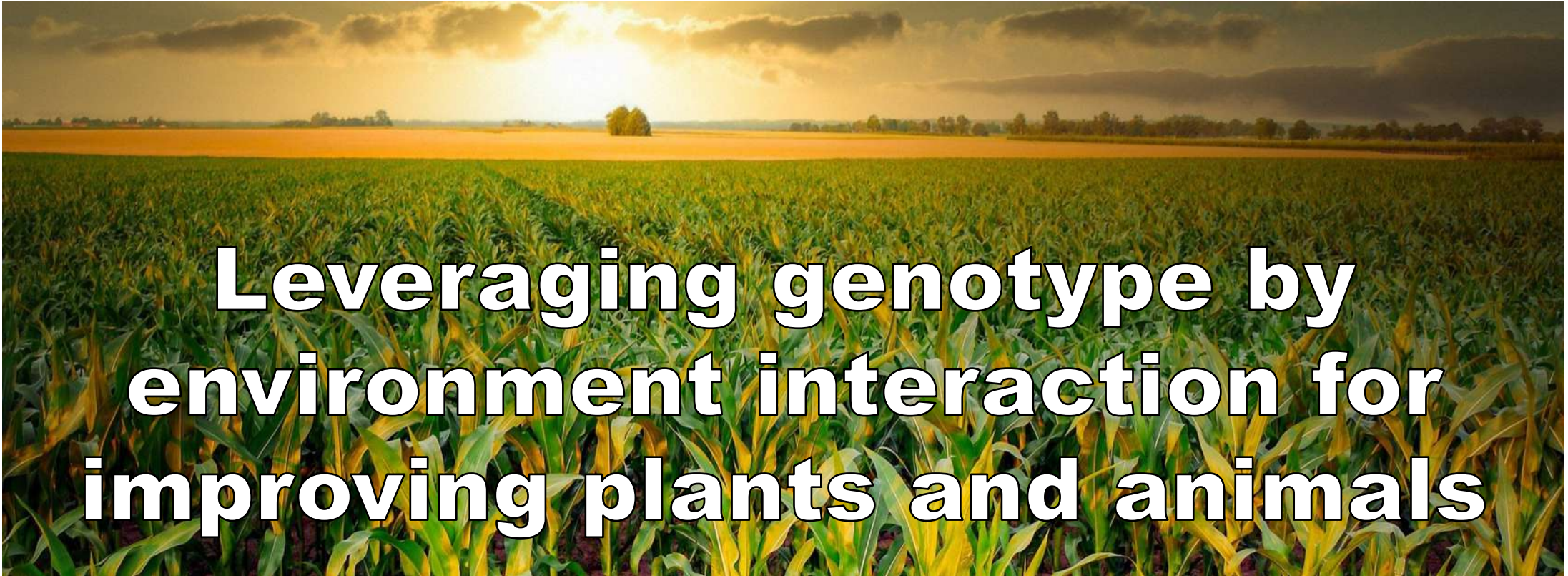




Leveraging genotype by environment interaction for improving plants and animals

COST Action Insect-IMP Meeting, Serbia

21/05/2026

Daniel Tolhurst

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THE UNIVERSITY of EDINBURGH
Royal (Dick) School of
Veterinary Studies



Acknowledgments



- **Dominic Waters (Roslin, now U. New England), Sven Weber (U. Giessen), Christina Finnegan (Bayer), Brian Gardunia (Bayer, now Gates), Gregor Gorjanc (HoD, Roslin)**



- **Edinburgh Innovations Fellowship at The Roslin Institute**



Overview

- 1. Introduction: genotype by environment (GxE) interaction**
- 2. Population improvement vs product development**
- 3. The role of stability measures in plant breeding**
- 4. dCross: designing high performing, stable genotypes through complimentary crossing**
- 5. Some practical examples in plants and animals**

Introduction

Genotype by environment (GxE) interaction

Introduction

- **GxE interaction complicates breeder's and grower's selection decisions**

→ Genotypes respond differently to changes in their environment

Breeders are interested in genotypes well adapted to their target population of environments (TPE)

→ e.g. high yielding and/or stable across years and locations

- Ignore, reduce*, **leverage...**

*repeatable groupings / geographic regions / market segments



Plant breeding field trials

- **Formally designed comparative field experiments**

Image: B. Ovenden

Multi-environment trials (MET)

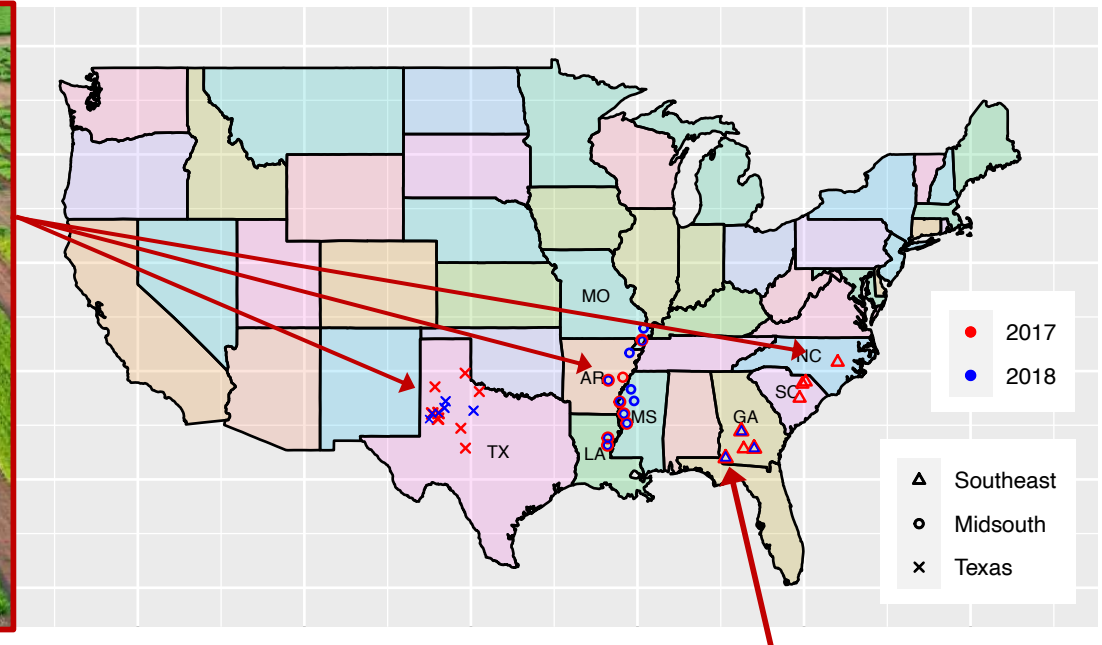
Formally designed comparative experiments conducted over multiple years and locations



Image: Crop Circle Consulting and Research

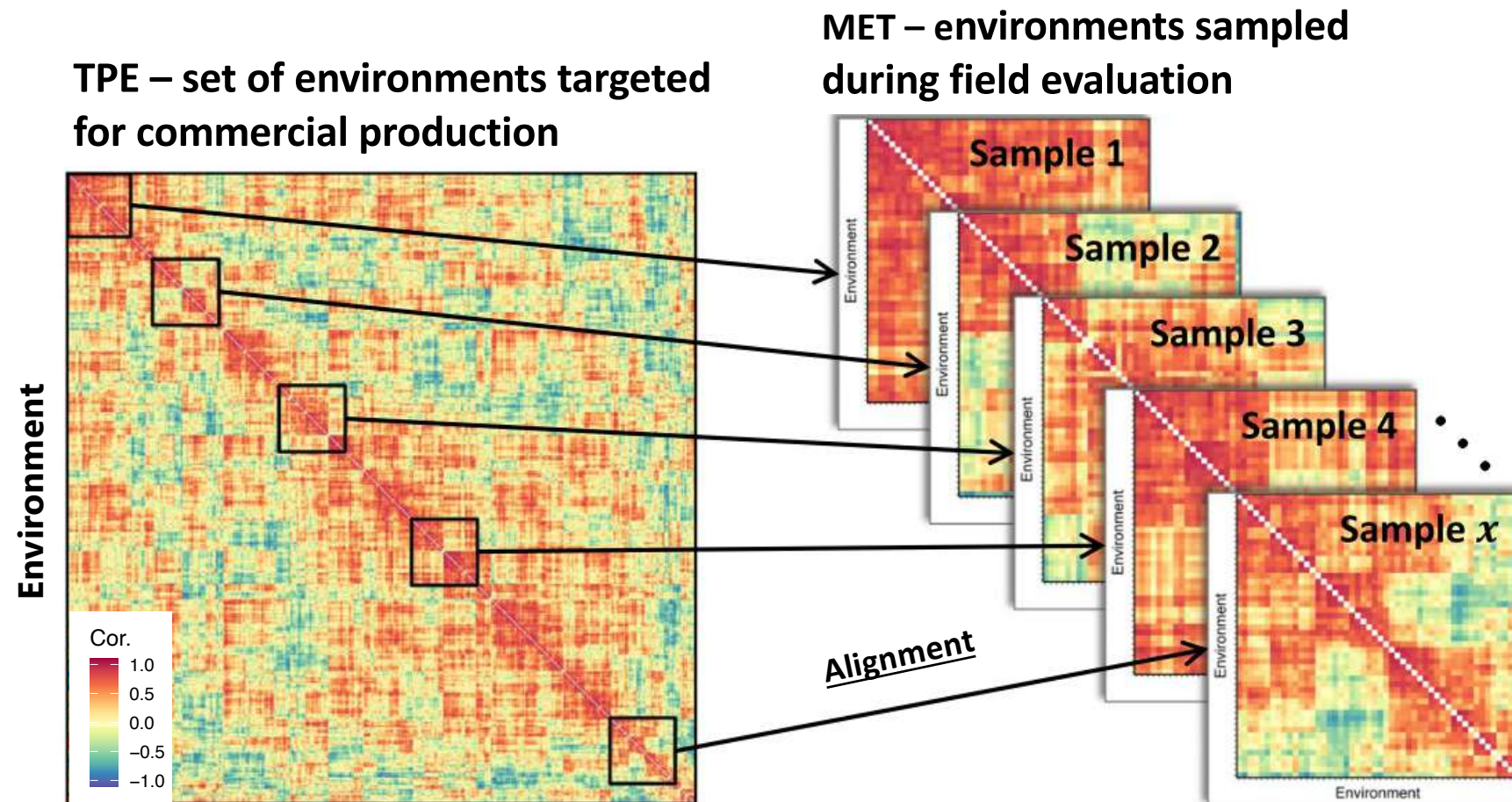
Assume 1 plot = 1 unique genotype

Bayer late-stage cotton breeding trials (Tolhurst et al. 2024)

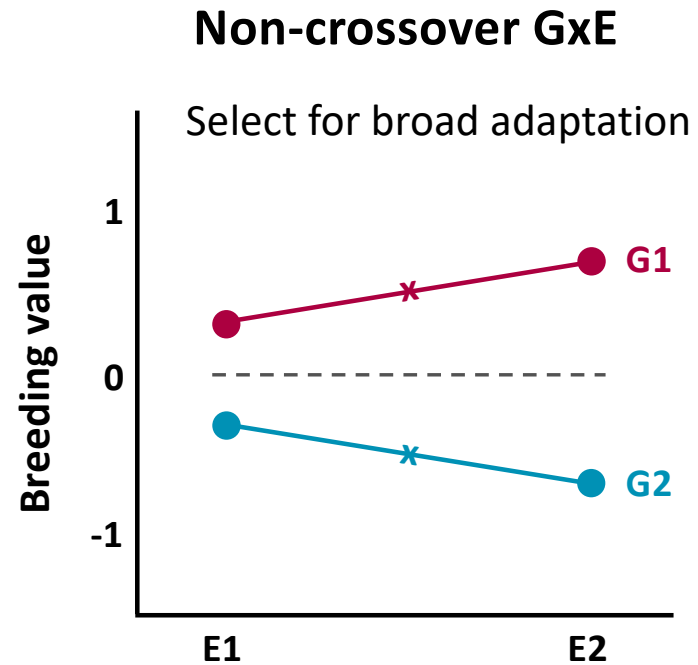


1 environment = 1 year x Location combination

Target population of environments

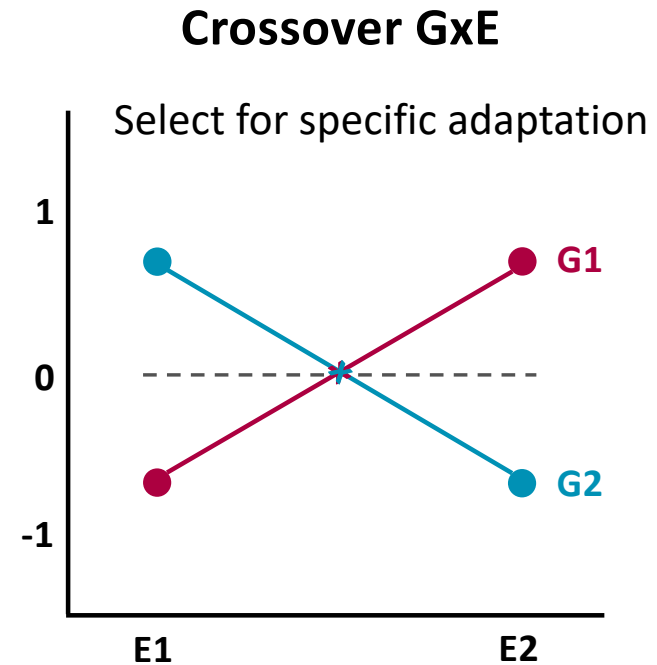


Different forms of GxE interaction



Relative response of G1 and G2 changes, lines don't intersect

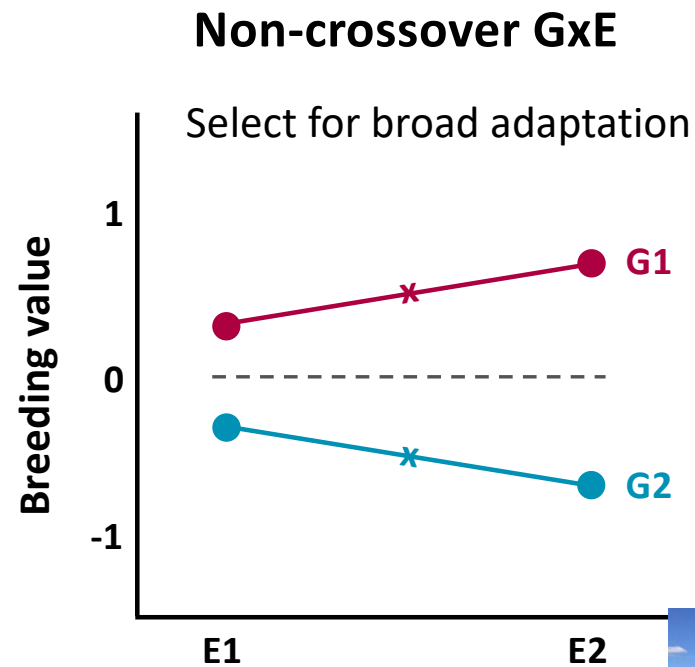
- G1 yields more in E1 and E2



Relative response of G1 and G2 changes, lines do intersect

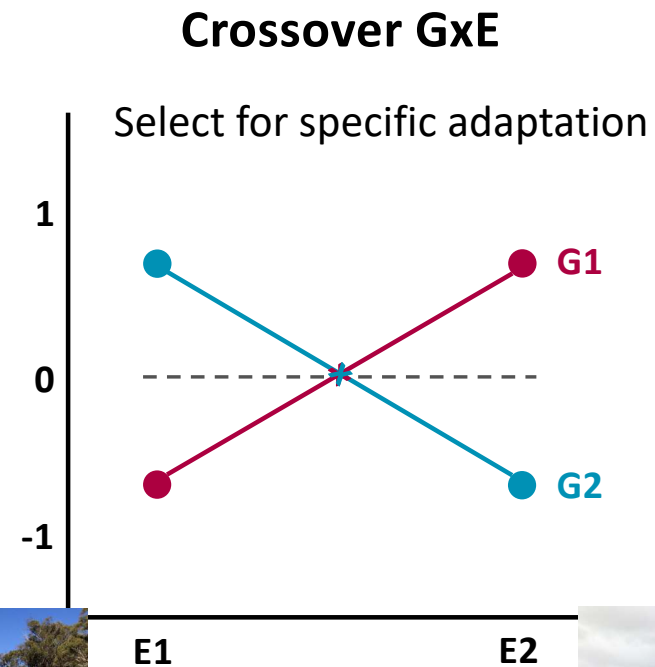
- G1 yields more in E2 but not E1

Different forms of GxE interaction



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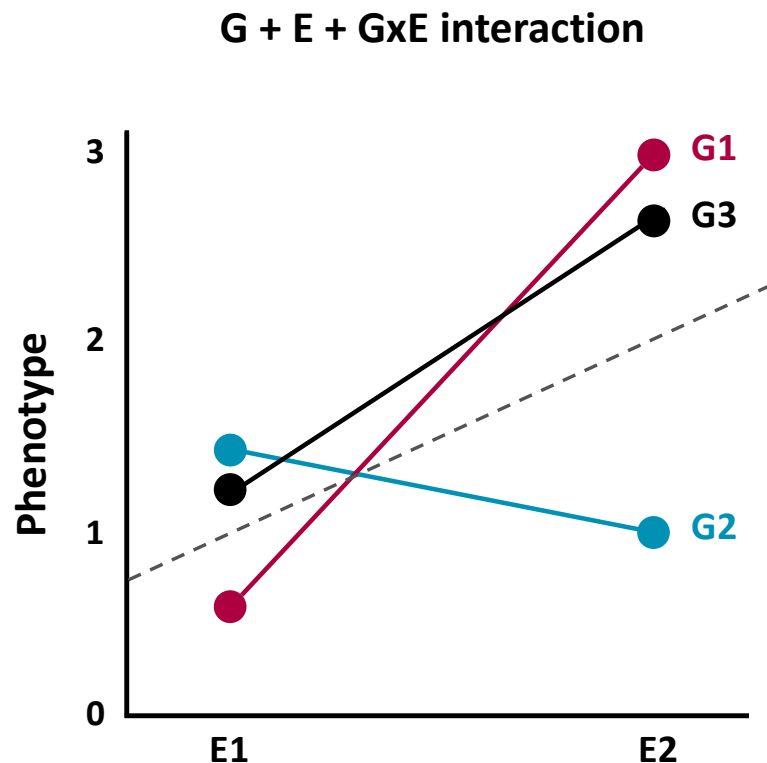


Relative response of G1 and G2 changes, lines do intersect

- G1 yields more in E2 but not in E1



Leveraging GxE: broad vs specific adaptation

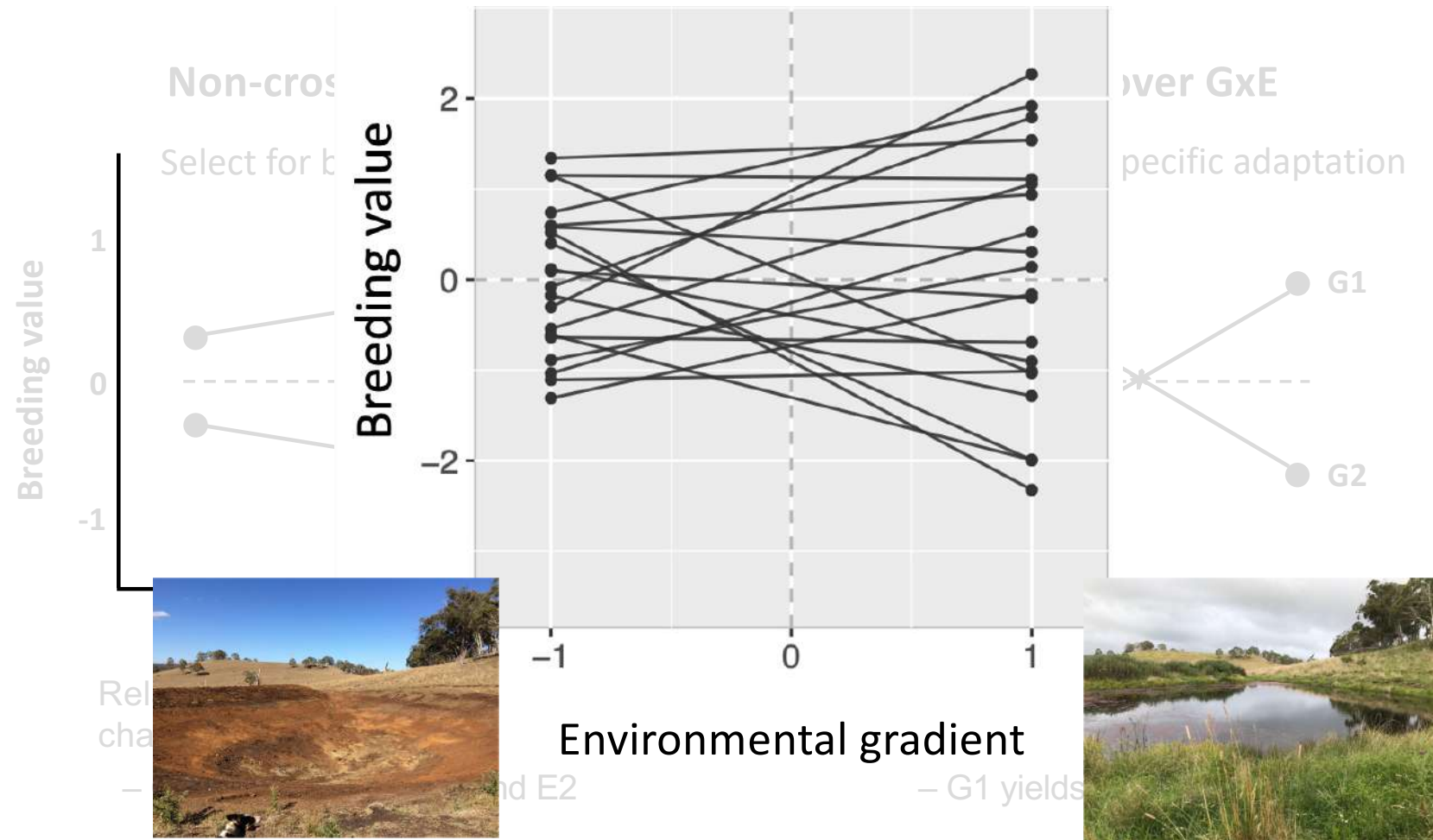


- G1 demonstrates specific adaptation within E2
- G2 demonstrates specific adaptation within E1
- G3 demonstrates broad adaptation across E1 and E2 (high yielding and stable)

→ **Dependent on the form of GxE interaction present**

Different forr

Some complex combination of non-crossover and crossover interaction



Different forms of GxE interaction

Non-crossover GxE

Crossover GxE

Breeding value

How do we leverage GxE interaction for

a) Improving a breeding population

VS

b) Developing products for release

???

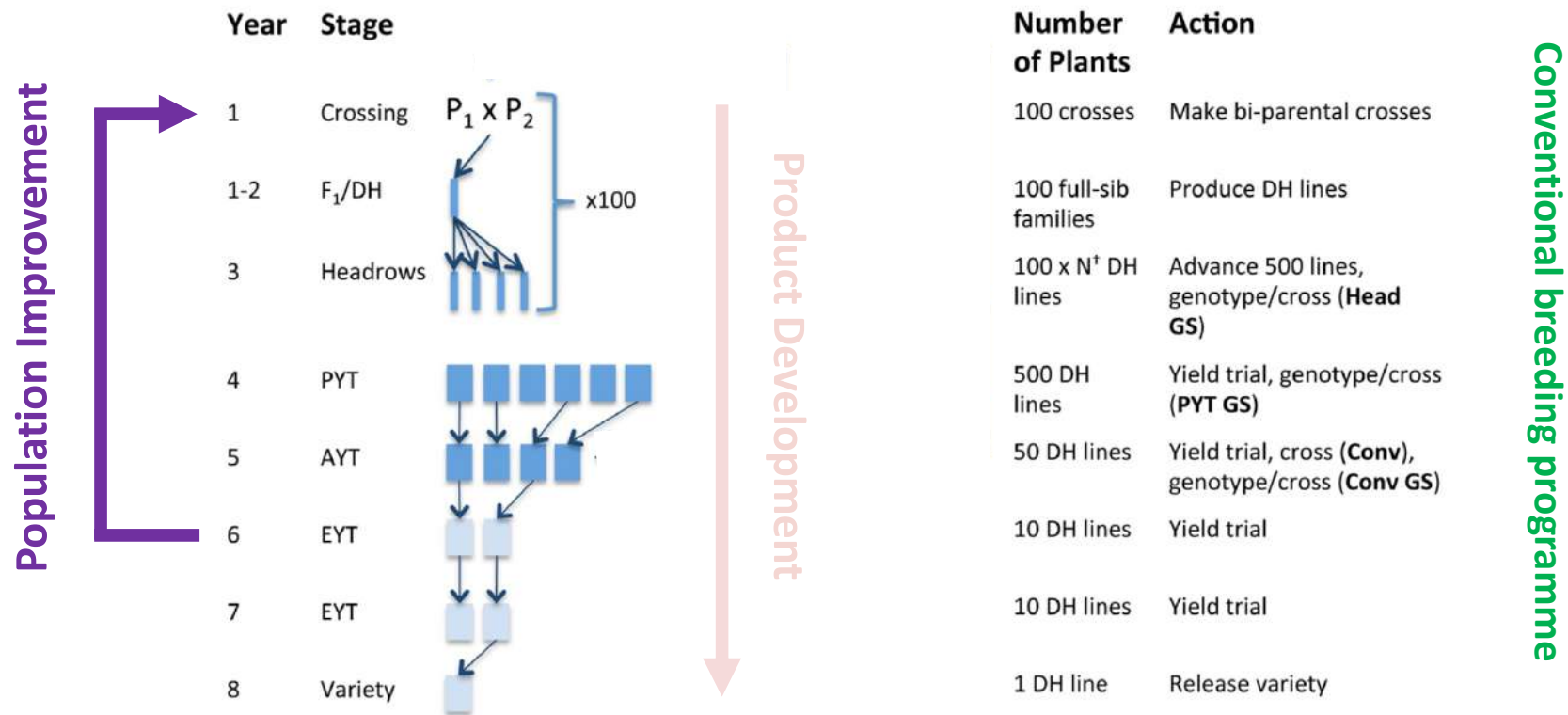
– G1 yields more in E1 and E2

– G1 yields more in E2 but not E1



**Population improvement
vs
product development**

Population improvement vs product development

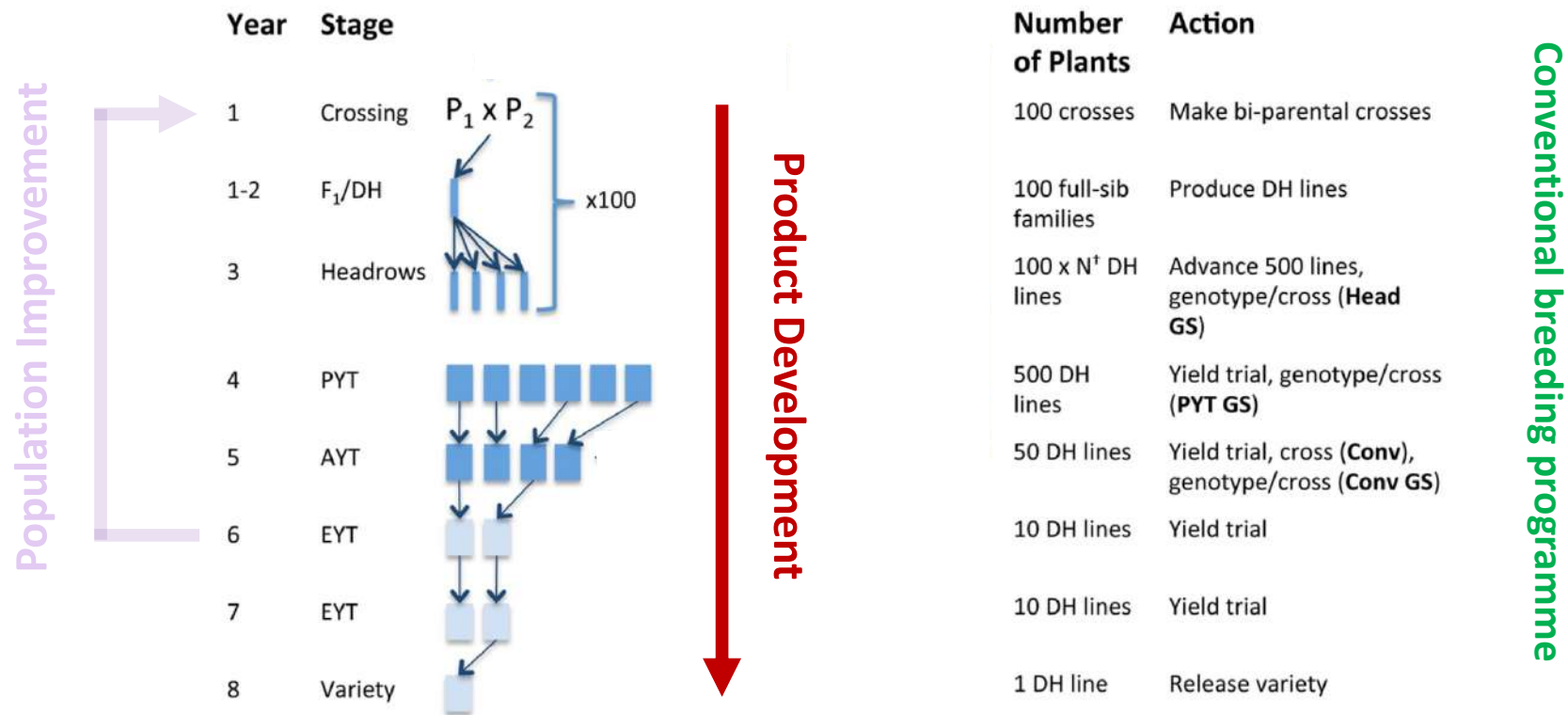


Improve the population mean for key traits of importance

Evaluate, advance and release superior varieties (products) to growers

Gaynor et al. (2017)

Population improvement vs product development

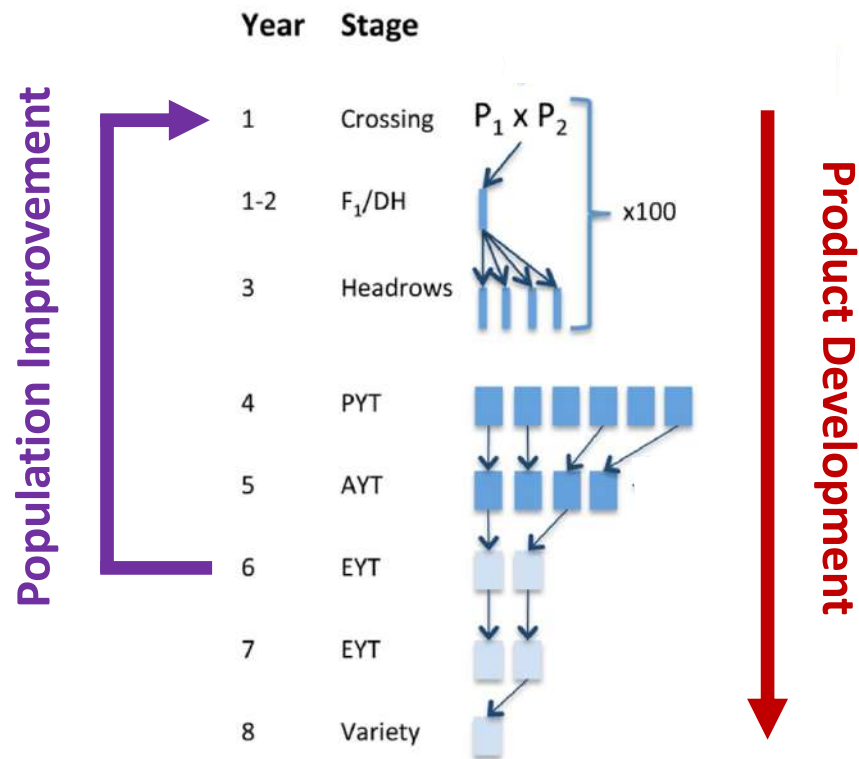


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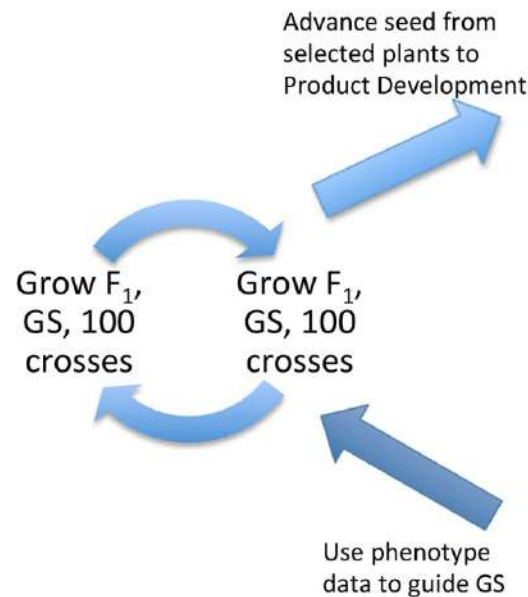
	Year					
Stage	2021	2022	2023	2024	2025	2026
PYT	A	B	C	D	E	F
AYT	NA	A	B	C	D	E
EYT1	NA	NA	A	B	C	D
EYT2	NA	NA	NA	A	B	C

Improve the population mean for key traits of importance

Evaluate, advance and release superior varieties (products) to growers

Population improvement vs product development

Population Improvement



Improve the population mean for key traits of importance

Product Development

Year	Stage		Number of Plants	Action
1-2	F ₁ /DH		200 half-sib families	Produce DH lines
3	Headrow		200 x N ⁺ DH lines	Advance 500 lines, genotype (2Part+H)
4	PYT		500 DH lines	Yield trial, genotype (2Part)
5	AYT		50 DH lines	Yield trial
6	EYT		10 DH lines	Yield trial
7	EYT		10 DH lines	Yield trial
8	Variety		1 DH line	Release variety

Evaluate, advance and release superior varieties (products) to growers

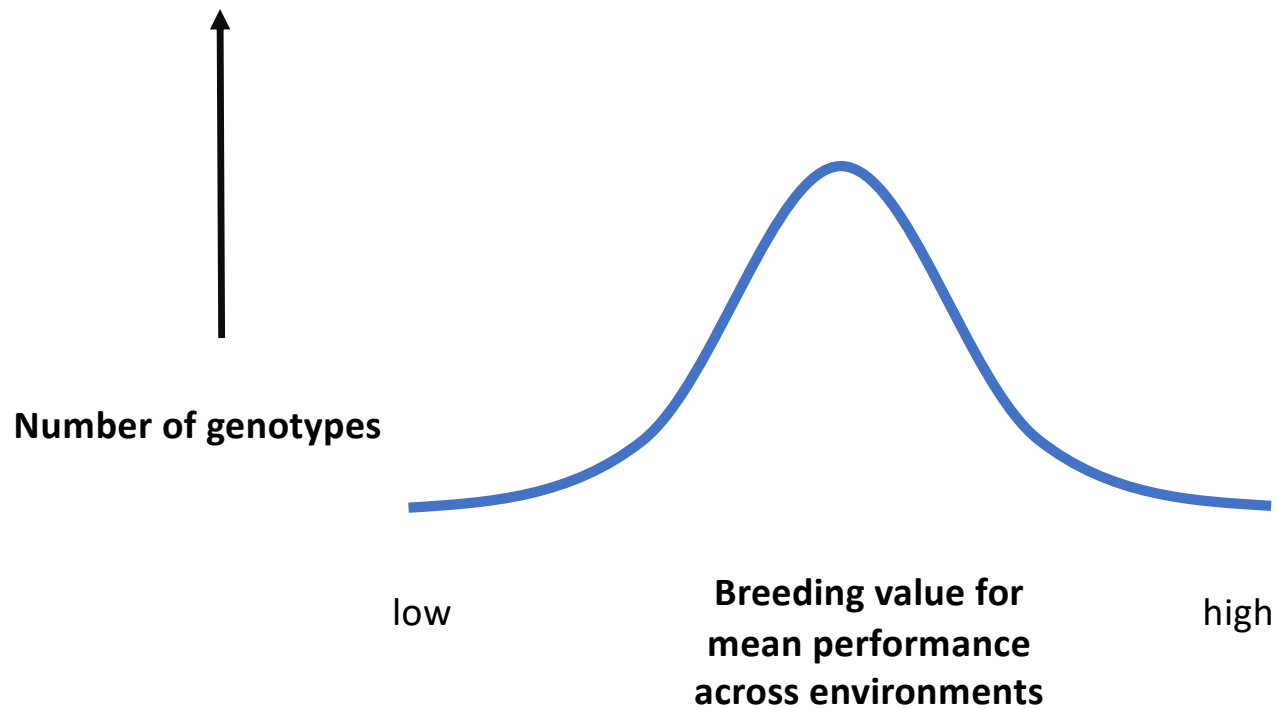
Two-part breeding programme

Gaynor et al. (2017)

Population improvement selection - directional vs stabilising

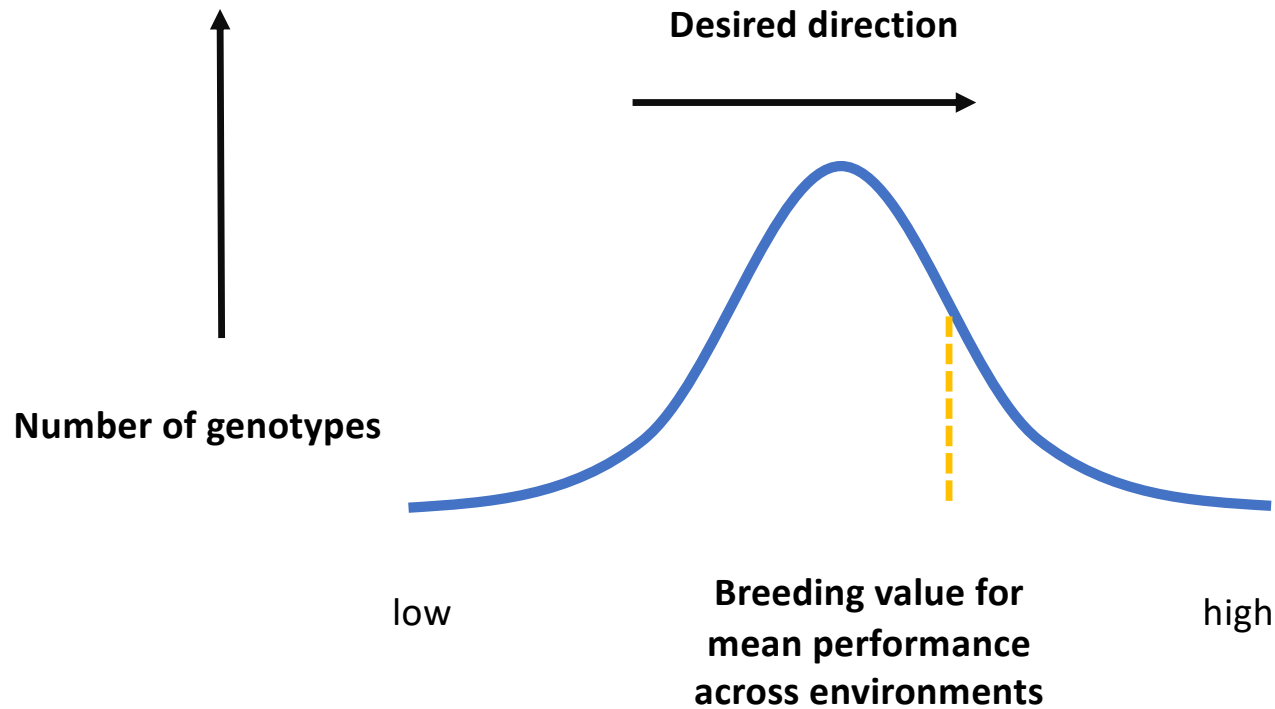
What is population improvement?

- Moving the **population average** in a desired direction for different traits



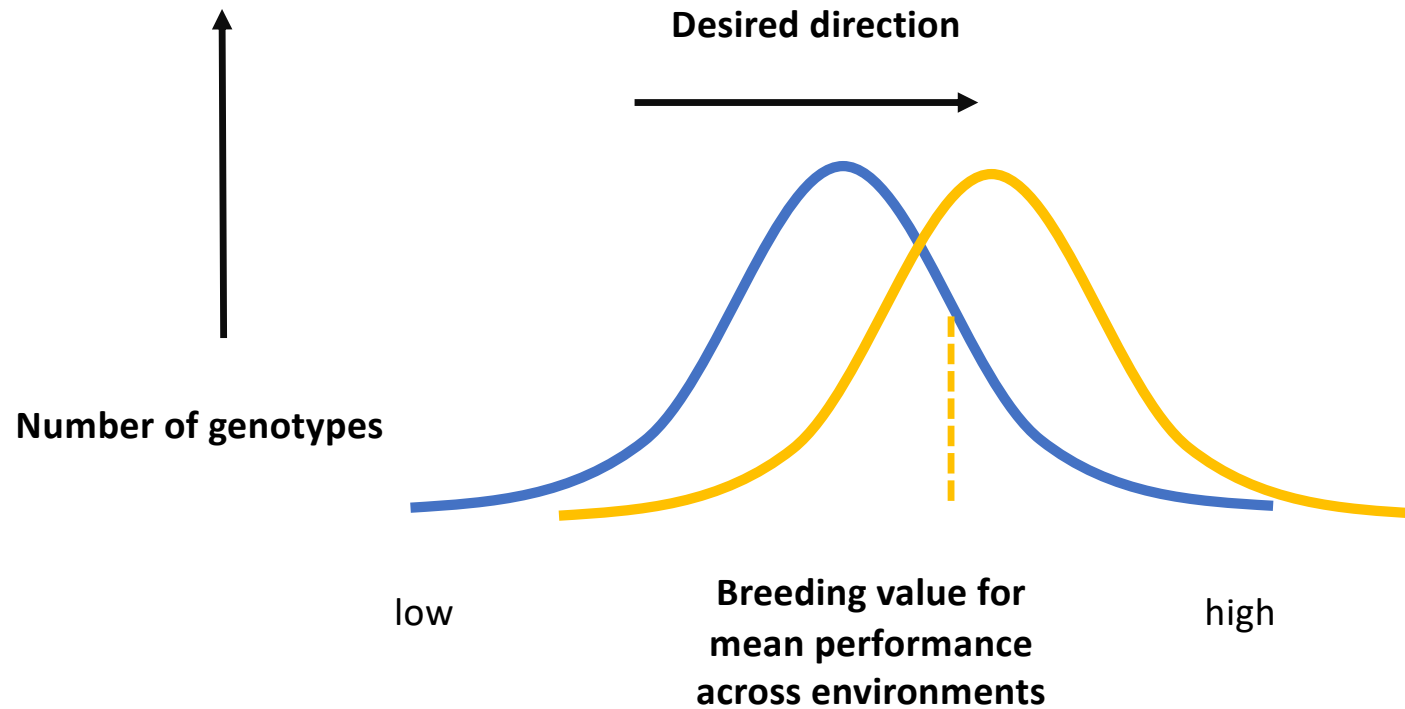
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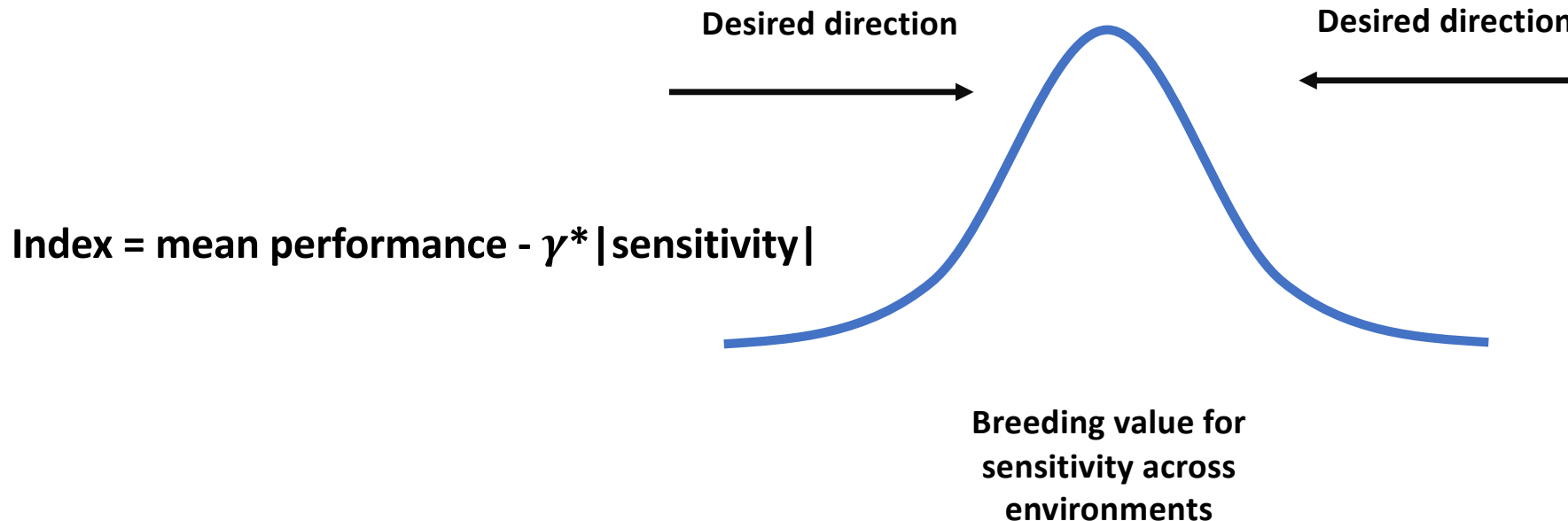
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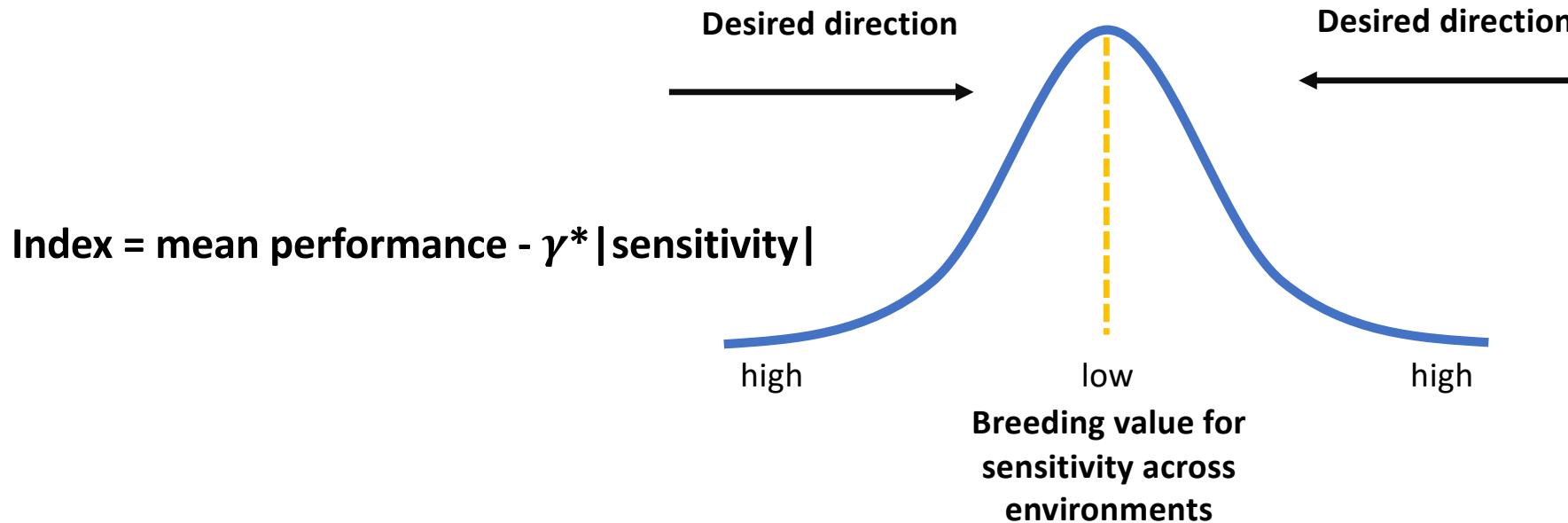
Stability: population improvement

- A slope of zero is desirable for sensitivity (high stability)
- Penalised indexes have been developed for this purpose



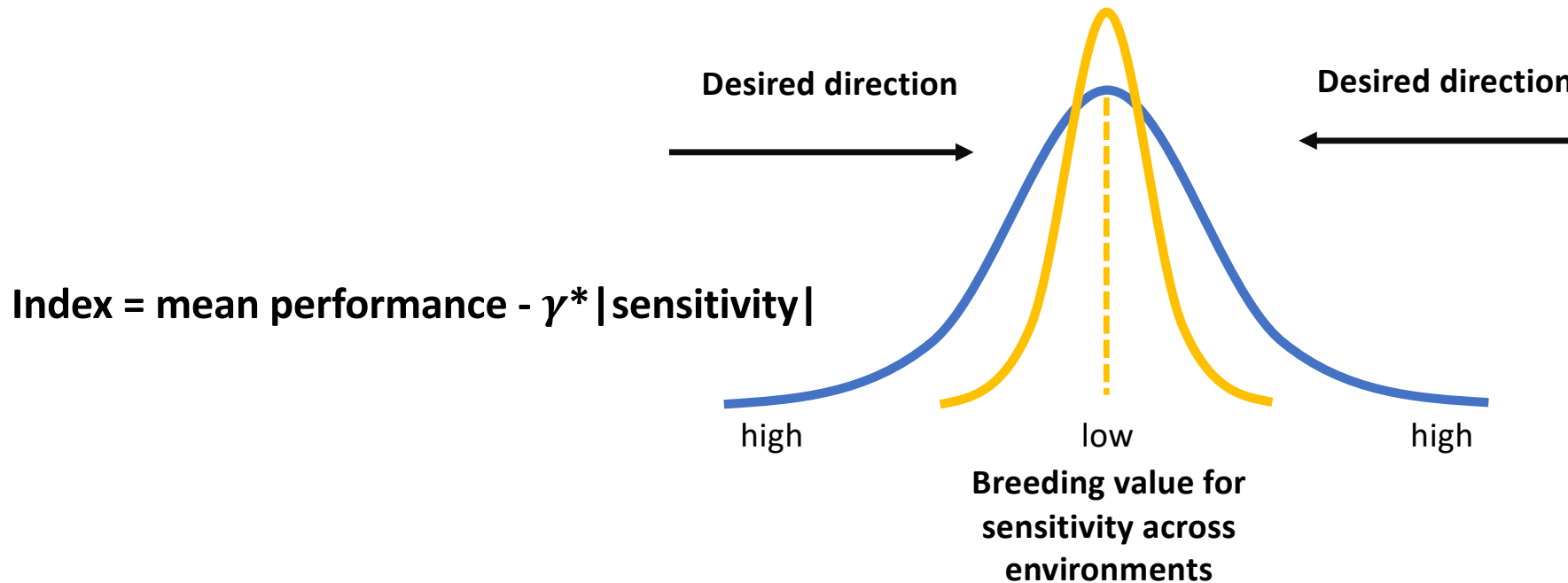
Stability: population improvement

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Stability: population improvement

- A slope of zero is desirable for sensitivity (high stability)
- Penalised indexes have been developed for this purpose

**Does selection for stability make sense within
population improvement**

???

Index = mean performance - γ^* |sensitivity|

high

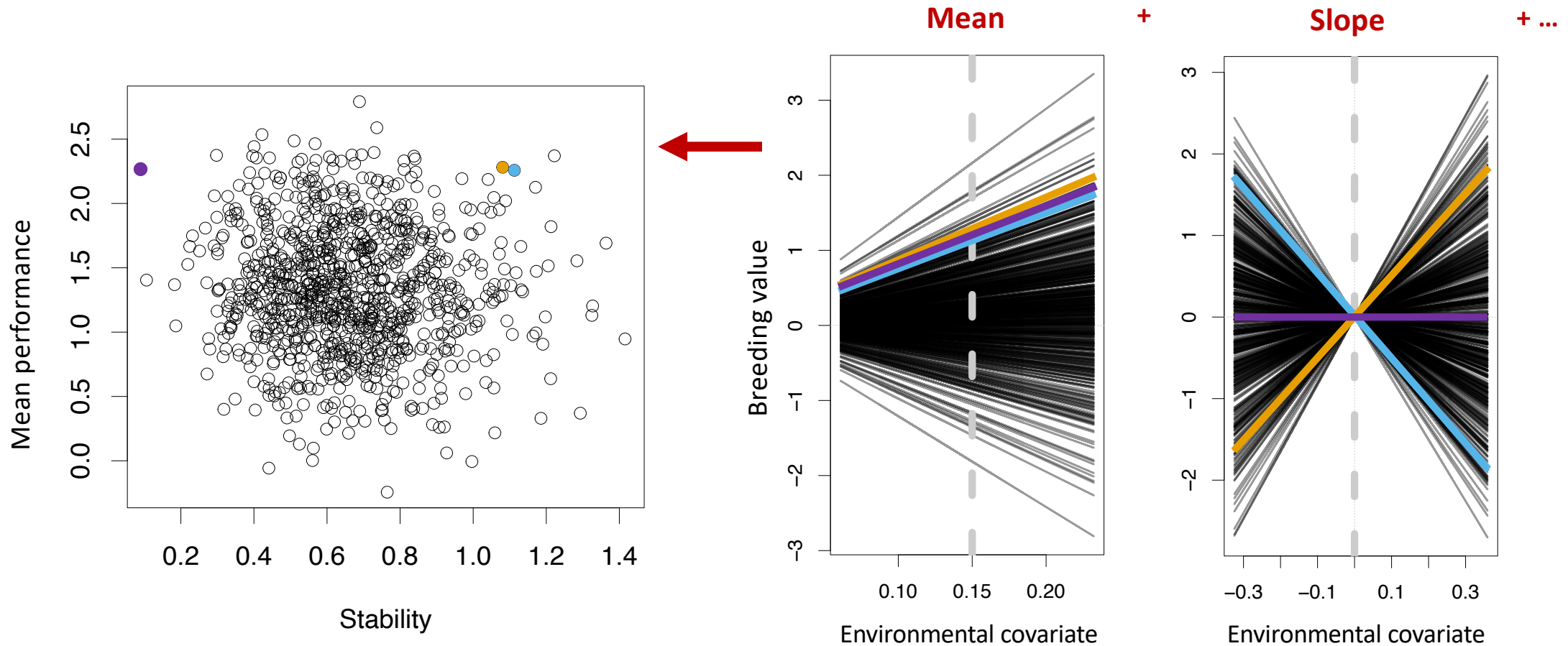
low

high

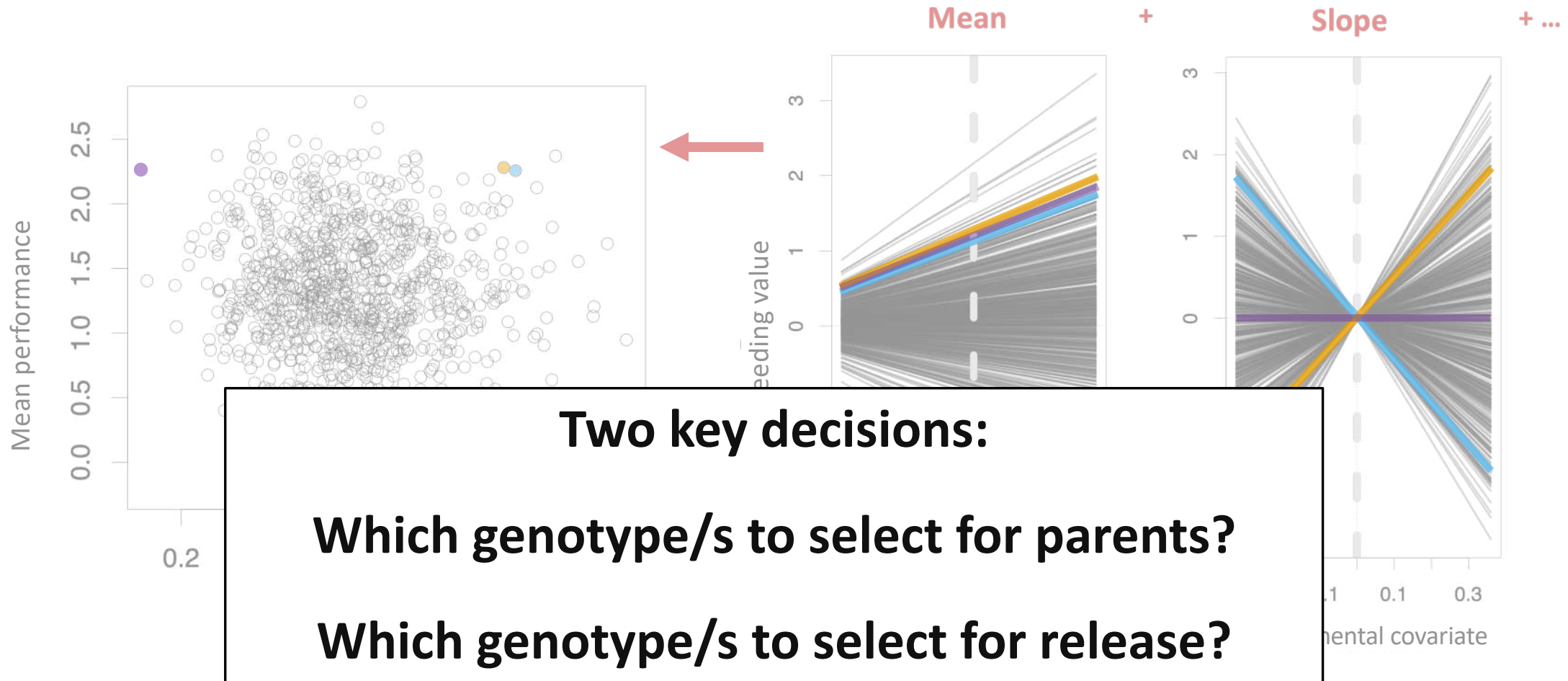
Breeding value for
sensitivity across
environments

A simple example

The role of stability for selection and crossing

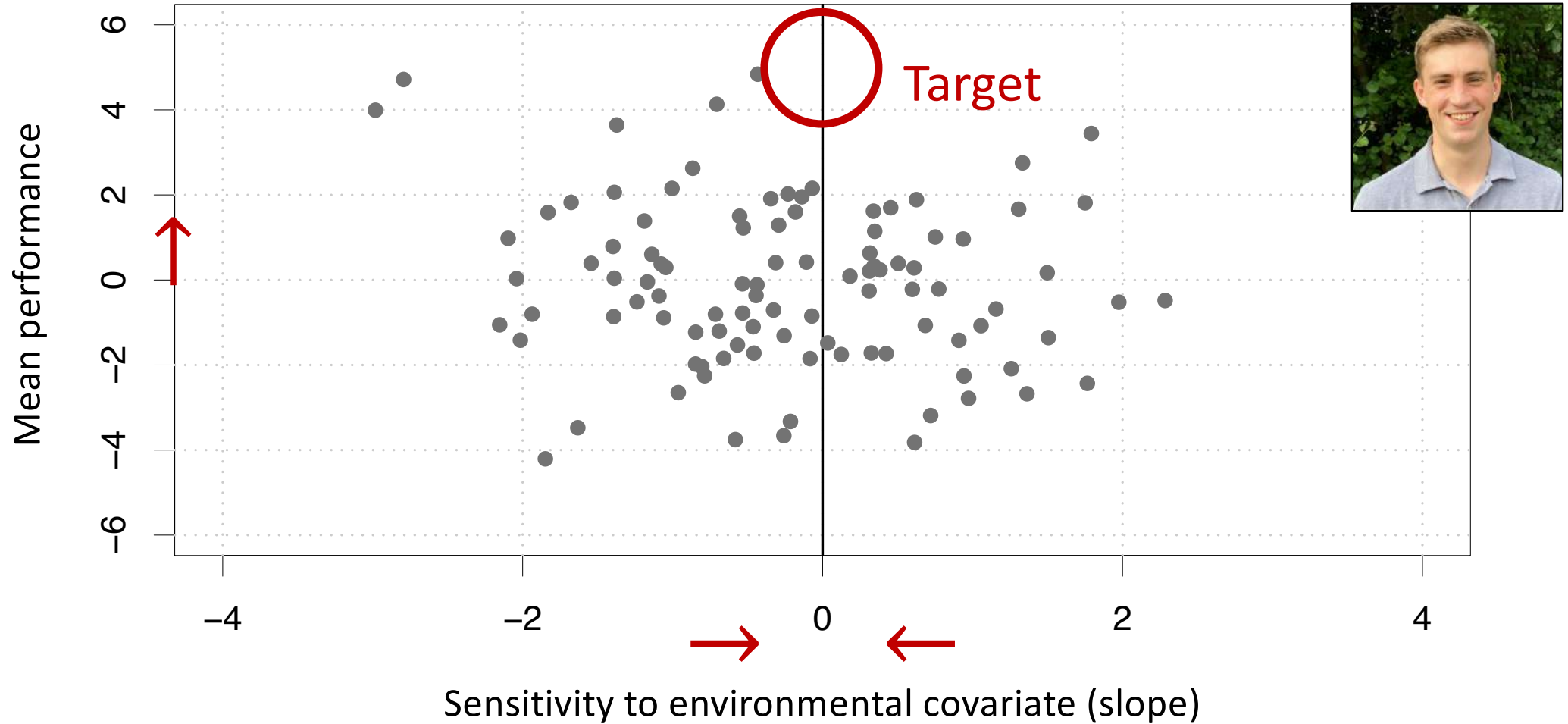


The role of stability for selection and crossing

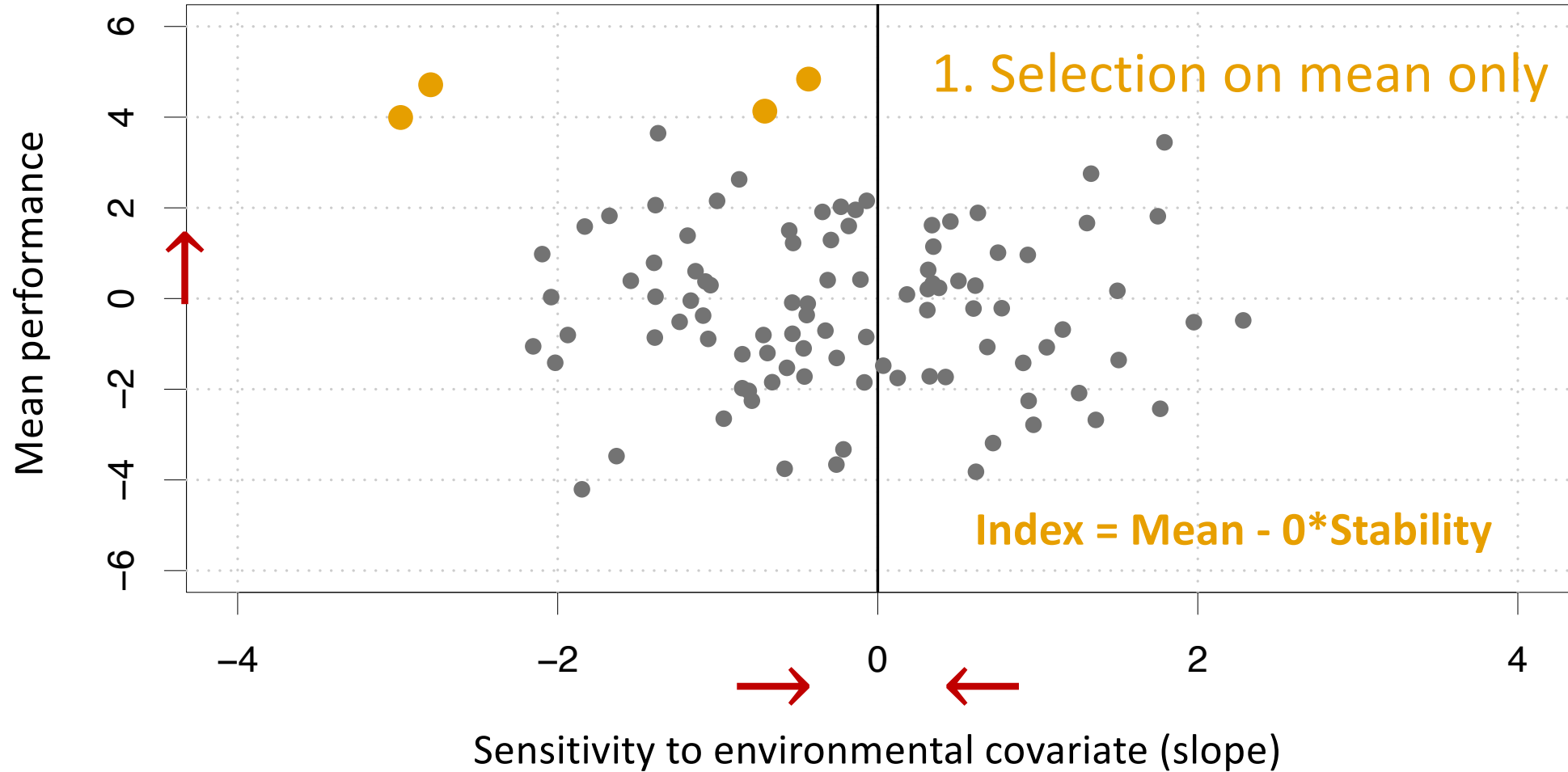


**dCross: designing high performing, stable
genotypes through complimentary crossing**

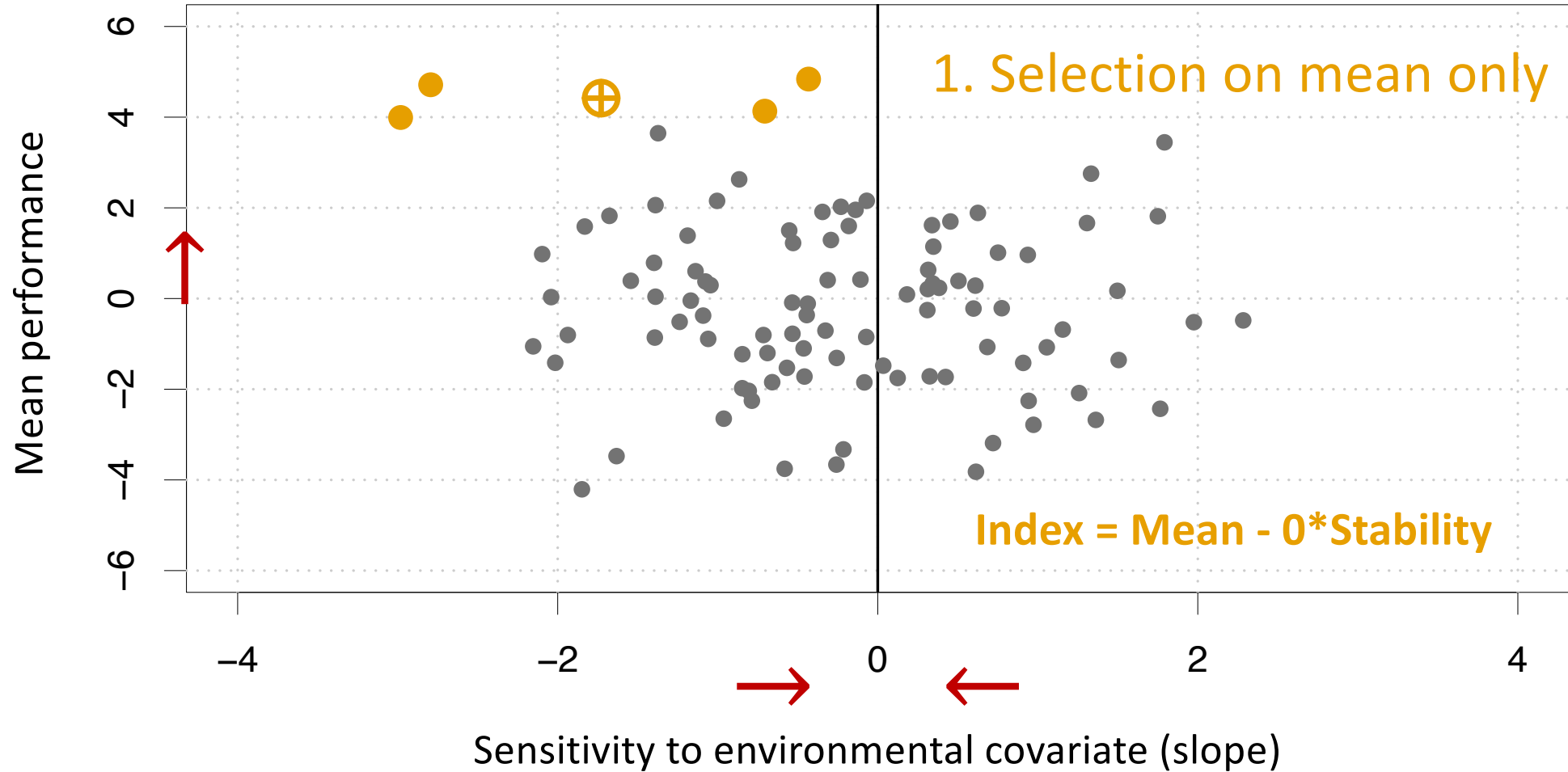
Consider the following example... 100 candidates



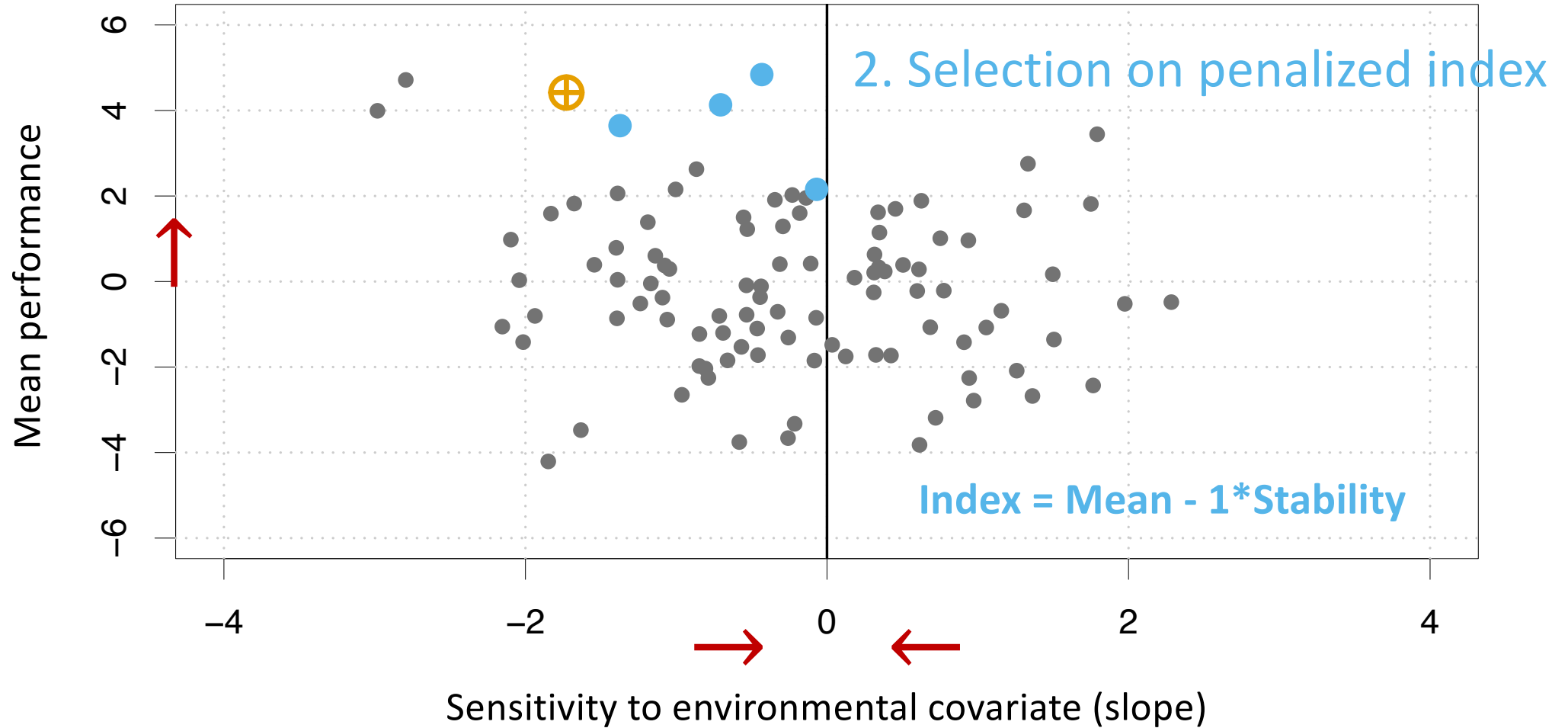
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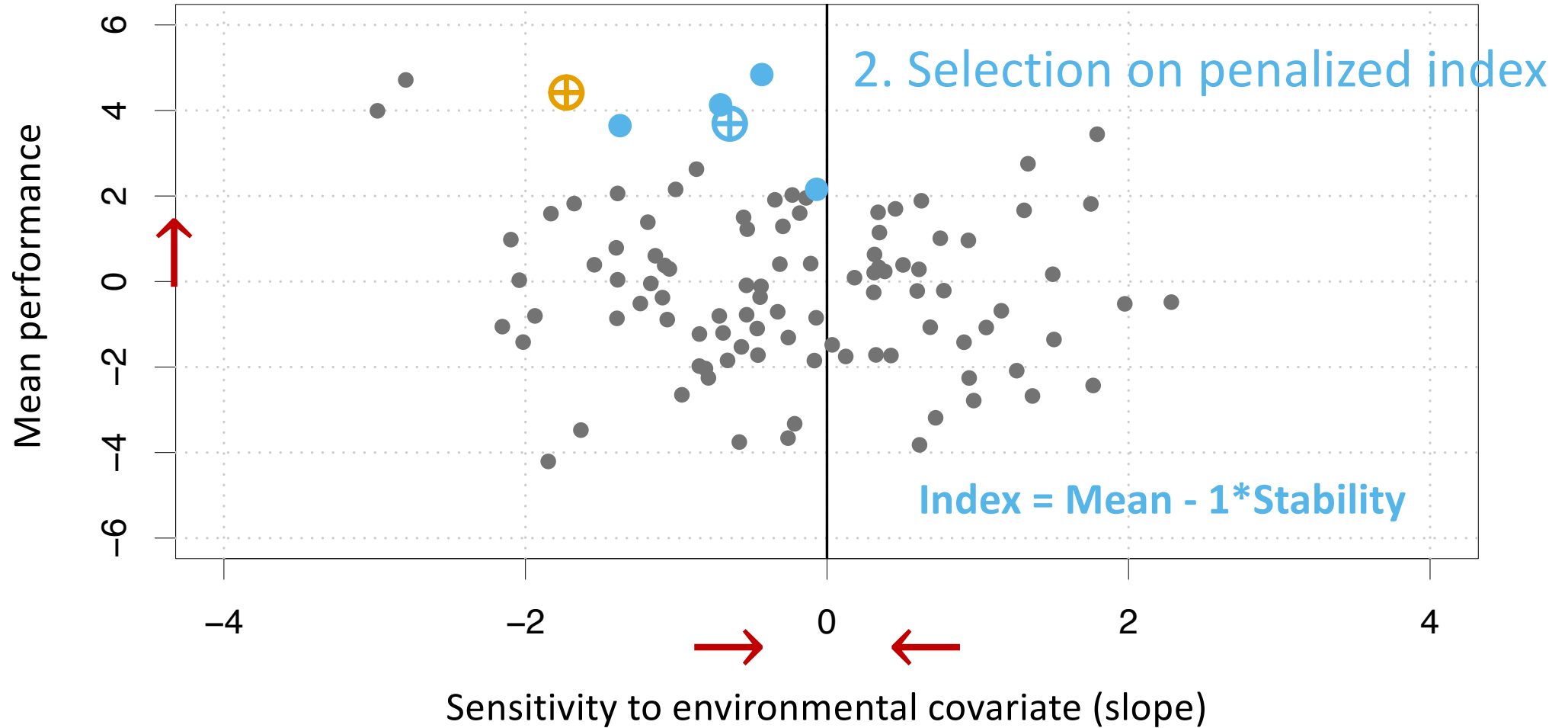
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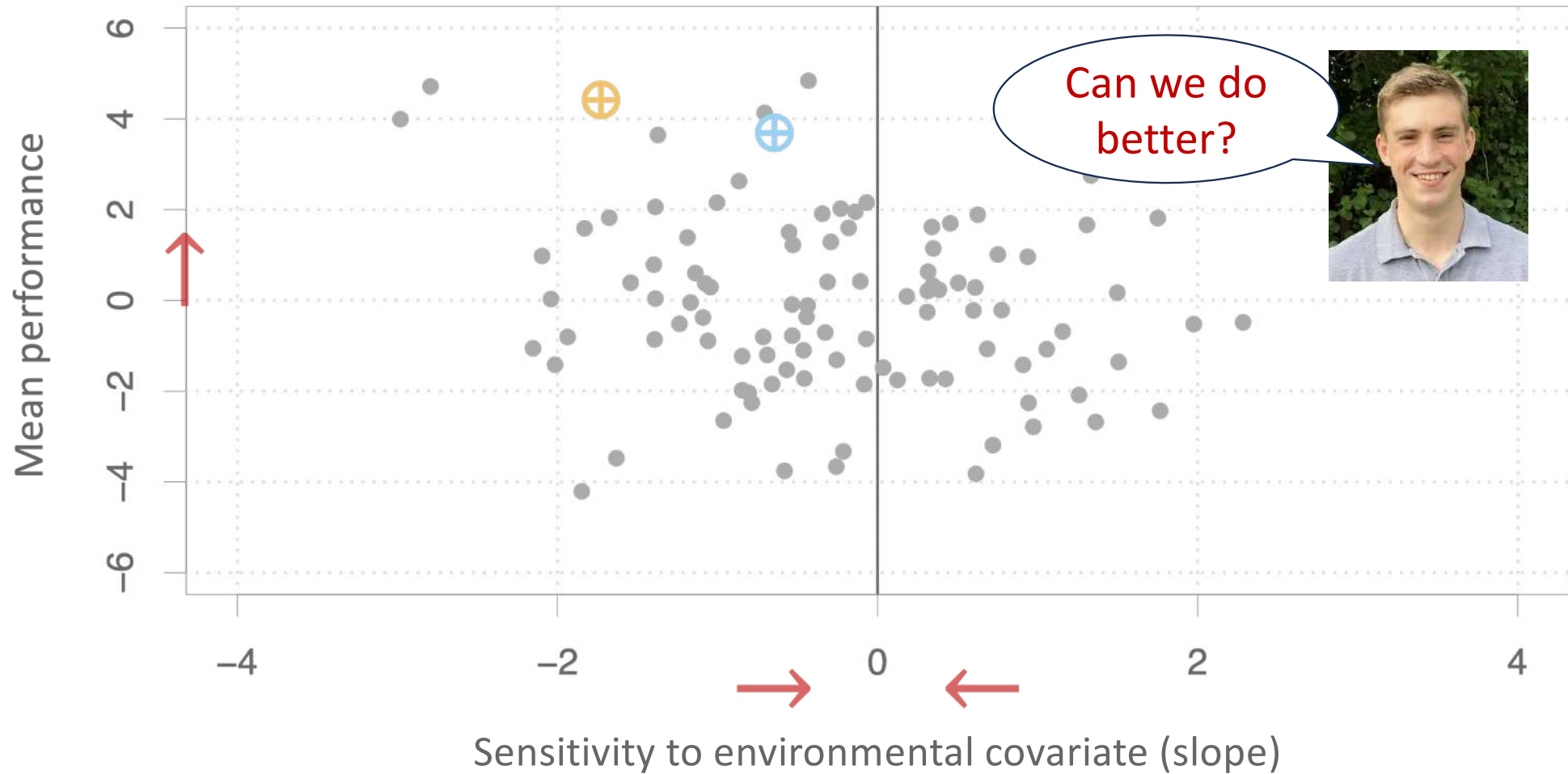
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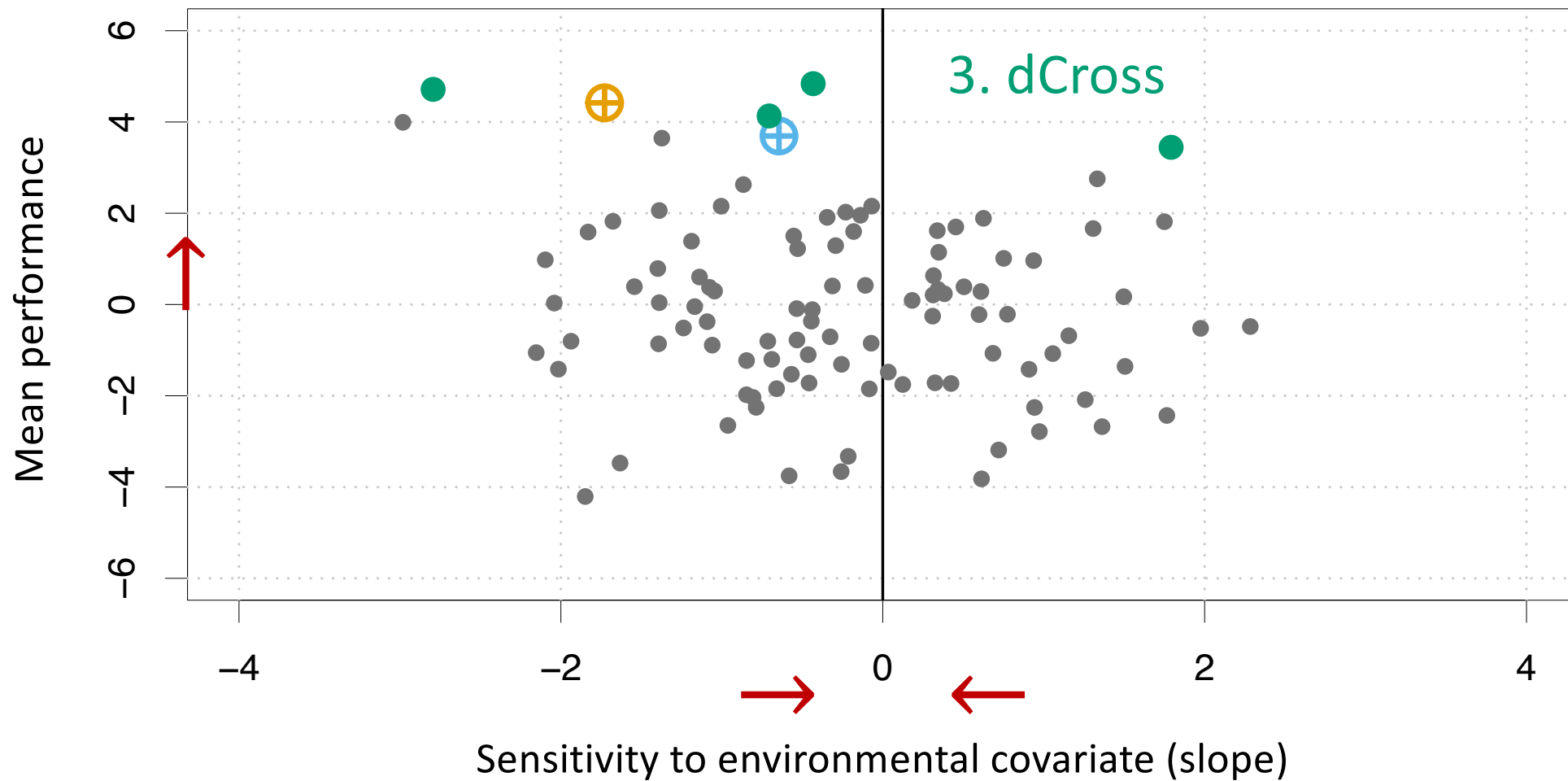
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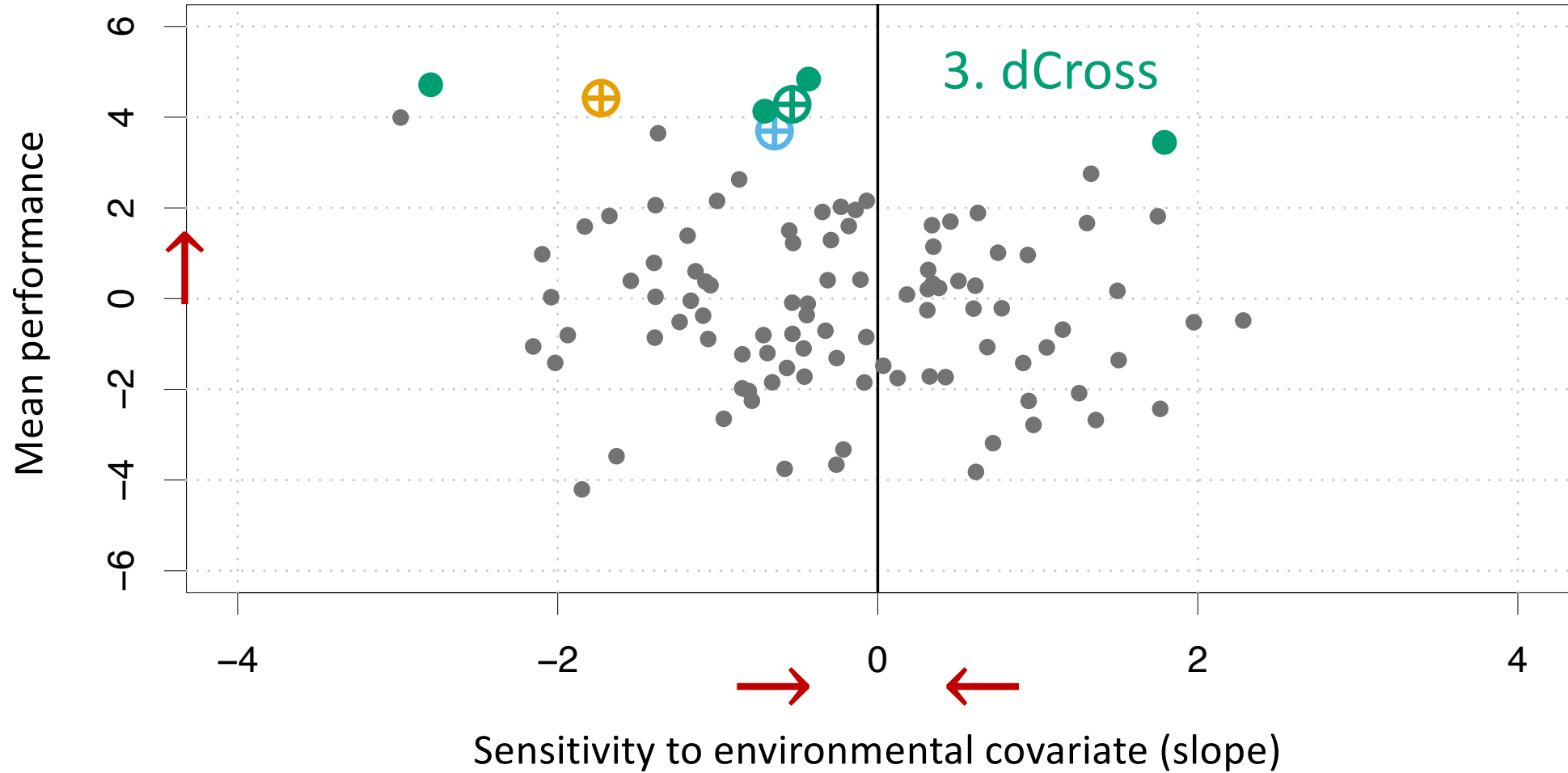
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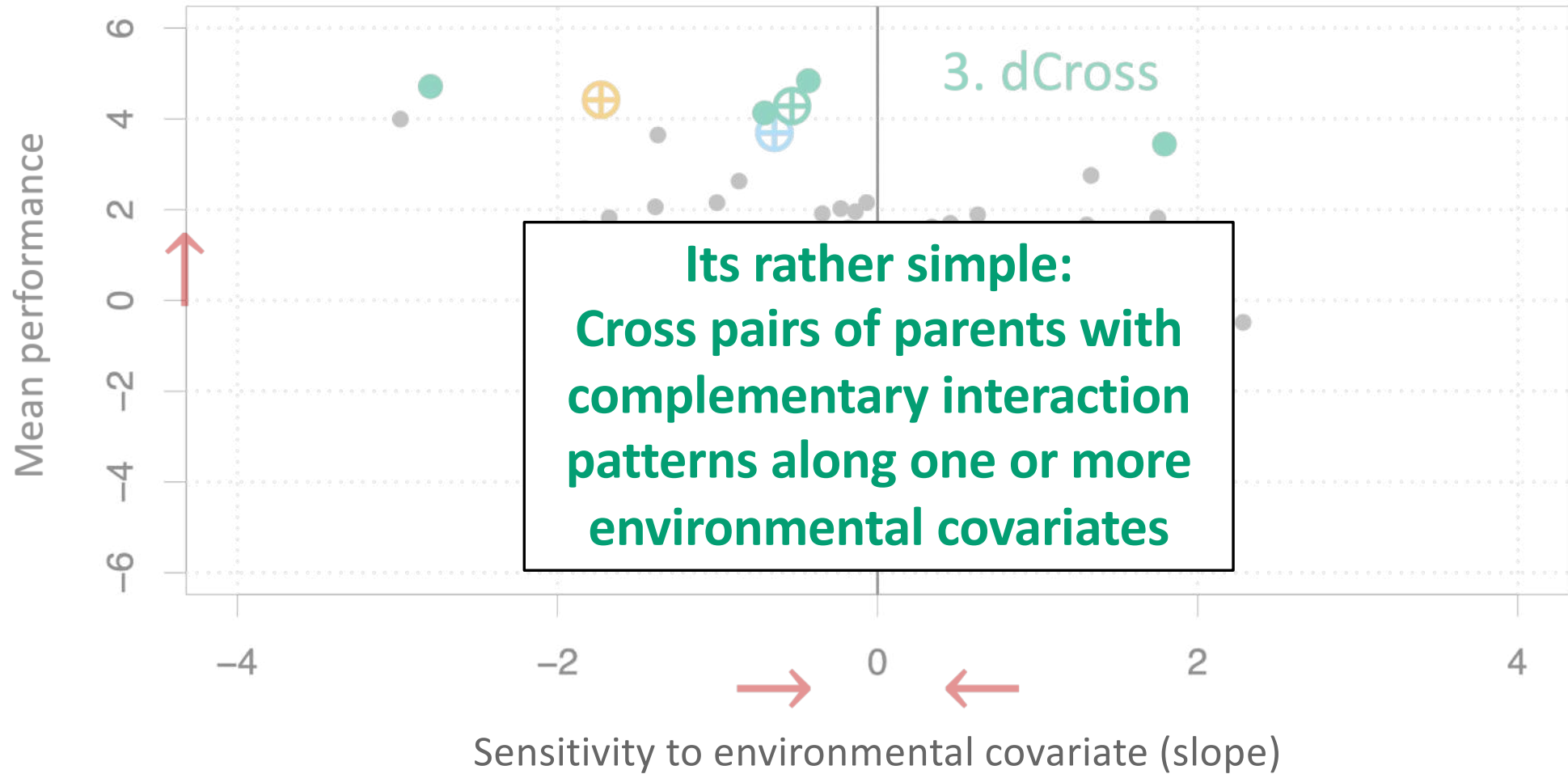
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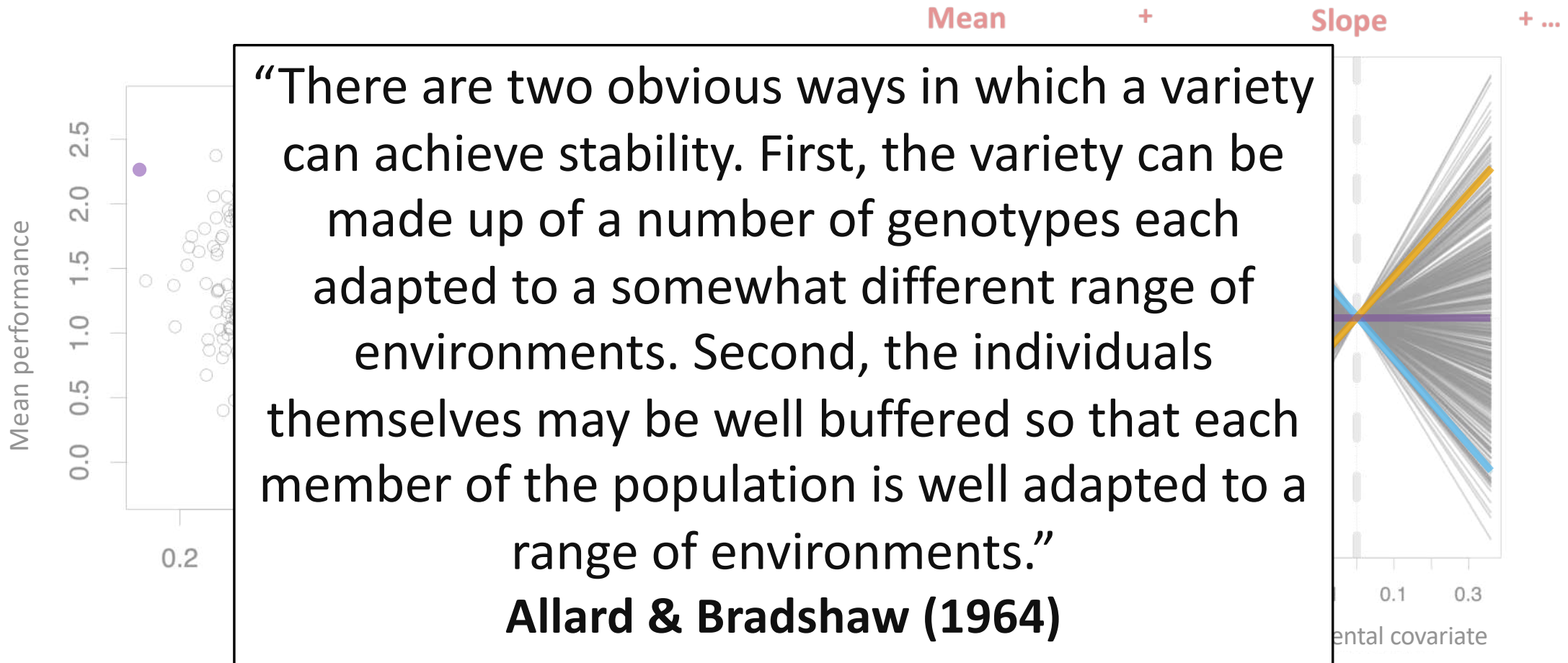
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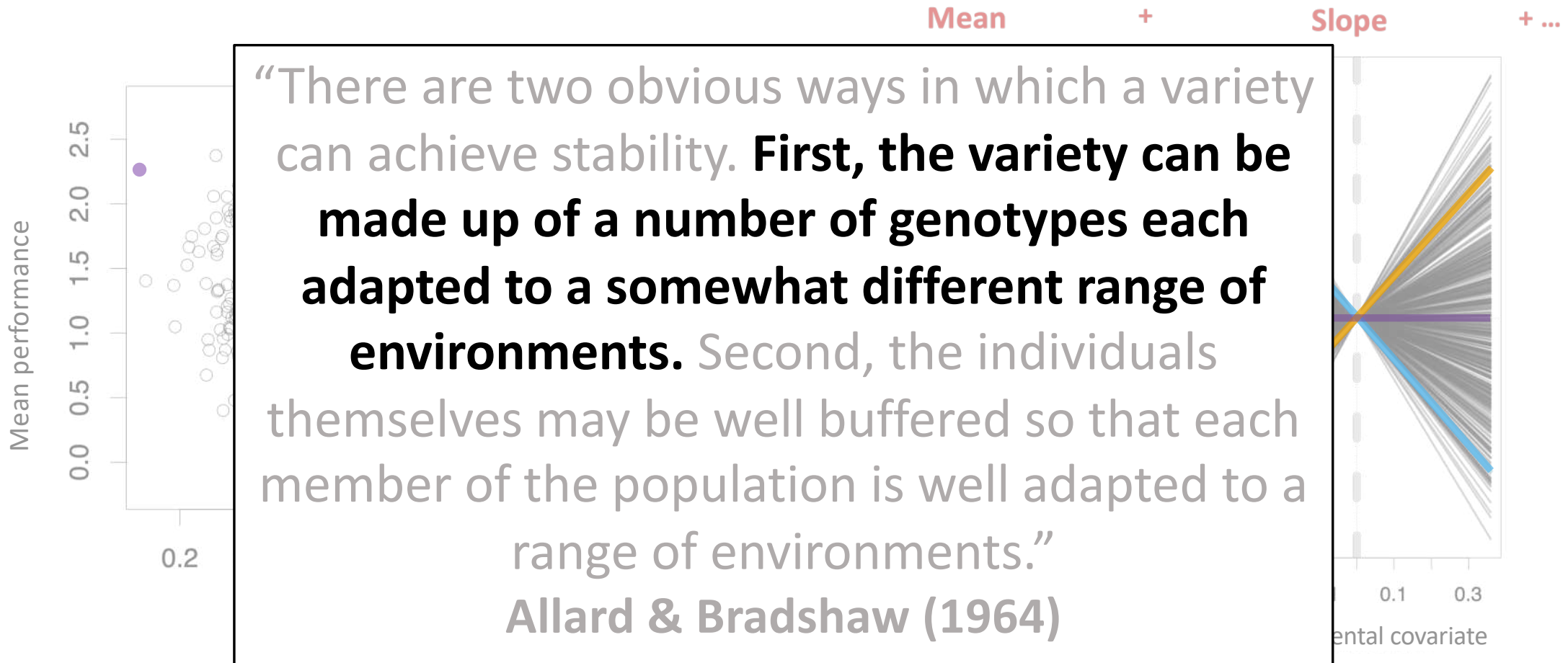
So how does dCross work?



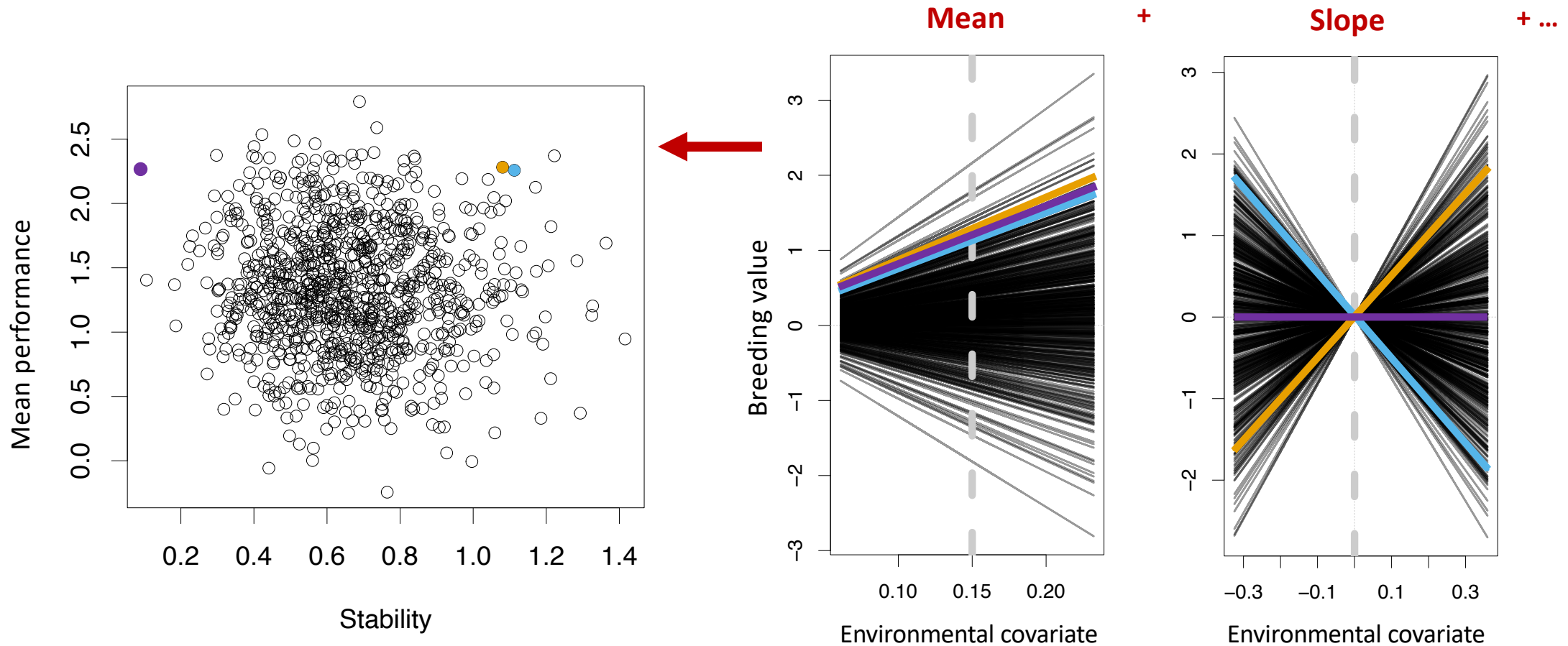
The role of stability for selection and crossing



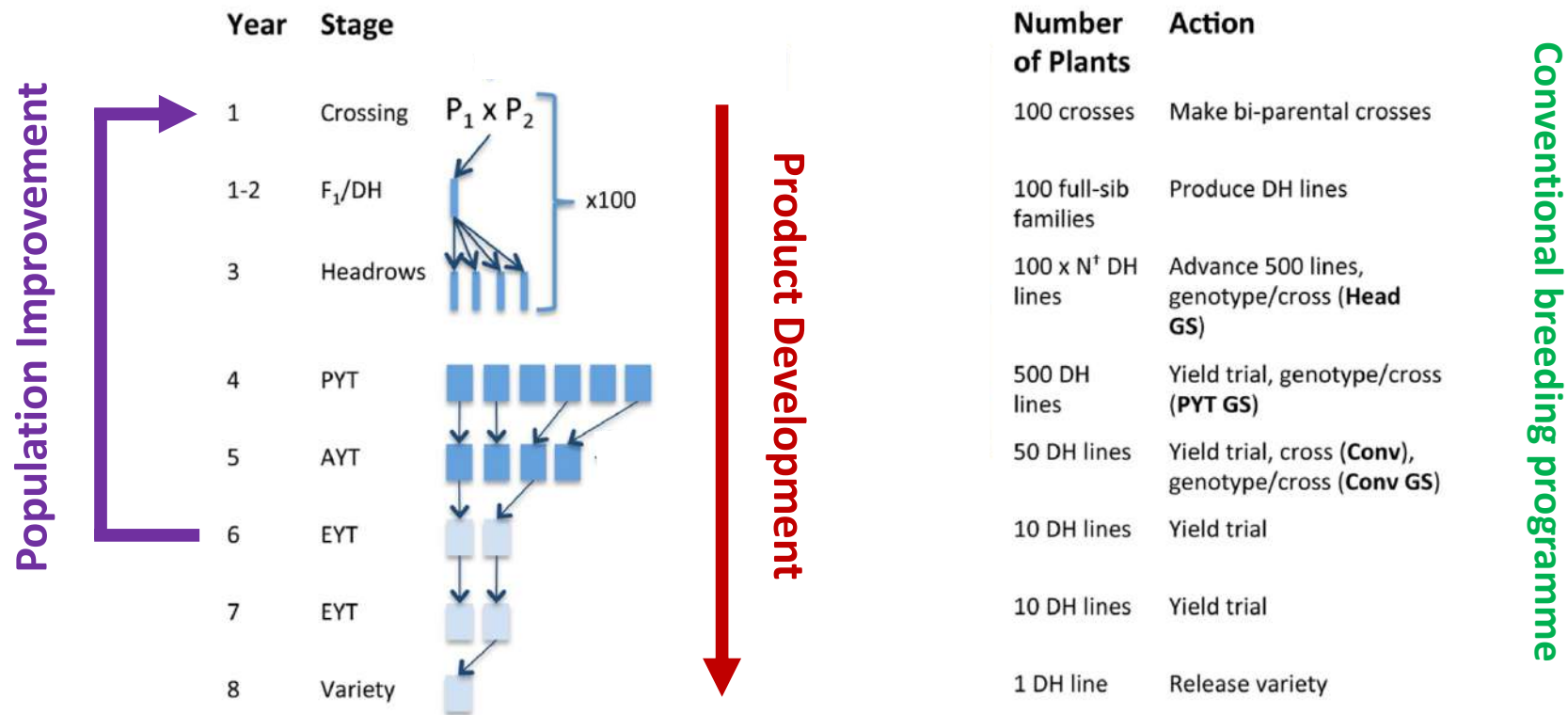
The role of stability for selection and crossing



Complementary interaction patterns



Population improvement vs product development



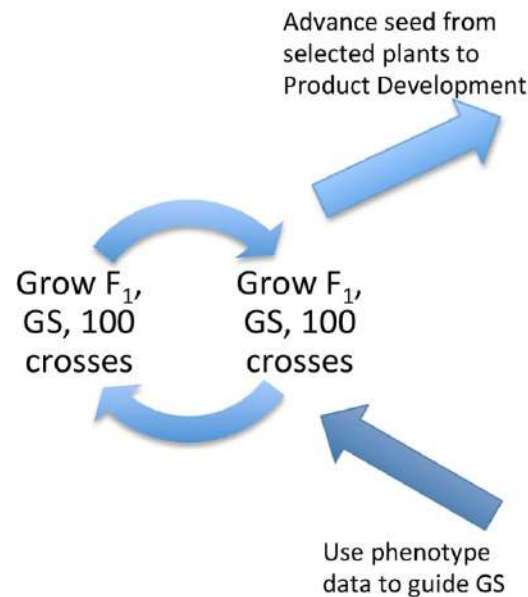
Improve the population mean for key traits of importance

Evaluate, advance and release superior varieties (products) to growers

Gaynor et al. (2017)

Population improvement vs product development

Population Improvement



Improve the population mean for key traits of importance

Product Development

Year	Stage		Number of Plants	Action
1-2	F ₁ /DH		200 half-sib families	Produce DH lines
3	Headrow		200 x N ⁺ DH lines	Advance 500 lines, genotype (2Part+H)
4	PYT		500 DH lines	Yield trial, genotype (2Part)
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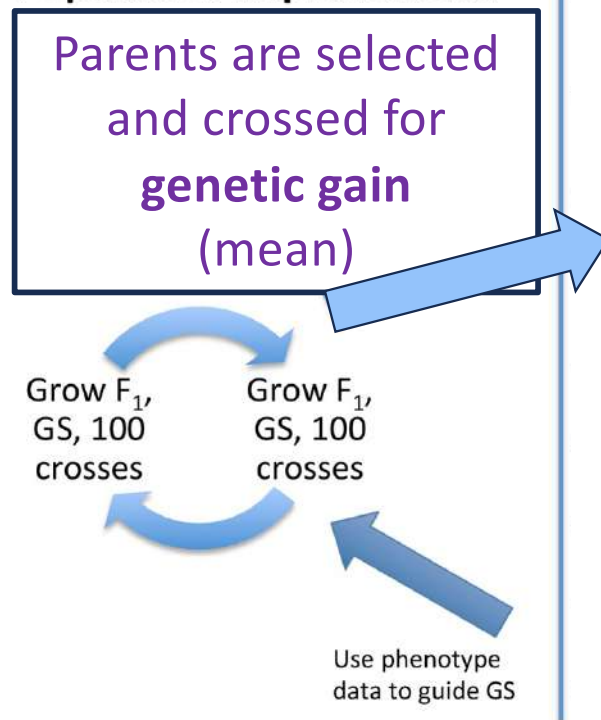
Evaluate, advance and release superior varieties (products) to growers

Two-part breeding programme

Gaynor et al. (2017)

Selection and crossing for genotype stability

Population Improvement



Improve the population mean for key traits of importance

Product Design

Parents are selected and paired to create stable **products (dcross)**

Design crosses for high performing stable genotypes

Product Development

Year	Stage	Number of Plants	Action
1-2	F ₁ /DH	200 half-sib families	Produce DH lines
3	Headrow	200 x N ⁺ DH lines	Advance 500 lines, $200 \times (200 + H)$
4	PYT	Varieties are evaluated & selected for release (index)	
5	AYT		
6	EYT	10 DH lines	Field trial
7	EYT	10 DH lines	Yield trial
8	Variety	1 DH line	Release variety

Evaluate, advance and release superior varieties (products) to growers

Takeaway messages

- Consider how to include stability into selection and crossing decisions
 - Appropriate for product development, but not population improvement
 - Implies a population that reacts identically to environmental stimuli (diversity loss)
 - “Unstable” genotypes are valuable and should not be ignored from parent selection
- dCross involves 3 key steps for designing high yielding stable products:
 1. Set the selection focus/direction (e.g., mean performance over environments)
 2. Disentangle non-crossover and crossover interaction around this focus
 3. Pair parents with complementary interaction patterns
- GEtools: tools & resources for disentangling, visualizing and leveraging GxE interaction for parents and products, built on selection index theory

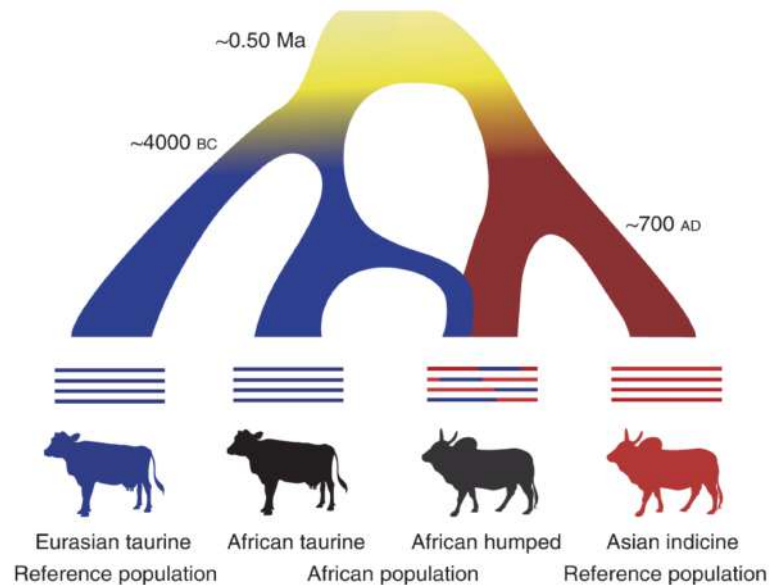
Some practical examples in plants and animals

Uncovering the impacts of genotype by environment interaction in crossbreeding dairy cattle

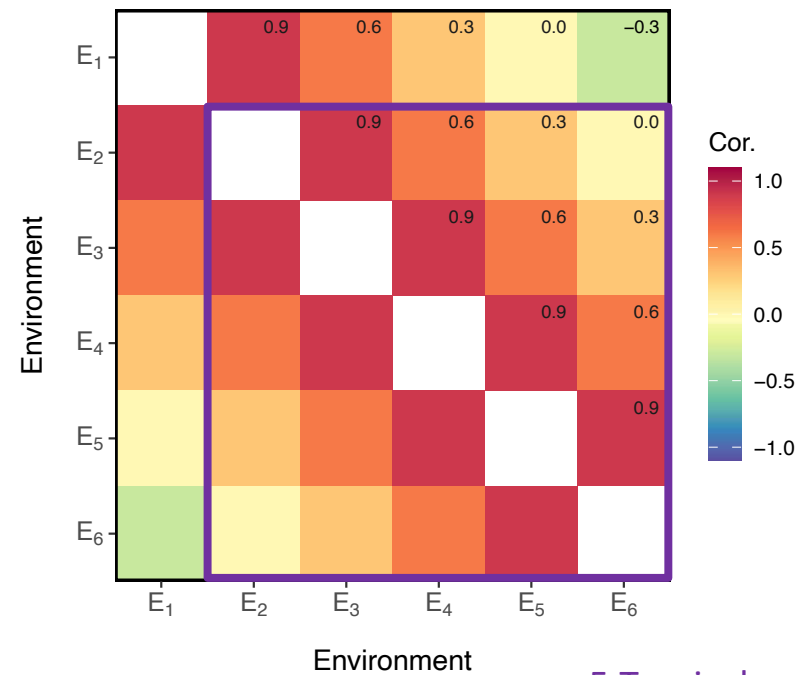


Gabriela Mafrá Fortuna

1 temperate environment



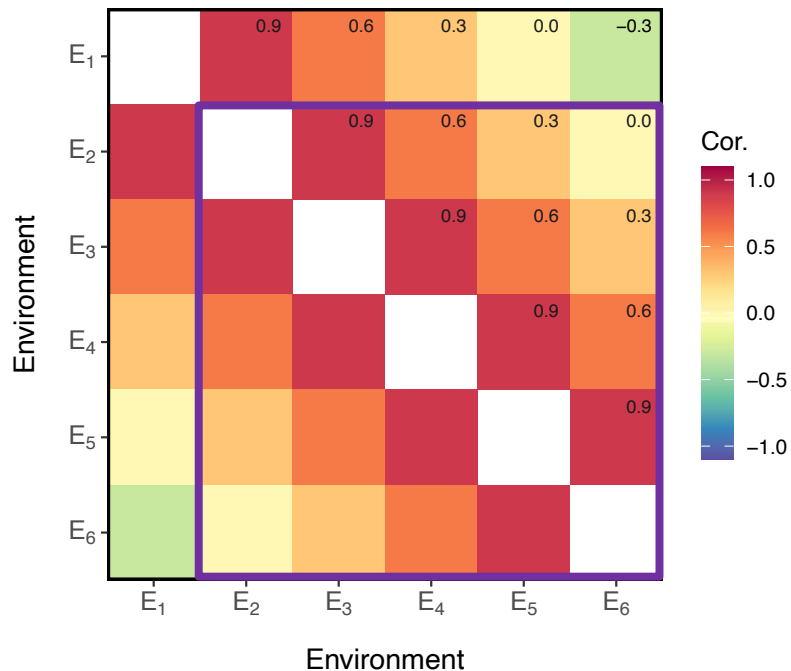
Kim et al., 2020



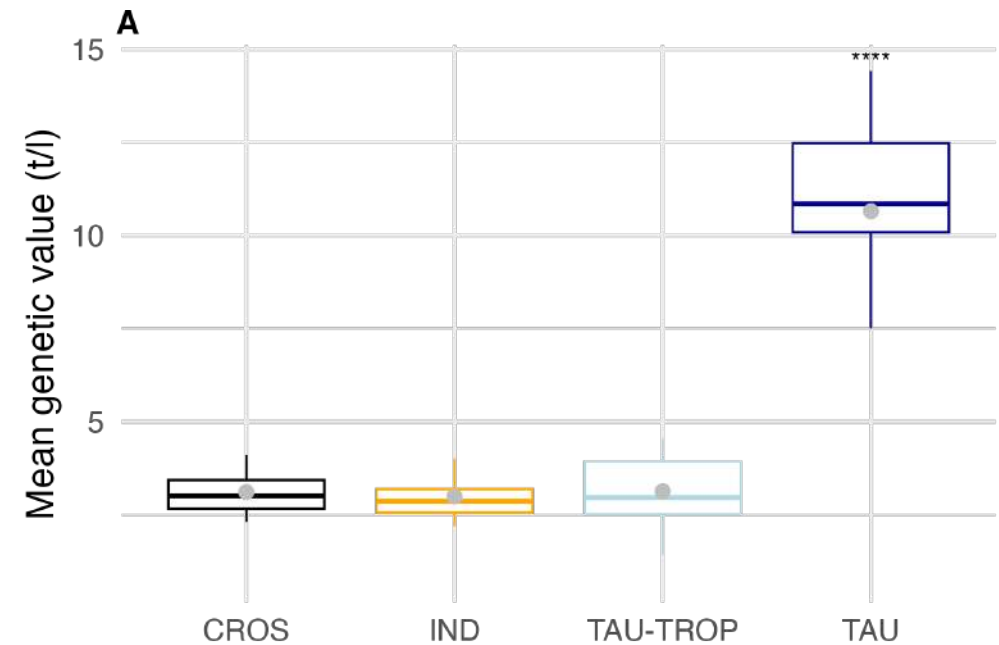
5 Tropical environments

Uncovering the impacts of genotype by environment interaction in crossbreeding dairy cattle

1 temperate environment

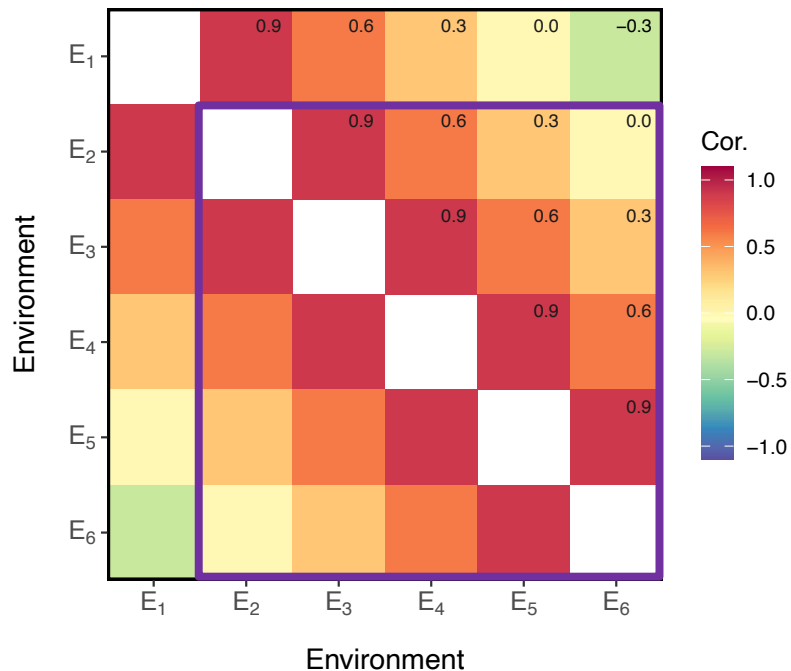


5 Tropical environments

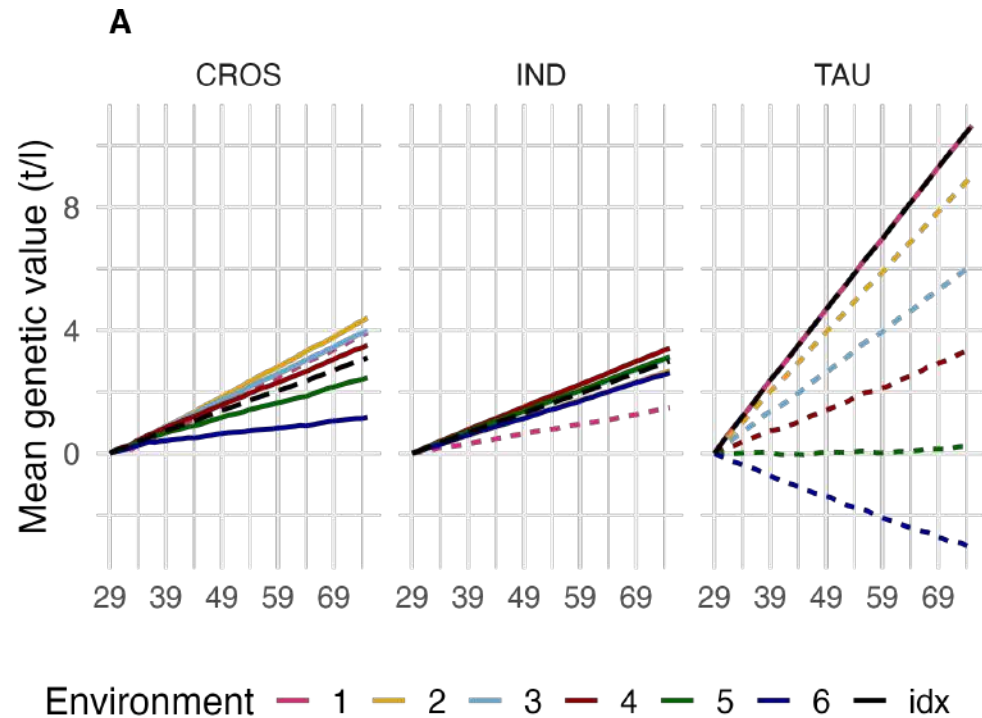


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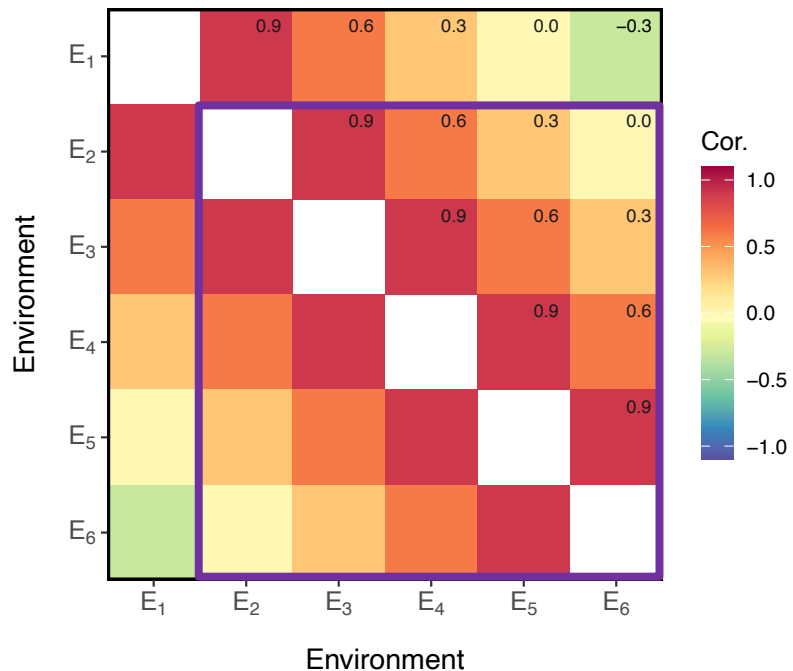


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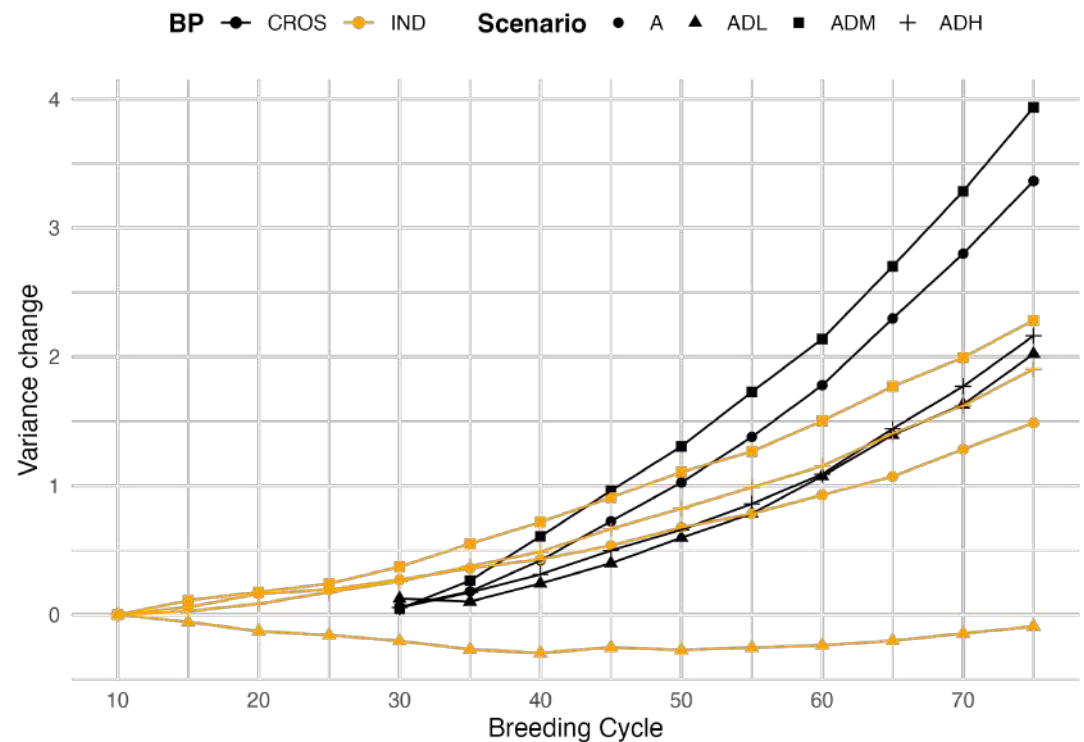


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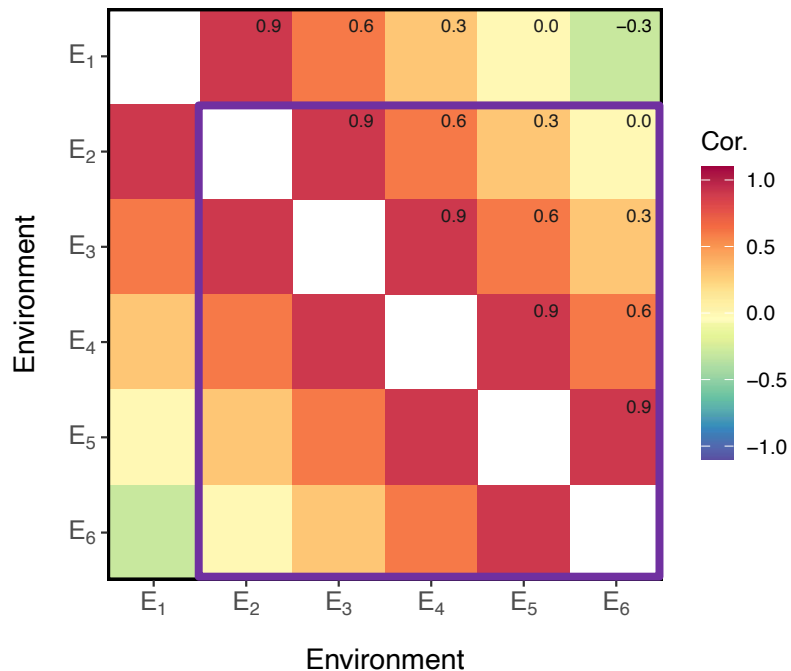


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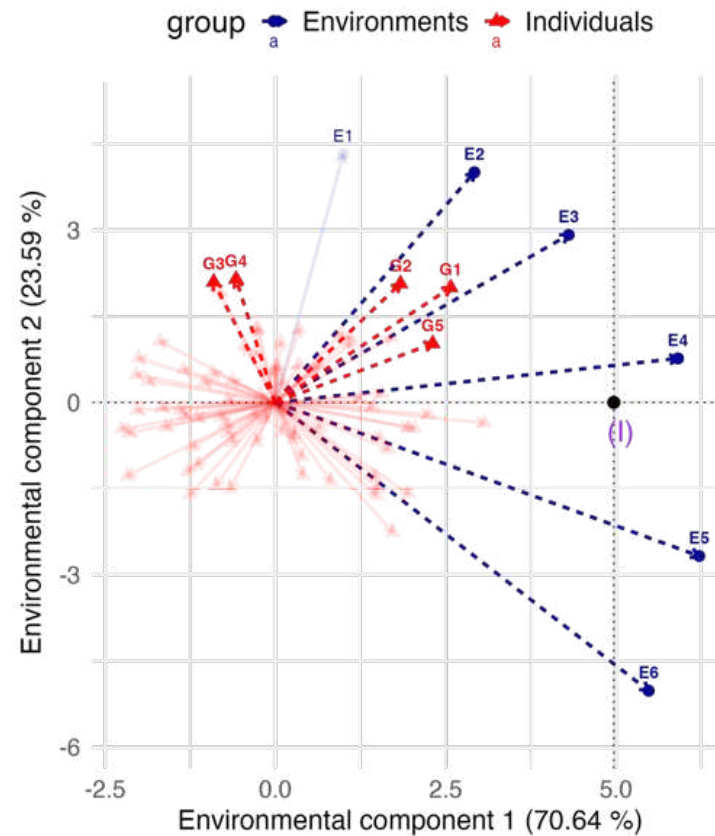


Uncovering the impacts of genotype by environment interaction in crossbreeding dairy cattle

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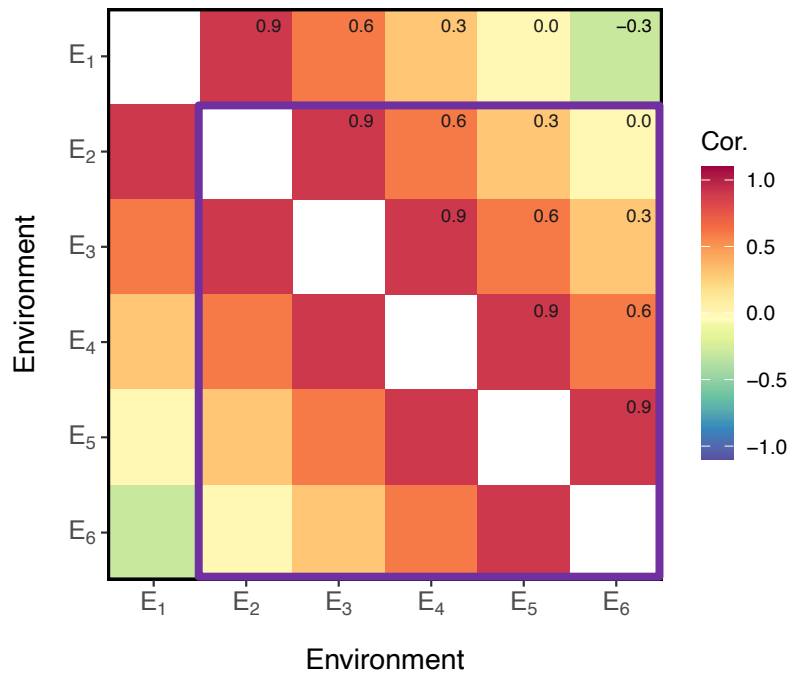


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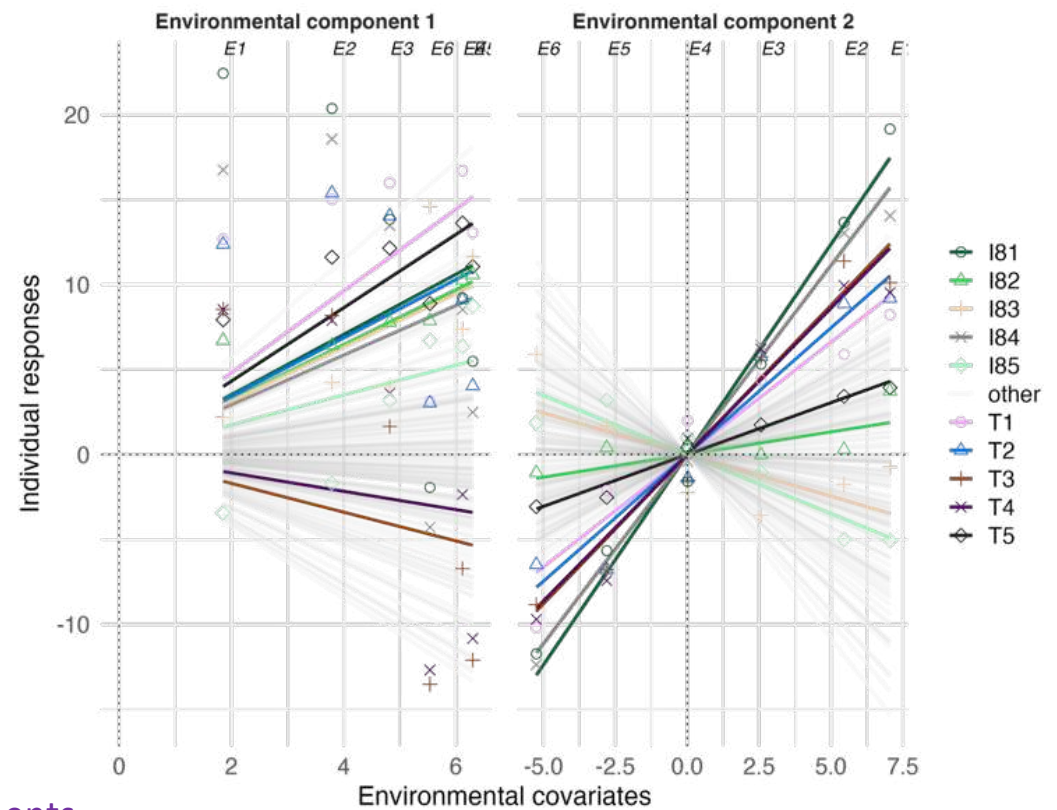


Uncovering the impacts of genotype by environment interaction in crossbreeding dairy cattle

1 temperate environment



5 Tropical environments



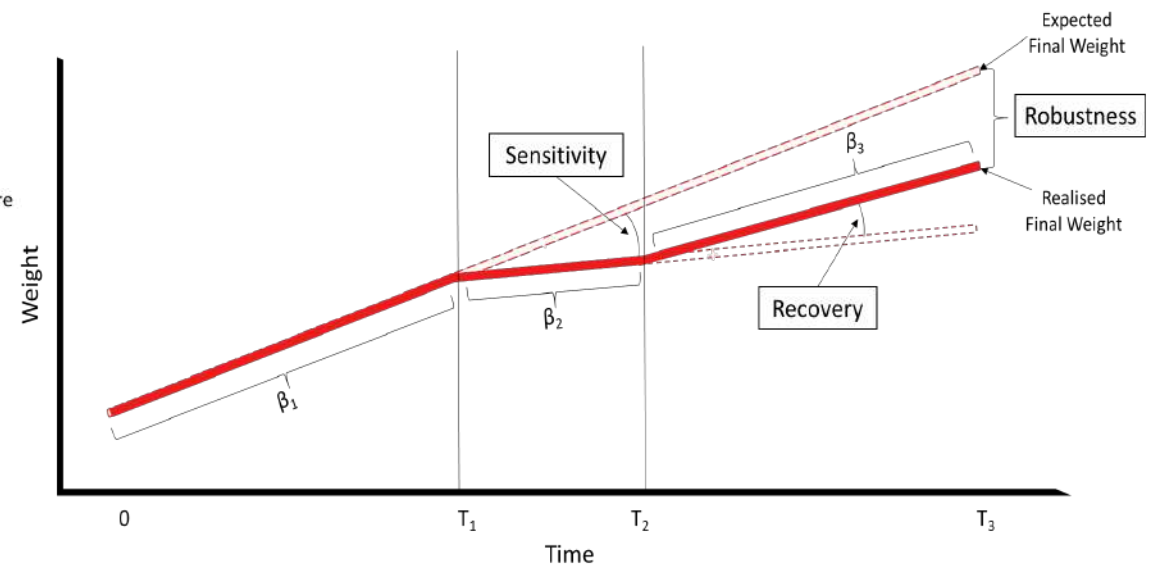
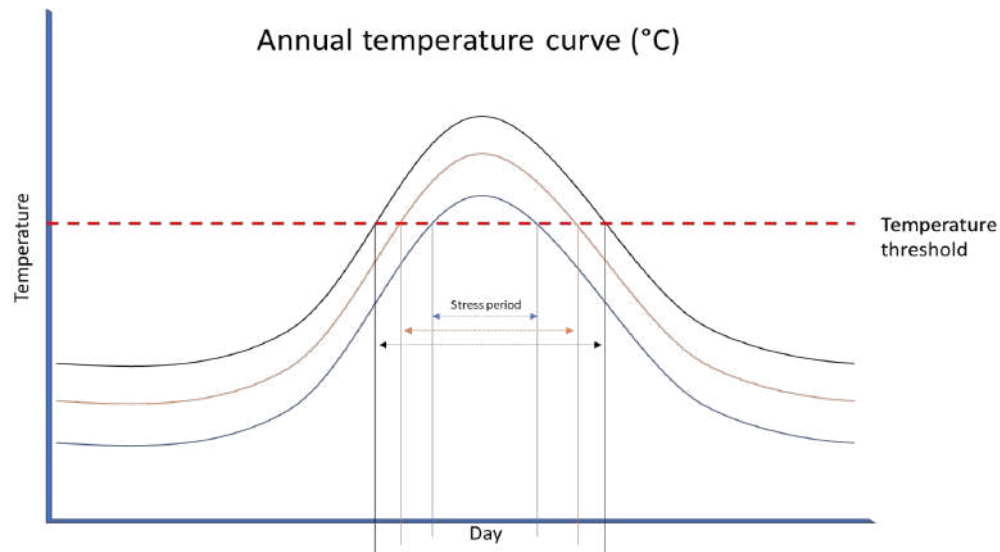
Takeaway messages

- There is an increasing interest to import exotic genetics into crossbreeding
- There is little knowledge on how to use these genetics to improve the performance *and* stability of crossbred animals within diverse environments
- We showed that:
 - There is potentially useful genetic variation in the reactions (slopes) of exotic and local individuals across diverse environments
 - This variation can be used for optimising mating schemes
 - Designing crossbred populations that are high performing and stable

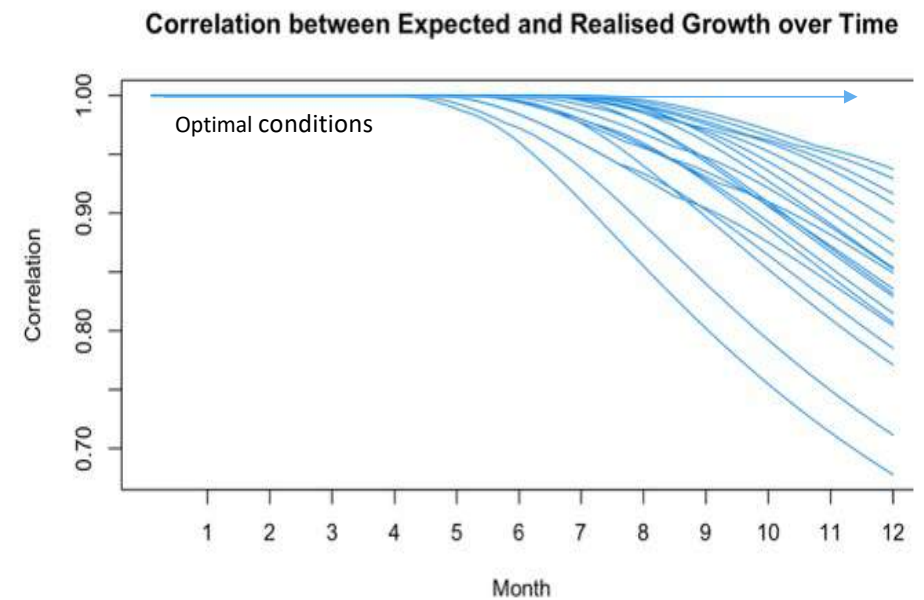
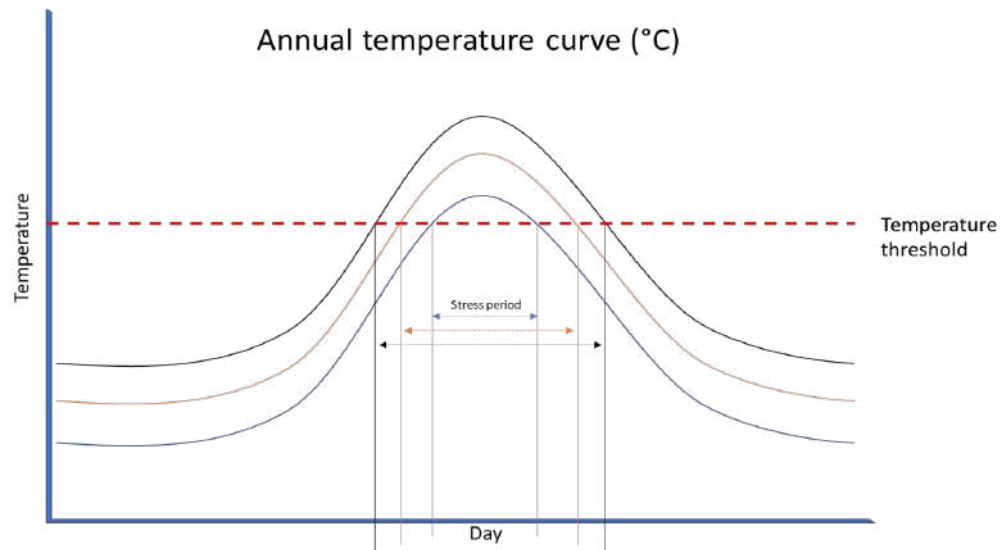
Simulating resilience traits in aquaculture



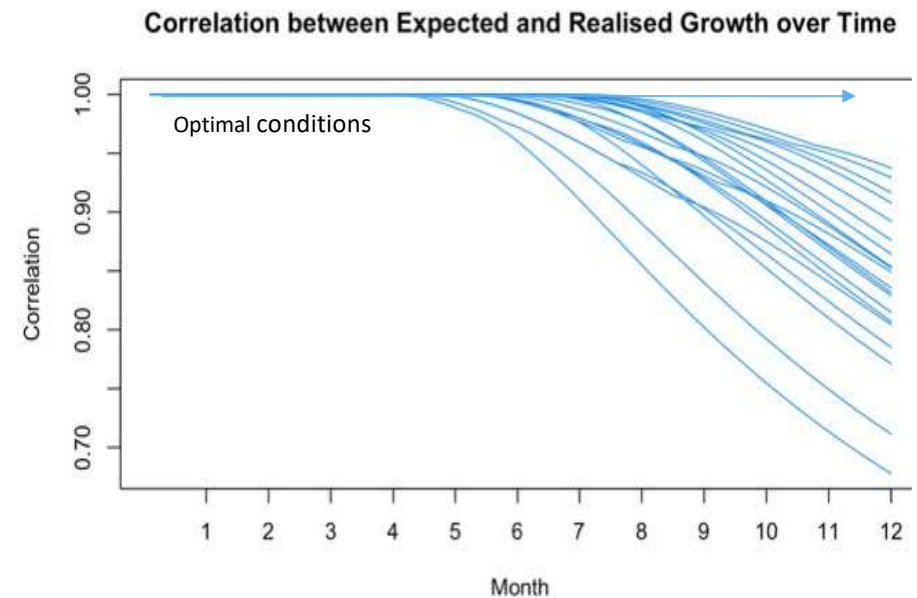
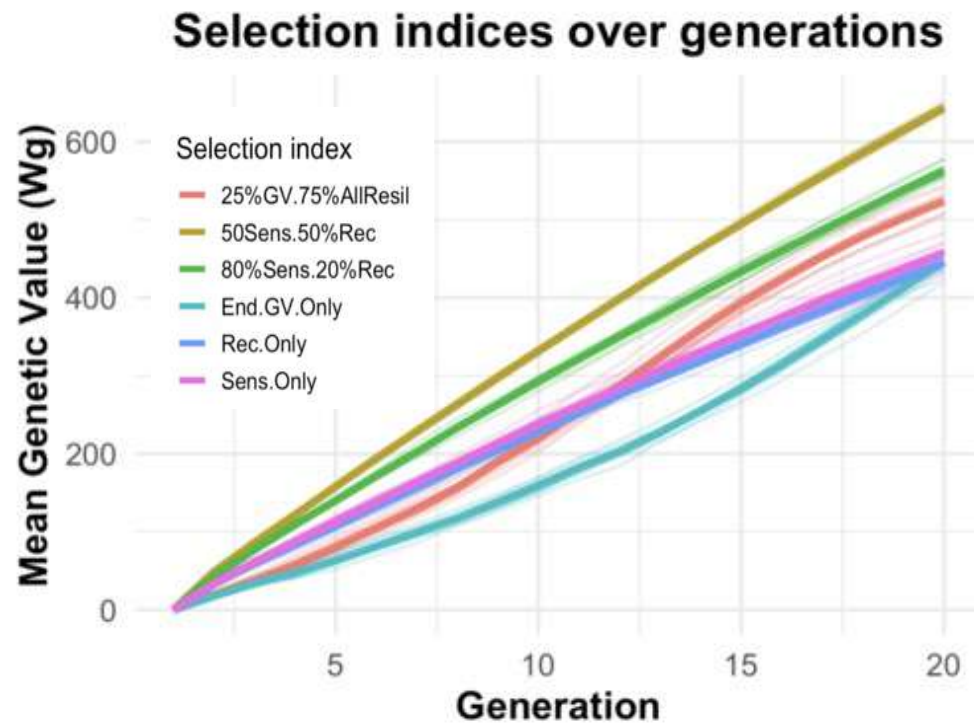
Duncan Henderson



Simulating resilience traits in aquaculture



Simulating resilience traits in aquaculture

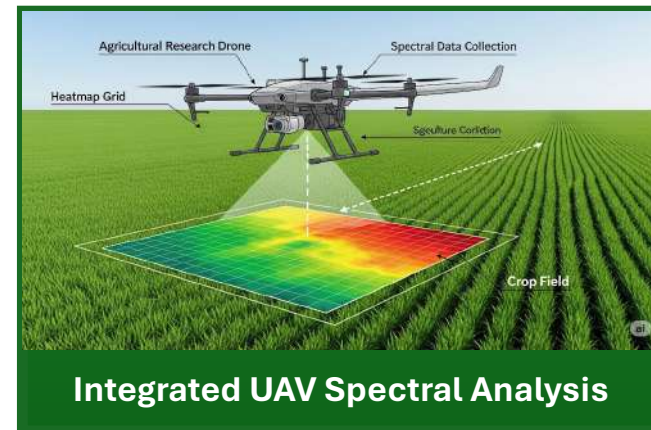
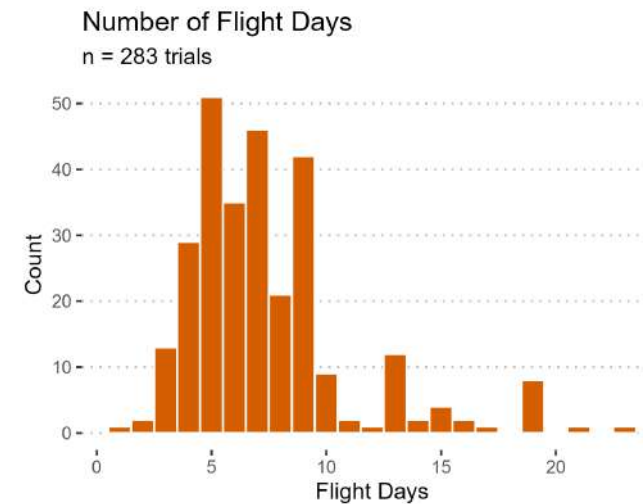
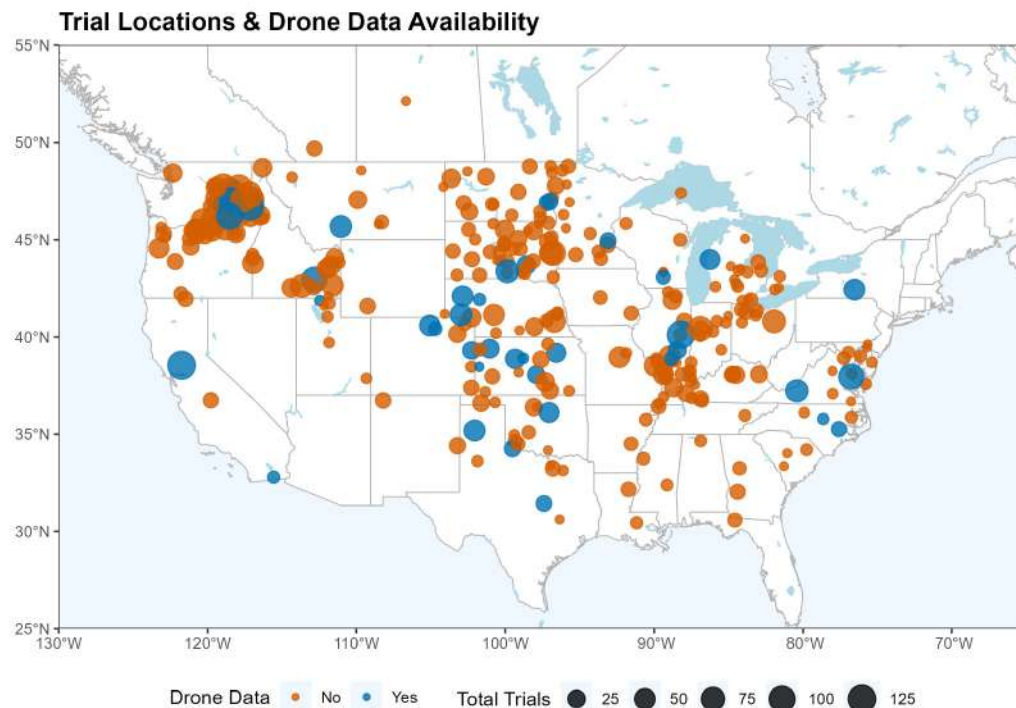


Takeaway message / next steps

- Genotype by environment interaction is becoming increasingly important in aquaculture due to the diverse set of production environments and changing environments (e.g., increasing sea temperature)
- The aim here was:
 - Demonstrate that even small fluctuations in the timing and duration of simple stresses can have substantial impact on growth and rankings of individuals
 - Propose how resilience can be incorporated within the breeding objective through a selection index
 - **But again**, we don't want "stable" parent populations, we want product populations that can cope with current and new stresses – designing crosses.

Leveraging high-throughput phenotyping across the US wheat belt

WheatCAP: National effort to accelerate breeding cycles & mitigate climate change impacts on wheat productivity

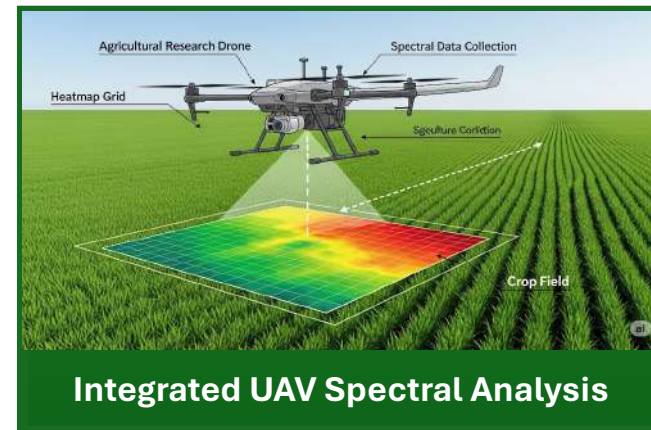
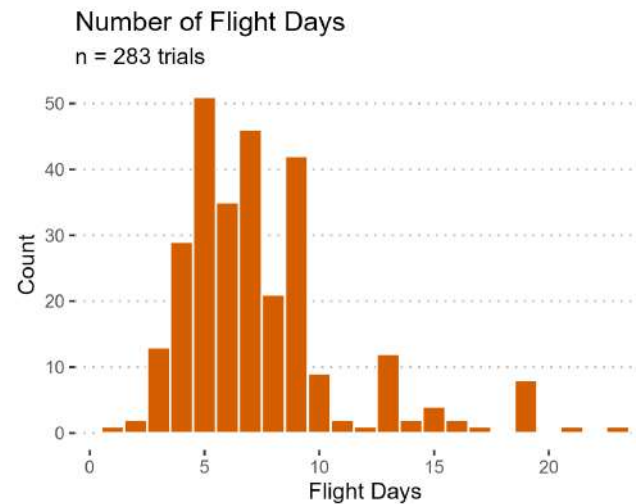
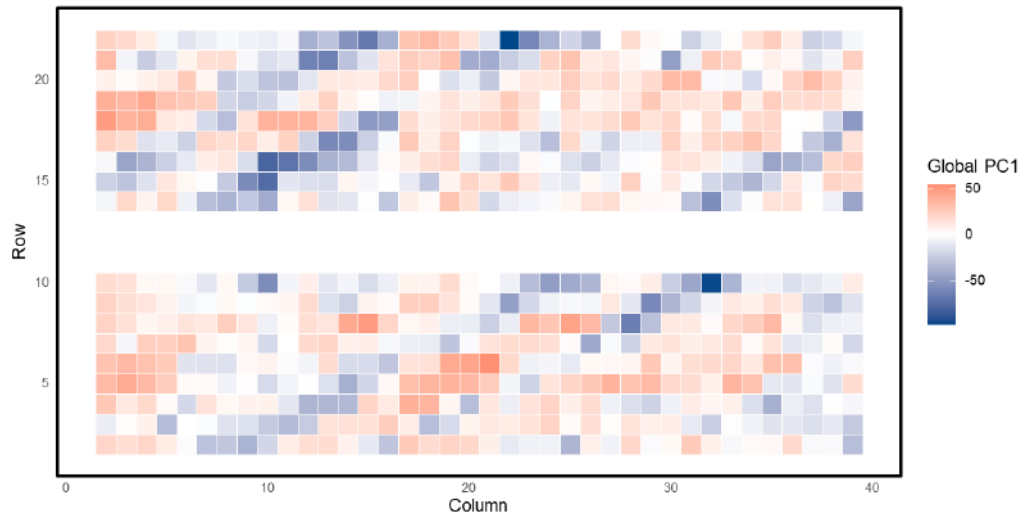
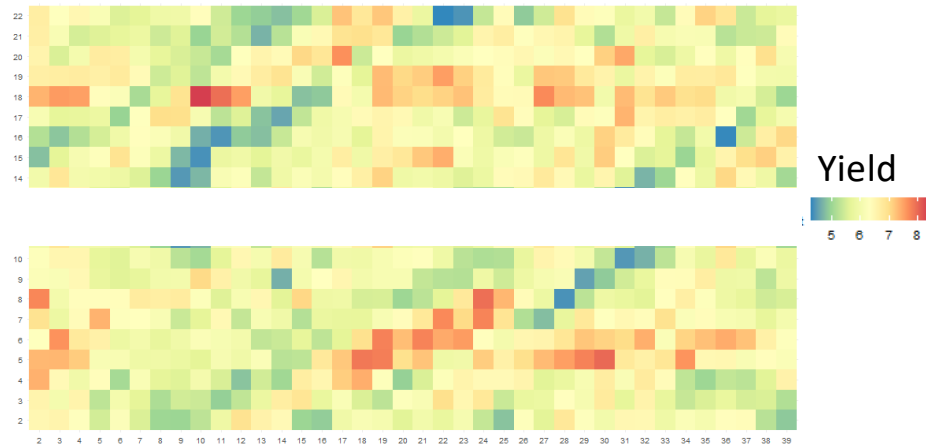


Zac Aldiss



Jessica Rutkoski

Leveraging high-throughput phenotyping across the US wheat belt



Zac Aldiss



Jessica Rutkoski

Takeaway message / next steps

- There is an increasing demand to collect secondary phenotypes from novel sources such as drones
- There is little knowledge on how to use this data effectively for improving breeding decisions (beyond minor accuracy improvements)
- The aim here is:
 - Improve prediction through genetic *and* residual modelling
 - Construct novel phenotypes which dissect genotype “stability” to various stresses within sites
 - Link these across sites (using environmental data), thereby identifying meaningful stresses (and their phenotypes) for breeding

Tools for designing optimal crossing schemes in breeding programmes

CrossingTools: Available on CRAN soon!



Sven Weber

Cross value estimation

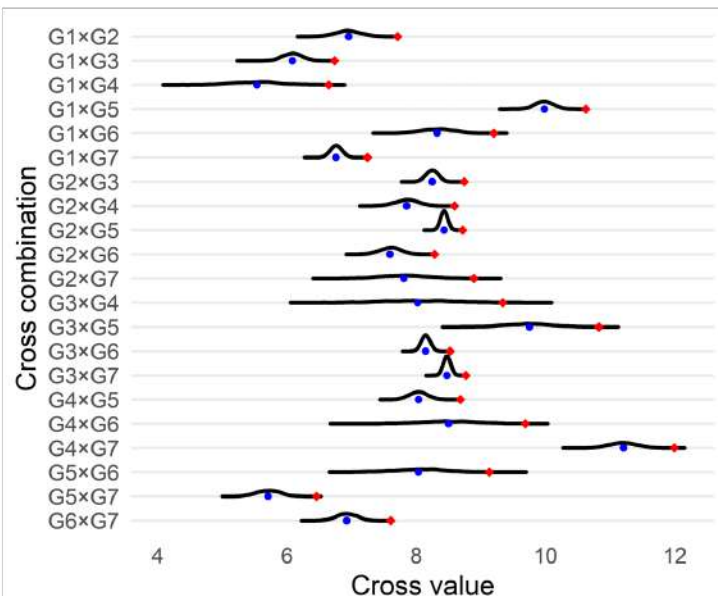


Fig. 1. Schematic plot of cross performance. Each layer shows the expected family distribution (black line), the mean cross value (blue dot), and the superior progeny value (red square).

Cross selection

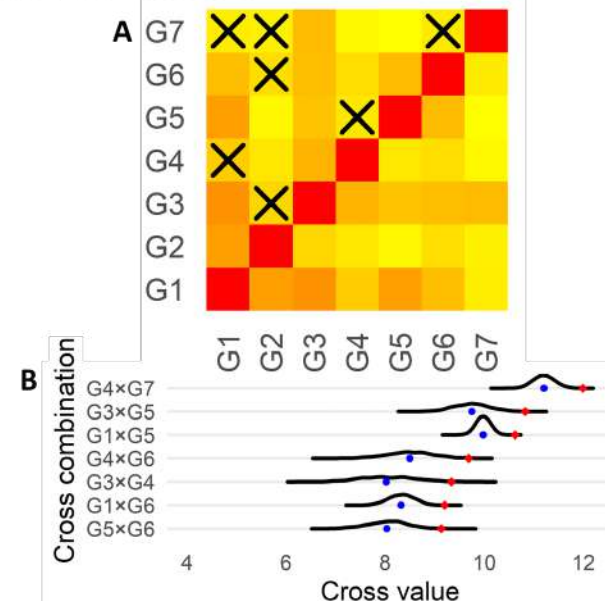


Fig. 2. Cross selection strategies. **A** Optimal cross selection. **B** Selection of the crosses with the highest value, here superior progeny value.

Mating

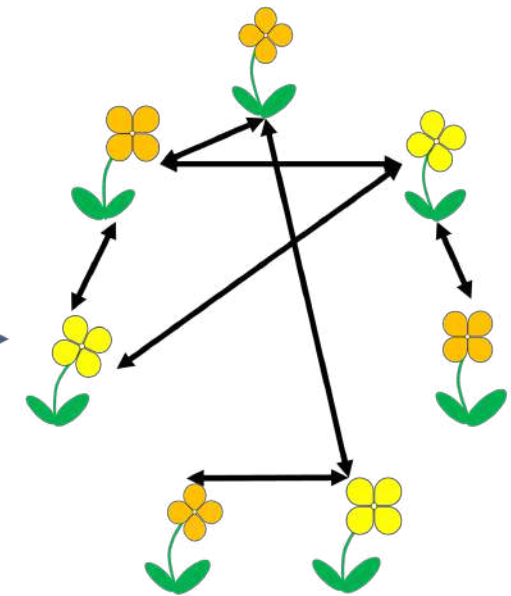


Fig. 3. Schematic of cross execution in a breeding programme

Takeaway message

- Crossing tools allows us to design high performing and stable individuals through optimal mating plans
- Scalable and general to various (animal and plant) breeding programmes
- Plug-and-play with optimal contribution selection for managing genetic diversity
- Utilise genetic variation in GxE interaction for improving breeding outcomes amid climate change

Leveraging genotype by environment interaction for improving crossing and selection decisions in plants and animals

Taking GxE from an impediment to breeding towards a mechanism for generating future-ready climate-resilient plants and animals

Pre-prints and R packages coming soon...

Disentangling non-crossover and crossover genotype by environment interaction for selection: A theoretical framework

D.J. Tolhurst

+ GEtools

Designing high performing and stable genotypes through complementary crossing schemes

D.L. Waters, C. Finegan, S.E. Weber, B. Gardunia, D.J. Tolhurst

Tools for designing optimal crossing schemes in plant breeding programmes

S.E. Weber · D.L. Waters · C.R. Werner · D.J. Tolhurst

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