

Modeling the genotype ~ environment relationship in a climate change context

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LECA Laboratoire d'Ecologie Alpine

Genotype-environment association (GEA): the basics

Pop	SNP1	SNP2	SNP3	…
1	0.78	1	0.20	…
2	0.75	1	0.22	…
3	0.80	0.95	0.64	…
4	0.60	0.94	0.65	…
5	0.50	0.70	0.70	…
…	…	…	…	

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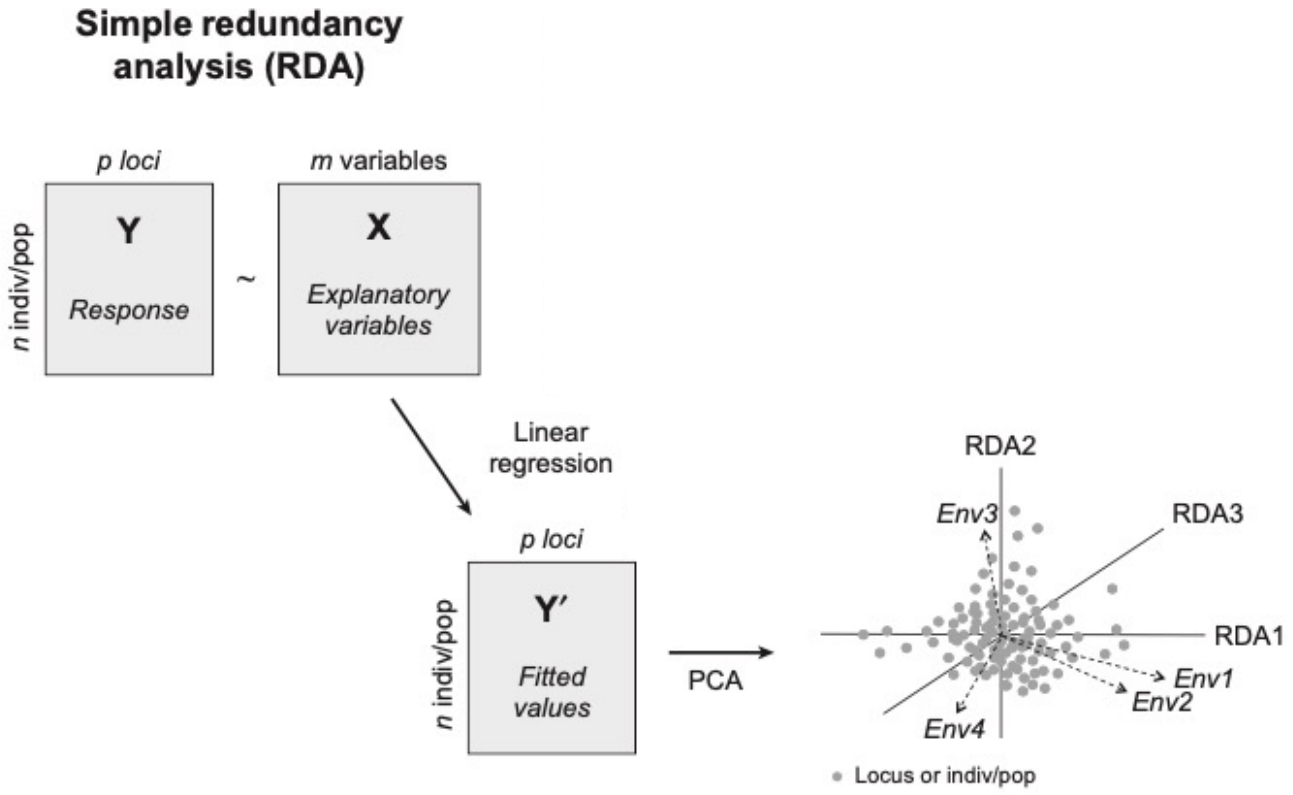
Ind	T°C	Prec	…
1	12	240	…
2	11	210	…
3	12.5	180	…
4	8	150	…
5	9.5	260	…
…	…	…	

Genetic ~ **Environment**

Redundancy analysis (RDA)



Genotype-environment association (GEA): confounding factors

Pop	SNP1	SNP2	SNP3	…
1	0.78	1	0.20	…
2	0.75	1	0.22	…
3	0.80	0.95	0.64	…
4	0.60	0.94	0.65	…
5	0.50	0.70	0.70	…
…	…	…	…	

~

Ind	T°C	Prec	…
1	12	240	…
2	11	210	…
3	12.5	180	…
4	8	150	…
5	9.5	260	…
…	…	…	

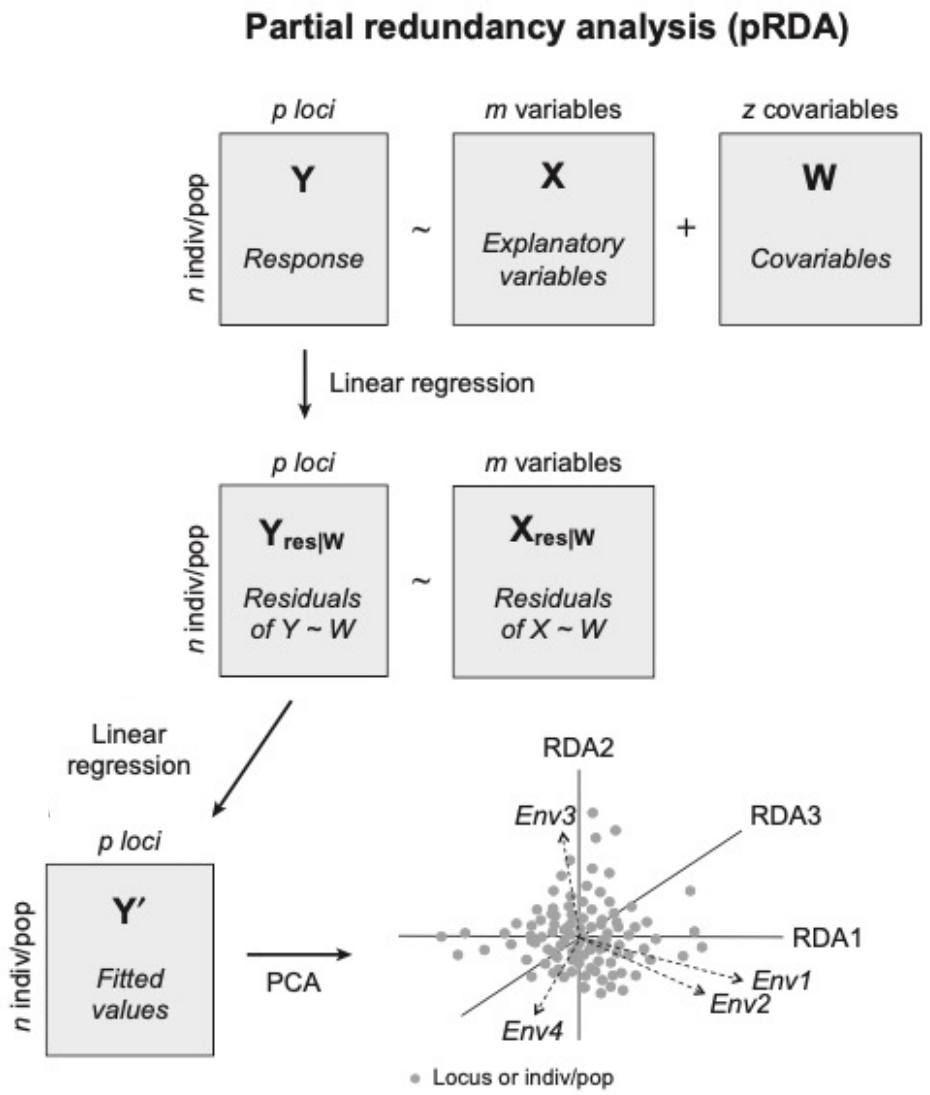
+

Ind	X	Y	…
1	6.3	45.12	…
2	6.4	46.3	…
3	5.8	45.2	…
4	6	47.8	…
5	5.7	44.6	…
…	…	…	

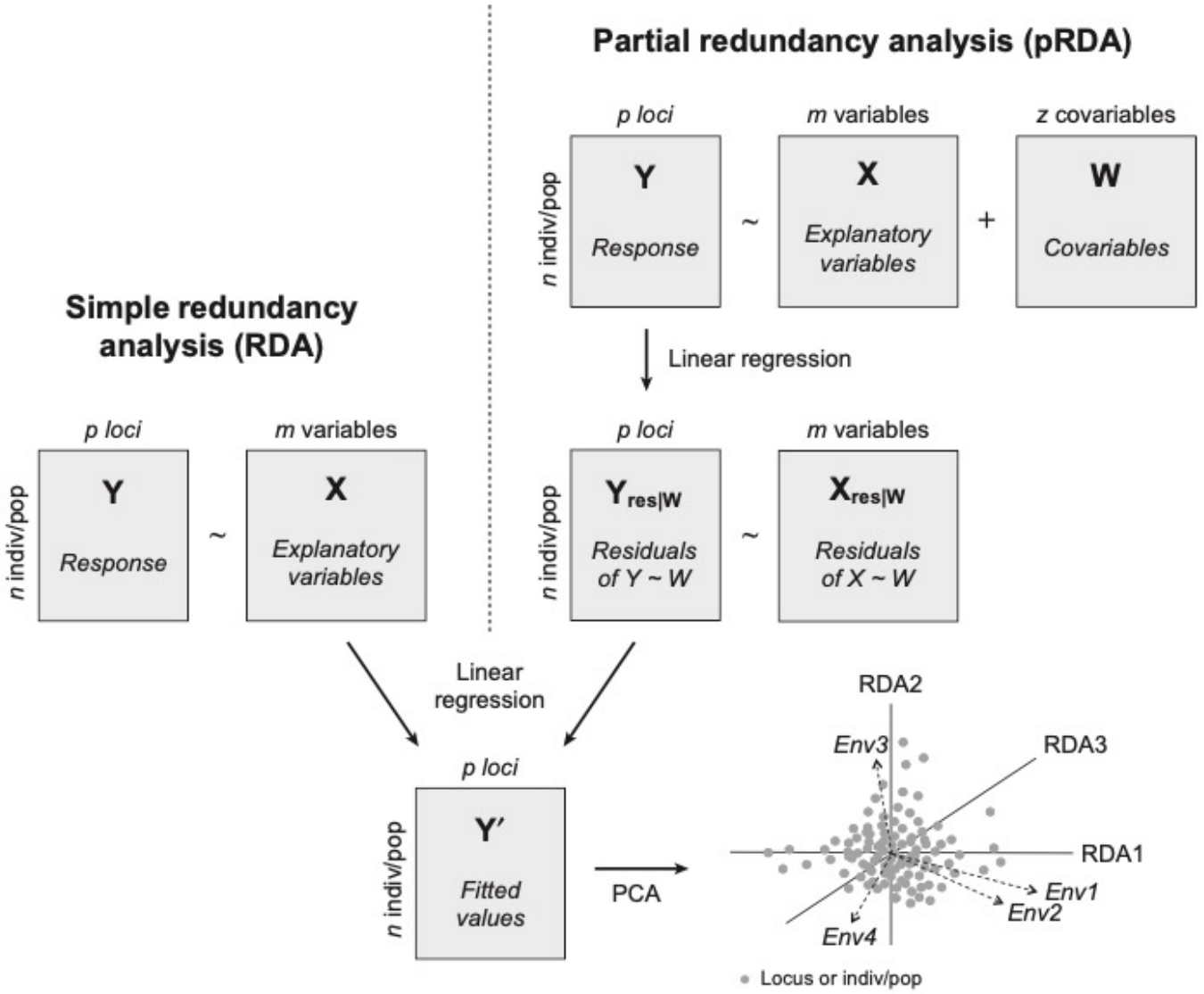
Genetic ~ **Environment** + **Confounding factors**

(e.g., Geography, demography…)

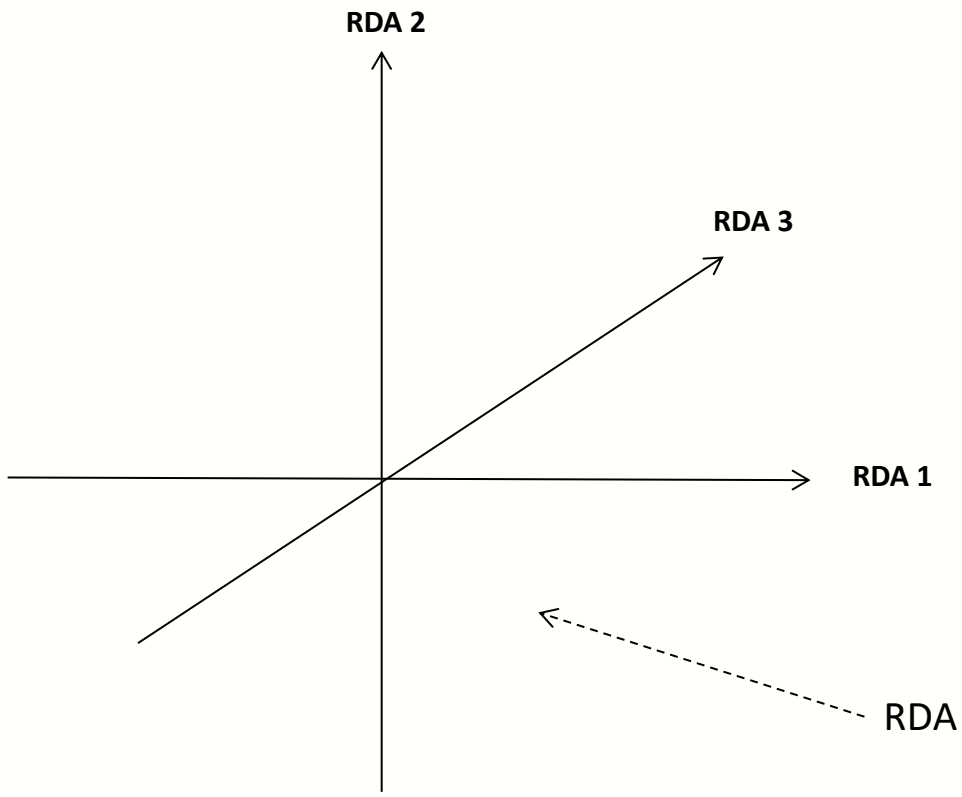
Partial redundancy analysis (pRDA)



Two ways of conducting redundancy analysis (RDA)

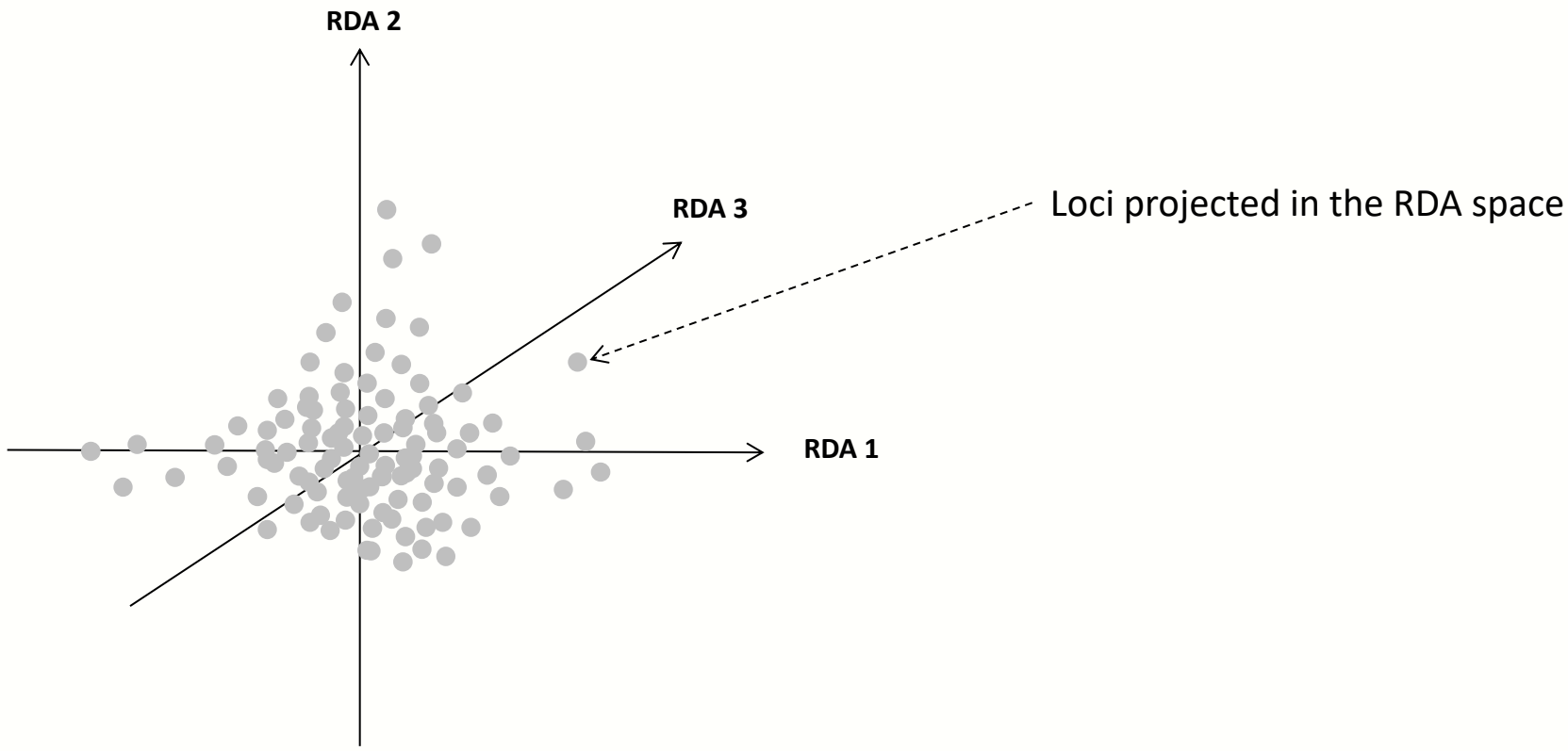


The outputs of redundancy analysis (RDA): a new space

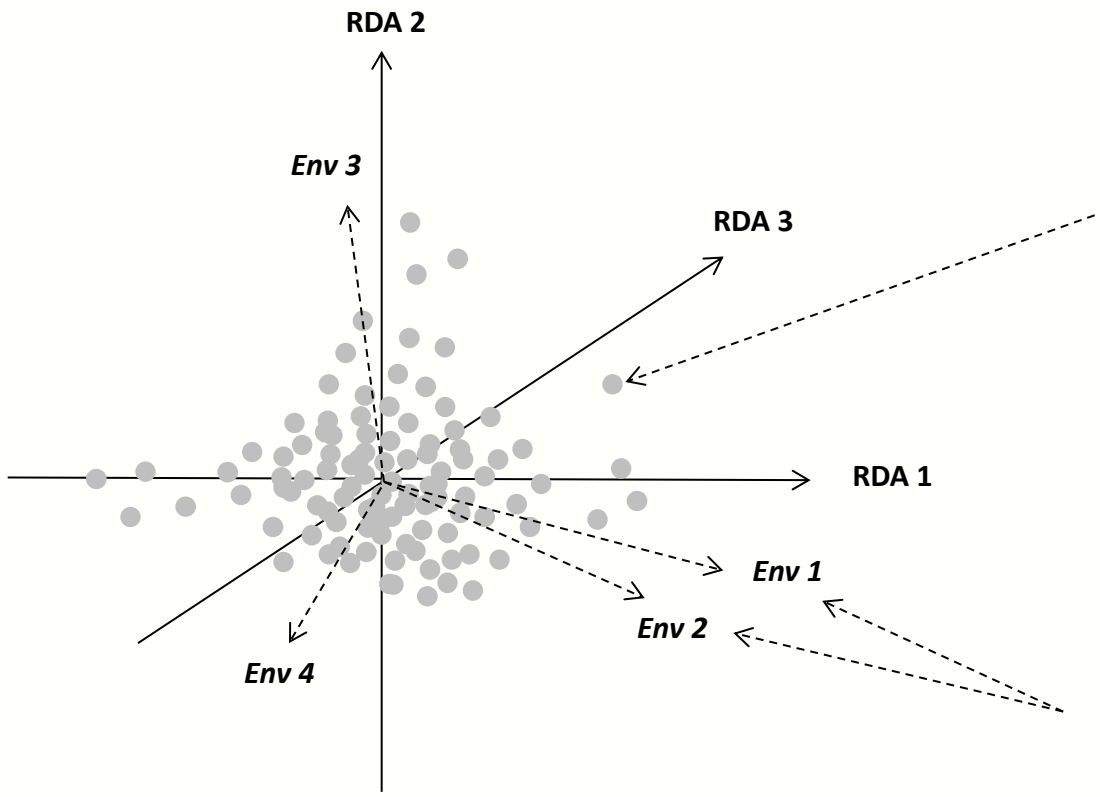


RDA space constrained by the environmental variables

The outputs of redundancy analysis (RDA): loci



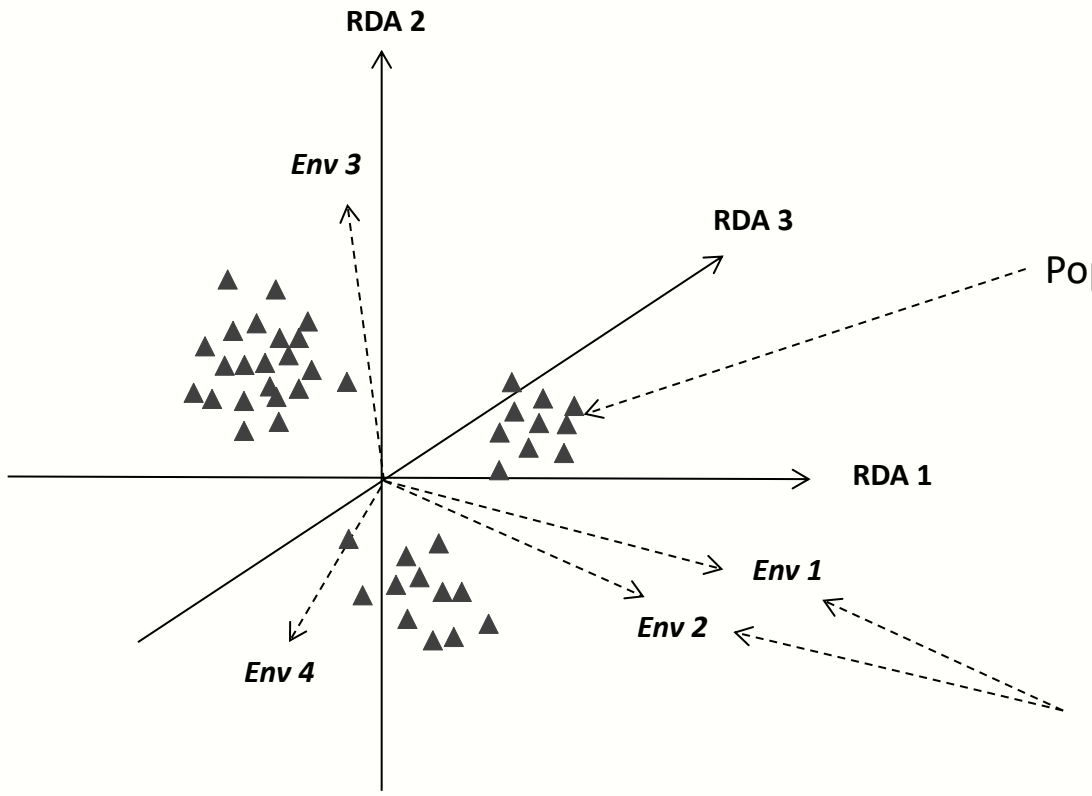
The outputs of redundancy analysis (RDA): predictors



Loci projected in the RDA space

Projection of the environmental variables in the RDA space

The outputs of redundancy analysis (RDA): sites/populations



Populations projected in the RDA space

Projection of the environmental variables in the RDA space

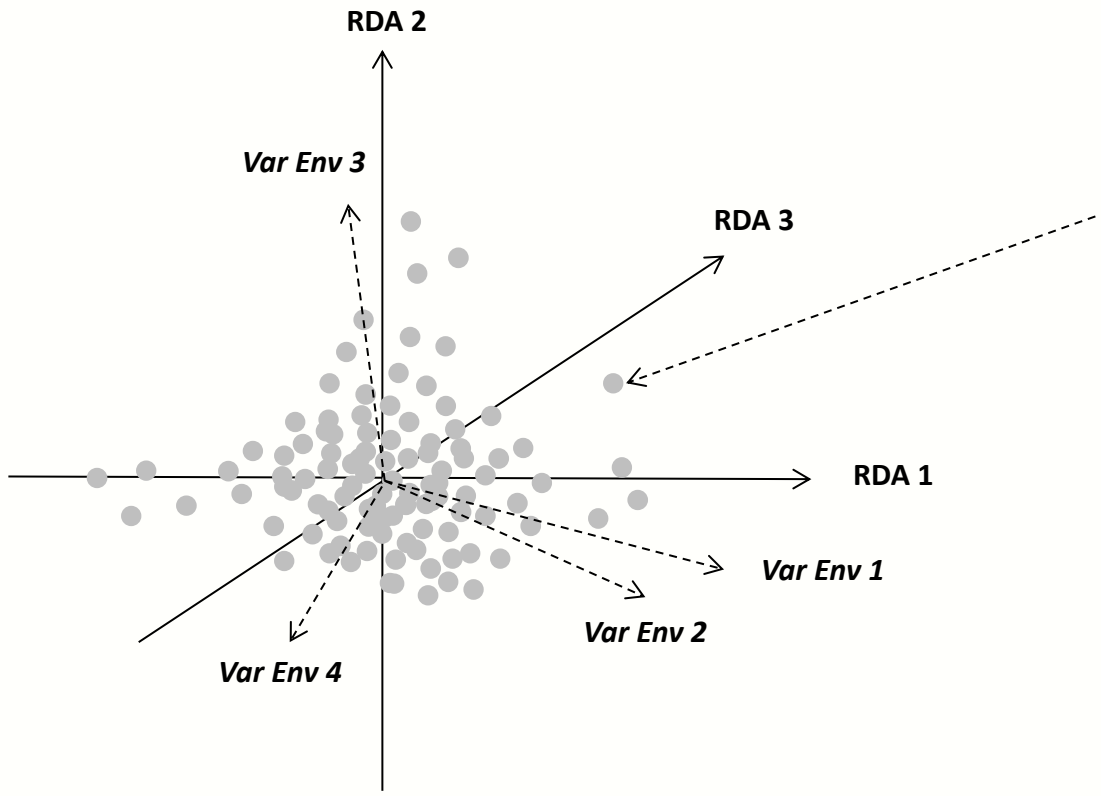
Identifying the adaptive genetic component

Identifying the adaptive genetic component

Lodgepole pine *(Pinus contorta)*

Identifying the adaptive genetic component

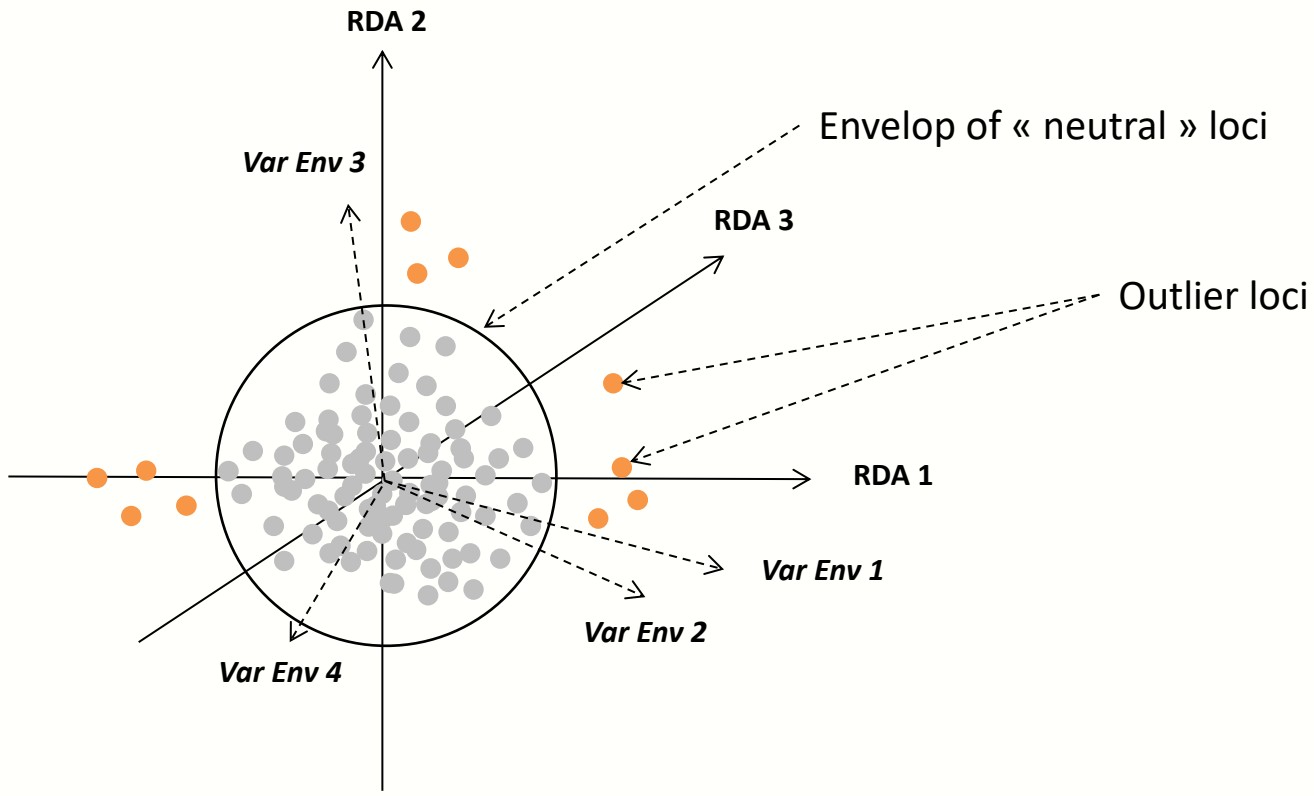
Lodgepole pine *(Pinus contorta)*



Loci projected in the RDA space

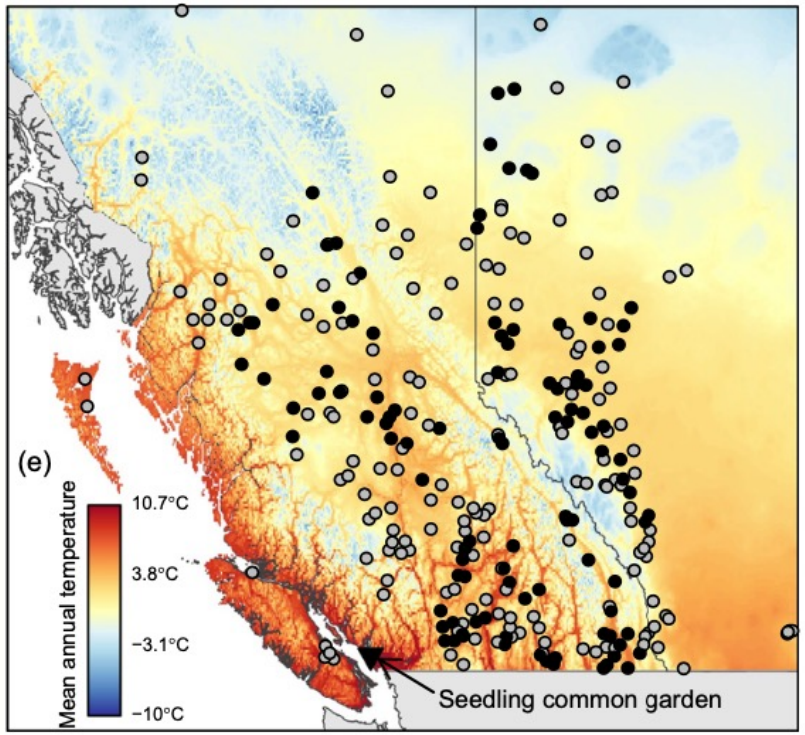
Identifying the adaptive genetic component

Lodgepole pine *(Pinus contorta)*



Capblancq *et al.* (2018). Evaluation of redundancy analysis to identify signatures of local adaptation. *Molecular Ecology Resources*

Estimating population (mal)adaptation to future climates



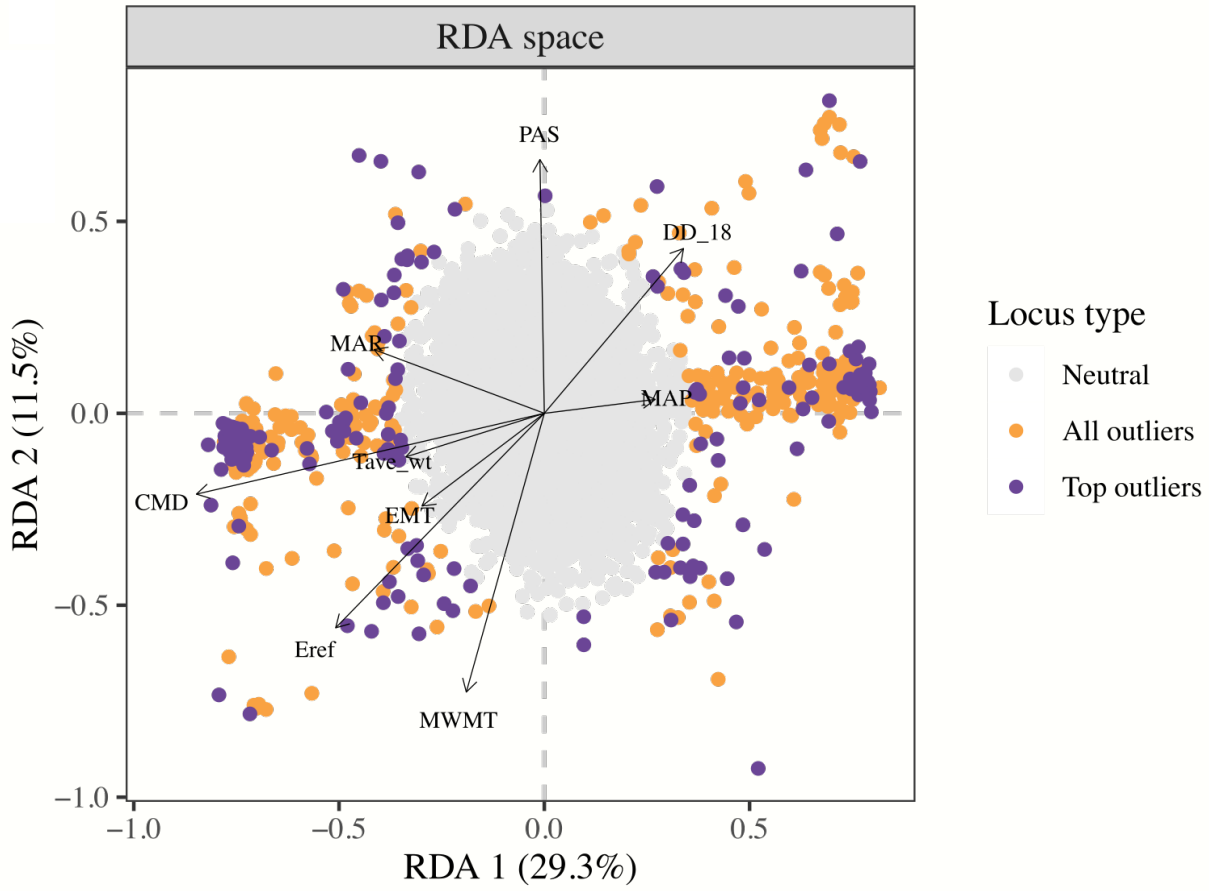
Mahony *et al.* (2020). Evaluating genomic data for management of local adaptation in a changing climate: A lodgepole pine case study. *Evolutionary Applications*

Brenna Forester - *US fish and wildlife service*

Capblancq & Forester (2021). Redundancy Analysis (RDA): a Swiss Army knife for landscape genomics. *Methods in Ecology and Evolution*

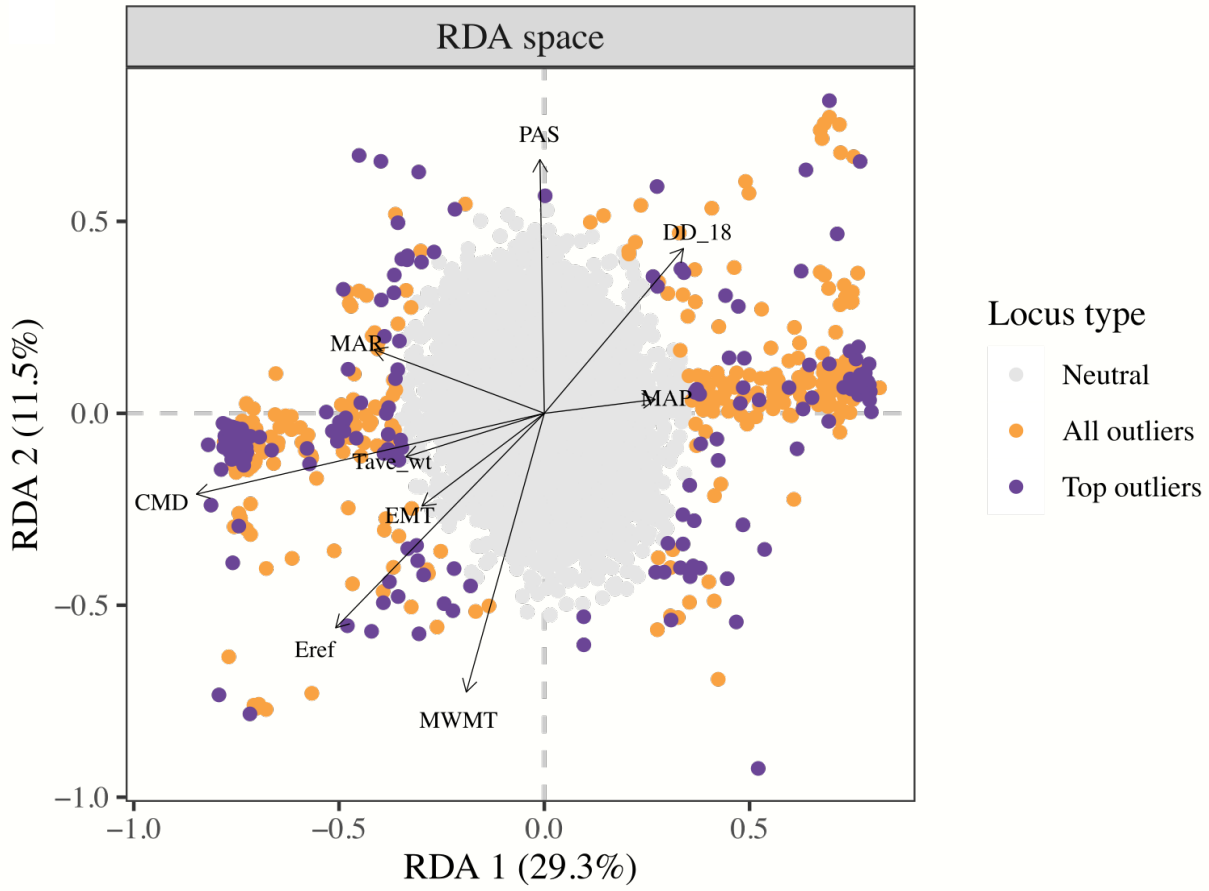
Identifying the adaptive genetic component

Lodgepole pine *(Pinus contorta)*



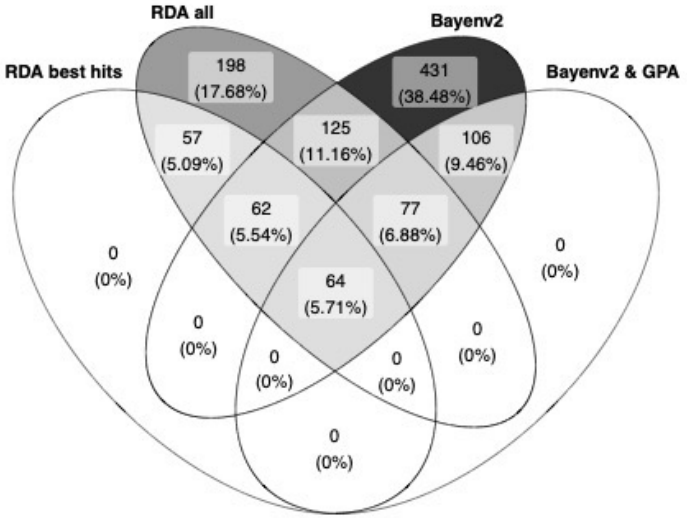
Identifying the adaptive genetic component

Lodgepole pine *(Pinus contorta)*



Locus type

- Neutral
- All outliers
- Top outliers



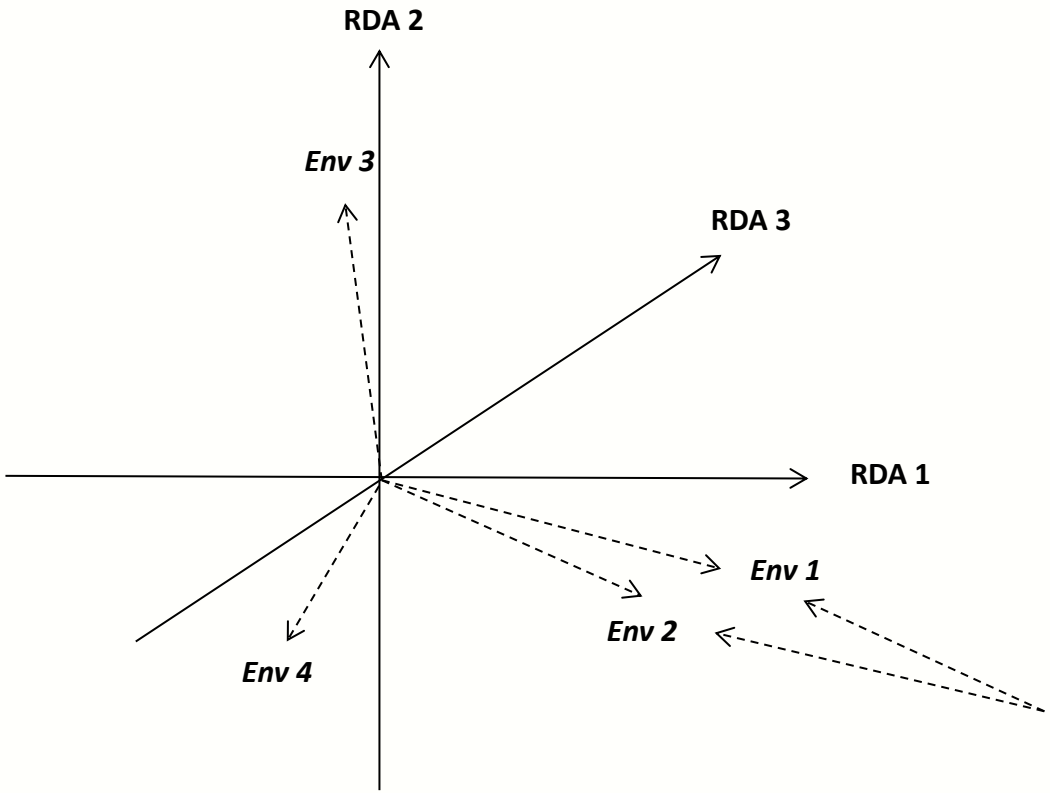
Estimating population (mal)adaptation to future climates

Genetic turnover across the species range

Lodgepole pine *(Pinus contorta)*

Genetic turnover across the species range

Lodgepole pine *(Pinus contorta)*

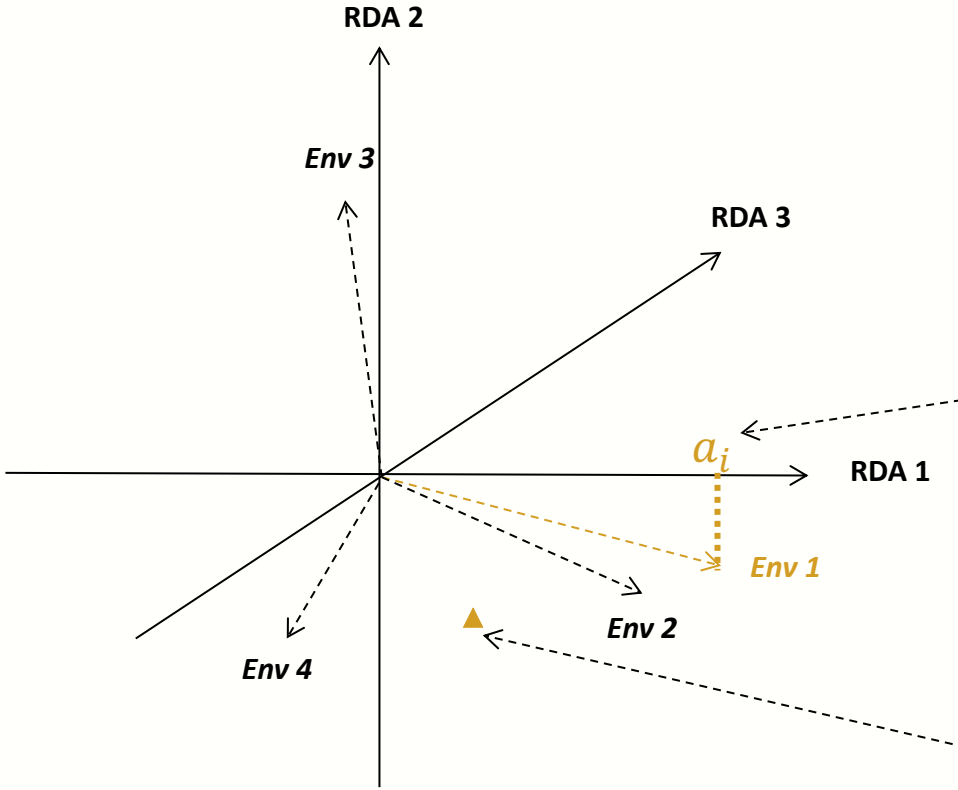


Projection of the environmental variables in the RDA space

Steane et al. (2014). Genome-wide scans detect adaptation to aridity in a widespread forest tree species. *Molecular Ecology*

Genetic turnover across the species range

Lodgepole pine *(Pinus contorta)*



$$\boldsymbol{Adaptive\ index} = \sum_{i=1}^{n} \boldsymbol{a_i b_i}$$

a_i : score of climatic variable *i* along the RDA axis

b_i : standardized value of climate variable *i* for a focal pixel

Steane et al. (2014). Genome-wide scans detect adaptation to aridity in a widespread forest tree species. *Molecular Ecology*

Genetic turnover across the species range

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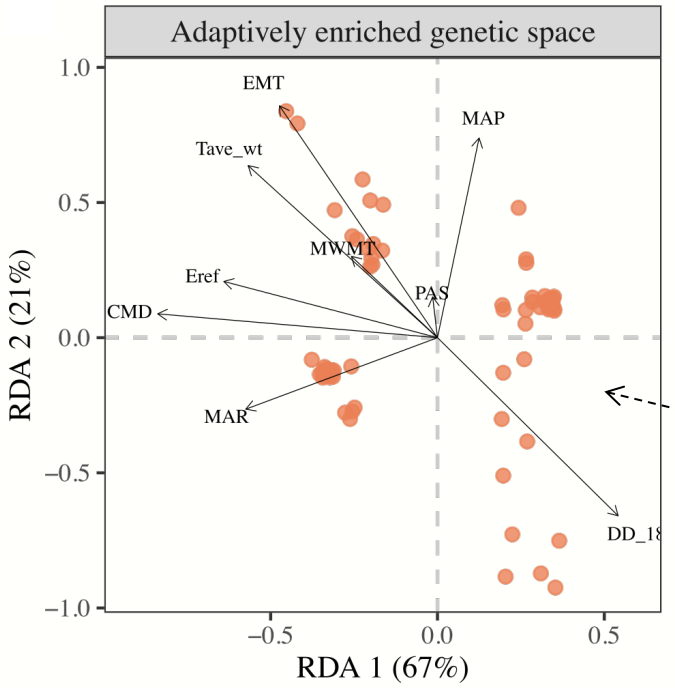
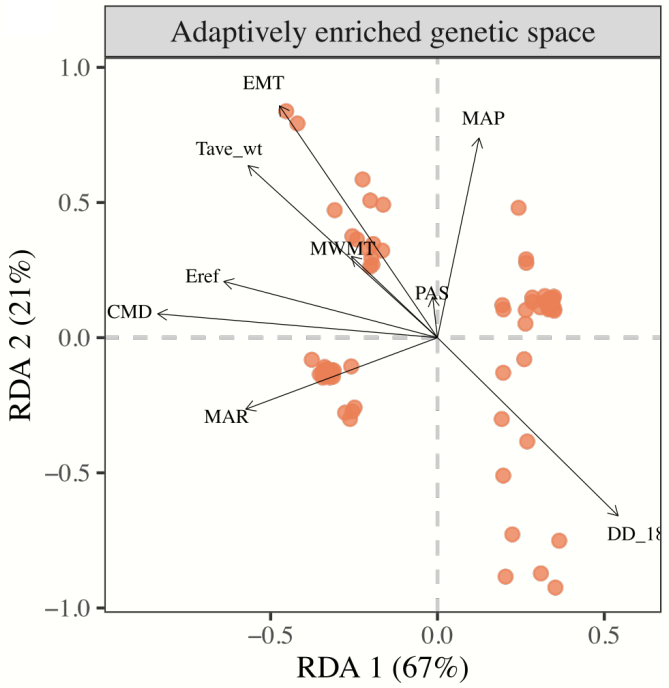


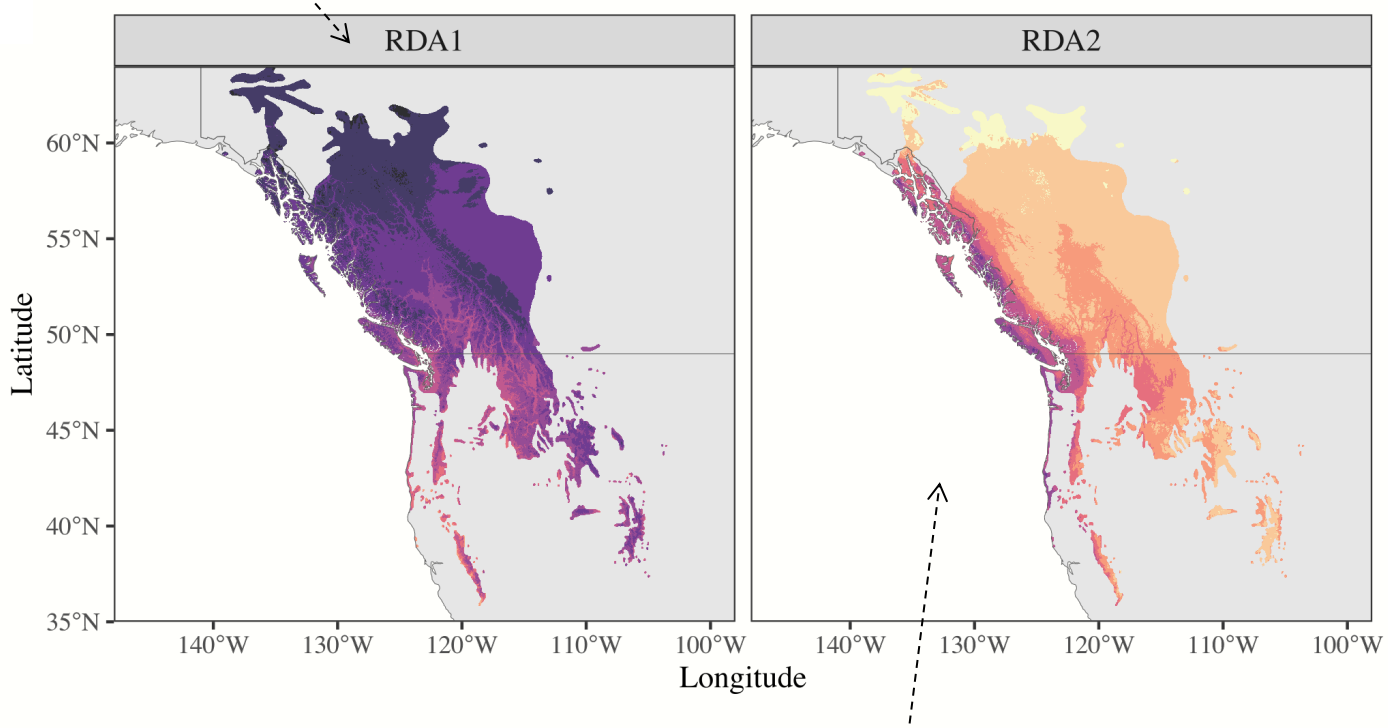
Adaptively enriched RDA space

Genetic turnover across the species range

Lodgepole pine *(Pinus contorta)*

Main adaptive gradient linked to temperature factors





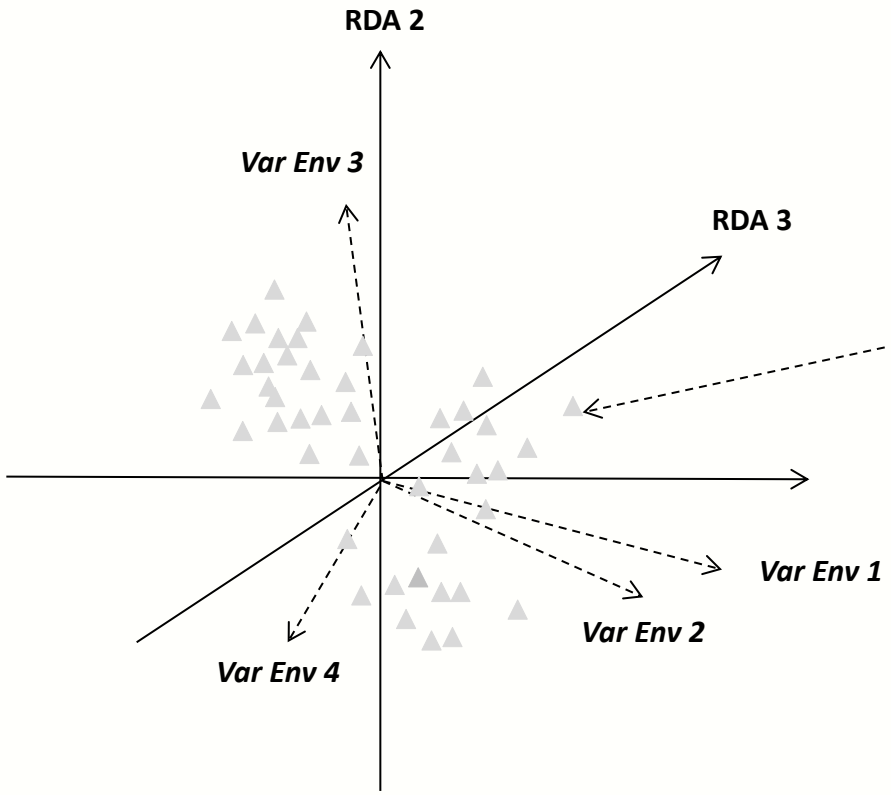
Secondary adaptive gradient linked to precipitation regimes

Genetic mismatch associated with changing climates

Lodgepole pine *(Pinus contorta)*

Genetic mismatch associated with changing climates

Lodgepole pine *(Pinus contorta)*

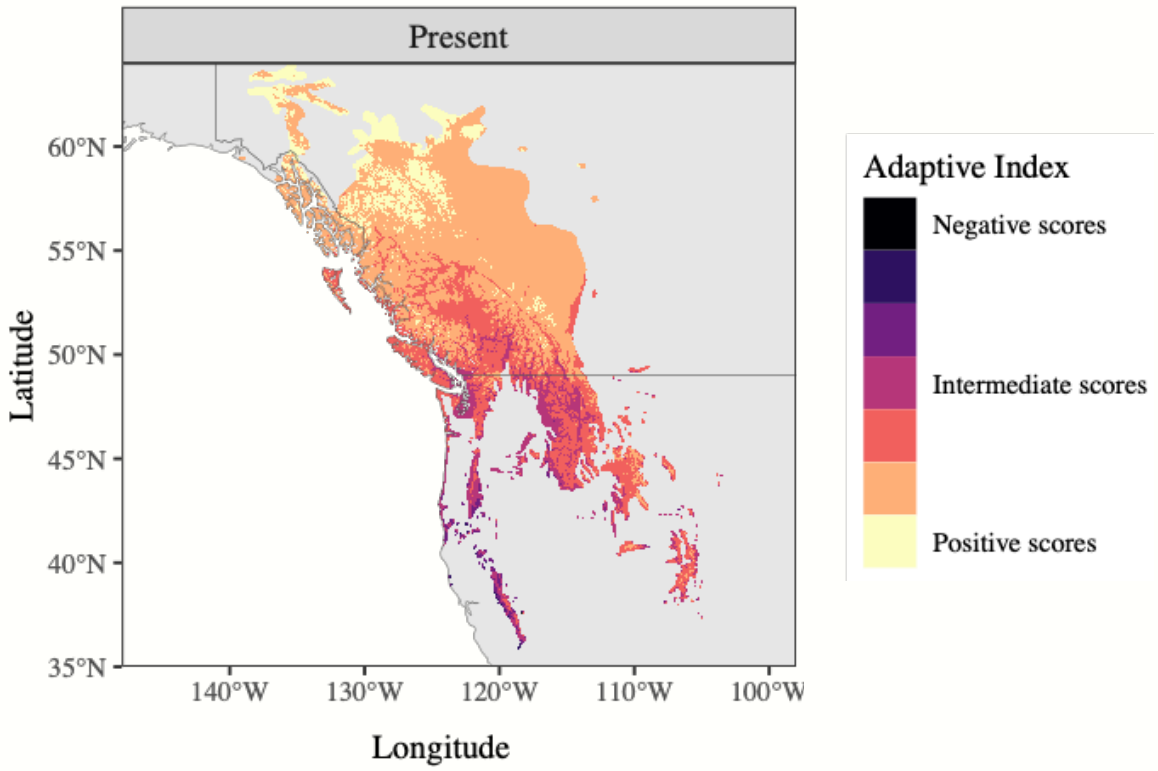


Population position under current climate conditions

Capblancq *et al.* (2020). Climate-associated genetic variation in Fagus sylvatica and potential responses to climate change in the French Alps. *Journal of Evolutionary Biology*

Genetic mismatch associated with changing climates

Lodgepole pine *(Pinus contorta)*



Genetic mismatch associated with changing climates

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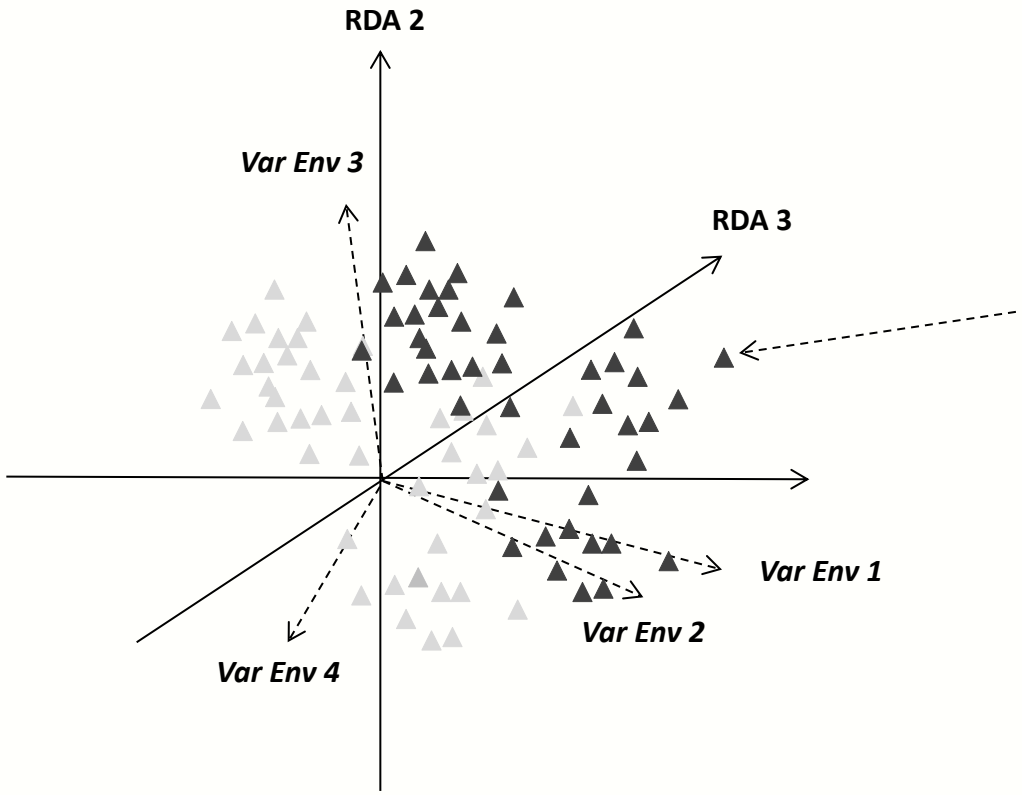

Population position under future climate conditions

Capblancq *et al.* (2020). Climate-associated genetic variation in Fagus sylvatica and potential responses to climate change in the French Alps. *Journal of Evolutionary Biology*

Genetic mismatch associated with changing climates

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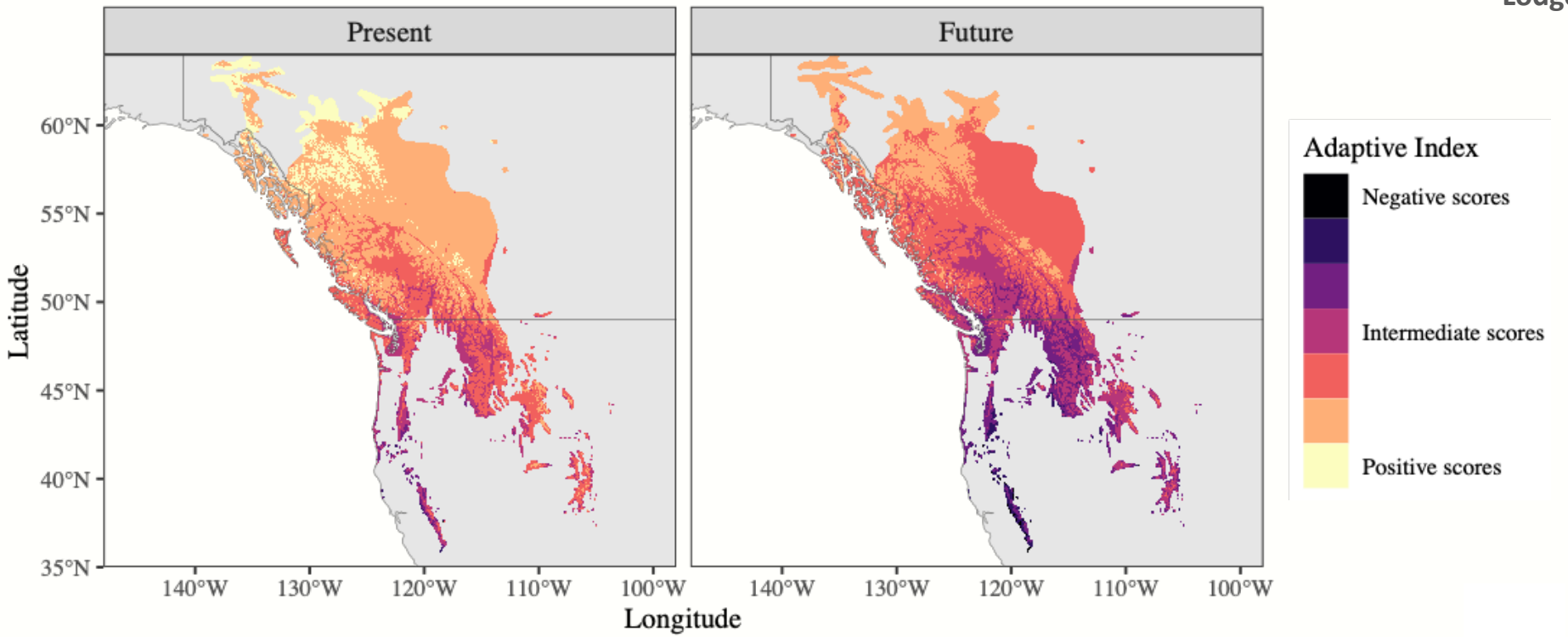

Genetic mismatch associated with changing climates

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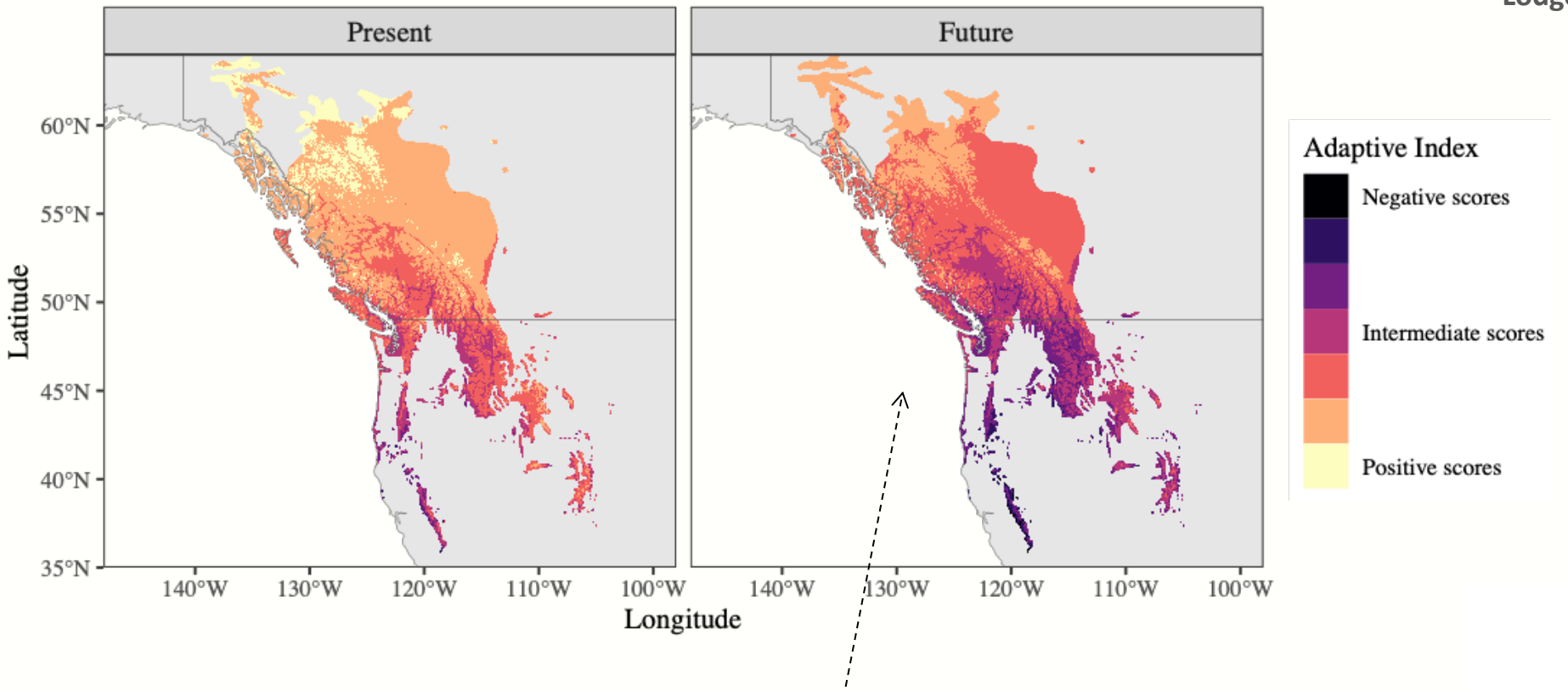

Necessary change in genetic composition to remain optimally adapted to new climates

Genetic mismatch associated with changing climates

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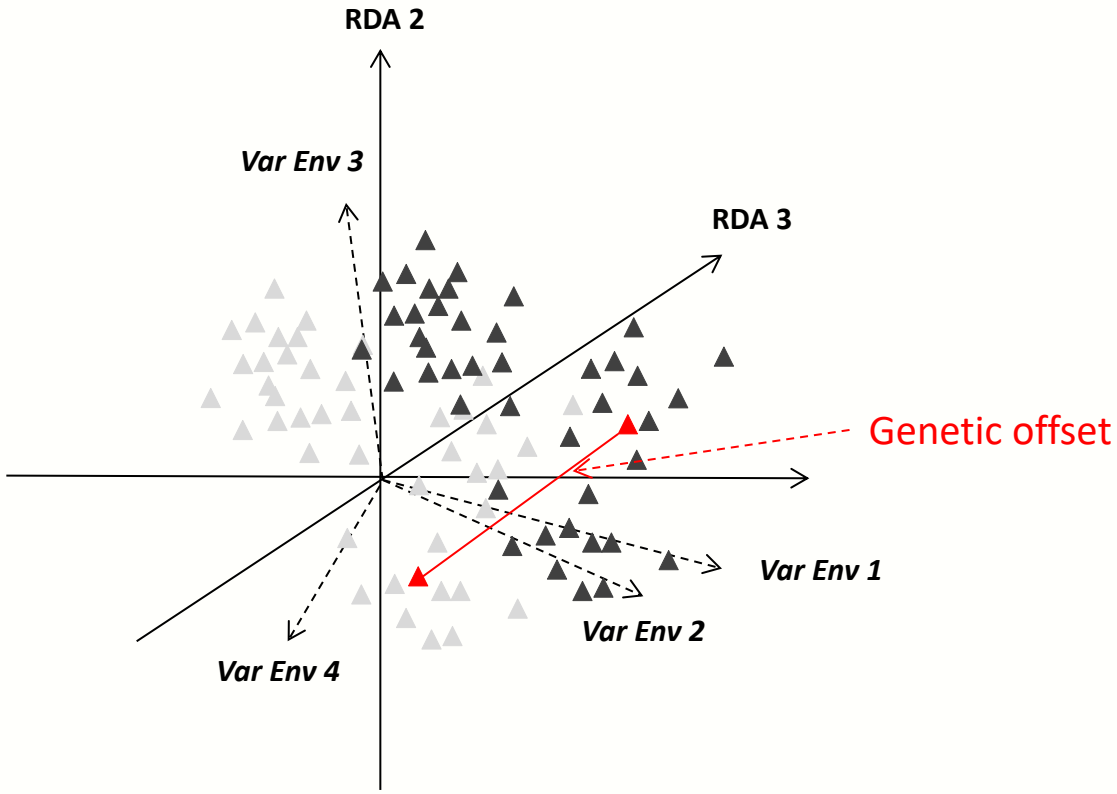

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Genetic mismatch associated with changing climates

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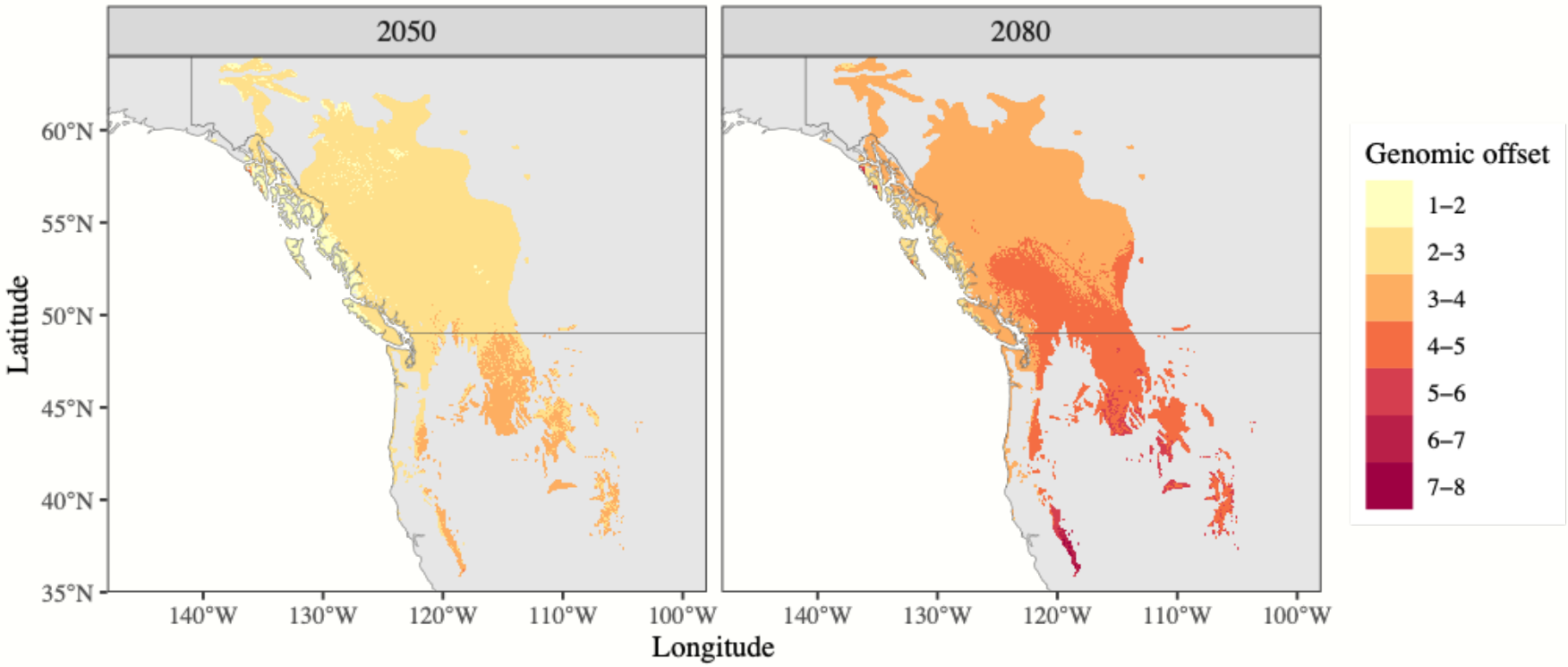
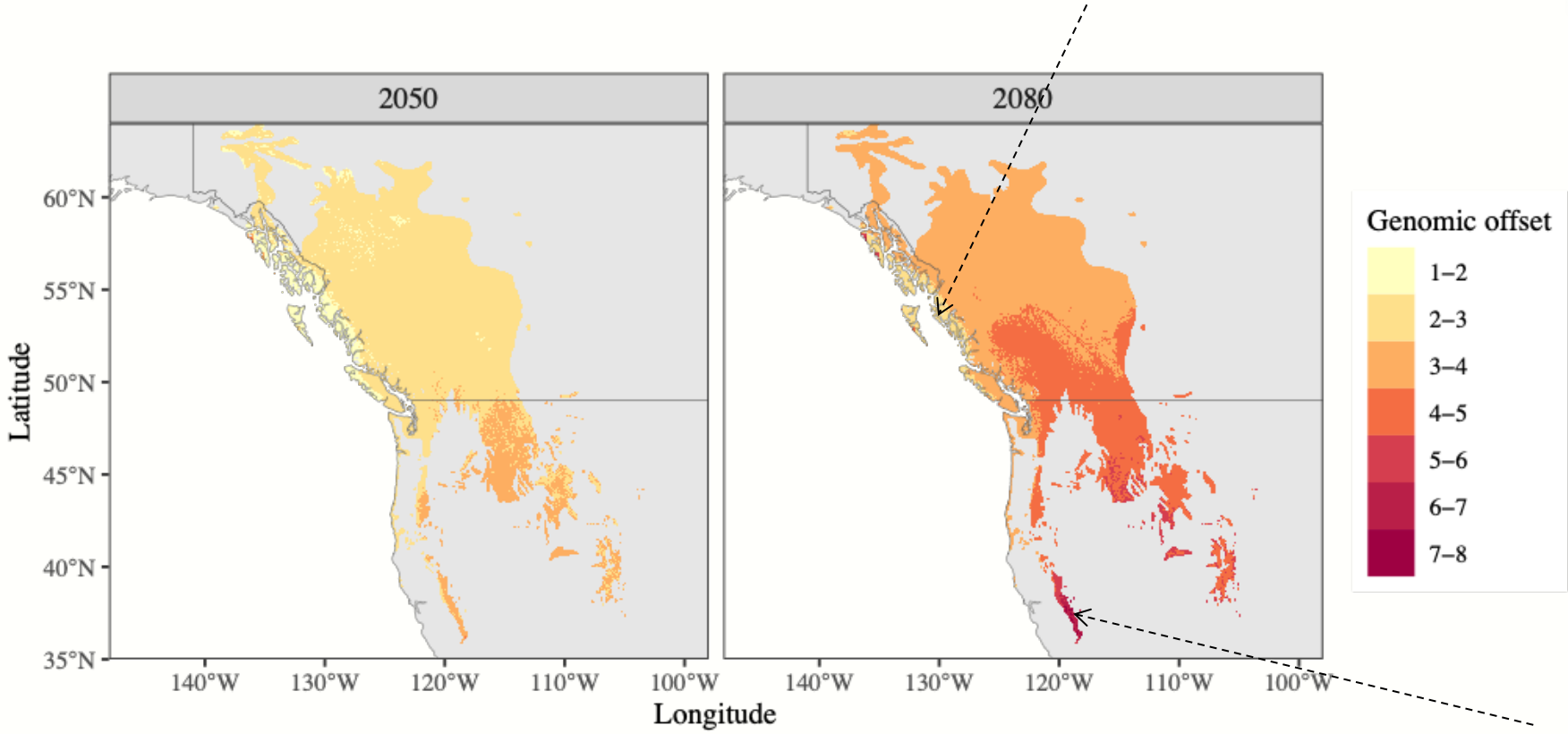


Genetic mismatch associated with changing climates

Lodgepole pine *(Pinus contorta)*

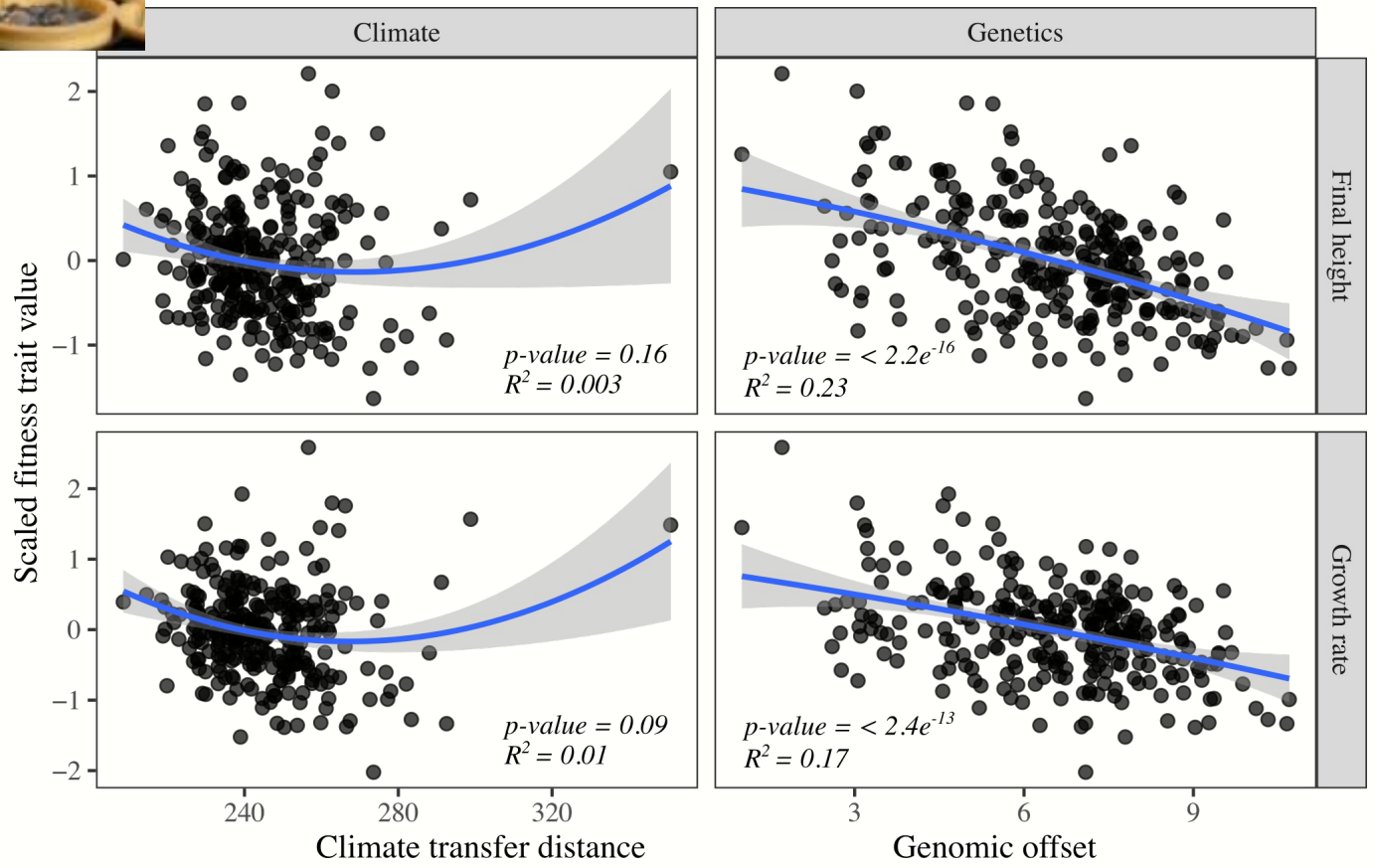
Lower offset on the coast



Higher offset in the Sierras

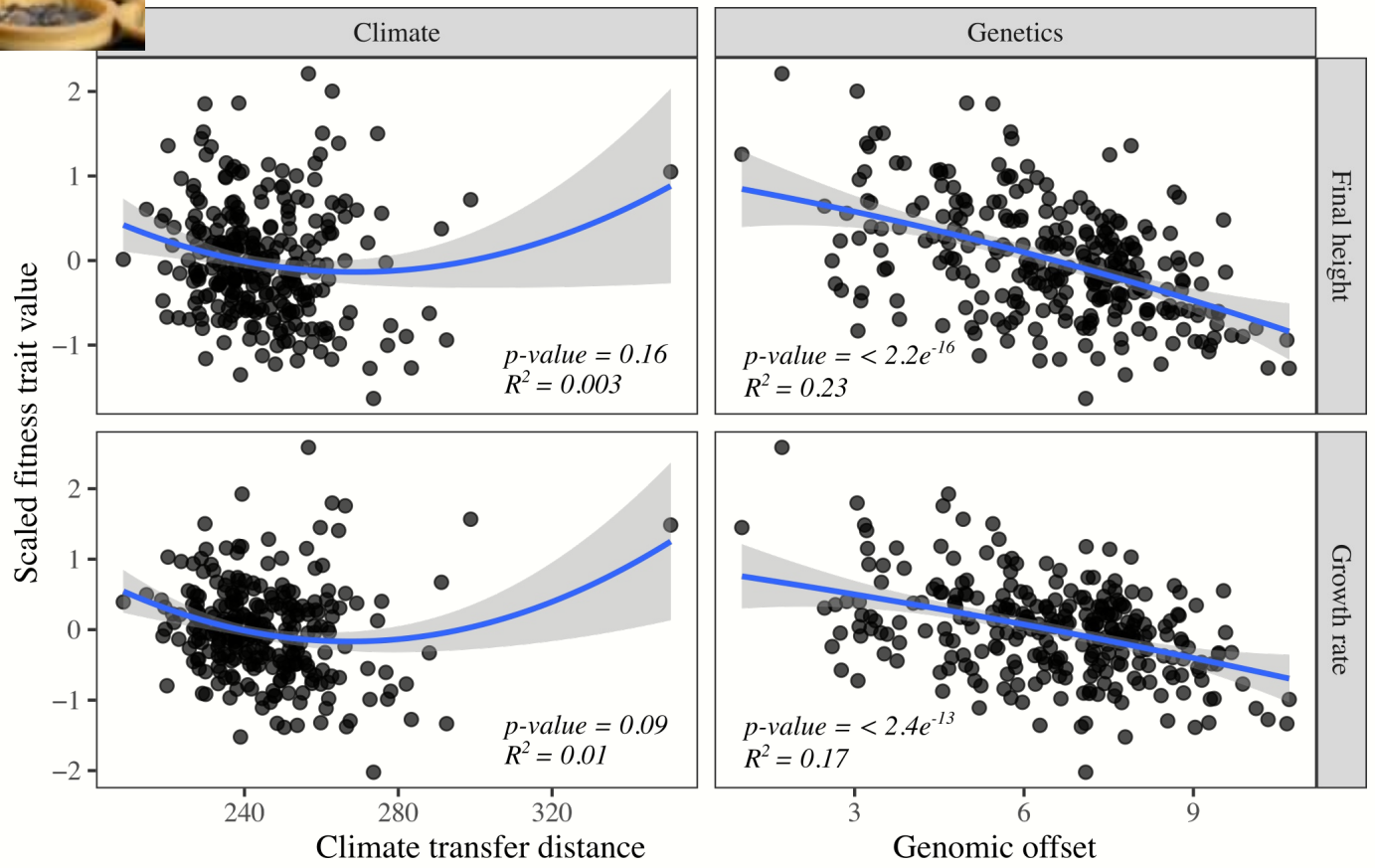
Genetic mismatch associated with changing climates

Lodgepole pine *(Pinus contorta)*



Genetic mismatch associated with changing climates

Lodgepole pine *(Pinus contorta)*

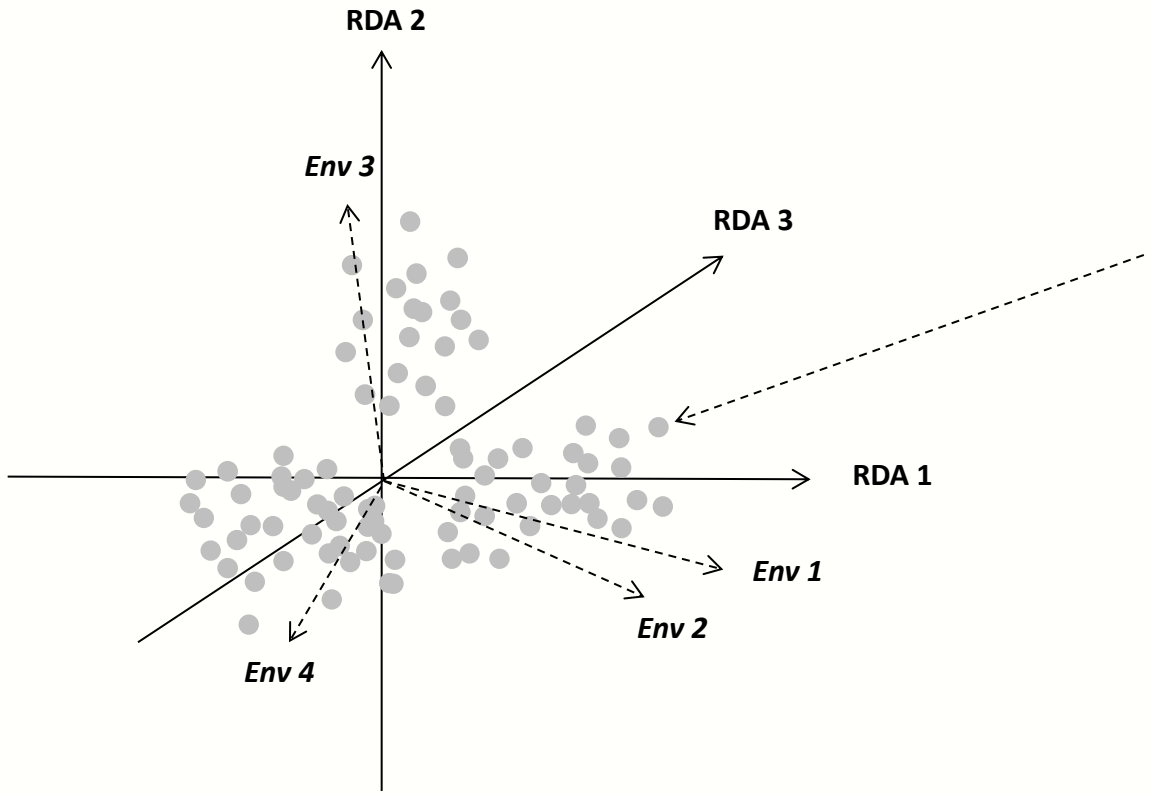


Genomic offset better **explains a decrease in fitness-related traits** than climate transfer distance alone

Identifying modules of covarying adaptive loci

Modules of adaptive genes along environmental gradients

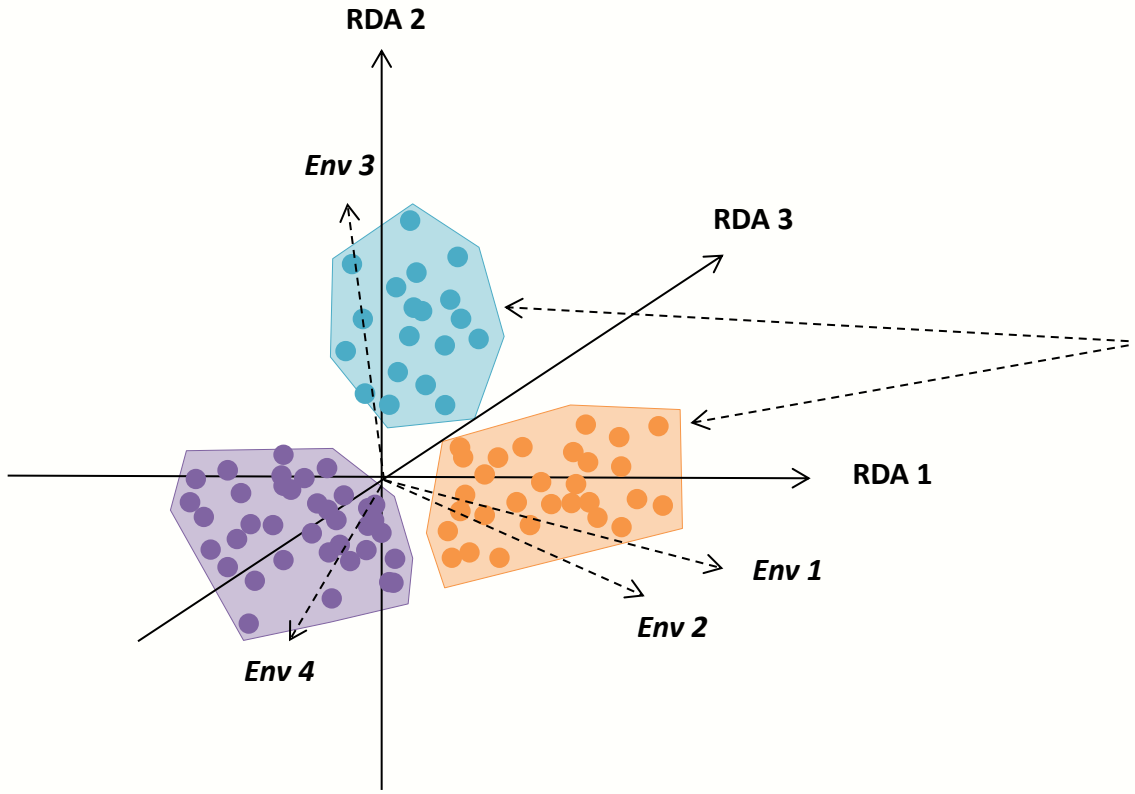
Red spruce *(Picea rubens)*



Adaptive loci projected in the RDA space

Modules of adaptive genes along environmental gradients

Red spruce *(Picea rubens)*



Different “modules” of adaptive loci

Capblancq *et al.* (2022). From common garden to candidate genes: exploring local adaptation to climate in red spruce. *New Phytologist*

Modules of adaptive genes along environmental gradients

Red spruce *(Picea rubens)*

Stephen Keller - *University of Vermont*

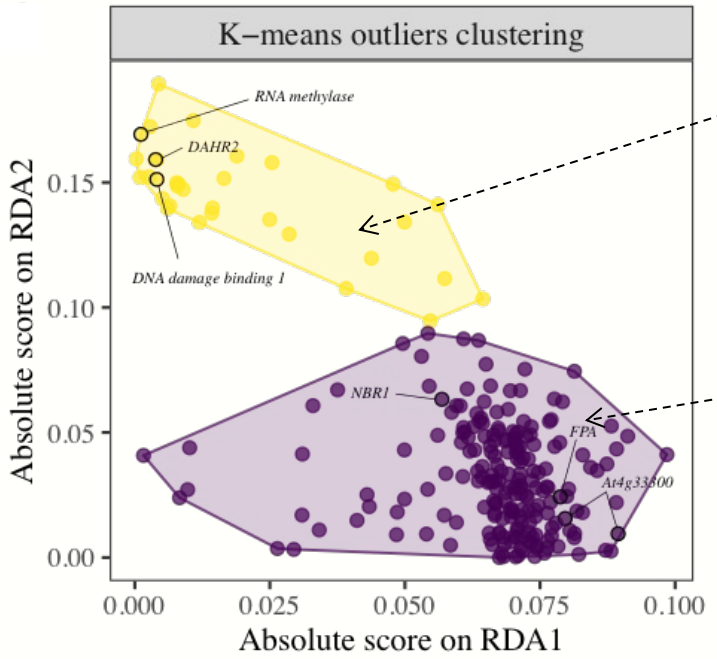
Susanne Lachmuth - *University of Maryland*

Matt Fitzpatrick - *University of Maryland*

Capblancq *et al.* (2022). From common garden to candidate genes: exploring local adaptation to climate in red spruce. *New Phytologist*

Modules of adaptive genes along environmental gradients

Red spruce *(Picea rubens)*

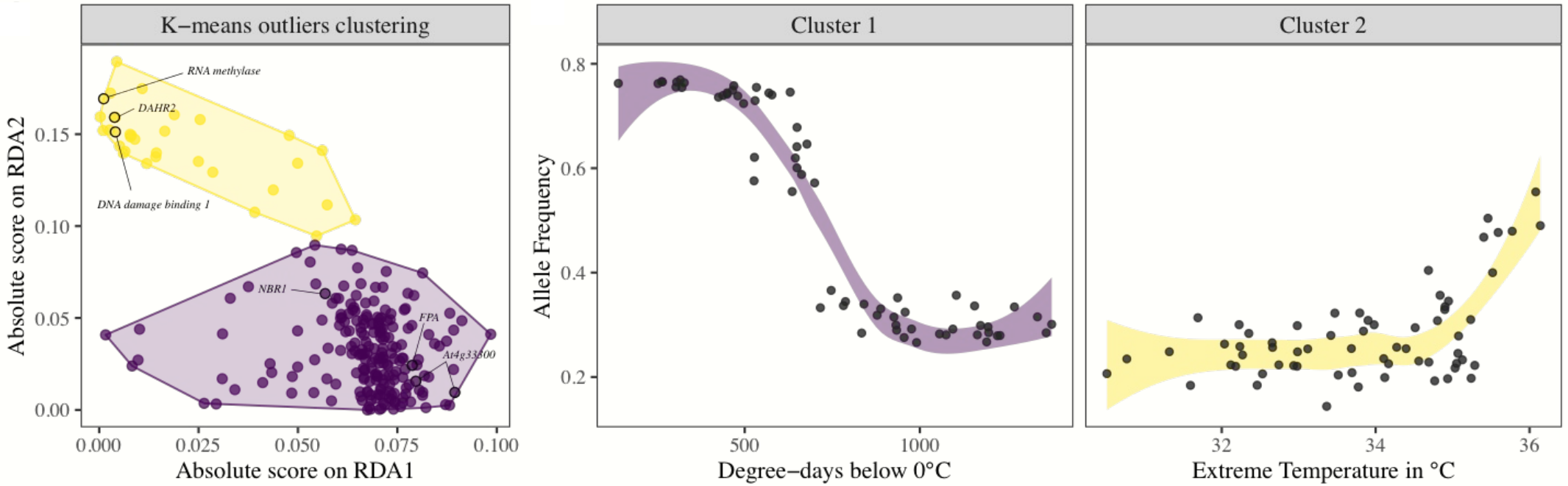


Genes associated with **acute stress response**

Genes associated with **drought, flowering time and pathogen resistance**

Modules of adaptive genes along environmental gradients

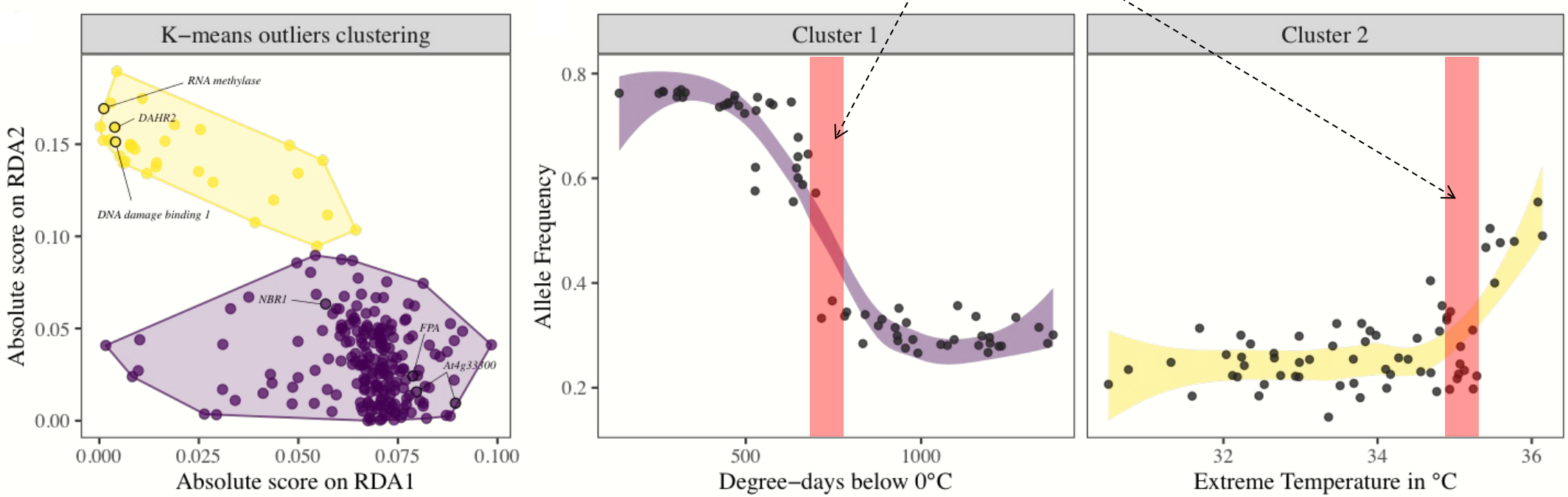
Red spruce *(Picea rubens)*



Modules of adaptive genes along environmental gradients

Red spruce *(Picea rubens)*

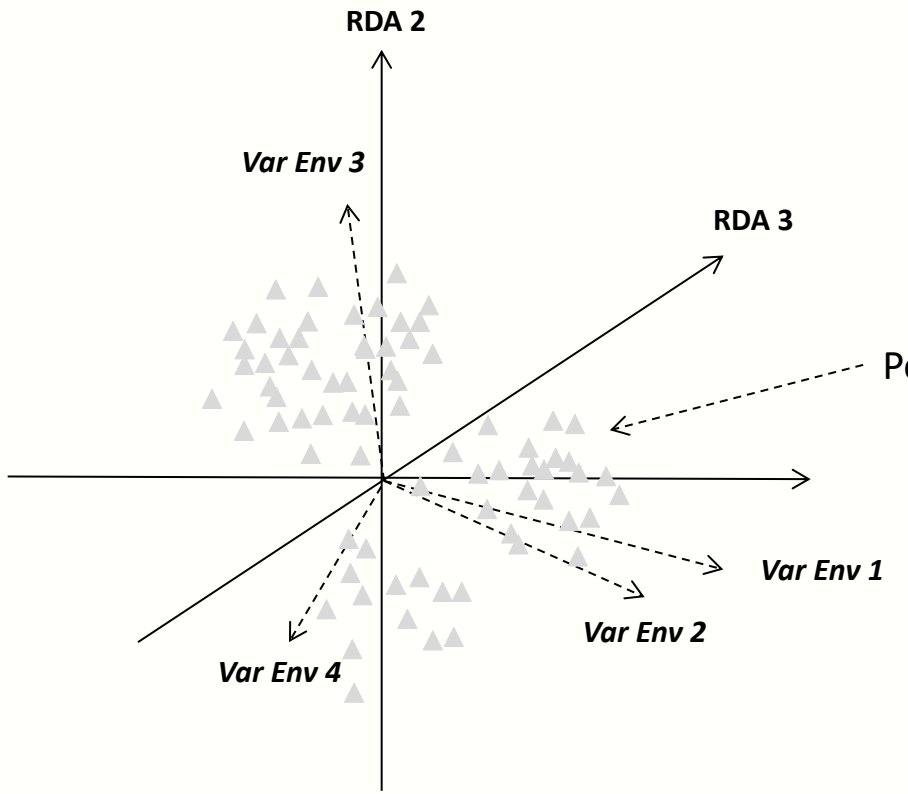
Important **climate thresholds**



Delineating adaptive genetic groups

Delineating adaptive genetic groups

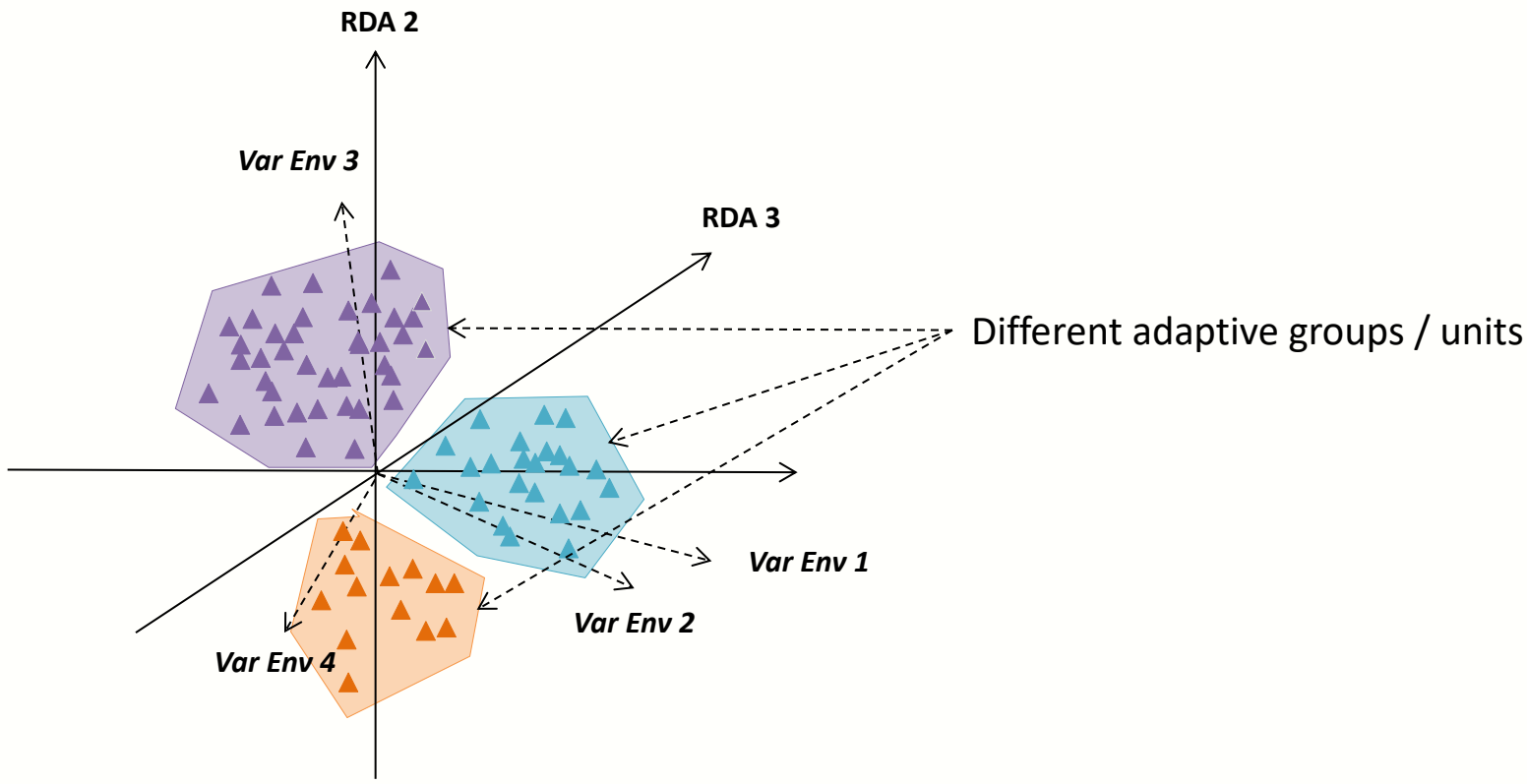
Northern chamois
(Rupicapra rupicapra)



Populations projected in the RDA space

Delineating adaptive genetic groups

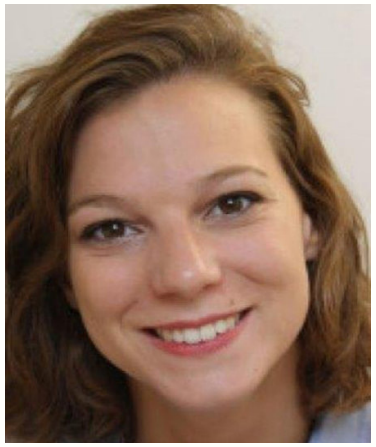
Northern chamois
(Rupicapra rupicapra)



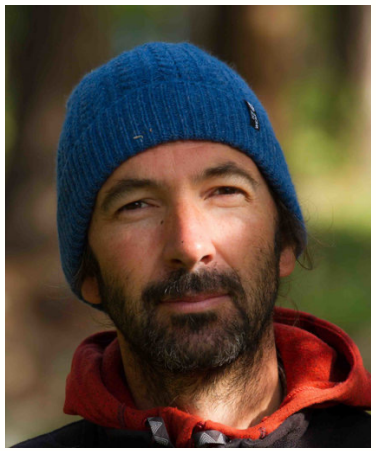
Hoste *et al.* (in review). Delineation of adaptive genetic units in an alpine ungulate: projection of current and future distributions.

Distribution of adaptive genetic groups on the landscape

Northern chamois
(Rupicapra rupicapra)



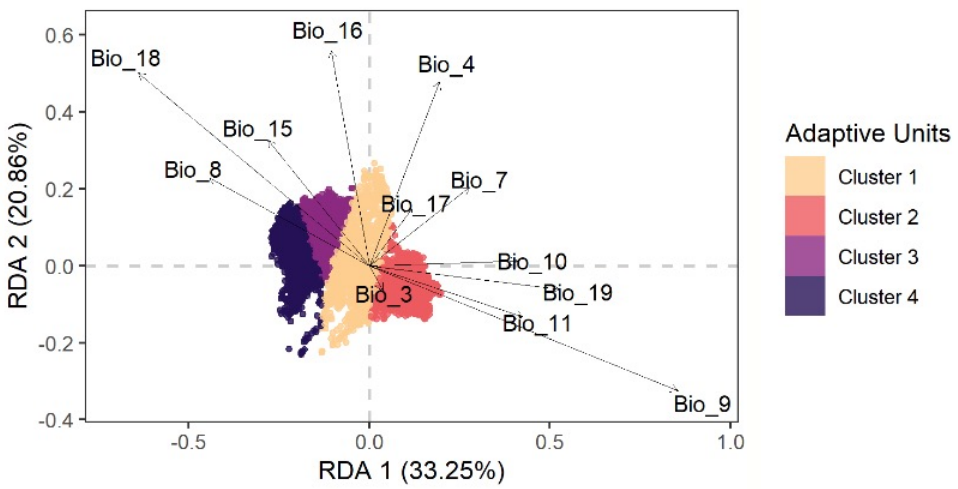
Amélie Hoste - *Master student*



Glenn Yannic - *University of Savoie Mont Blanc*

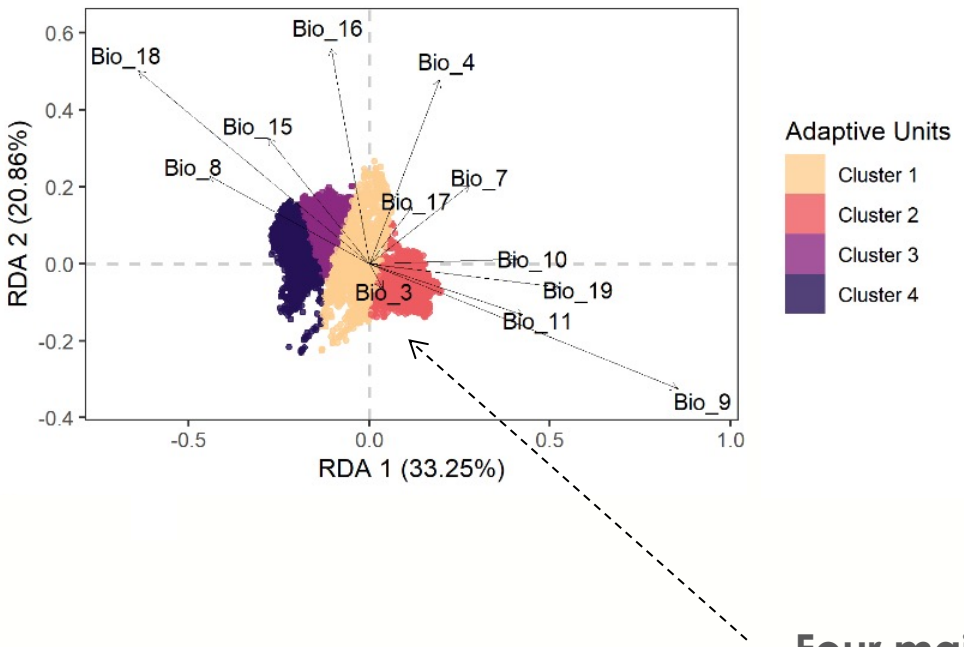
Hoste *et al.* (in review). Delineation of adaptive genetic units in an alpine ungulate: projection of current and future distributions.

Delineating adaptive genetic groups



Northern chamois
(Rupicapra rupicapra)

Delineating adaptive genetic groups

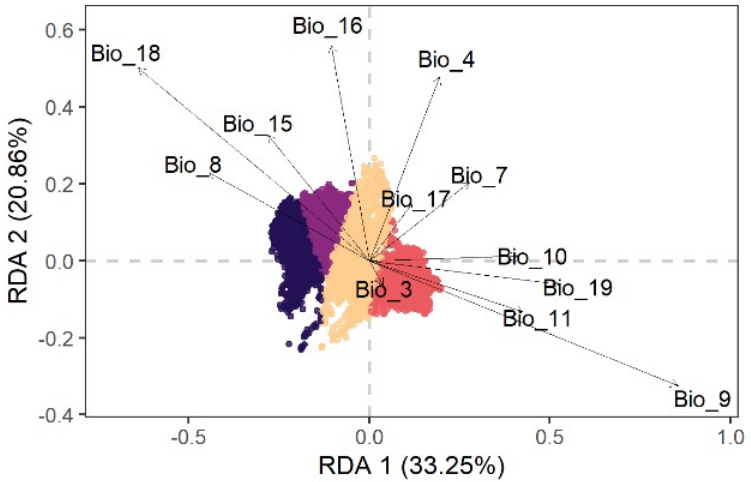


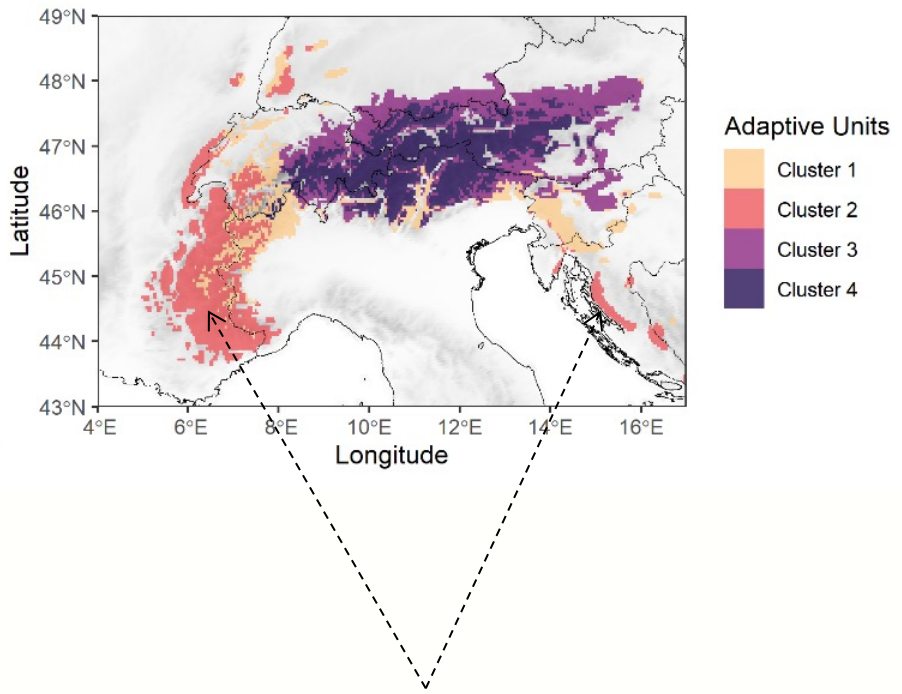
Northern chamois
(Rupicapra rupicapra)

Four main adaptive groups across the range of the species

Delineating adaptive genetic groups

Northern chamois
(Rupicapra rupicapra)

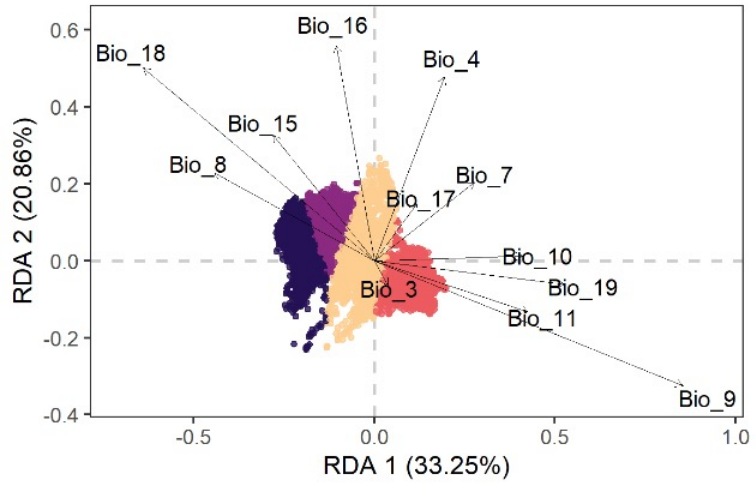


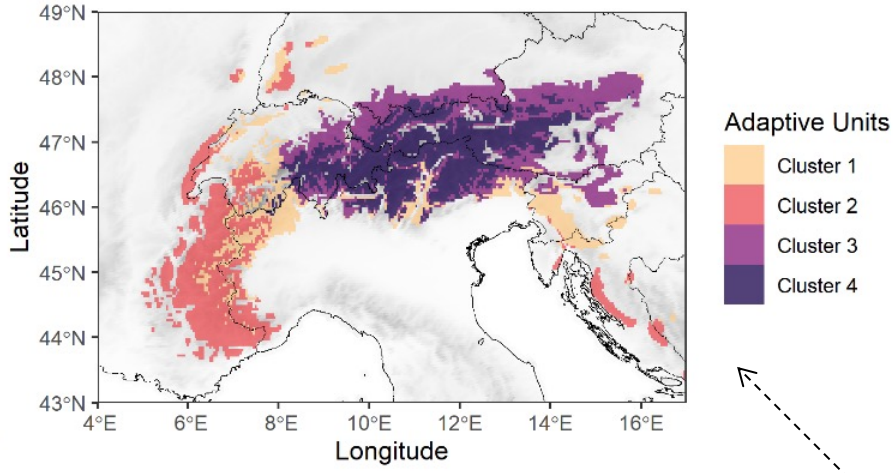


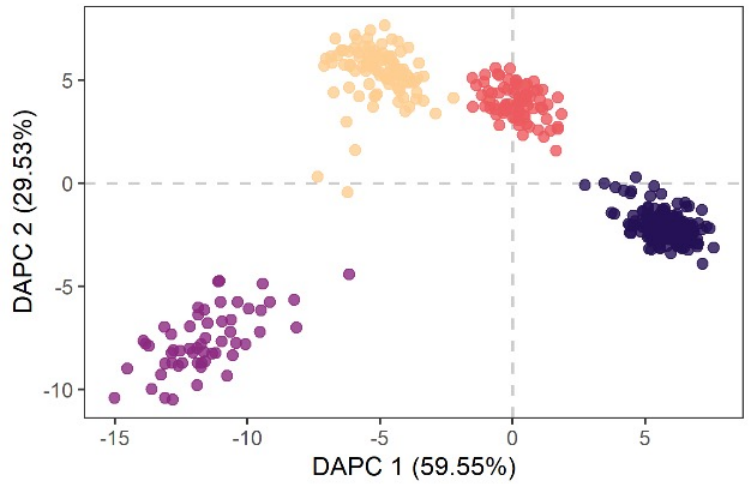
Two distant parts of the range exhibiting **similar adaptive genetic composition**

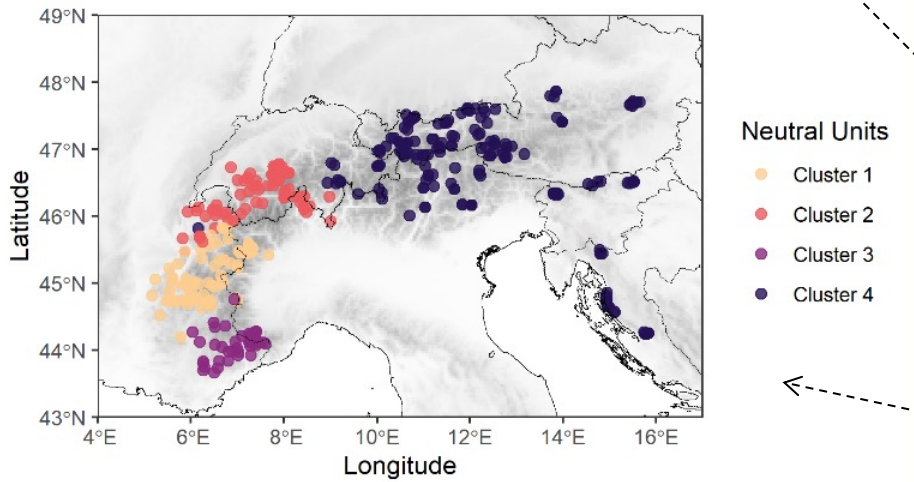
Delineating adaptive genetic groups

Northern chamois
(Rupicapra rupicapra)



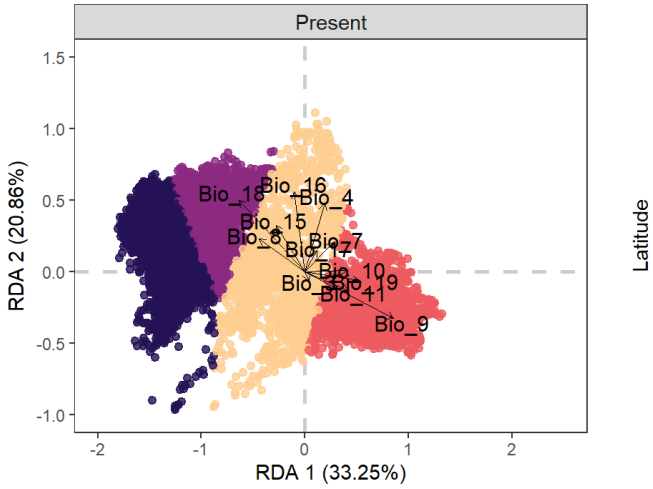


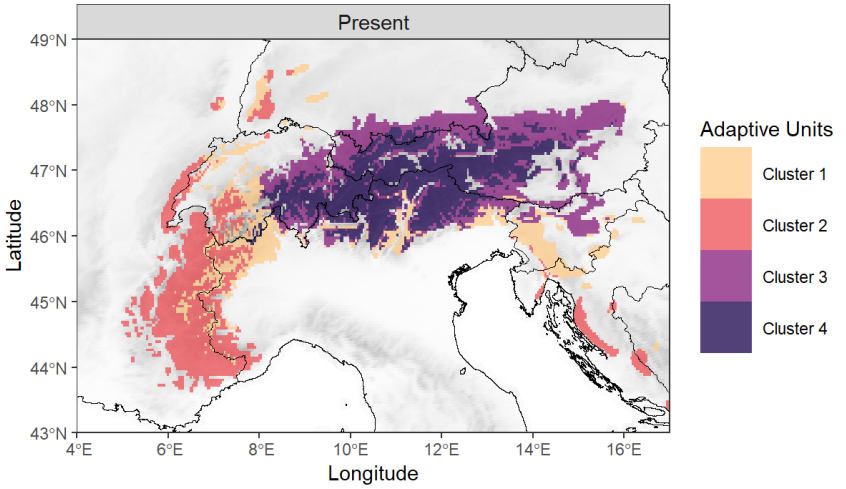


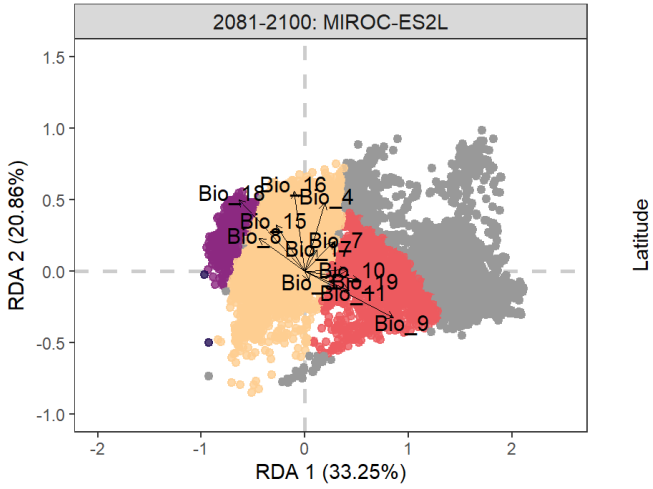


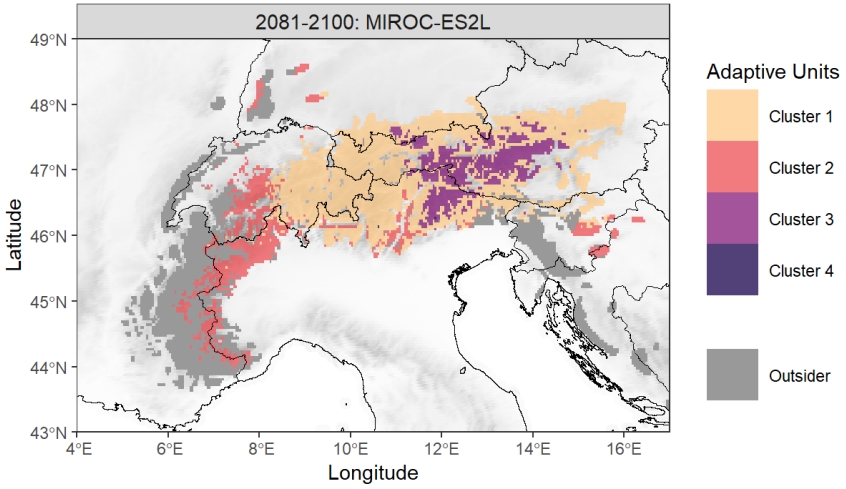
Divergent from **neutral structure**

Adaptive groups and climate change



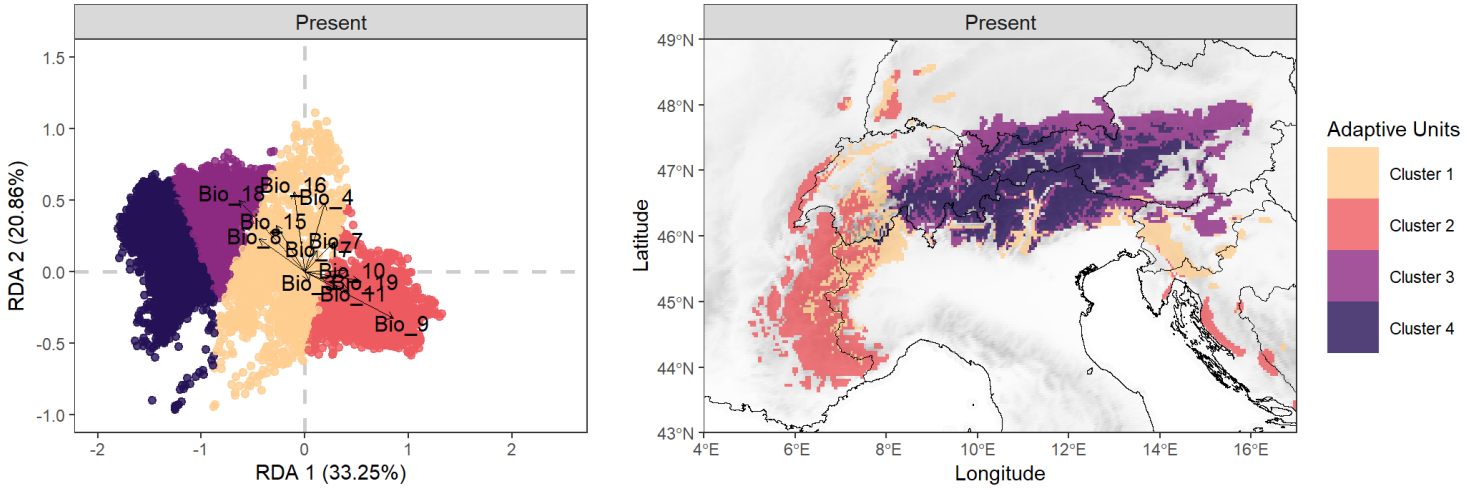






Northern chamois
(Rupicapra rupicapra)

Adaptive groups and climate change

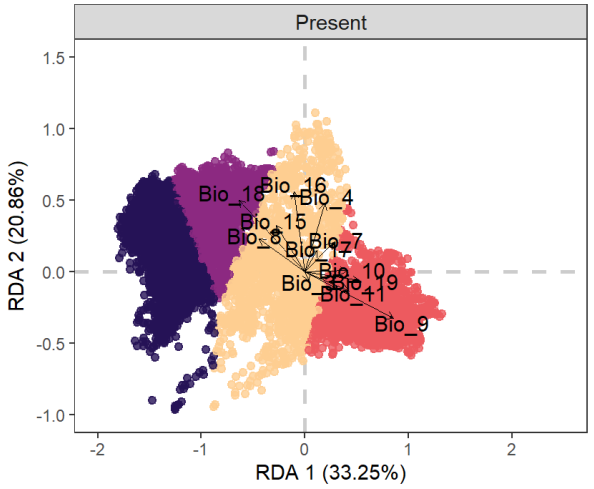


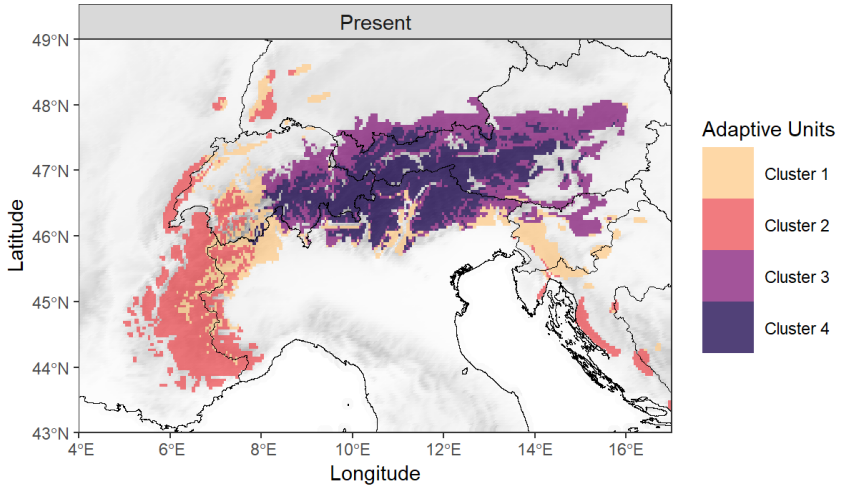
Northern chamois
(Rupicapra rupicapra)

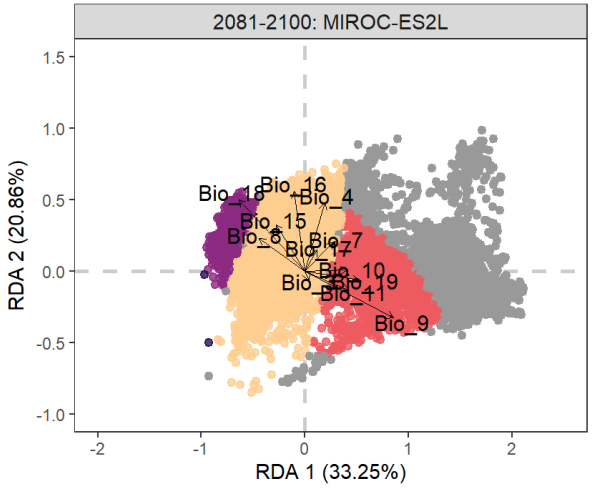
A third of the range will be **outside the current climate capacities** of the species

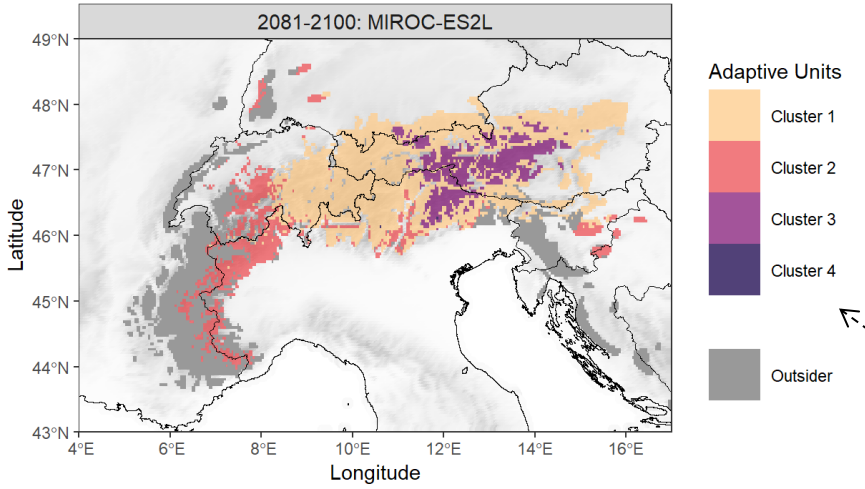
Adaptive groups and climate change

Northern chamois
(Rupicapra rupicapra)





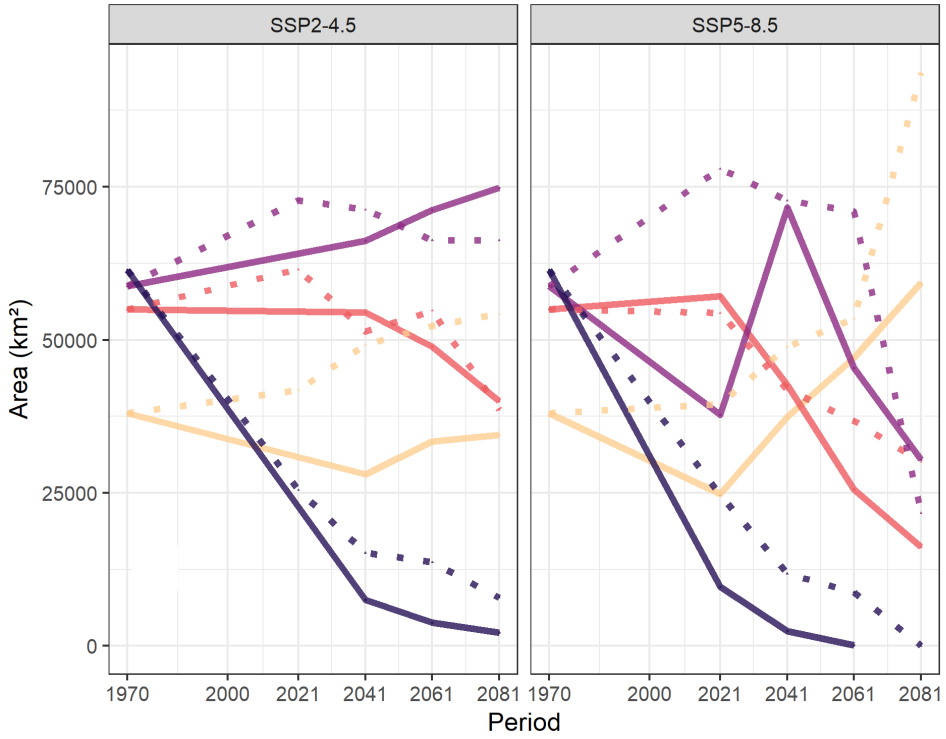


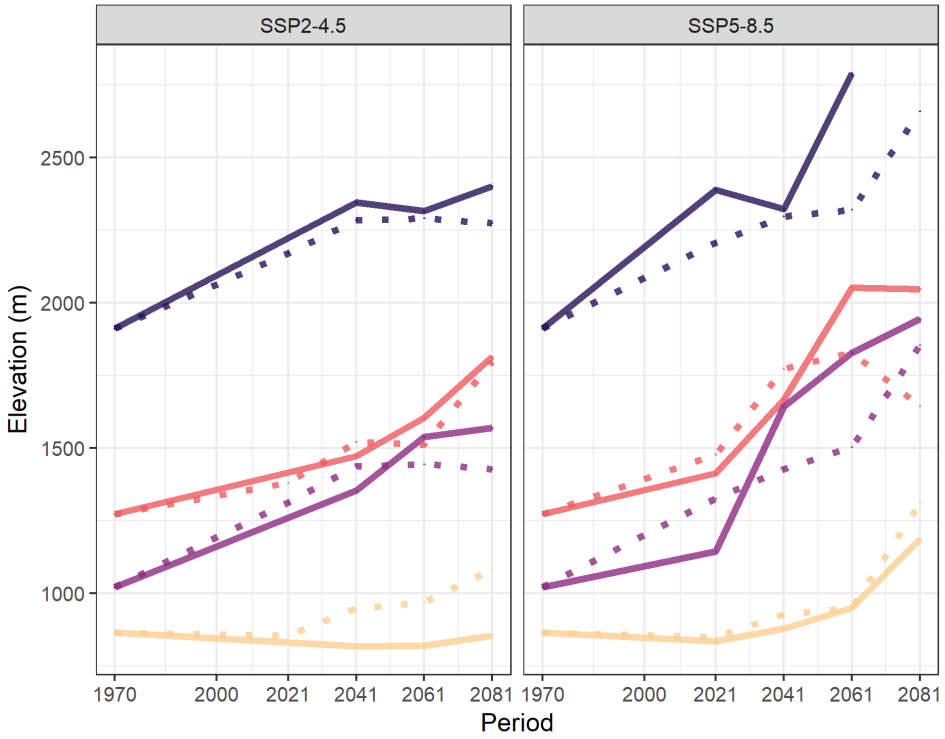


Disappearance of cluster 4

Adaptive groups and climate change

Northern chamois
(Rupicapra rupicapra)





Cluster
- Cluster 1
- Cluster 2
- Cluster 3
- Cluster 4

GCM
- IPSL-CM6A-LR
- MIROC-ES2L



Thanks !

The UNIVERSITY of VERMONT

LECA Laboratoire d'Ecologie Alpine

UGA Université Grenoble Alpes

cnrs dépasser les frontières