Modeling eco-evolutionary dynamics

Sylvie Oddou-Muratorio

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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

Modelling eco-evolutionary dynamics

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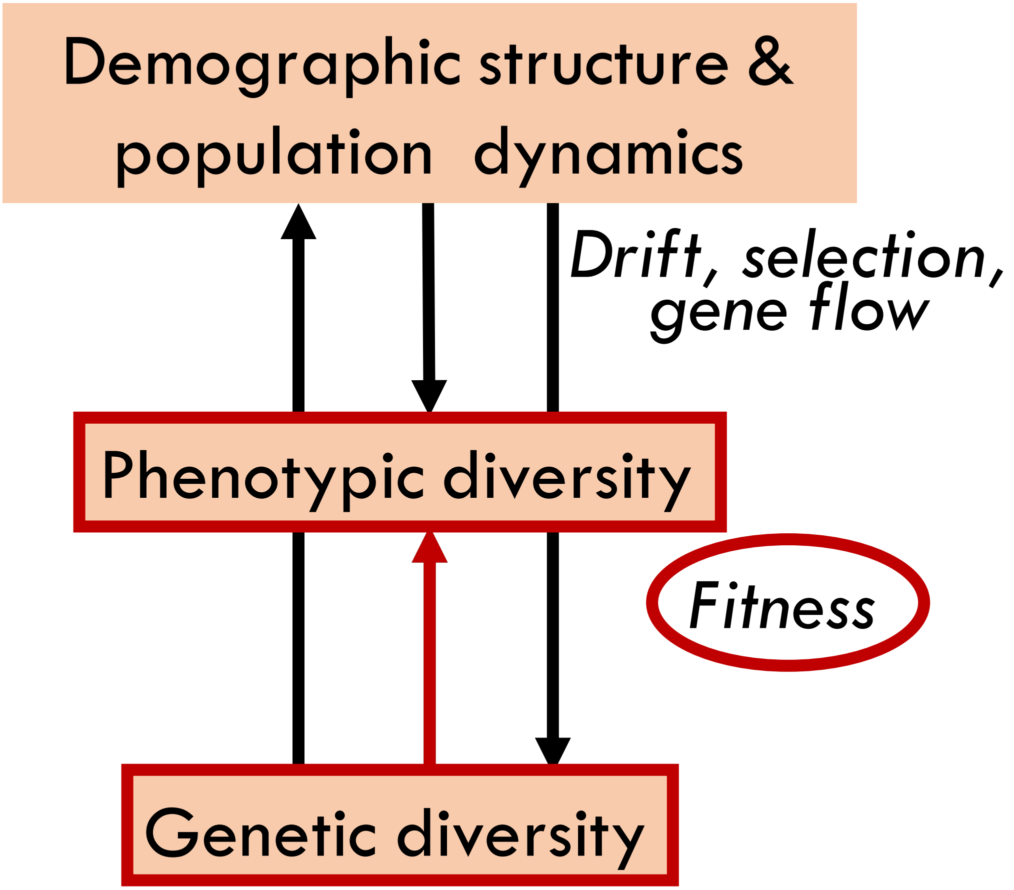
PERSPECTIVE

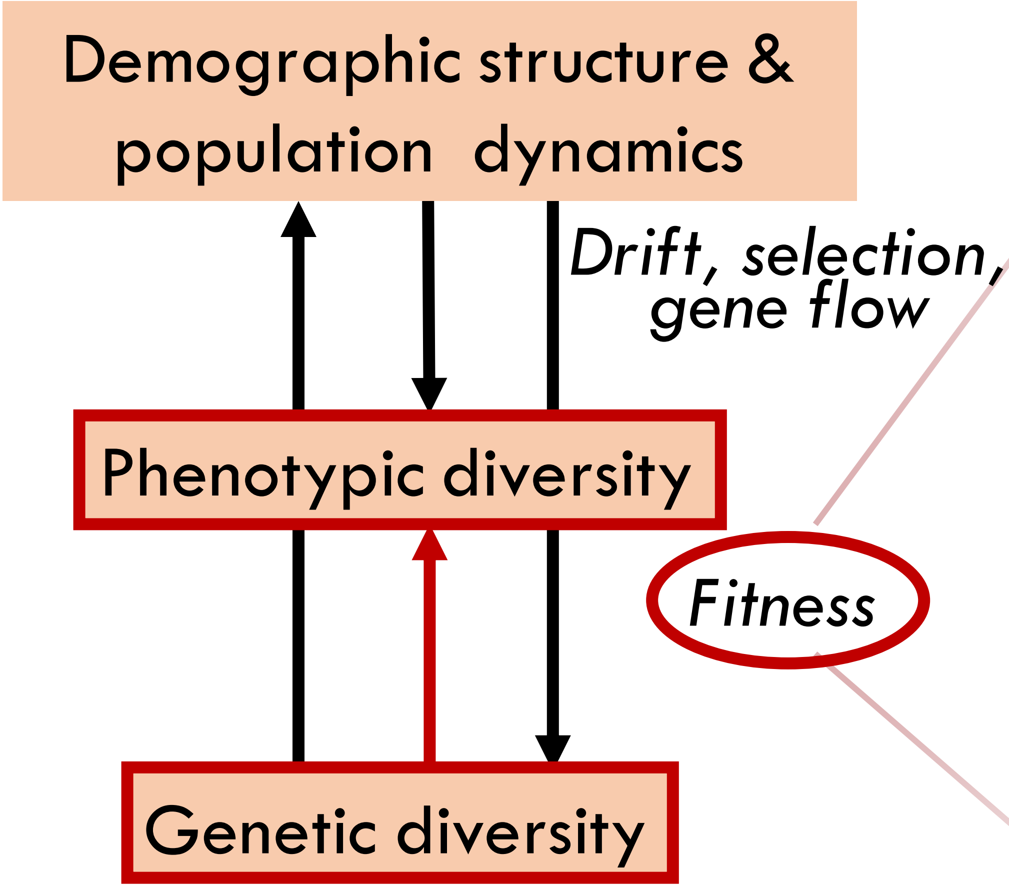
Importance of interindividual interactions in eco-evolutionary population dynamics: The rise of demo-genetic agent-based models

Amaïa Lamarins[1,2] | Victor Fririon[3] | Dorinda Folio[1] | Camille Vernier[4] | Léa Daupagne[1] | Jacques Labonne[1] | Mathieu Buoro[1] | François Lefèvre[3] | Cyril Piou[4] | Sylvie Oddou-Muratorio[1]

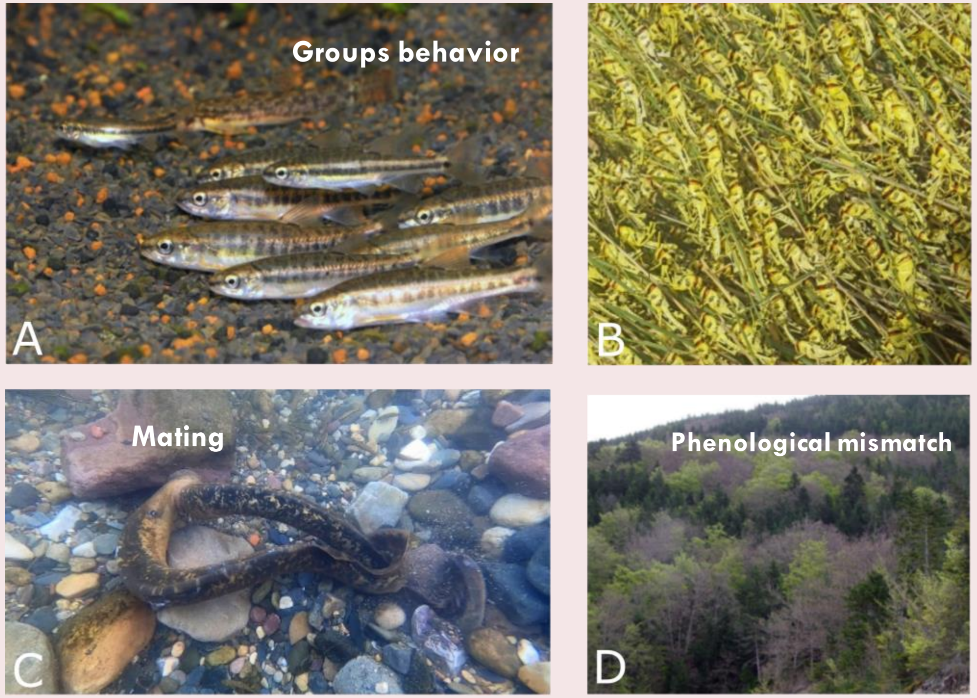
Eco-evolutionary dynamics and interindividual interactions



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

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

Analytical models:

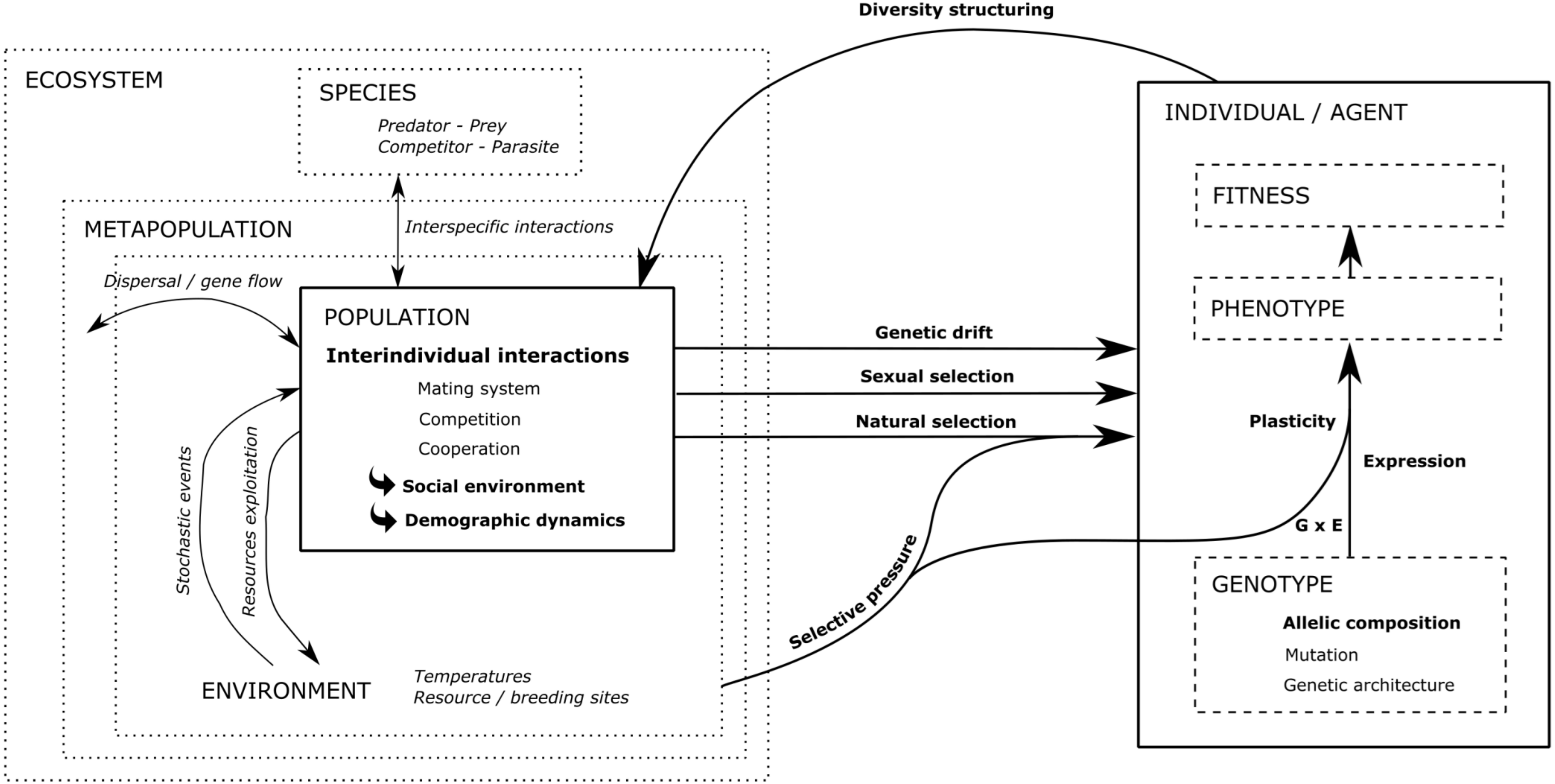
- Homogeneous processes within groups of individuals (populations or life stages)
- *A priori* fitness

DG-ABMs:

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

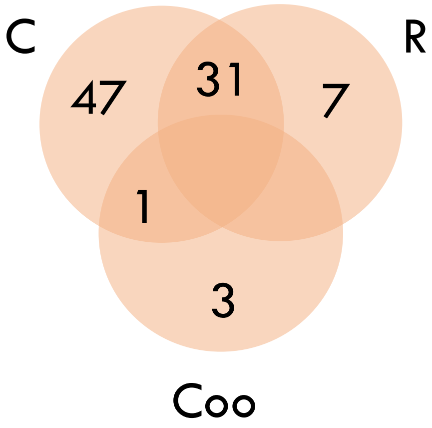
DG-ABM definition

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



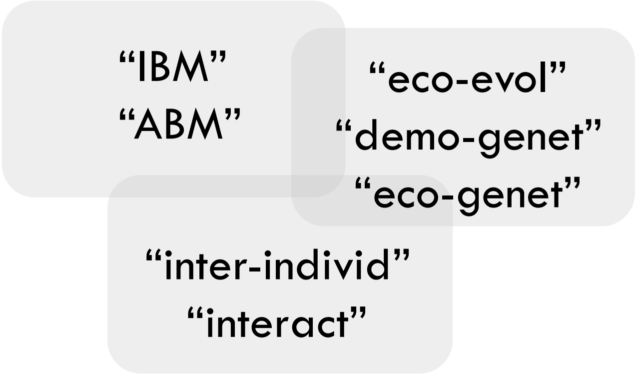
Sylvie Oddou-Muratorio, 1/10/2024

Litterature review



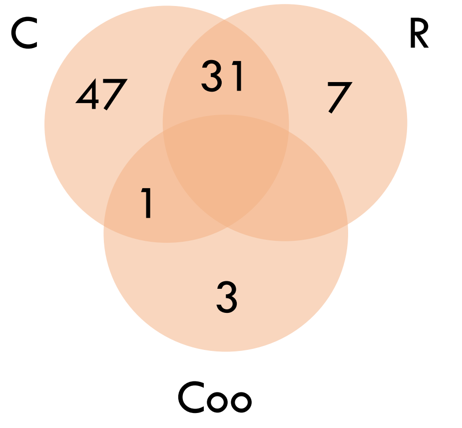
Type of interactions

Web of Science (1955-2022)



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

Litterature review



Type of interactions

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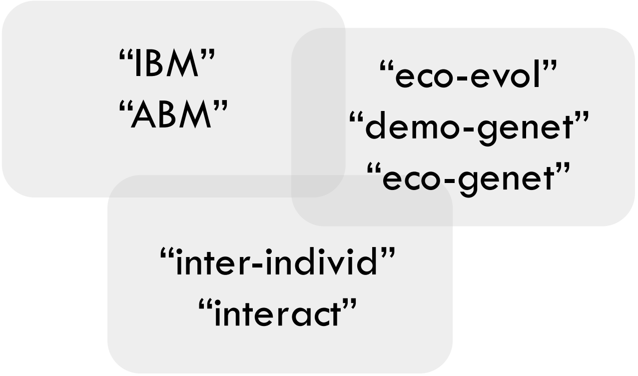

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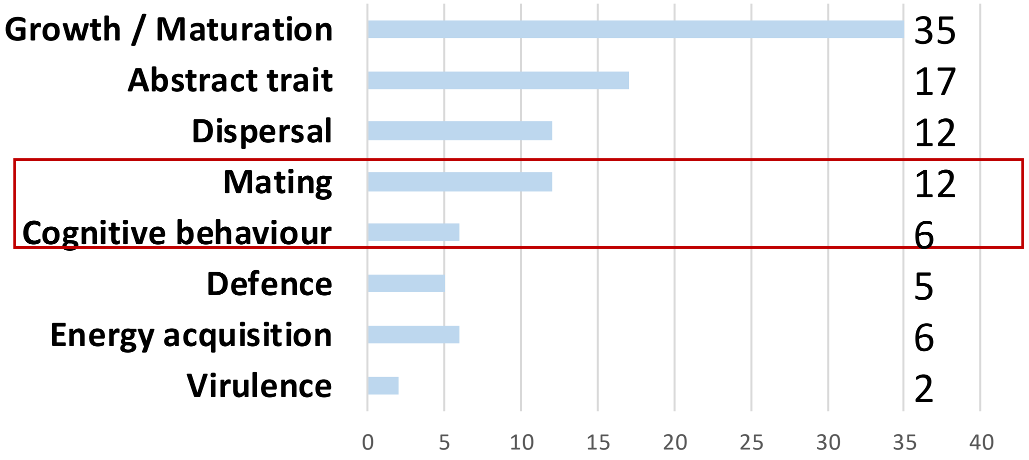
Evolving fitness-related traits



Size

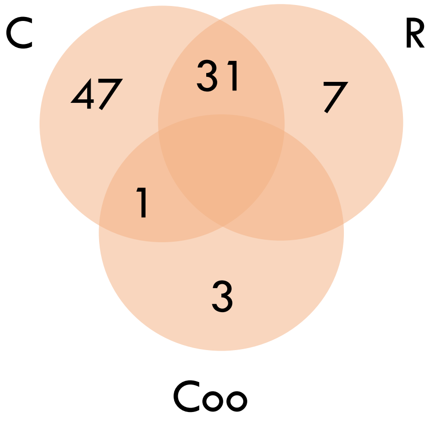
Avoidance of predators/competition

Direct effects on individual interaction

Sylvie Oddou-Muratorio, 1/10/2024

Litterature review

Type of interactions



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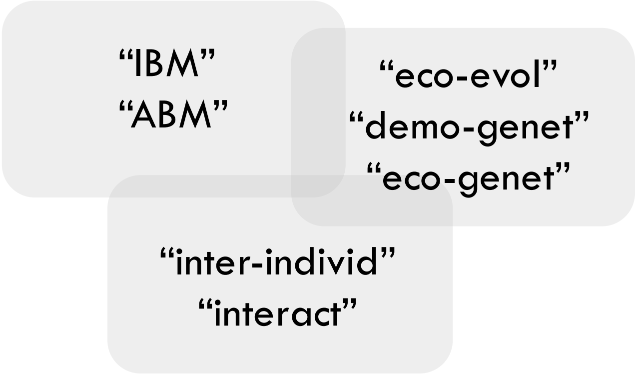

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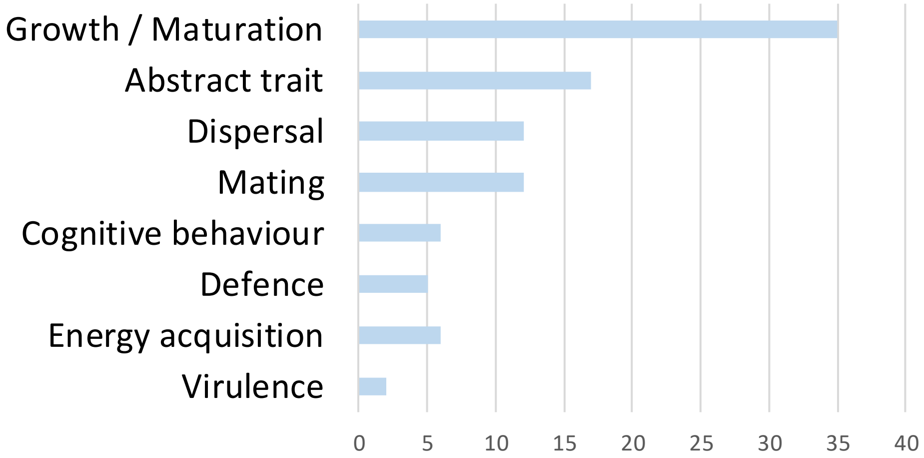
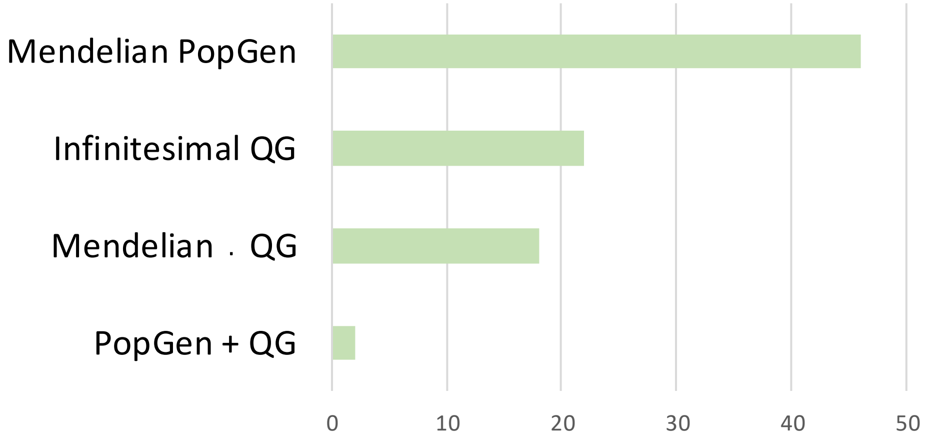
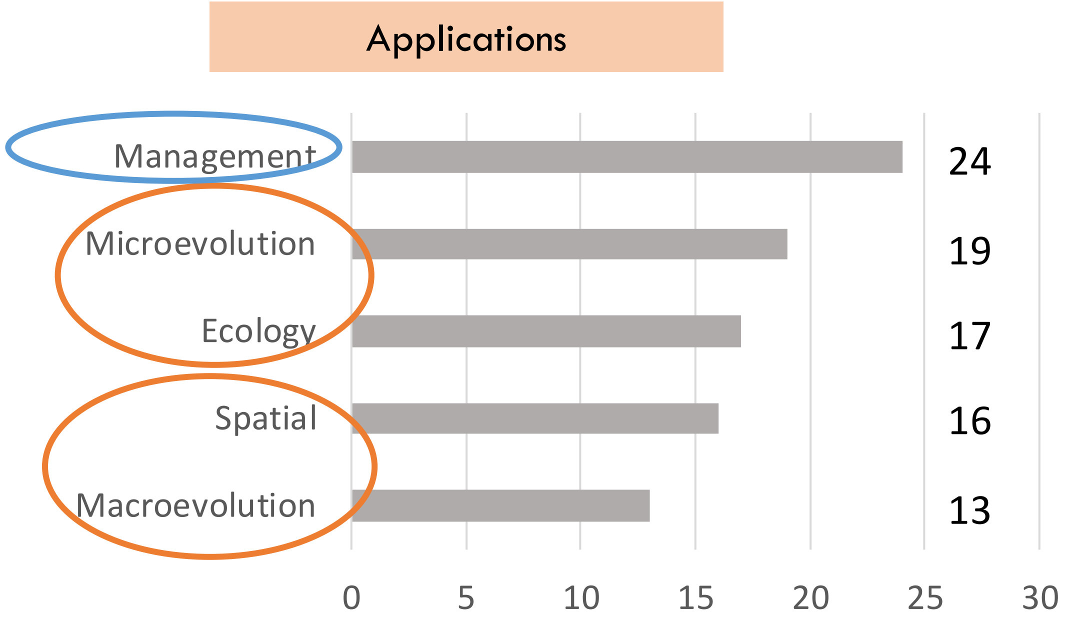


Inheritance framework



Litterature review



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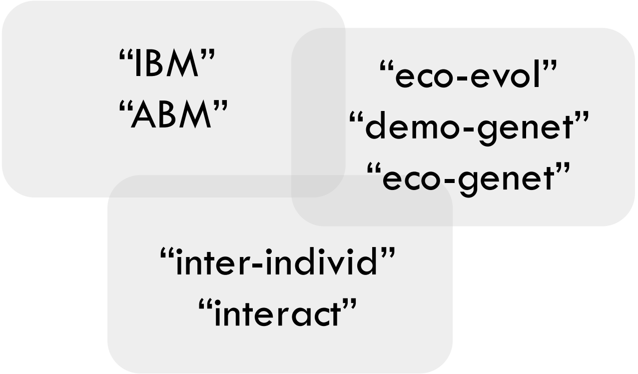


89 studies (after filtering: 1/ IBM, 2/ N generations, 3/ interaction, 4/ trait variability, 5/ heritability)

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

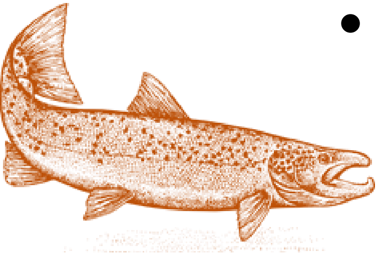
→ Larger spatio-temporal scale: metapopulation / communities dynamics, speciation

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

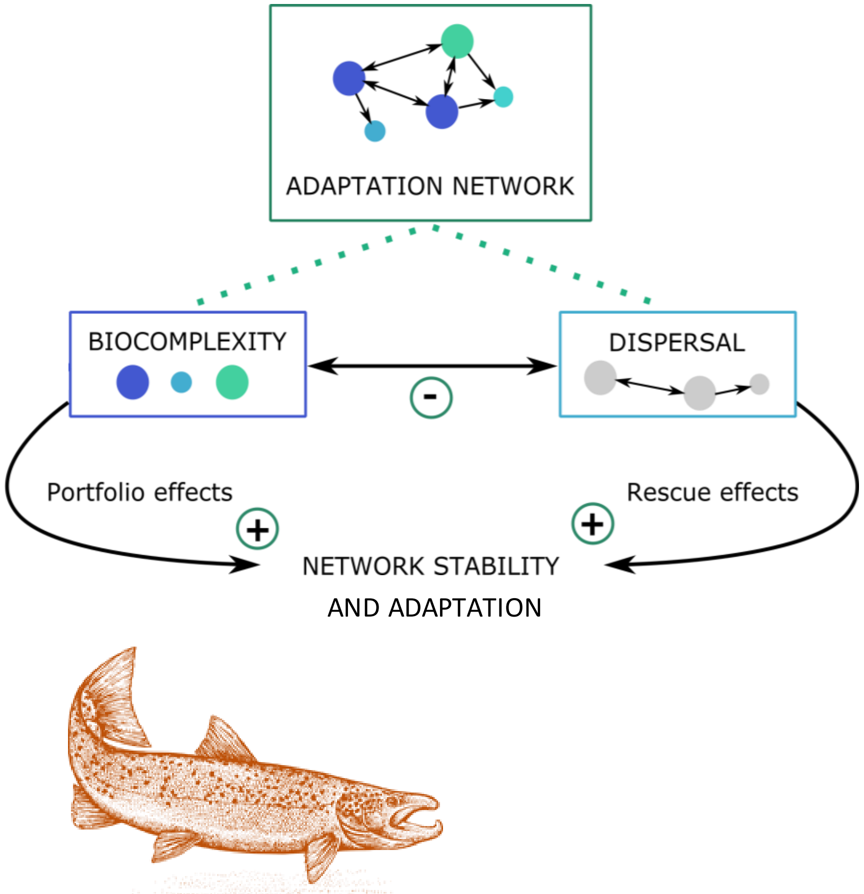


- Amaia Lamarins (2022) : Adaptation, persistence and management of Atlantic salmon in a metapopulation context
- Dorinda Folio (2022): Evolutionary management of brown trout intraspecific diversity

- 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

Thèse de Amaia Lamarins (2022)

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)

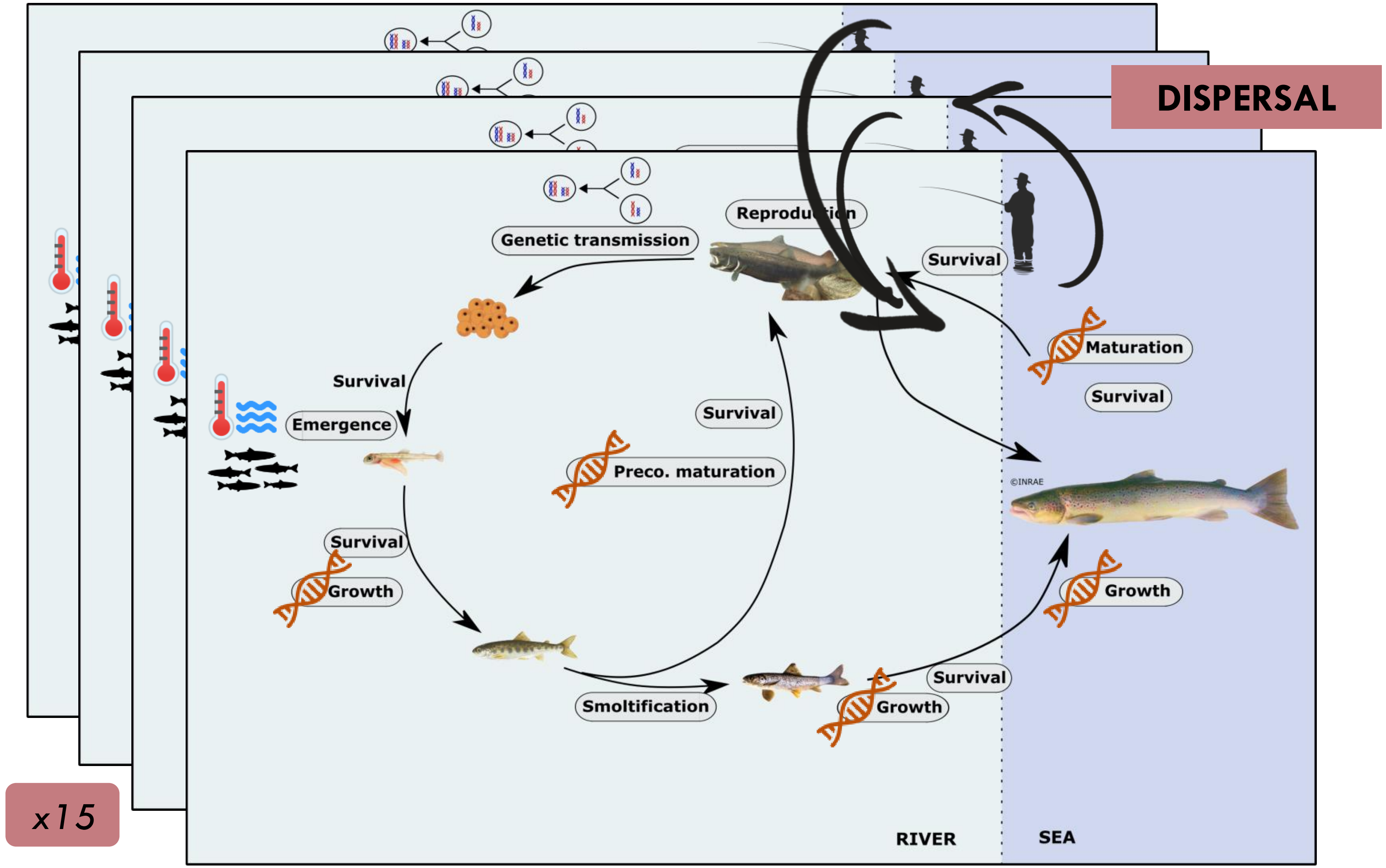
How connectivity and diversity influence metapopulation eco-evolutionary dynamics, stability and adaptation ?

Co-direction M. Buoro, S Carlson

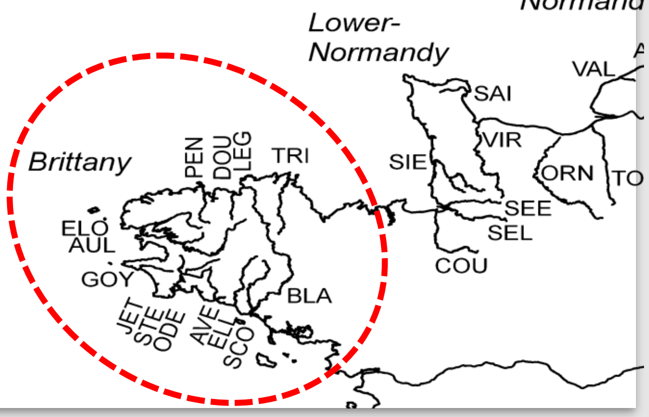
The model

IBASAM (Individual Based Atlantic SAlmon Model)… Towards MetaIBASAM

MetaIBASAM



Perrier et al., 2011, Mol. Ecol.



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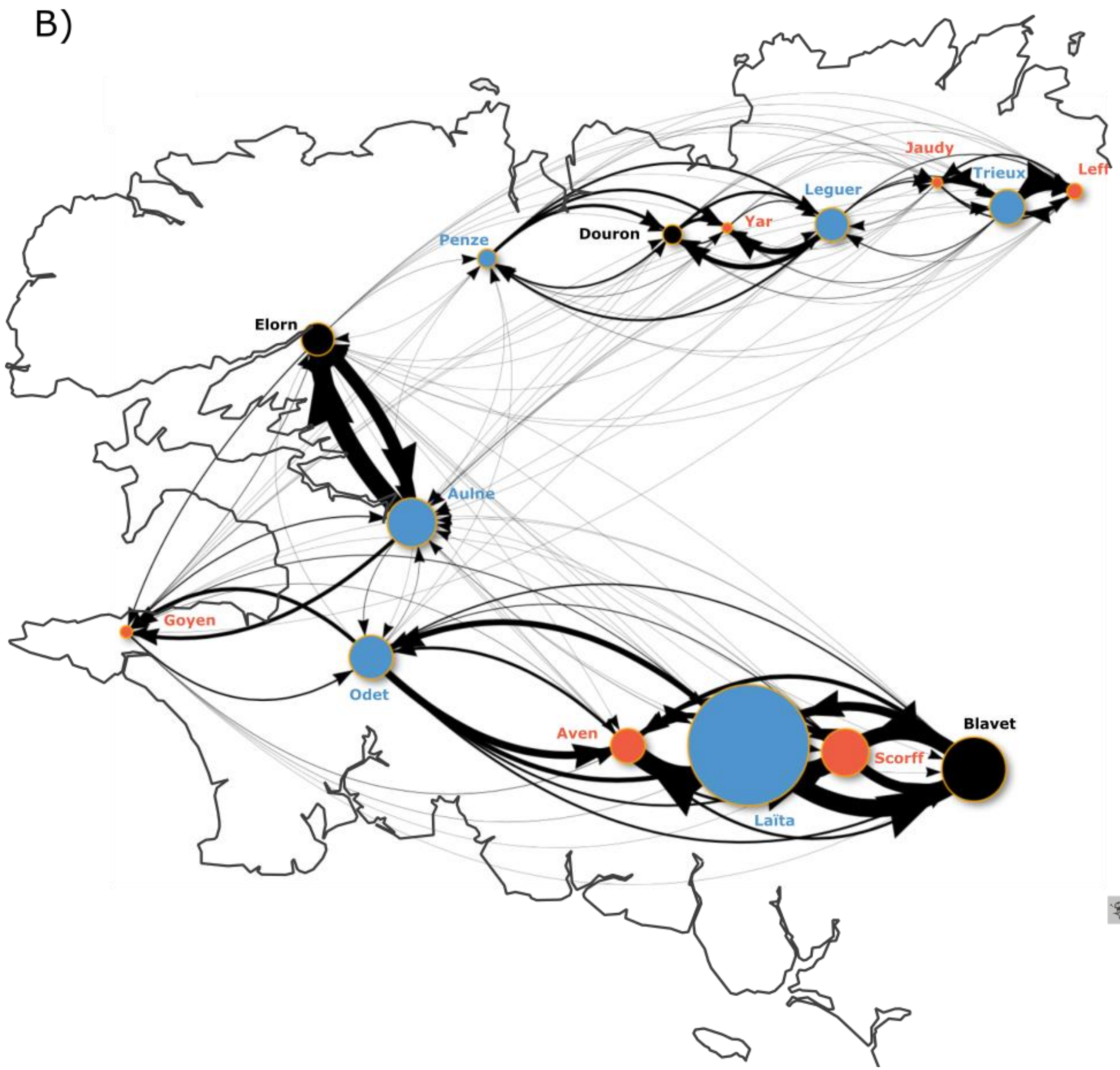
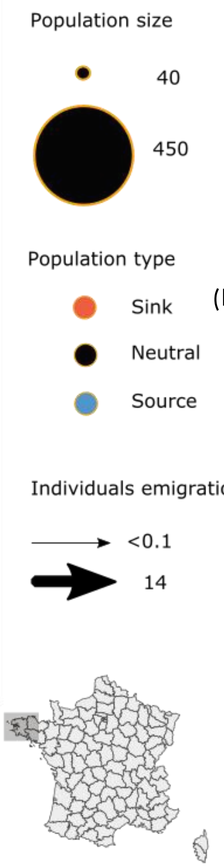
1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS



Dispersal rate: 10%



(Ratio Immigrants/ Emigrants)
(>1)
(~1)
(<1)

REALISTIC METAPPULATION SPATIAL CONTEXT

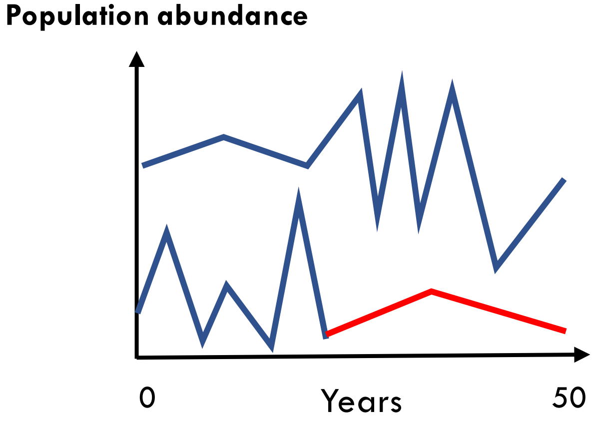
→ Carrying capacities
→ Distance

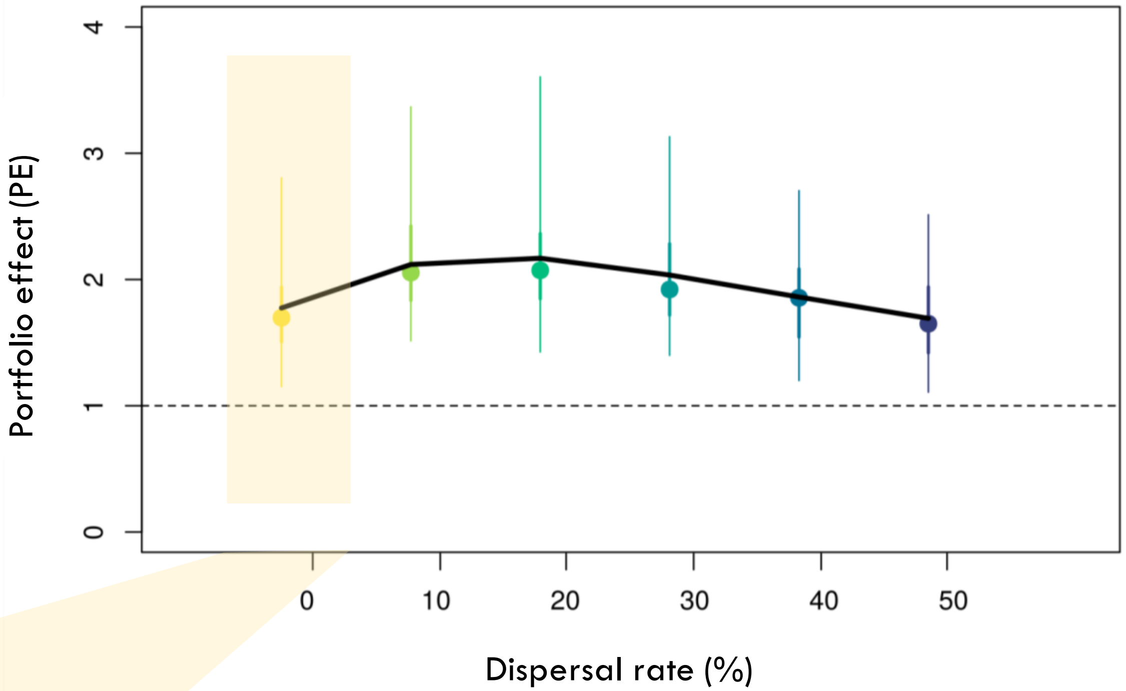
DEMOGRAPHIC MODEL

→ Dispersing vs philopatric individuals

1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS



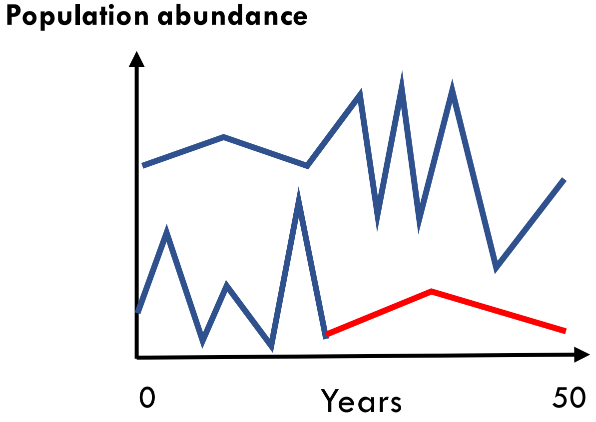


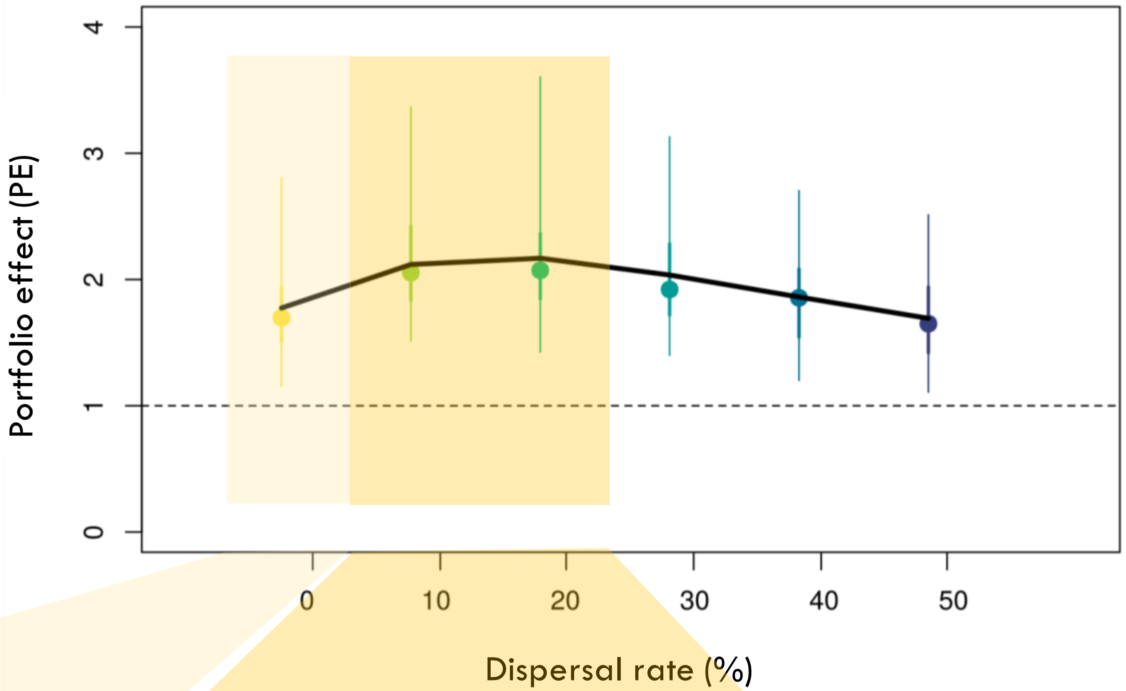
0%

- Asynchrony
- High risk of extinction of small populations

1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS





0%

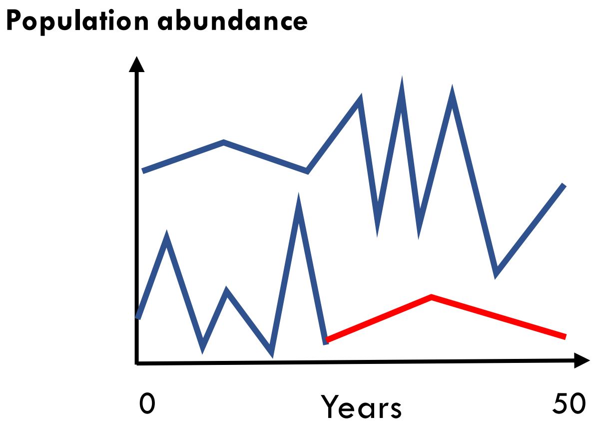
10-20%

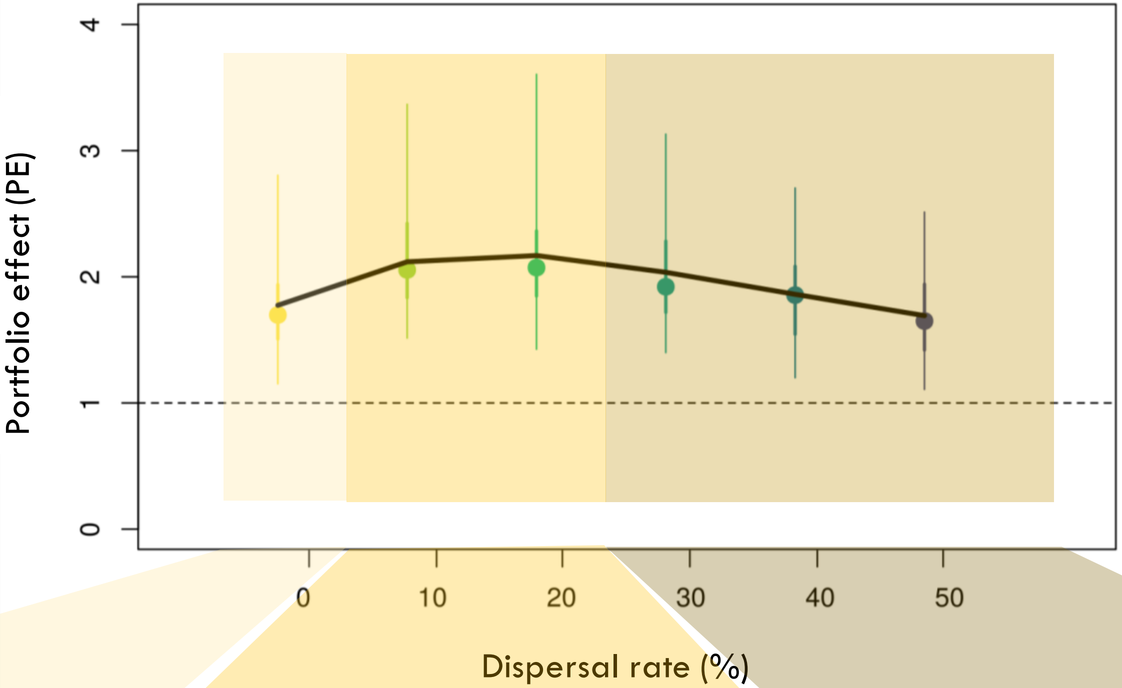
- Asynchrony
- High risk of extinction of small populations

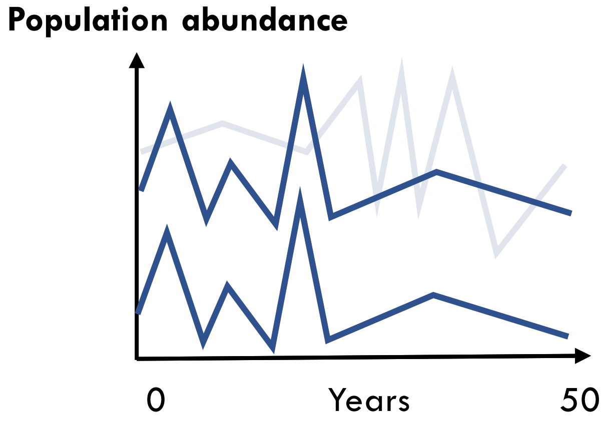
- Demographic rescue of small populations
- Optimum ?
  ≈ wild average rate: 15%

1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS







0%

- Asynchrony
- High risk of extinction of small populations

10-20%

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

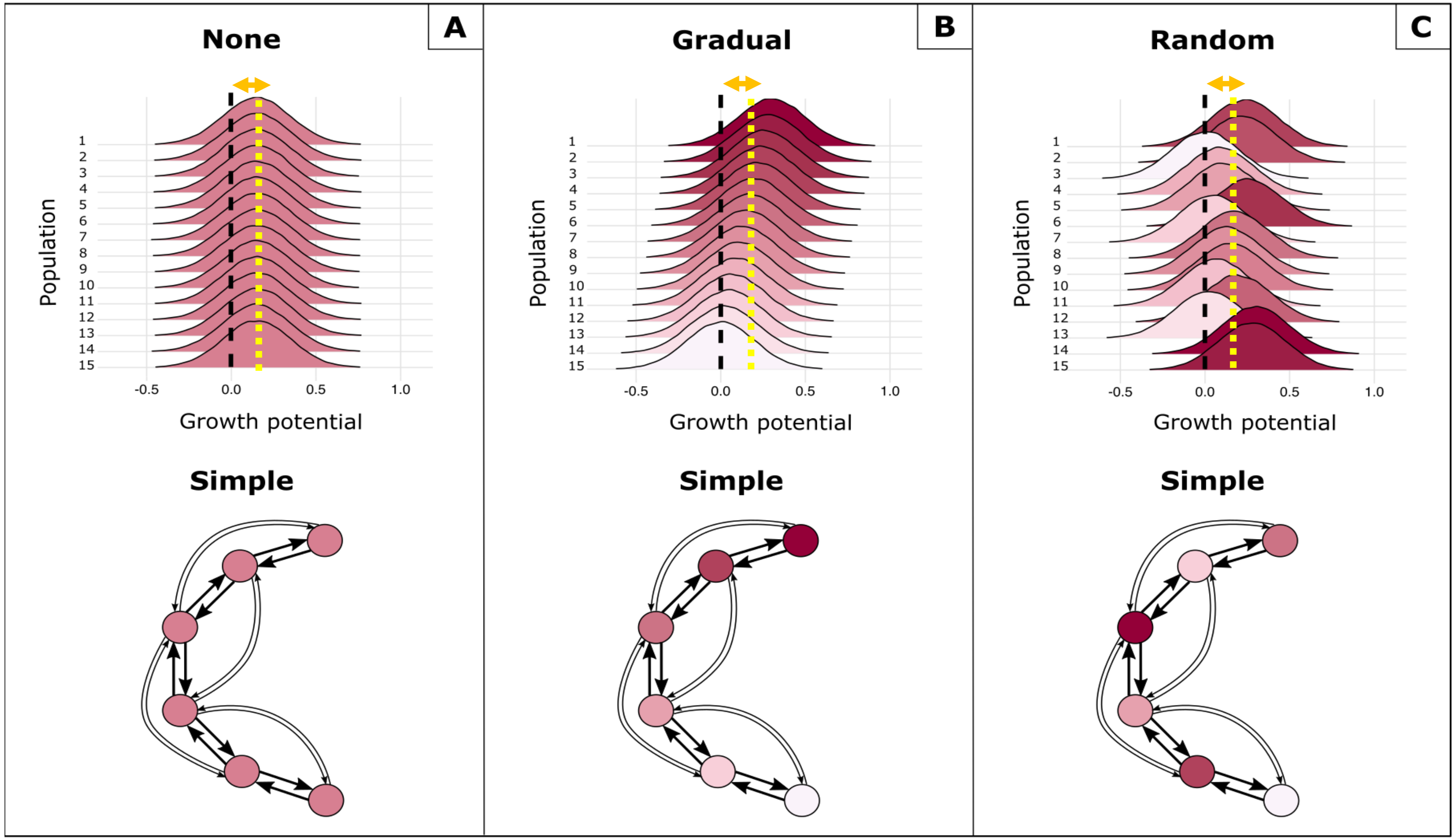
> 20%

- ↗ ↗ synchrony
- « Anti-rescue » effect

Sylvie Oddou-Muratorio, 1/10/2024

2) Evolutionary consequences – network scale

Lamarins et al., Ecography (2023)



SPATIAL GENETIC STRUCTURE OF GROWTH POTENTIAL

→ Maladapted populations

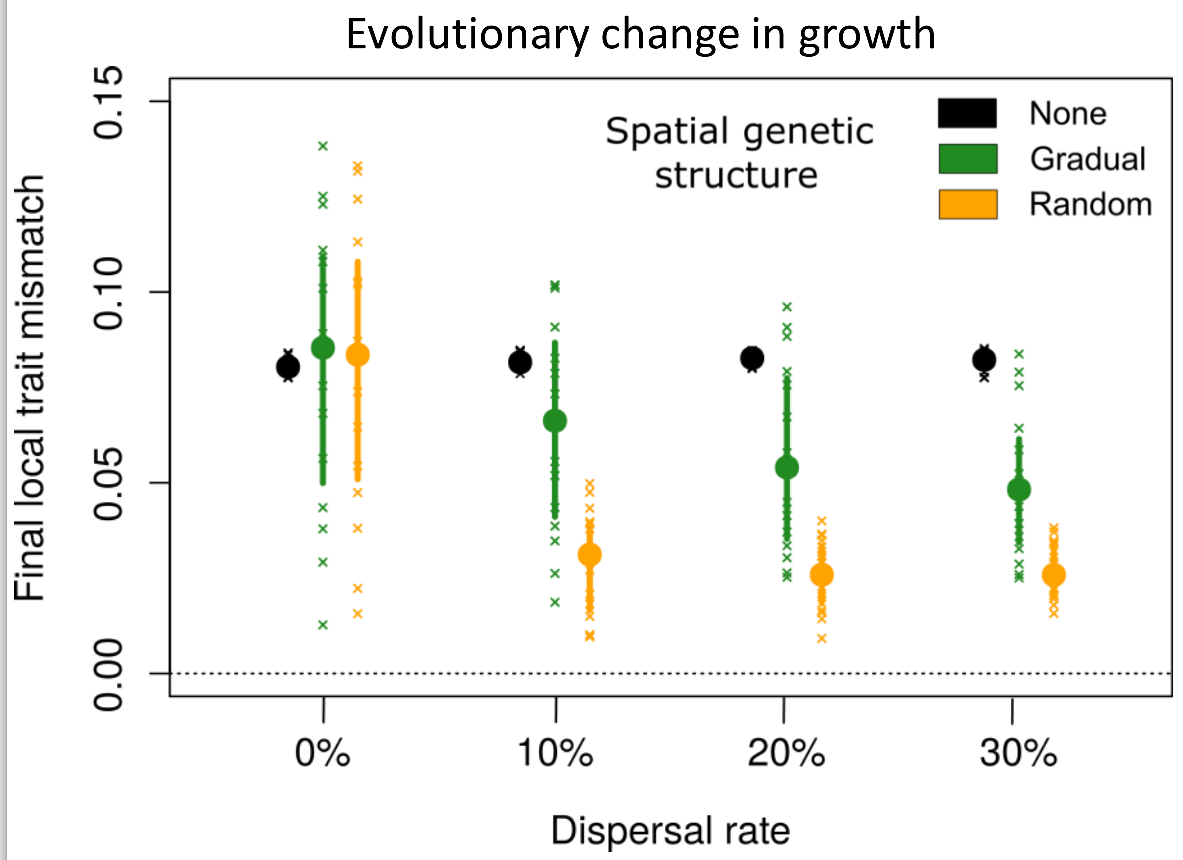
→ Contrasted spatial genetic structures among populations

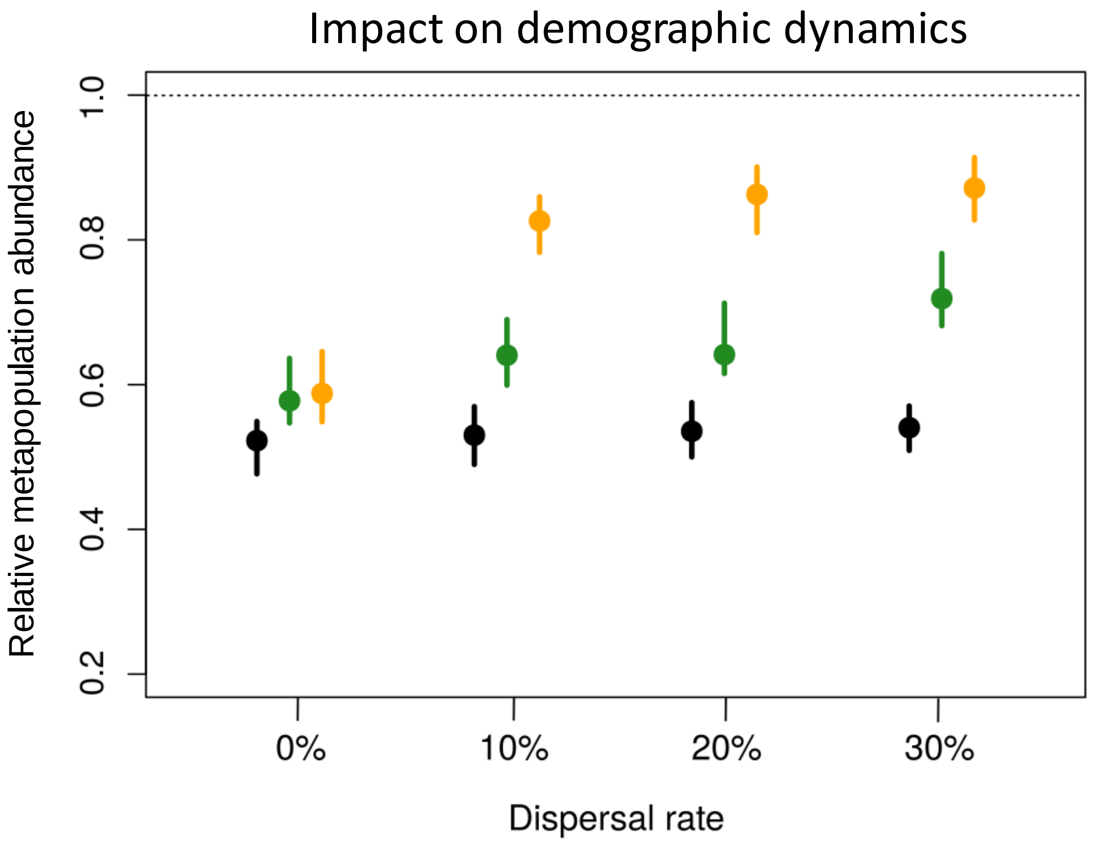
SPATIAL CONFIGURATION

→ Simple configuration

2) Evolutionary consequences – network scale

Lamarins et al., Ecography (2023)





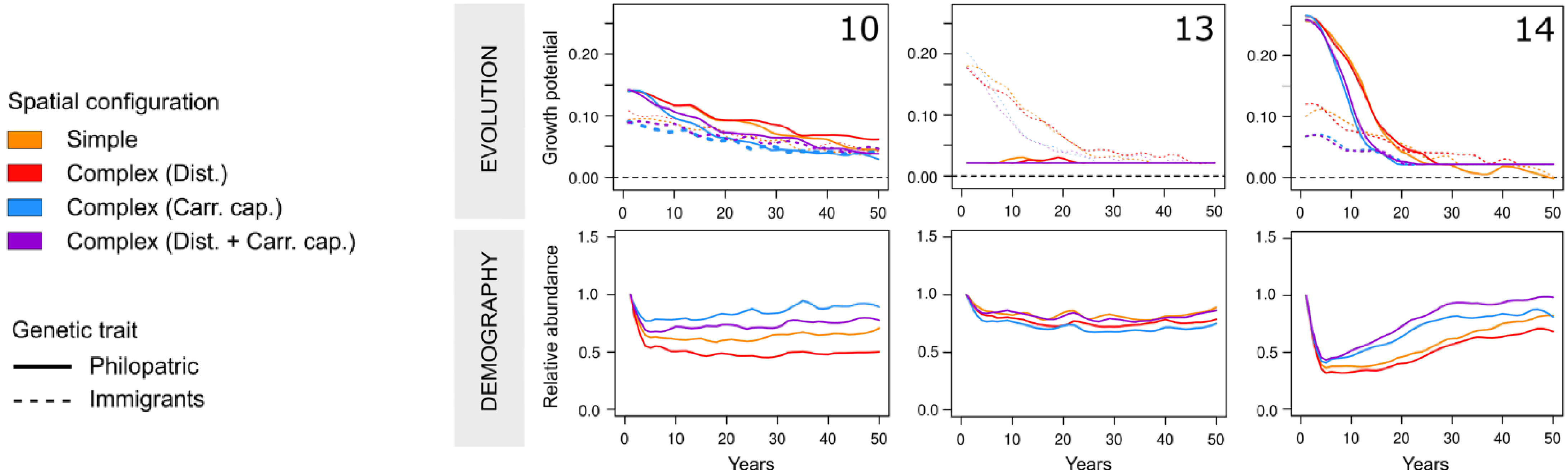
Trait mismatch: distance from optimum

- → 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.

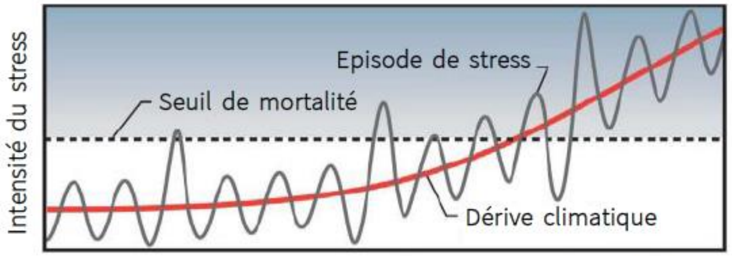


Thèse de Victor Fririon (2022)

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 ?



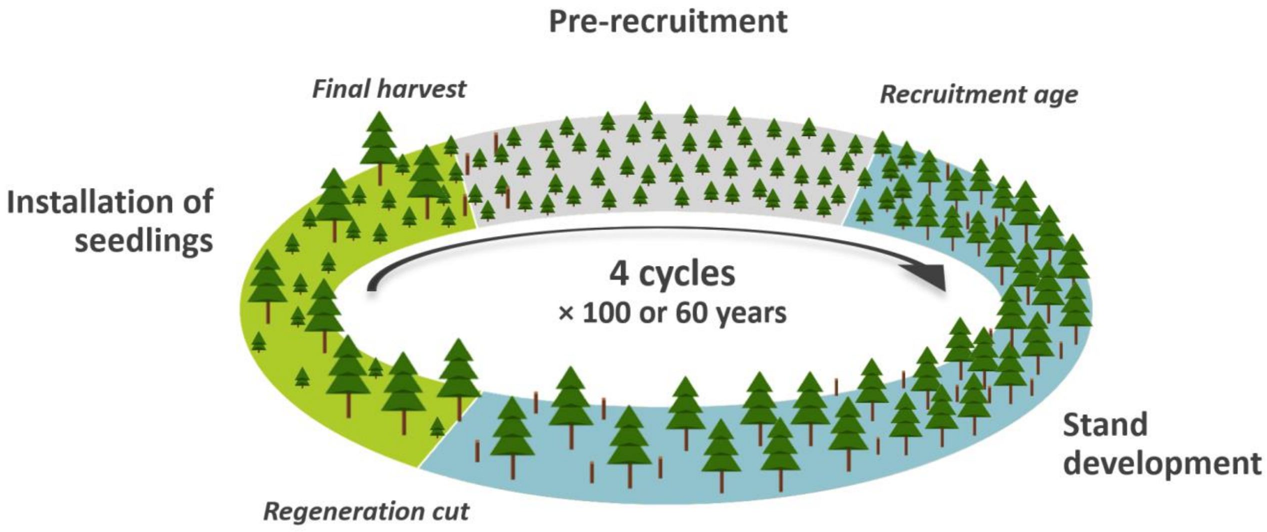
Allen et al. 2015

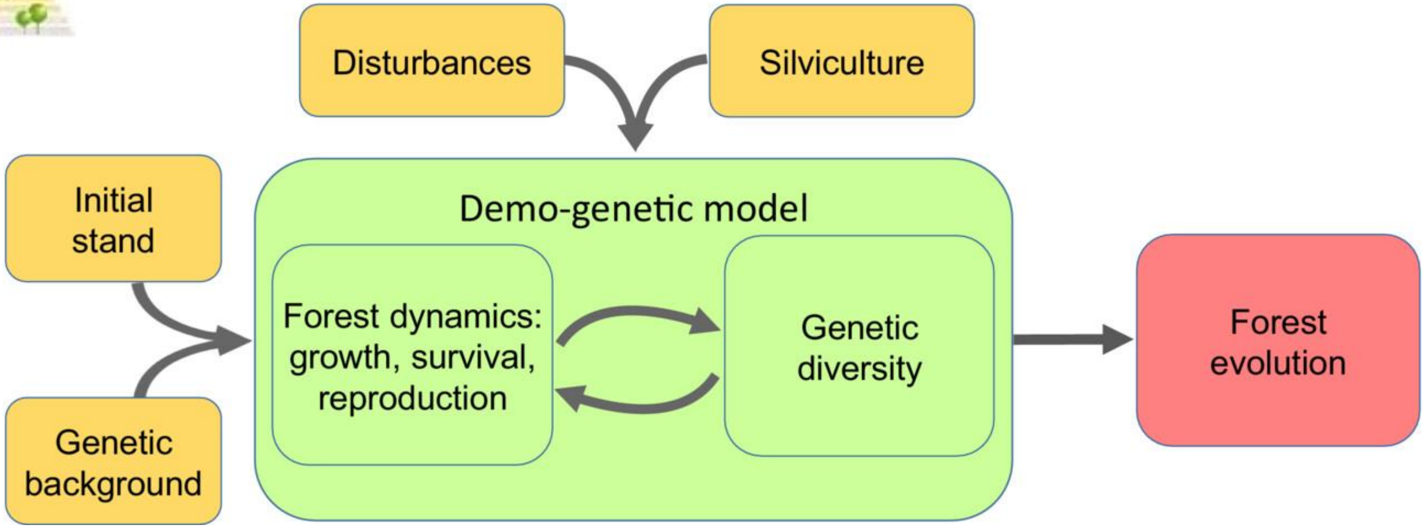
Can adaptive changes occur rapidly in tree populations ?
How does sylviculture affect the adaptive capacity of forest stands ?

Co-encadrement F Lefèvre, H Davi, S Muratorio

The model: Luberon2

+ DISTURBANCE

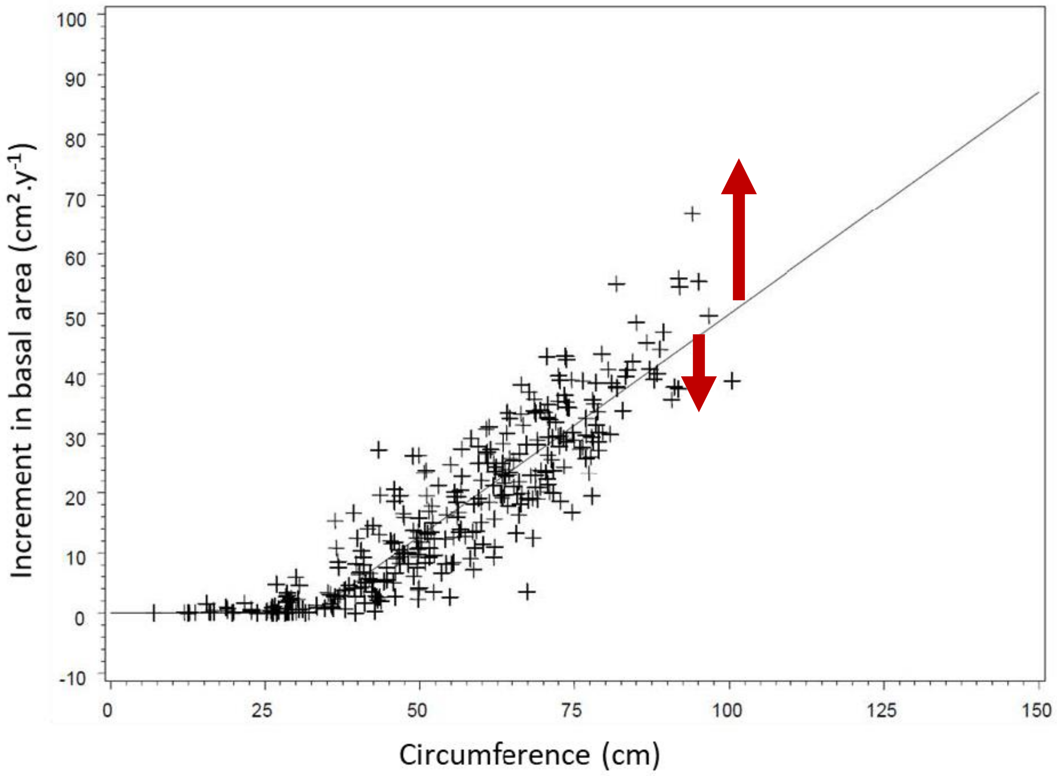




Godineau, Fririon et al. Evol Appl. 2023

The focal trait: growth vigor

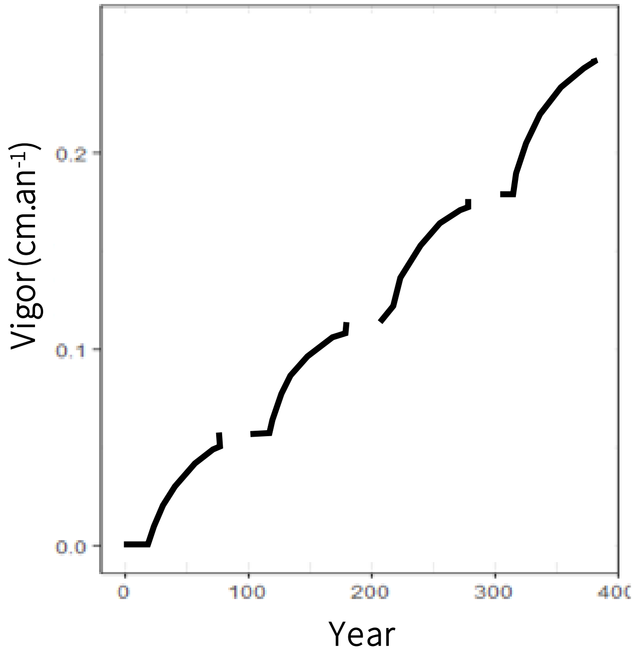
Individual annual increment in basal area as a function of tree circumference in C. atlantica: empirical individual data and model prediction (taken from Courbet, 2002).

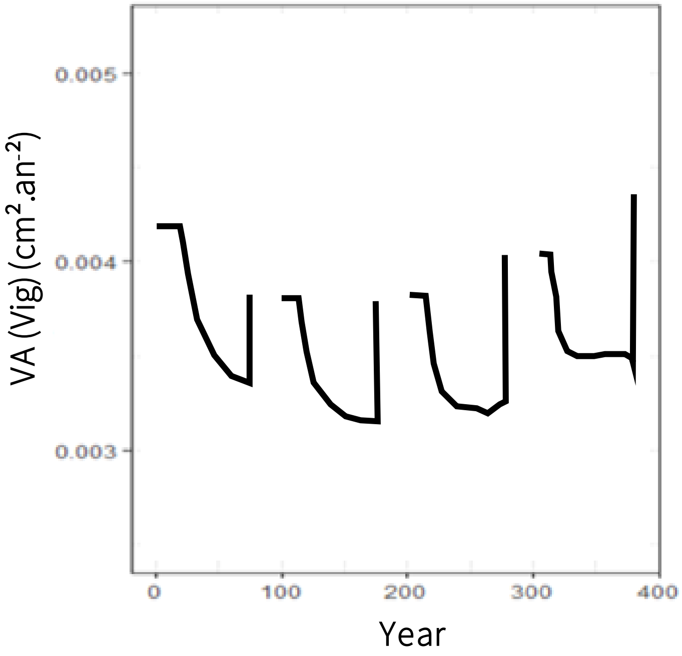


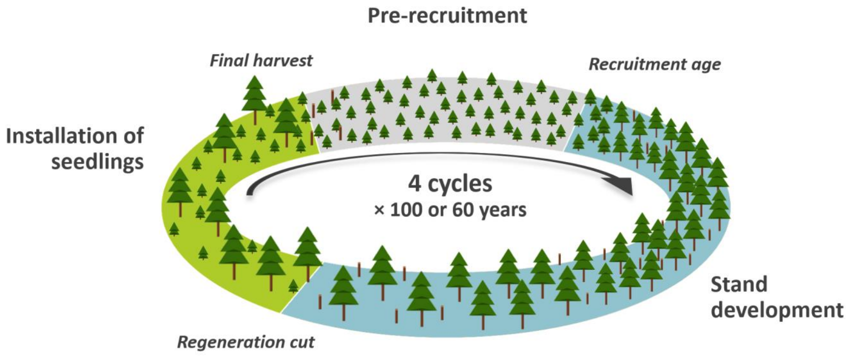
- Natural mortality by competition, i.e., self-thinning, is **selective** with regard to tree size
- Mortality by disturbance and by silviculture were not **selective** (no variation in sensitivity to disturbance and random thinning)

1) Evolution of tree vigor

Without thinning







Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

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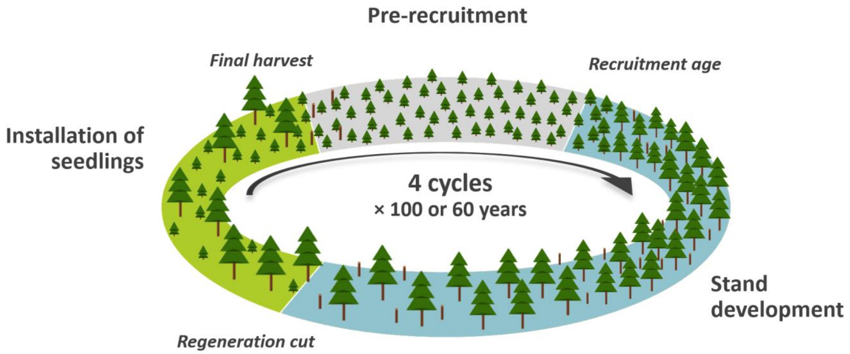
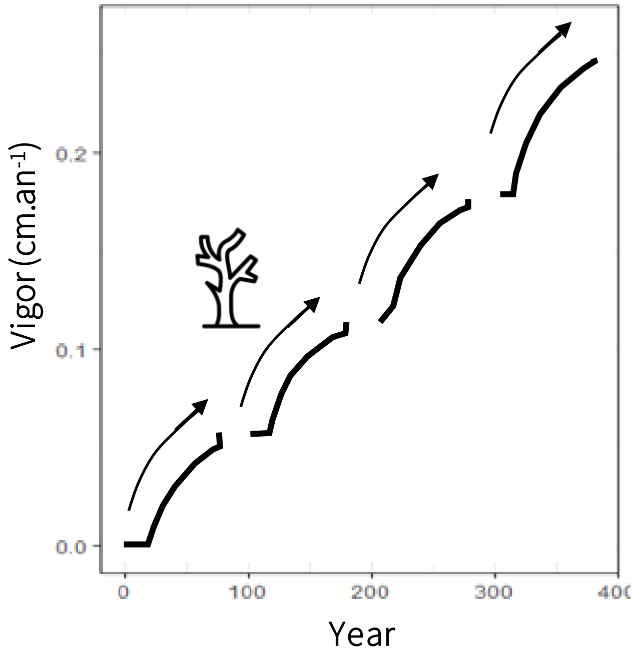
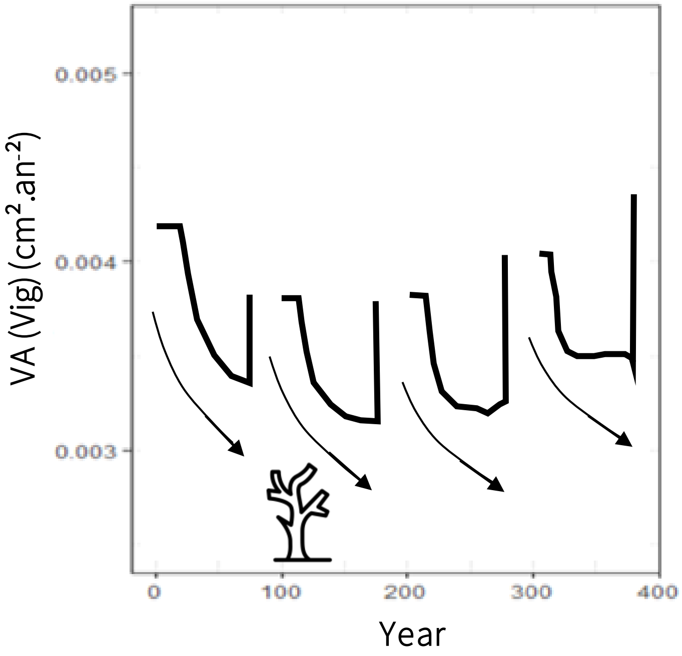




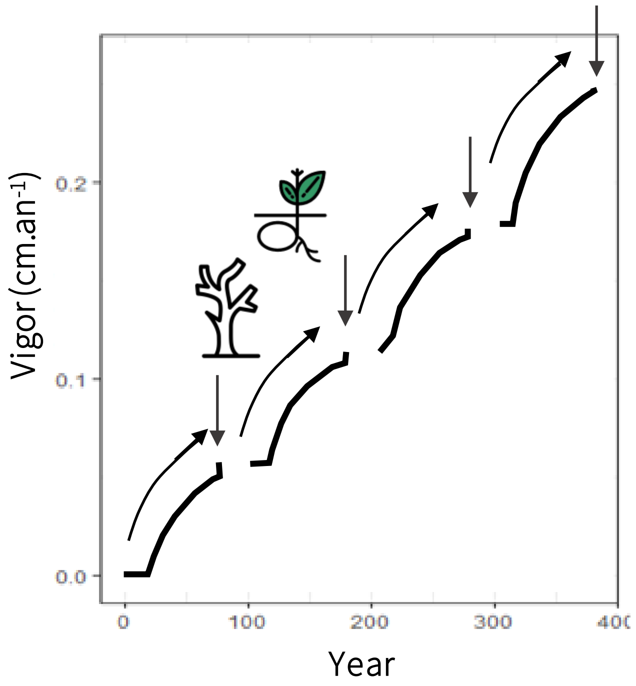


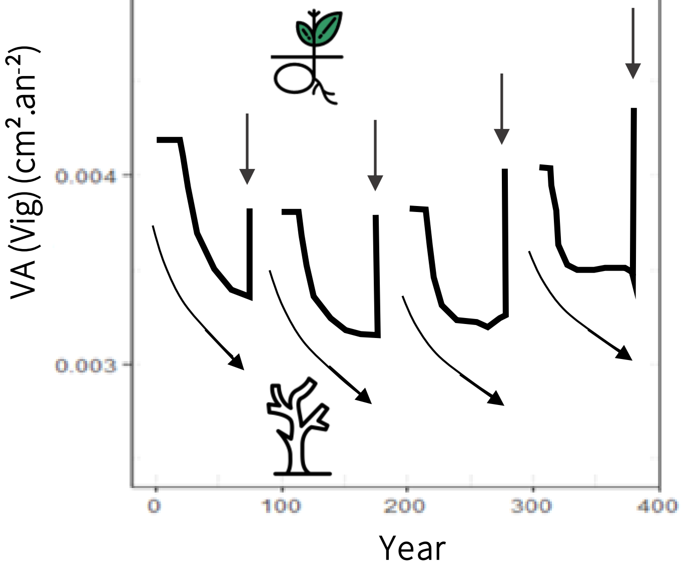
- Selection on survival (competition)

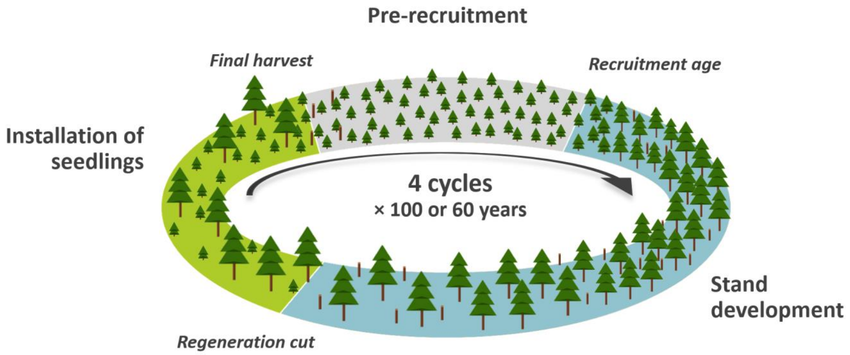
Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

Without thinning





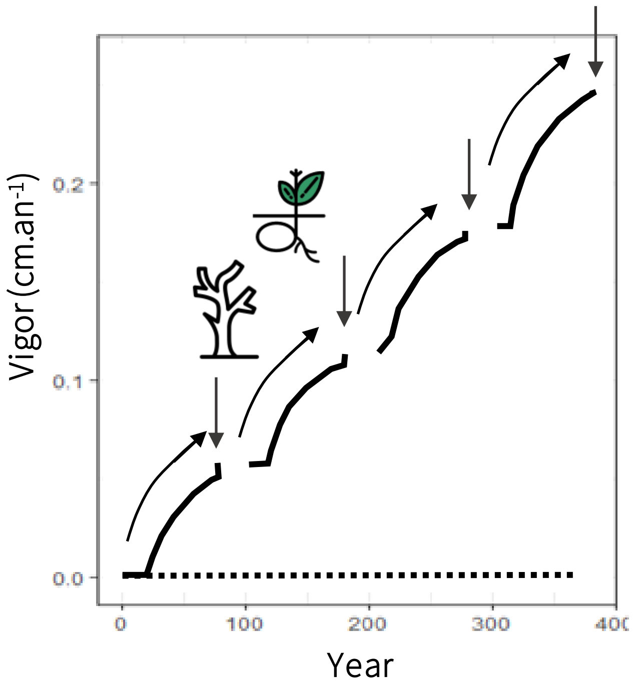


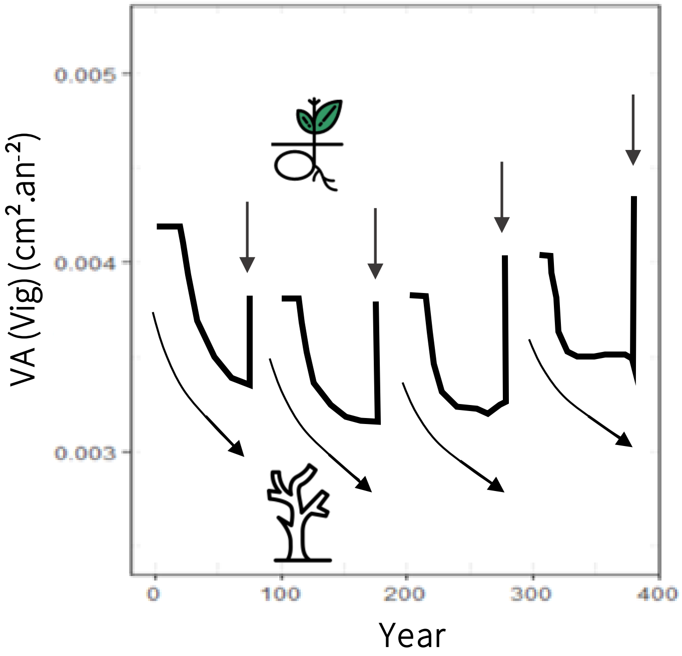
- Selection on survival (competition)
- Selection on fertility
- Restoration of genetic diversity during reproduction

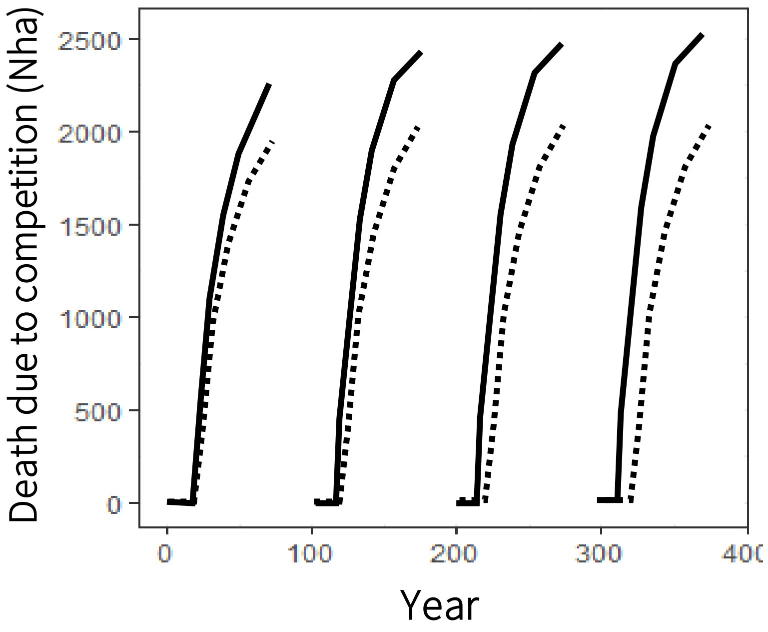
Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

Without thinning







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	Regenration cut	Final cut
trend	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
no thinning	[redacted]						-	-

– Intensive +

Godineau, Fririon et al. Evol Appl. 2023

Thinning scenarios

Non selective thinning

Intensive + / –

Scenario	Thinning 1	Thinning 2	Thinning 3	Thinning 4	Thinning 5	Thinning 6	Regenration cut	Final cut
trend	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
relaxed	-				-	-	-	-
delayed				-	-	-	-	-
low intensity	× 4	× 4	× 4	× 4	× 4	× 4	-	-
no thinning							-	-

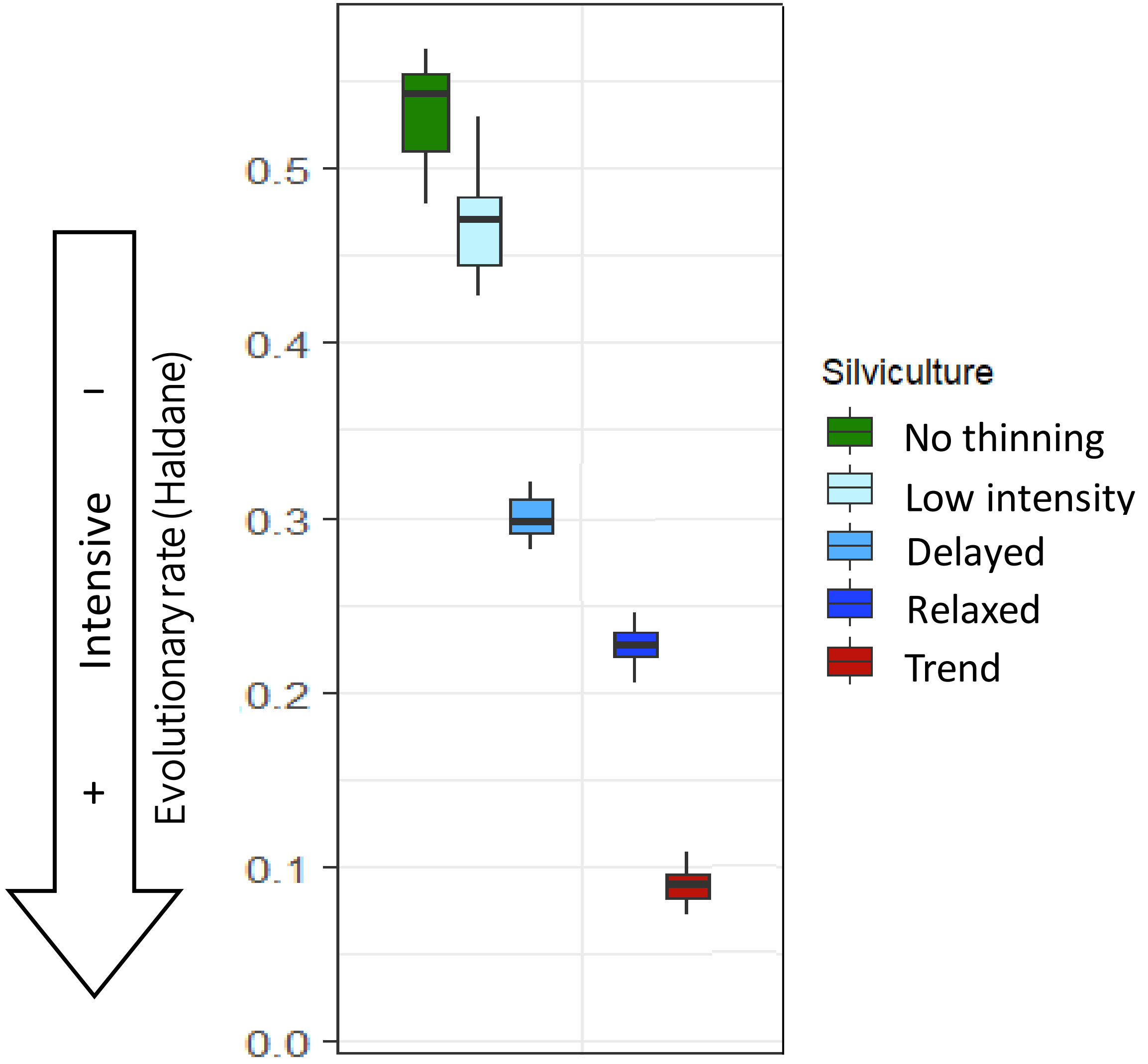
Godineau, Fririon et al. Evol Appl. 2023

Dynamic of adaptive change

(without perturbation)

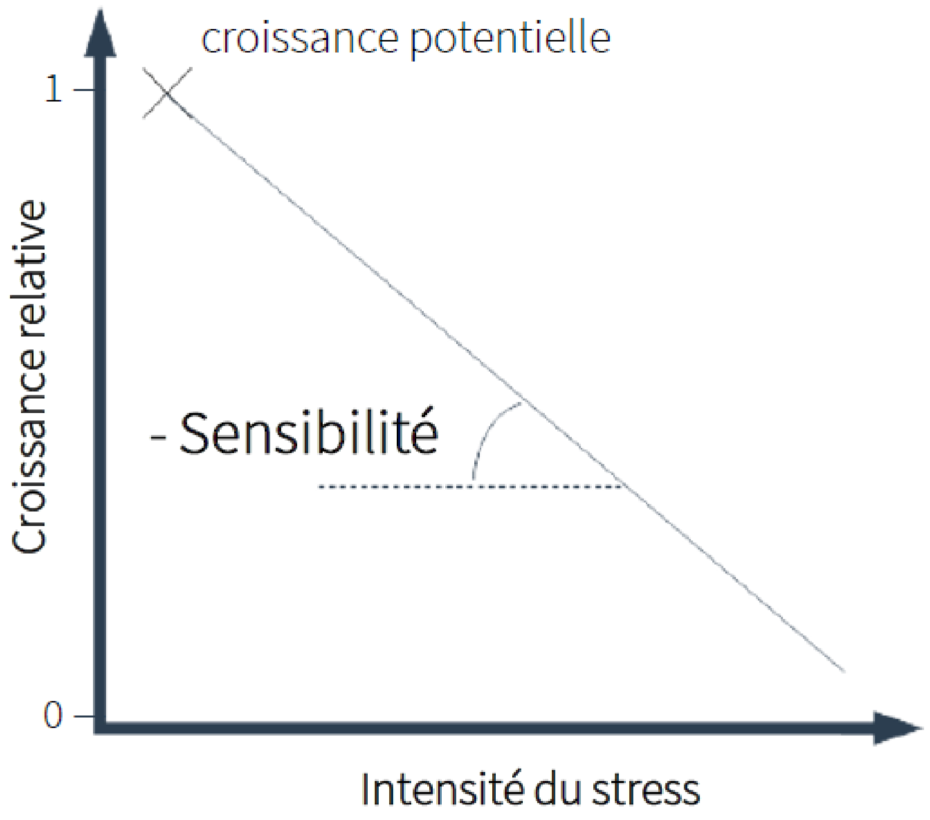
$$H_o = (zdiff_i/\sqrt{zvar.w_i})/n.gen$$

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

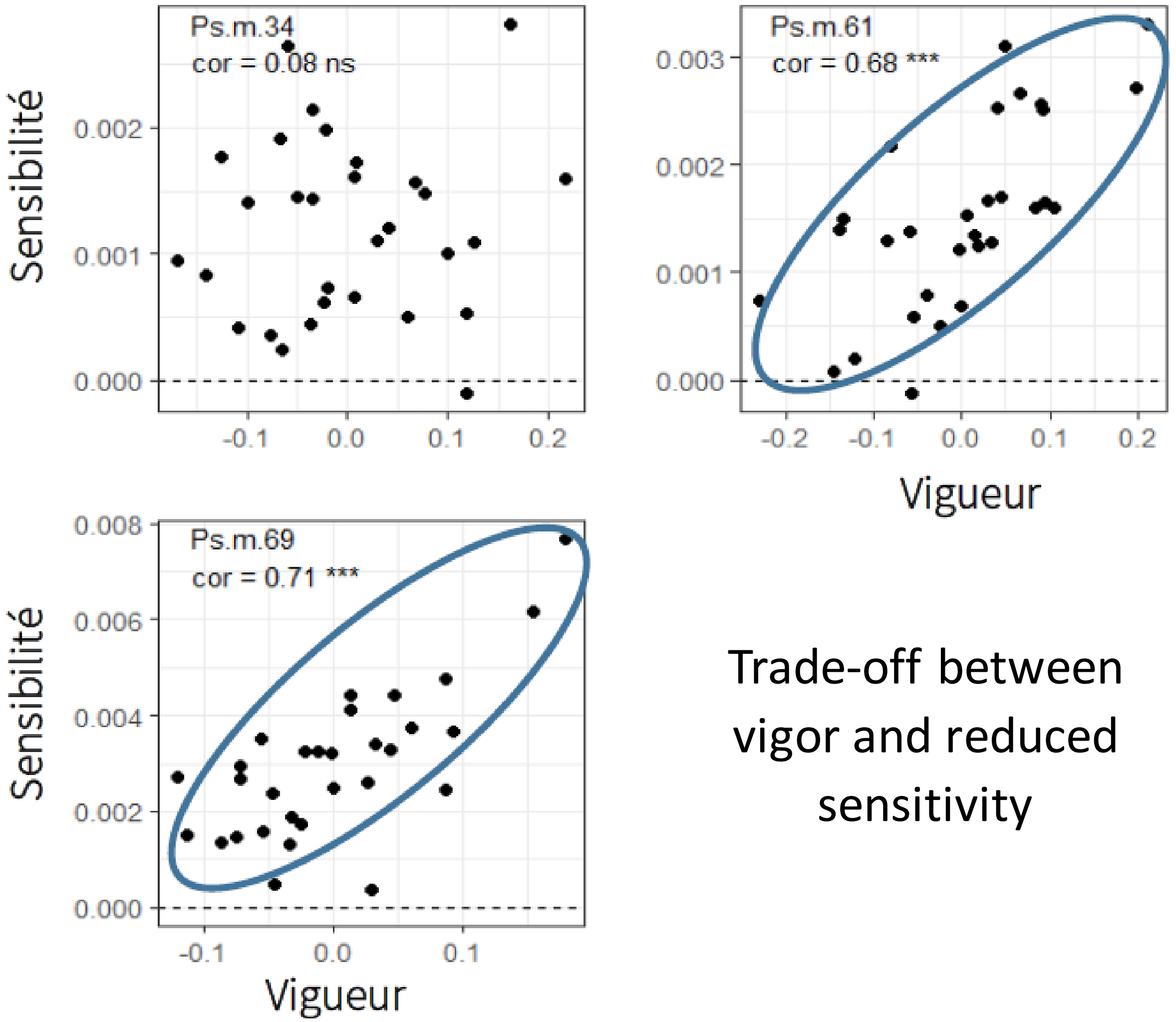


Godineau, Fririon et al. Evol Appl. 2023

2 focal traits: vigour + sensitivity to disturbances



➢La perte relative de croissance par unité de stress

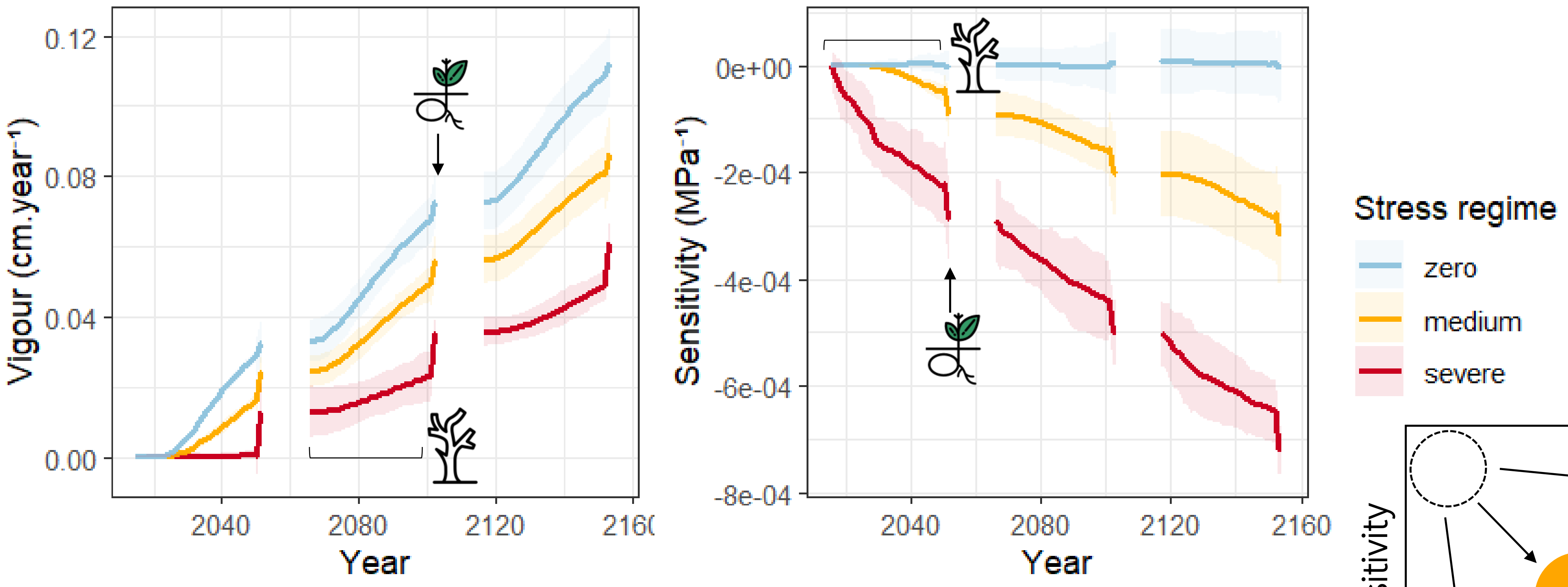


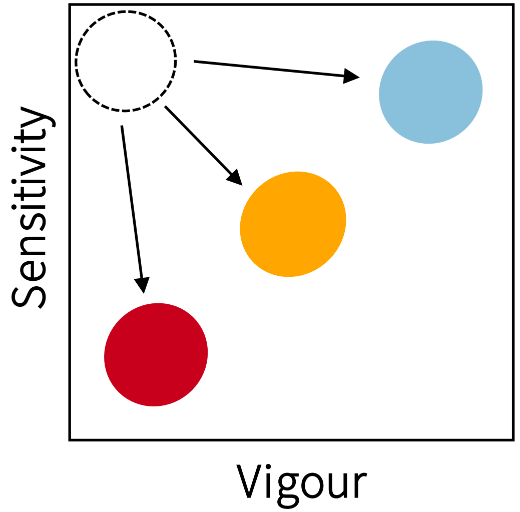
Trade-off between vigor and reduced sensitivity

Fririon et al. Forest Ecol Management 2022

Evolution of vigor and sensitivity

(with disturbance, without thinning)



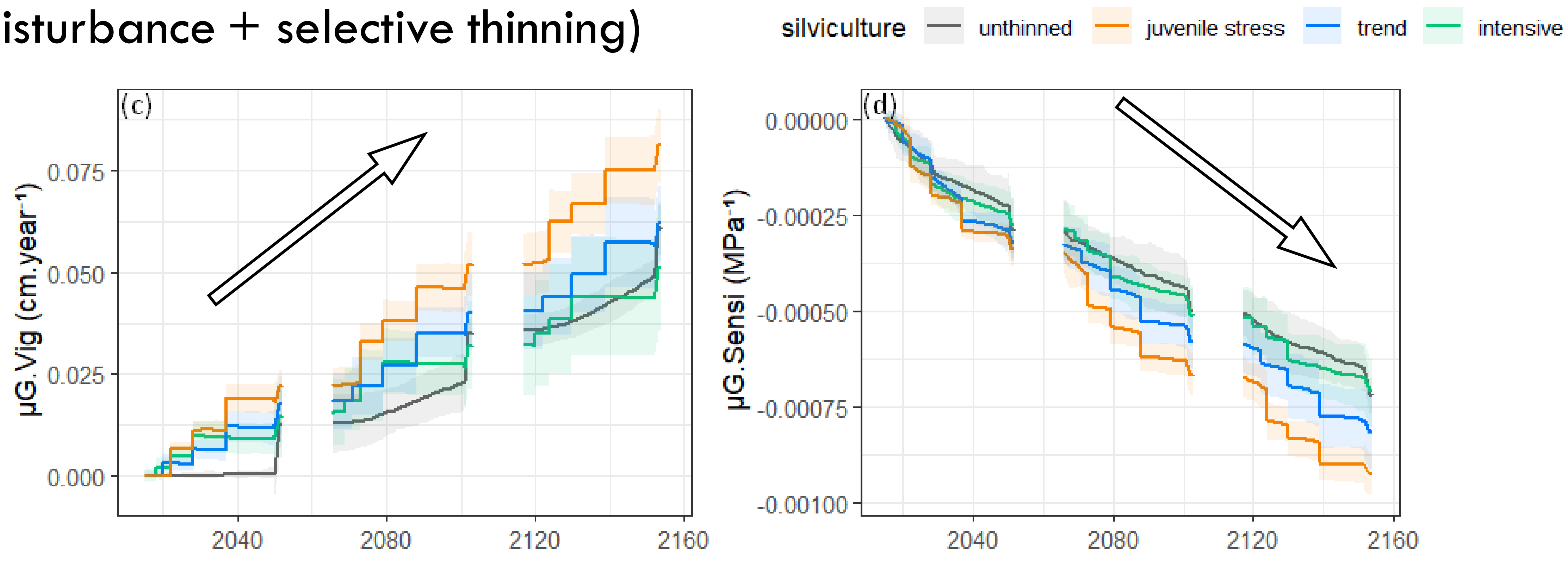


- Realistic evolution rates (0.1 to 0.3 haldane)
- Realistic genetic gain (+8% growth per generation)
- Antagonistic selection between vigor and sensitivity

Sylvie Oddou-Muratorio, 1/10/2024

Evolution of vigor and sensitivity

(disturbance + selective thinning)

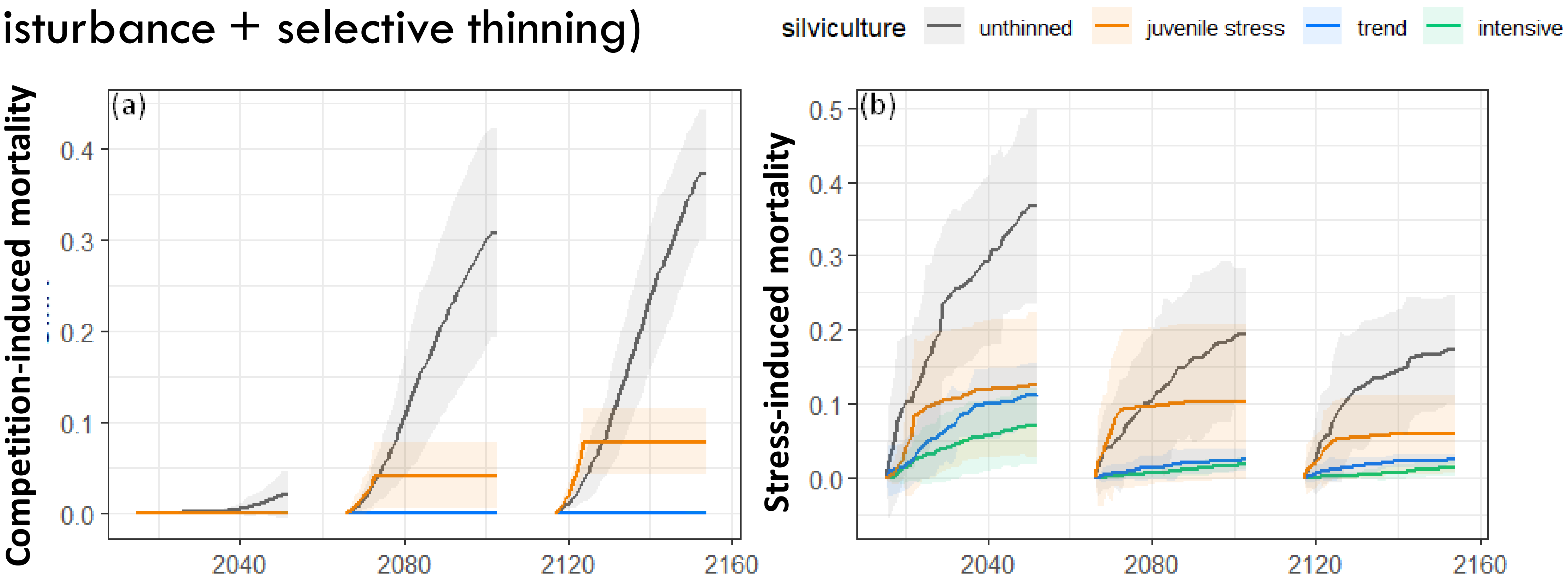


- ➢ Selective thinning can outperform natural selection.

Fririon et al. in revision

Evolution of vigor and sensitivity

(disturbance + selective thinning)

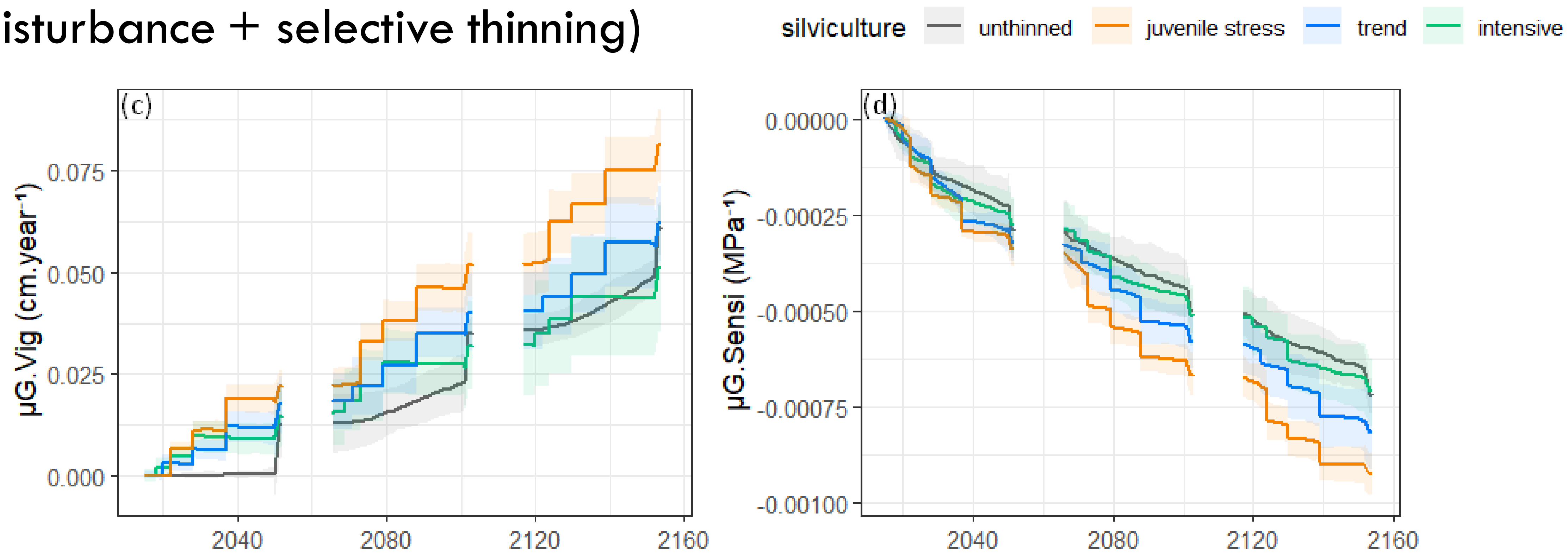


- Selective thinning can outperform natural selection.
- Forestry reduce mortality (both competition-induced and stress induced)

Fririon et al. in revision

Evolution of vigor and sensitivity

(disturbance + selective thinning)

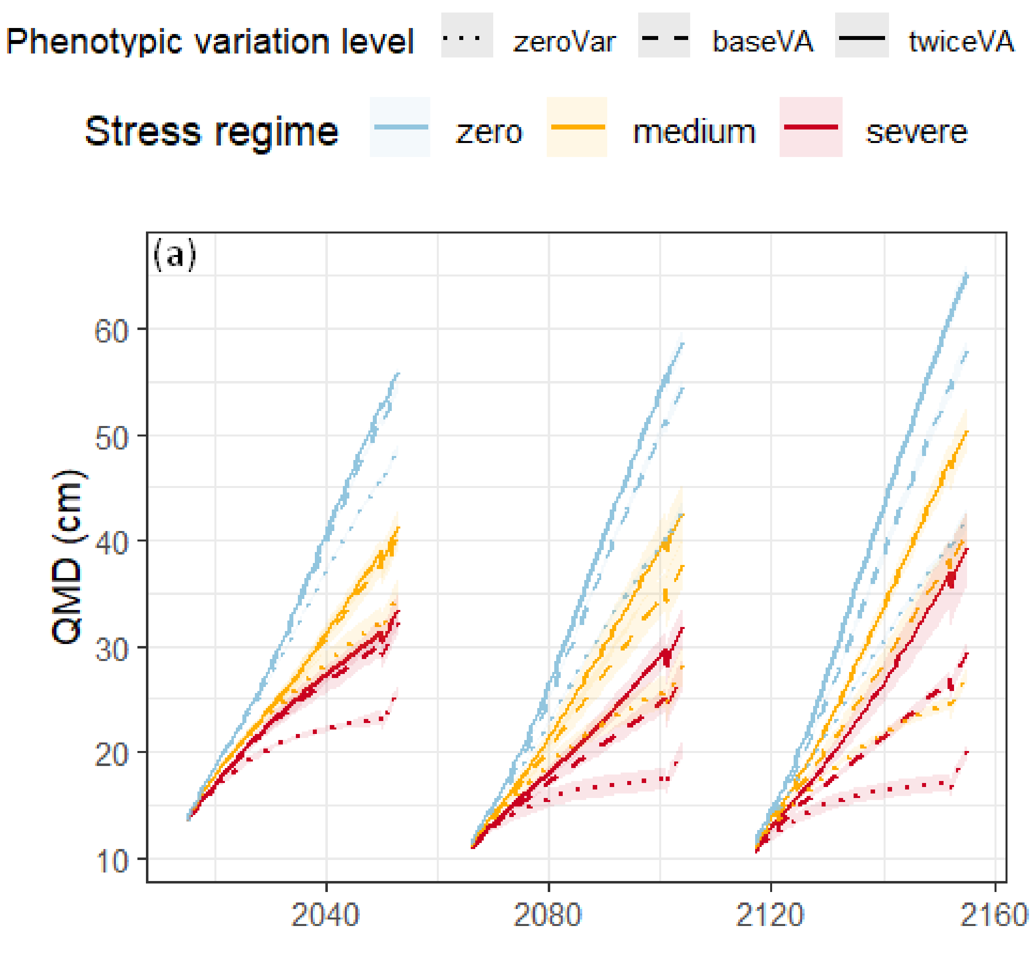


- Selective thinning can outperform natural selection.
- More intensive forestry = less genetic evolution :
  - ✓ *Reduced stress = reduced selection pressure*
  - ✓ *Early random thinning = fewer selection opportunities*

Fririon et al. in revision

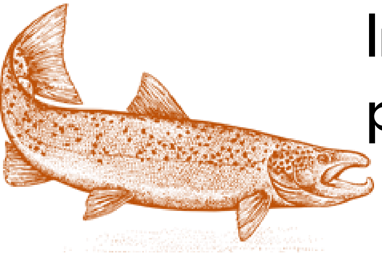
Conclusions

- 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.



Fririon et al. in revision

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.

Sylvie Oddou-Muratorio, 1/10/2024

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.

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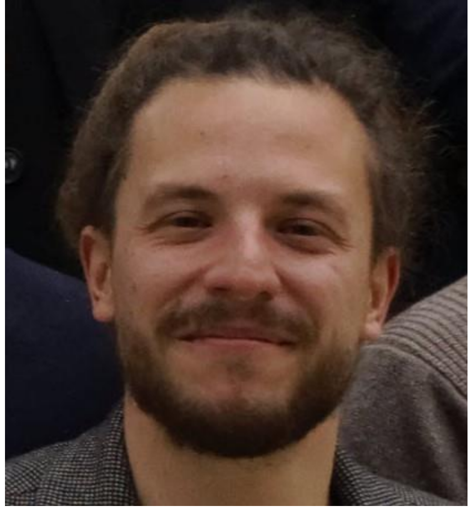
- Sensitivity to assumptions: The outcomes of these models are highly sensitive to the underlying assumptions, which can lead to misleading results if the assumptions are incorrect.
- Allows capturing the emerging effects of individual interactions (bottom up)
- Benefits from the existence of platforms (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.)

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



Amaia Lamarins

Victor Fririon

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