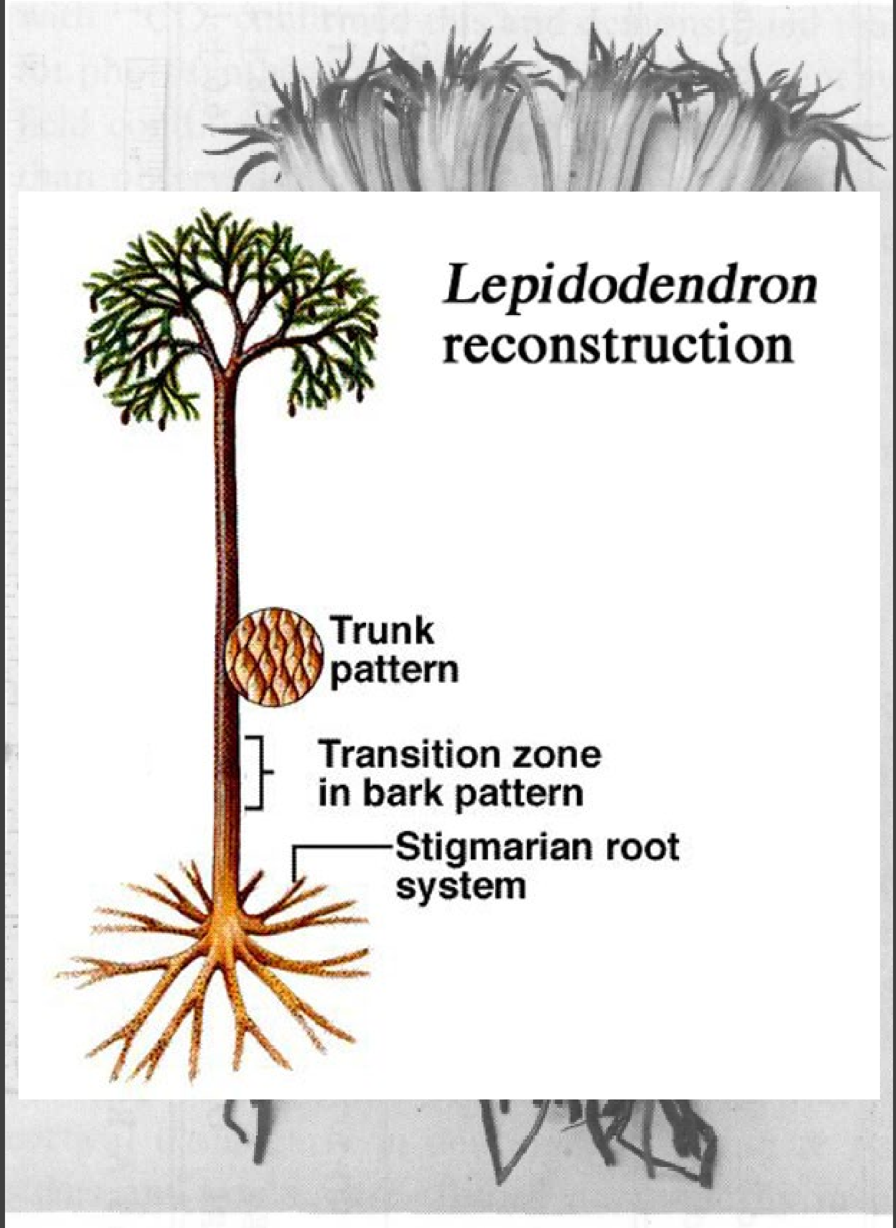
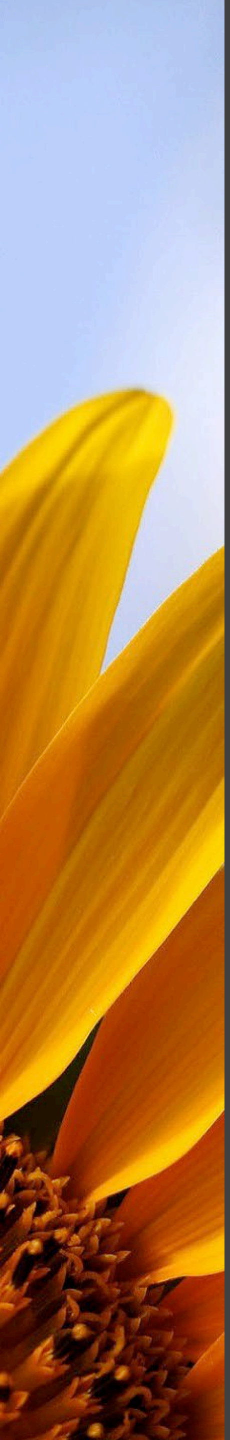
Plant of the Day

Isoetes andicola

- Lycophyte endemic to Peru at high elevations
- Restricted to the edges of bogs and lakes
- Leaves lack stomata and so CO_2 is obtained from sediment via the roots
- Carbon fixation occurs via the C_3 pathway by day, but via a CAM-like process at night
- Members of the quillwort family (*Isoetaceae*) are the nearest living relatives of the ancient "scale trees" (e.g. Lepidodendron)



Crop evolution



How can evolutionary biology contribute to plant improvement?

1. History and concepts
2. Evolutionary applications
    - Reconstructing crop demographic history
    - Reconstructing crop evolutionary history
    - Circumventing evolutionary trade-offs

3 Conclusions

Theodosius Dobzhansky 1900-1975

“Nothing in biology makes sense except in the light of evolution”

History and Concepts

Historical contributions of evolutionary biology to breeding:

Fisher

- Statistical theory of quantitative inheritance (R.A. Fisher – 1920s)

Wright

- Mathematical framework for predicting responses to selection (R.A. Fisher, S. Wright - 1930s)

Donald

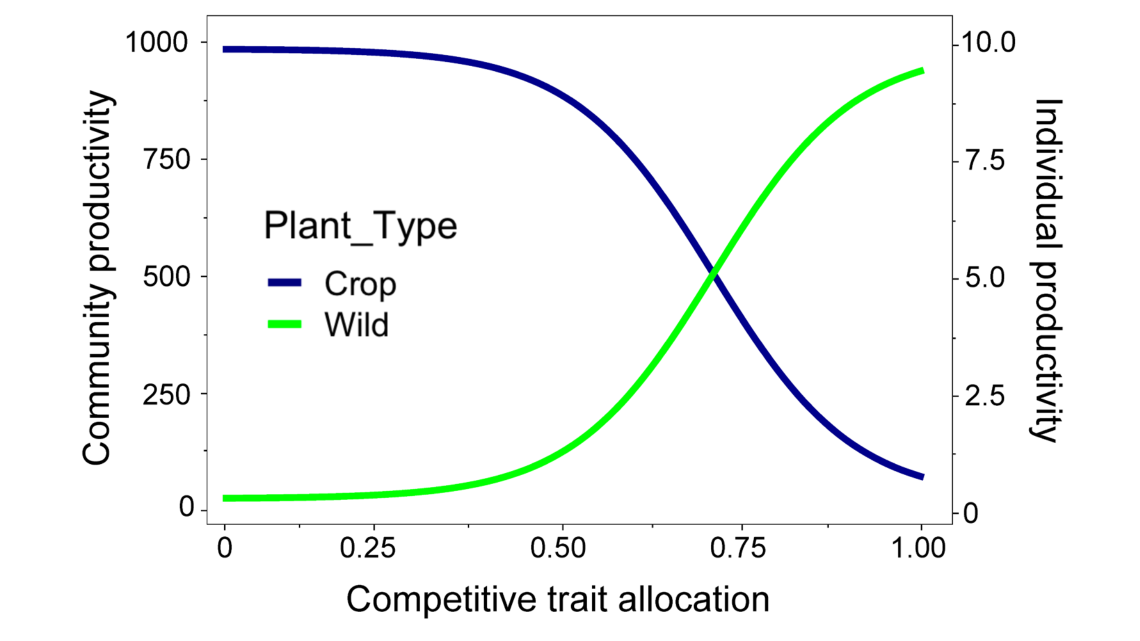
- Conceptual framework for understanding the characteristics likely to contribute to success in crops versus wild species (C.M. Donald, J.L. Harper – 1960s)

History and Concepts

Main difference between evolution of crops versus wild species:

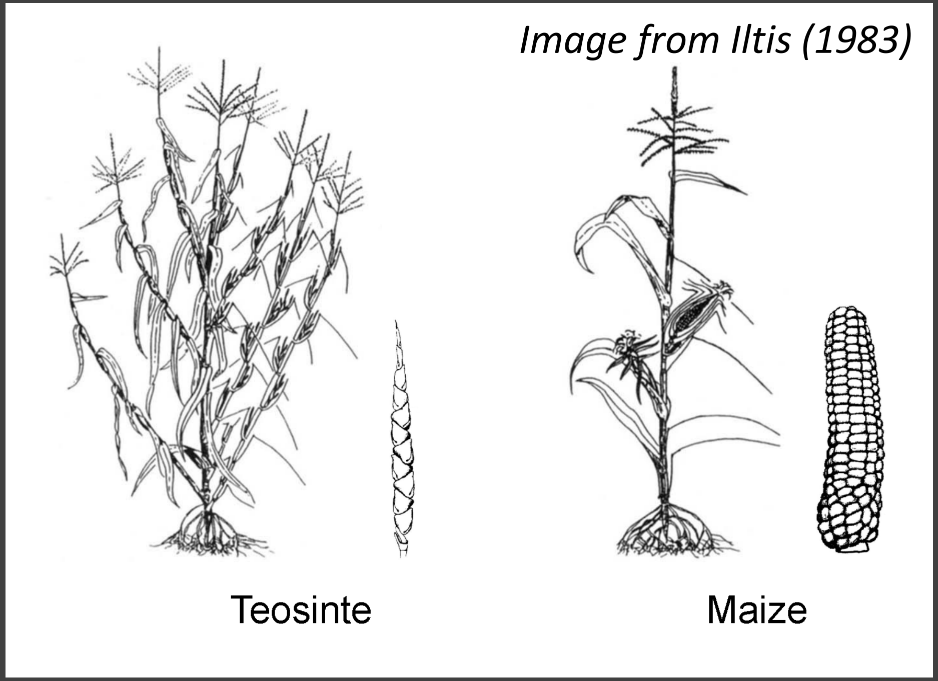
- Natural Selection favors competitiveness of individual genotypes
- Traits that minimize individual competition are predicted to improve crop and maximize group performance productivity
- Crop ideotypes refer to the set of phenotypic traits that maximize productivity per unit of land area (i.e., yield)
- Successful crop ideotypes represent weak competitors, thereby minimizing competition within the crop community.

Relationship between competitive trait allocation and productivity in wild vs crop plants



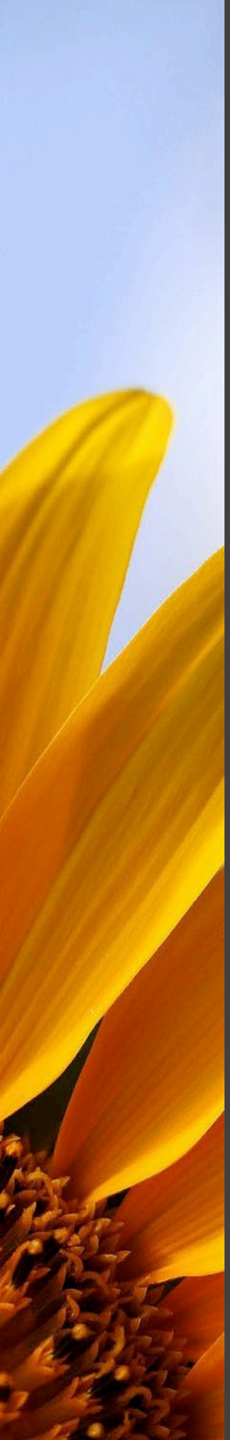
Examples of successful crop ideotypes (traits that reduce individual competitiveness)

Reduced Branching (maize)



Reduced Height (rice)

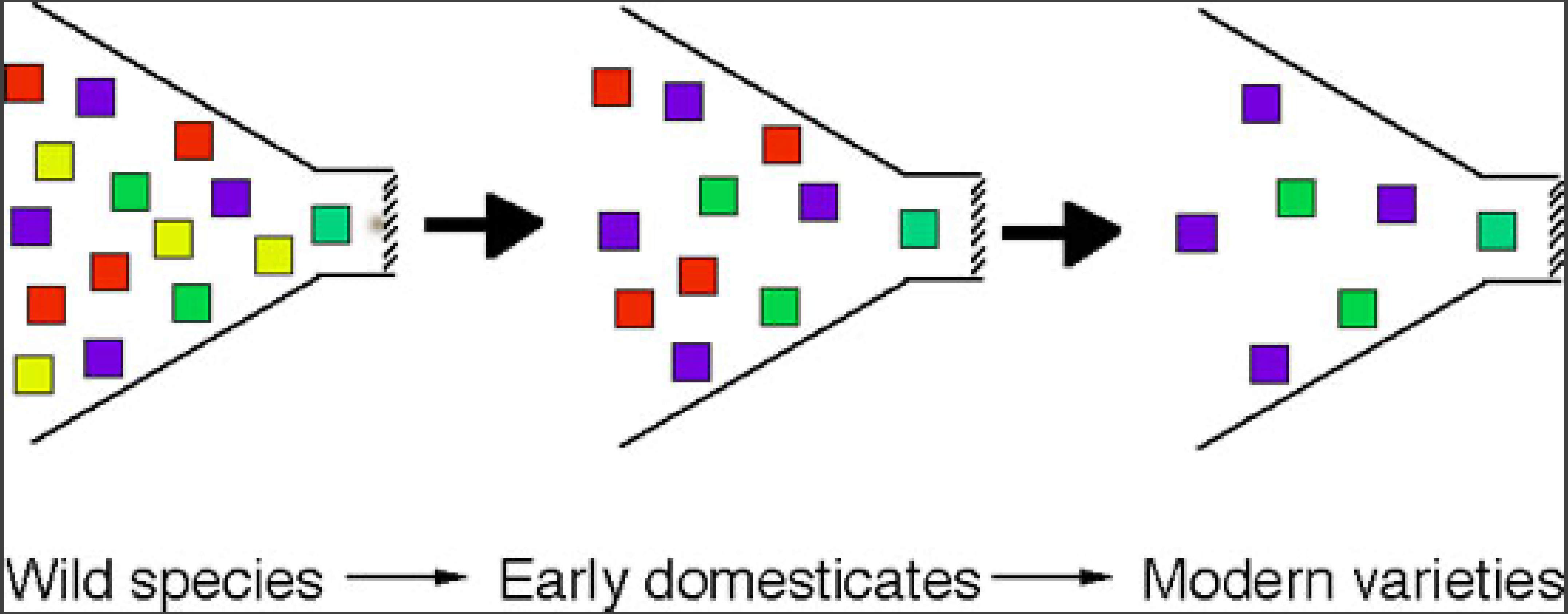
Ideas underpinned the development of the short, unbranched crop plants that helped drive yield gains during the green revolution



What are some other examples of other crop ideotypes?

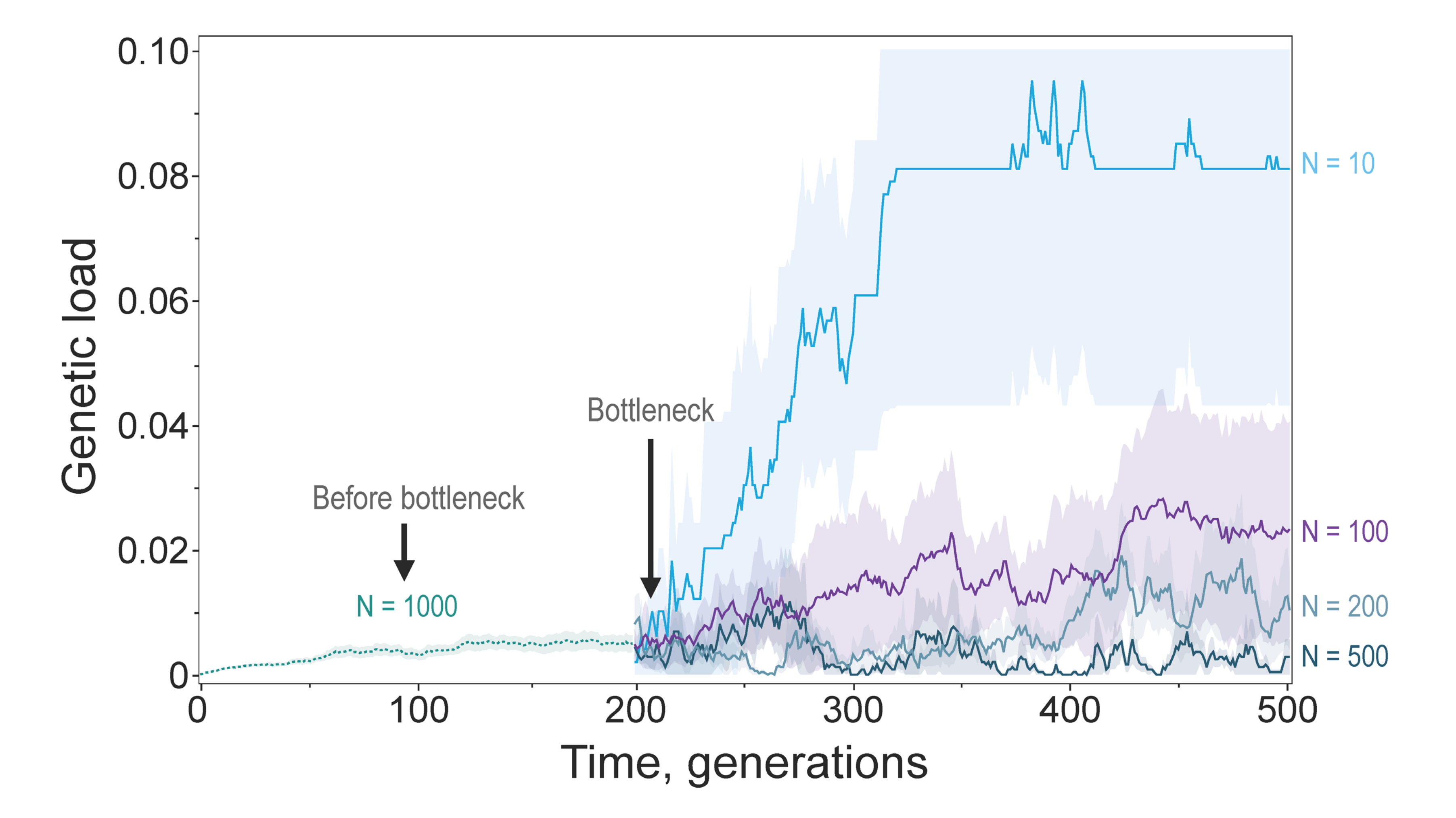
Evolutionary applications

- Reconstructing crop demographic history



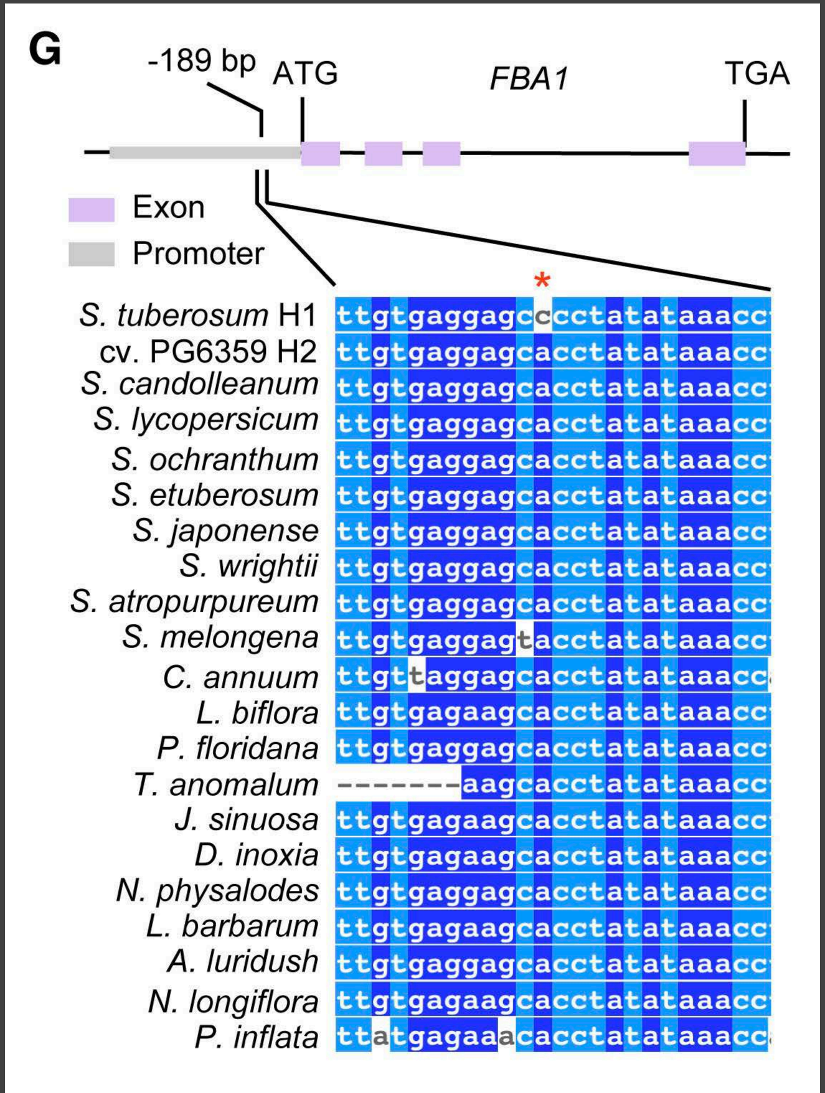
Genetic diversity is lost during domestication and improvement

Cost of domestication – increased genetic load



Increase in accumulation of deleterious mutations after population bottlenecks

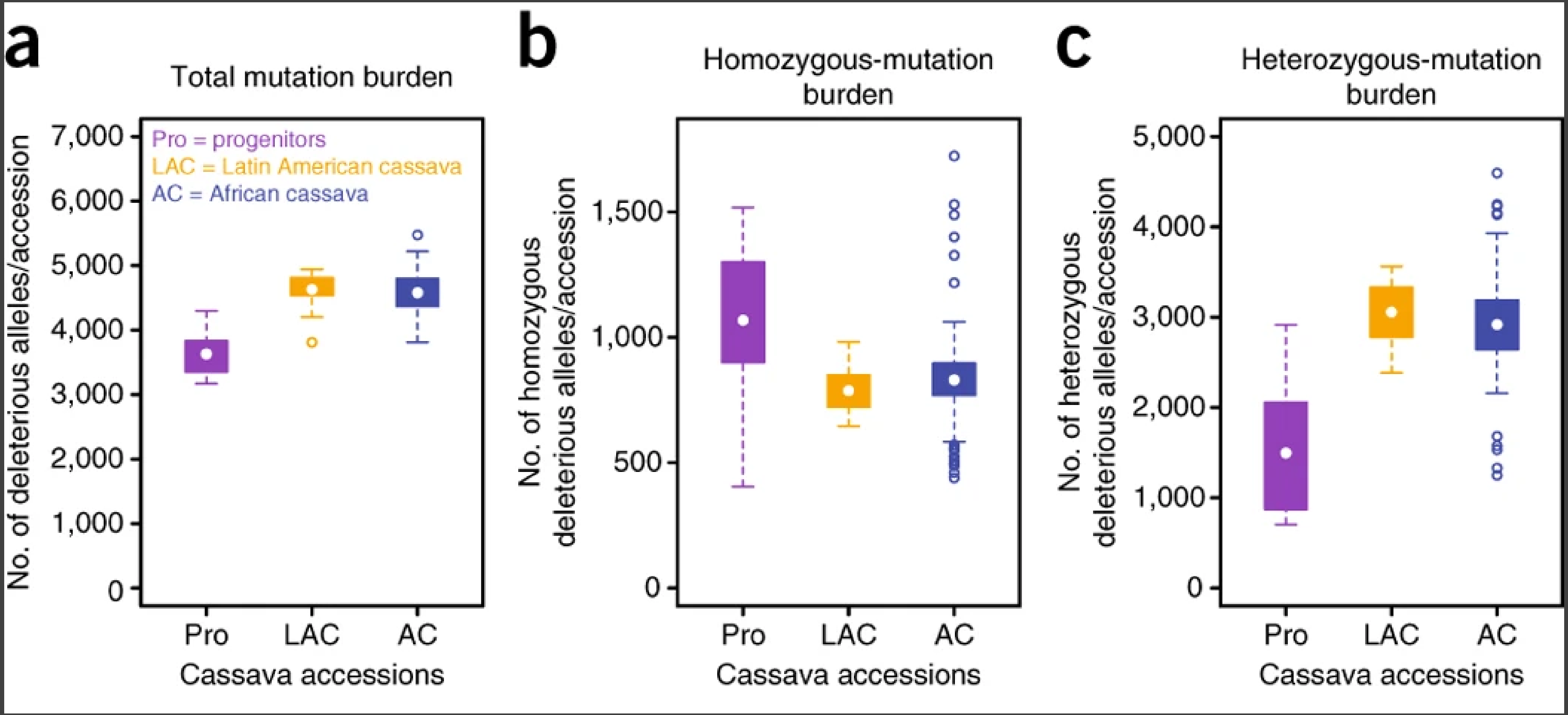
Evolutionary conservation can be used to predict deleterious mutations



Part of promotor sequence for *floral bud abortion 1* (*fba1*) among 20 Solanaceaae species. Predicted deleterious mutation shown with red asterisk.

Wu et al. (2023, *Cell*)

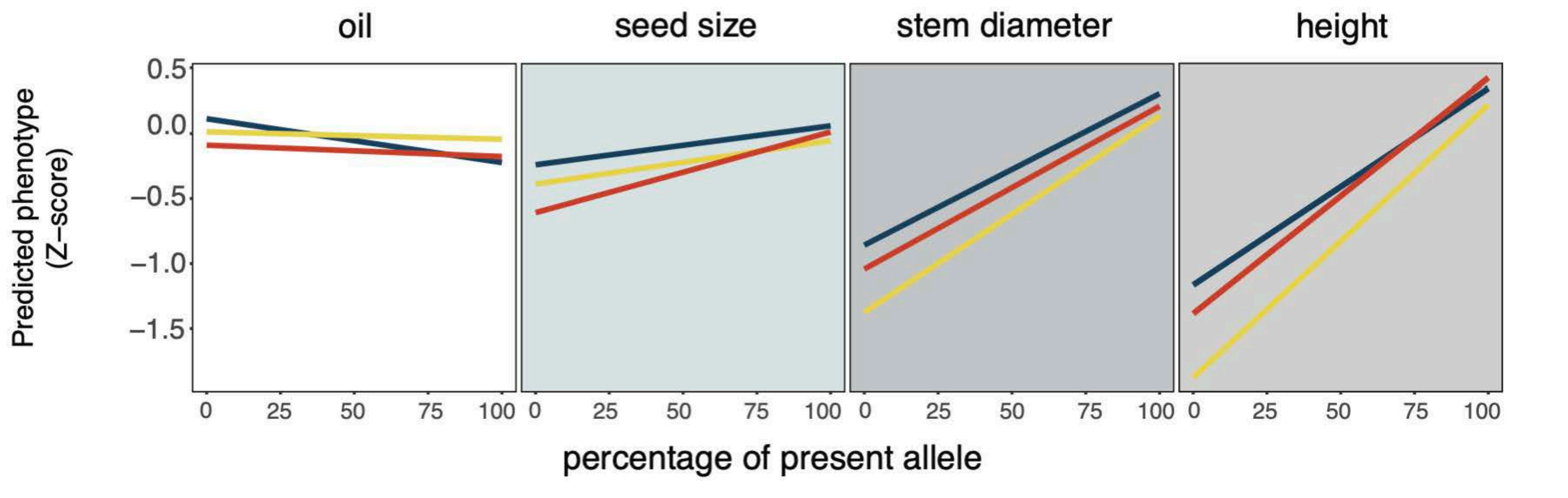
Evolutionary conservation can be used to predict deleterious mutations



Increase in accumulation of deleterious load in Cassava

Ramu et al. (2017, *Nature Genetics*)

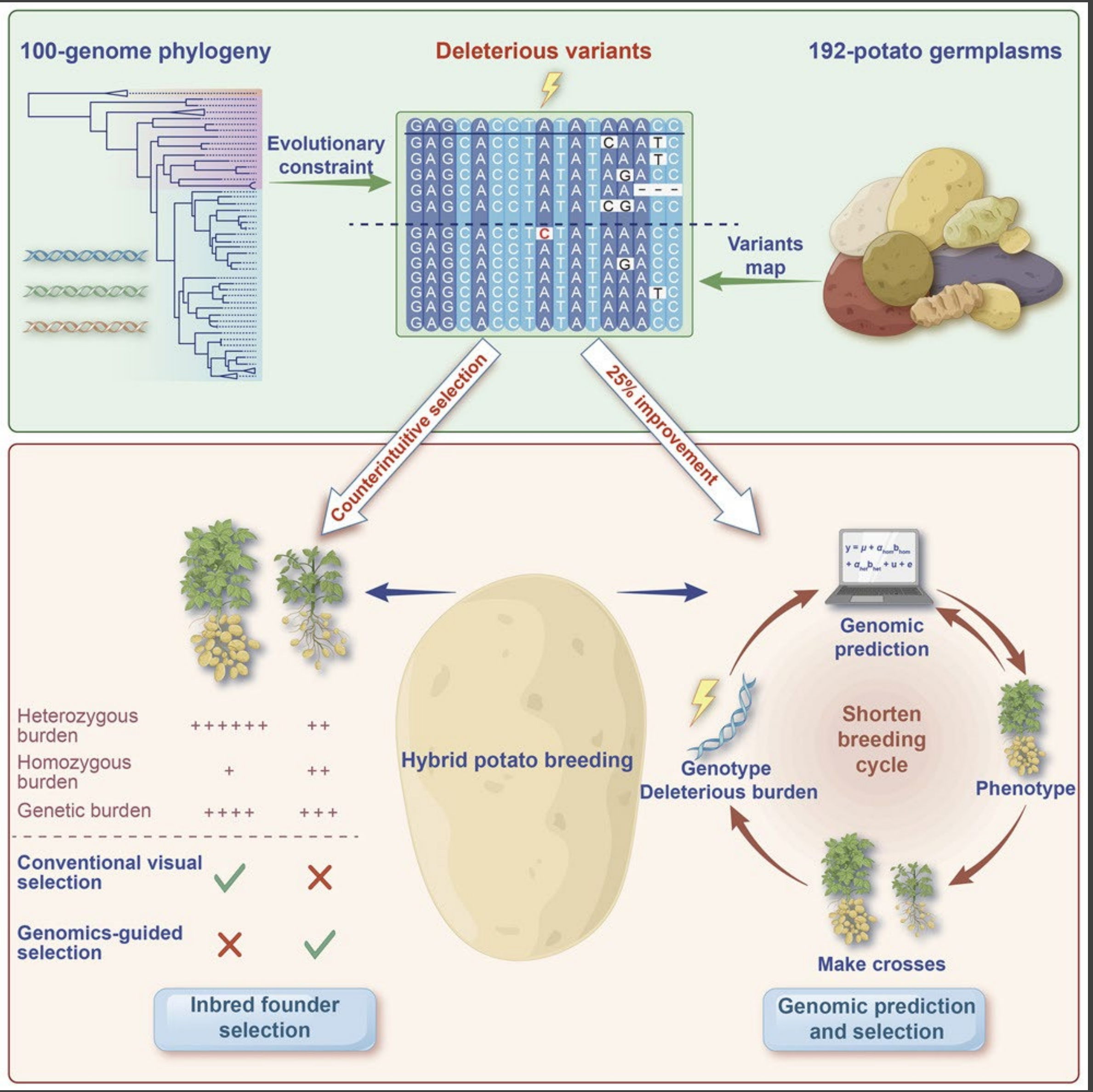
Deleterious mutation predictions can improve genomic prediction accuracy



Gene presence absence polymorphisms predict growth-related phenotypes in sunflower

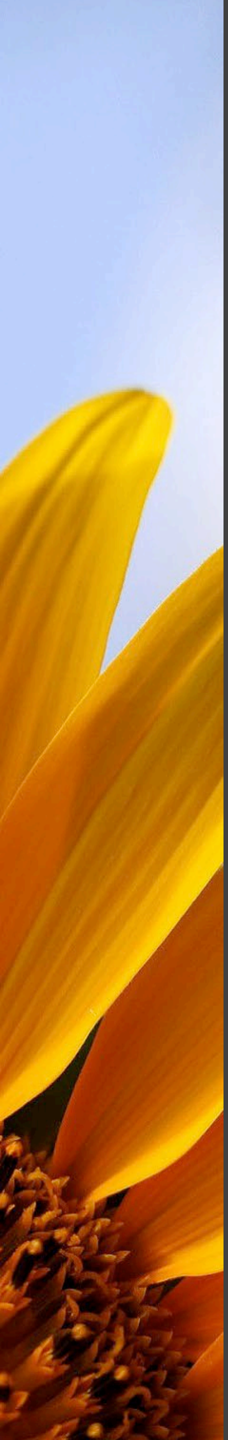
Lee et al. (2022, *Journal of Advanced Research*)

Example of work flow from potato



A selection of the thousands of native potato varieties that grow in Peru. Photograph: The International Potato Centre

Wu et al. (2023, *Cell*)

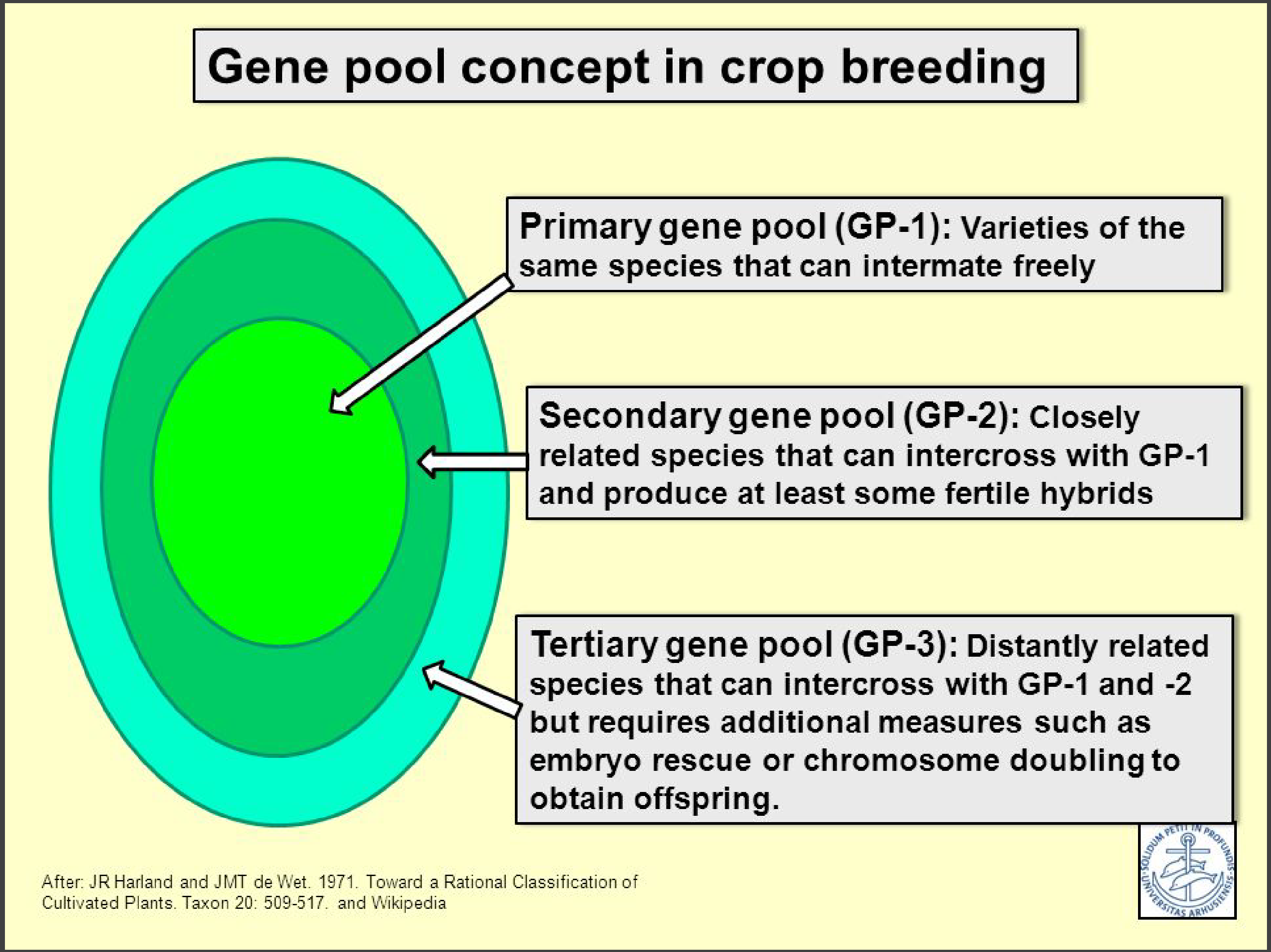


Strategies for reducing the cost of domestication

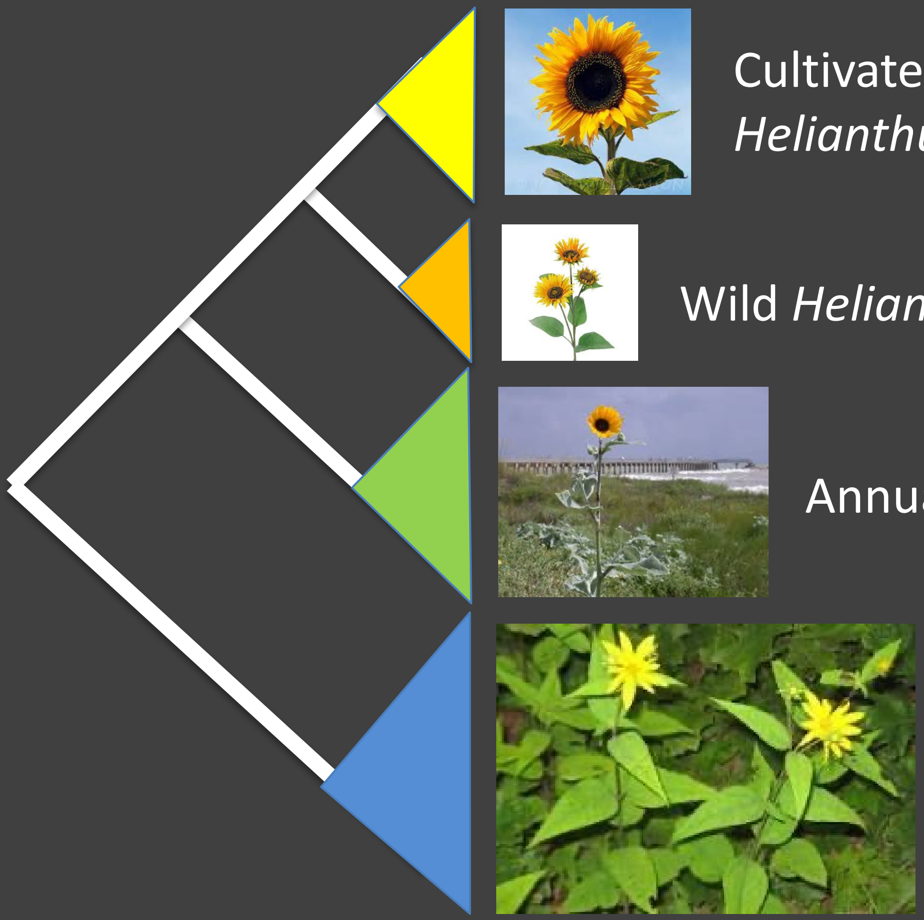
- Targeted removal of deleterious mutations in breeding program
  - but deleterious mutations more frequent in low recombination regions
- Employ genome editing to repair deleterious sites
  - but off-target editing can occur in pericentric areas of the genome
- Hybrid production
  - identify inbred lines that maximize masking of recessive deleterious mutations

Evolutionary applications

- Reconstructing crop evolutionary history



Phylogeny predicts crop gene pools



Cultivated sunflower
Helianthus annuus

Wild *Helianthus annuus*

Primary Gene Pool

Annual wild sunflowers

Secondary Gene Pool

Perennial wild sunflowers

Tertiary Gene Pool

Benefits from tapping wild sunflower relatives

Contributions Include:

- Pest and disease resistance
- Resistance to abiotic stress
- tolerance to herbicides

Trial of crop-wild pre-bred lines in Uganda

Value:

- $185 million annually in 2012 dollars (Tyack and Dempewolf, in *Crop Wild Relatives and Climate Change,* 2015)
- $267 to 384 million annually (Hunter and Heywood, *Crop wild relatives, a manual of in situ conservation,* 2011)

Potential negative impacts of wild introgressions

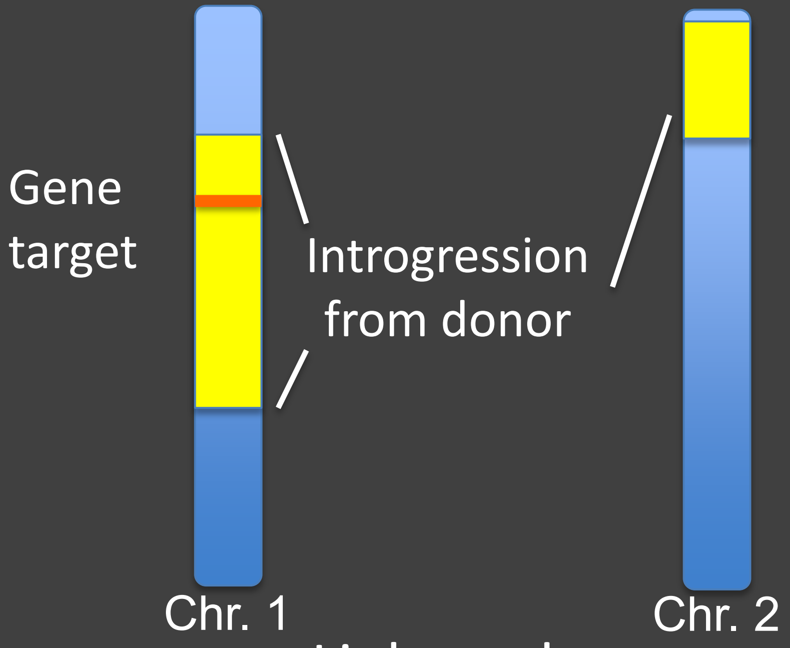
House cat X
wildcat hybrid

Phenotypic Impacts:

Breeding with wild species is “a bit like crossing a house cat with a wildcat. You don't automatically get a big docile pussycat. What you get is a lot of wildness that you probably don't want lying on your sofa. Guarino and Lobell (*Nature Climate Change*, 2011)

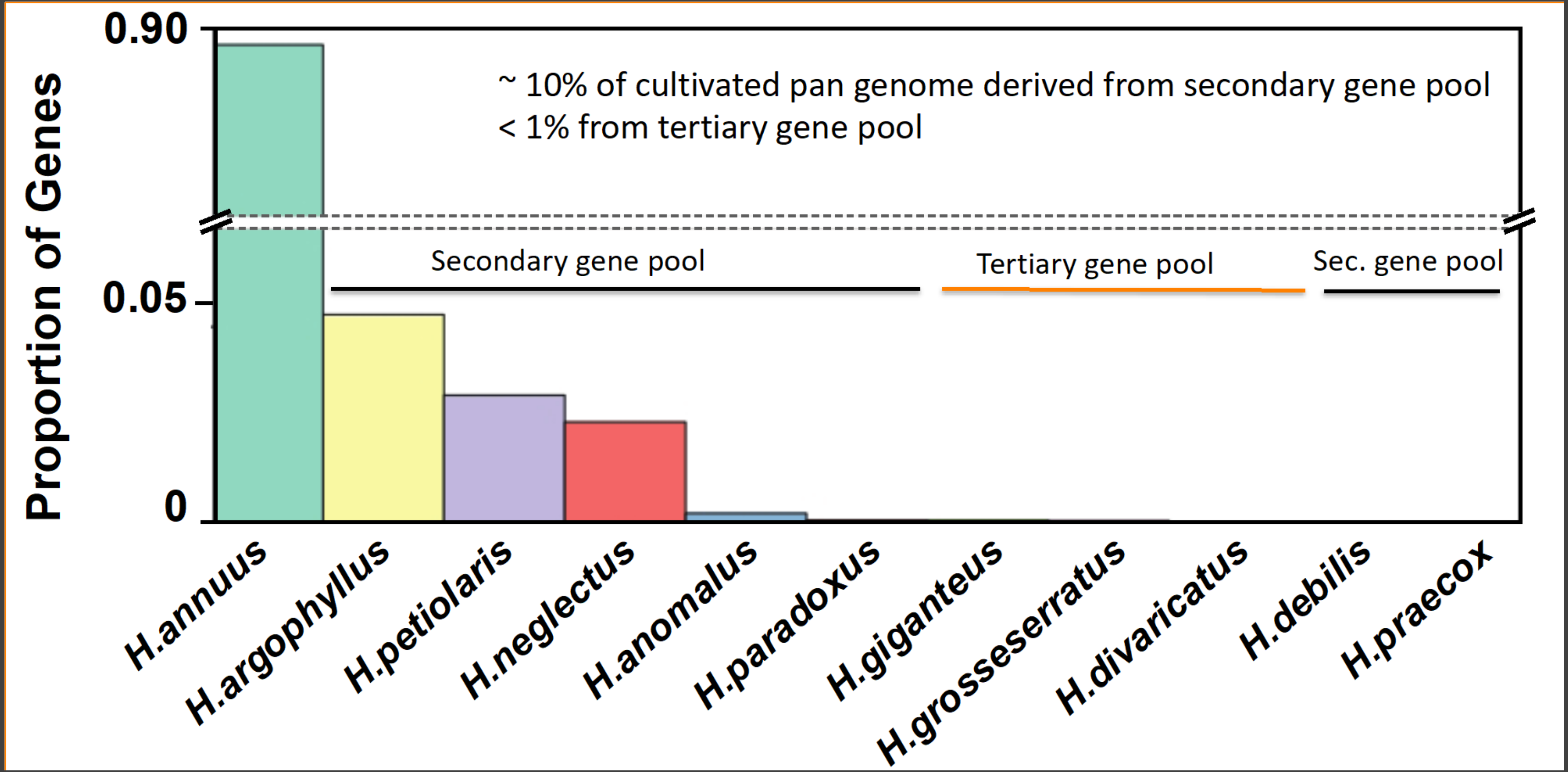
Genomic Impacts:

- Retention of maladaptive donor genetic material (i.e., **linkage drag**)

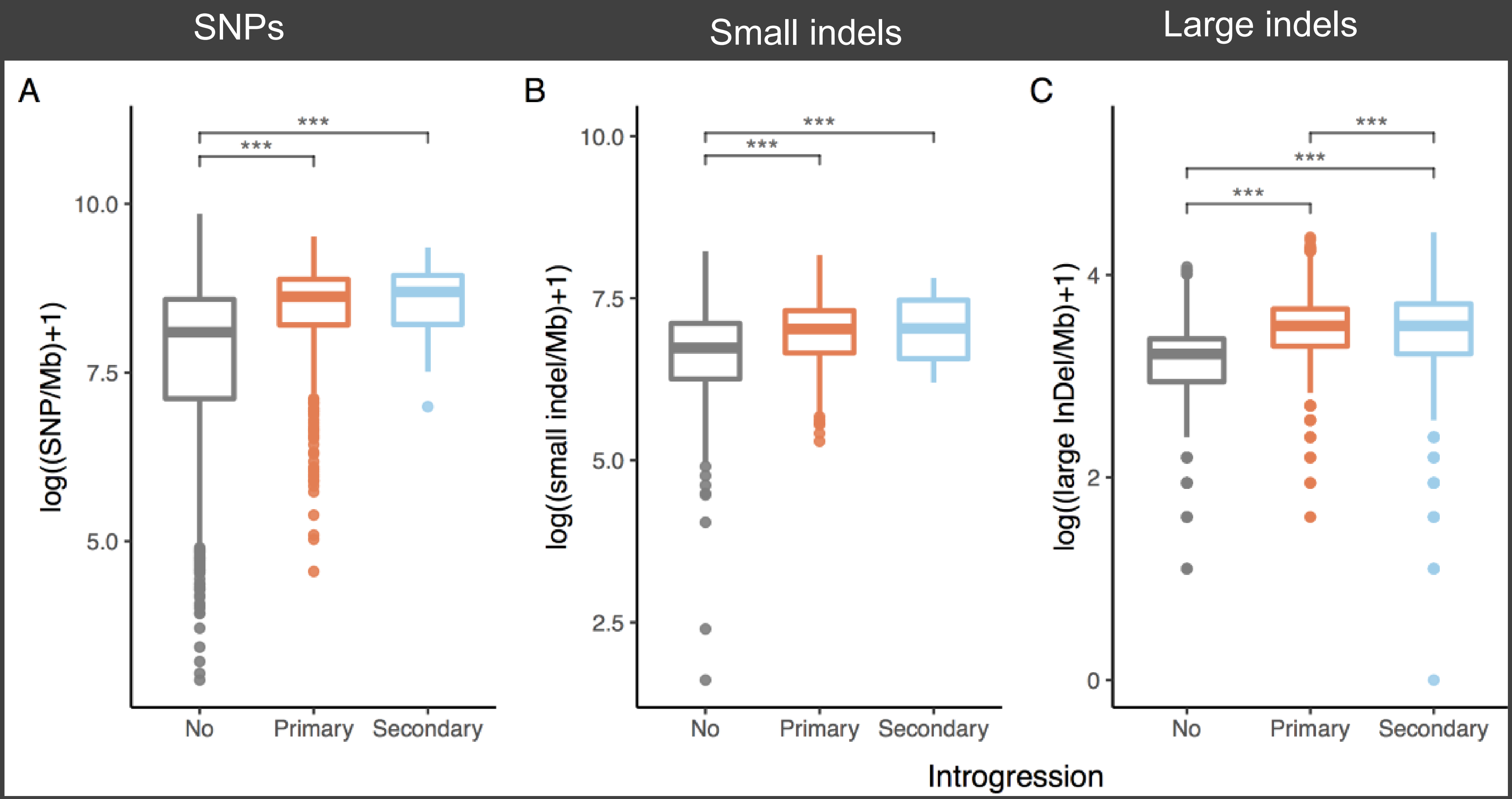


Linkage drag

Ancestry of cultivated sunflower pan-genome



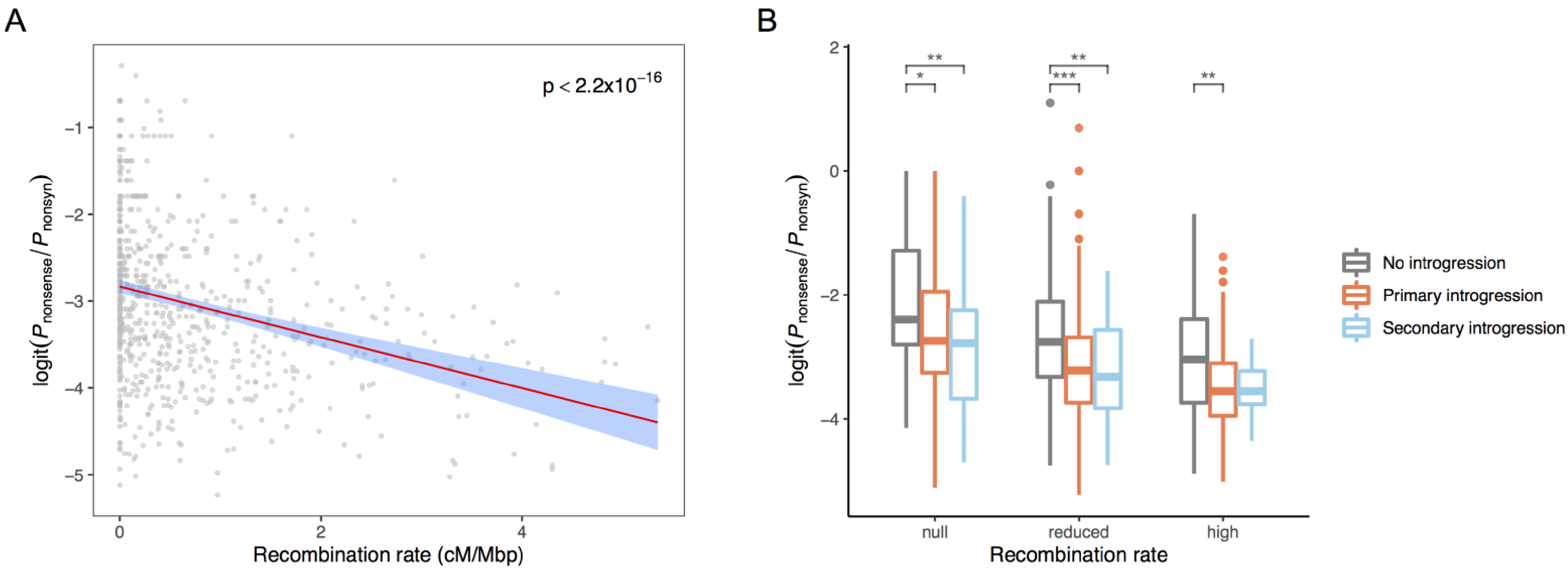
Ancestry of cultivated sunflower pan-genome



Increased genetic diversity

Huang et al. (2023, *PNAS*)

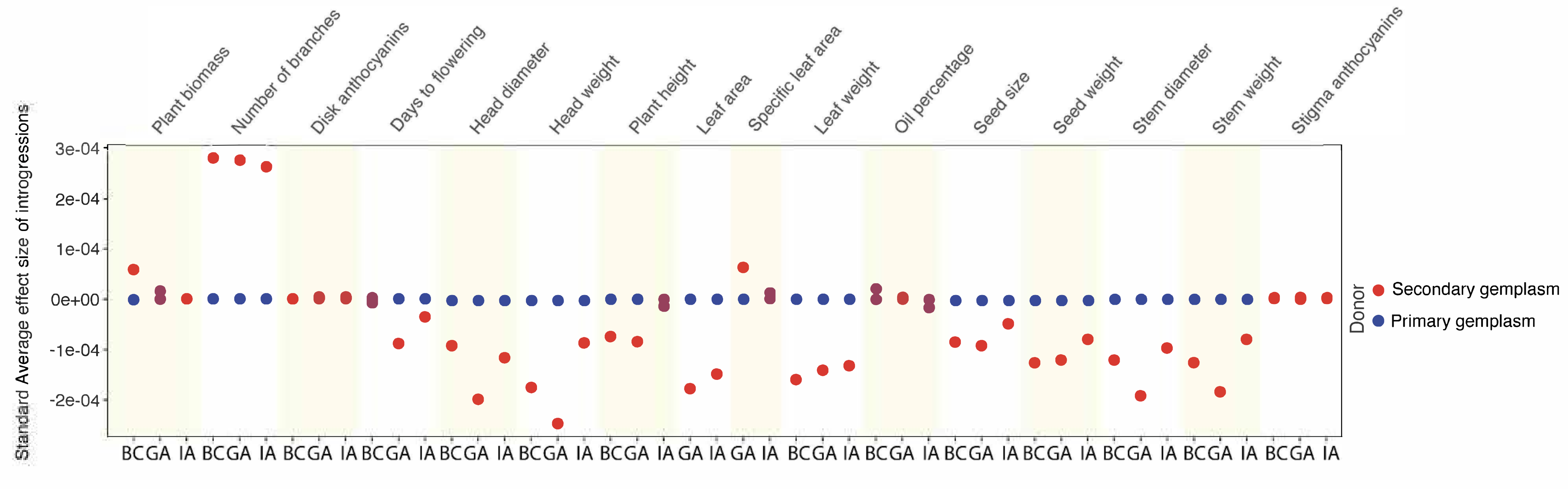
Consequences of crop wild introgressions in sunflower



Wild introgressions reduce genetic load

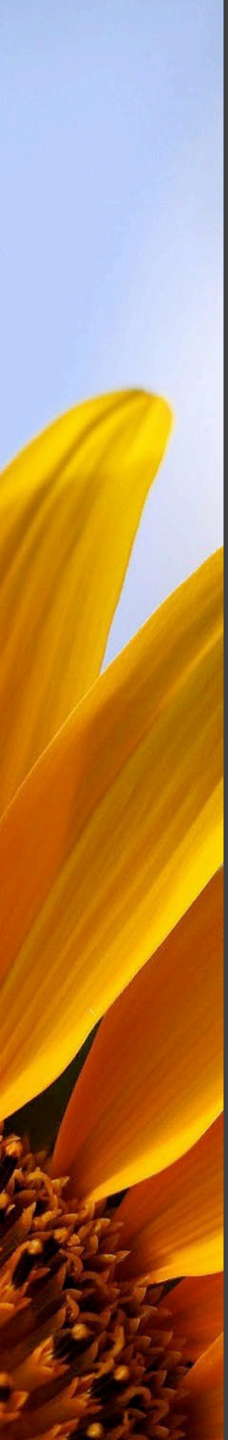
Huang et al. (2023, *PNAS*)

Consequences of crop wild introgressions in sunflower



Wild introgressions from secondary (but not primary) germplasm have strong negative effects on most cultivar traits

Huang et al. (2023, *PNAS*)



Potential Solutions

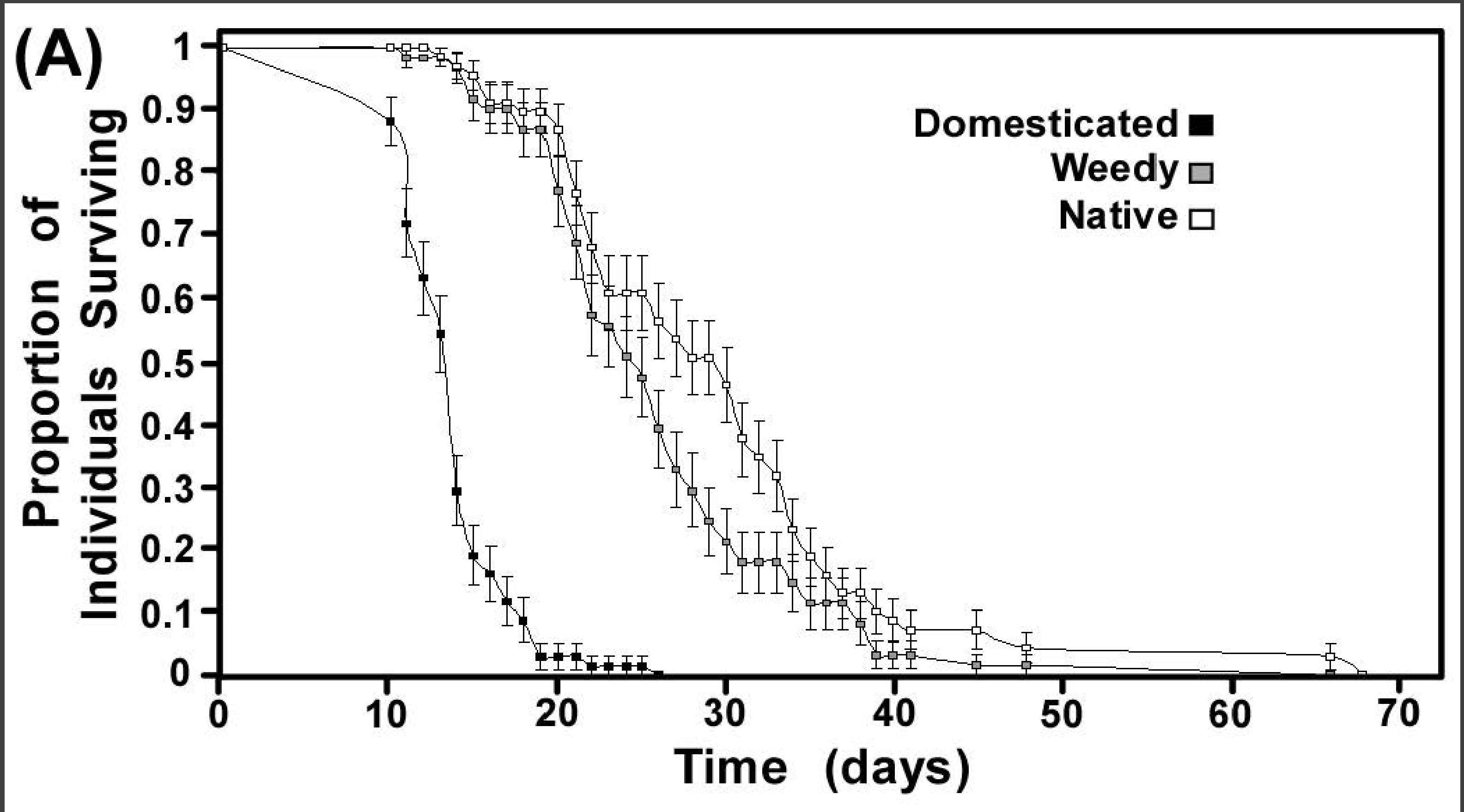
- Focus on primary gene pool in pre-breeding experiments
- Hybrid crop production (complement introgressions)
- Employ new breeding techniques (e.g., genome editing)

Huang et al. (2023, *PNAS*)

Evolutionary applications

- Circumventing evolutionary trade-offs

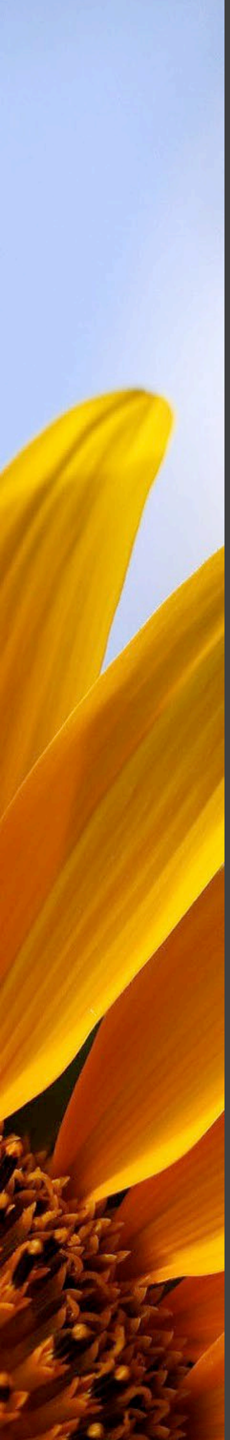
Attempts to breed for resistance to biotic and abiotic stresses often lead to reductions in productivity under ideal conditions (i.e., evolutionary trade-offs)



Drought stress trial involving cultivated sunflower and wild and weedy relatives

(Mayrose et al. 2011, Molecular Ecology)

Evolutionary trade-offs: a paradox



- Trade-off free solutions likely to be rare because natural selection has had ample time to discover them (Denison 2012).
- Argued to be a significant constraint on the development of environmentally resiliant crops.
- Nevertheless, numerous studies report the discovery of resistance alleles that appear to lack a yield penalty .

Yu, L., Chen, X., Wang, Z., Wang, S., Wang, Y., Zhu, Q., Li, S., and Xiang, C. (2013). **Arabidopsis Enhanced Drought Tolerance1/HOMEODOMAIN GLABROUS11 Confers Drought Tolerance in Transgenic Rice without Yield Penalty.** Plant Physiology 162:1378-1391. 10.1104/pp.113.217596.

- How can this be explained?
- Are there lessons for developing environmentally resilient crops?

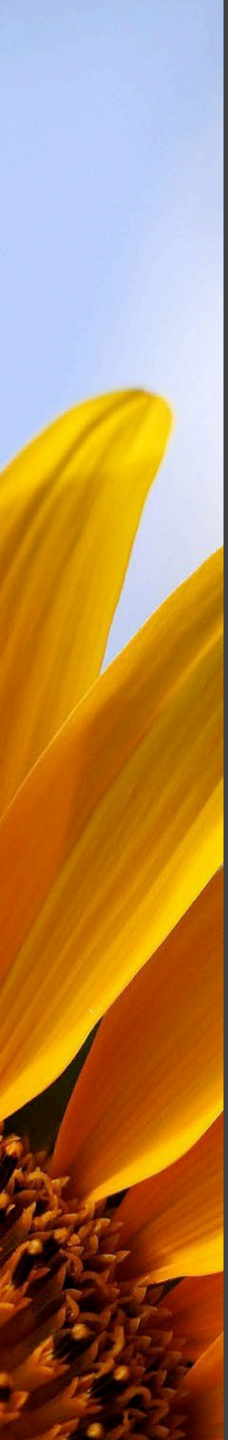
How can trade-off free improvements be explained?

- Inadequate testing.
- Resistance is inducible rather than constitutive.
- The crop environment differs from the environment in which trait initially evolved.

“Genetic modification can improve crop yields — but stop overselling it.”

Nature, September 20, 2024

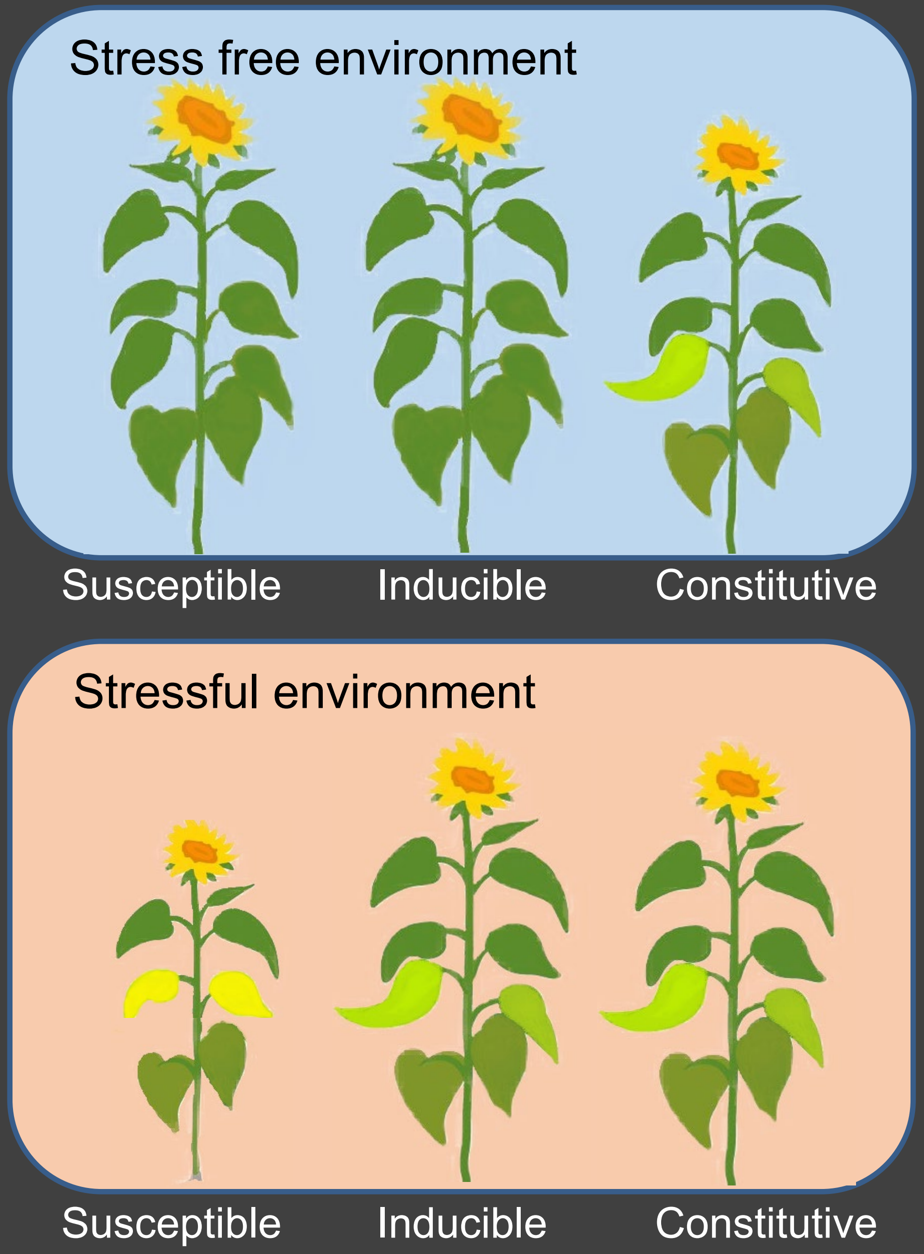
Wheat varietal trials



Solution: Inducible resistance

- Inducible resistance has lower yield penalty by providing protection only when needed.
- No loss of productivity is expected in stress-free environments.
- Why does constitutive resistance evolve at all?

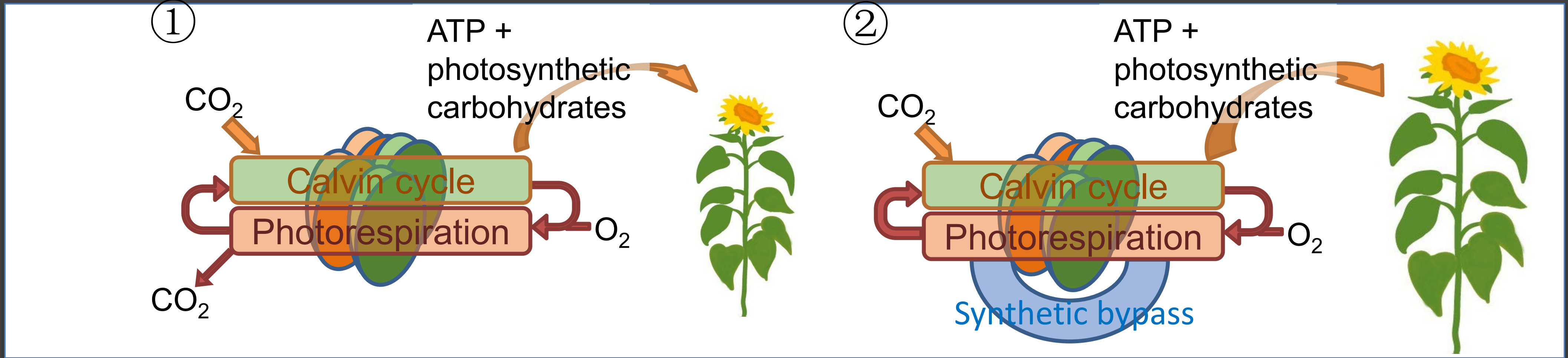
- *Inducible resistance may be too slow*
- *Cues unreliable*
- *Natural selection more effective in populations experiencing a single environment*

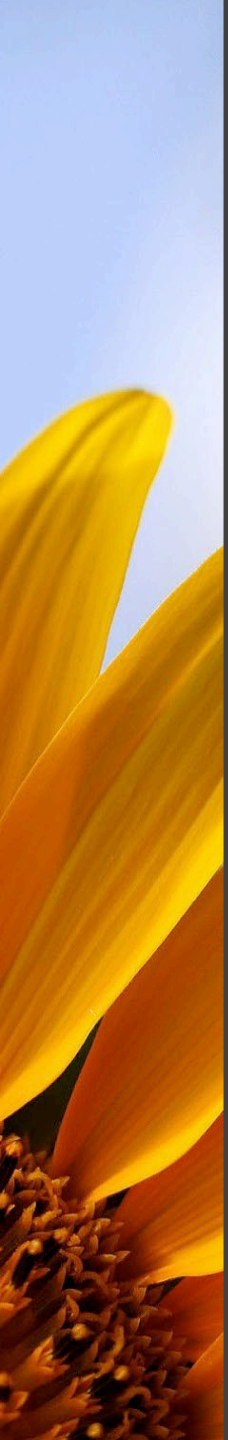


Solution: exploit differences between environment of crop and that in which trait initially evolved

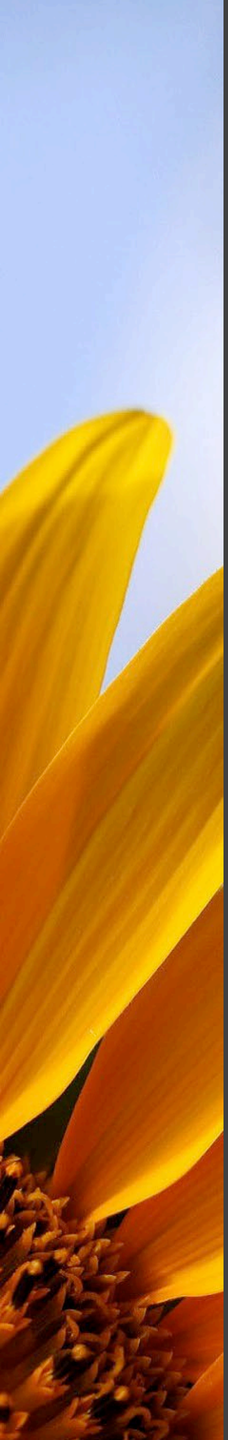
Examples

- Recent increase in CO2 concentration due to the burning of fossil fuels.
  - Improvements that take advantage of higher CO2 concentrations should be feasible without incurring yield penalties
- RubisCO originated in an atmosphere without oxygen. Thus, it cannot reliably distinguish CO2 from O2, reducing photosynthetic rates by 30%.
  - Recent genetic engineering studies resolved problem by modifying plastid glycolate metabolic pathways (South et al., 2019)





Brainstorming session: Can you think of other differences between crop and wild environments that could be exploited by breeders?



Unanswered Questions

- Can we feed the world and sustain the planet?
- What will be (or will there be) the next revolution in crop breeding?
- Multi-cropping is good for biodiversity; could it also enhance crop production?
- Should we re-think crop ideotypes?