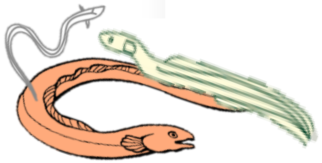
L'essor des modèles démo-génétiques individus centrés pour mieux comprendre les rétroactions entre processus écologiques et évolutifs et évaluer des scénarios de gestion des populations

Sylvie Oddou-Muratorio, INRAE



2004-2020 URFM Avignon

Adaptation des arbres aux variations climatiques

2021 ECOBIOP Saint Pée/Nivelle

Adaptation des poissons migrateurs aux variations environnementales

Approches par modélisation (physio-démo-génétique) et observations (inférence des processus évolutifs en population naturelle)

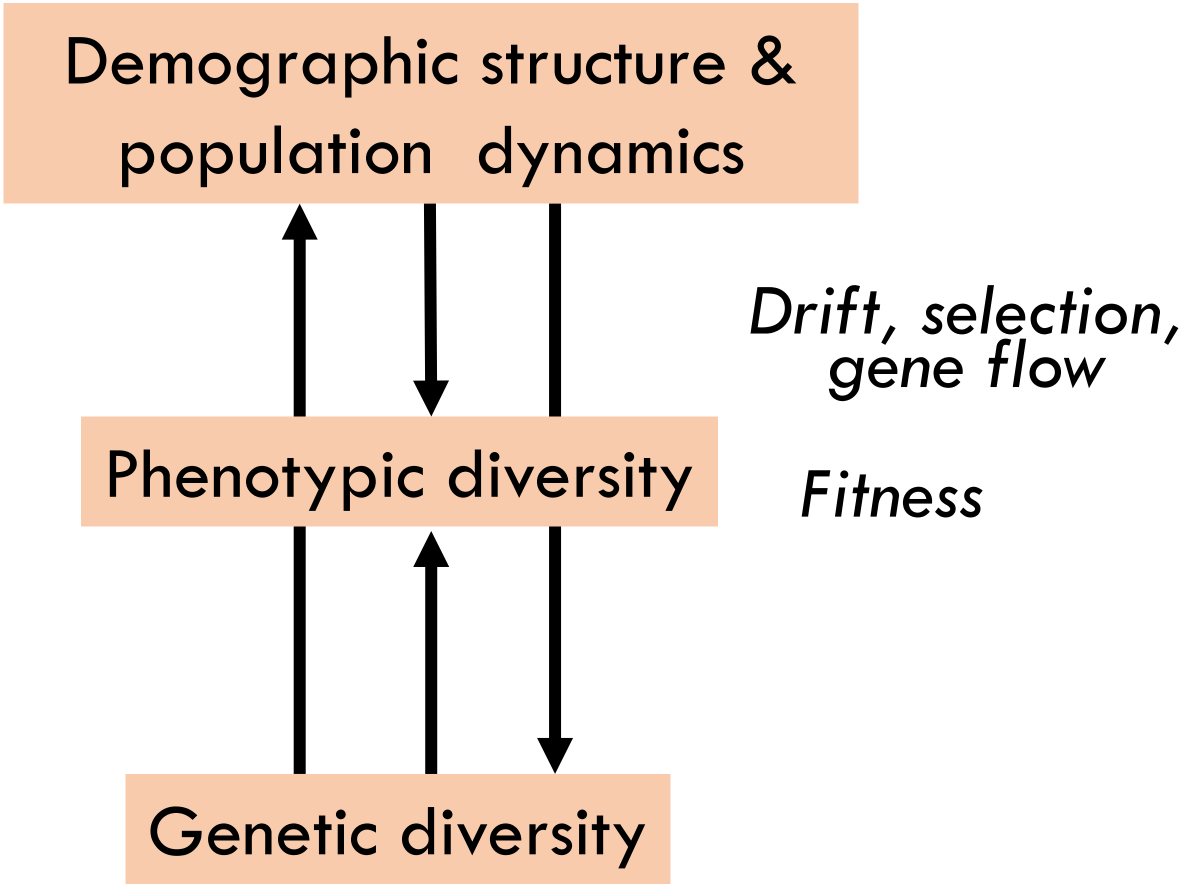
INRAE

Ecole chercheur «Intégrer les échelles en écologie», 27/03/2024

Contents

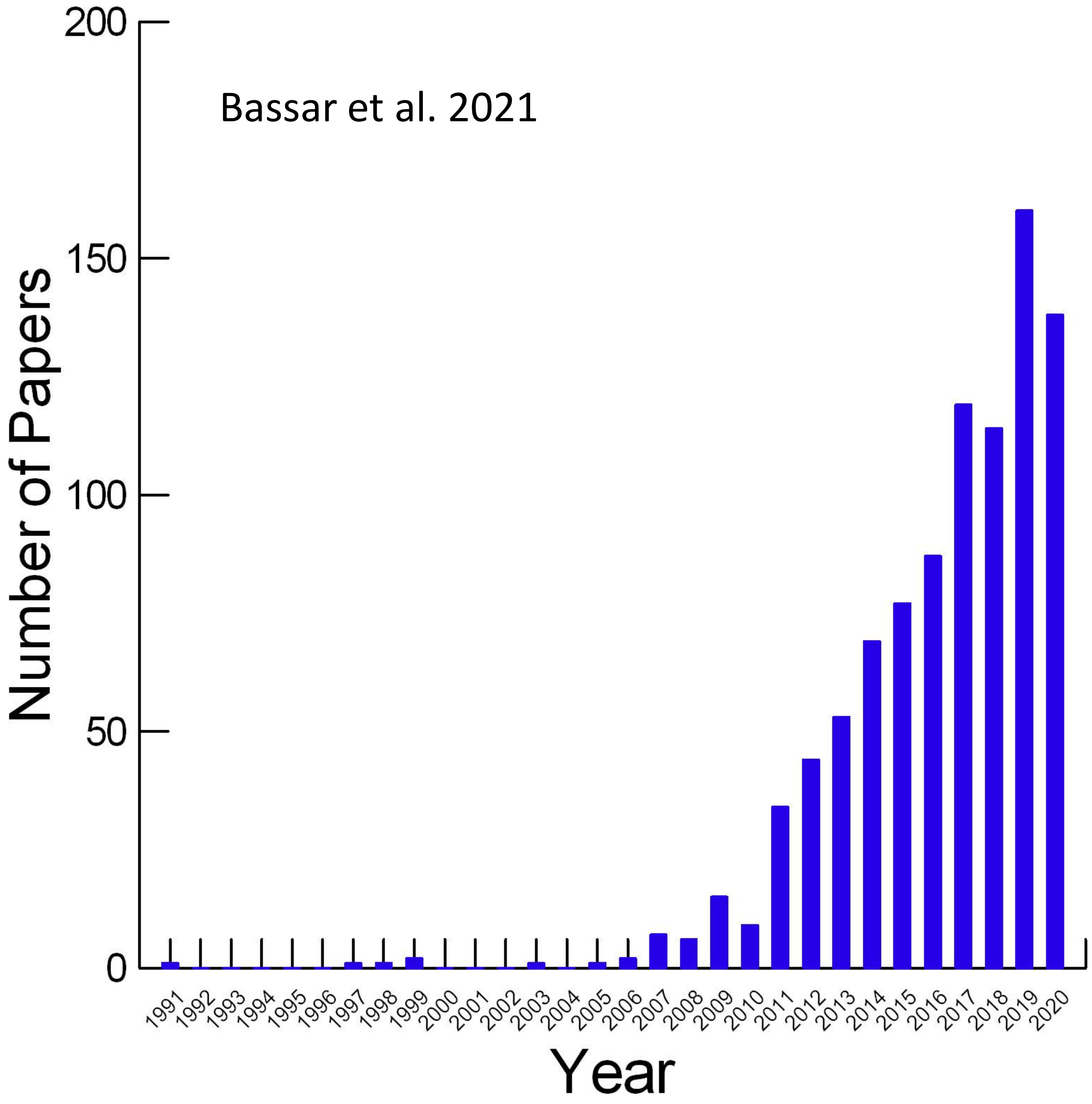
- ✓ Concepts related to eco-evolutionary dynamics
- ✓ A synthesis study on demo-genetic models
- ✓ Two study cases:
  - ➢ Adaptation, persistence and management of Atlantic salmon in a metapopulation context
  - ➢ Vulnerability of forests in face of climate change: DG-ABMs to investigate adaptive management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

Eco-evolutionary dynamics



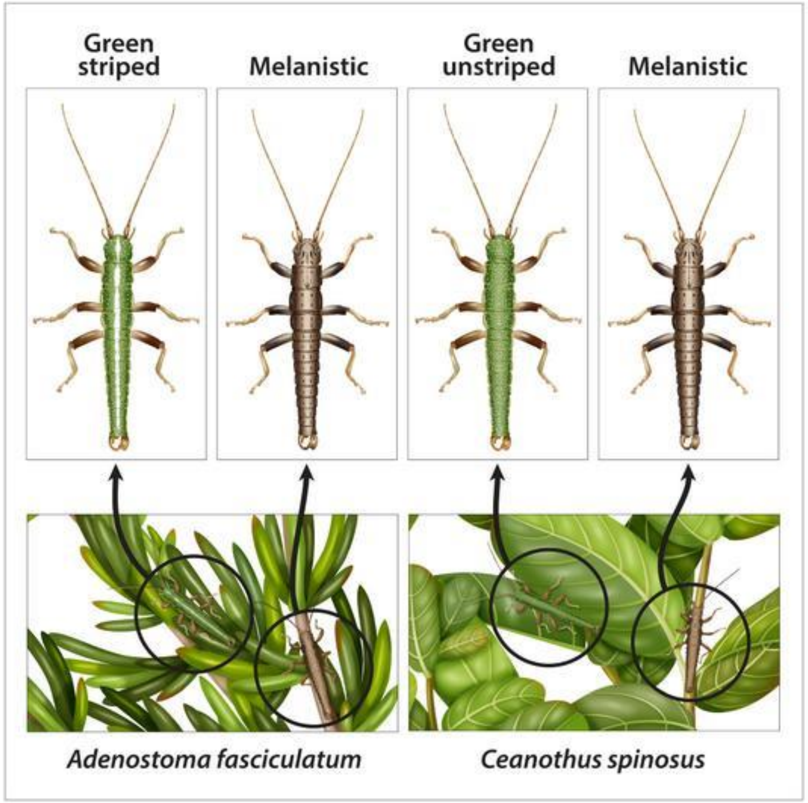
- ✓ Rétroaction et échelle contemporaine (Coulson et al. 2006)

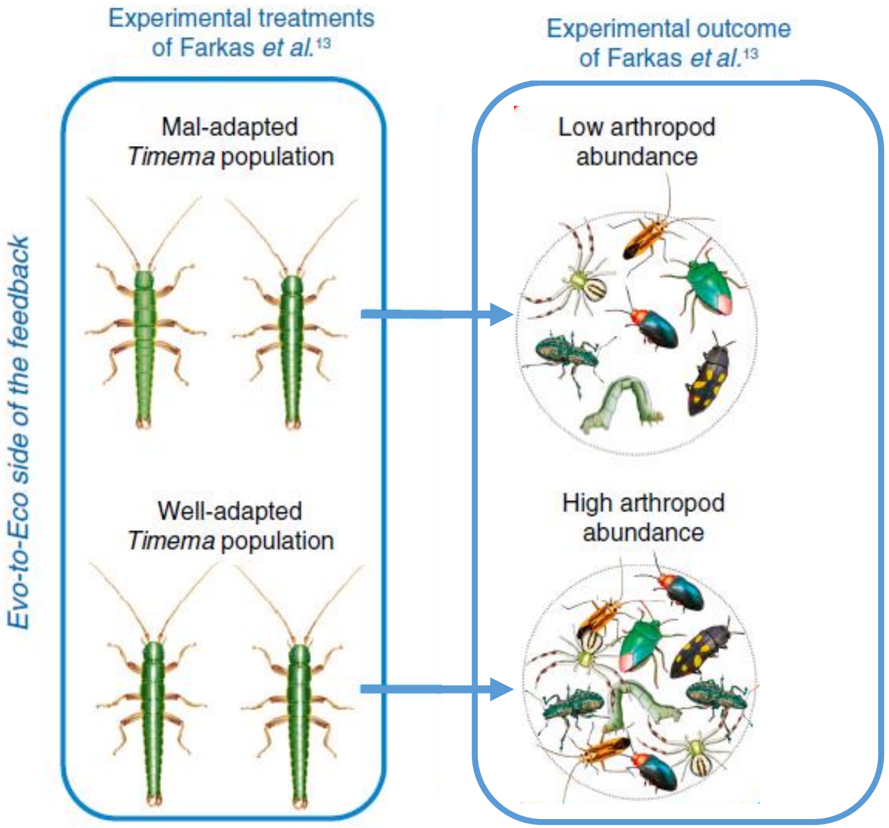
Eco-evolutionary dynamics



- ✓ Rétroaction et échelle contemporaine (Coulson et al. 2006)
- ✓ Essor lié à la réalisation que dynamiques écologiques et évolutives se produisent sur des échelles temps similaires (Caroll et al. 2007, Hendry 2017, Bassar et al. 2021)

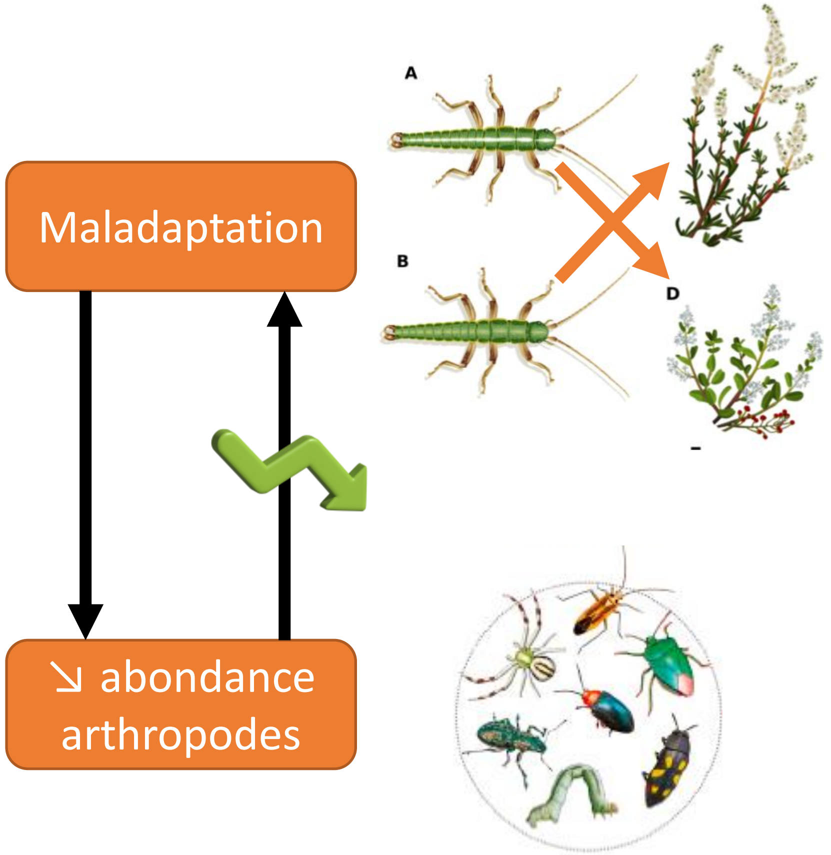
Demonstrating eco-evolutionary feedbacks in natural populations

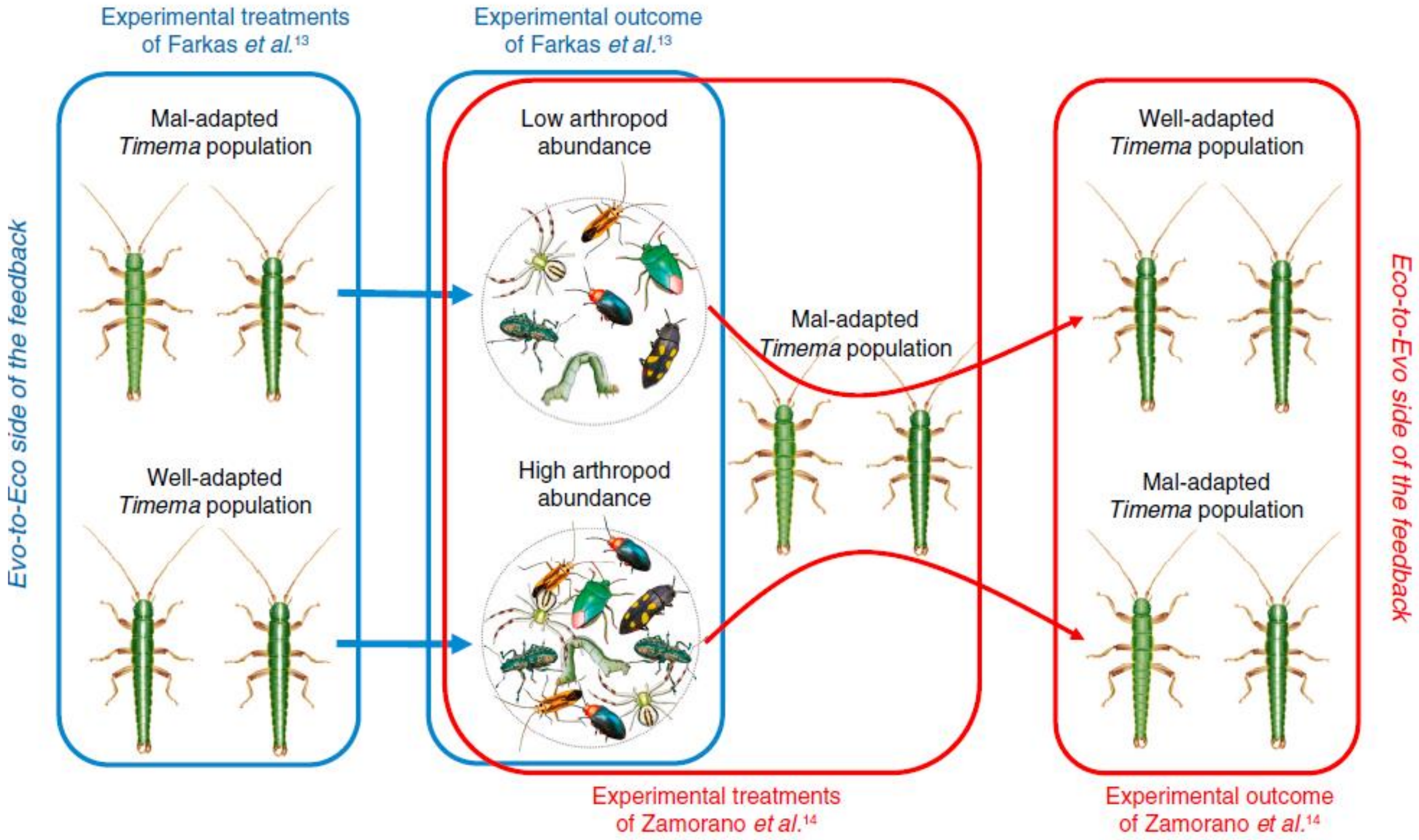




Farkas et al. 2013; Zamorano et al. 2023; Hendry 2023

Demonstrating eco-evolutionary feedbacks in natural populations





Réseau DG-ABMs (Demo-genetic Agent based models)

Octobre 2019, réunion à Enlène, Ariège: 5 doctorants, 5 chercheurs

INRAE

ECODIV

Received: 29 March 2022 | Revised: 26 October 2022 | Accepted: 28 October 2022

DOI: 10.1111/eva.13508

PERSPECTIVE

Evolutionary Applications Open Access WILEY

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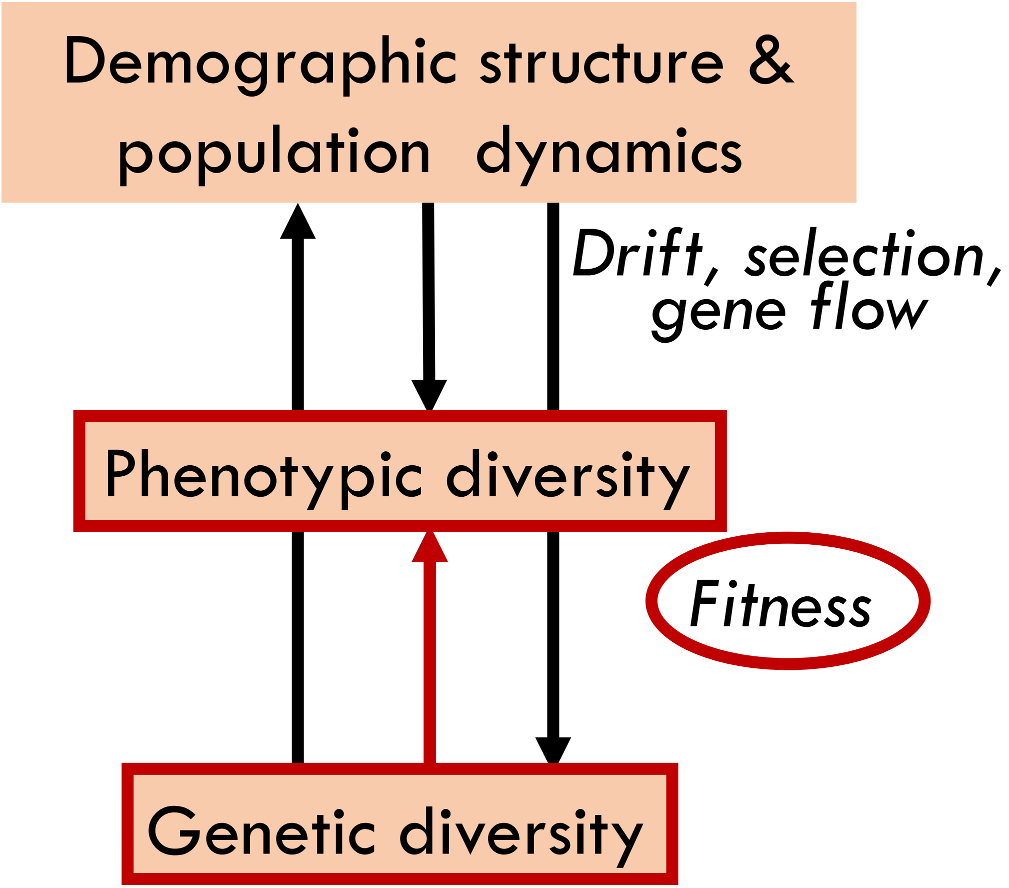
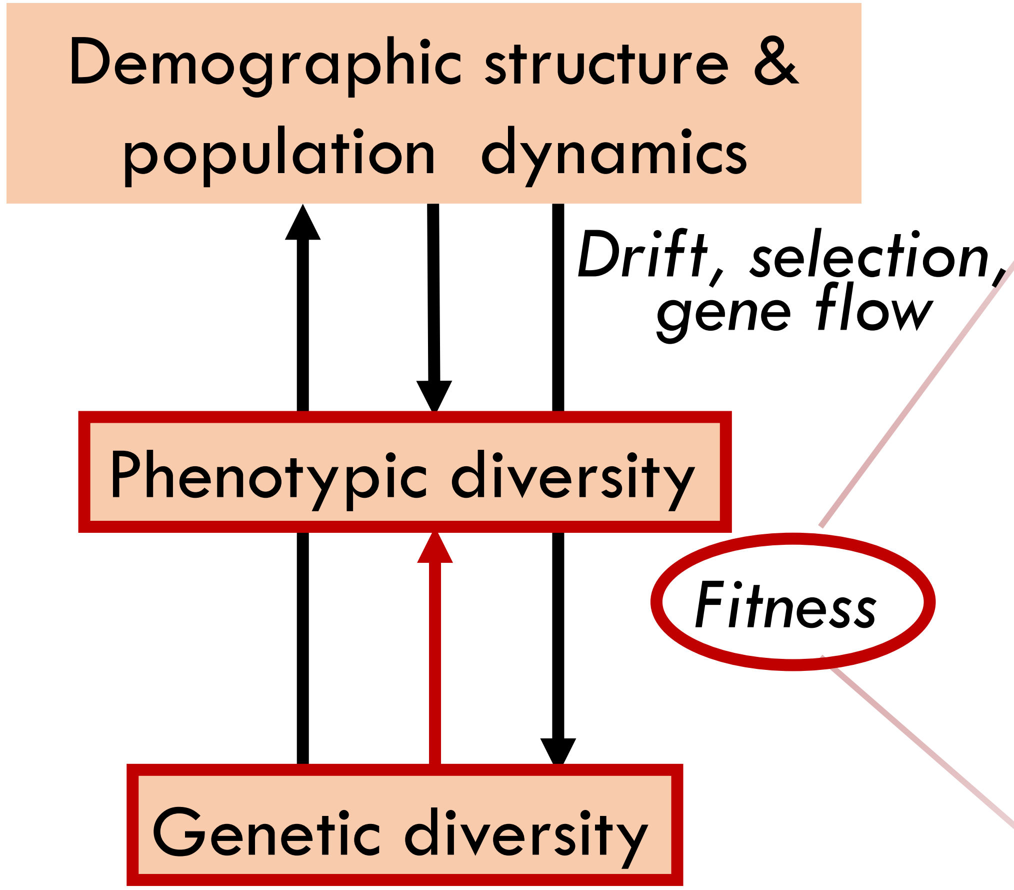
Importance of interindividual interactions in eco-evolutionary population dynamics: The rise of demo-genetic agent-based models

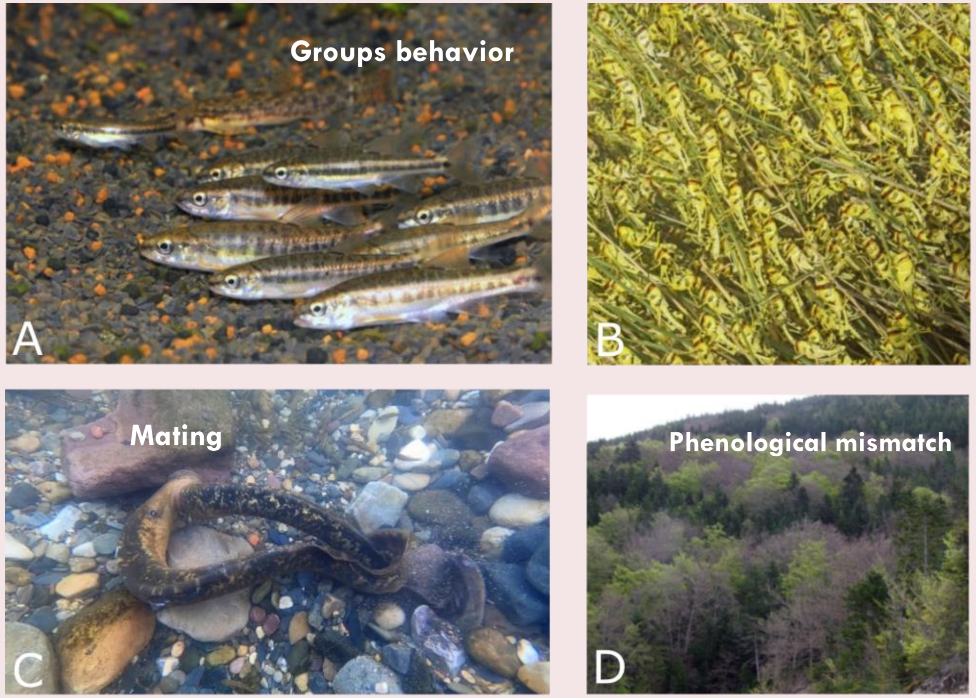
Amaïa Lamarins[1,2] | Victor Fririon[3] | Dorinda Folio[1] | Camille Vernier[4] | Léa Daupagne[1] | Jacques Labonne[1] | Mathieu Buoro[1] | François Lefèvre[3] | Cyril Piou[4] | Sylvie Oddou-Muratorio[1]

Eco-evolutionary dynamics and interindividual interactions





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:

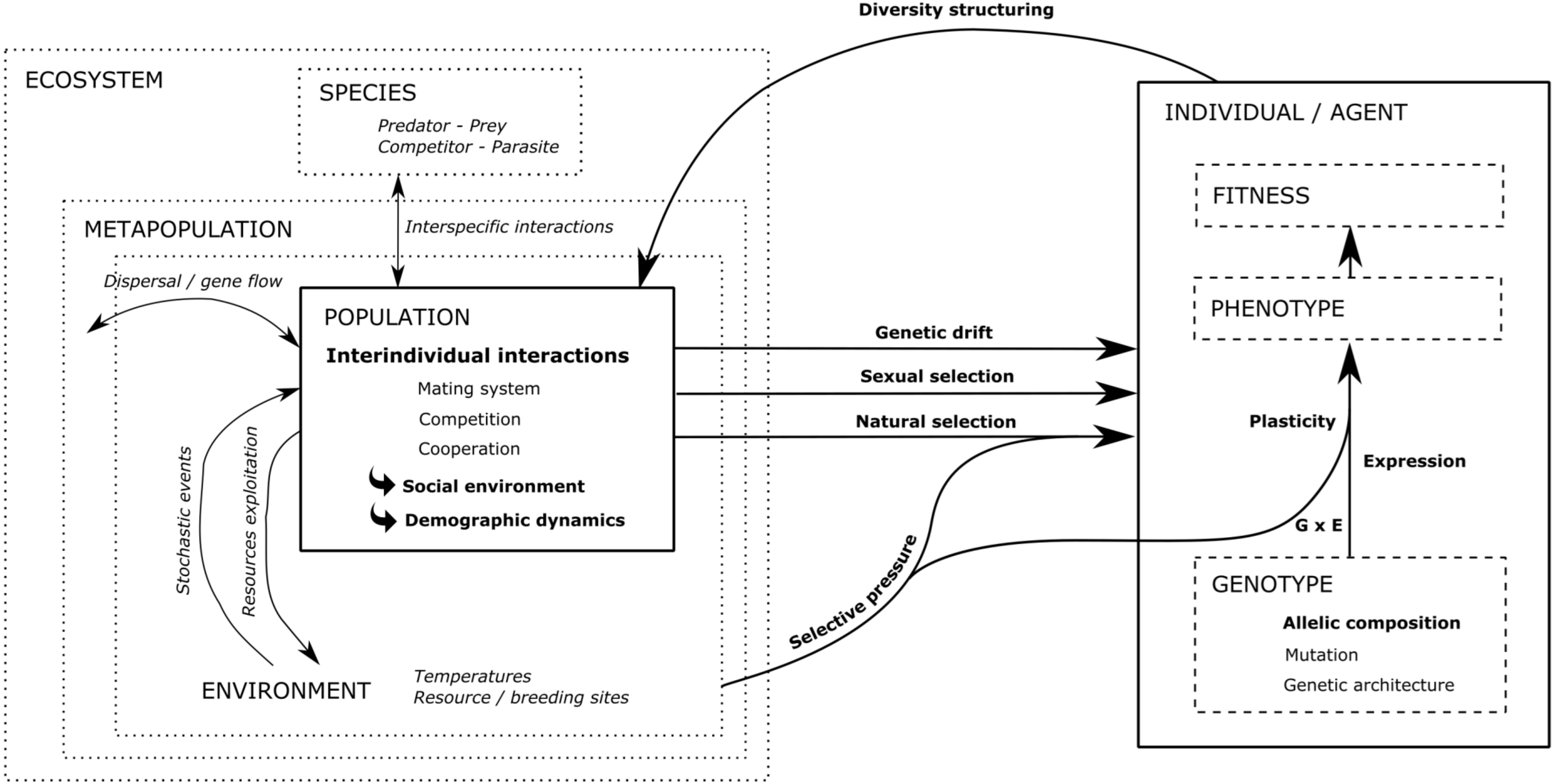
- Homogeneous processes within groups of individuals (populations or life stages)
- *A priori* fitness

DG-ABMs:

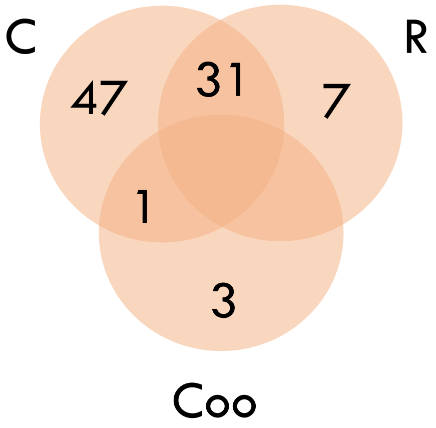
- Variation in group composition (phenotypes and genotypes) and interactions: individual decisions but emerging patterns at group level
- Emerging fitness

DG-ABM definition

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



Litterature review



Type of interactions

Web of Science (1955-2022)

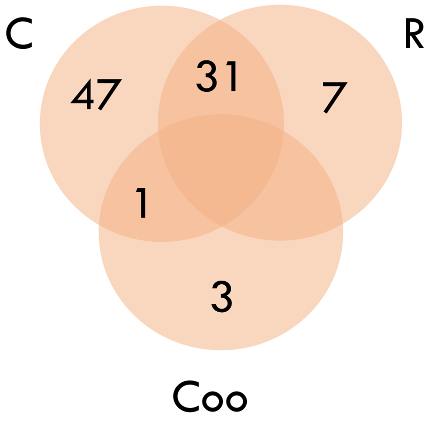
"IBM"
"ABM"

"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)

Litterature review



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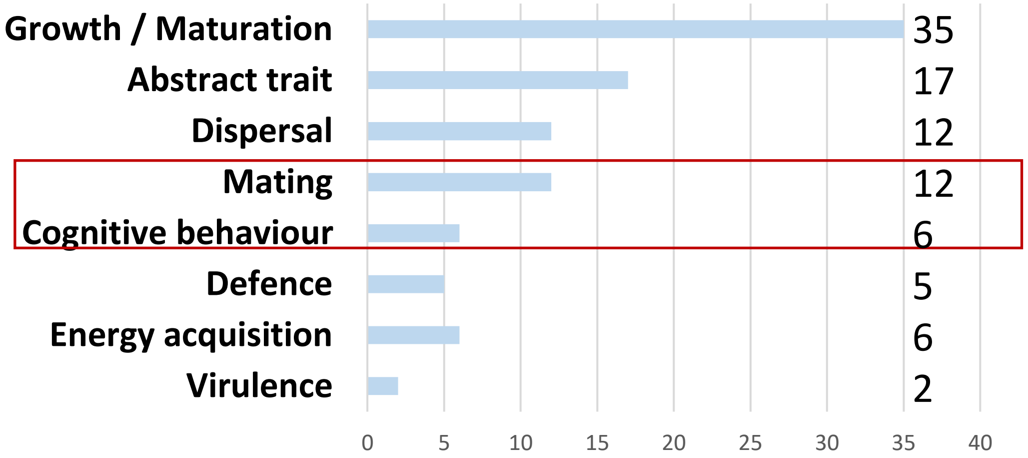
Evolving fitness-related traits



Size

Avoidance of predators/competition

Direct effects on individual interaction

Litterature review

Web of Science (1955-2022)

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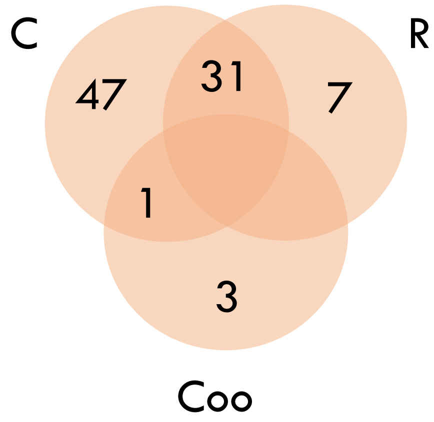
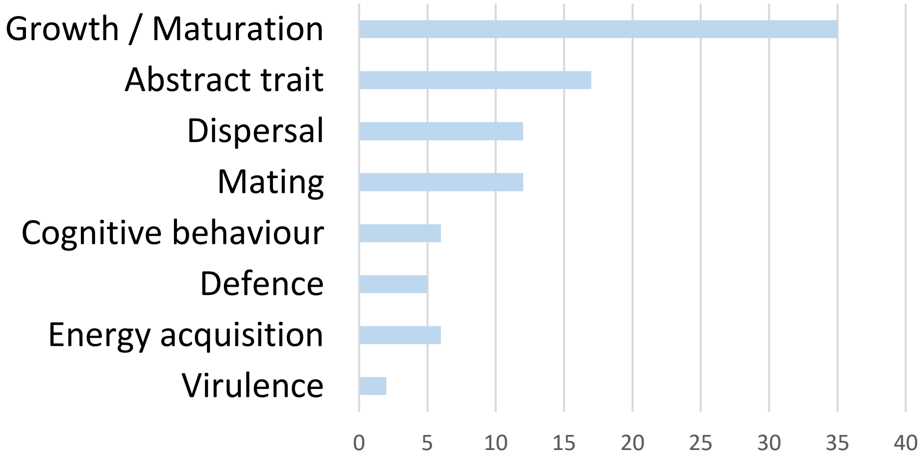
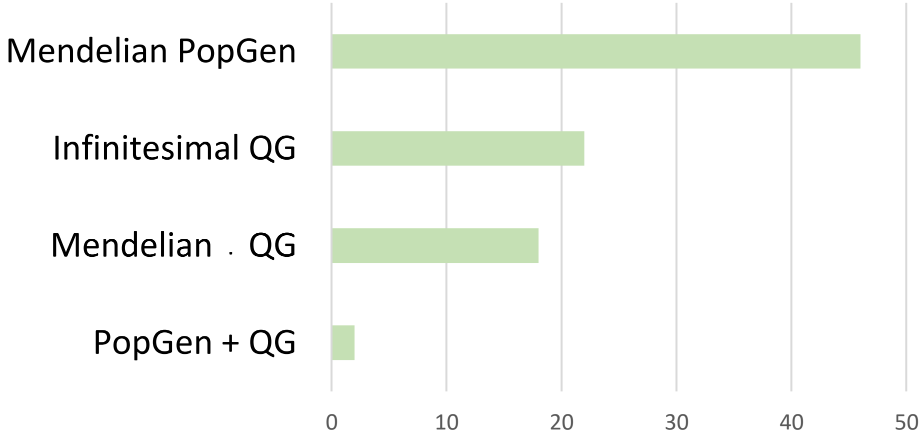


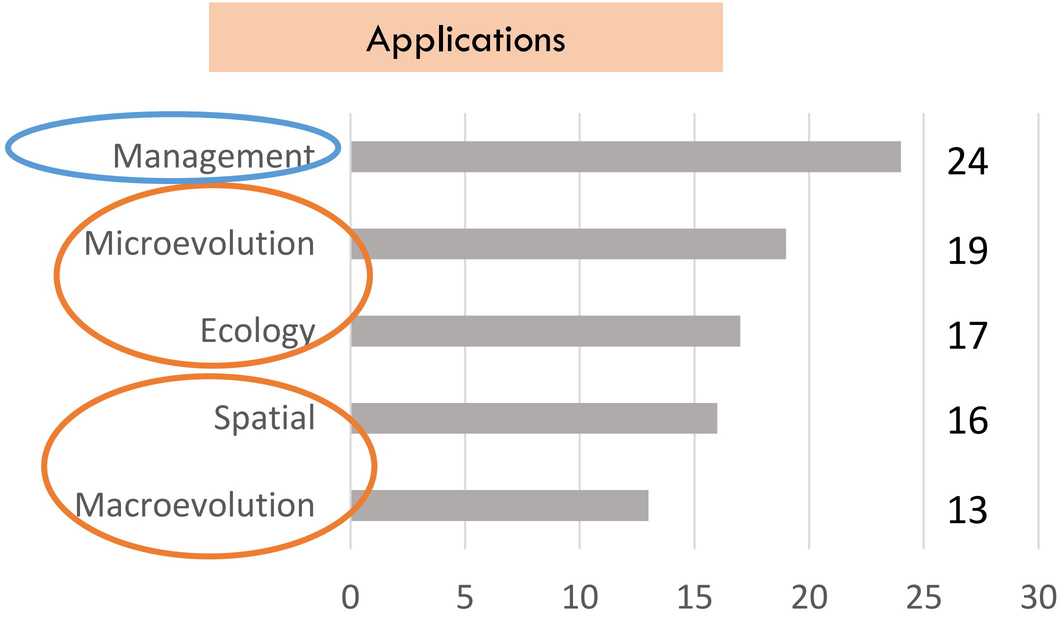
Evolving fitness-related traits



Inheritance framework



Litterature review



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"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

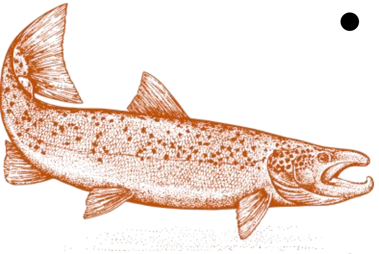
→ Larger spatio-temporal scale: metapopulation / communities dynamics, speciation

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

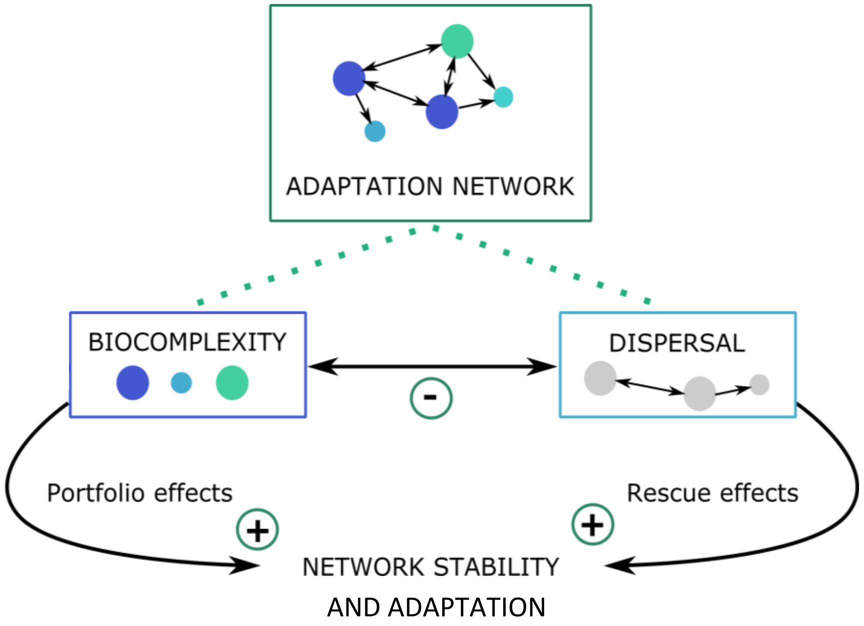


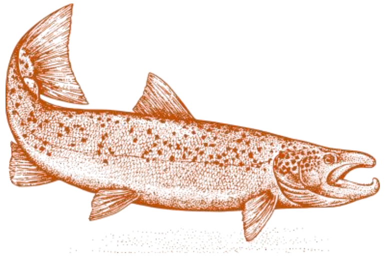
- Amaia Lamarins (2022) : Adaptation, persistence and management of Atlantic salmon in a metapopulation context
- Dorinda Folio (2022): Evolutionary management of brown trout intraspecific diversity

- 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

Thèse de Amaia Lamarins (2022)

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





Context:

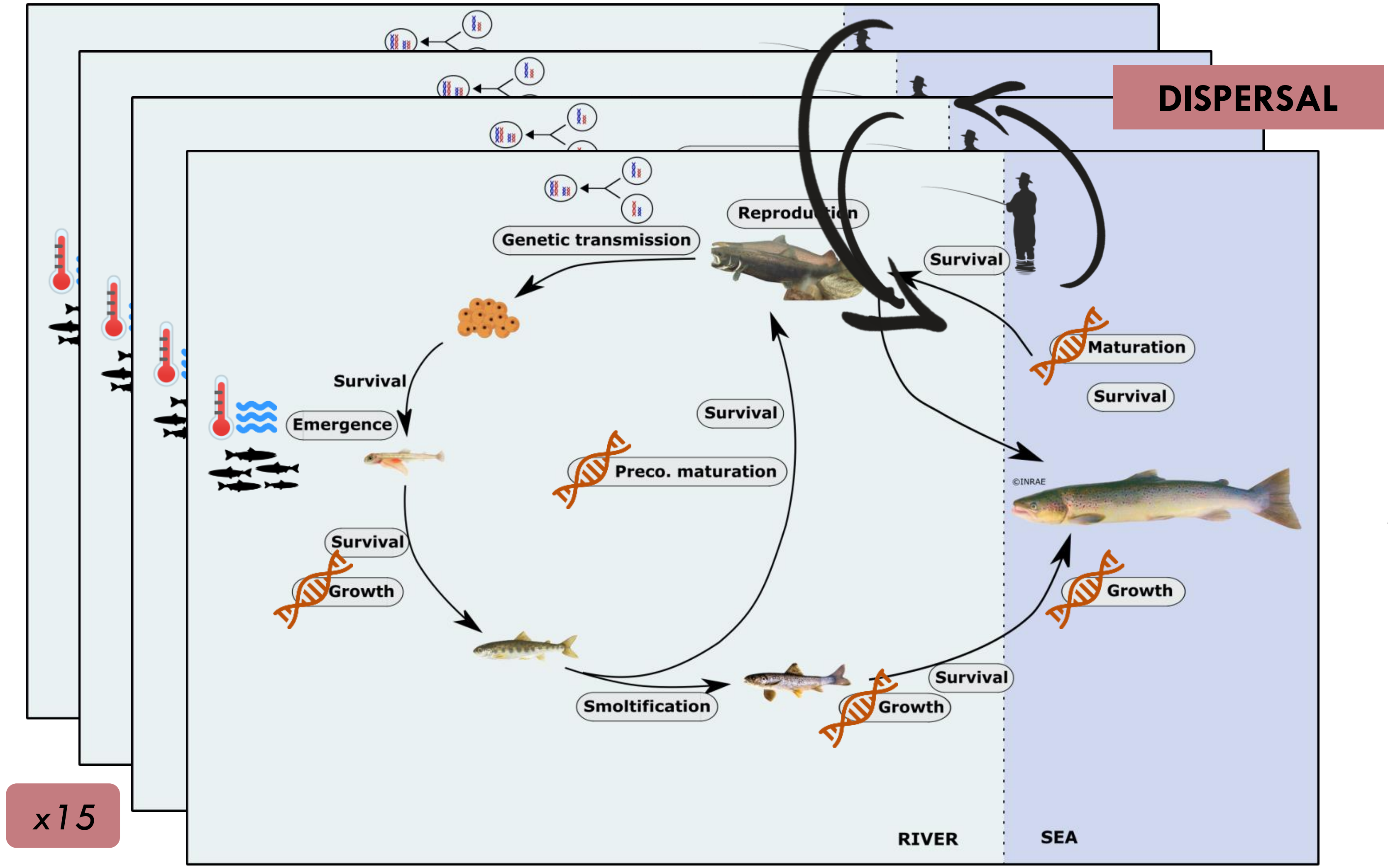
- Dispersal and genetic adaptation can promote species persistence under environmental change (depending on the balance btw selection & geneflow, Lenormand 2004)
- Portfolio theory: biocomplexity + asynchronous dynamics → stability of population complexes (Hilborn et al. 2003)
- Ibasam, a DG-ABM to study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

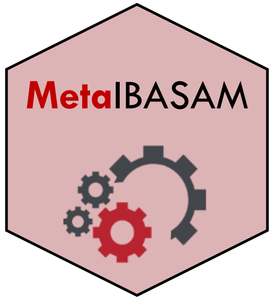
How connectivity and diversity influence metapopulation eco-evolutionary dynamics, stability and adaptation ?

Co-encadrement M. Buoro, S Carlson

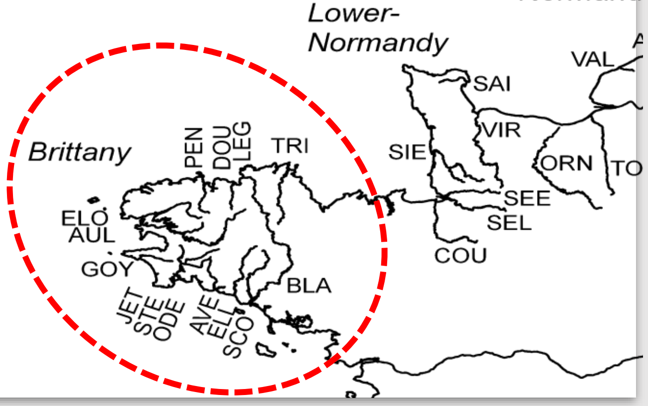
The model

IBASAM (Individual Based Atlantic SAlmon Model)… Towards MetaIBASAM



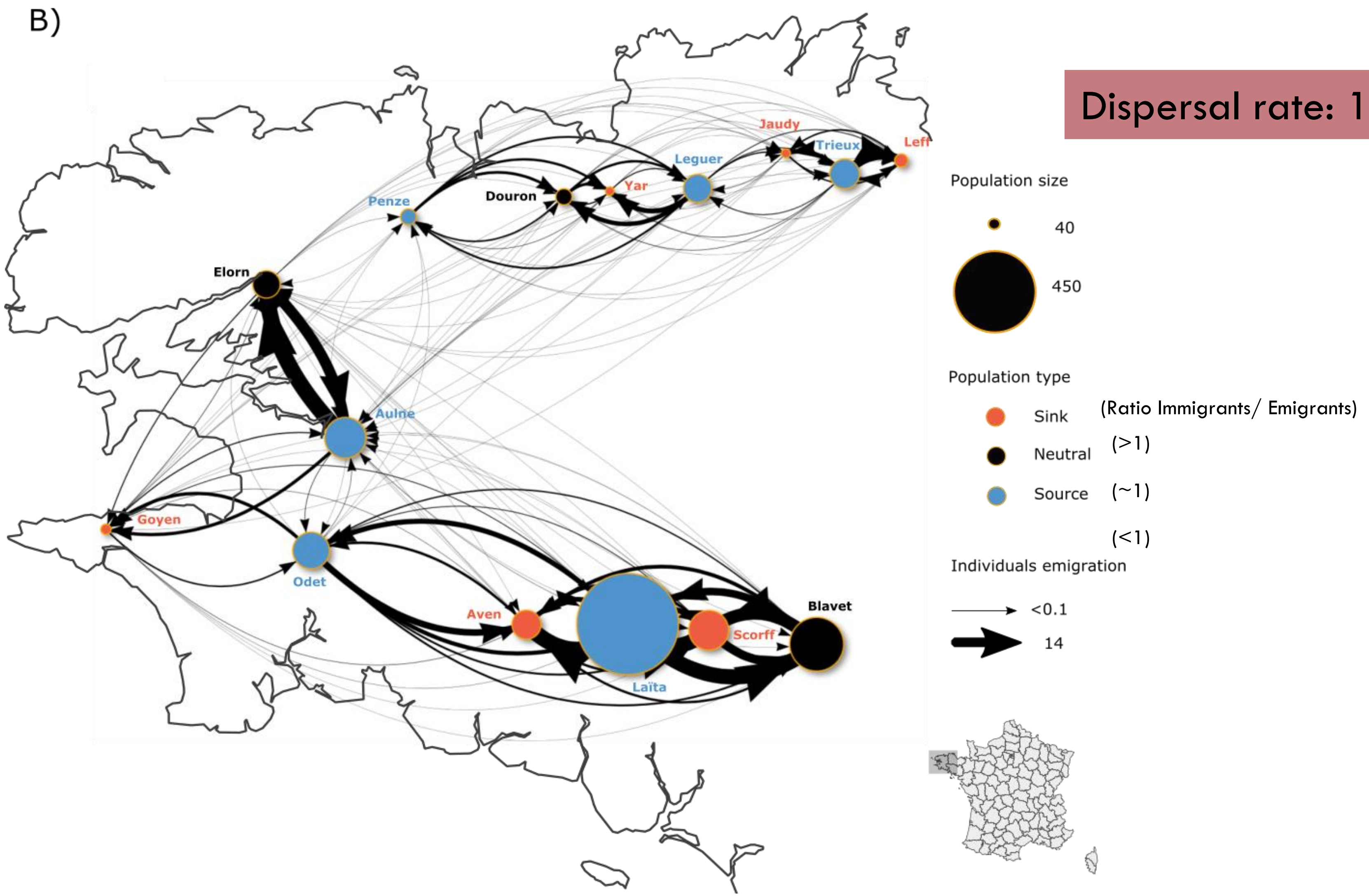


Perrier et al., 2011, Mol. Ecol.



1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS



Dispersal rate: 10%

REALISTIC METAPPULATION SPATIAL CONTEXT

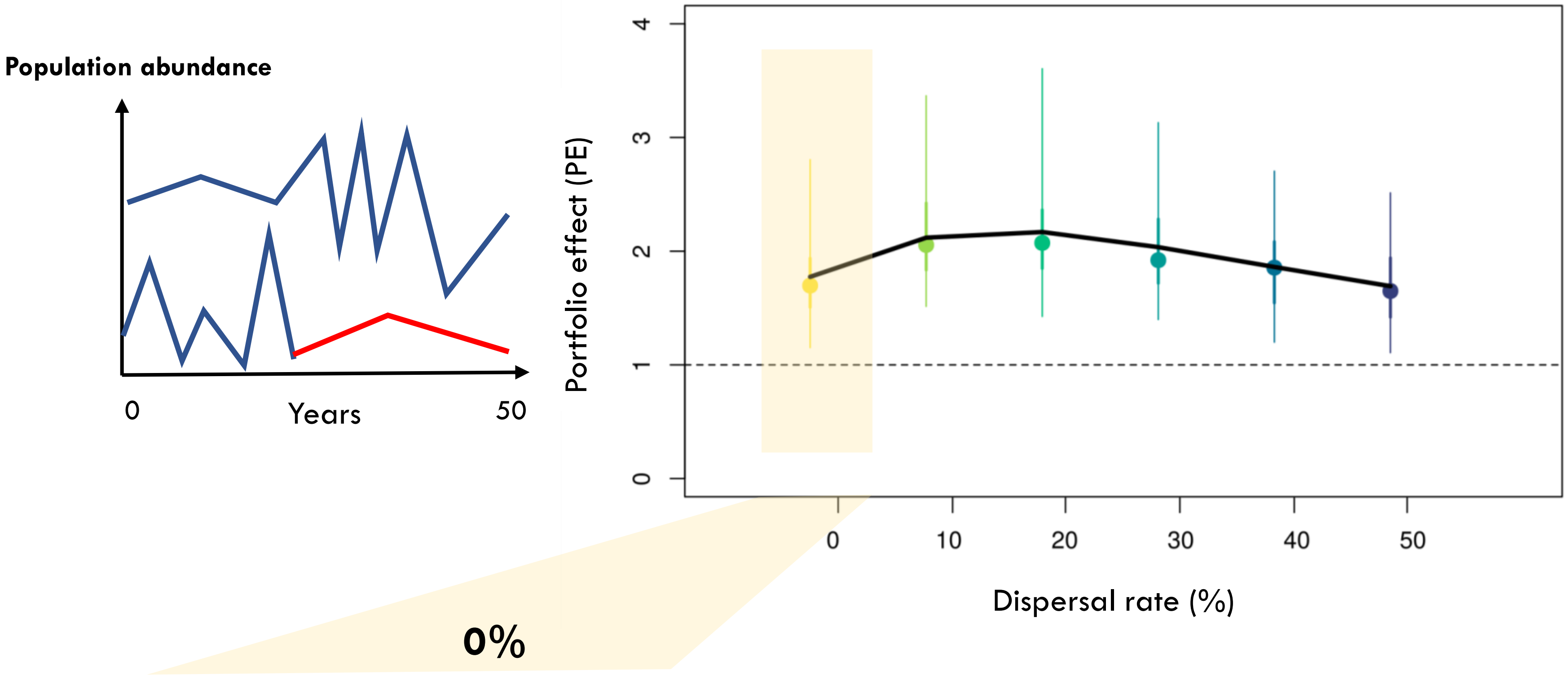
→ Carrying capacities
→ Distance

DEMOGRAPHIC MODEL

→ Dispersing vs philopatric individuals

1) Demographic consequences of dispersal

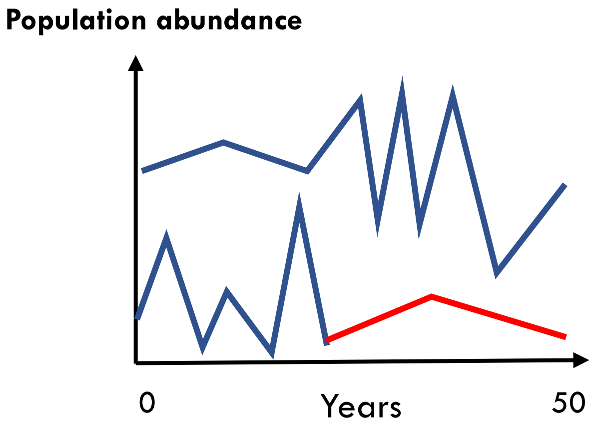
Lamarins et al. 2022, CJFAS

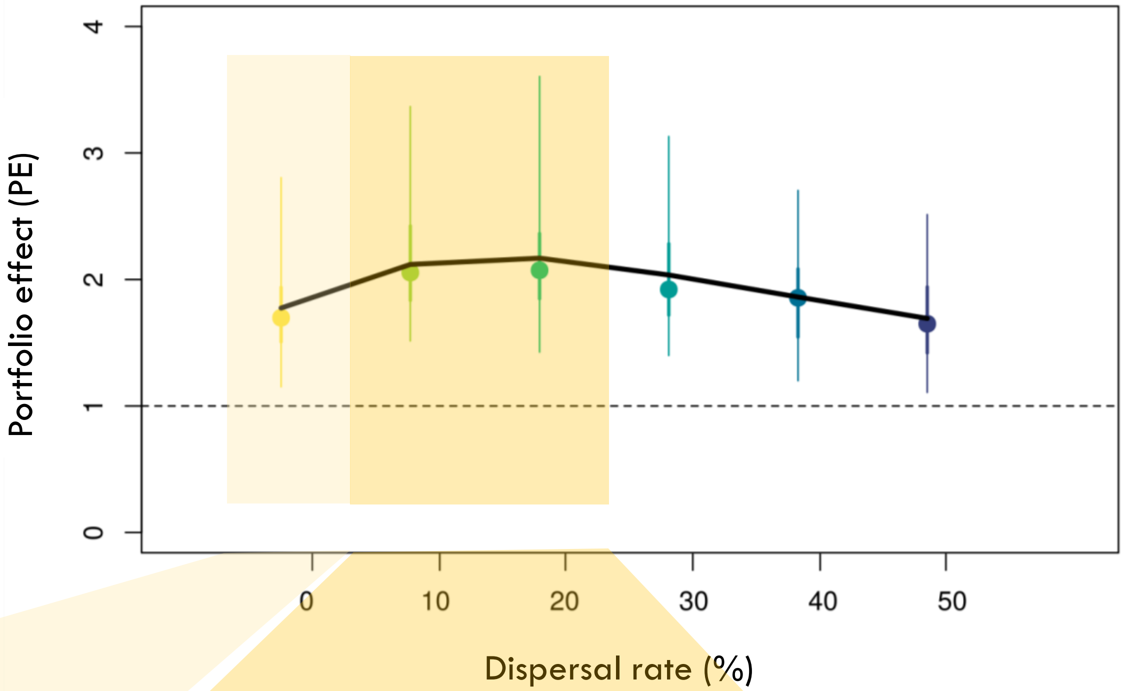


- Asynchrony
- High risk of extinction of small populations

1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS





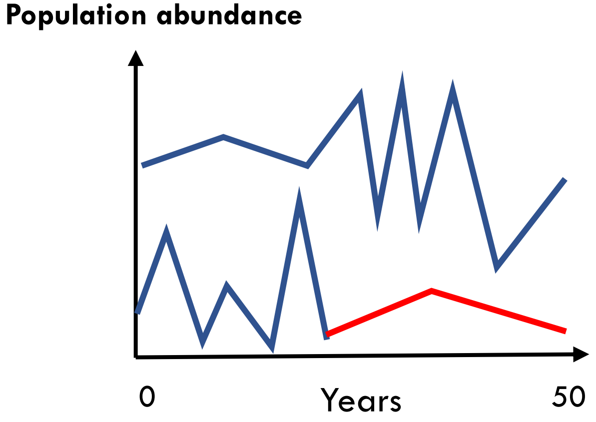
0% | **10-20%**

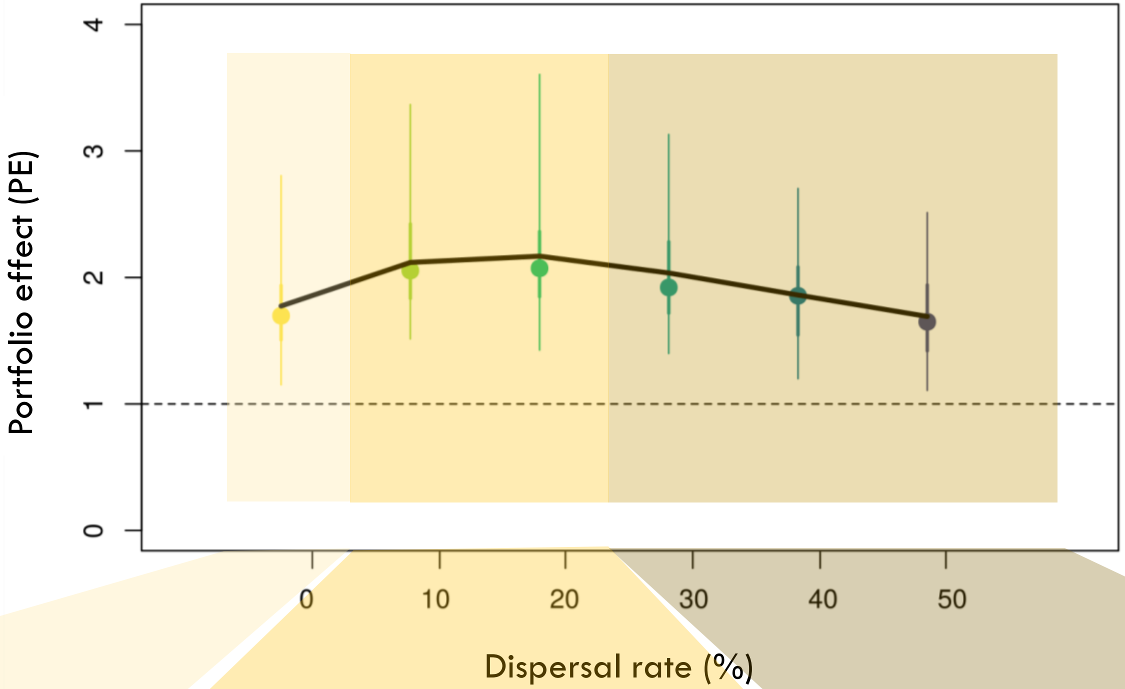
- Asynchrony
- High risk of extinction of small populations

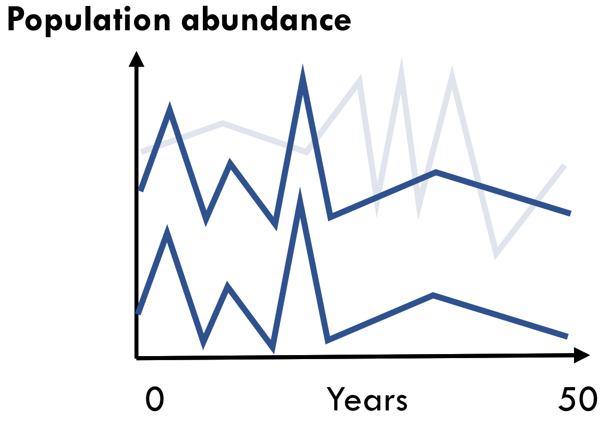
- Demographic rescue of small populations
- Optimum ?
  ≈ wild average rate: 15%

1) Demographic consequences of dispersal

Lamarins et al. 2022, CJFAS







0%

- Asynchrony
- High risk of extinction of small populations

10-20%

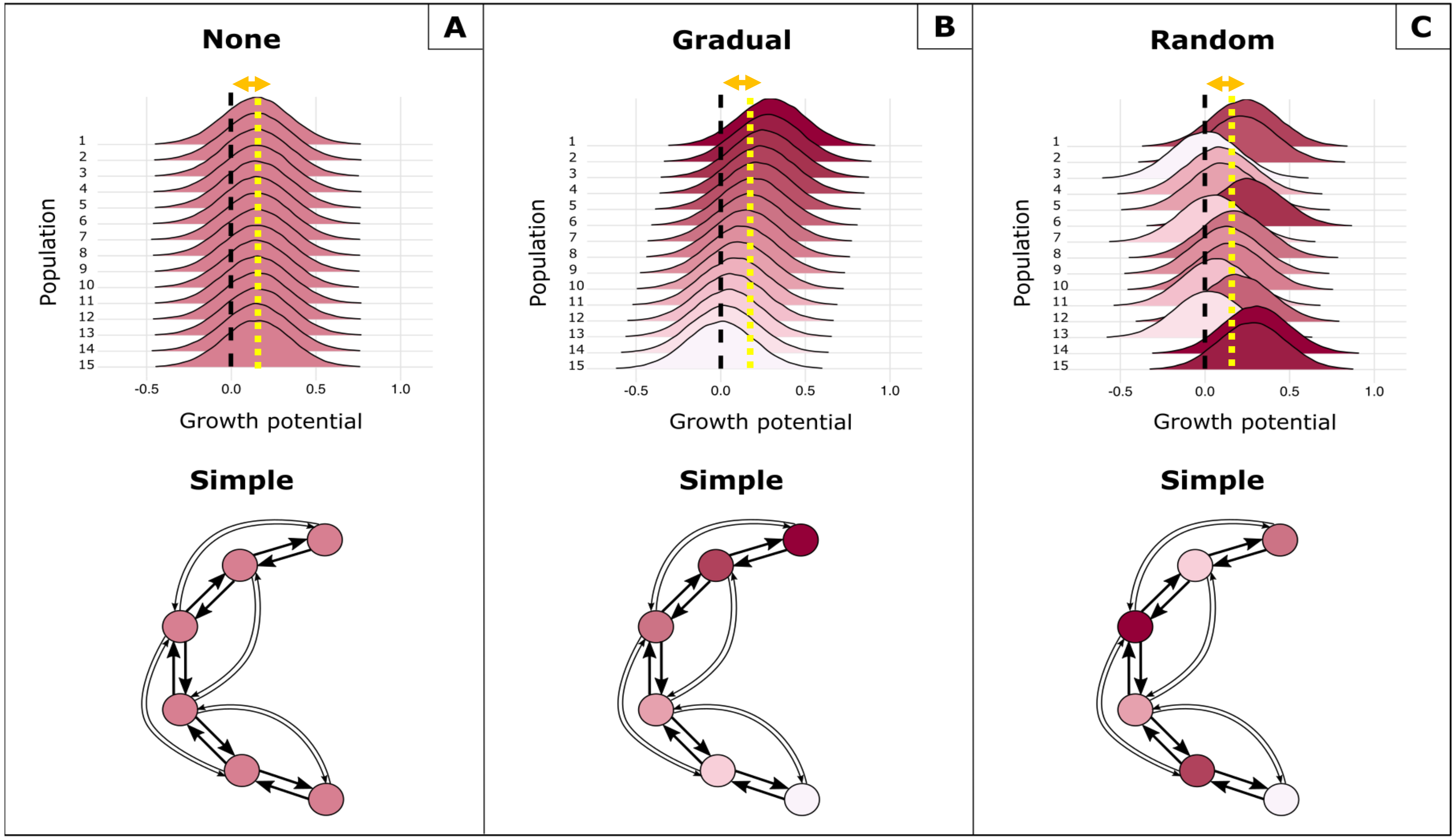
- Demographic rescue of small populations
- Optimum ?
  ≈ wild average rate: 15%

> 20%

- ↗ ↗ synchrony
- « Anti-rescue » effect

2) Evolutionary consequences – network scale

Lamarins et al., Ecography (2023)



SPATIAL GENETIC STRUCTURE OF GROWTH POTENTIAL

→ Maladapted populations

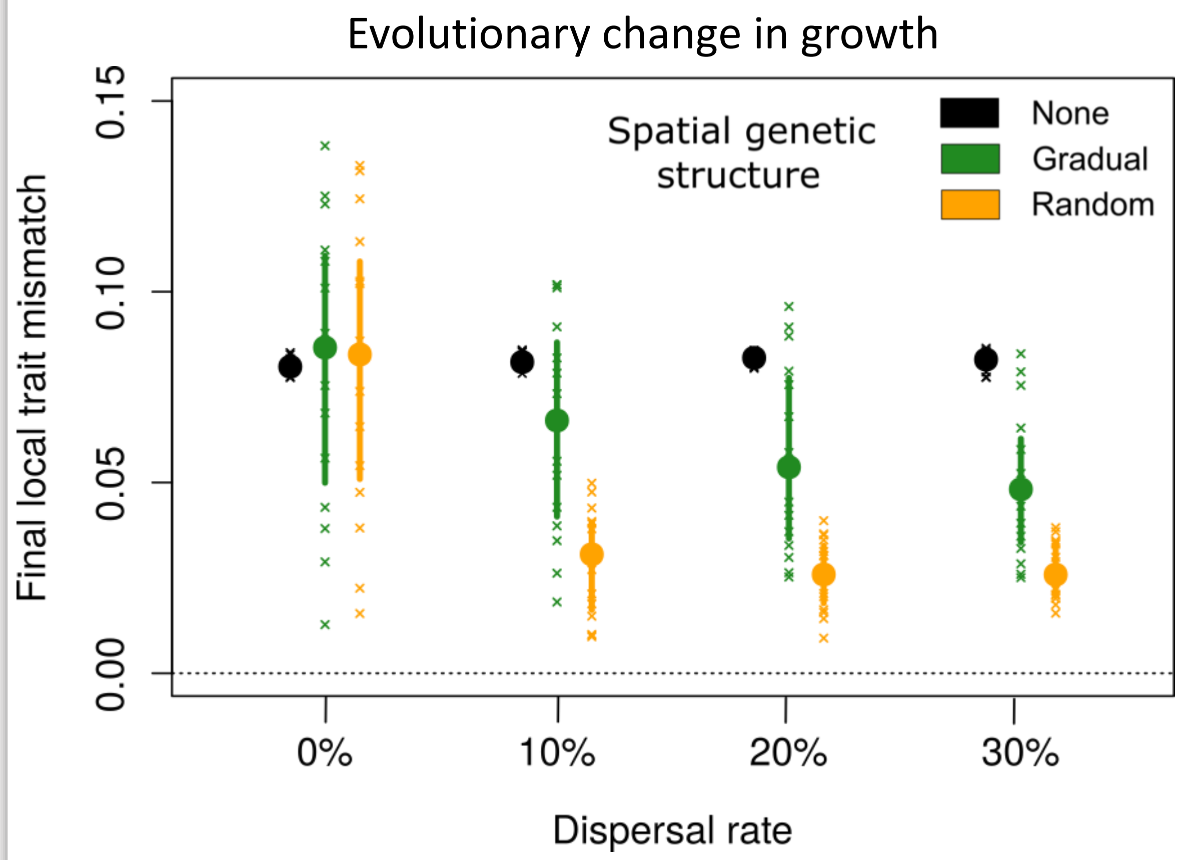
→ Contrasted spatial genetic structures among populations

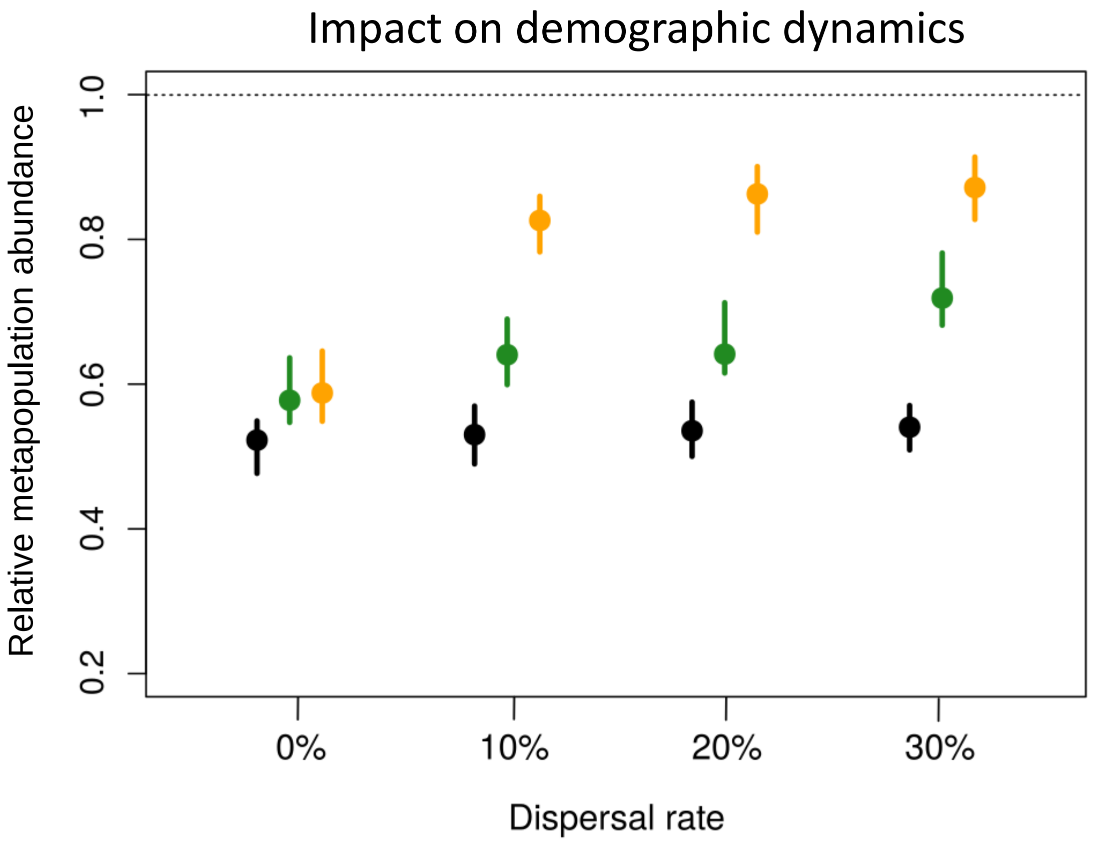
SPATIAL CONFIGURATION

→ Simple configuration

2) Evolutionary consequences – network scale

Lamarins et al., Ecography (2023)





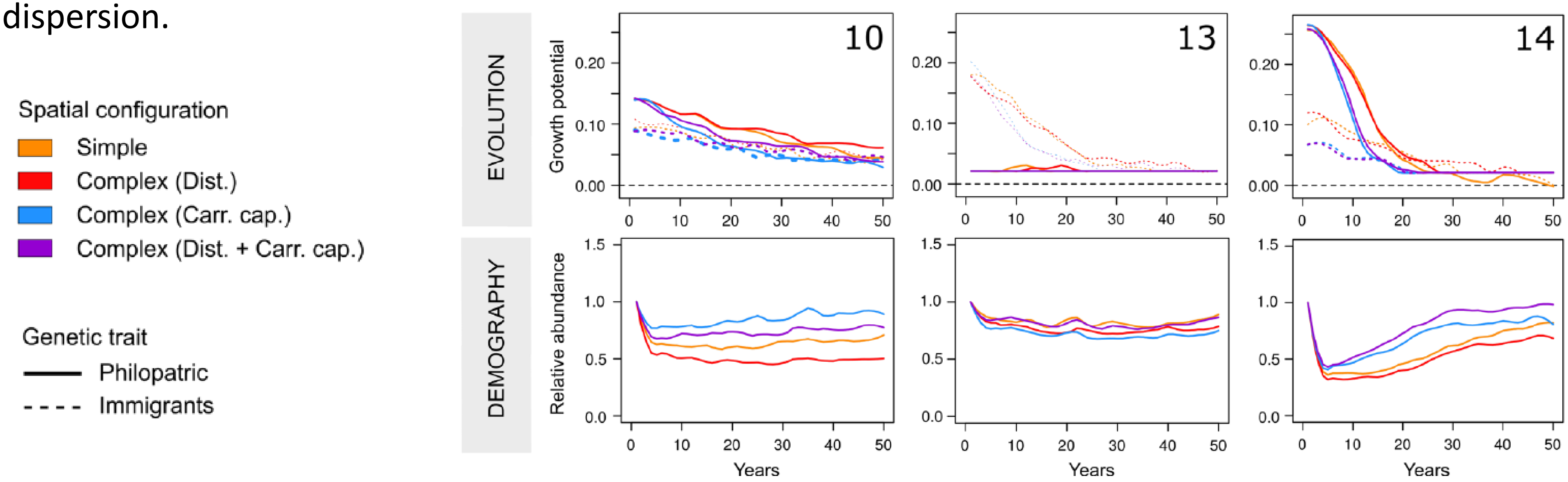
Trait mismatch: distance from optimum

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

Conclusions

Lamarins et al., Ecography (2023)

- L'adaptation et le sauvetage démographique des populations locales sont renforcés par la dispersion entre des populations initialement différenciées.
- Cela est particulièrement vrai pour les taux de dispersion fort et une structure génétique spatiale aléatoire (plus d'opportunité pour l'adaptation).
- Ce modèle spatialement réaliste montre que les trajectoires évolutives et démographiques des populations locales dépendent du contexte et de la configuration spatiale des populations liées par la dispersion.



Thèse de Victor Fririon (2022)

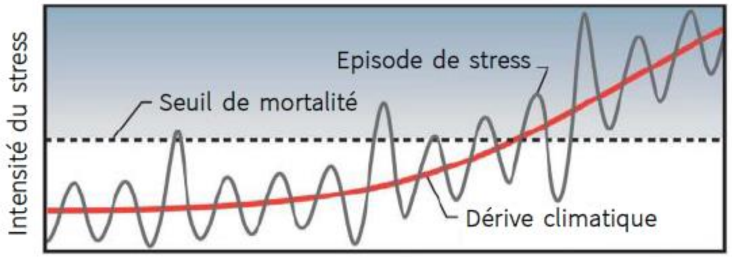
Vulnerability of forests in face of climate change: DG-ABMs to investigate adaptive management strategies in Cedar and Douglas stands

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 ?

Can adaptive changes occur rapidly in tree populations ?

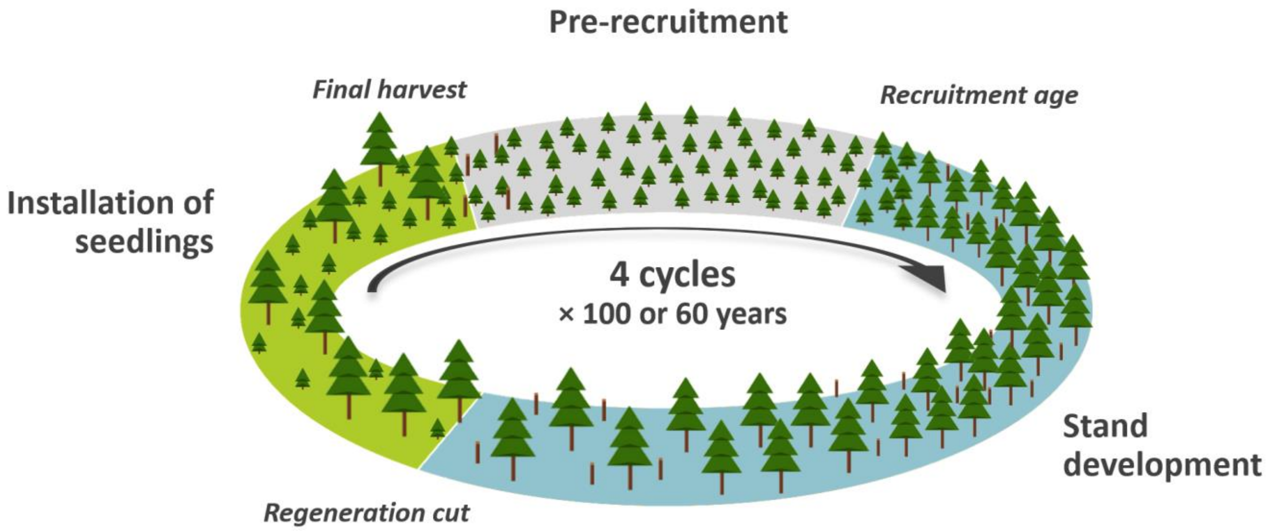
How does sylviculture affect the adaptive capacity of forest stands ?

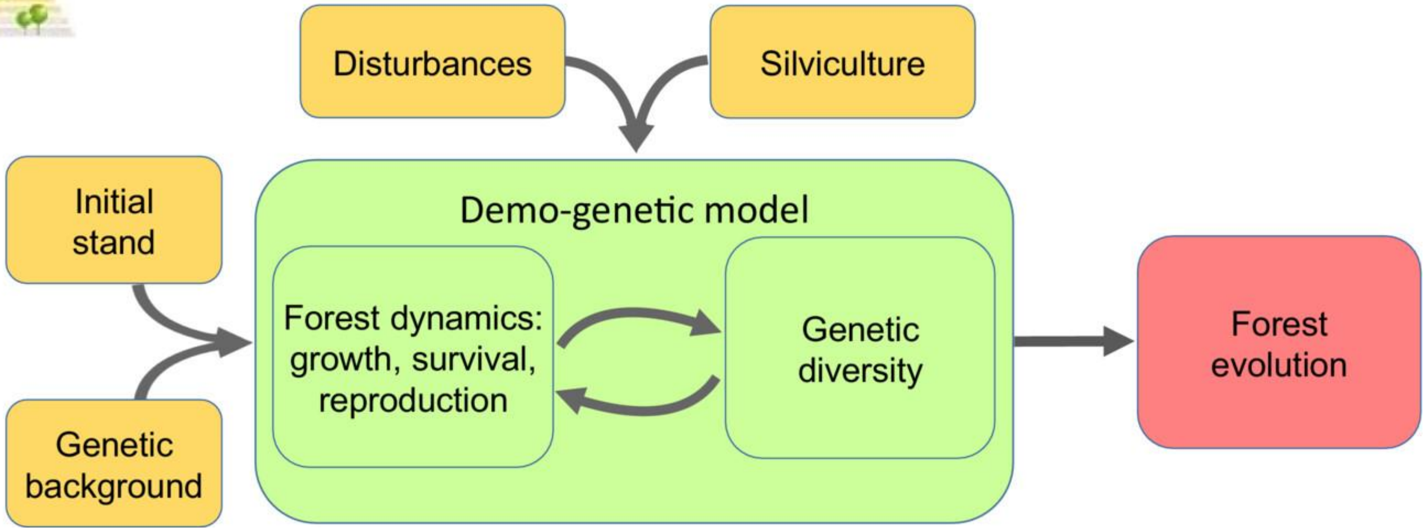


Allen et al. 2015

Co-encadrement F Lefèvre, H Davi, S Muratorio

The model: Luberon2

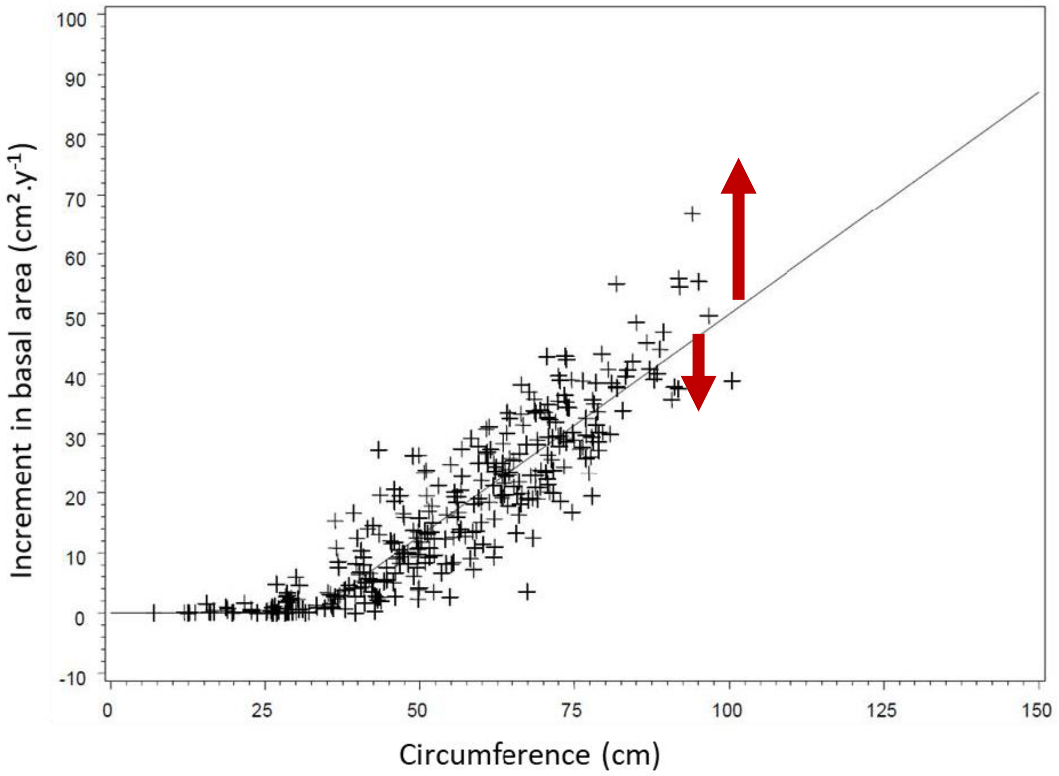




Godineau, Fririon et al. Evol Appl. 2023

The focal trait: growth vigor

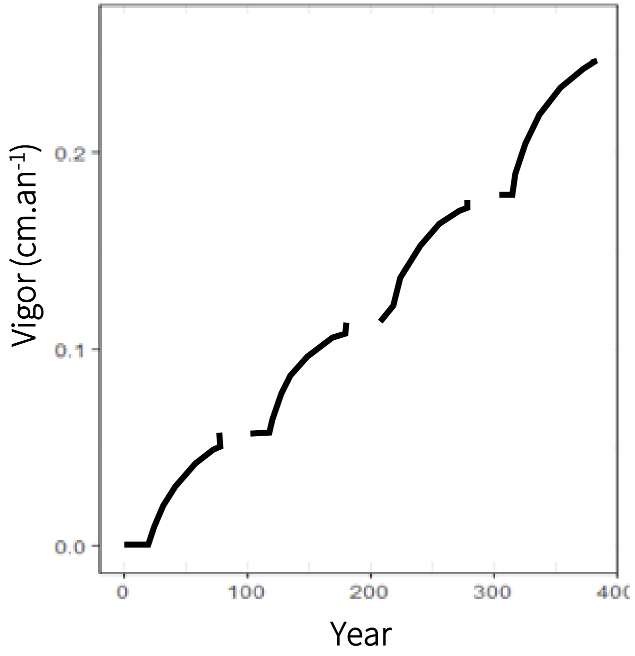
Individual annual increment in basal area as a function of tree circumference in C. atlantica: empirical individual data and model prediction (taken from Courbet, 2002).

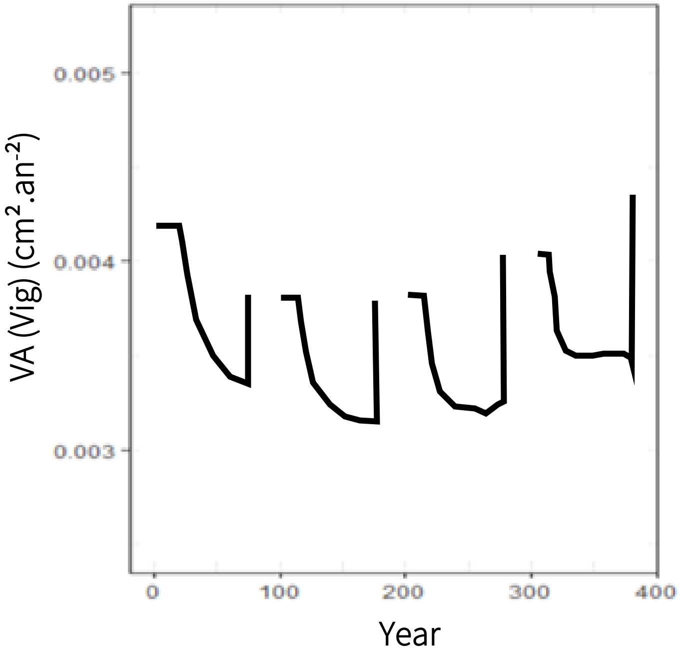


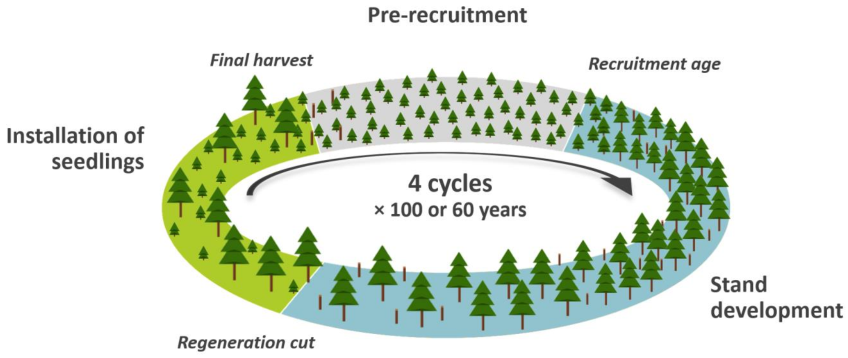
- Natural mortality by competition, i.e., self-thinning, is selective with regard to tree size
- Mortality by disturbance and by silviculture were not selective (no variation in sensitivity to disturbance and random thinning).

1) Evolution of tree vigor

Without thinning





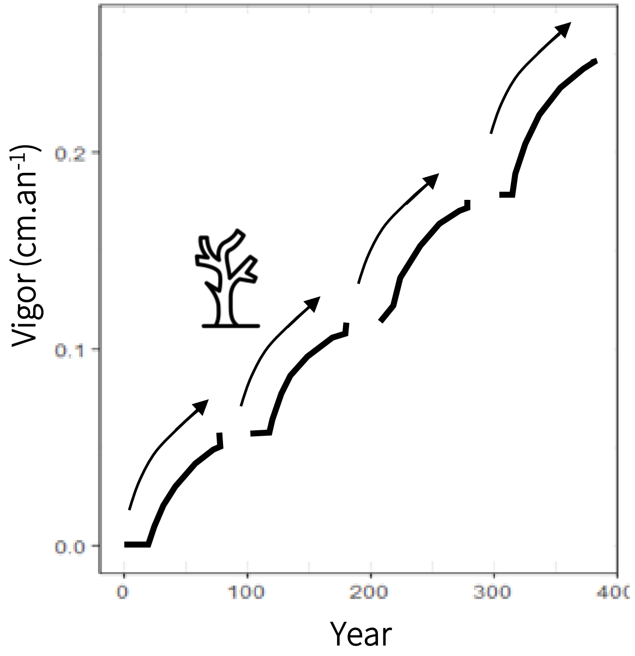


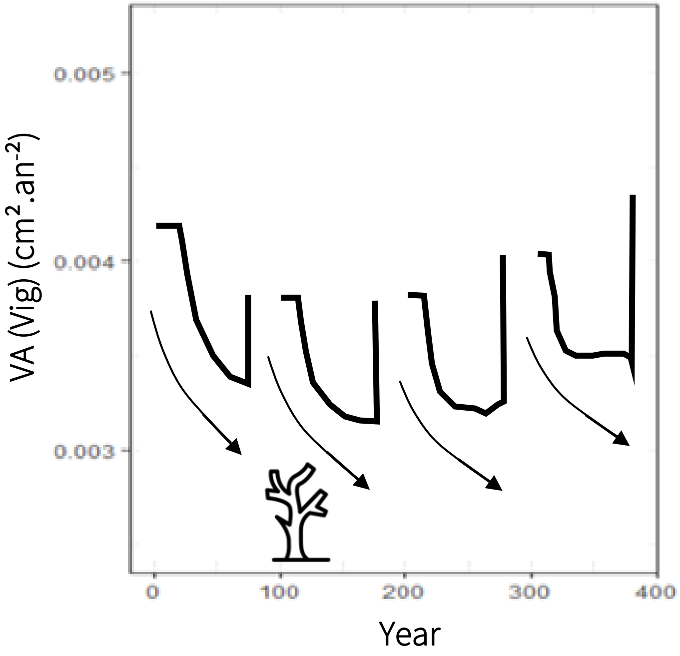
- Selection on survival (competition)
- Selection on fertility
- Restoration of genetic diversity during reproduction

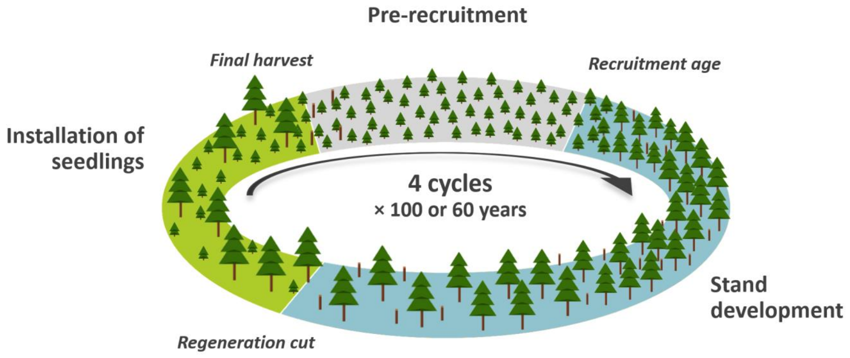
Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

Without thinning







- ➢ Selection on survival (competition)
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Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

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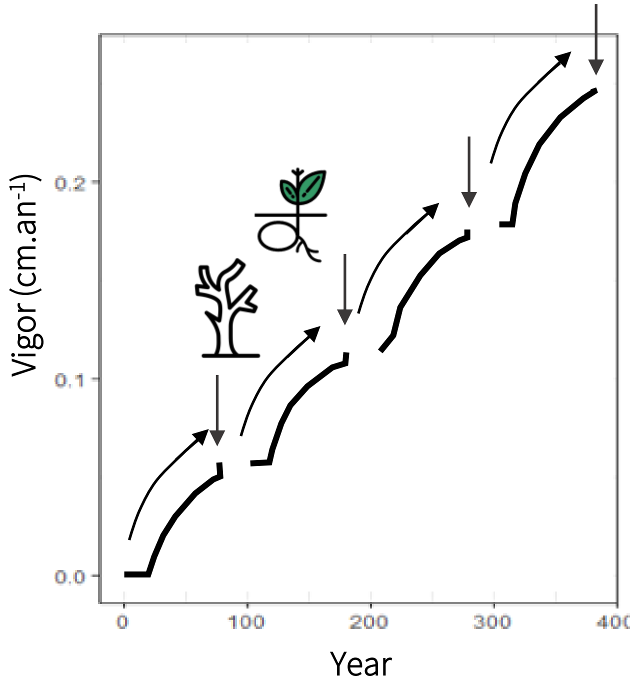

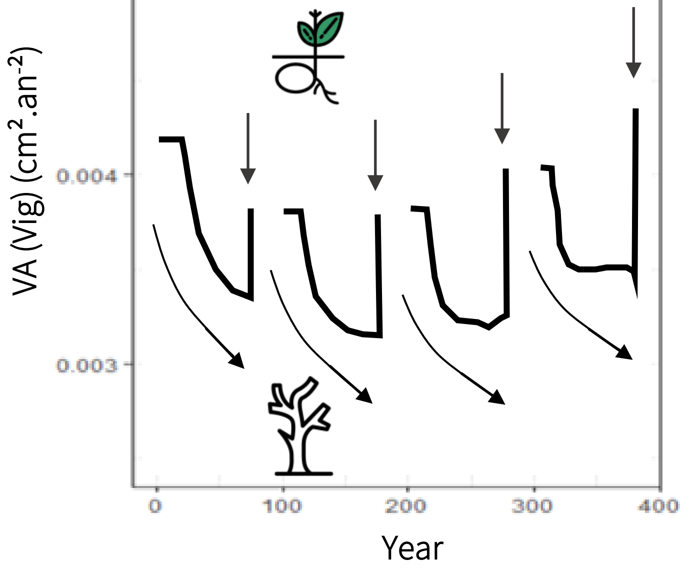

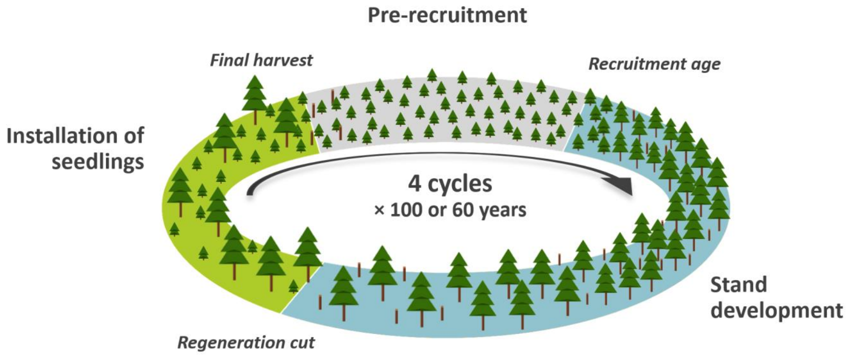

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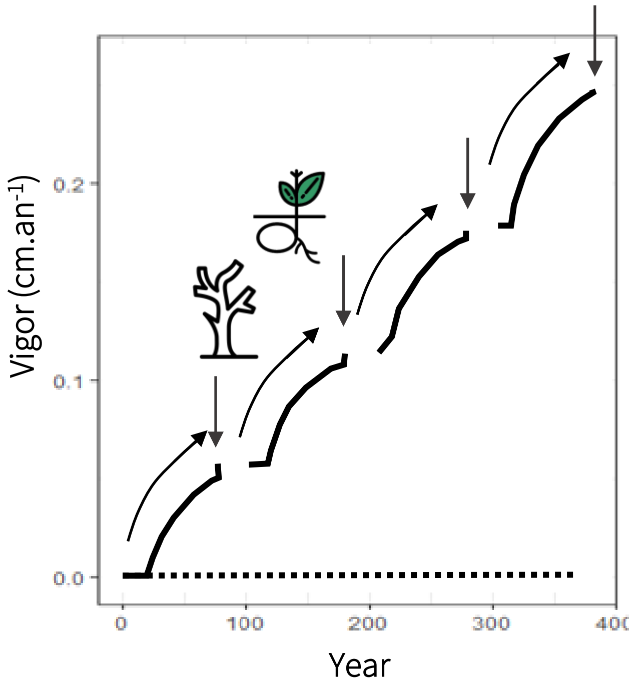
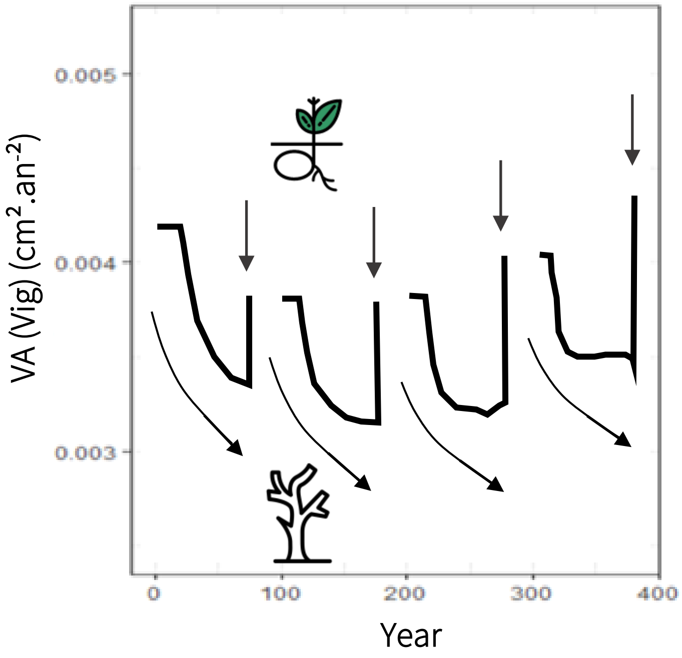
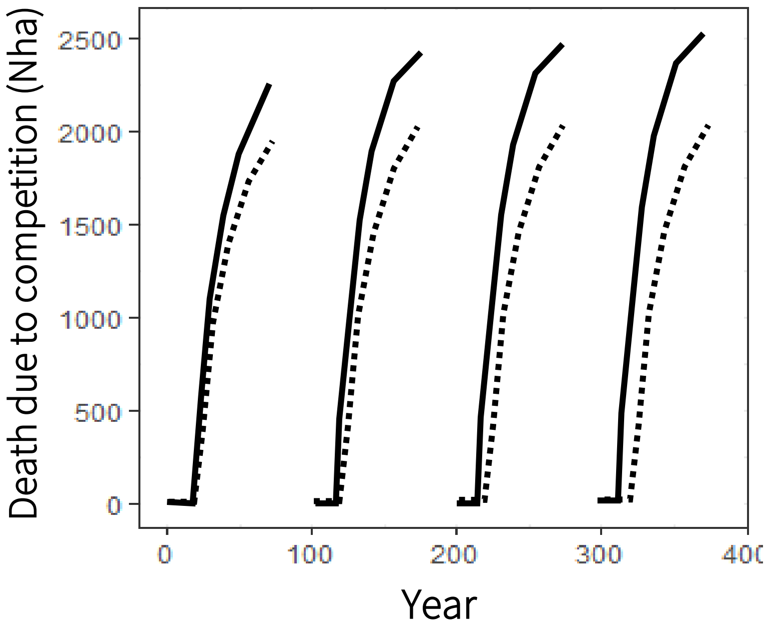
Godineau, Fririon et al. Evol Appl. 2023

1) Evolution of tree vigor

Without thinning







Realistic genetic gain (+12% growth per generation)

Increased growth = increased competition

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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 +

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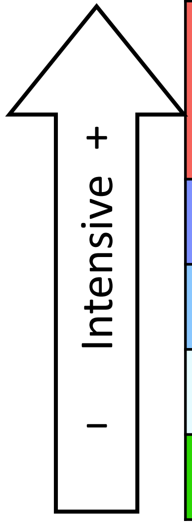
Thinning scenarios

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
relaxed	-				-	-	-	-
delayed				-	-	-	-	-
low intensity	× 4	× 4	× 4	× 4	× 4	× 4	-	-
no thinning							-	-

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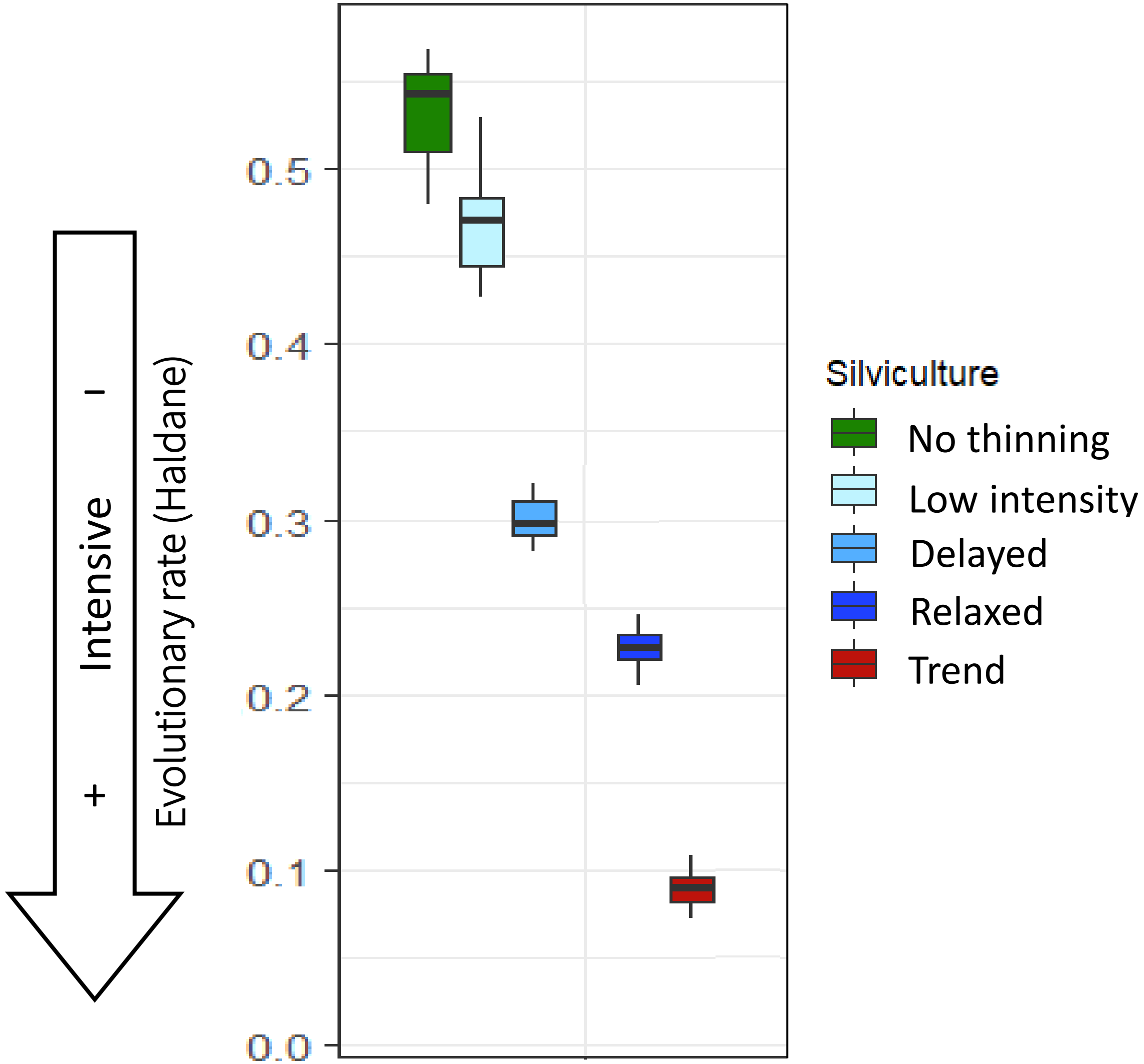
Dynamic of adaptive change

(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.



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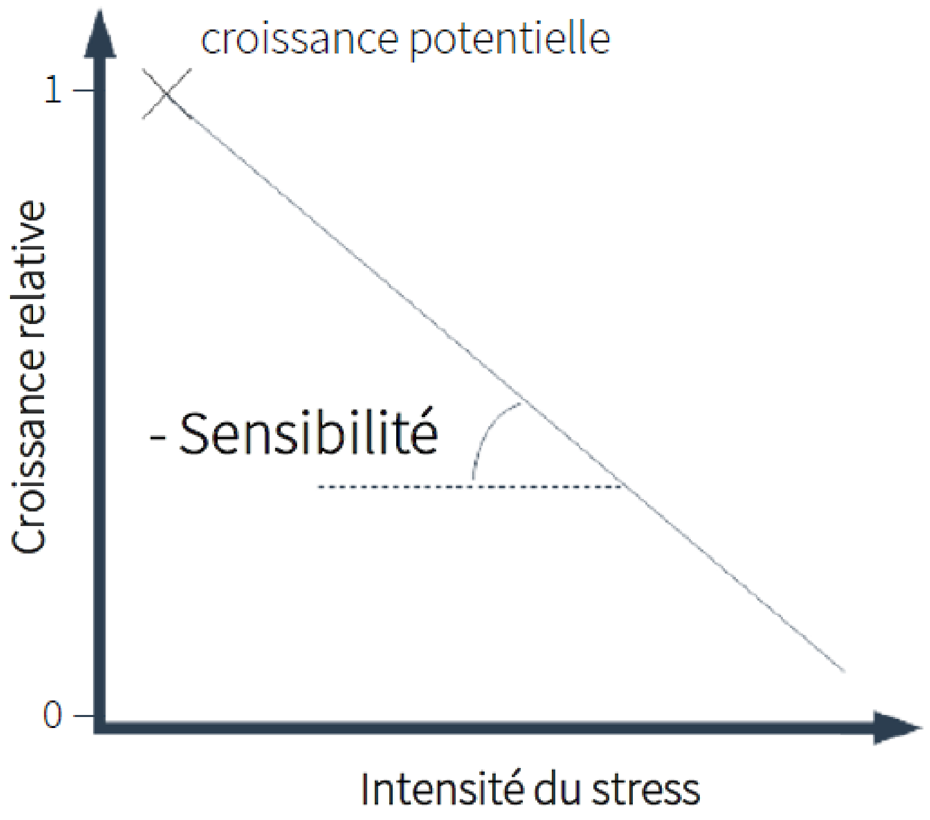
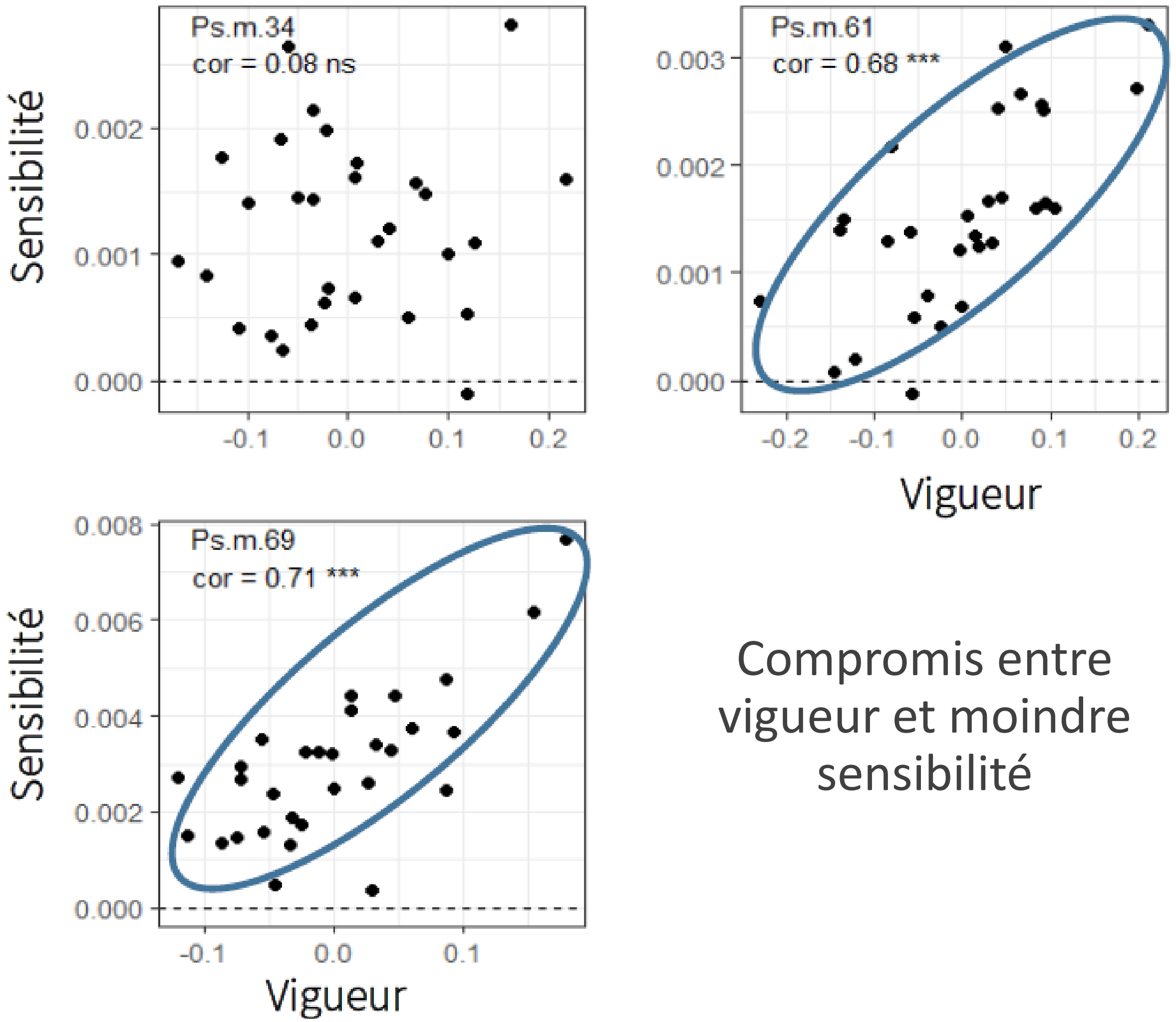
2 focal traits: vigour + sensitivity to disturbances



➢La perte relative de croissance par unité de stress

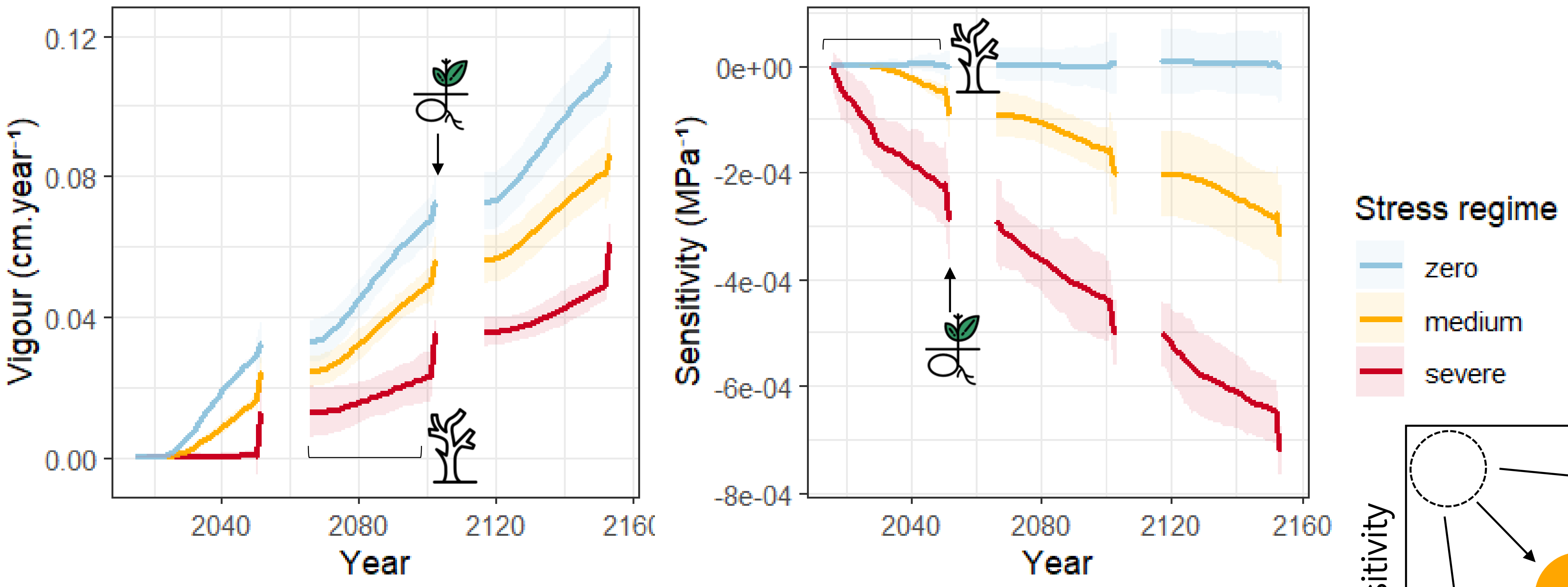


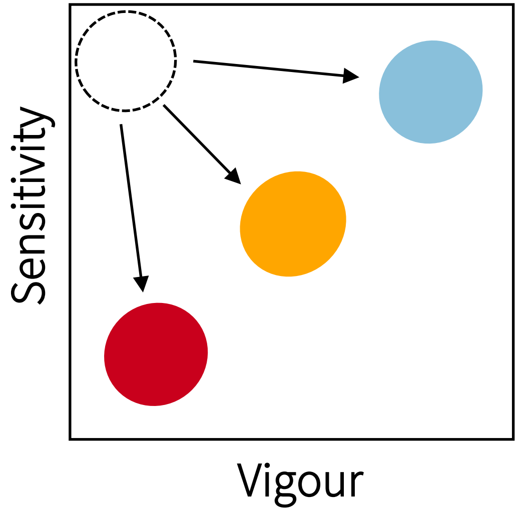
Compromis entre vigueur et moindre sensibilité

Fririon et al. Forest Ecol Management 2022

Evolution of vigor and sensitivity

(with disturbance, without thinning)

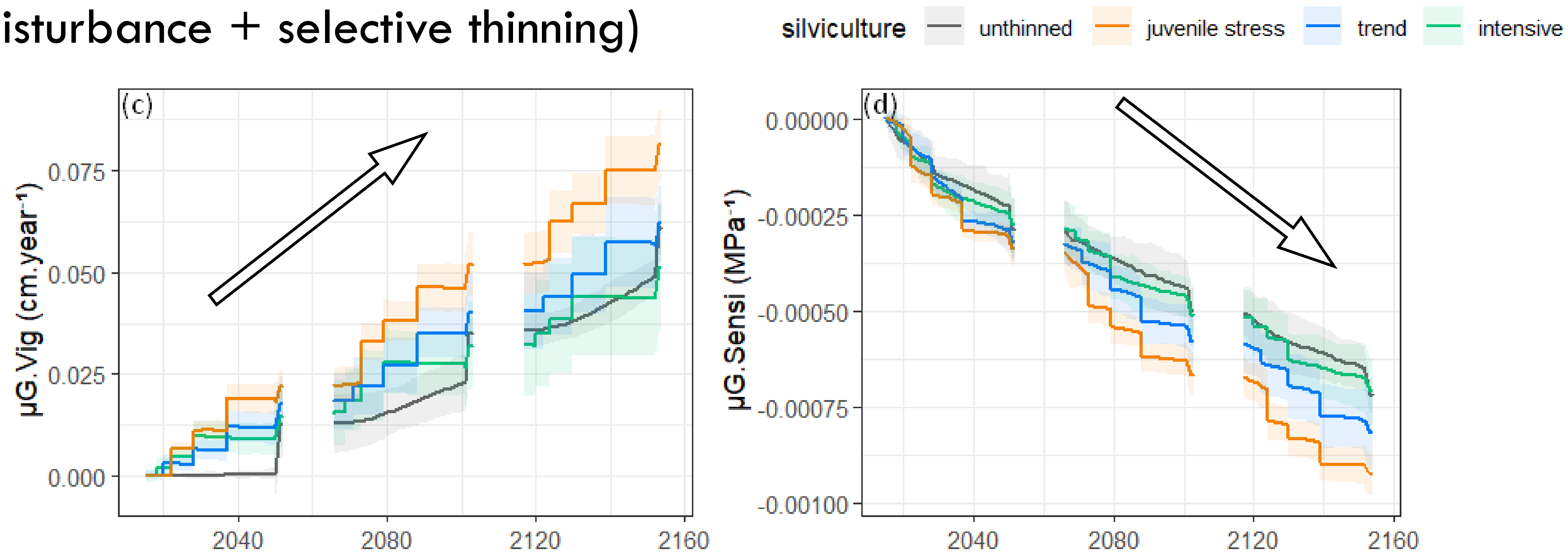




- Realistic evolution rates (0.1 to 0.3 haldane)
- Realistic genetic gain (+8% growth per generation)
- Antagonistic selection between vigor and sensitivity

Evolution of vigor and sensitivity

(disturbance + selective thinning)

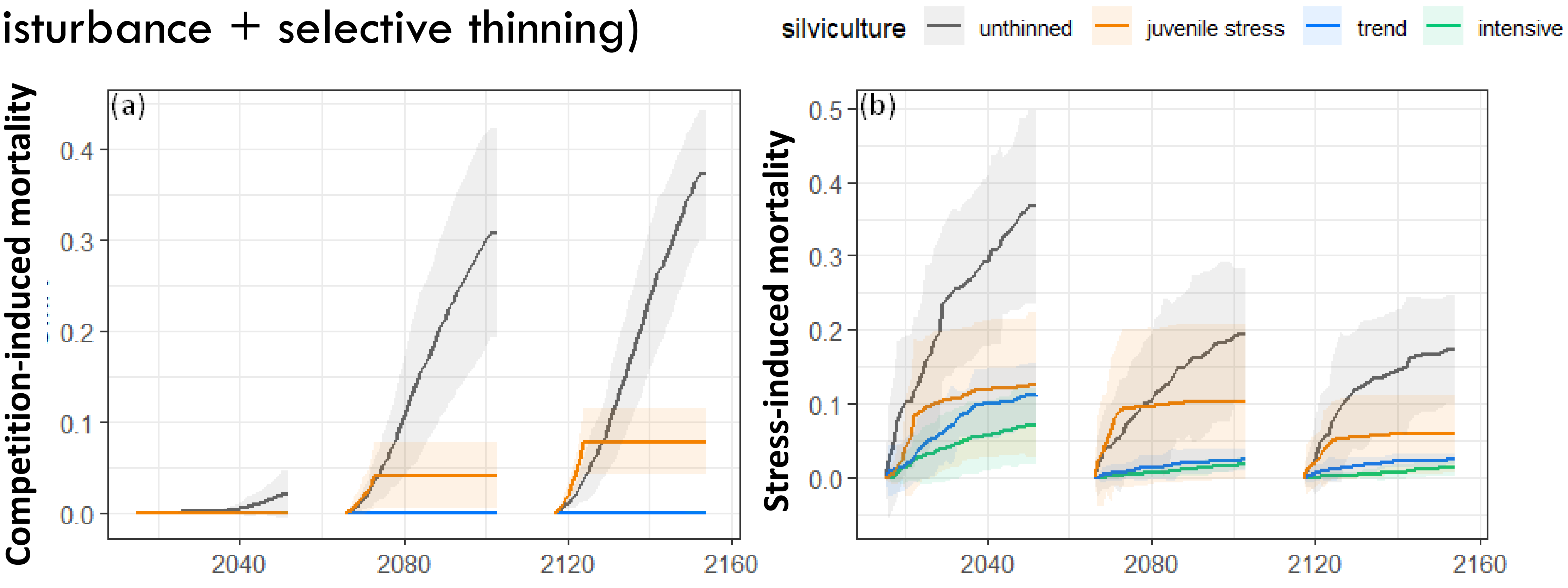


➢ Selective thinning can outperform natural selection.

Fririon et al. in prep

Evolution of vigor and sensitivity

(disturbance + selective thinning)

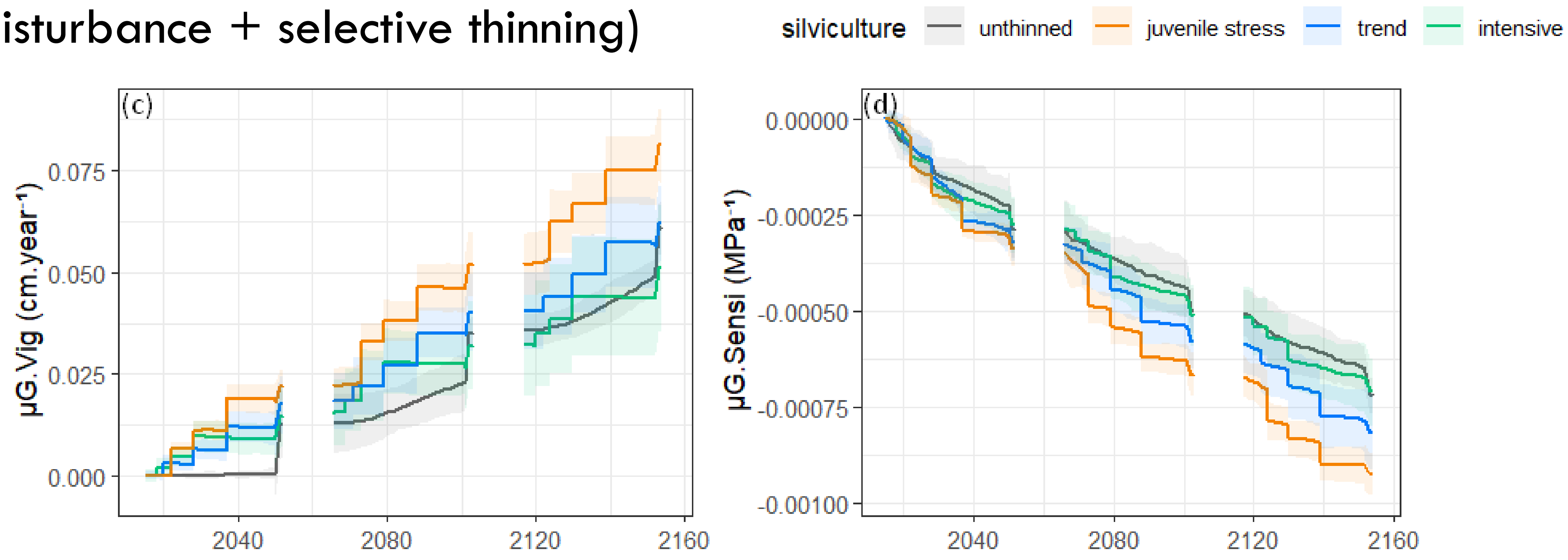


- ➢ Selective thinning can outperform natural selection.
- ➢ Forestry reduce mortality (both competition-induced and stress induced)

Fririon et al. in prep

Evolution of vigor and sensitivity

(disturbance + selective thinning)

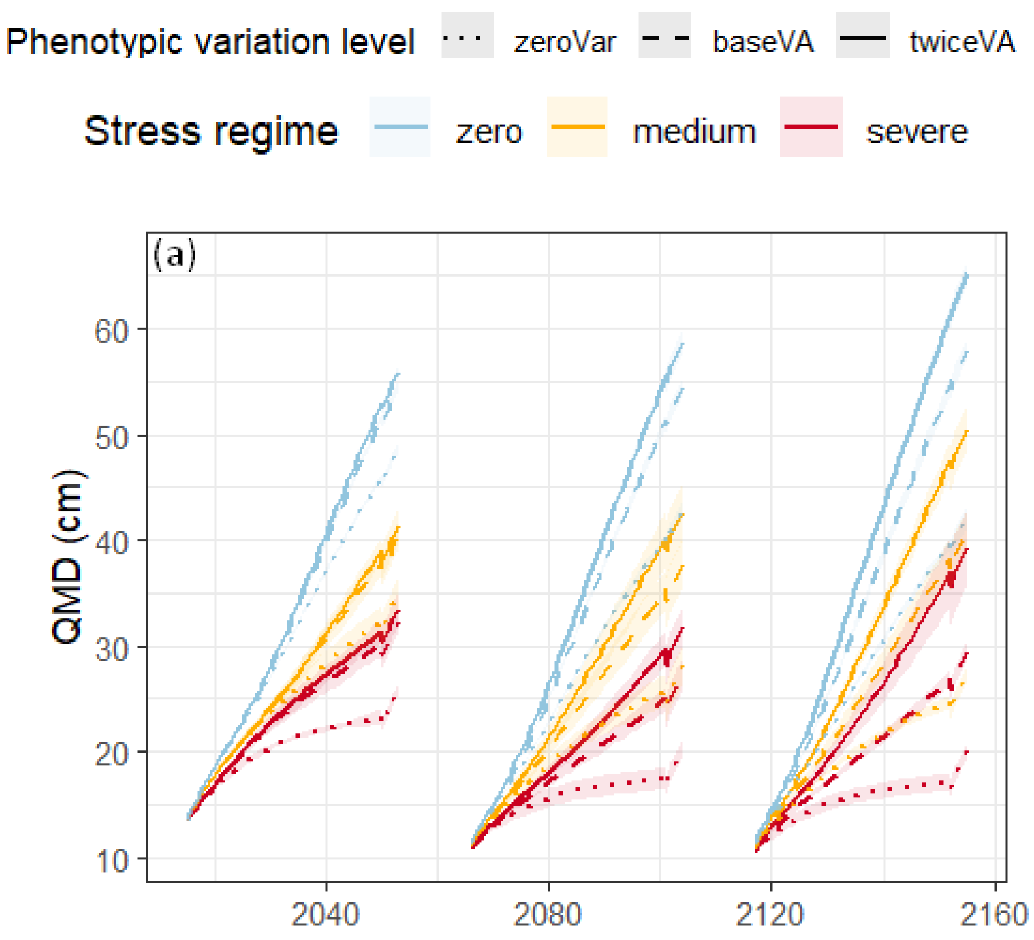


- ➢ Selective thinning can outperform natural selection.
- ➢ More intensive forestry = less genetic evolution :
  - ✓ *Reduced stress = reduced selection pressure*
  - ✓ *Early random thinning = fewer selection opportunities*

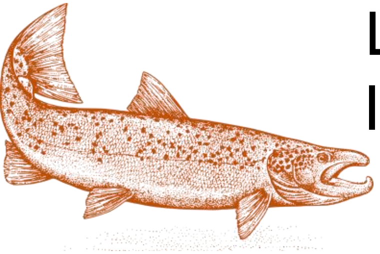
Fririon et al. in prep

Conclusions

- La boucle de rétroaction entre processus démographique (compétition) et évolutif (sélection pour ↗ vigueur) amplifie la vitesse d'évolution
- La sylviculture ↘ la mortalité naturelle sélective due à la compétition et à la sécheresse mais entraine une sélection indirecte sur la vigueur et la sensibilité
- La sélection anthropique peut amener à des taux d'évolution plus élevés que la sélection naturelle seule
- C'est particulièrement vrai quand pas d'éclaircies précoces, pq favorise la sélection naturelle et anthropique
- Intérêt des stratégies sylvicoles axées sur l'évolution



Ce *qu'il faut retenir*:



Les interactions entre dispersion et dynamique éco-évolutive des populations locales affectent la dynamique de la métapopulation et réciproquement

Un modèle intégrant les processus adaptatifs prédit mieux la dynamique d'introgression observée par les gestionnaires

Des éclaircies non sélectives peuvent réduire l'intensité de la sélection naturelle (par exemple sur la vigueur) mais des éclaircies sélectives (sur la taille) peuvent surpasser la sélection naturelle

La selection sexuelle affecte l'évolution mais aussi l'architecture des traits liés à la reproduction

Limites et intérêt des DG-ABMs

- ➢Modèles complexes intégrant différentes formes de connaissances (empiriques, mécanistes, généralistes), processus, échelles…
- ➢La validation est un défi conceptuel et technique (données)

Limites et intérêt des DG-ABMs

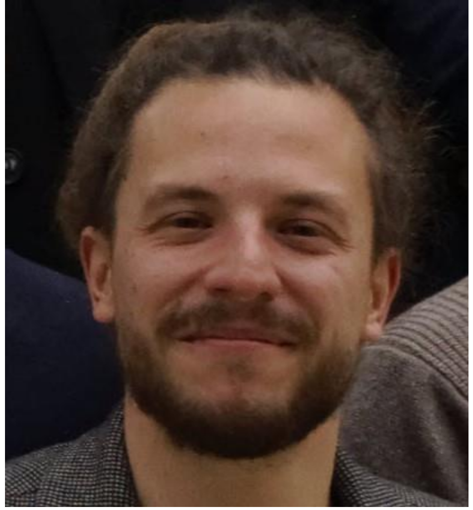
- Modèles complexes intégrant différentes formes de connaissances (empiriques, mécanistes, généralistes), processus, échelles…
- La validation est un défi conceptuel et technique (données)

- Permet de capturer les effets émergeant des interactions individuelles (bottom up)
- Bénéficie de l'existence de plateformes (CAPSIS), de communautés (ABMs), de BDD
- Outil pour identifier de nouveaux fronts de sciences, pour favoriser l'interdisciplinarité, pour explorer des « solutions fondées sur la nature »
- Outil de dialogue avec les autres acteurs de la gestion (ONF, OFB…)

Capsis4
Capsis
Computer-aided projection of strategies in silviculture

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

Amaia Lamarins



Victor Fririon

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Thèses

Chevalier, Louise (2021) Co-évolution des traits et du génome sous l'effet de la sélection sexuelle : la démo-génétique rencontre l'écologie comportementale. Thèse de Université de Pau et des Pays de l'Adour

Fririon, Victor (2022) Vulnérabilité des forêts face aux perturbations climatiques, une approche par simulation démo-génétique pour raisonner des stratégies de gestion adaptative du cèdre et du sapin douglas. Thèse de Université de Montpellier

Lamarins, Amaia (2022) Adaptation, persistence and management of Atlantic salmon in a metapopulation context Thèse de Université de Pau et des Pays de l'Adour.

Folio, Dorinda (2022) Evolutionary management of brown trout intraspecific diversity. Thèse de Université de Pau et des Pays de l'Adour.