

Plant breeding through the lens of quantitative genetics

CJ Yang

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About me



1. Malaysia
2. Indiana (BSc Biotech, Maths)
3. Wisconsin (PhD Genetics)
4. Freising, DE (Postdoc)
5. Edinburgh, UK (Postdoc)

Map from R/maps

Talk outline

- Introduction
- Project 1: Crop domestication
- Project 2: Genetic diversity and pre-breeding
- Project 3: Novel crop breeding
- Future directions

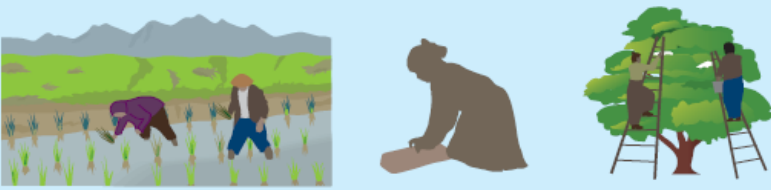
Introduction

Plant breeding, complex traits and genetic gain

Plant Breeding

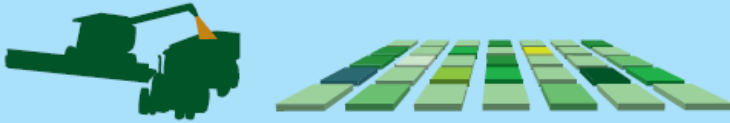
BREEDING 1.0

Incidental selection by farmers



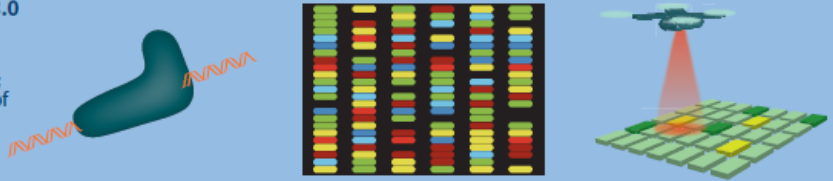
BREEDING 2.0

Statistical and experimental design to improve selection effort



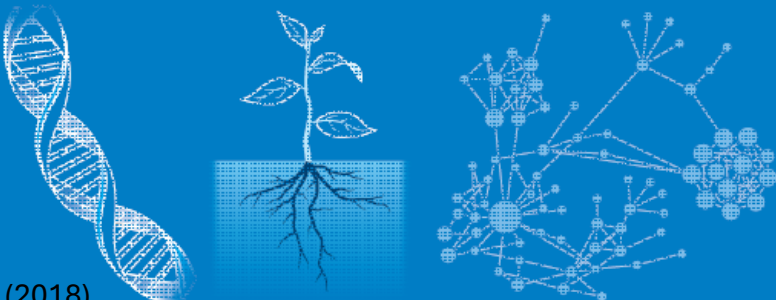
BREEDING 3.0

Integration of genetic and genomic data; current state of the art



BREEDING 4.0

Ability to combine any known alleles into optimal combinations; will be reached soon for some crops

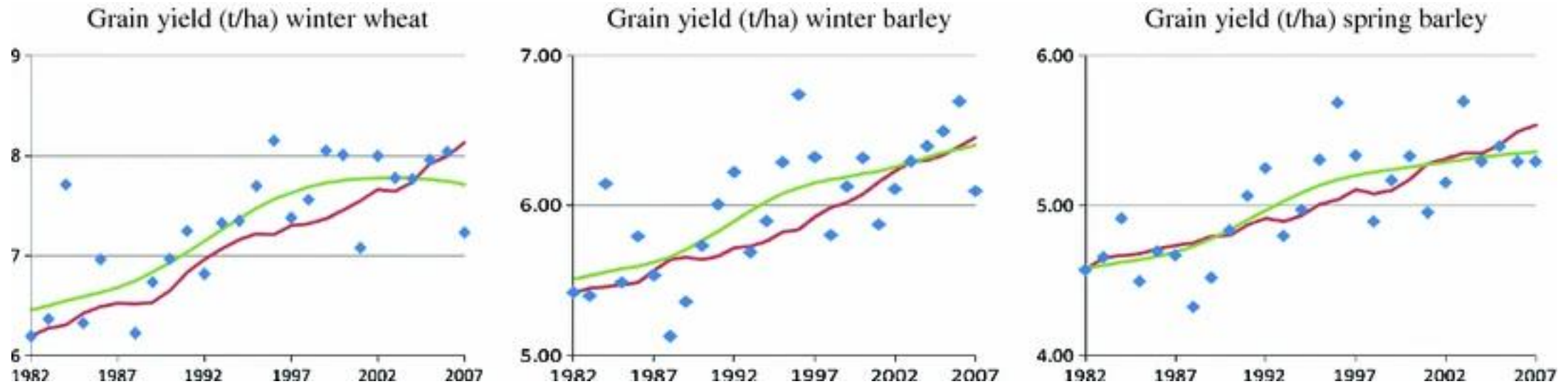


Wallace et al (2018)

- Domestication
- Improvement
- Experimental design
- Marker assisted selection (MAS)
- Genomic/Phenomic selection (GS/PS)
- Biology-Breeding
- Gene editing (GE)
- Functional variants
- Machine learning (ML/AI)

Breeding in major crops

Yield increase is largely driven by genetic improvement.



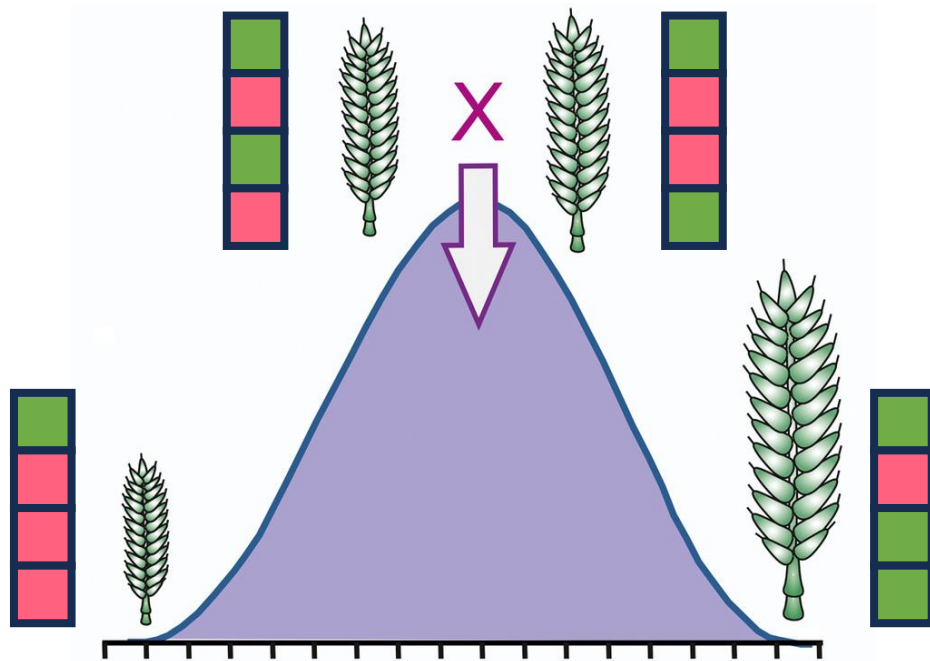
Mackay et al (2011)

Green/blue: national yield

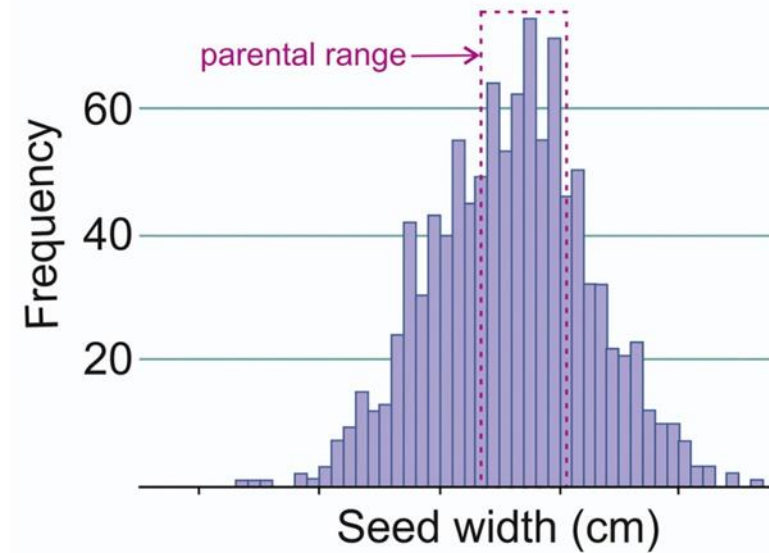
Red: variety effect

Success in line breeding

Transgressive segregation: recombination and shuffling of causative genetic loci.



(d) Transgressive segregation for seed width in 'NIAB Elite MAGIC'



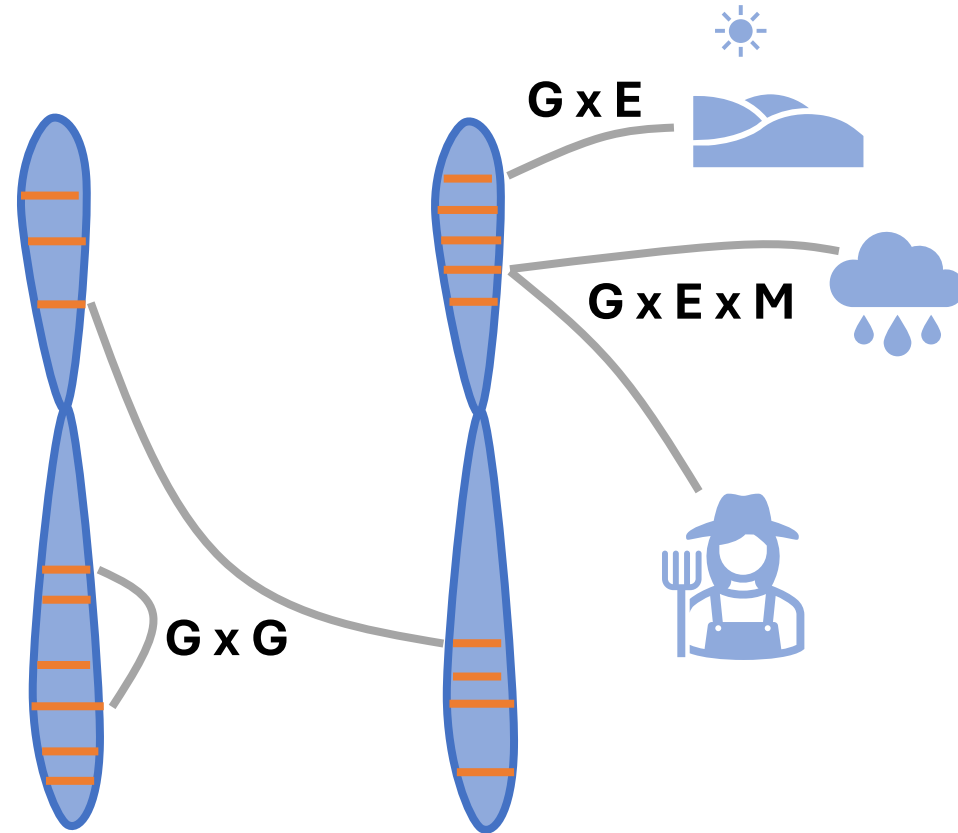
Mackay et al (2021)

Complex traits

Breeding targets: yield, flowering time, plant architecture, resource use efficiencies.

Quantitative/polygenic traits

Working model:



Genetic Gain

Breeder's equation
(Lush 1937)

$$R = h^2 S$$

$$R = \frac{\sigma_g^2}{\sigma_p^2} \sigma_p i$$

$$R = \frac{\sigma_g}{\sigma_p} \sigma_g i$$

$$R = h \sigma_g i$$

Rate of genetic gain

$$\Delta R = \frac{h \sigma_g i}{t}$$

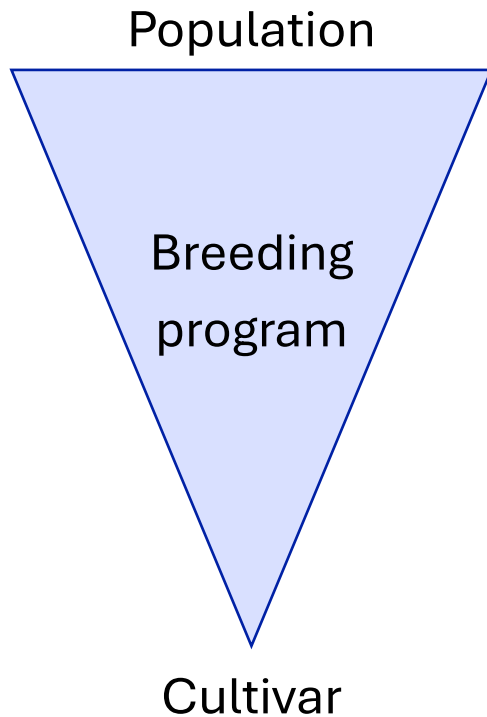
$$\Delta R = \frac{\text{sel. accuracy} \times \text{genetic variation} \times \text{sel. intensity}}{\text{time}}$$



Framework for quantitative genetics

Improving ΔR

$$\Delta R = \frac{\textit{sel. accuracy} \times \textit{genetic variation} \times \textit{sel. intensity}}{\textit{time}}$$



- Multiparental population, mutation, pre-breeding.
- MAS, GS, GE, phenomics.
- Larger/efficient trials.
- Rapid cycling, speed breeding (SB/RGA).

Plant breeding: a journey through time

Project 1: crop domestication

Project 2: genetic diversity and pre-breeding

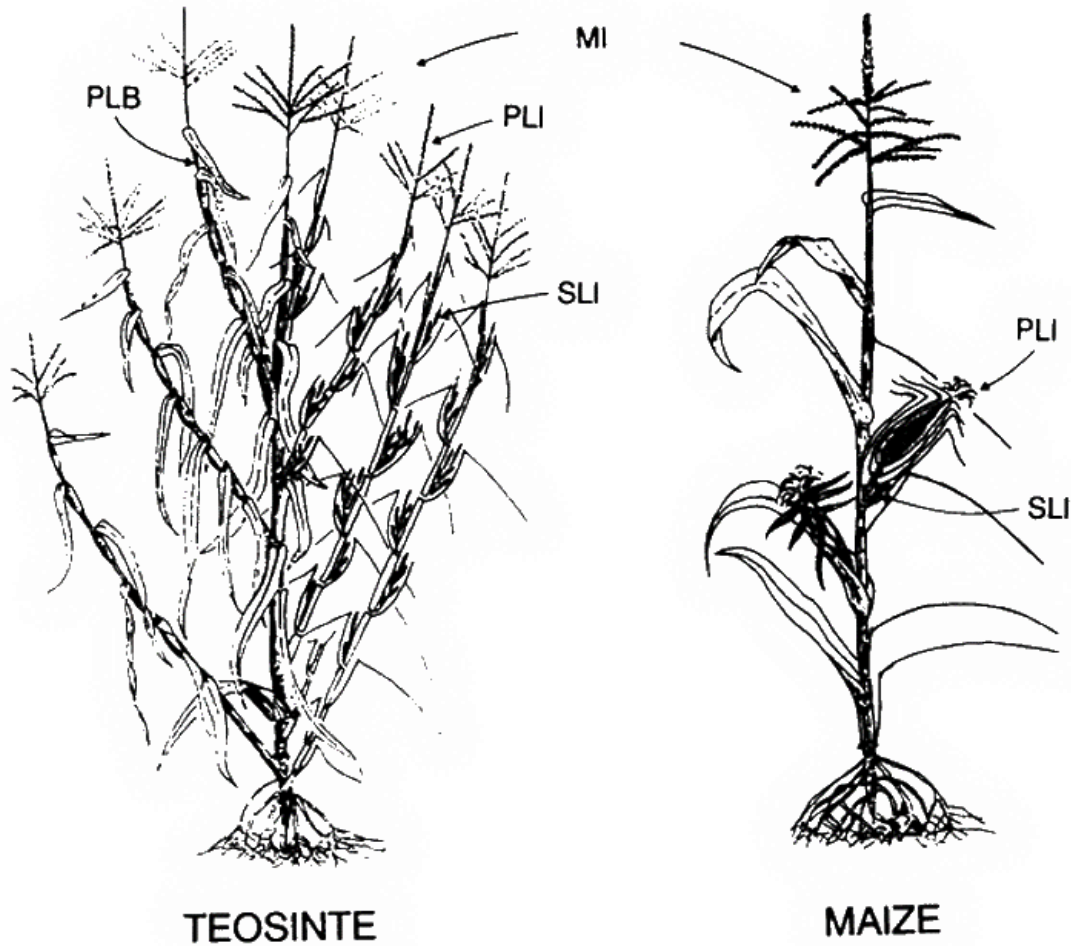
Project 3: novel crop breeding

Domestication

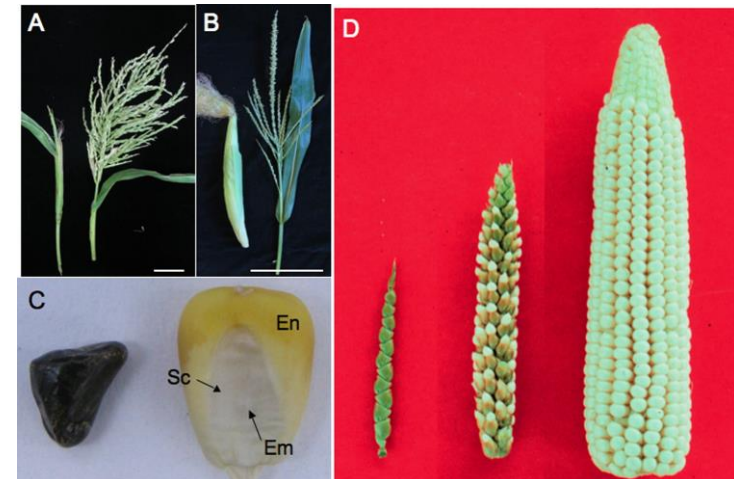
This earliest form of plant breeding is known as domestication, where plants were selected to be more productive, easier to harvest, or more aesthetically or gastronomically pleasing (Flint-Garcia 2013).

Maize-teosinte model

- Tillers
- Lateral branches
- Terminal inflorescence
- Ear length/diameter/number
- Kernel number/size/glume



Doebley et al (1990)



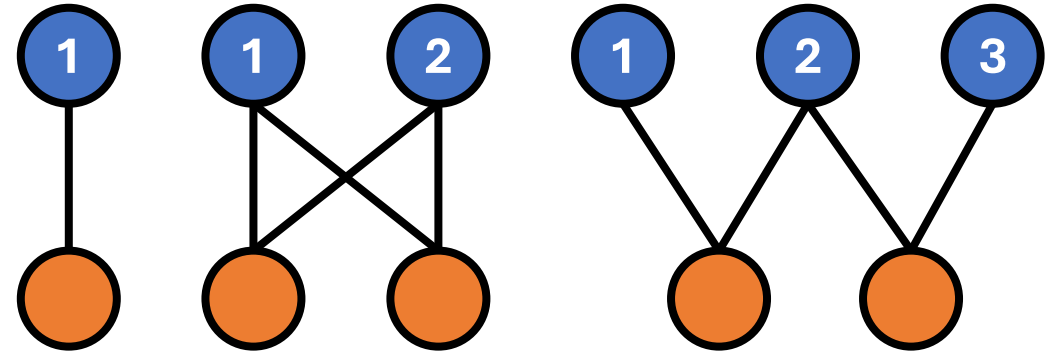
Hake and Ross-Ibarra (2015)

Study population

50 parents from Palmar Chico – Rio Balsas



Crossing schemes



Field trials

- Homestead, FL, 2013 – 2017
- 3,000 plants/year, randomized
- 18 domestication traits
- GBS, WGS



Field trials

- Homestead, FL, 2013 – 2017
- 3,000 plants/year, randomized
- 18 domestication traits
- GBS, WGS



Teosinte



Maize landrace

Variance/covariance partitioning

Fitted standard mixed linear model $y = X\beta + a + d + ay + e$

*Trait = Fixed + Additive + Dominance + Additive * Year + Residual*

$$a \sim N(0, K_A \sigma_A^2)$$

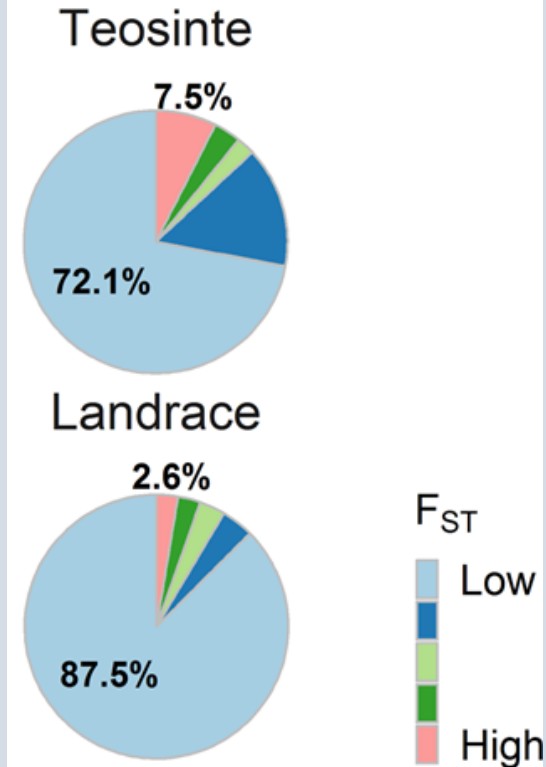
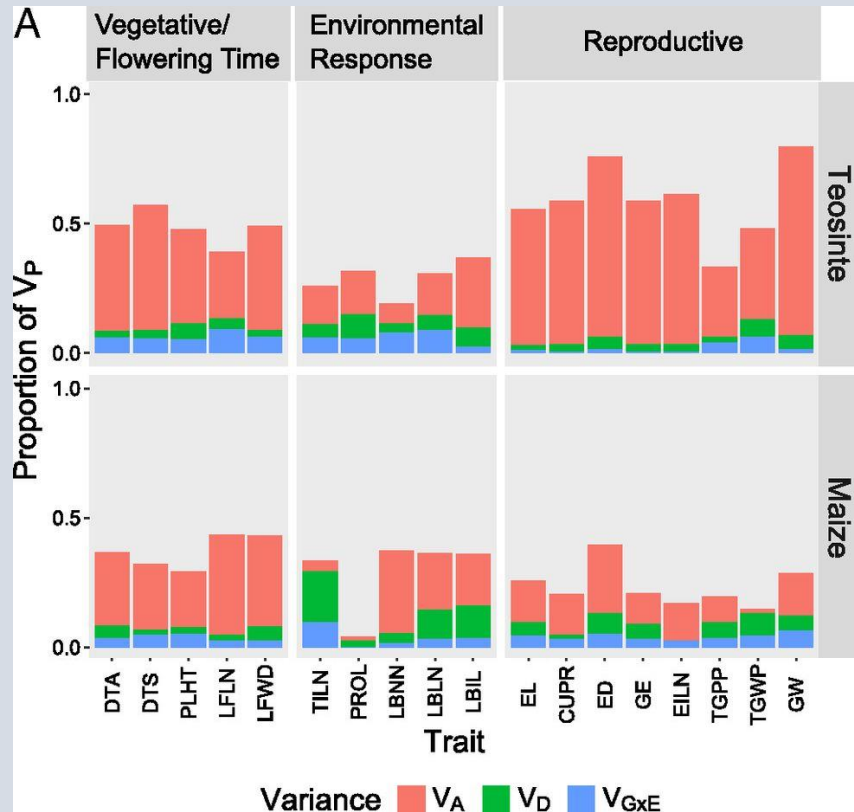
$$d \sim N(0, K_D \sigma_D^2)$$

$$ay \sim N(0, K_{AY} \sigma_{AY}^2)$$

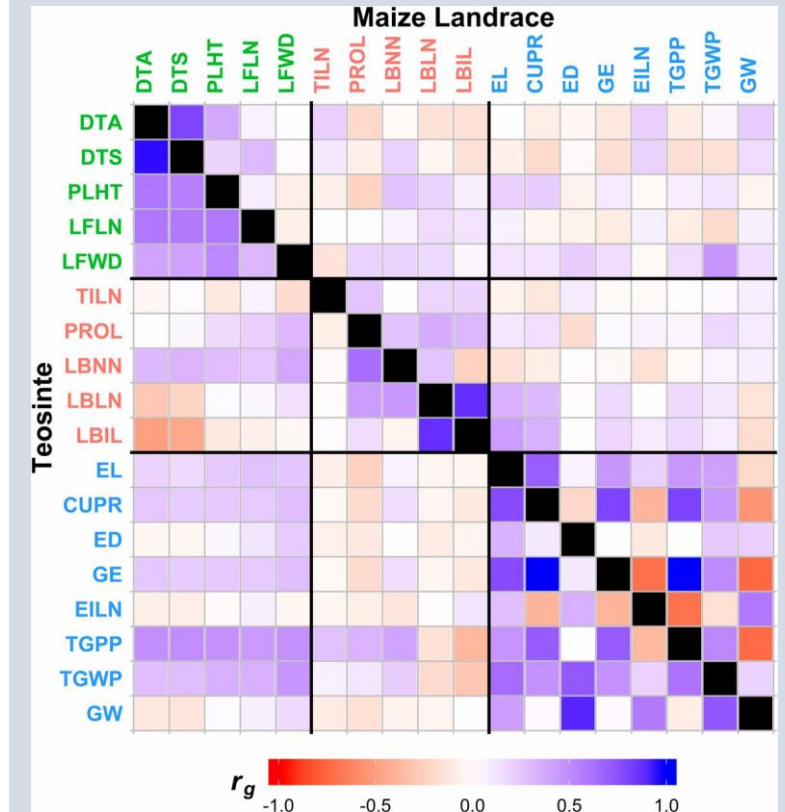
Only the additive term was fitted in the bivariate model.

QG modelling of domestication

Reduction in genetic variances (in high F_{ST} regions).



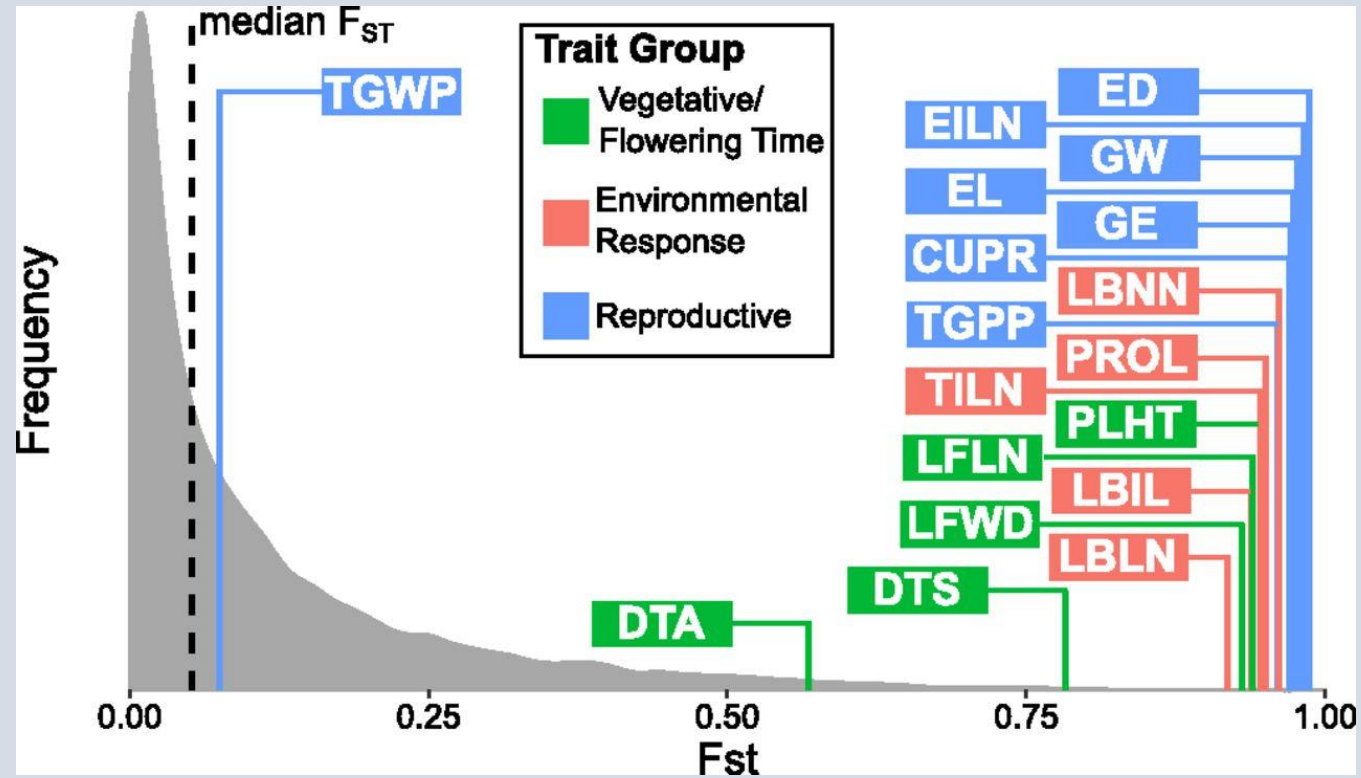
Change in genetic correlations.



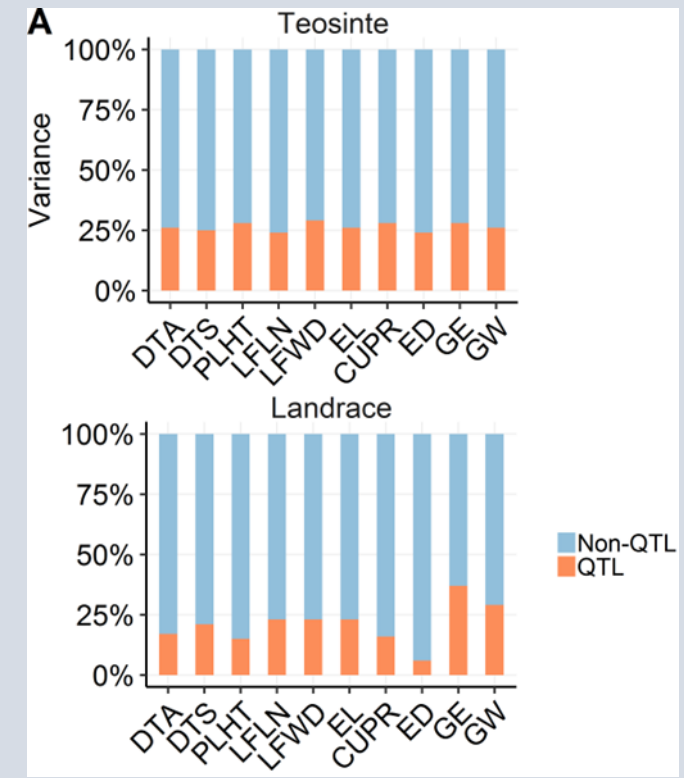
Yang et al (2019), Chen et al (2020, 2021)

QG modelling of domestication

Divergence in traits (Qst-Fst)



Importance of small effect QTLs.



Yang et al (2019), Chen et al (2020, 2021)

Plant breeding: a journey through time

Project 1: crop domestication

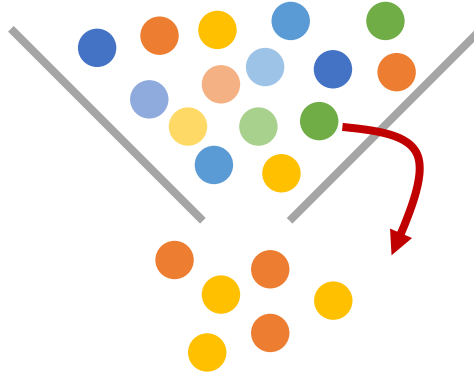
Project 2: genetic diversity and pre-breeding

Project 3: novel crop breeding

Shuffling genetic diversity

Domestication/Improvement

- Bottleneck
- Selection



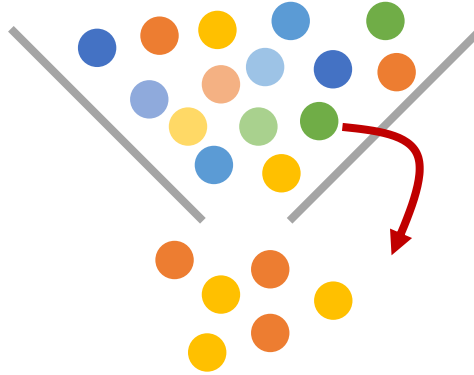
Marker assisted selection (MAS)

- Great for oligogenic traits.
- E.g. disease resistance.
- Inefficient for polygenic traits.

Shuffling genetic diversity

Domestication/Improvement

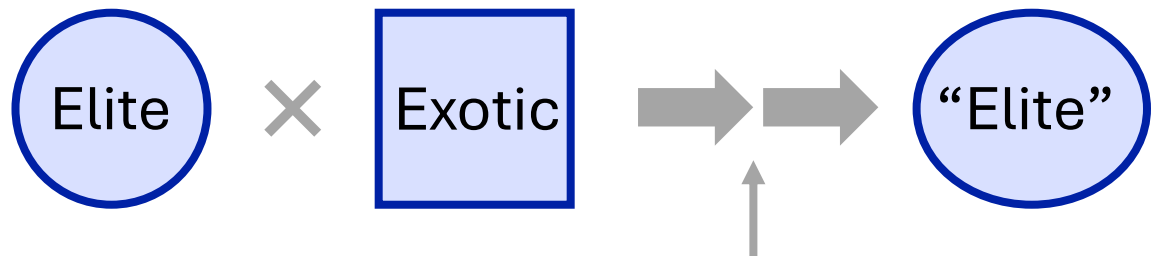
- Bottleneck
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Marker assisted selection (MAS)

- Great for oligogenic traits.
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Polygenic introgression is challenging

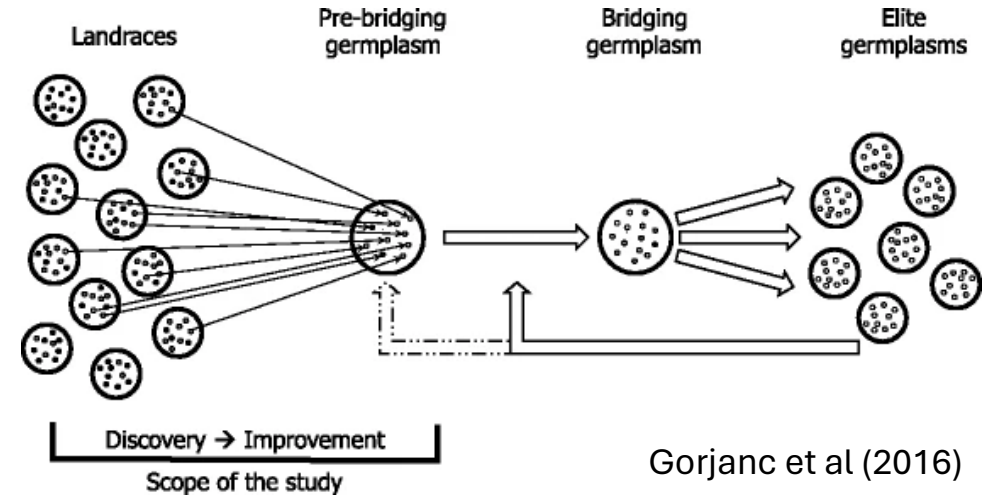


Phenotypic/genomic selection

Pre-breeding



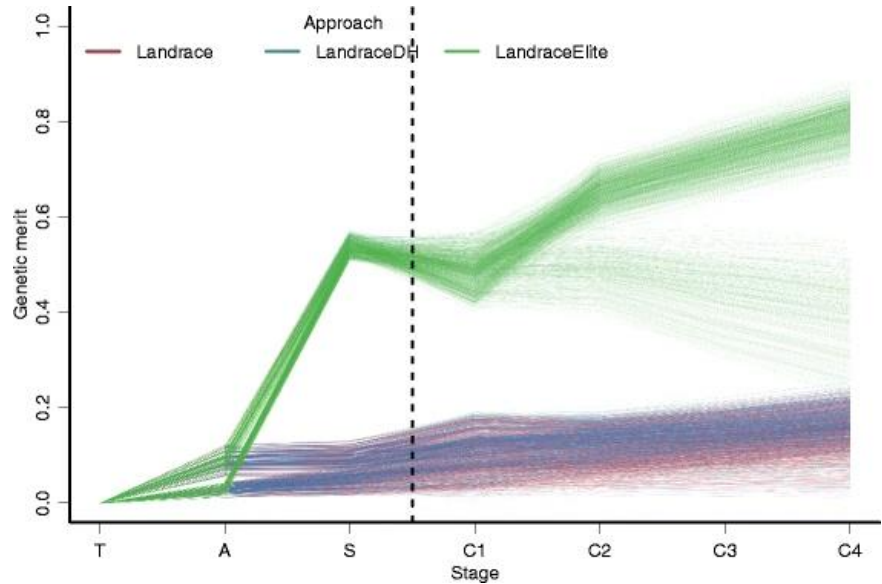
Seeds of Discovery (SeeD) studies and characterizes maize and wheat genetic diversity for use in breeding programs, which develop wheat varieties and maize hybrids improved through conventional technologies. These hybrids are better adapted to climate change, more resistant to pests and diseases and have higher yield potential.



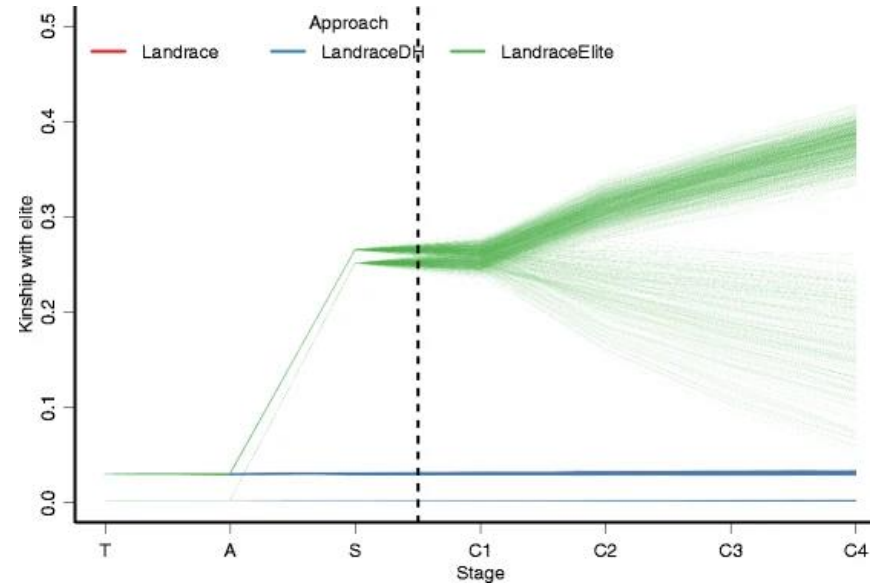
- Bridging population with elite-exotic crosses.
- Improve in elite-exotic first, then introduce into elite population.

Selection bias in pre-breeding (simulation)

Breeding value



Kinship with elite parents



Elite x Exotic

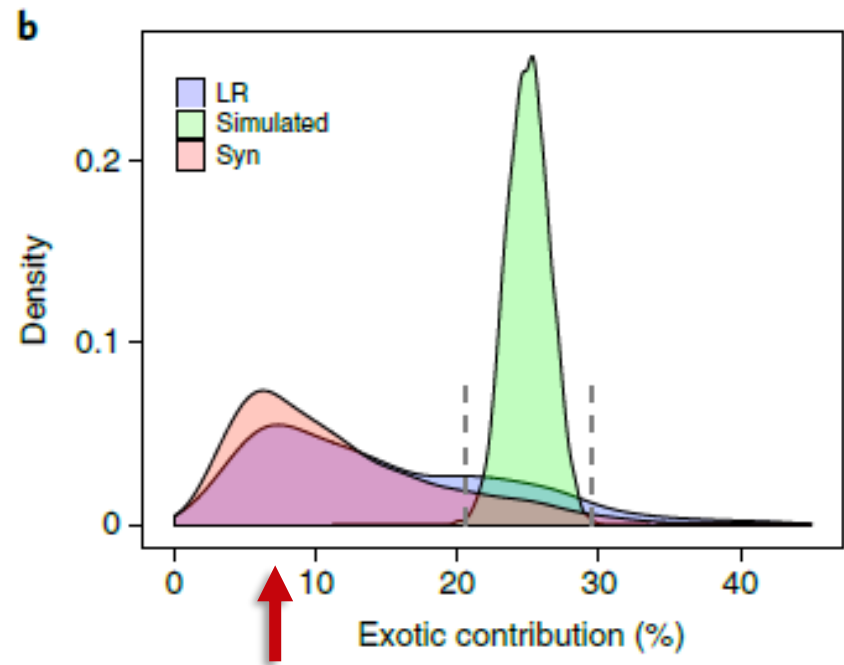
Exotic (landrace)

Gorjanc et al (2016)

- Selection within exotic is slower than elite-exotic.
- Selection within elite-exotic reconstitutes the elite parent genome.

Selection bias in pre-breeding (observed)

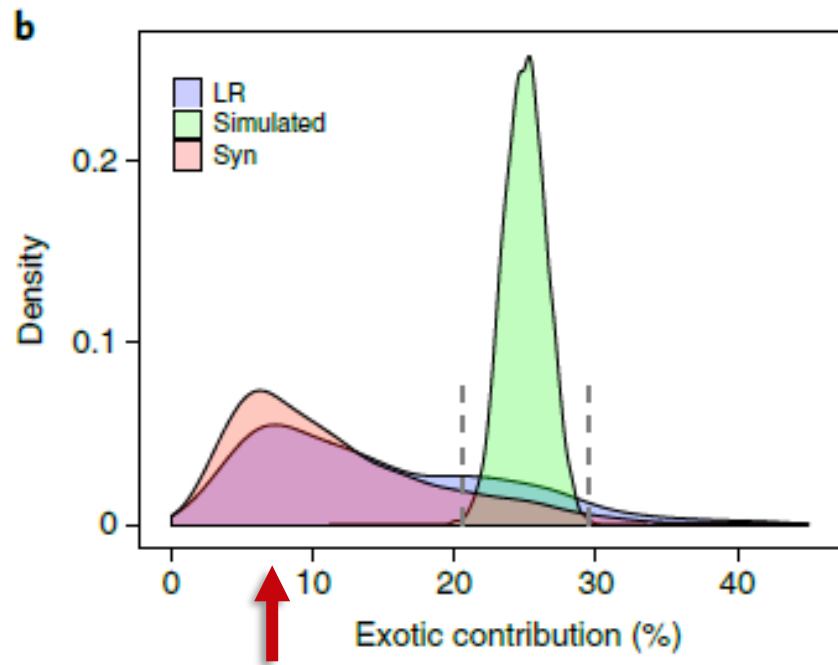
- Elite 2 x (Elite 1 x Exotic)
- Distribution of exotic parent genome after applying phenotypic selection.
- Validation of simulation outcomes in experimental observation.



Singh et al (2021)

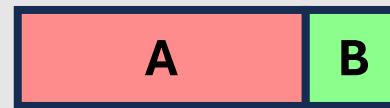
Selection bias in pre-breeding (observed)

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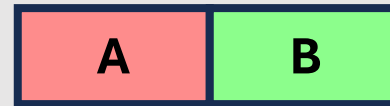


Singh et al (2021)

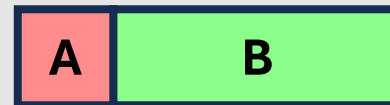
Example: Favourable allele in elite(A):exotic(B) = 6:4



$$BV = 0.75 * 0.6 + 0.25 * 0.4 = 0.55$$



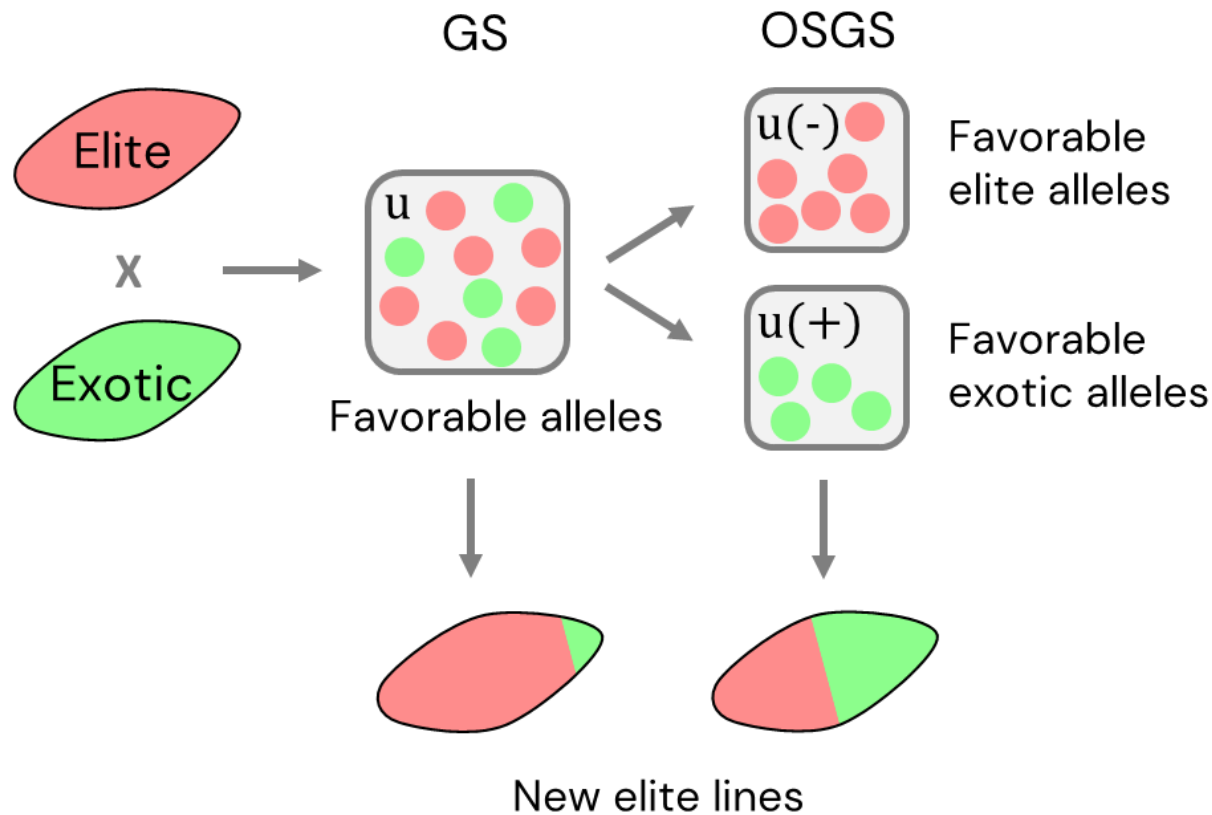
$$BV = 0.50 * 0.6 + 0.50 * 0.4 = 0.50$$



$$BV = 0.25 * 0.6 + 0.75 * 0.4 = 0.45$$

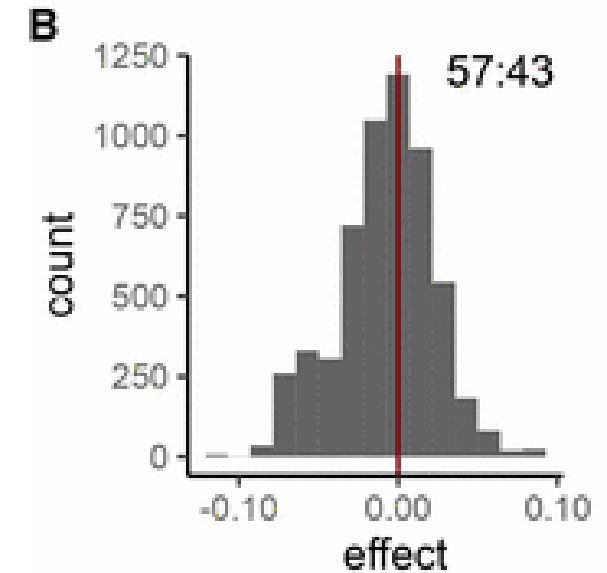
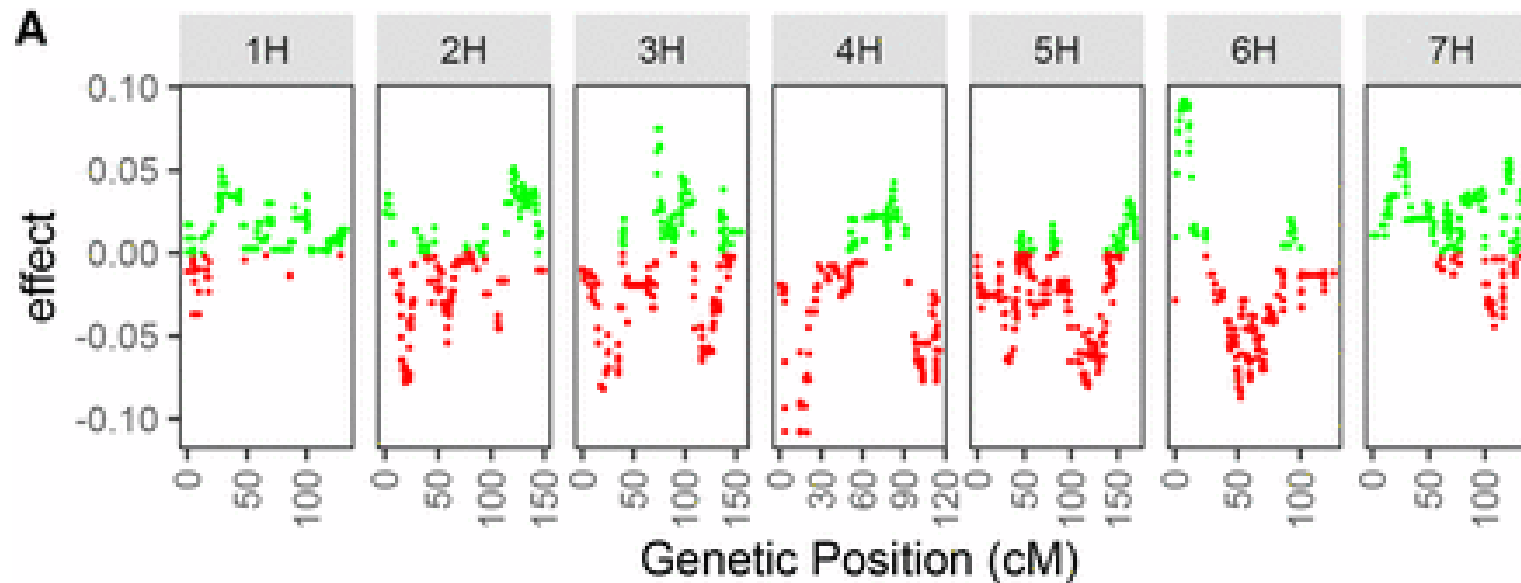
Origin specific genomic selection (OSGS)

OSGS: isolate and select on favorable parental contribution.



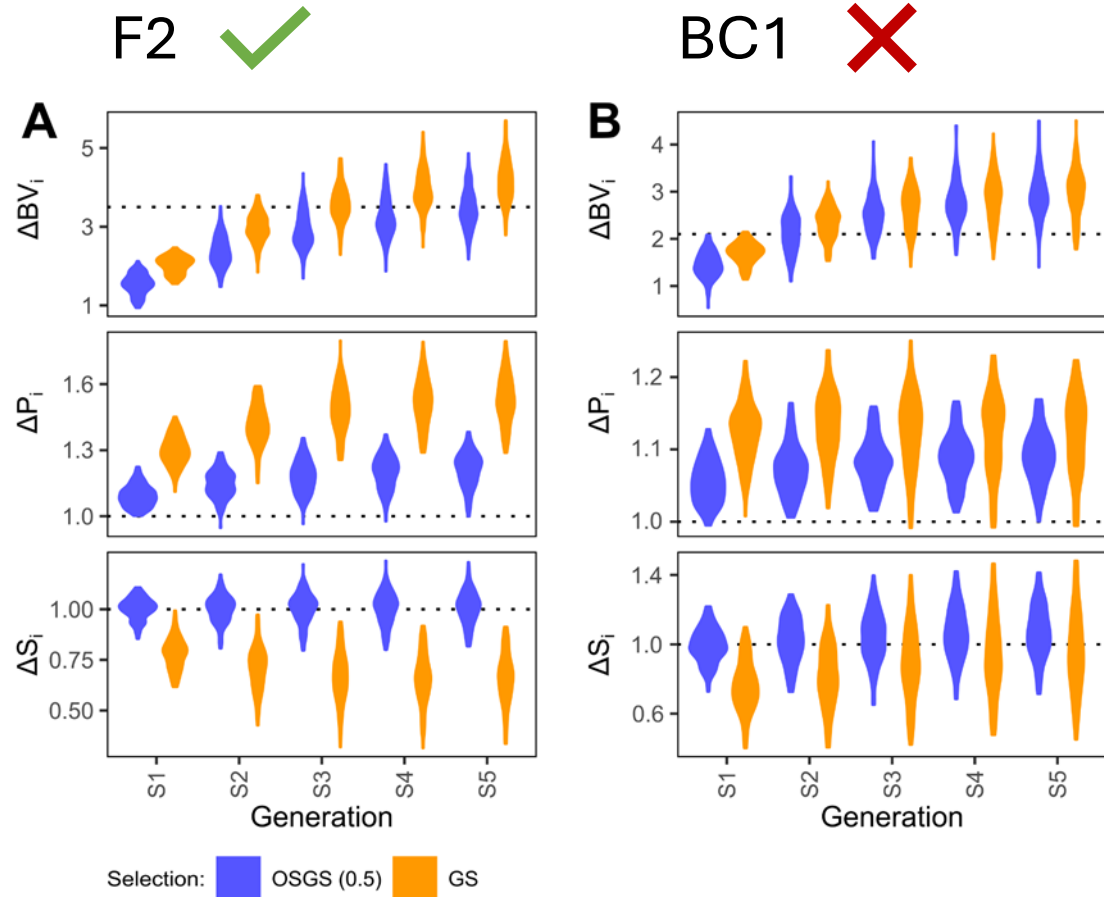
OSGS in barley NAM (yield)

Partitioning favorable parental contributions.



Yang et al (2020)

OSGS in simulated data



Yang et al (2020)

- OSGS vs GS.
- Weighted selection in OSGS.
- Comparable breeding values.
- OSGS maintains elite-exotic balance.
- $F2 > BC1$.

Plant breeding: a journey through time

Project 1: crop domestication

Project 2: genetic diversity and pre-breeding

Project 3: novel crop breeding

Novel crop – purslane (*Portulaca oleracea*)



Golden purslane



Green purslane

Developing a breeding program for purslane

- Env: Vertical farm
- Trait: Omega-3 level

TABLE 2: Plant sources of omega-3 fatty acids (g/100 g).

Category	Fruits/vegetables	Amount (g)
Low	Avocados, California raw	0.1
	Broccoli	0.1
	Strawberries	0.1
	Cauliflower, raw	0.1
	Kale, raw	0.2
	Spinach, raw	0.1
	Peas, garden dry	0.2
	Cowpeas, dry	0.3
	Beans, navy, sprouted, cooked	0.3
	Corn, germ	0.3
Medium	Bean, common dry	0.6
	Leeks, freeze-dried, raw	0.7
	Wheat, germ	0.7
	Spirulina, dried	0.8
	Purslane	0.9
	Oat, germ	1.4
	Beachnuts	1.7
	Soybeans kernels, roasted	1.5
	Soybeans, green	3.2

Uddin et al (2014)

Identify breeding targets.

Survey variation in phenotypes, GxExM.

Engage with stakeholders.

Register varieties.

Create populations and select.

Trial in vertical farms.

Short vs long day



Fluorescent vs LED



Developing a breeding program for purslane

Royal Highland Show



Identify breeding targets.

Survey variation in phenotypes, GxExM.

Engage with stakeholders.

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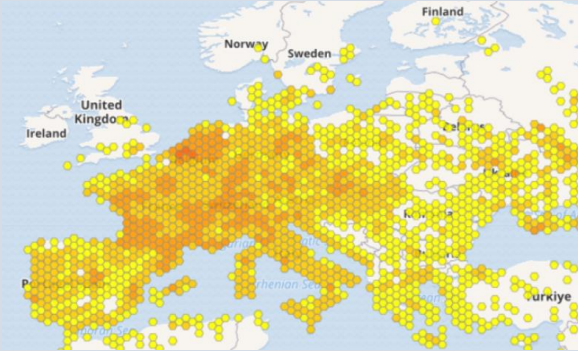
Trial in vertical farms.

Green vs golden purslane



Developing a breeding program for purslane

Sample collection



GBIF (2014-2023)



NBN Atlas

Identify breeding targets.

Survey variation in phenotypes, GxExM.

Engage with stakeholders.

Register varieties.

Create populations and select.

Trial in vertical farms.

Growth chambers



Hydroponic trials

VF – under construction



Future direction

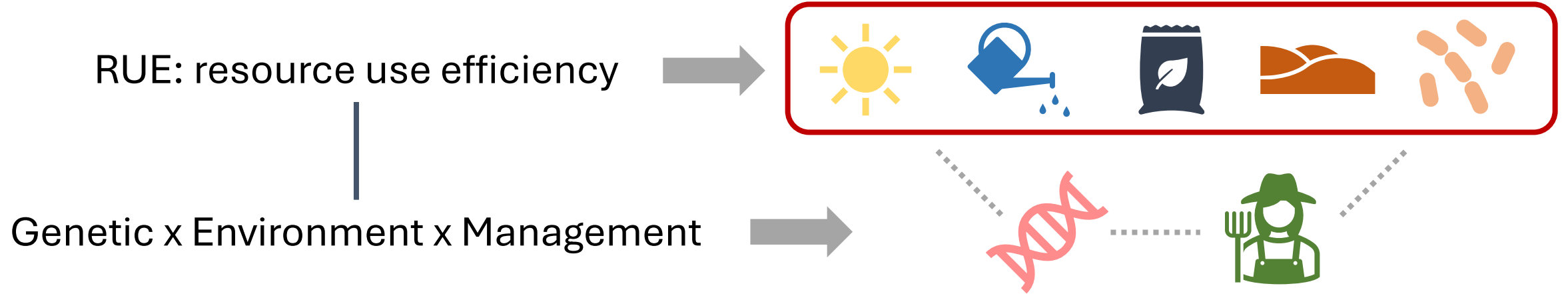
What's next?

Future direction

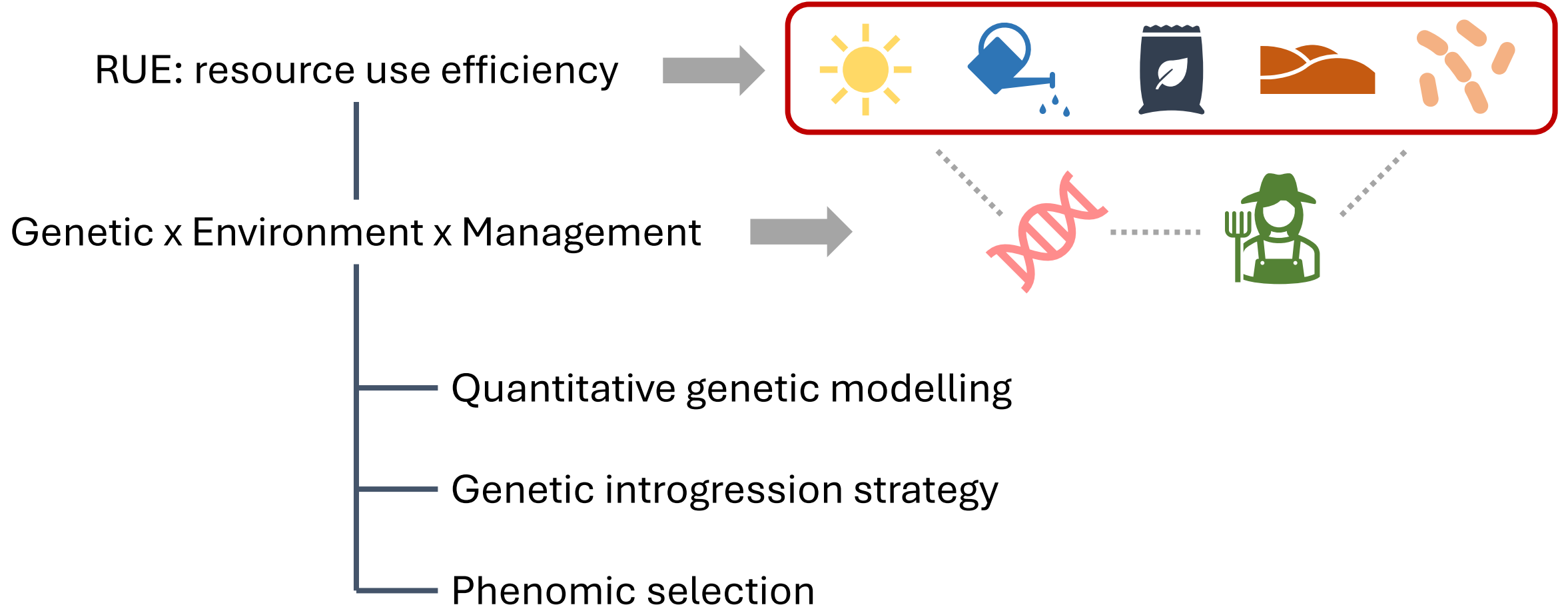
RUE: resource use efficiency



Future direction



Future direction



Summary

- Plant breeding, complex traits and genetic gain.
- Plant breeding: a journey through time:
 - QG-perspective on maize domestication
 - Genetic introgression in pre-breeding
 - Breeding for novel crop
- Interest in RUE and GEM.



- Breeding efficiency
- Sustainability
- Climate resilience

Acknowledgement

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Rodney Edmondson
Hans-Peter Piepho
Joanne Russell
Luke Ramsay
Bill Thomas
Funmi Ladejobi
Richard Mott



<https://cjyang-work.github.io/>



cyang@sruc.ac.uk



[@hataraku_cj](https://twitter.com/hataraku_cj)

