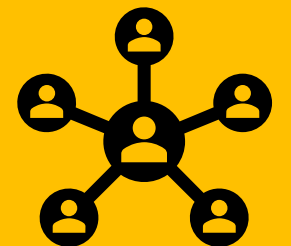
PERSPECTIVE

Evolutionary Applications Open Access WILEY

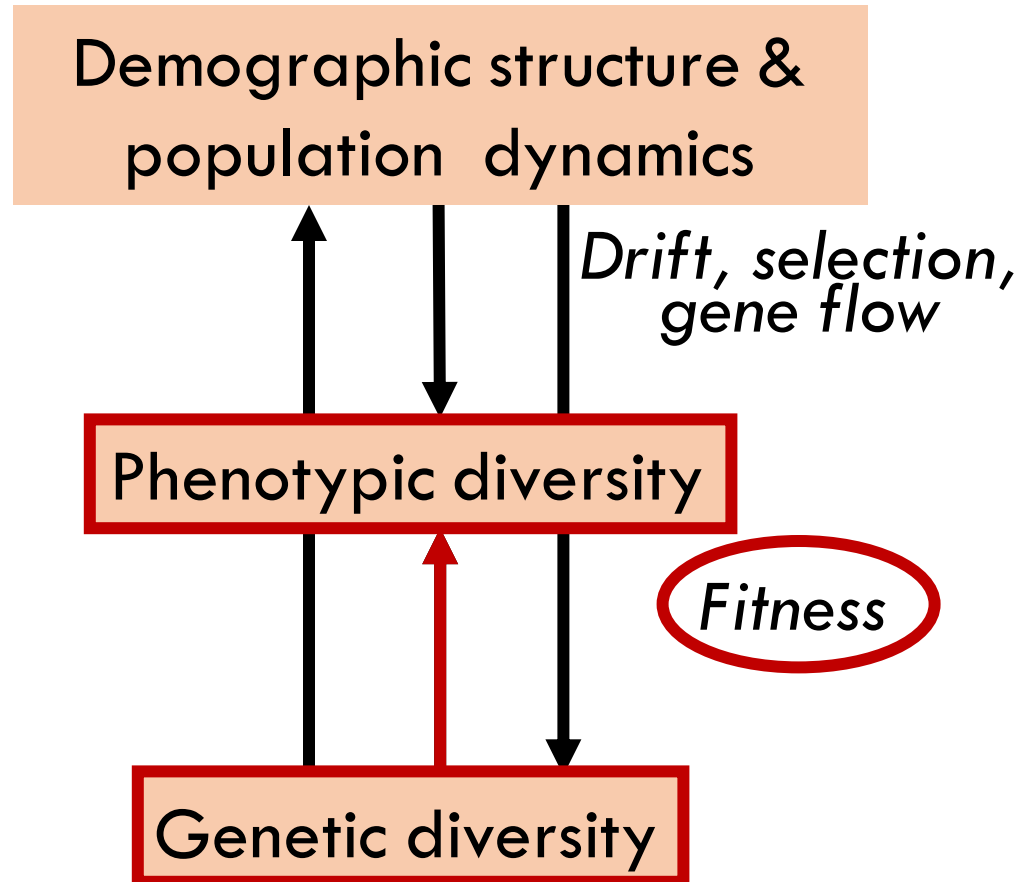


Importance of interindividual interactions in eco-evolutionary population dynamics: The rise of demo-genetic agent-based models

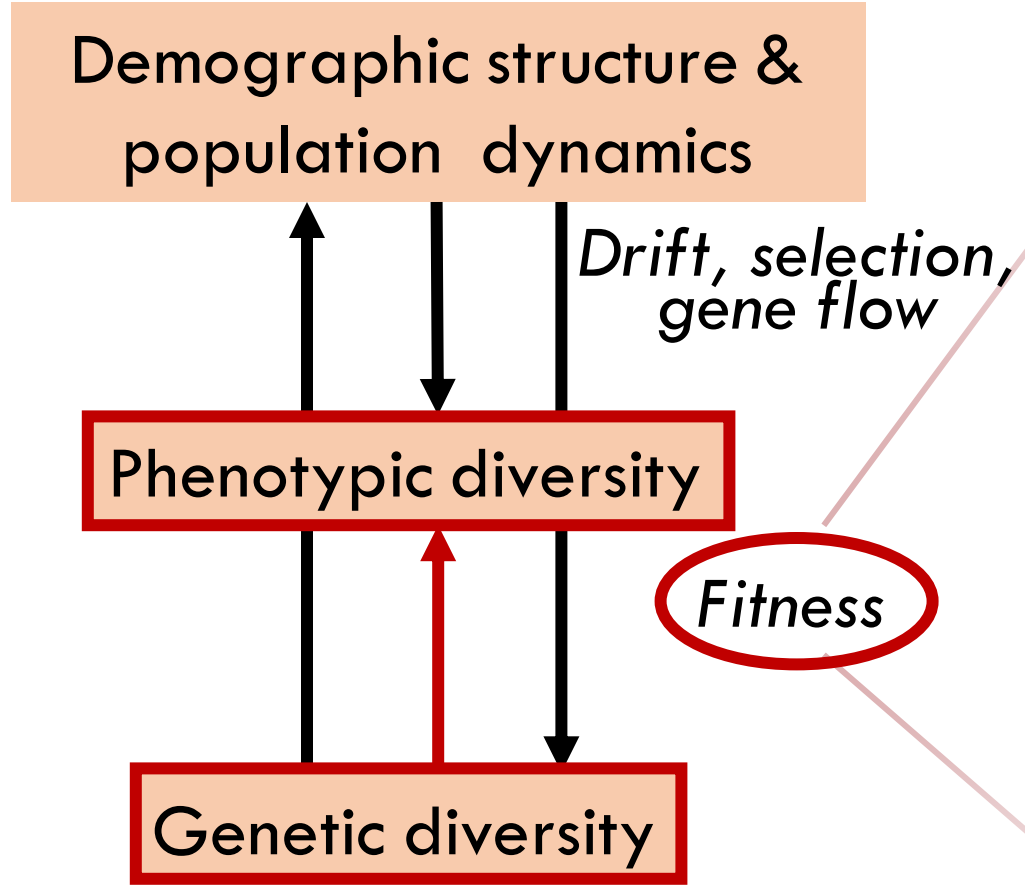
Amaïa Lamarins^{1,2} | Victor Fririon³ | Dorinda Folio¹ | Camille Vernier⁴ |
Léa Daupagne¹ | Jacques Labonne¹ | Mathieu Buoro¹ | François Lefèvre³ |
Cyril Piou⁴ | Sylvie Oddou-Muratorio¹



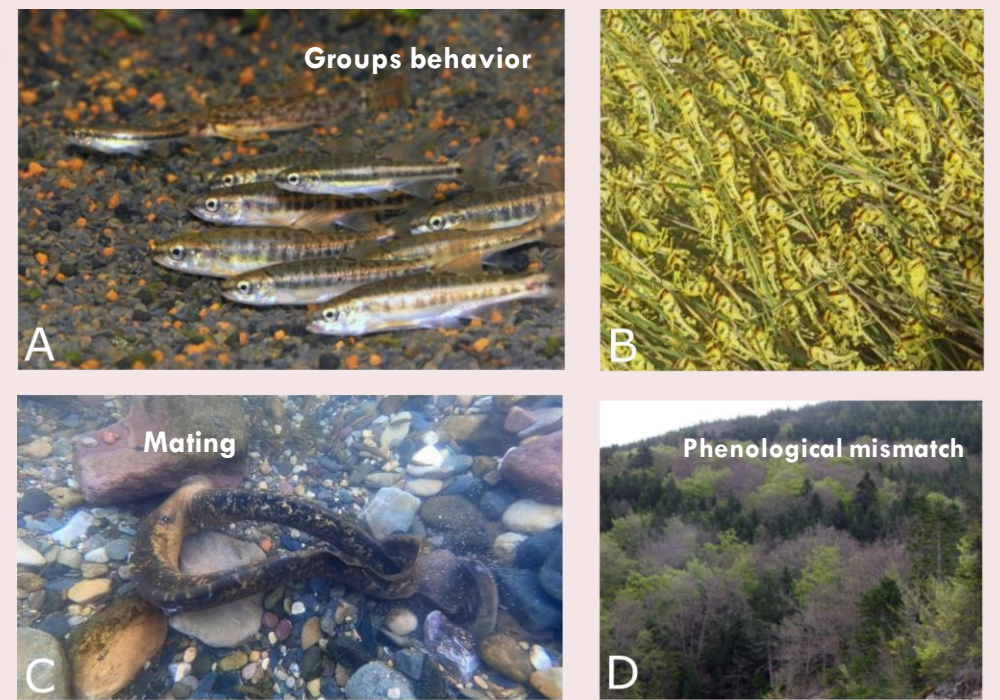
Eco-evolutionary dynamics and interindividual interactions



Eco-evolutionary dynamics and interindividual interactions



INTER-INDIVIDUAL INTERACTIONS



Within-population inter-individual interactions:

- competition
- cooperation
- mating

➤ **Fitness** (growth, reproduction, mortality)

➤ **Stochastic**

➤ **Context-dependent**

+ Inter-populations and interspecific interactions

Modeling strategy: analytical models vs DG-ABMs

(e.g. adaptive dynamics, quantitative genetics, integral projection models)

Analytical models

Scale	Population
Population dynamics	Uniform within-populations or within classes
Within-population variation	Simplified (2 variants) or Gaussian distribution, no structure
Inter-individual interactions	Uniform within-populations
Trait-fitness relationship	Input, not flexible
Management practises	Mean impact, not flexible

- Homogeneous processes within groups of individuals (populations or life stages)
- *A priori* fitness

Modeling strategy: analytical models vs DG-ABMs

(e.g. adaptive dynamics, quantitative genetics, integral projection models)

Analytical models

DG-ABMs

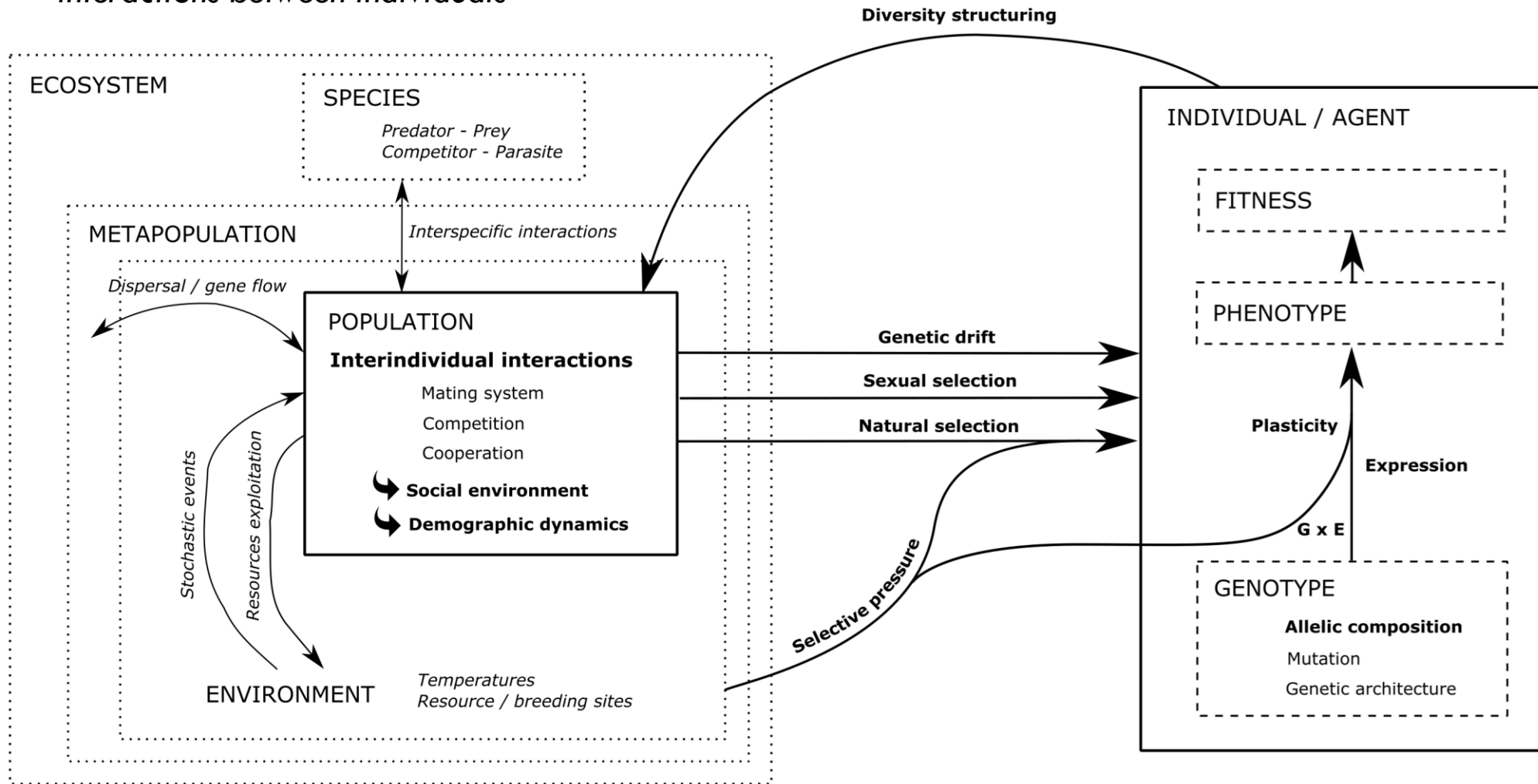
	Analytical models	DG-ABMs
Scale	Population	Individual
Population dynamics	Uniform within-populations or within classes	Not uniform, possible structure
Within-population variation	Simplified (2 variants) or Gaussian distribution, no structure	Distribution free, possible structure (e.g. spatial)
Inter-individual interactions	Uniform within-populations	None ↔ Not uniform, implicit or explicit
Trait-fitness relationship	Input, not flexible	Outcome, flexible, allows emerging effects
Management practises	Mean impact, not flexible	On individuals and interactions, allows emerging effects

- Homogeneous processes within groups of individuals (populations or life stages)
- *A priori* fitness

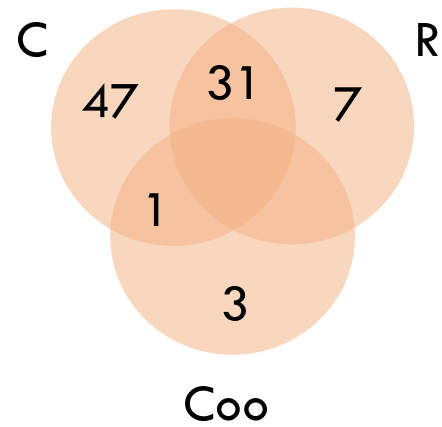
- Variation in group composition (phenotypes and genotypes) and interactions: individual decisions but emerging patterns at group level
- Emerging fitness

DG-ABM definition

“ individual-based (meta) population dynamics models with heritable variation and phenotype-dependent interactions between individuals”



Literature review



Type of interactions

Web of Science (1955-2022)

“IBM”

“ABM”

“eco-evol”

“demo-genet”

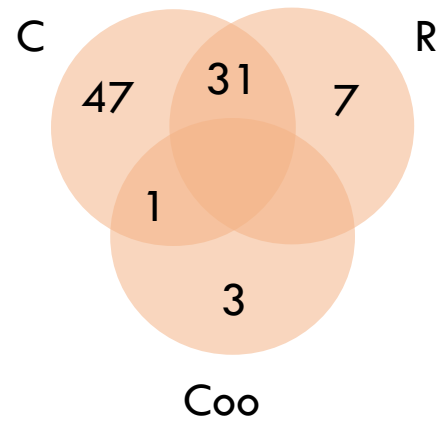
“eco-genet”

“inter-individ”

“interact”

89 studies (after filtering: 1 / IBM, 2 / N generations, 3 / interactions, 4 / trait variability, 5 / heritability)

Literature review



Type of interactions

Web of Science (1955-2022)

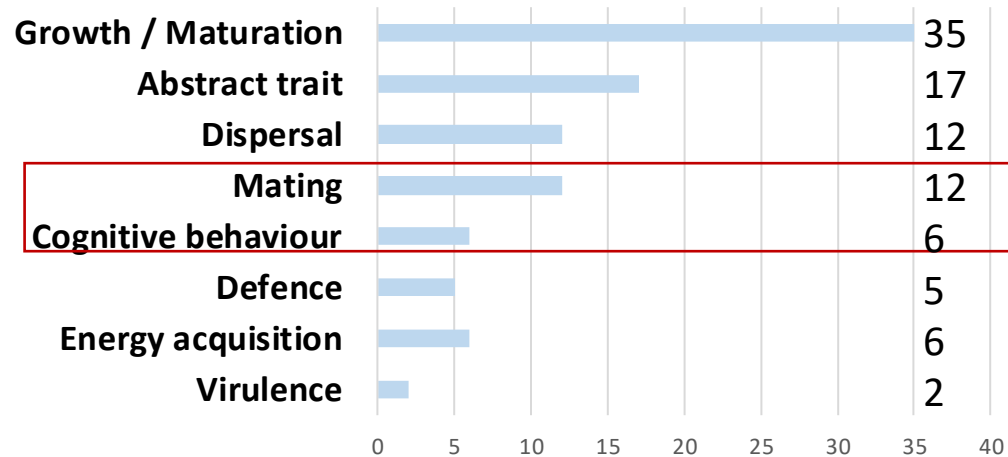
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Evolving fitness-related traits

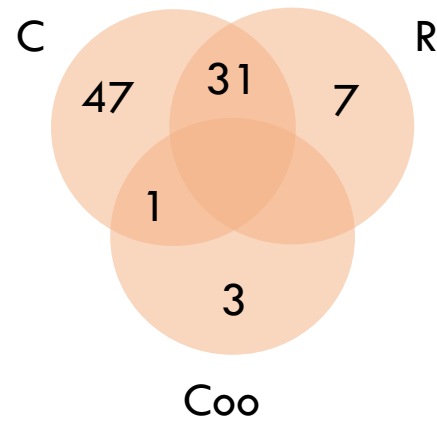


Size

Avoidance of predators/competition

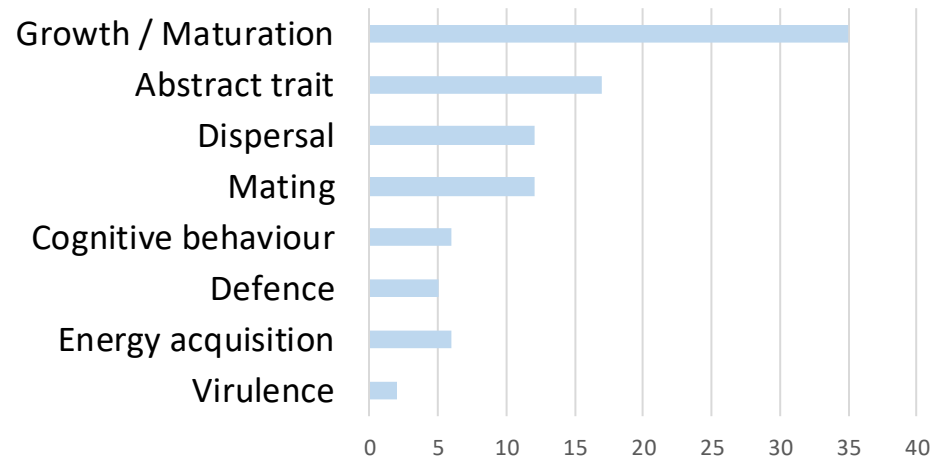
Direct effects on individual interaction

Literature review

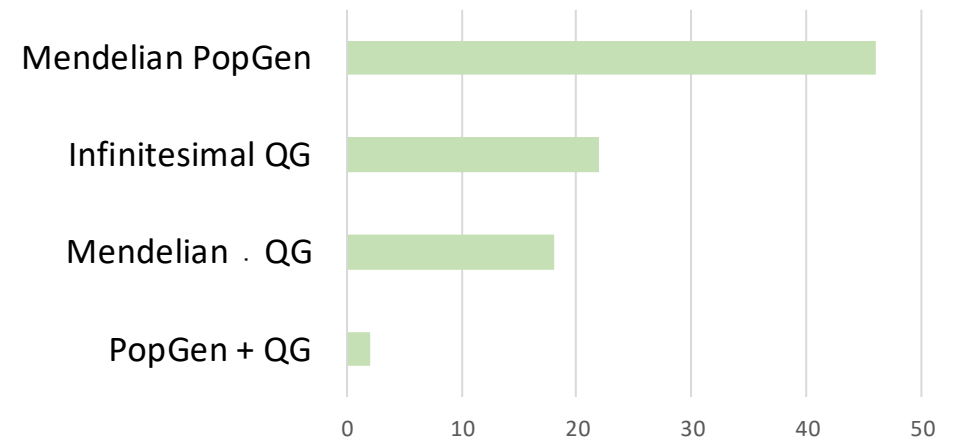


Type of interactions

Evolving fitness-related traits



Inheritance framework



Web of Science (1955-2022)

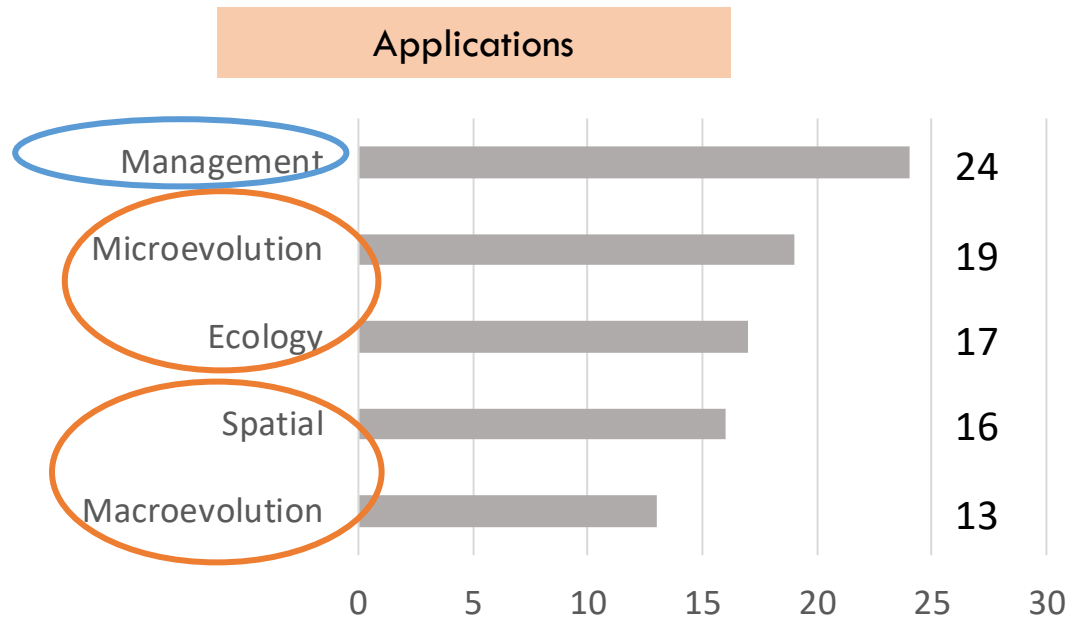
“IBM”
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Literature review



Web of Science (1955-2022)

“IBM”
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“eco-evol”
“demo-genet”
“eco-genet”

“inter-individ”
“interact”

89 studies (after filtering: 1 / IBM, 2 / N generations, 3 / interaction, 4 / trait variability, 5 / heritability)

Fundamental questions:

- Better understanding of eco-evolutionary loops at population scale: e.g. including competitive interactions, cooperation, reproduction, lead to different outcomes in population dynamics
- Larger spatio-temporal scale: metapopulation / communities dynamics, speciation

Prospective tool to assist management:

- Evaluate management practices together with eco-evolutionary processes
- e.g. selective harvesting, spatial management, introgression impact

Four examples through PhD theses of the DG-ABM network



- Amaia Lamarins (2022) : Adaptation, persistence and management of Atlantic salmon in a metapopulation context

- Dorinda Folio (2022): Evolutionary management of brown trout intraspecific diversity

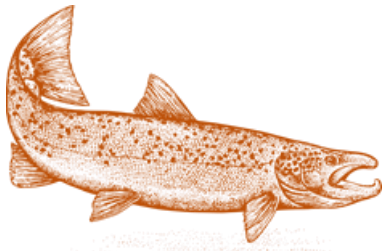
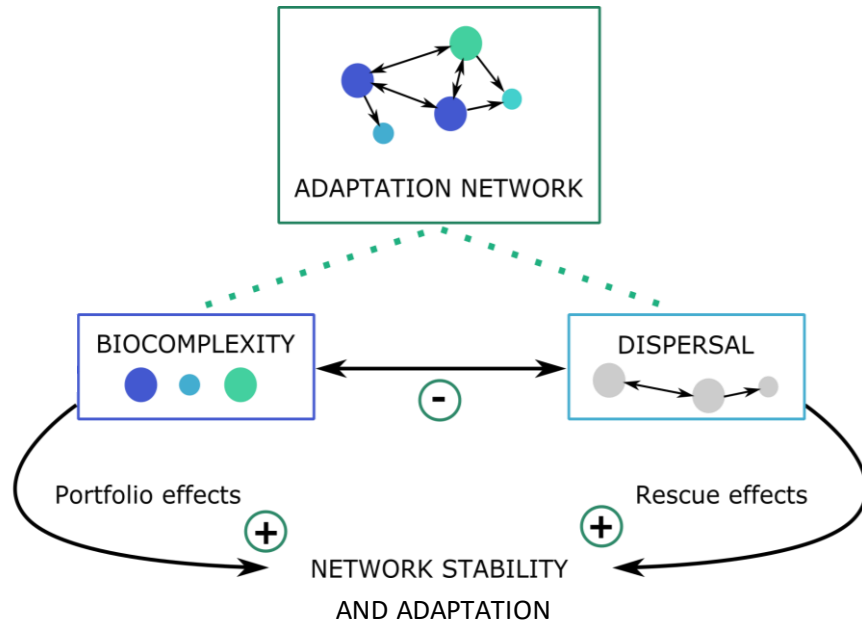


- Victor Fririon (2022): Vulnerability of forests in face of climate change: DG-ABMs to investigate adaptive management strategies in Cedar and Douglas stands

- Louise Chevalier (2021) : Coevolution between reproductive behaviors and genetic architecture under sexual selection



Adaptation, persistence and management of Atlantic salmon in a metapopulation context



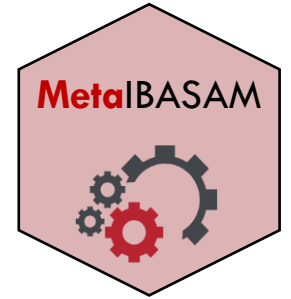
Context:

- Dispersal and genetic adaptation can promote species persistence under environmental change (depending on the balance btw selection & geneflow, Lenormand 2004)
- Portfolio theory: biocomplexity + asynchronous dynamics → stability of population complexes (Hilborn et al. 2003)
- Ibasam, a DG-ABM to study eco-evolutionary dynamics in *Salmo salar* populations (Piou & Prevost 2012, 2013)

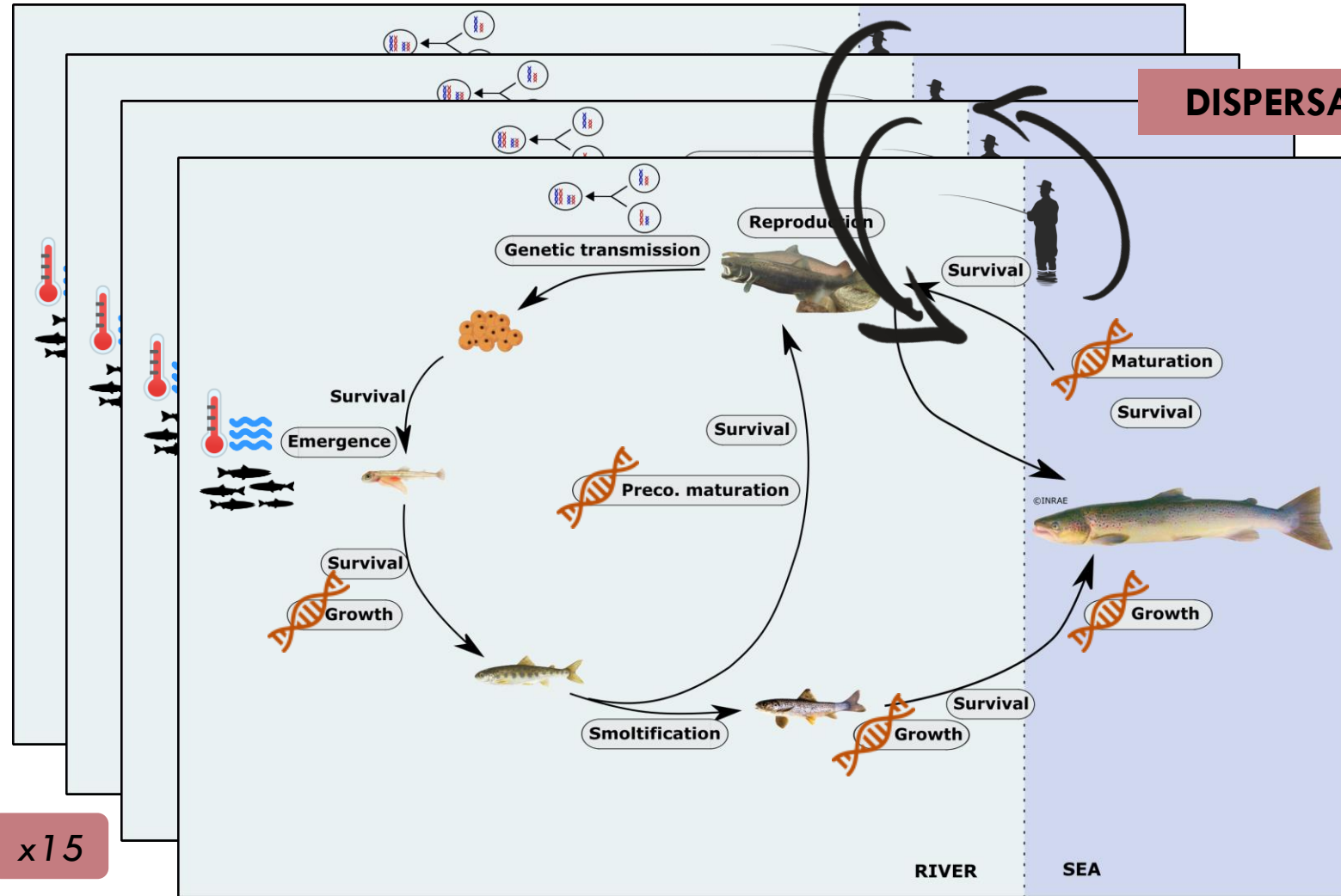
How connectivity and diversity influence metapopulation eco-evolutionary dynamics, stability and adaptation ?

The model

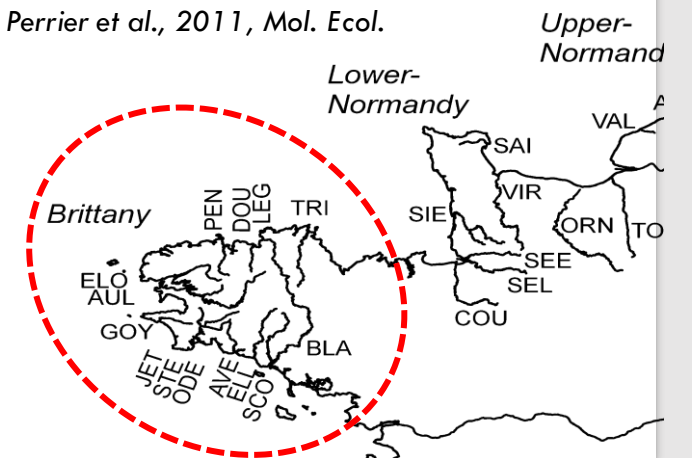
IBASAM (Individual Based Atlantic SALmon Model)... Towards MetaIBASAM



DISPERSAL



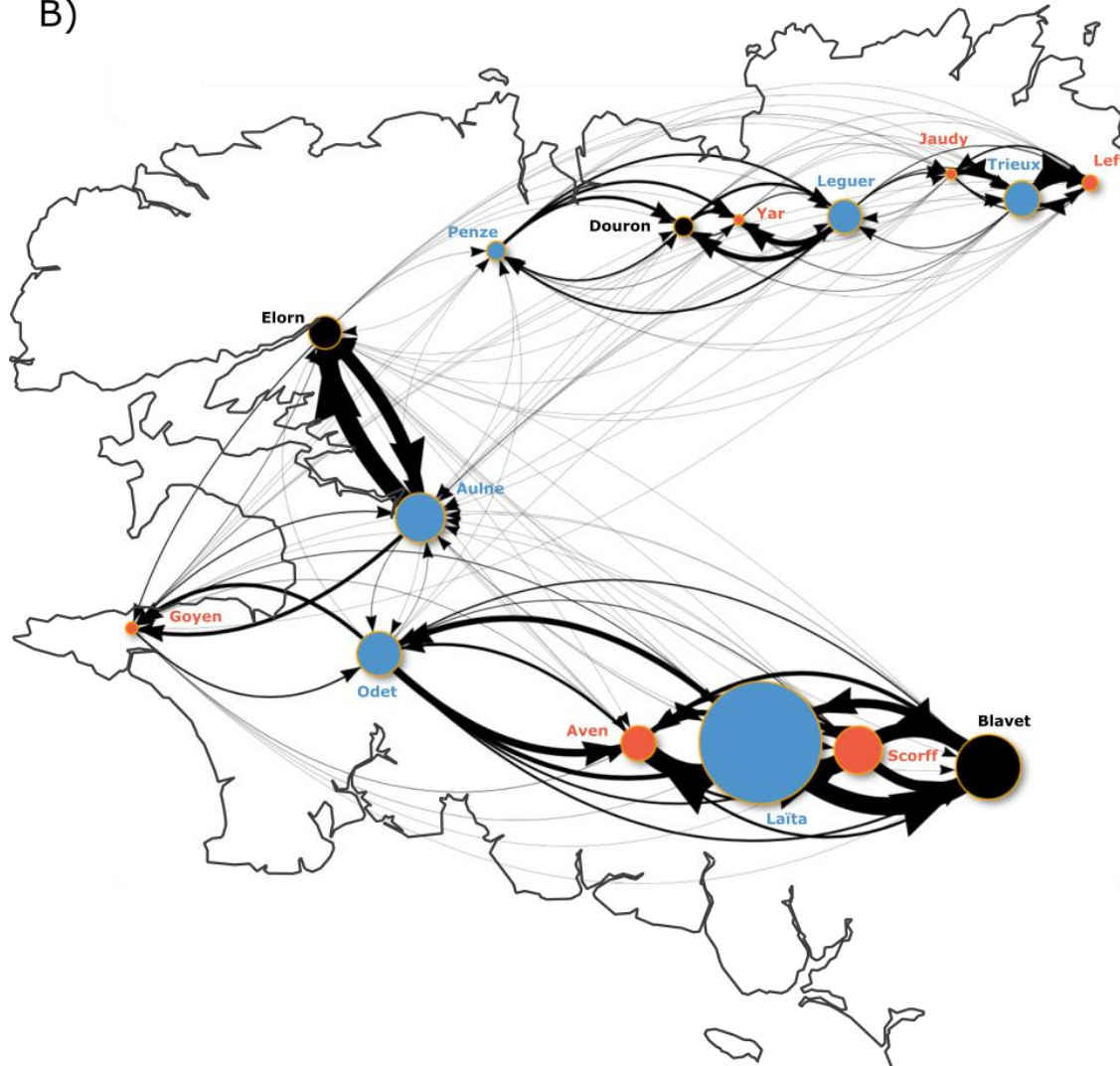
Perrier et al., 2011, Mol. Ecol.



1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS

B)



Dispersal rate: 10%

**REALISTIC
METAPPULATION
SPATIAL CONTEXT**

→ Carrying capacities
→ Distance

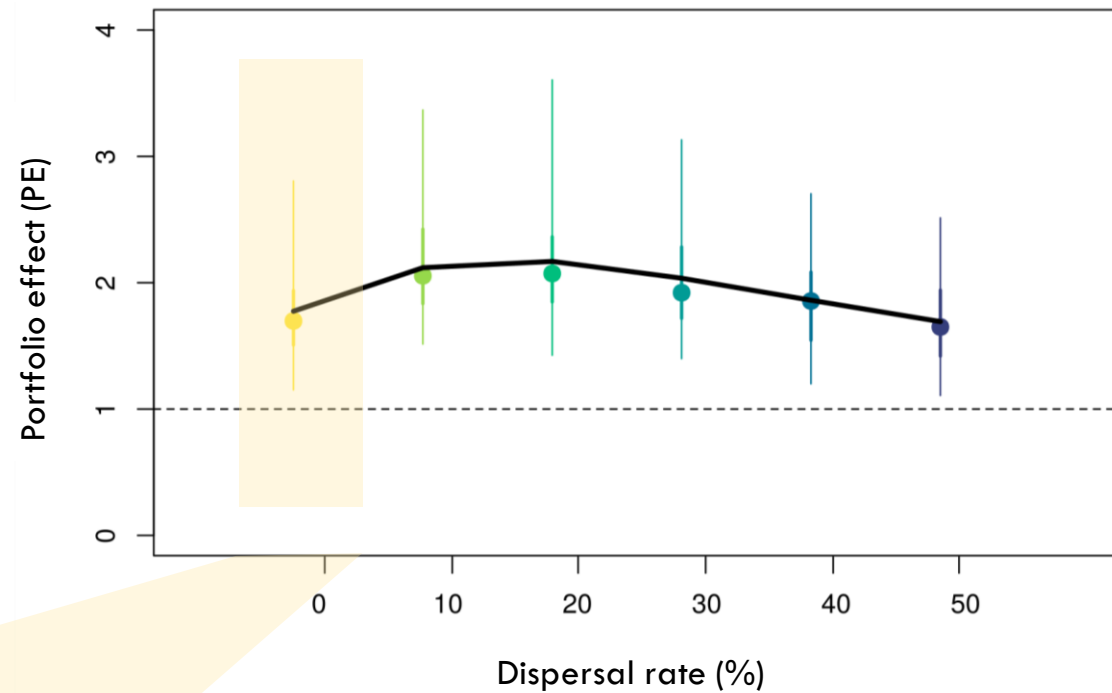
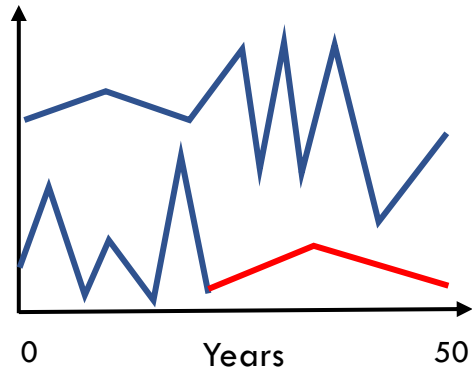
**DEMOGRAPHIC
MODEL**

→ Dispersing vs philopatric individuals

1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS

Population abundance



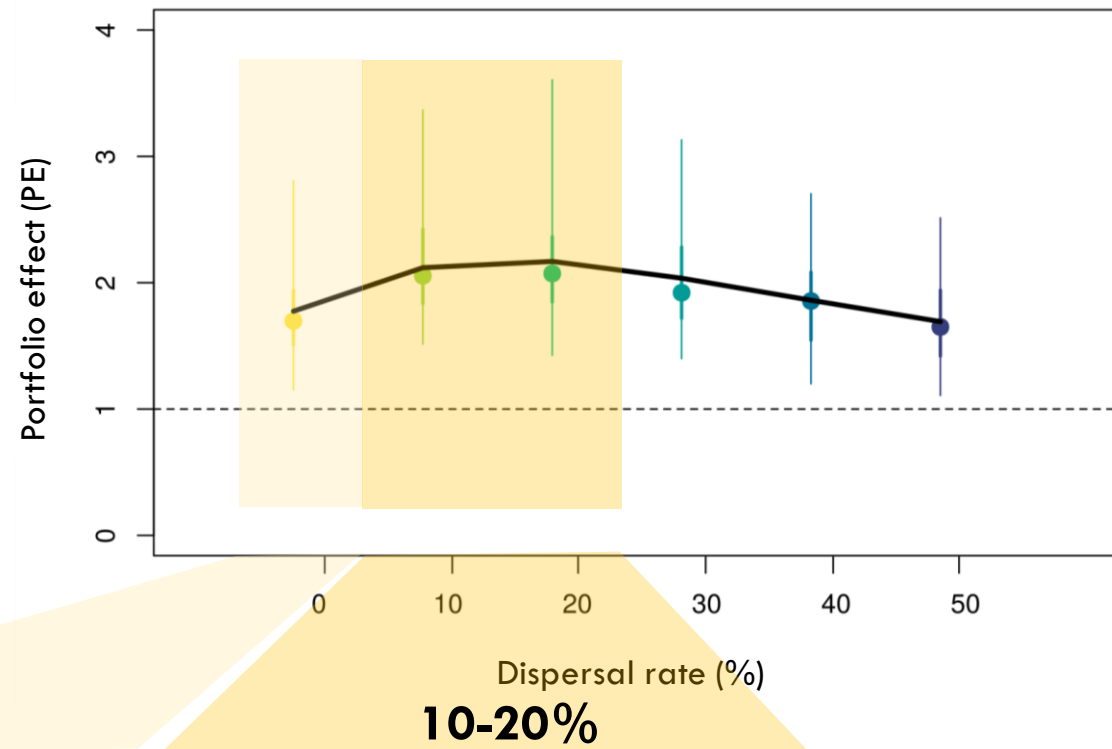
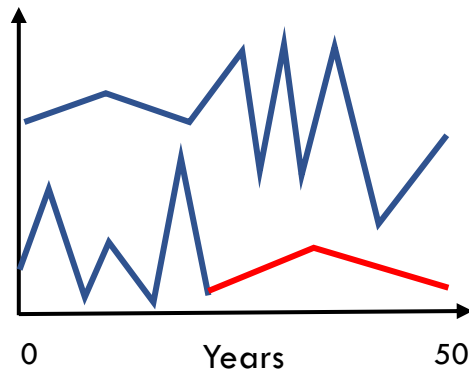
0%

- Asynchrony
- High risk of extinction of small populations

1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS

Population abundance



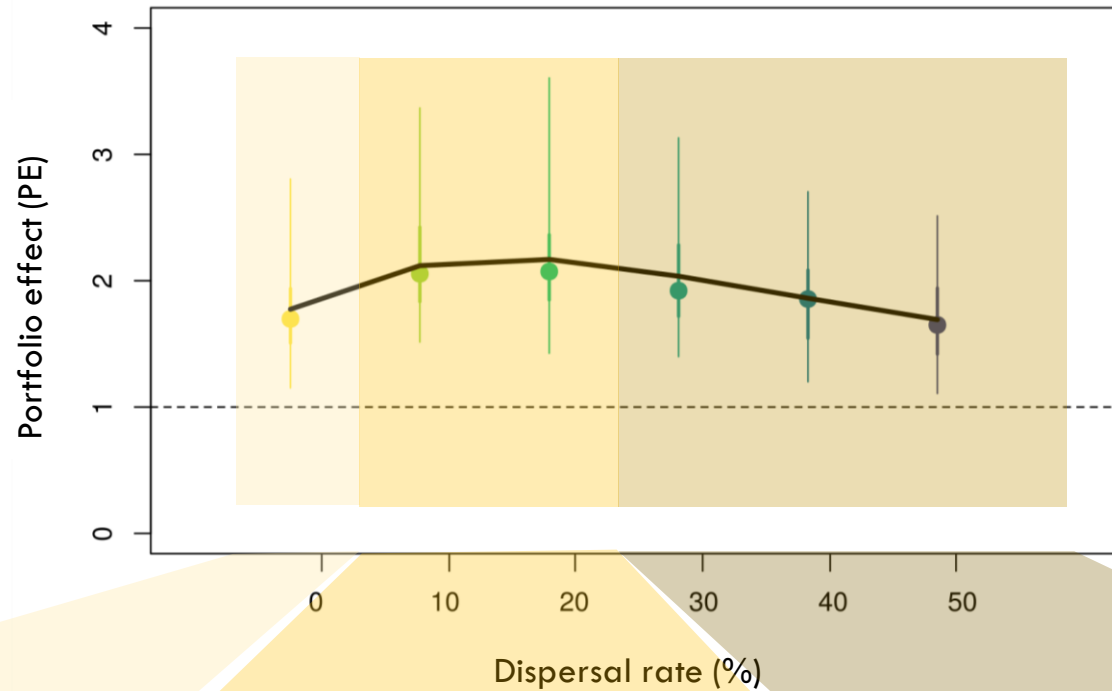
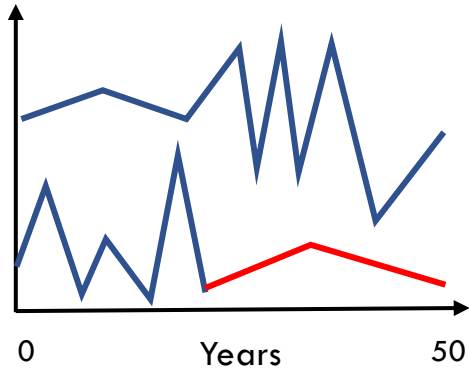
- Asynchrony
- High risk of extinction of small populations

- Demographic rescue of small populations
- Optimum ?
≈ wild average rate: 15%

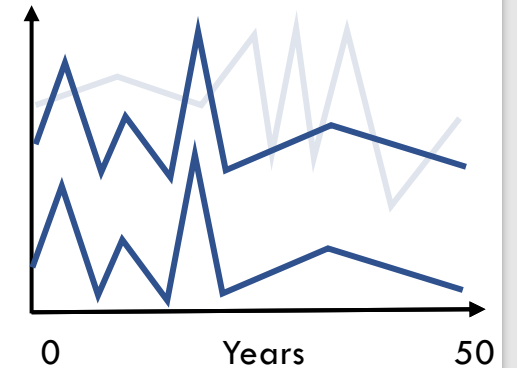
1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS

Population abundance



Population abundance



0%

10-20%

> 20%

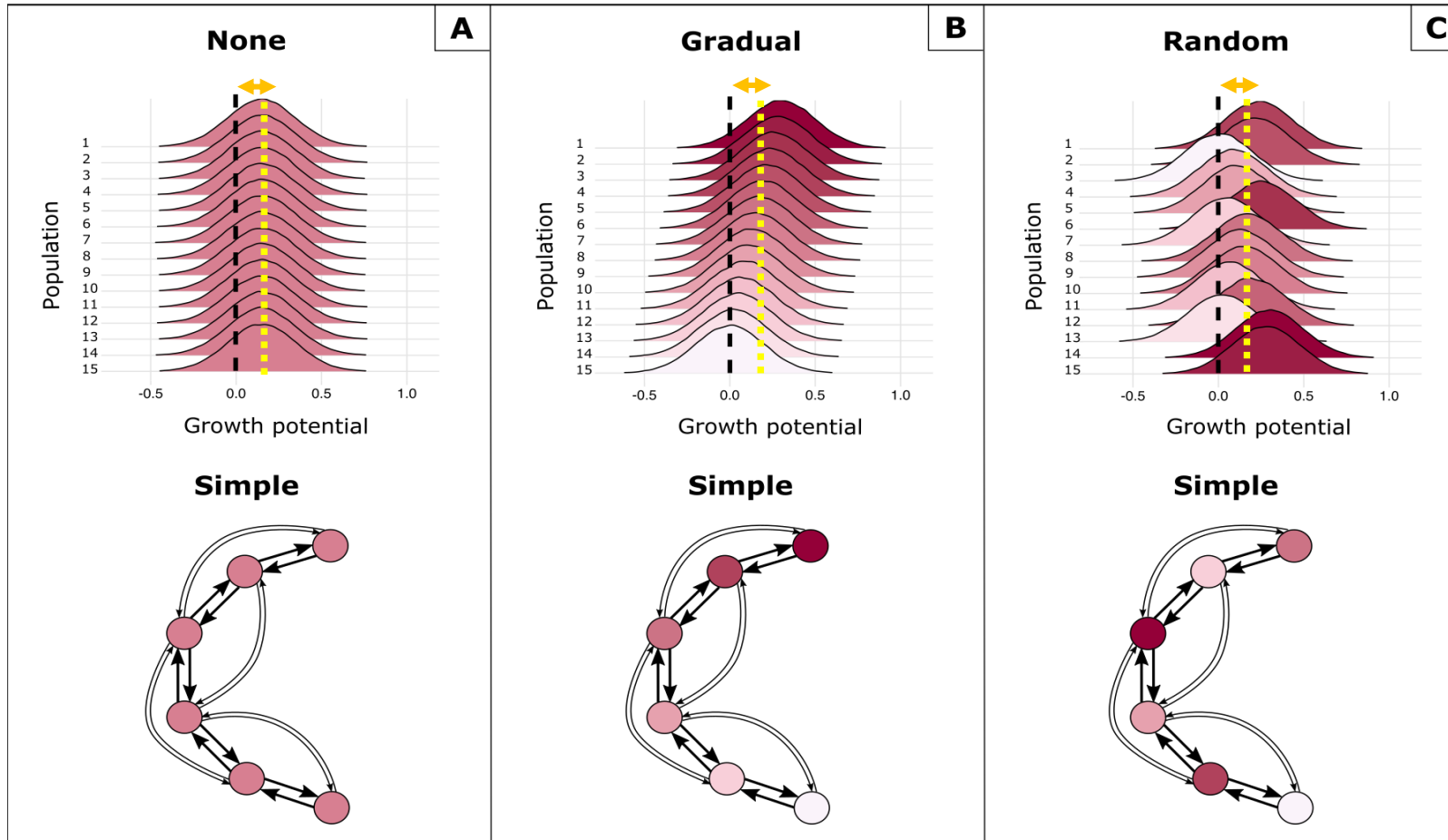
- Asynchrony
- High risk of extinction of small populations

- Demographic rescue of small populations
- Optimum ?
≈ wild average rate: 15%

- synchrony
- « Anti-rescue » effect

2) Evolutionary consequences - network scale

Lamarins et al., *Ecography* (2023)



SPATIAL GENETIC STRUCTURE OF GROWTH POTENTIAL

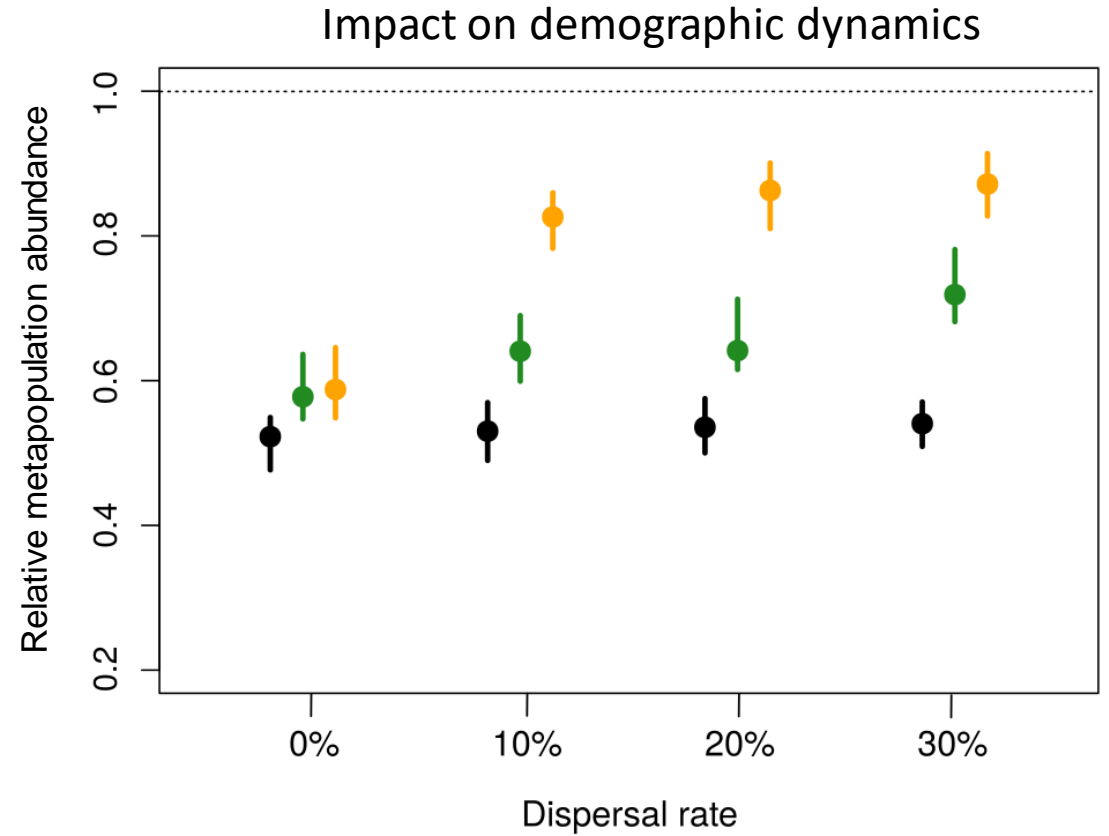
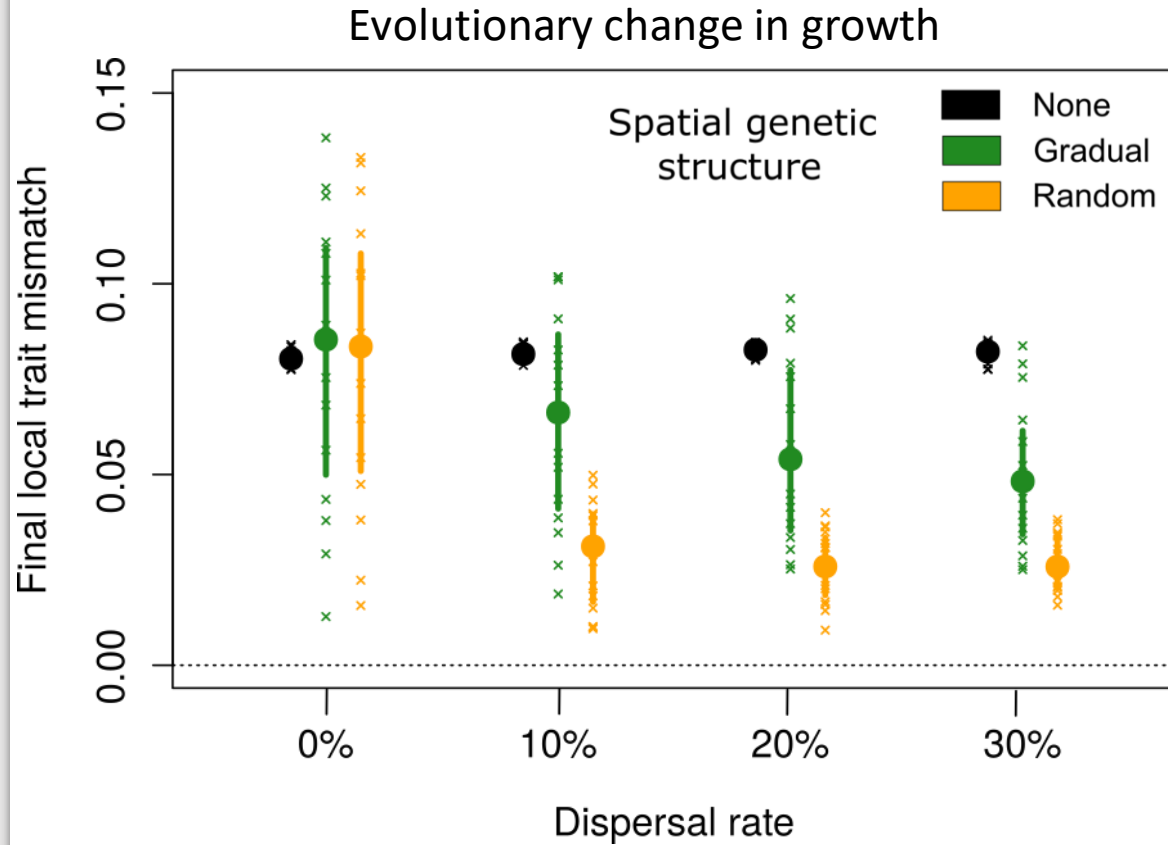
- Maladapted populations
- Contrasted spatial genetic structures among populations

SPATIAL CONFIGURATION

- Simple configuration

2) Evolutionary consequences - network scale

Lamarins et al., *Ecography* (2023)



Trait mismatch:
distance from
optimum

- Dispersal x genetic diversity among populations fostered adaptation
- Influence of spatial genetic structure

Conclusions

Lamarins et al., *Ecography* (2023)

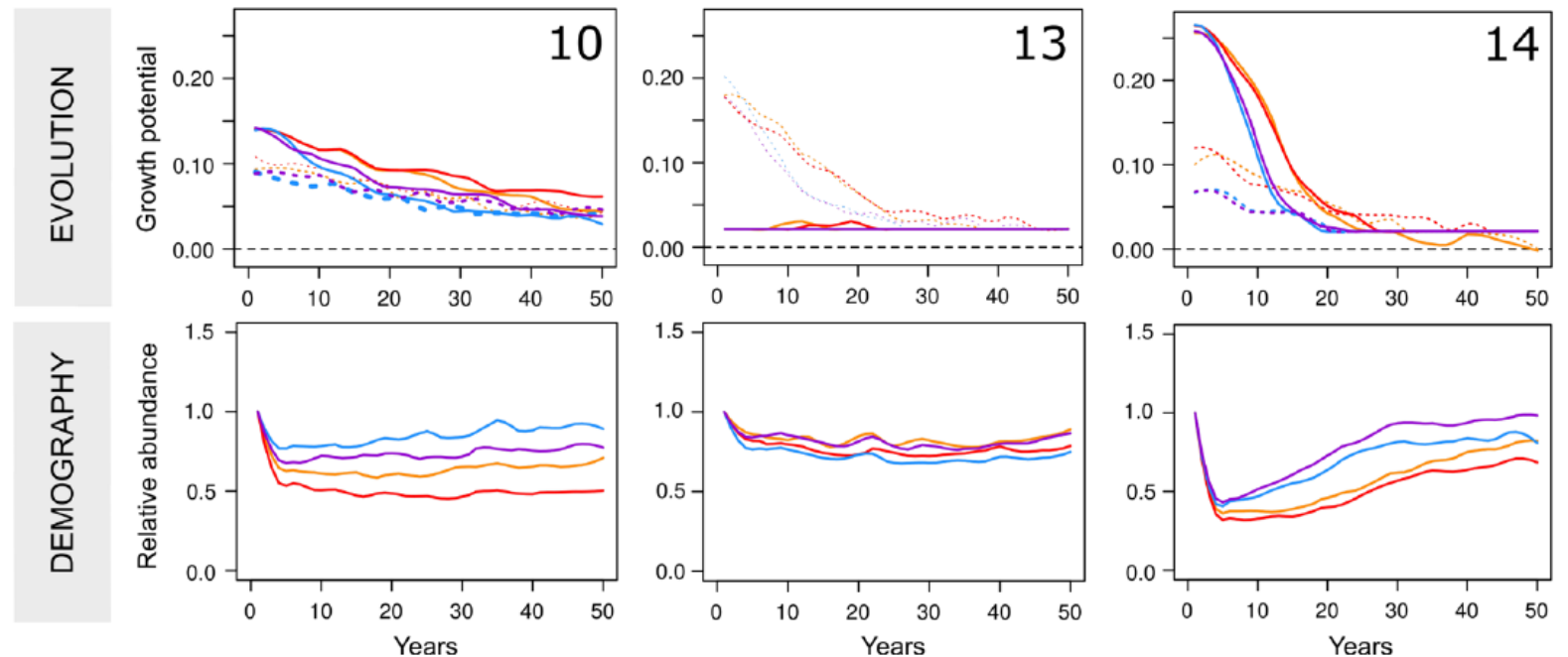
- Dispersal between distinct populations enhances both adaptation and demographic rescue, supporting the adaptive network theory.-
- High dispersal rates and random spatial genetic structure increase opportunities for adaptation.
- Evolutionary and demographic outcomes of local populations are context-dependent and strongly influenced by the spatial configuration of populations linked by dispersal.

Spatial configuration

- Simple
- Complex (Dist.)
- Complex (Carr. cap.)
- Complex (Dist. + Carr. cap.)

Genetic trait

- Philopatric
- - - Immigrants



Vulnerability of forests in face of climate change: DG-ABMs to investigate adaptive management strategies in Cedar and Douglas stands

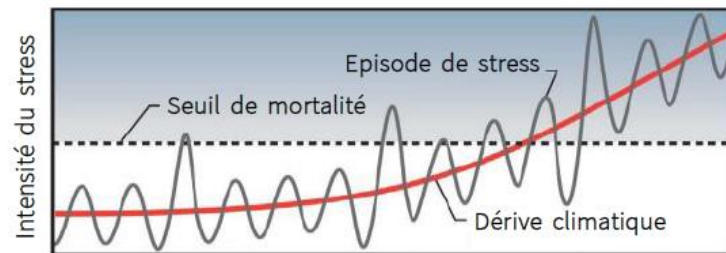


Context:

- Massive drought-induced mortality in forest stands worldwide (Allen et al 2015)
- A strategy is to reduce stand density → competition to adapt forest stand to drought
- How could forest management benefit from evolutionary processes ?

Can adaptive changes occur rapidly in tree populations ?

How does silviculture affect the adaptive capacity of forest stands ?



Allen et al. 2015

Co-encadrement F Lefèvre, H Davi, S Muratorio

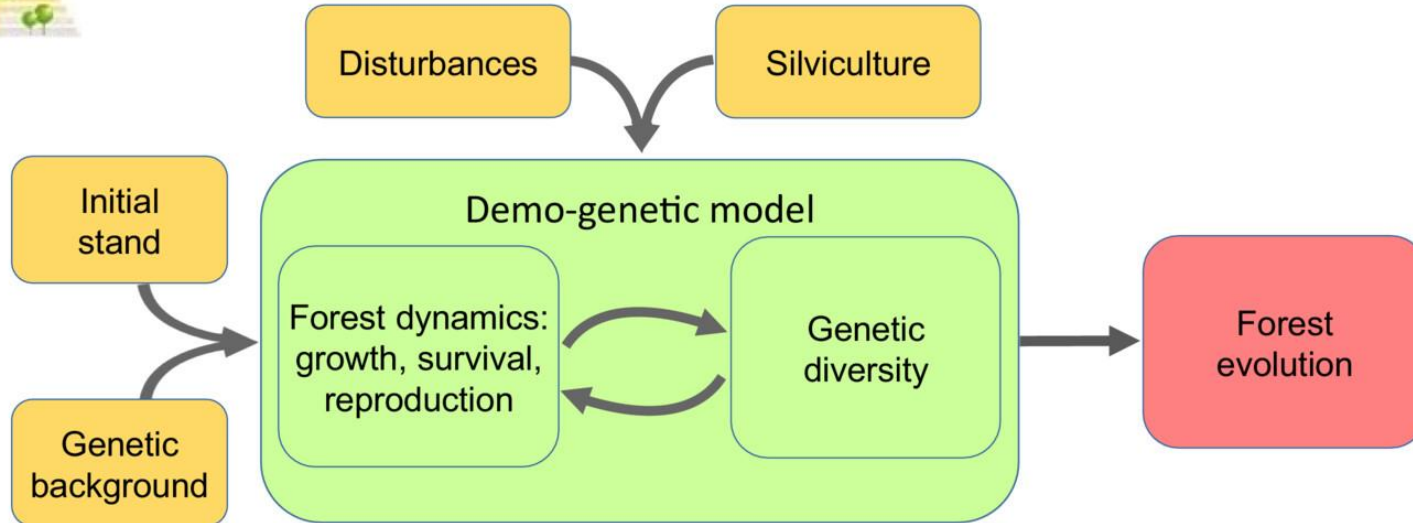
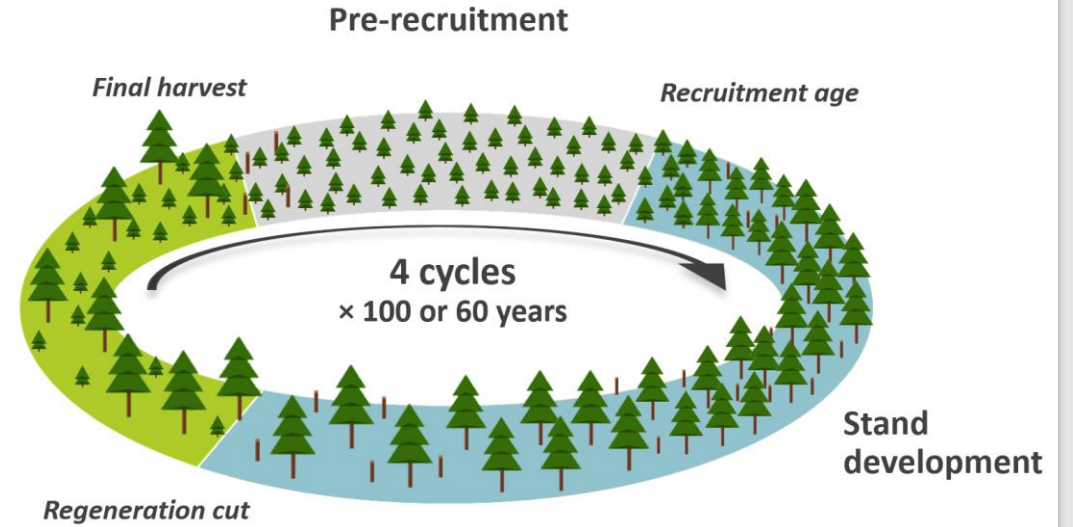
The model: Luberon2



+ DISTURBANCE



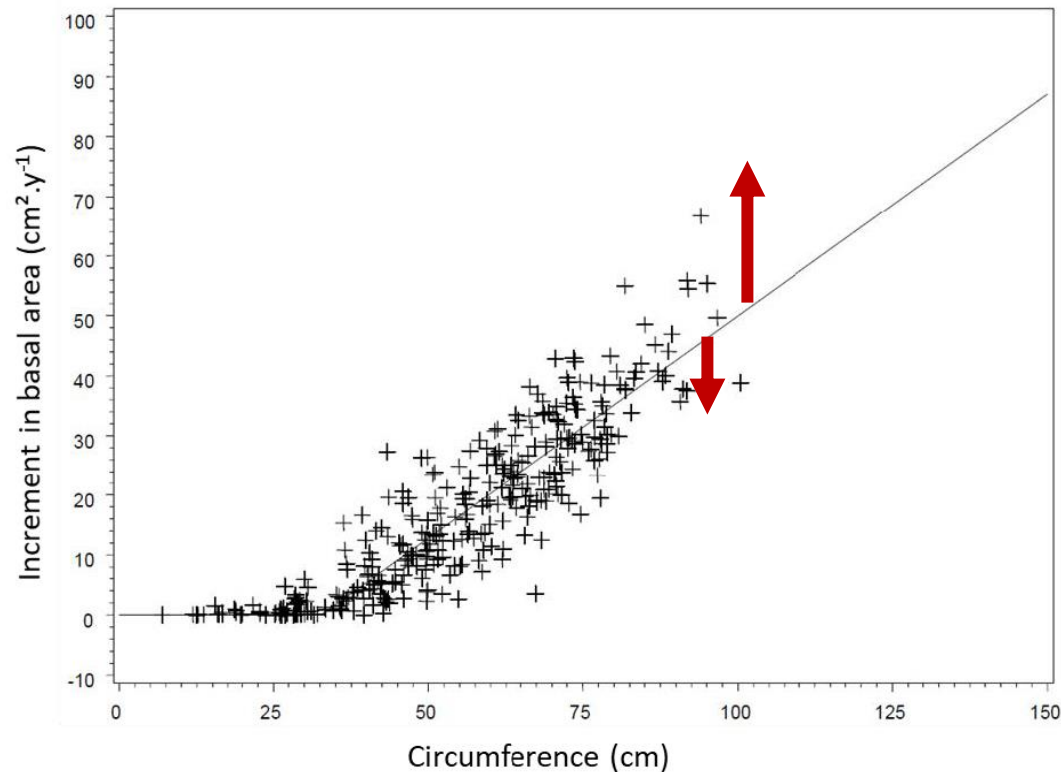
Installation of seedlings



Godineau, Fririon et al. *Evol Appl.* 2023

The focal trait: growth vigor

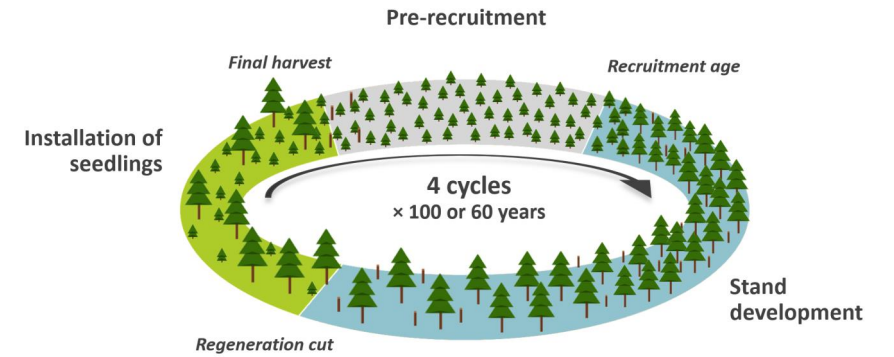
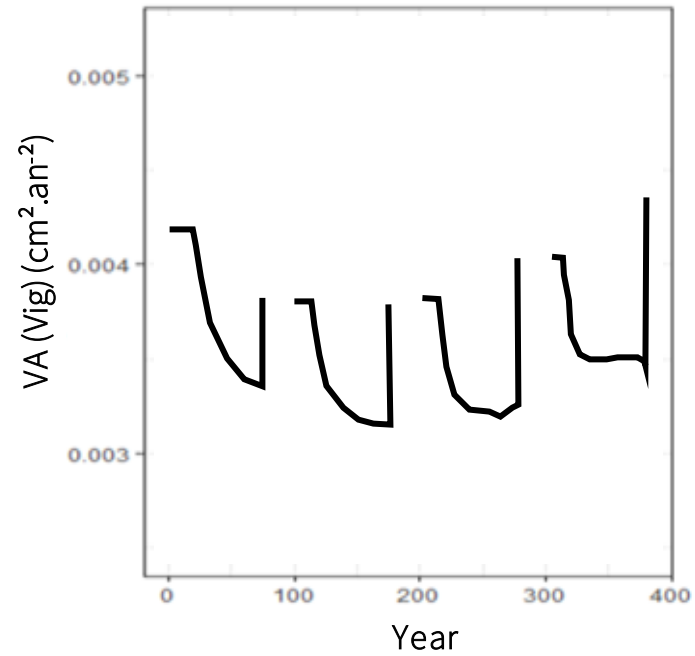
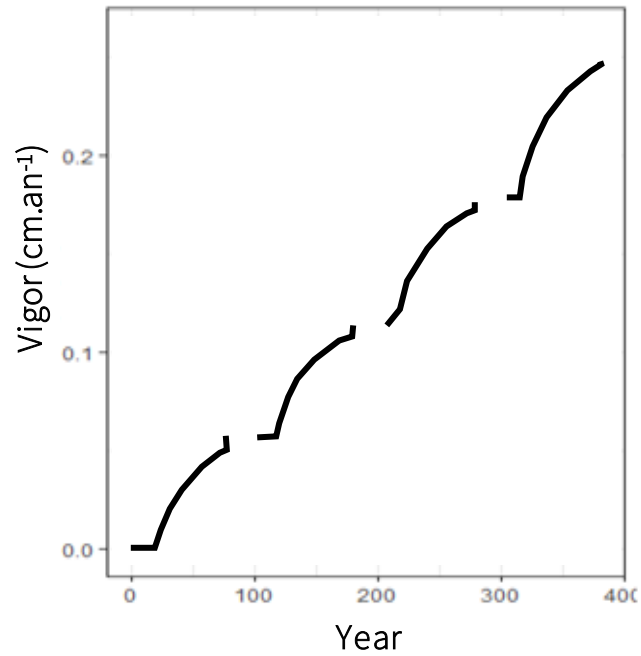
*Individual annual increment in basal area as a function of tree circumference in *C. atlantica*: empirical individual data and model prediction (taken from Courbet, 2002).*



- Natural mortality by competition, i.e., self-thinning, is **selective** with regard to tree size
- Mortality by disturbance and by silviculture were not **selective** (no variation in sensitivity to disturbance and random thinning)

1) Evolution of tree vigor

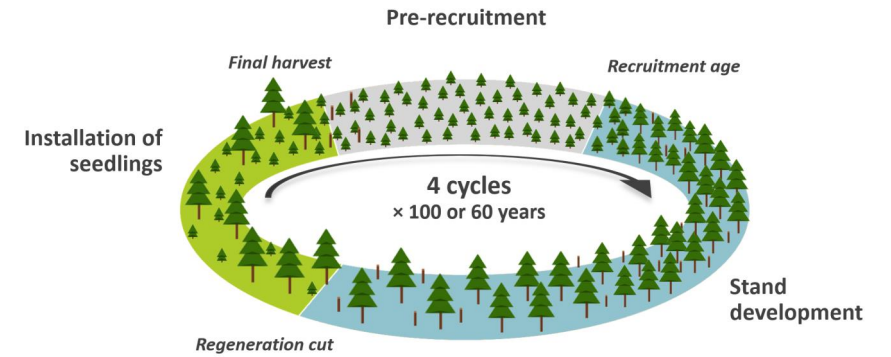
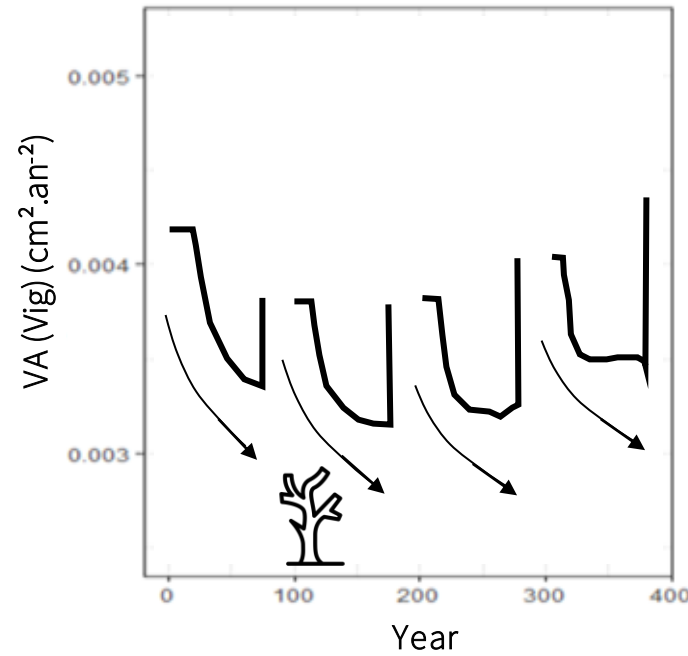
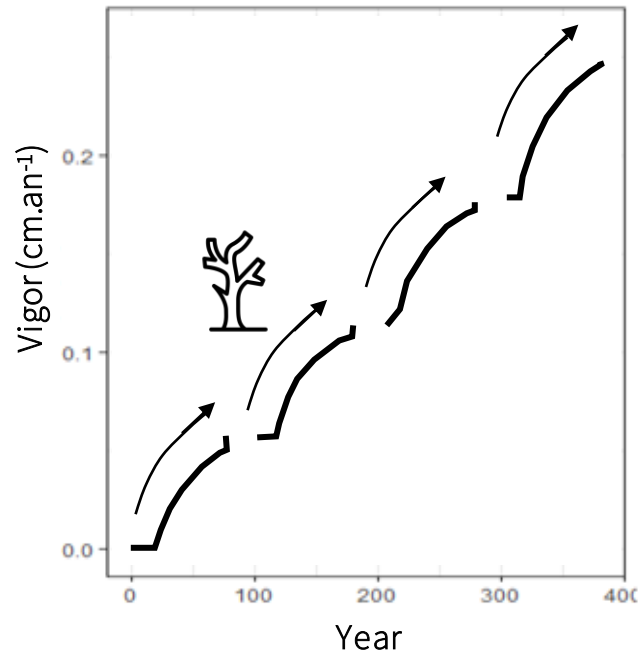
Without thinning



Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

Without thinning

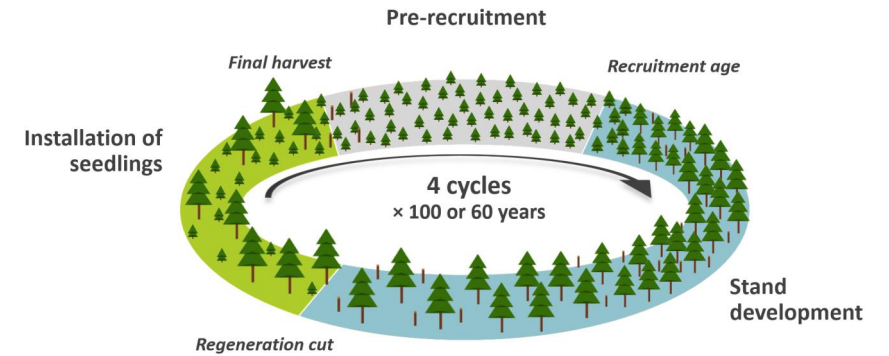
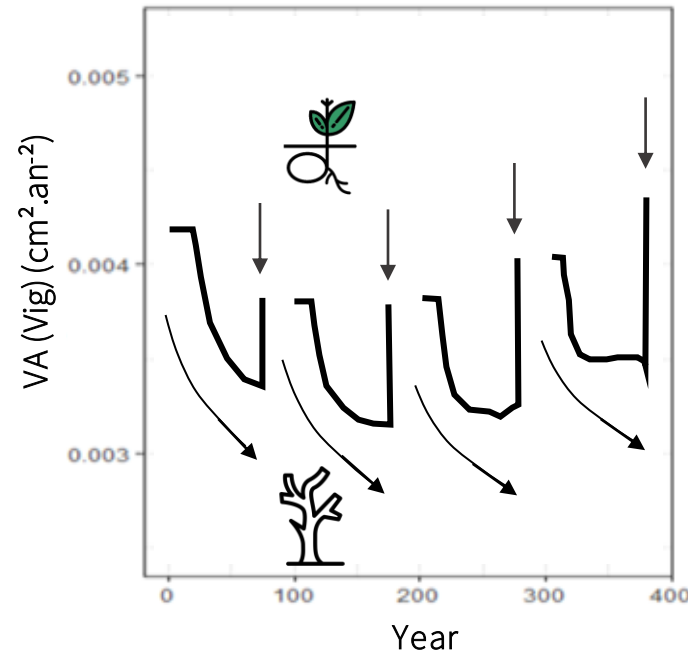
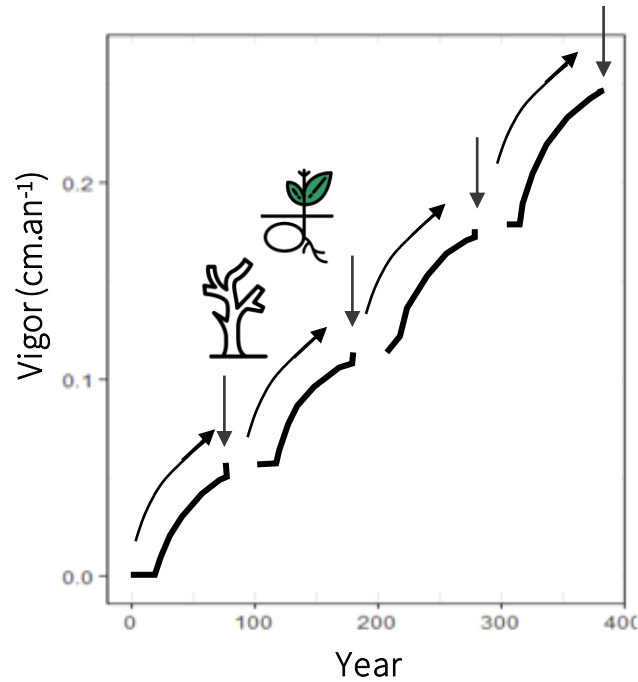


➤ Selection on survival (competition)

Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

Without thinning

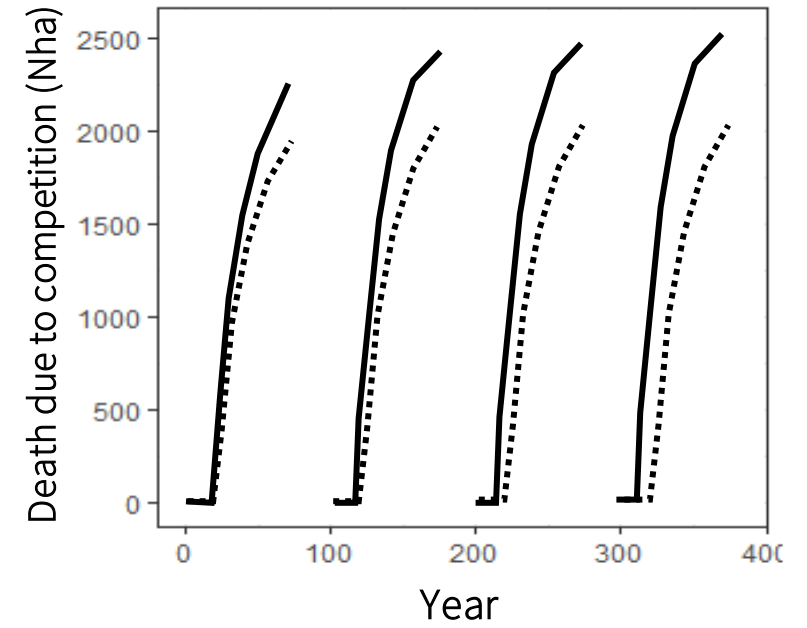
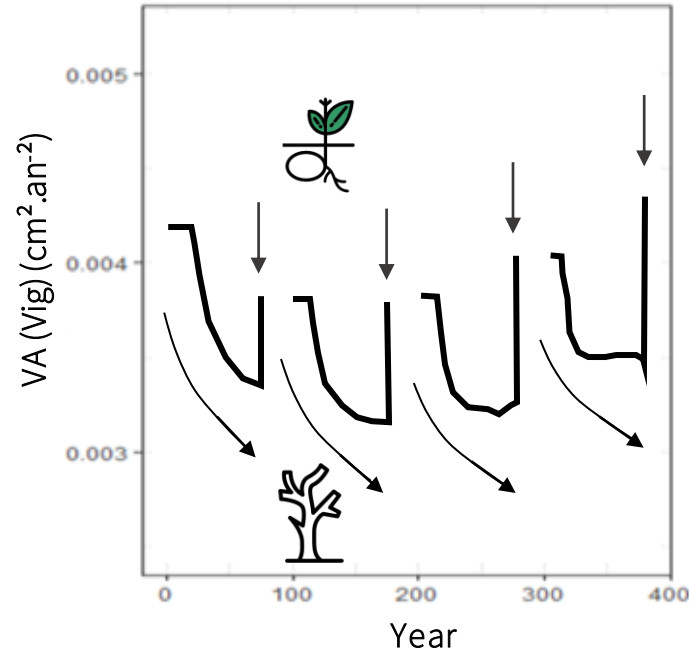
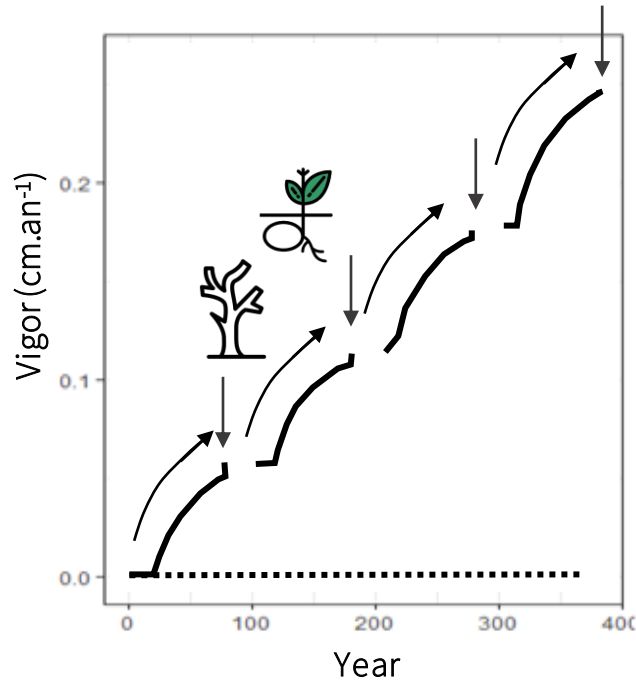


- Selection on survival (competition)
- Selection on fertility
- Restoration of genetic diversity during reproduction

Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

Without thinning



Inter-individual Variation

- without
- with

Realistic genetic gain (+12% growth per generation)

Increased growth = increased competition

Godineau, Fririon et al. *Evol Appl.* 2023

Thinning scenarios

Non selective thinning

Scenario	Thinning 1	Thinning 2	Thinning 3	Thinning 4	Thinning 5	Thinning 6	Regeneration cut	Final cut
<i>trend</i>	Age 25 : 1100 nha	Age 40 : 600 nha	Age 50 : 430 nha	Age 60 : 320 nha	Age 70 : 245 nha	Age 80 : 200 nha	Age 100 : 110 nha	Age 103 : 0 nha
<i>no thinning</i>							-	-

Godineau, Fririon et al. Evol Appl. 2023

Thinning scenarios

Non selective thinning

Scenario	Thinning 1	Thinning 2	Thinning 3	Thinning 4	Thinning 5	Thinning 6	Regeneration cut	Final cut
<i>trend</i>	Age 25: 1100 nha	Age 40 : 600 nha	Age 50 : 430 nha	Age 60 : 320 nha	Age 70 : 245 nha	Age 80 : 200 nha	Age 100 : 110 nha	Age 103 : 0 nha
<i>relaxed</i>	-	-			-	-	-	-
<i>delayed</i>	-			-	-	-	-	-
<i>low intensity</i>	× 4	× 4	× 4	× 4	× 4	× 4	-	-
<i>no thinning</i>	-						-	-

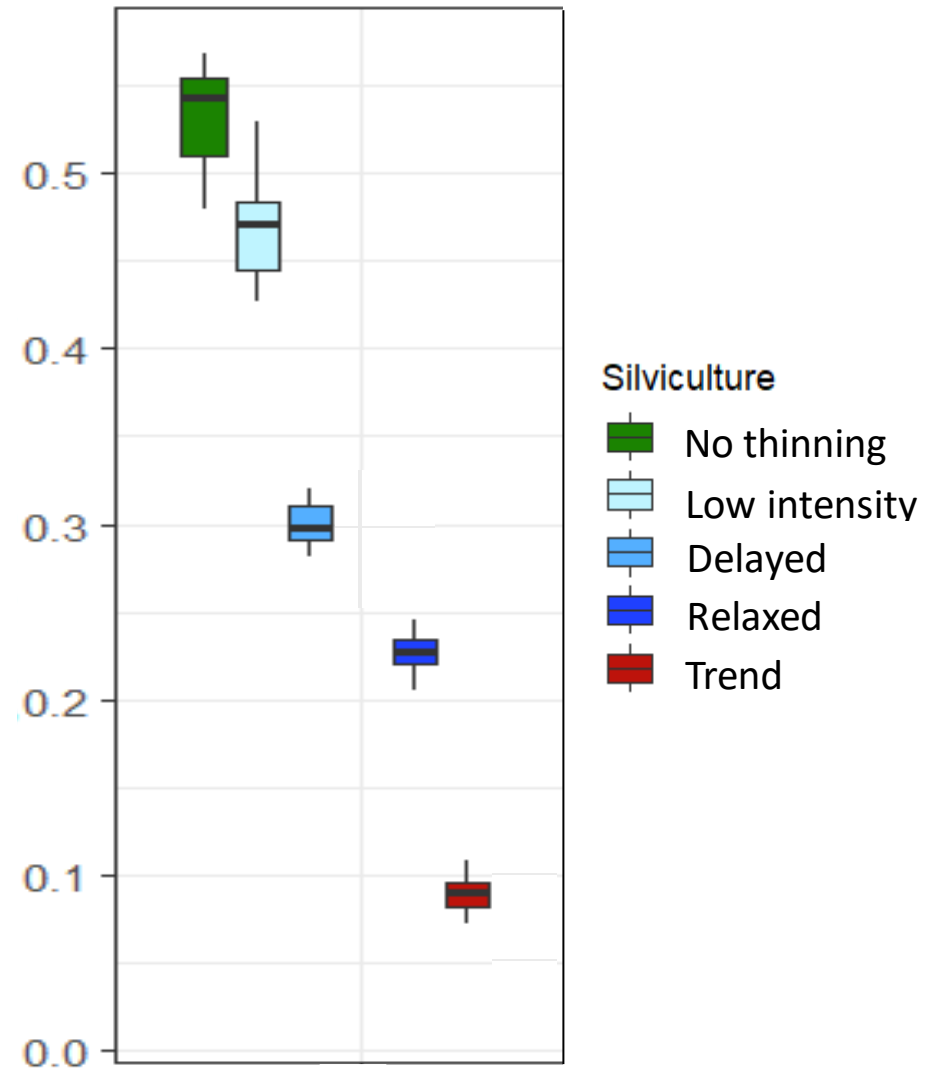
Godineau, Fririon et al. Evol Appl. 2023

Dynamic of adaptive change

(without perturbation)

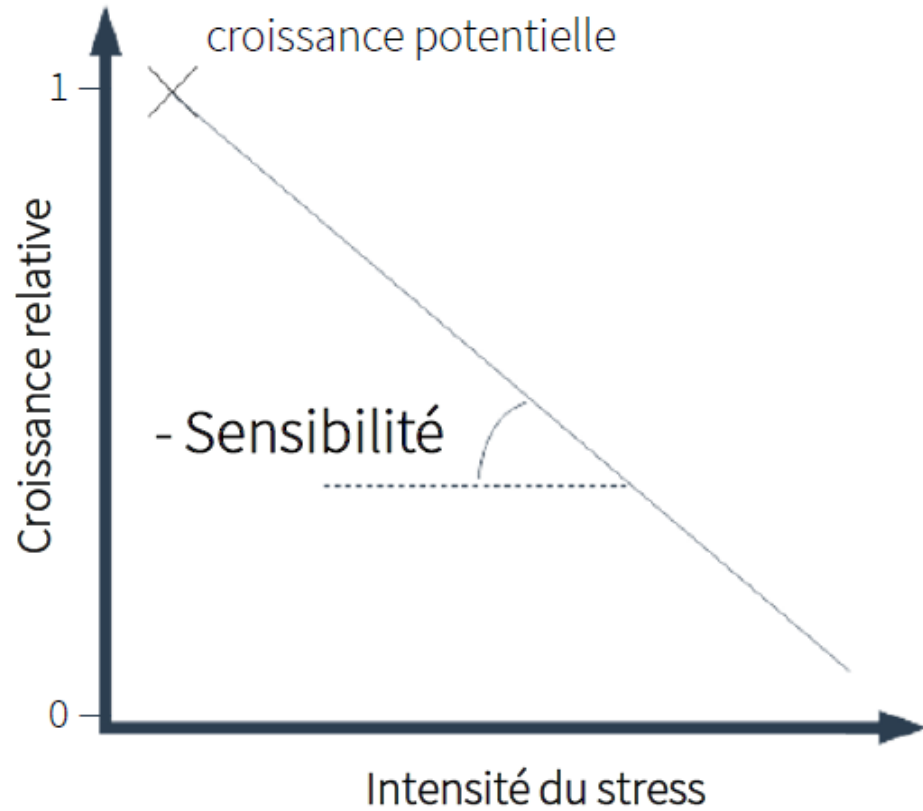
$$H_o = (zdiff_i / \sqrt{zvar \cdot w_i}) / n.gen$$

- Realistic rates of evolution
- Intensification reduces natural selection (on growth-related traits).
- Non-selective thinning slows down evolution.

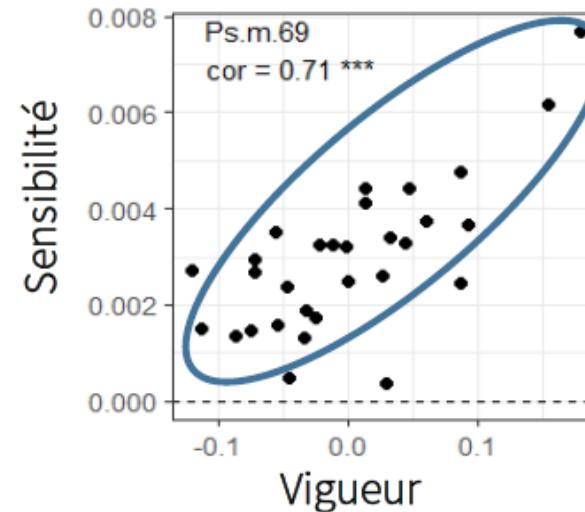
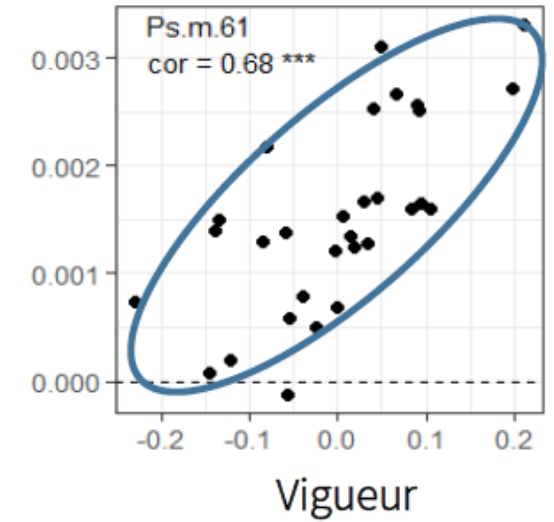
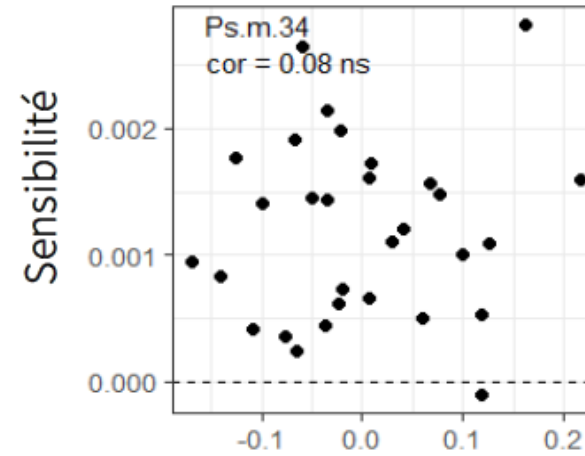


Godineau, Fririon et al. Evol Appl. 2023

2 focal traits: vigour + sensitivity to disturbances



➤ La perte relative de croissance par unité de stress

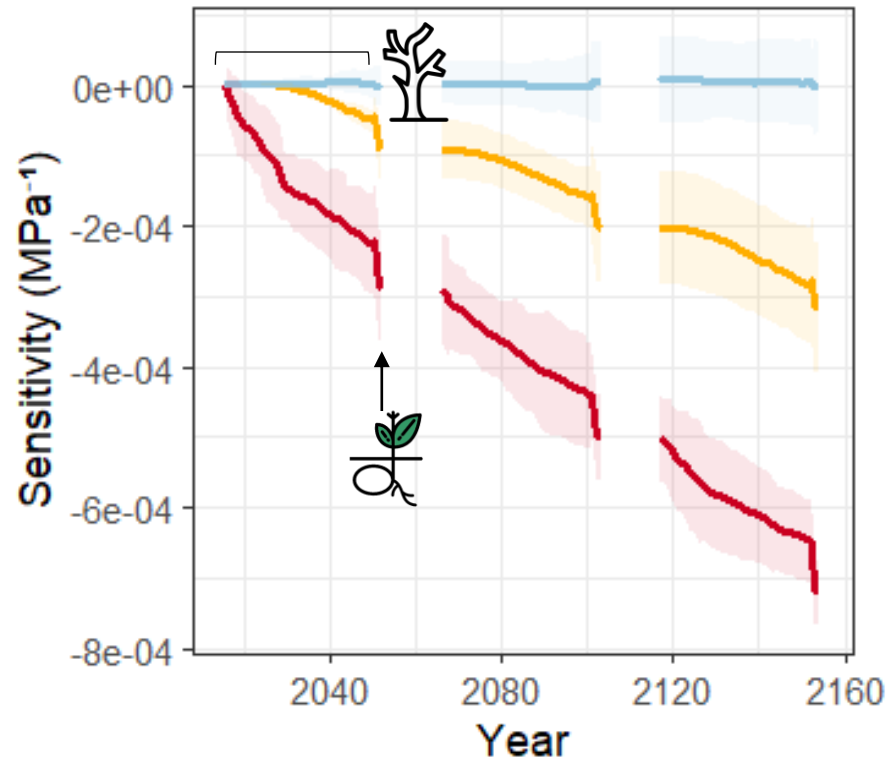
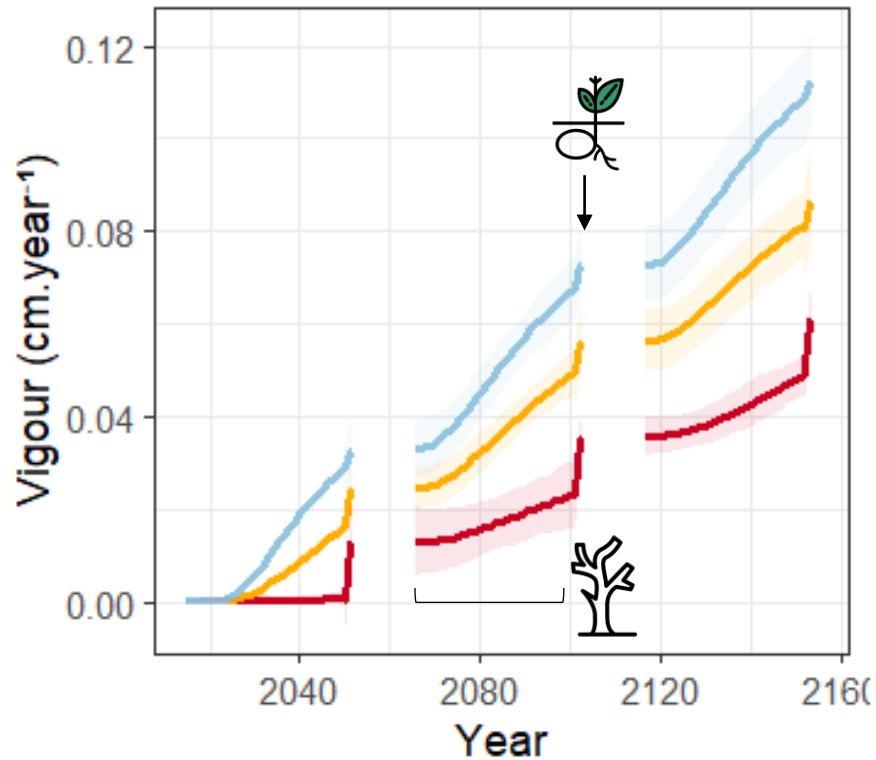


Trade-off between
vigour and reduced
sensitivity

Fririon et al. Forest Ecol Management 2022

Evolution of vigor and sensitivity

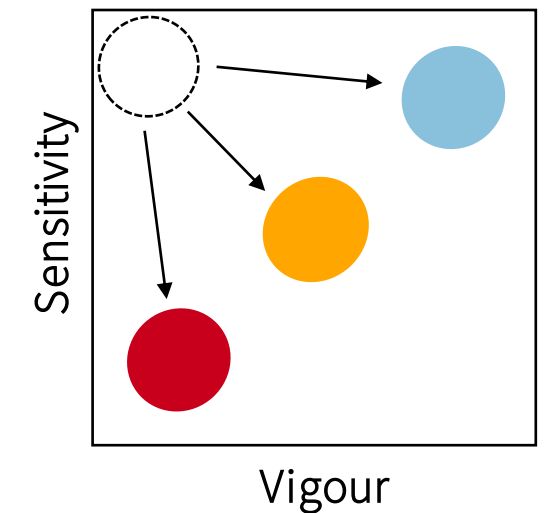
(with disturbance, without thinning)



Stress regime

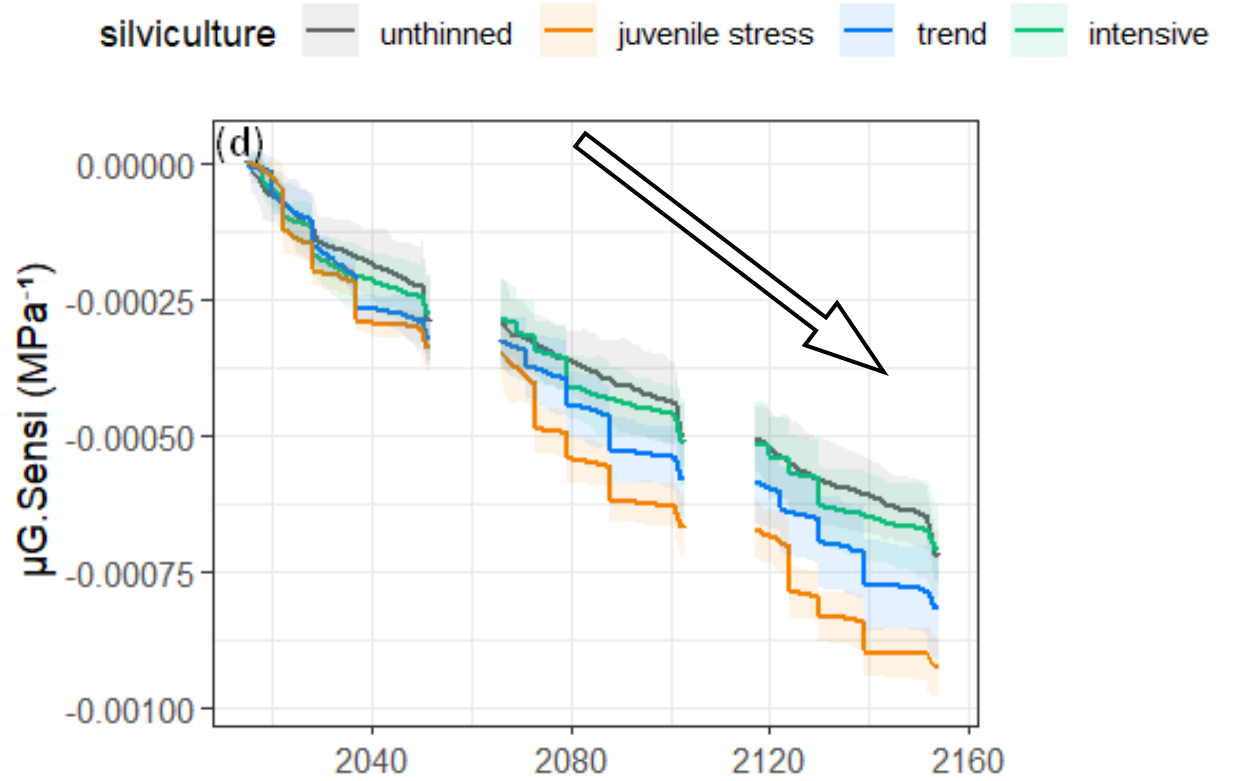
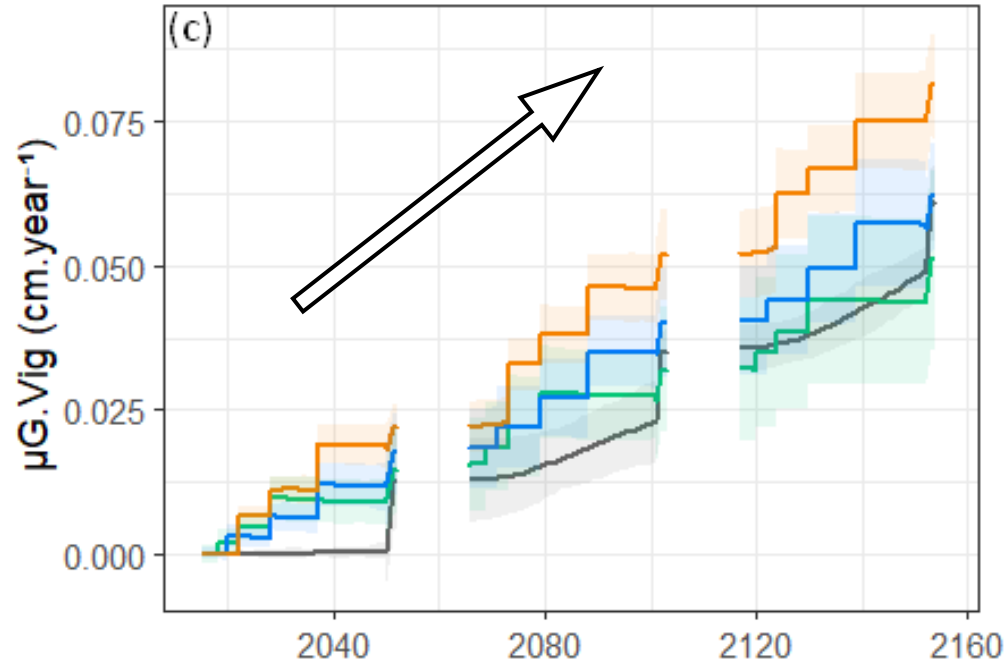
- zero
- medium
- severe

- Realistic evolution rates (0.1 to 0.3 haldane)
- Realistic genetic gain (+8% growth per generation)
- Antagonistic selection between vigor and sensitivity



Evolution of vigor and sensitivity

(disturbance + selective thinning)

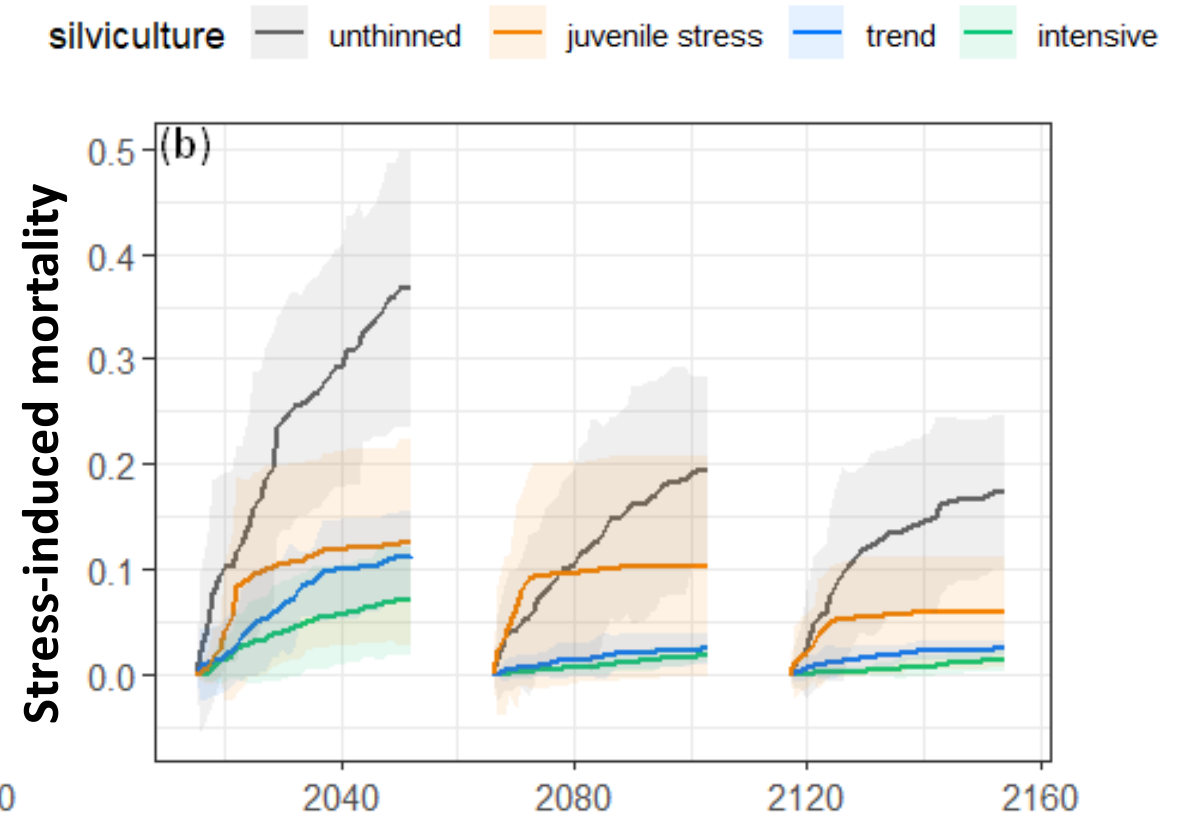
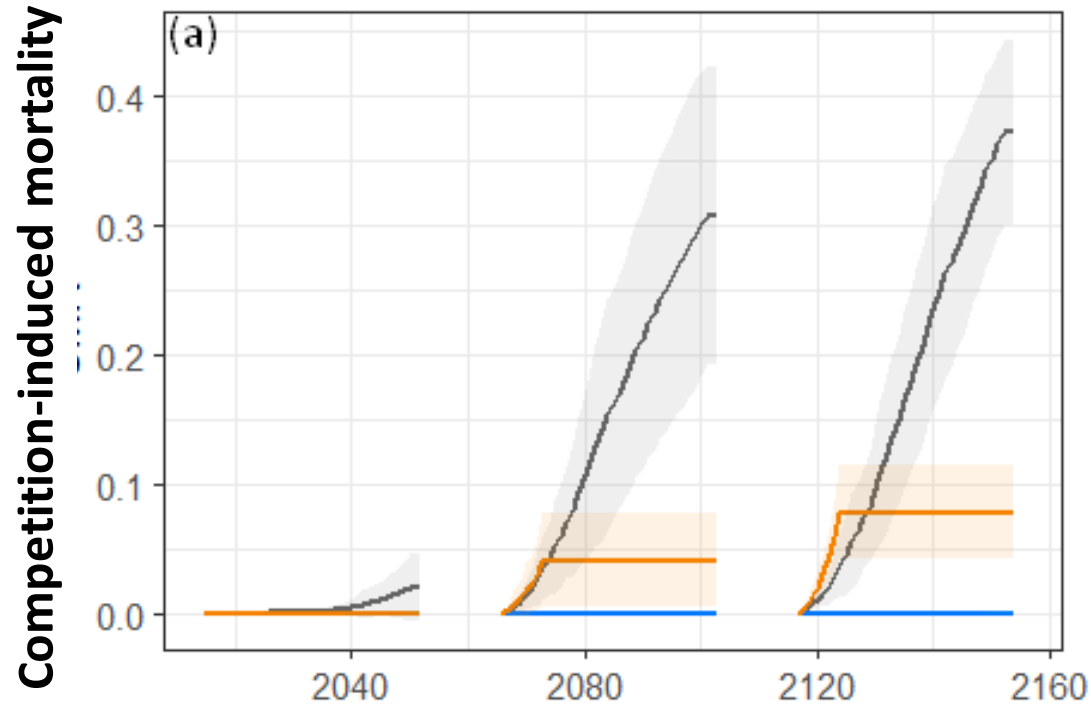


➤ Selective thinning can outperform natural selection.

Fririon et al. in revision

Evolution of vigor and sensitivity

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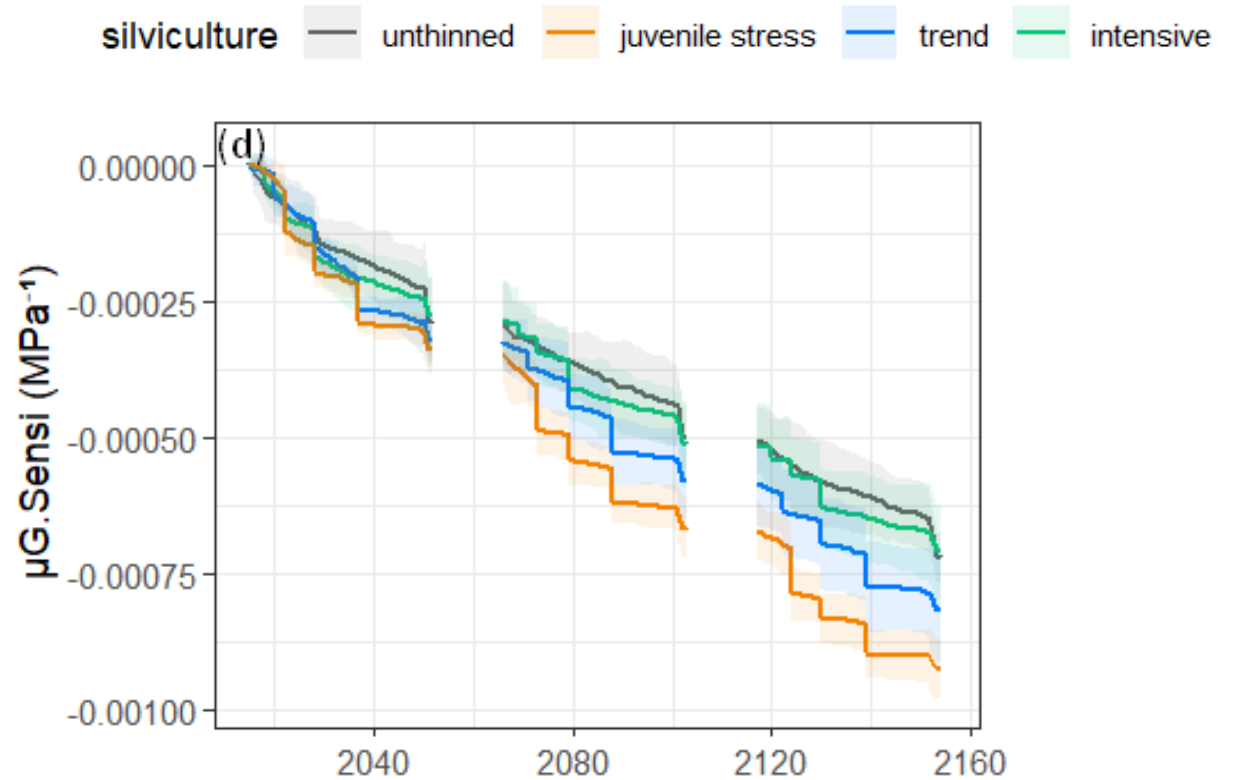
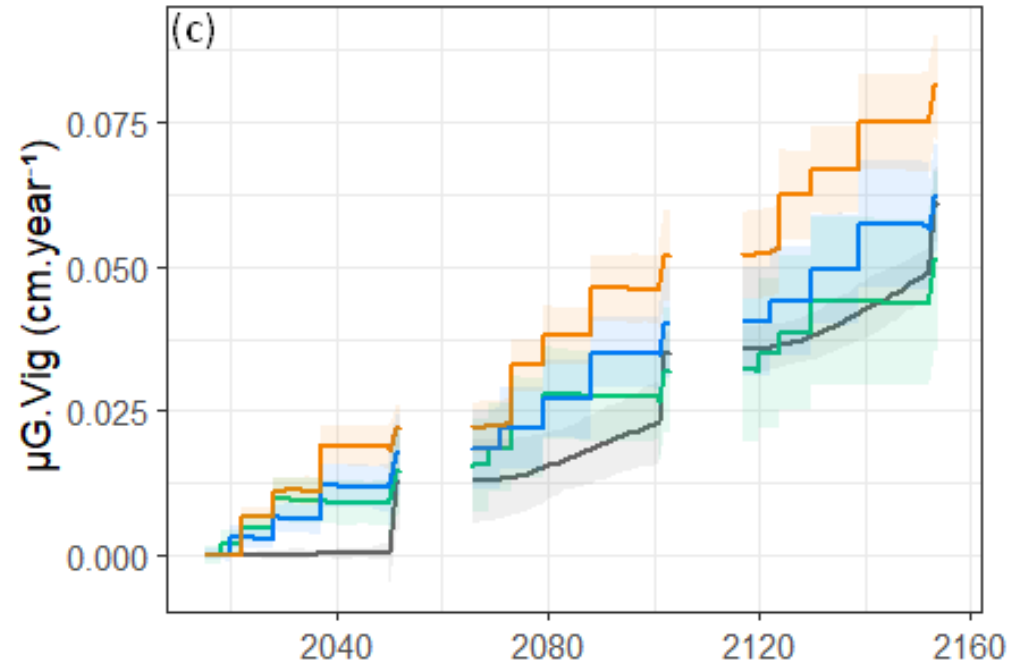


- Selective thinning can outperform natural selection.
- Forestry reduce mortality (both competition-induced and stress induced)

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Evolution of vigor and sensitivity

(disturbance + selective thinning)



- Selective thinning can outperform natural selection.
- More intensive forestry = less genetic evolution :
 - ✓ *Reduced stress = reduced selection pressure*
 - ✓ *Early random thinning = fewer selection opportunities*

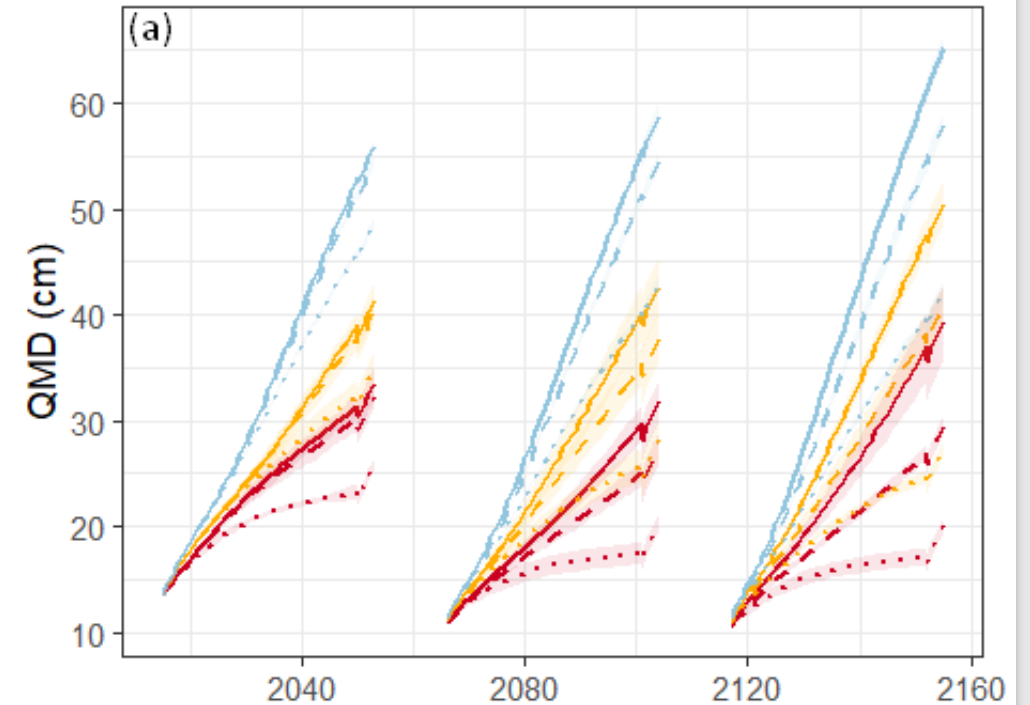
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Conclusions

- Feedback between demographic competition and evolutionary selection for vigor accelerates evolutionary rates.
- Silviculture reduces natural selective mortality but induces indirect selection on vigor and sensitivity.
- Anthropogenic selection, especially without early thinnings, can drive faster evolution than natural selection alone, highlighting the importance of evolution-focused silvicultural strategies.

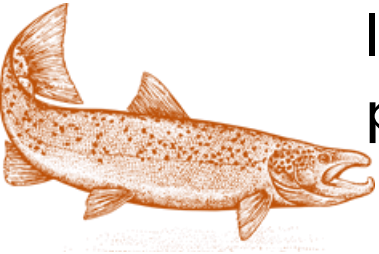
Phenotypic variation level ··· zeroVar - - - baseVA — twiceVA

Stress regime — zero — medium — severe



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Take-Home message



Interactions between dispersal and the eco-evolutionary dynamics of local populations affect metapopulation dynamics, and vice versa



Non-selective thinnings can reduce the intensity of natural selection (e.g., on vigor), while selective thinnings (based on size) can exceed the effects of natural selection.

Limits and benefits of DG-ABMs

- **Computational complexity:** Complex models integrating different forms of knowledge (empirical, mechanistic, generalist), processes, and scales.
- **Parameterization and validation challenges:** It can be difficult to accurately parameterize and validate DG-ABMs due to the large number of interacting variables.
- **Sensitivity to assumptions:** The outcomes of these models are highly sensitive to the underlying assumptions, which can lead to misleading results if the assumptions are incorrect.

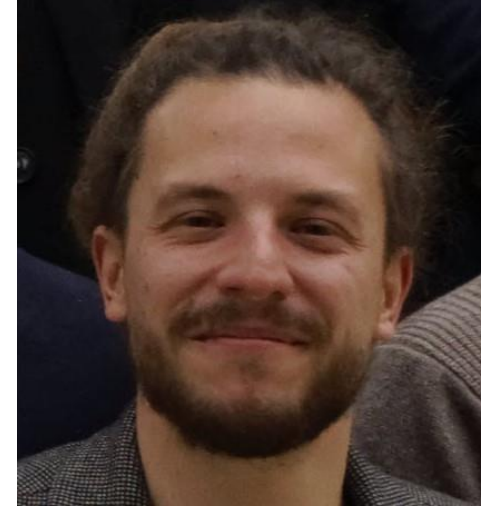


- **Computational complexity:** Complex models integrating different forms of knowledge (empirical, mechanistic, generalist), processes, and scales.
- **Parameterization and validation challenges:** It can be difficult to accurately parameterize and validate DG-ABMs due to the large number of interacting variables.
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- **Allows capturing the emerging effects of individual interactions (bottom up)**
- **Benefits from the existence of platforms (CAPSIS), communities (ABMs), and databases**
- **A tool to identify new scientific frontiers, promote interdisciplinarity, and explore "nature-based solutions"**
- **A tool for dialogue with other management stakeholders (ONF, OFB, etc.)**



Amaia Lamarins

*Merci au reseau DG-ABM et à vous pour
votre attention*



Victor Fririon



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