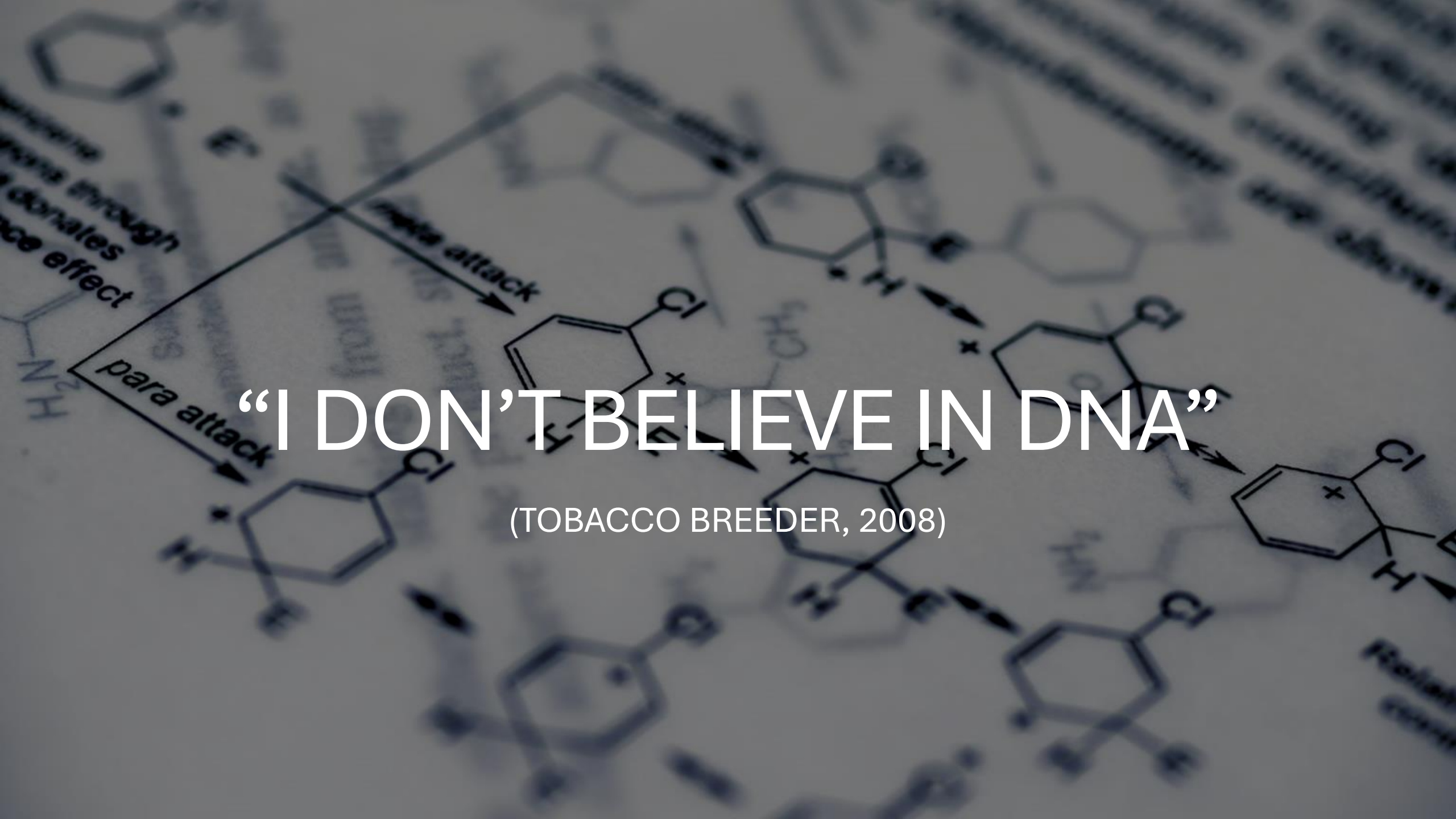
Il contributo della genetica alla soluzione dei problemi ambientali causati dall'intensificazione colturale

Carlo Pozzi

Dipartimento di Scienze Agrarie ed Ambientali, Università degli Studi di Milano

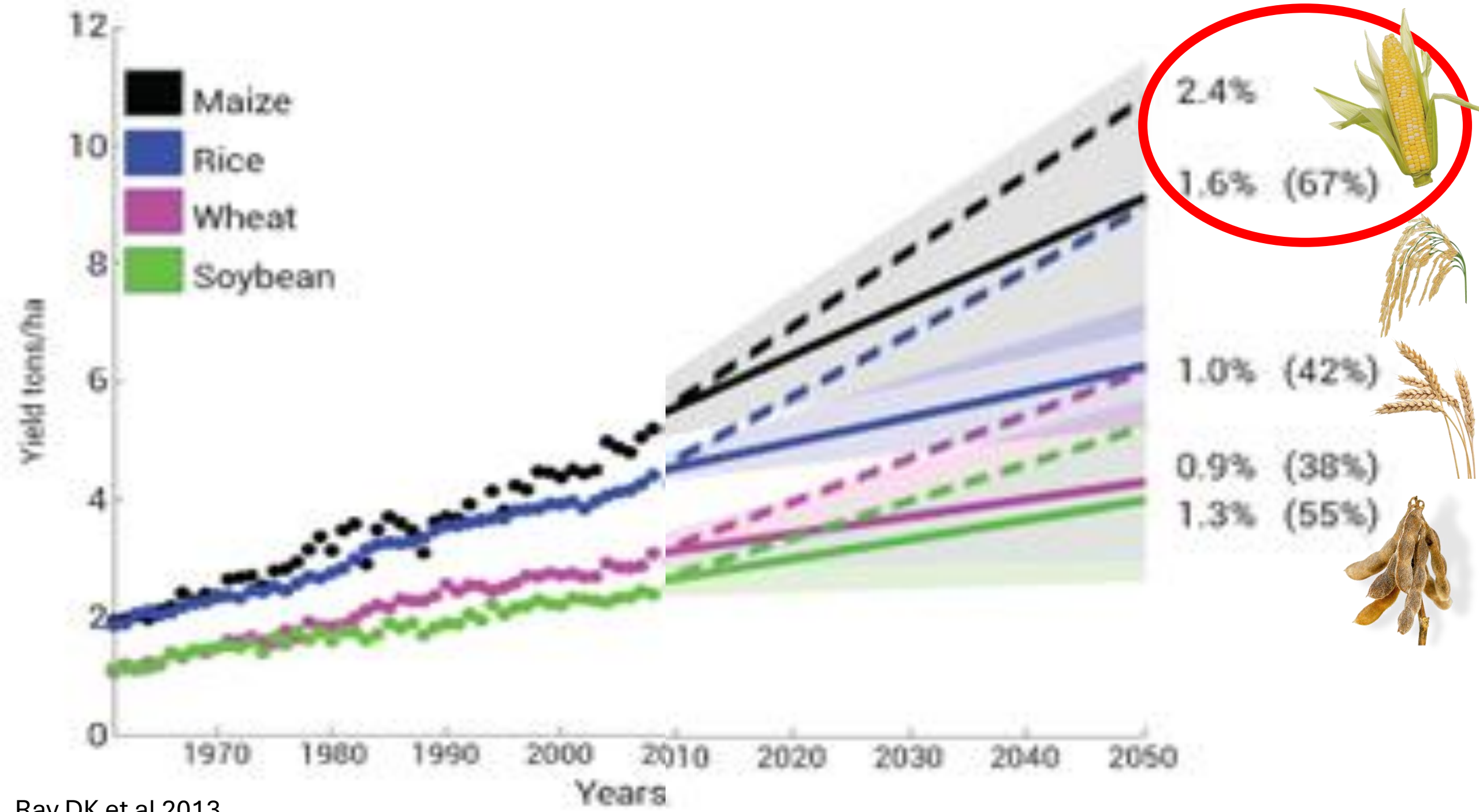
DiSAA
DIPARTIMENTO
di SCIENZE
AGRARIE e
AMBIENTALI

UNIVERSITÀ
DEGLI STUDI
DI MILANO



“I DON’T BELIEVE IN DNA”

(TOBACCO BREEDER, 2008)

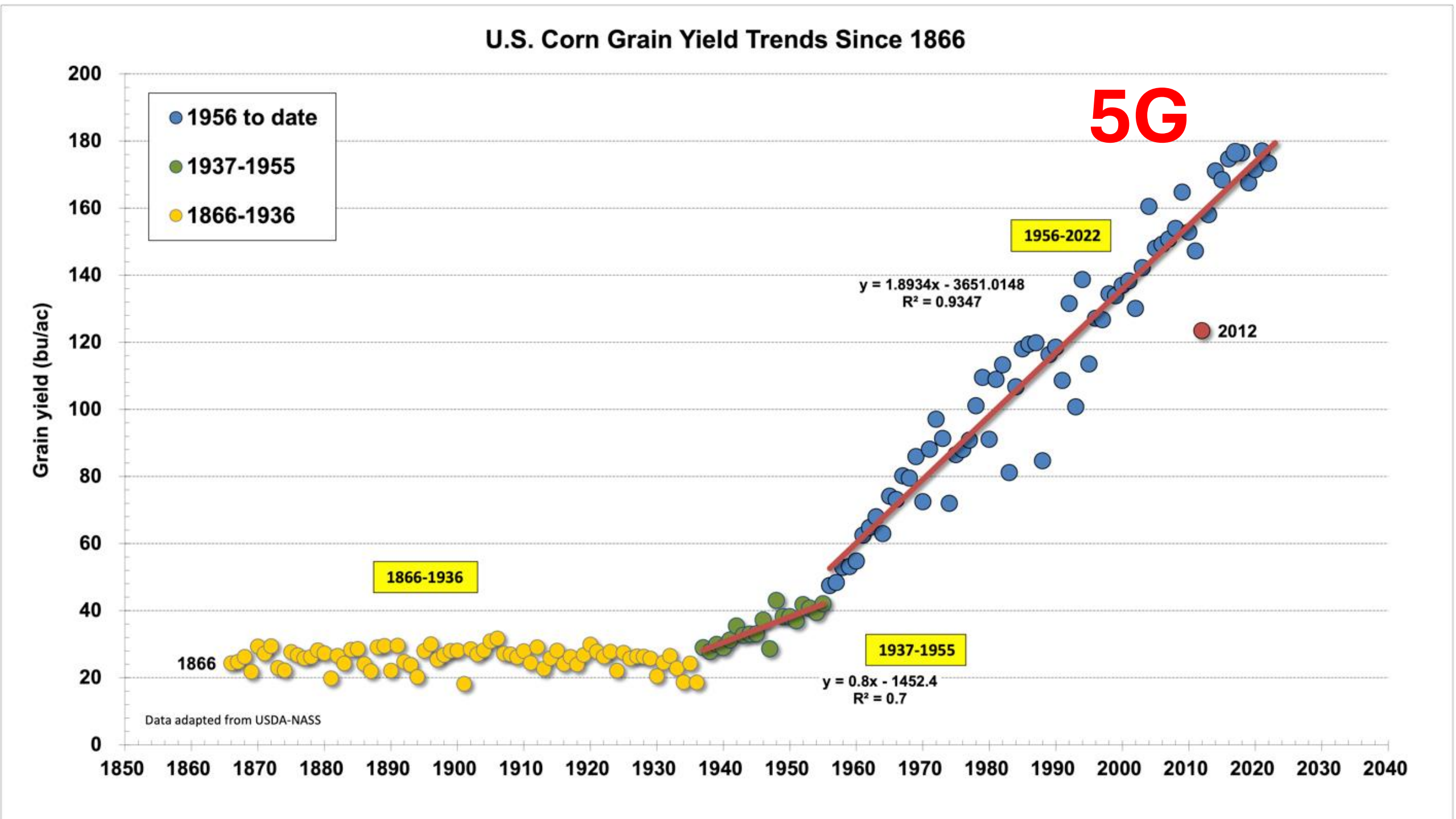


Ray DK et al 2013

The breeder's equation

$$\Delta G = \frac{i * r * \delta_G}{L_g}$$

i	Selection intensity
r	Selection accuracy/reliability
δg	Genetic variance
Lg	Length of breeding cycle


U.S. Corn Grain Yield Trends Since 1866
1956 to date
1937-1955
1866-1936
5G
1956-2022
y = 1.8934x - 3651.0148
R² = 0.9347
2012
1866-1936
1866
1937-1955
y = 0.8x - 1452.4
R² = 0.7
Data adapted from USDA-NASS
Grain yield (bu/ac)
0
20
40
60
80
100
120
140
160
180
200
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040

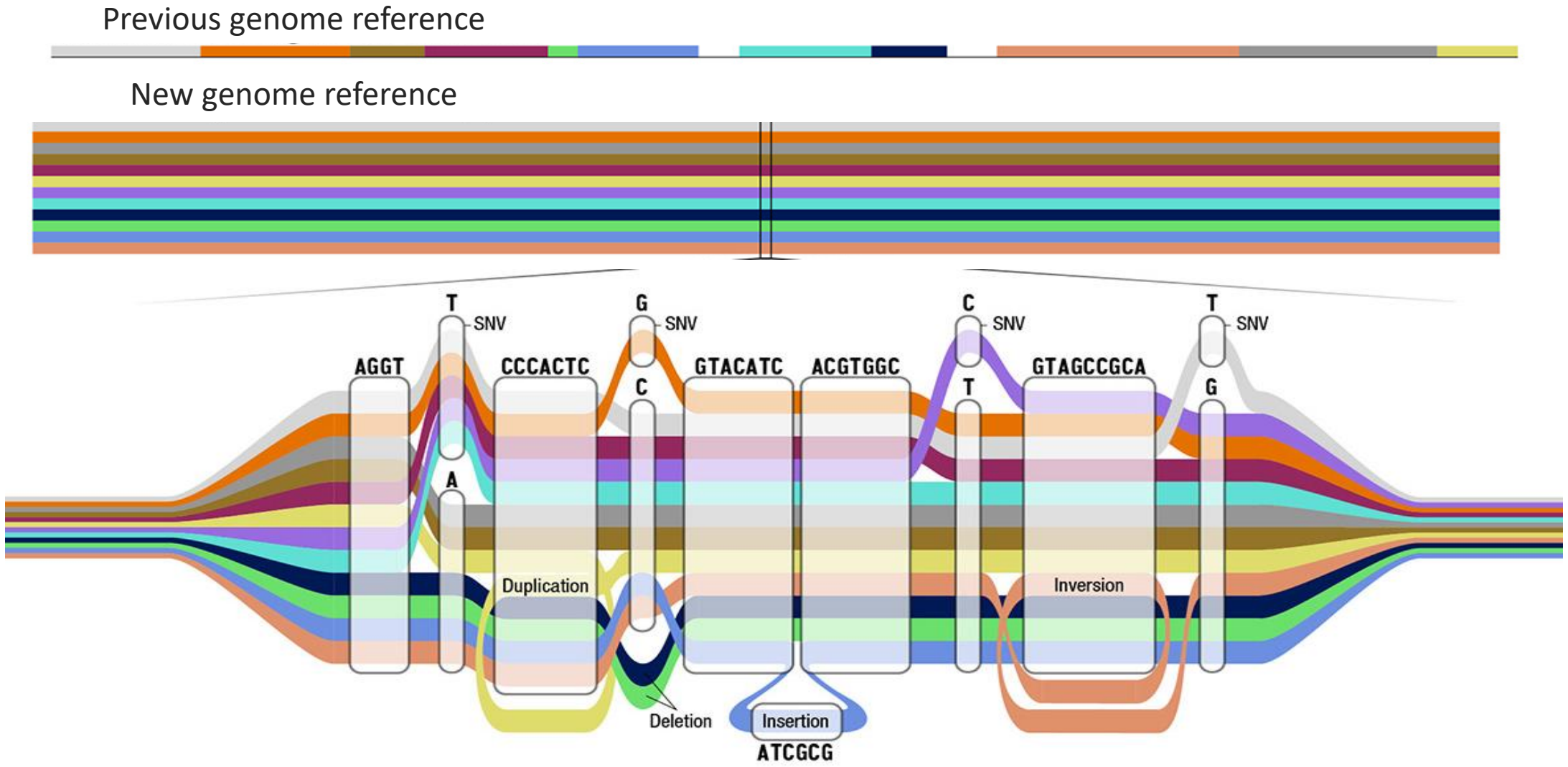
5G: the molecular genetics tools in the new breeding

- Genome assembly
- Germplasm characterization
- Gene Function
- Genomic breeding
- Genome Editing

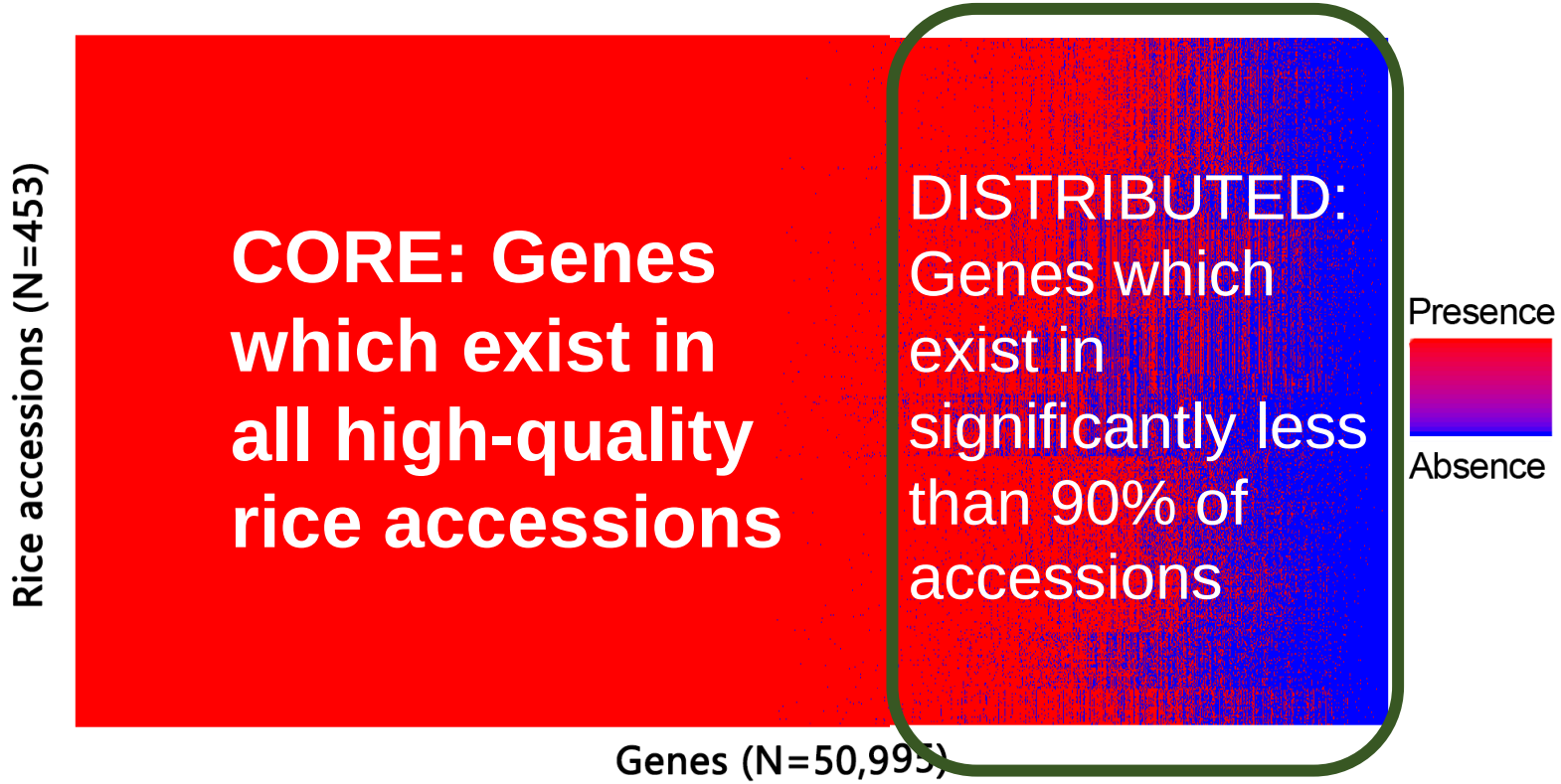
Varshney et al., 2020

Genome assembly

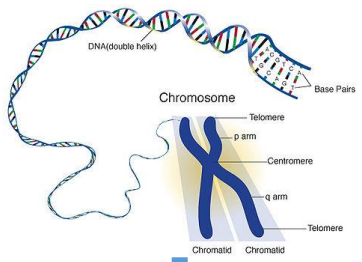
Pangenome graph

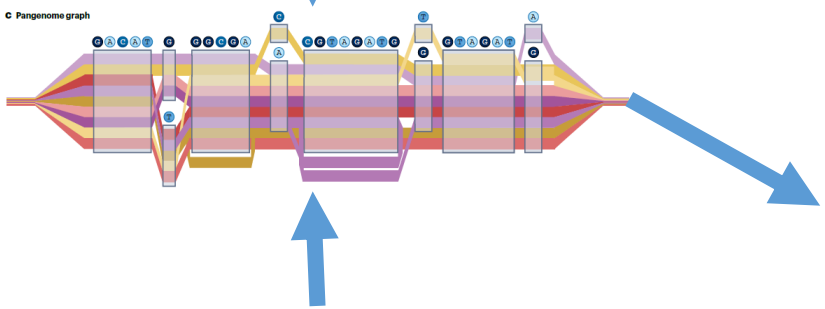


Strength of resenquencing



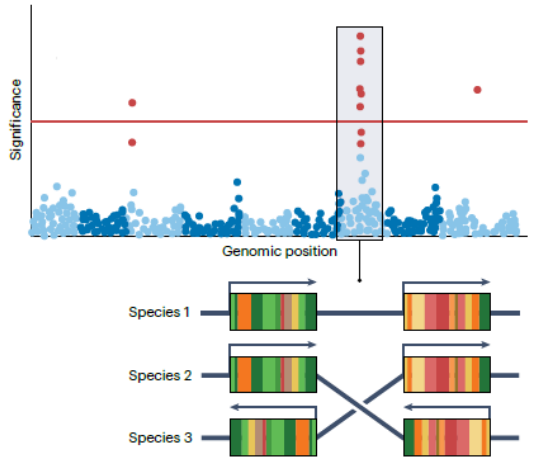
Benefit to plant breeding from pangenomics





IMPROVED GENE PREDICTION / ANNOTATION

MACHINE LEARNING

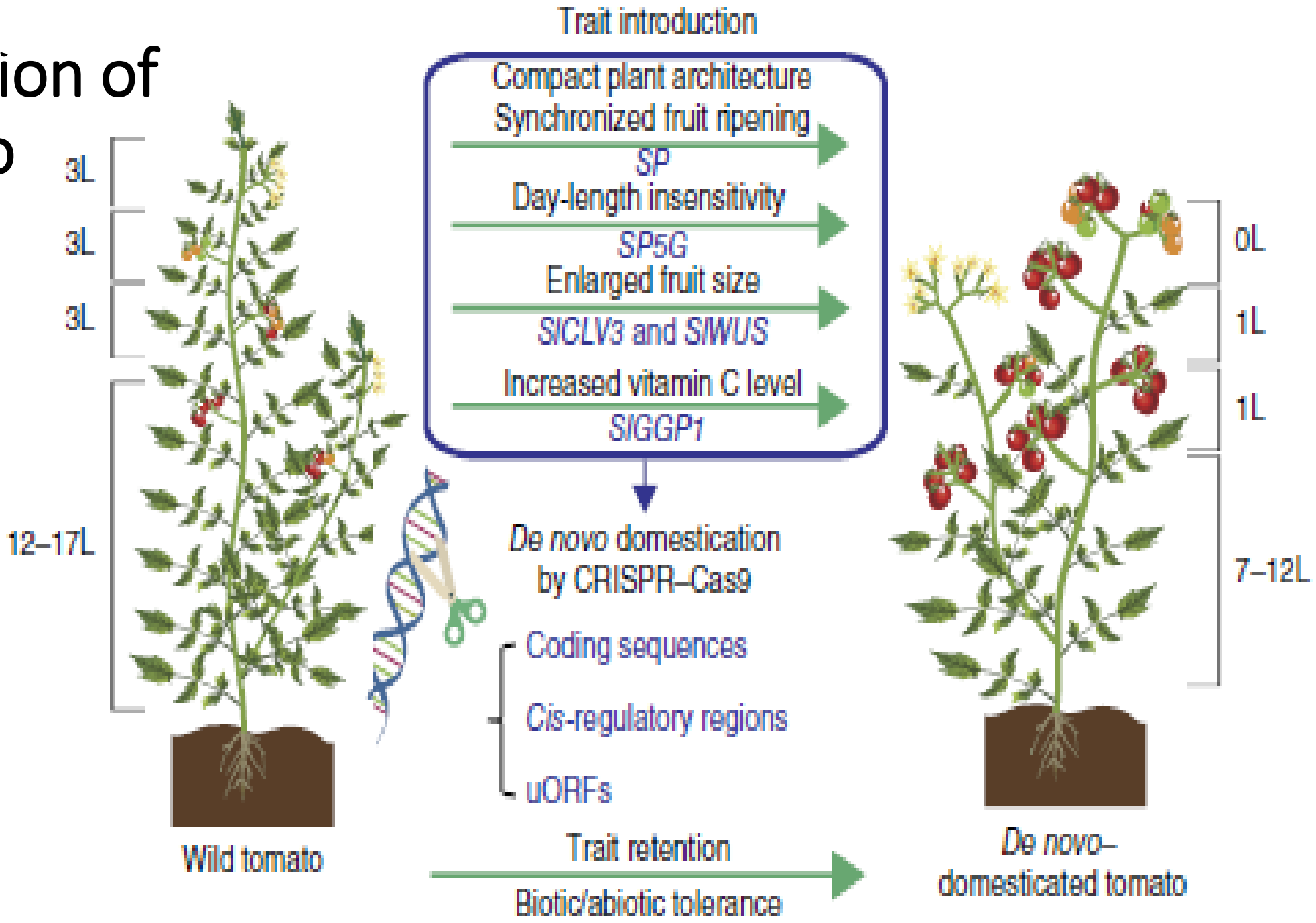


Link structural variation to quantitative traits

1. Identify genes lost during domestication
2. Domesticate new varieties

https://pmc.ncbi.nlm.nih.gov/articles/PMC8910360/

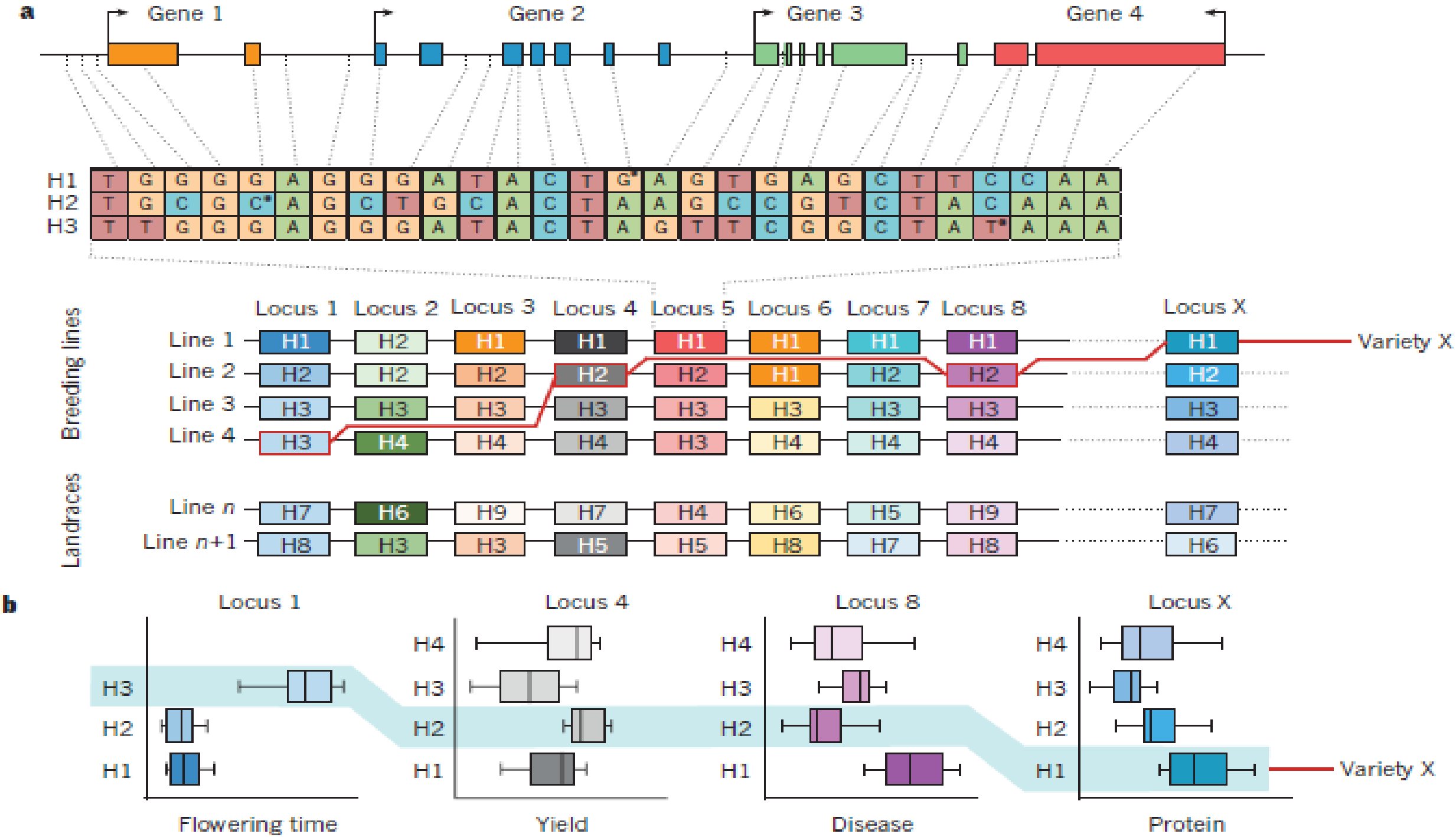
Domestication of wild tomato




Swarna-Sub1
Swarna


PodGard
Traditional

Genomic breeding

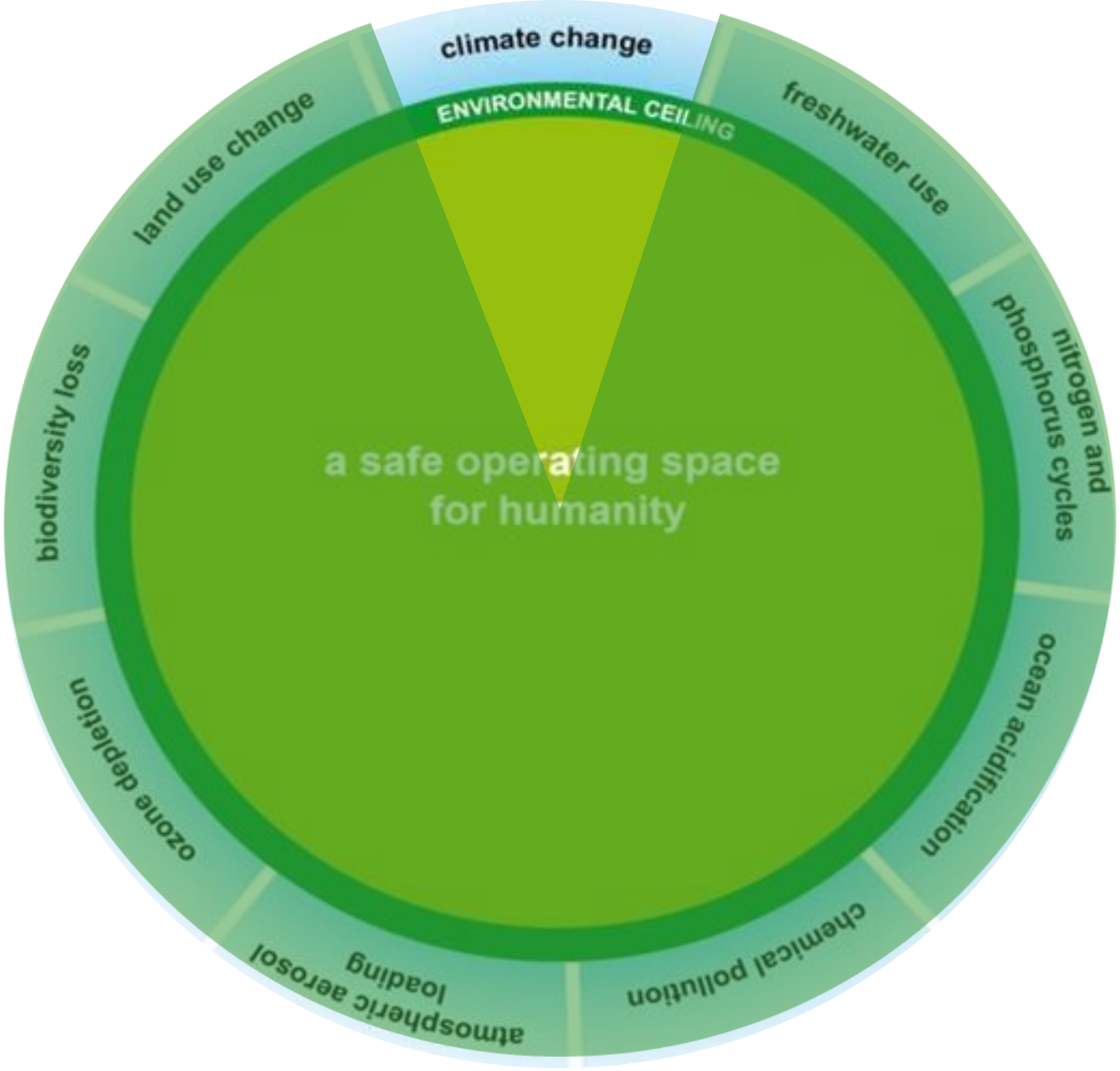

a
Gene 1
Gene 2
Gene 3
Gene 4
H1 T G G G G A G G G A T A C T G* A G T G A G C T T C C A A
H2 T G C G C* A G C T G C A C T A A G C C G T C T A C A A A
H3 T T G G G A G G G A T A C T A G T T C G G C T A T* A A A
Breeding lines
Landraces
Locus 1 Locus 2 Locus 3 Locus 4 Locus 5 Locus 6 Locus 7 Locus 8 Locus X
Line 1 H1 H2 H1 H1 H1 H1 H1 H1 H1
Line 2 H2 H2 H2 H2 H2 H1 H2 H2 H2
Line 3 H3 H3 H3 H3 H3 H3 H3 H3 H3
Line 4 H3 H4 H4 H4 H3 H4 H4 H4 H4
Line n H7 H6 H9 H7 H4 H6 H5 H9 H7
Line n+1 H8 H3 H3 H5 H5 H8 H7 H8 H6
Variety X
b
Locus 1
Locus 4
Locus 8
Locus X
H4
H3
H2
H1
Flowering time
Yield
Disease
Protein
Variety X

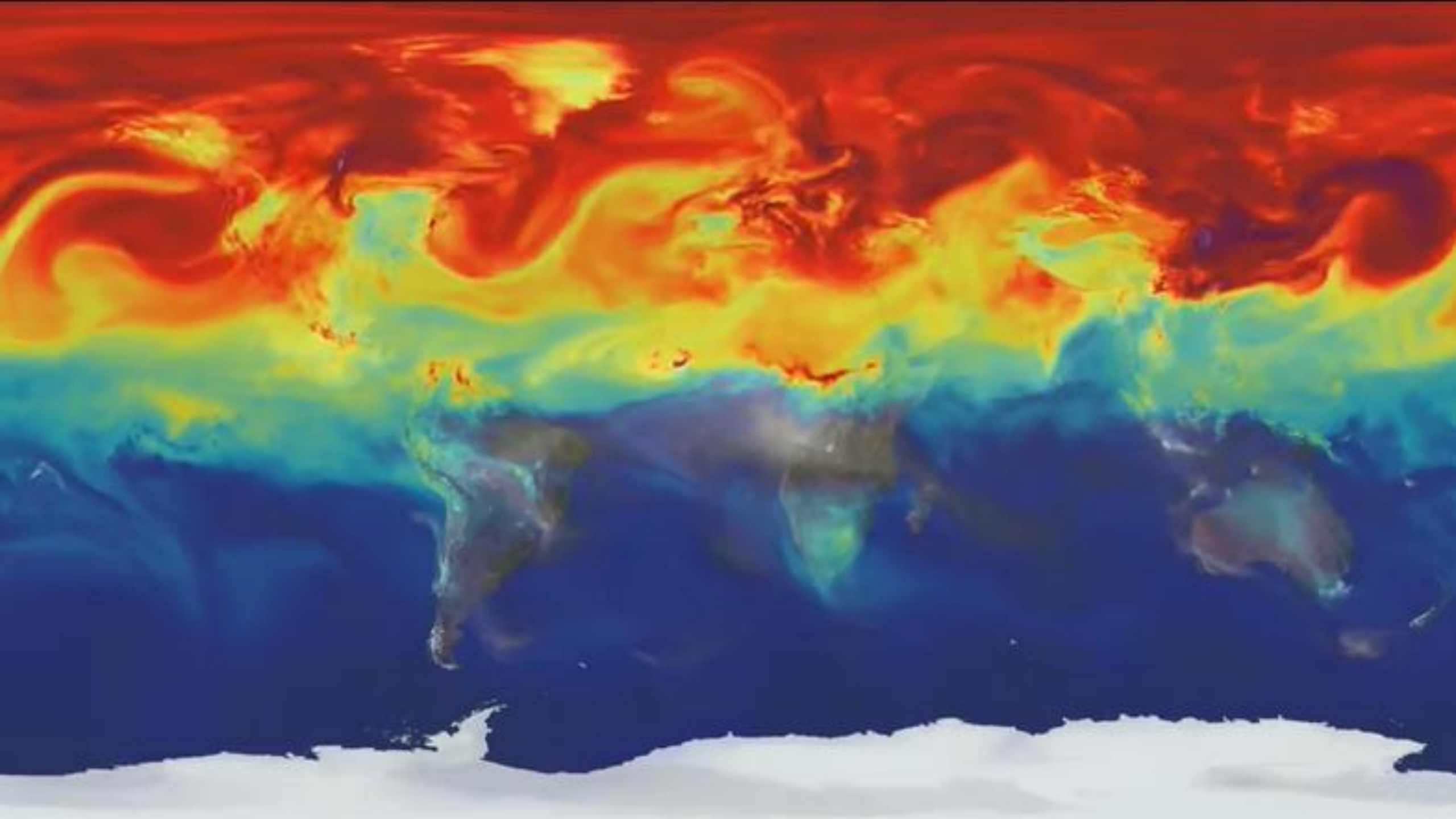
Genomic breeding

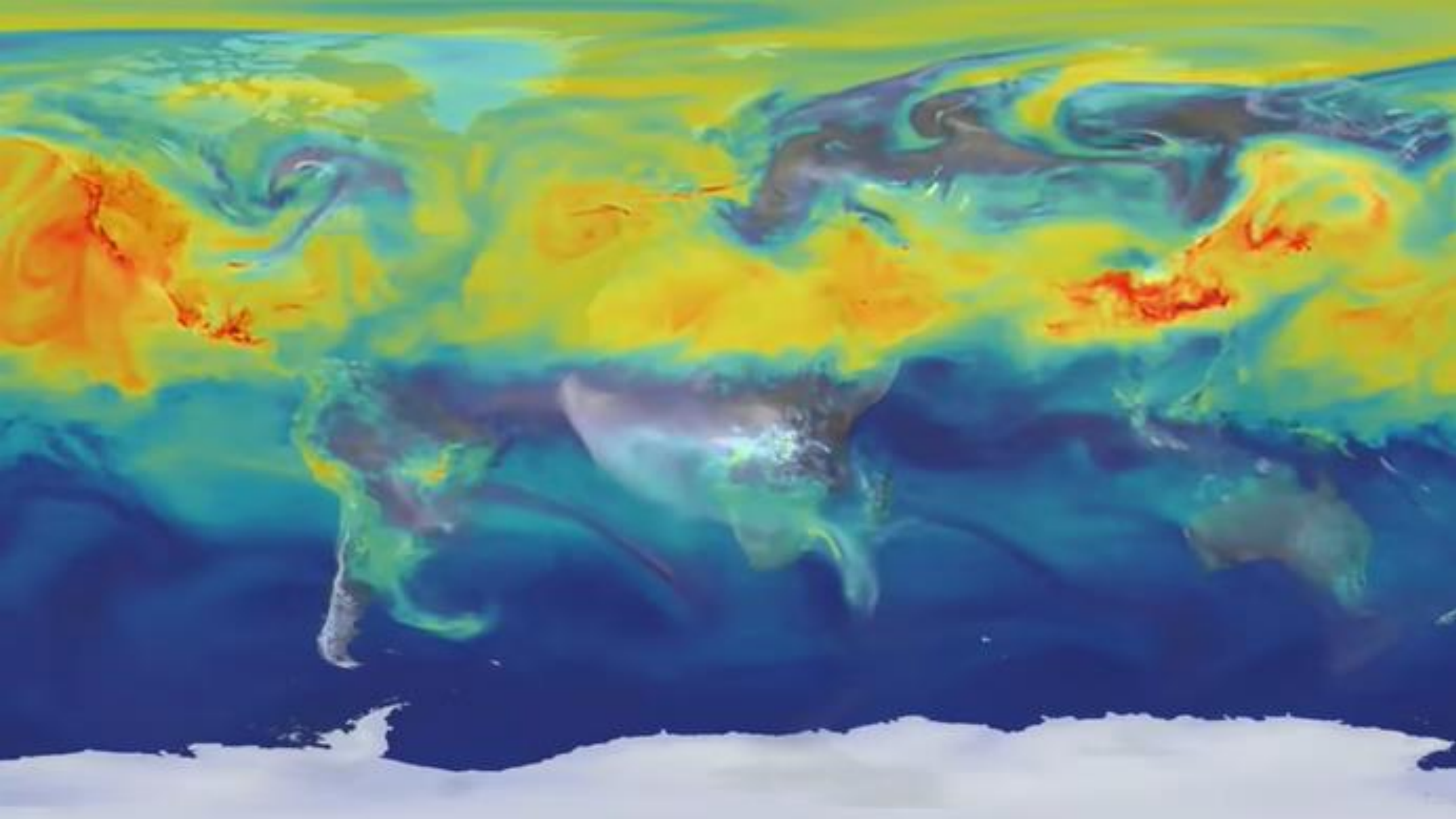
Accession no.	Biological status	Origin	Region	Sequence variation in "QTL-hotspot" region		
				Ca_04546	*Ca_04557*	*Ca_04558*
				Exon 3	Intron 2	Exon 6
				T/A	T/C	A/C
				Asn/Tyr		Ile/Ser
				2888*	598*	2922*
ICC 5002	Breeding material	India	South & East Asia	T	T	A
ICC 9974	Landrace	India	South & East Asia	T	T	A
ICC 6464	Landrace	Iran	West Asia	T	T	A
ICC 14340	Breeding material	India	South & East Asia	T	C	A
ICC 2342	Landrace	Iran	West Asia	T	C	A
ICC 9994	Landrace	India	South & East Asia	T	T	A
ICC 14083	Landrace	Ethiopia	Africa	T	C	A
ICC 16171	Landrace	Myanmar	South & East Asia	T	T	A
ICC 12288	Landrace	Nepal	South & East Asia	T	T	A
ICC 16215	Landrace	Myanmar	South & East Asia	T	T	A
ICC 1790	Landrace	India	South & East Asia	T	T	A
ICC 12299	Landrace	Nepal	South & East Asia	T	T	A
ICC 4065	Landrace	Iran	West Asia	T	C	A
ICC 9978	Landrace	India	South & East Asia	T	T	A
ICC 10673	Landrace	Turkey	Russian Federation	T	C	A
ICC 3617	Landrace	Iran	West Asia	T	C	A
ICC 4310	Landrace	Iran	West Asia	T	C	A
ICC 4623	Landrace	India	South & East Asia	T	T	A
ICC 7485	Landrace	India	South & East Asia	T	T	A
ICC 9970	Landrace	India	South & East Asia	T	T	A
ICC 1836	Landrace	India	South & East Asia	A	C	C
ICC 6122	Landrace	India	South & East Asia	T	C	C
C 5003LN	Breeding material	ICRISAT	South & East Asia	A	C	C
12379	Landrace	Iran	South & East Asia	A	C	C
12197	Breeding material	India	South & East Asia	T	C	C
15762	Landrace	Syrian Arab Republic	Mediterranean	T	C	A
3200	Landrace	Iran	West Asia	T	C	C
932	Landrace	India	South & East Asia	T	C	C
2	Advanced cultivar	ICRISAT	South & East Asia	A	C	C
53	Landrace	India	South & East Asia	T	C	N
9	Landrace	Nepal	South & East Asia	T	C	C
97	Landrace	India	South & East Asia	T	C	C
CC 8474	Landrace	Spain	Mediterranean	T	C	C
CC 12951	Breeding material	India	South & East Asia	A	C	C
ICC 4958	Advanced cultivar	India	South & East Asia	T	C	C
ICC 8348	Landrace	India	South & East Asia	T	C	C
ICCC 37	Breeding material	ICRISAT	South & East Asia	T	T	A
ICC 15574	Breeding material	India	West Asia	A	C	C
ICC 7672	Landrace	Morocco	Mediterranean	A	C	C
ICC 15554	Landrace	Morocco	South & East Asia	A	C	C
		Variation-index	Lowest bulk	1.00	0.65	1.00
			Highest bulk	0.60	0.05	0.11
		ΔVariation-index		-0.40	-0.60	-0.89

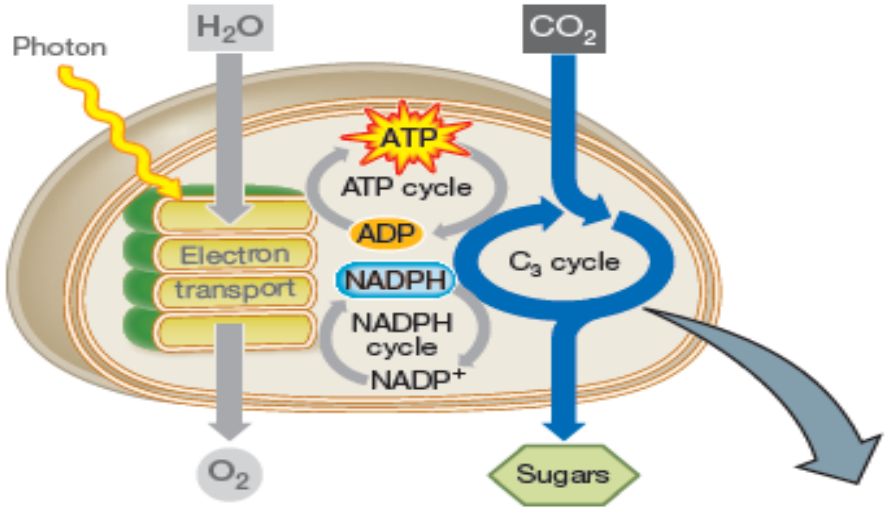

The planet
boundaries &
biotech


climate change
freshwater use
nitrogen and phosphorus cycles
ocean acidification
chemical pollution
atmospheric aerosol loading
ozone depletion
biodiversity loss
land use change
ENVIRONMENTAL CEILING
a safe operating space for humanity


climate change
ENVIRONMENTAL CEILING
freshwater use
nitrogen and phosphorus cycles
ocean acidification
chemical pollution
atmospheric aerosol loading
ozone depletion
biodiversity loss
land use change
a safe operating space for humanity







2 In a reaction catalyzed by Rubisco, CO_2 combines with the 5-carbon RuBP to produce 2 molecules of 3PG (3 carbons each).

Rubisco

RuBP

3PG

ADP

ATP

NADPH

$NADP^+$

C_3 cycle

CO_2

1 CO_2 from the atmosphere enters the chloroplast.

RuBP

G3P

ADP

ATP

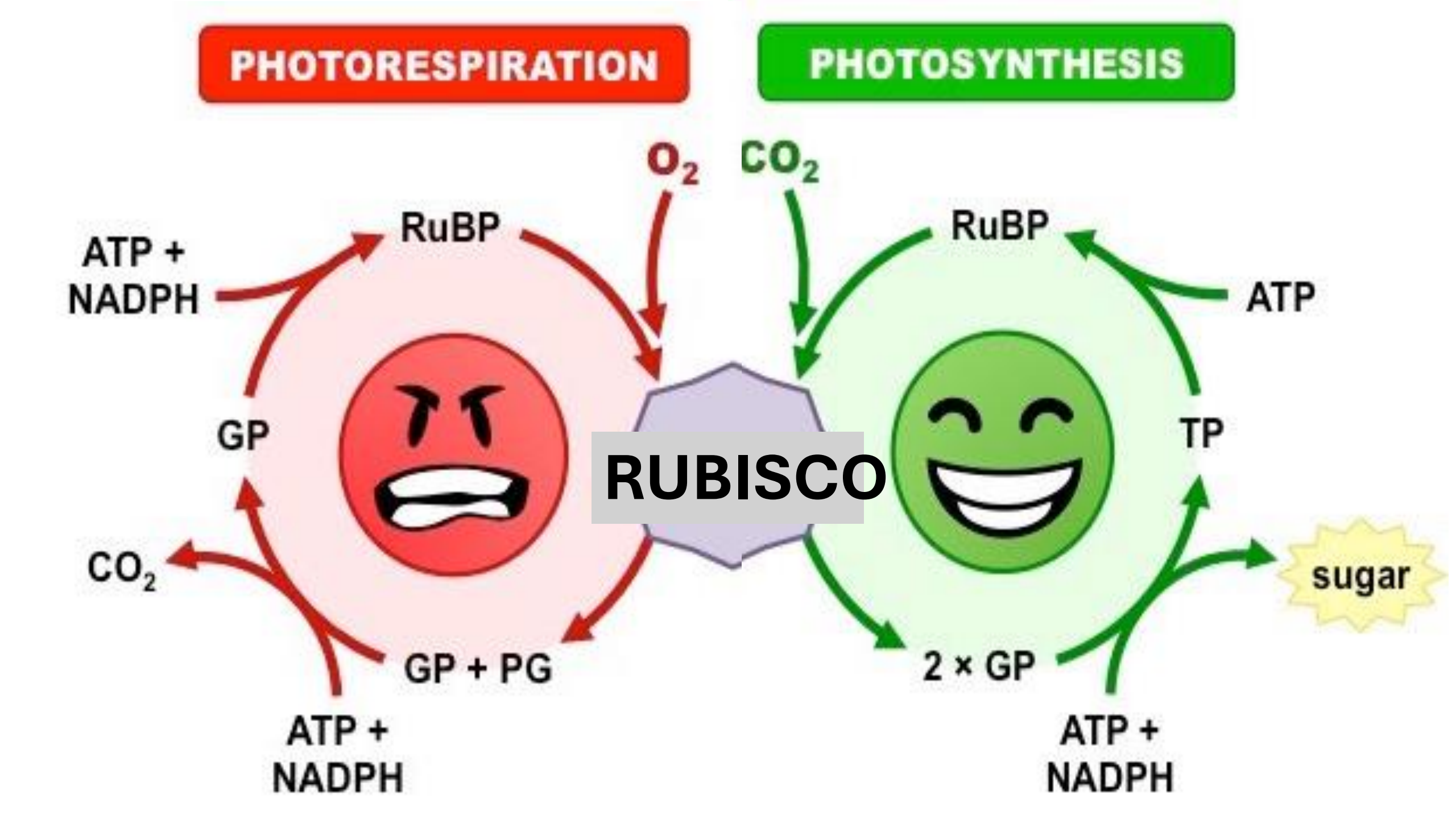
Sugars

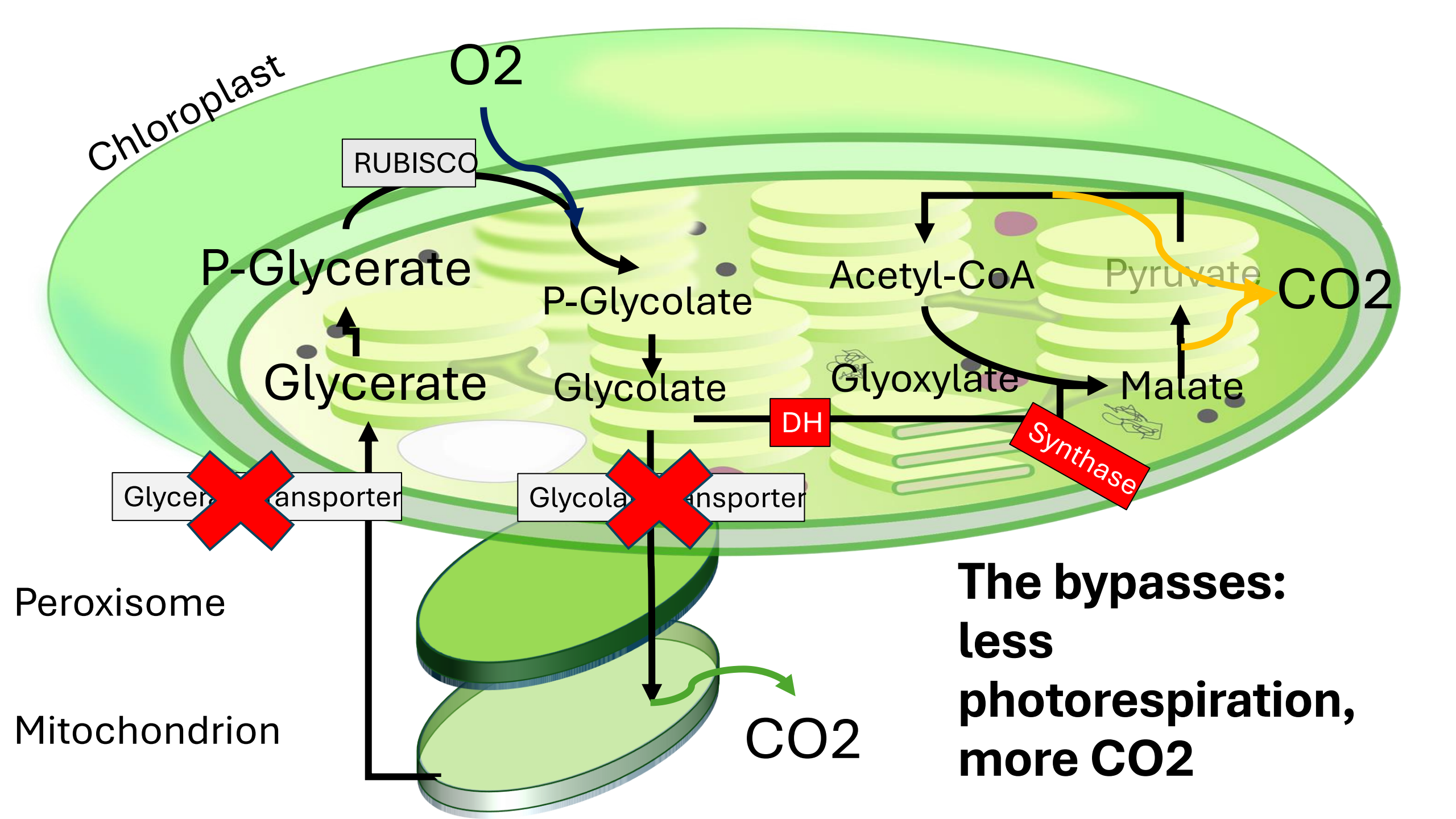
4 The remaining five-sixths of the G3P molecules undergo a series of ATP-requiring reactions to regenerate RuBP, which is now ready to accept another CO_2.

3 The presence of G3P is a branch point in the cycle. About one-sixth of the G3P molecules are used to synthesize sugars (carbohydrates).

What is the maximum yield we may expect for a crop?


CONVERSION
EFFICIENCY


PHOTORESPIRATION
PHOTOSYNTHESIS
O_2
CO_2
RuBP
RuBP
ATP +
NADPH
ATP
GP
TP
RUBISCO
CO_2
sugar
GP + PG
2 × GP
ATP +
NADPH
ATP +
NADPH



The bypasses: less photorespiration, more CO2

Project leader Paul South assesses the progress of engineered tobacco plants grown in real-world conditions © Claire Benjamin/RIPE Project

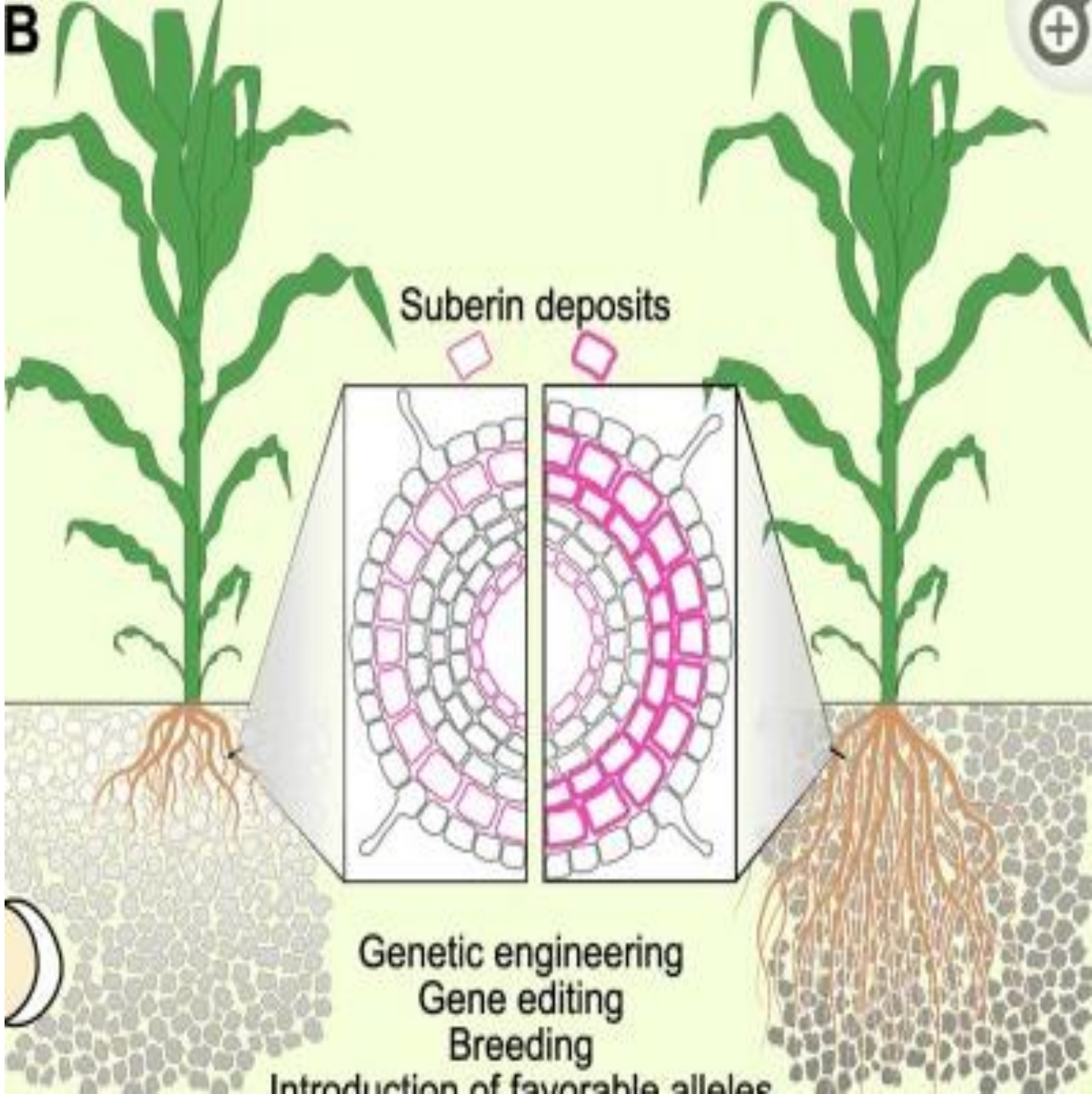
Radical solutions

- introduction of perennialism into annual crops
- de novo domestication of wild, perennial species.

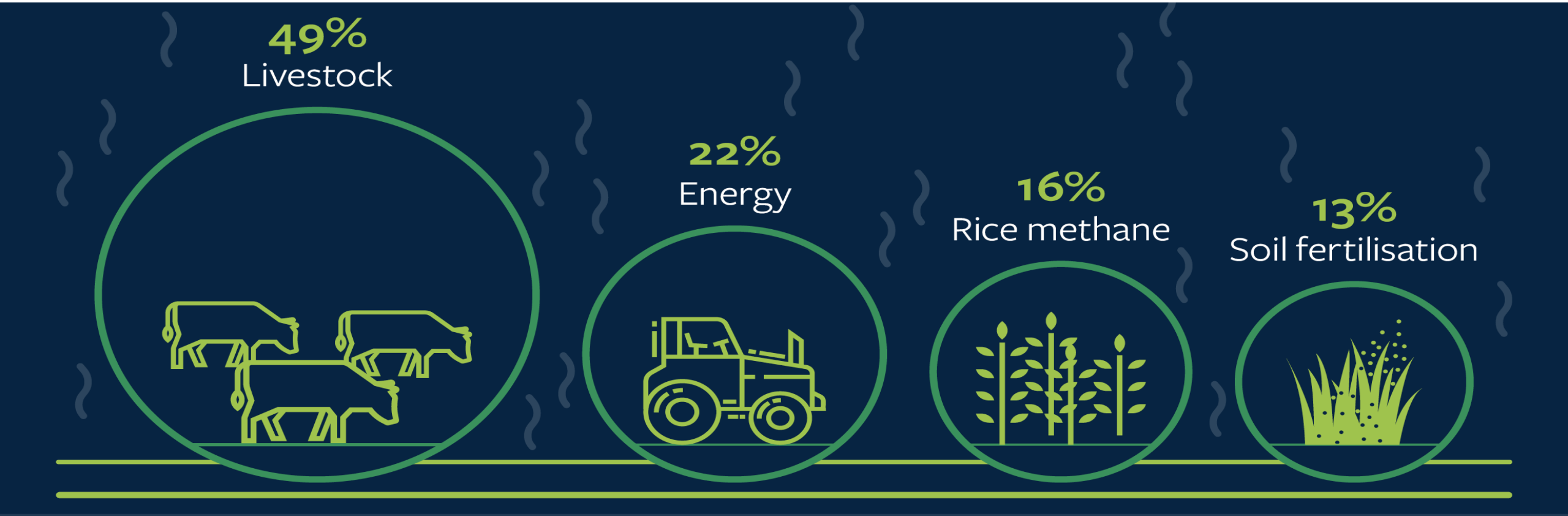
Thinopyrum intermedium


Perennial Rice 23 (PR23; 6.8 t/ha)

Toward an ideal carbon-capturing crop plant.



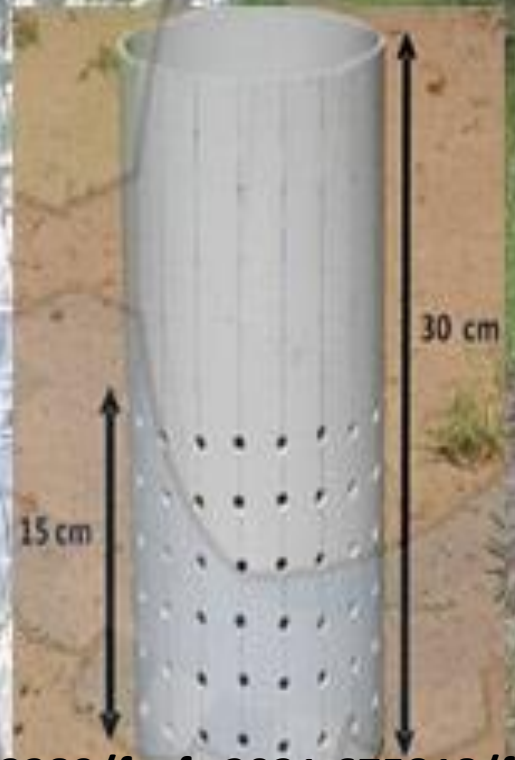
Methane emissions



Read more at **odi.org/agricultural-reform**

Source: World Resources Report (Searchinger et al, 2019)

Sustainable rice intensification (SRI)

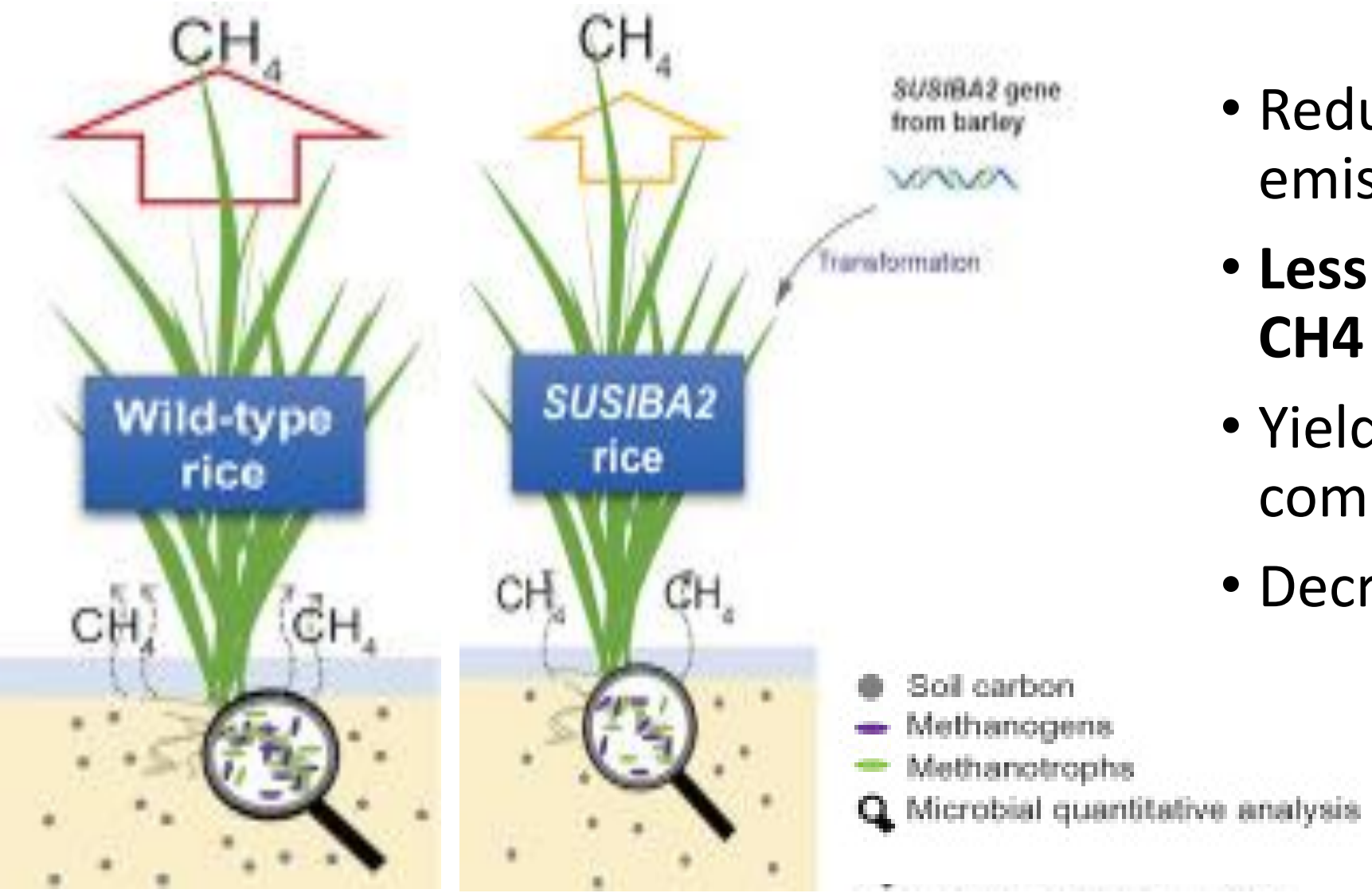


Alternate wetting drying

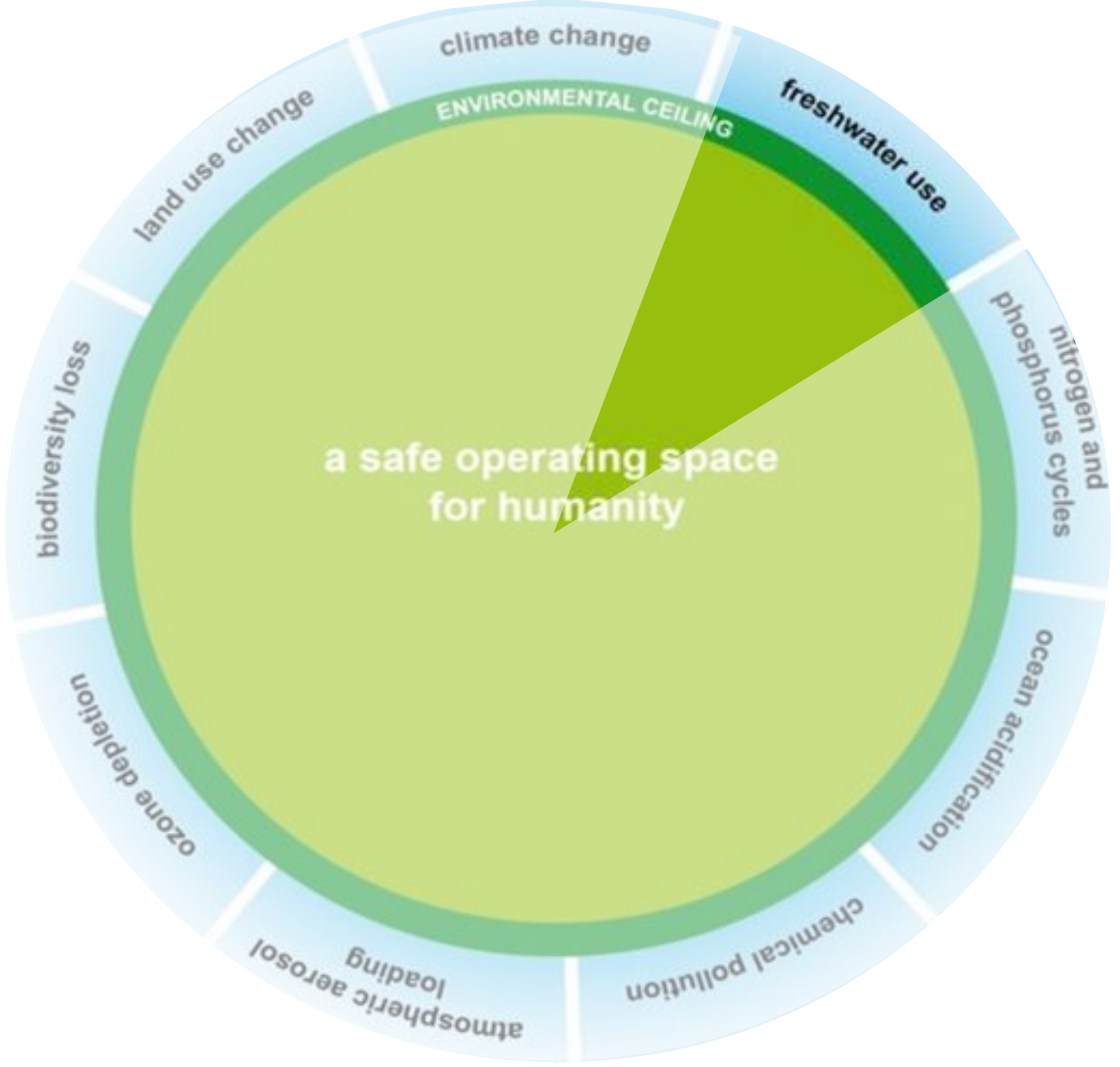
technique to save water in flooded rice

https://www.frontiersin.org/articles/10.3389/fsufs.2021.675818/f

SUSIBA rice



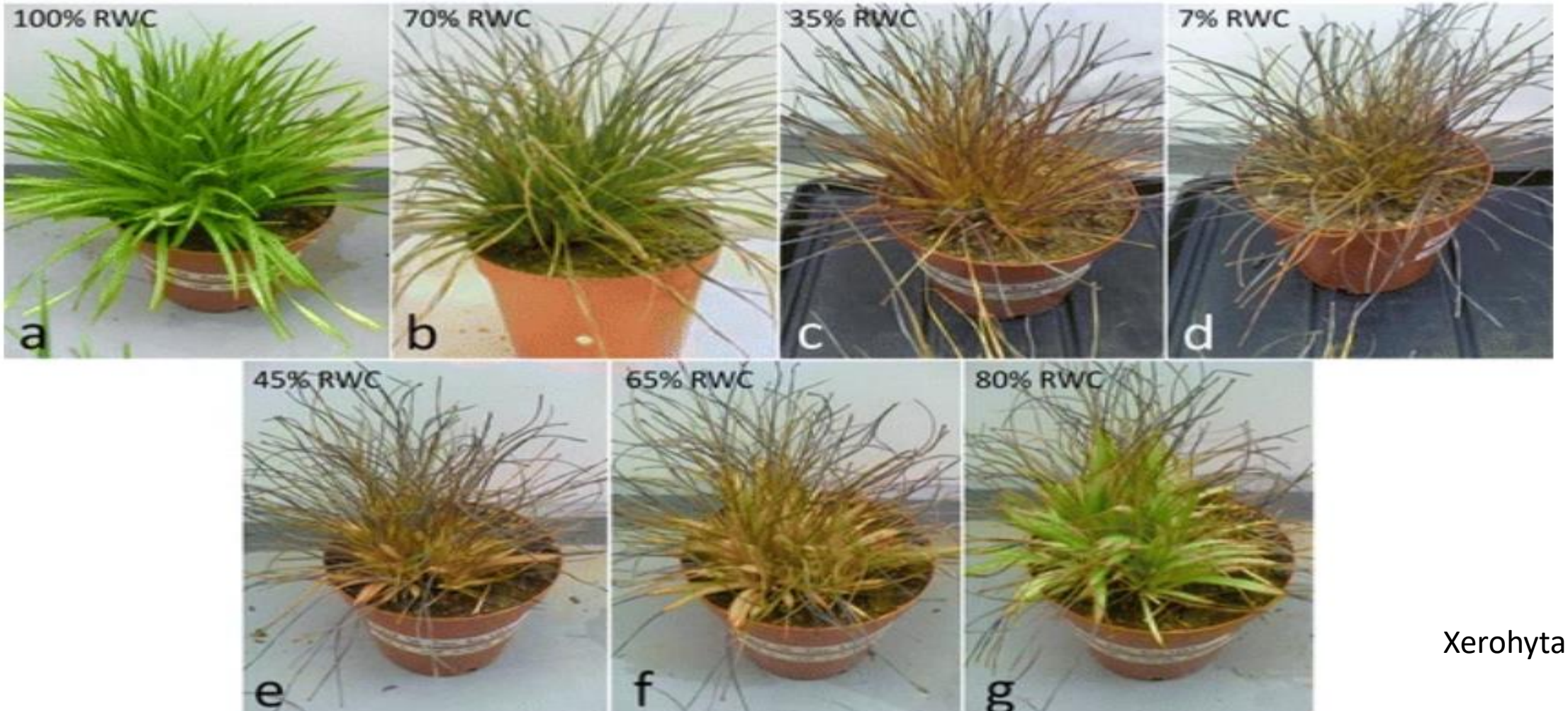
- Reduced total CH4 emissions
- **Less microbes involved in CH4 emissions**
- Yield traits are comparable or greater
- Decrease in soil organic C


climate change
freshwater use
nitrogen and phosphorus cycles
ocean acidification
chemical pollution
atmospheric aerosol loading
ozone depletion
biodiversity loss
land use change
ENVIRONMENTAL CEILING
a safe operating space for humanity

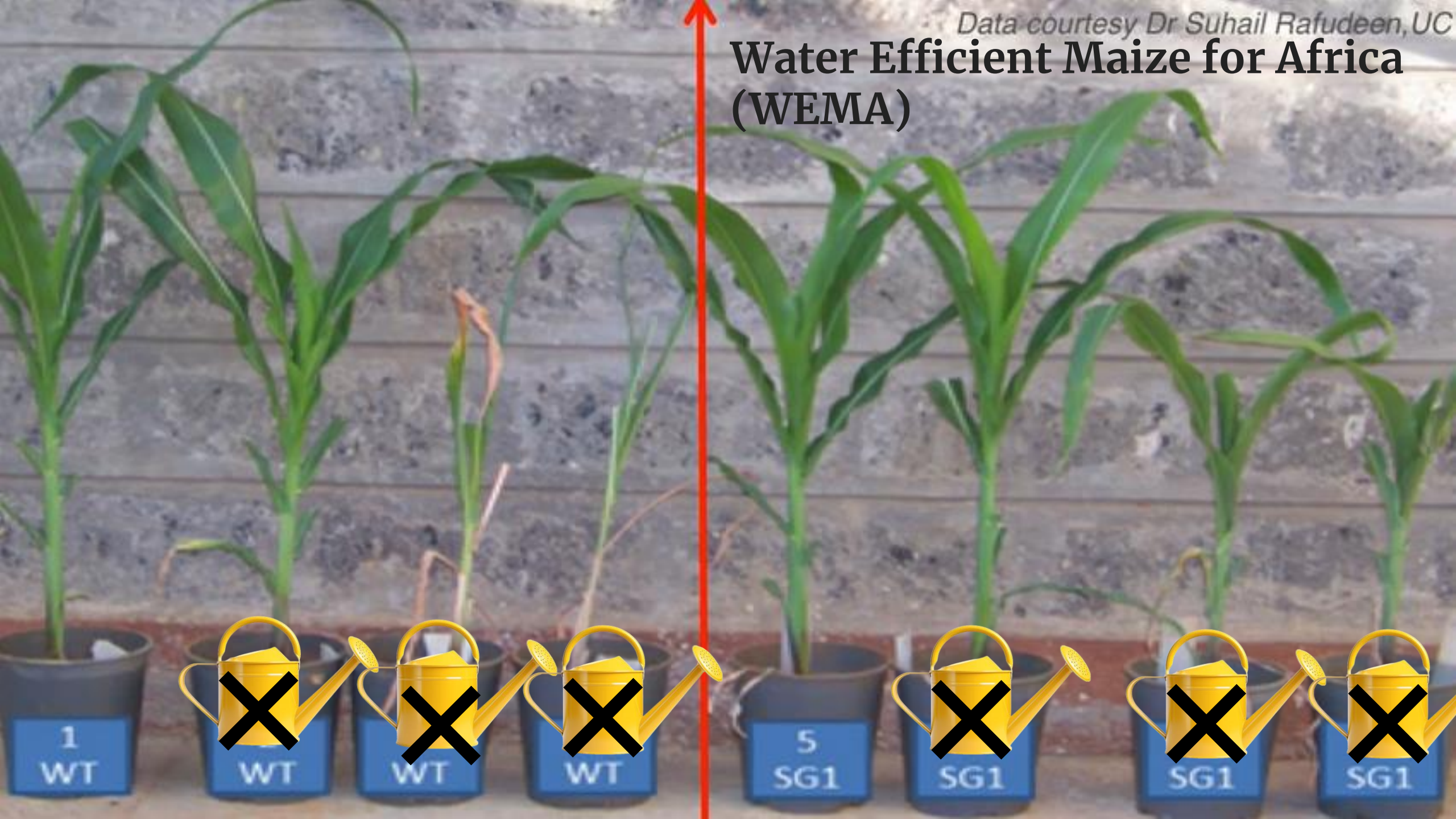
DROUGHT-INDUCED PROMOTER FROM A RESURRECTION PLANT

XvSap, *XvPrx2* and *XvAld* ANTIOXIDANT GENES FROM RESURRECTION PLANTS

TERMINATOR



Xerohyta viscosa


Data courtesy Dr Suhail Rafudeen, UC
Water Efficient Maize for Africa (WEMA)
1
WT
WT
WT
WT
5
SG1
SG1
SG1
SG1

HB4

- First drought and salt tolerant soybean in 2019.
- The gene responsible for the new technology is HB4, → soybeans, wheat
- The seed is owned by **Bioceres**.

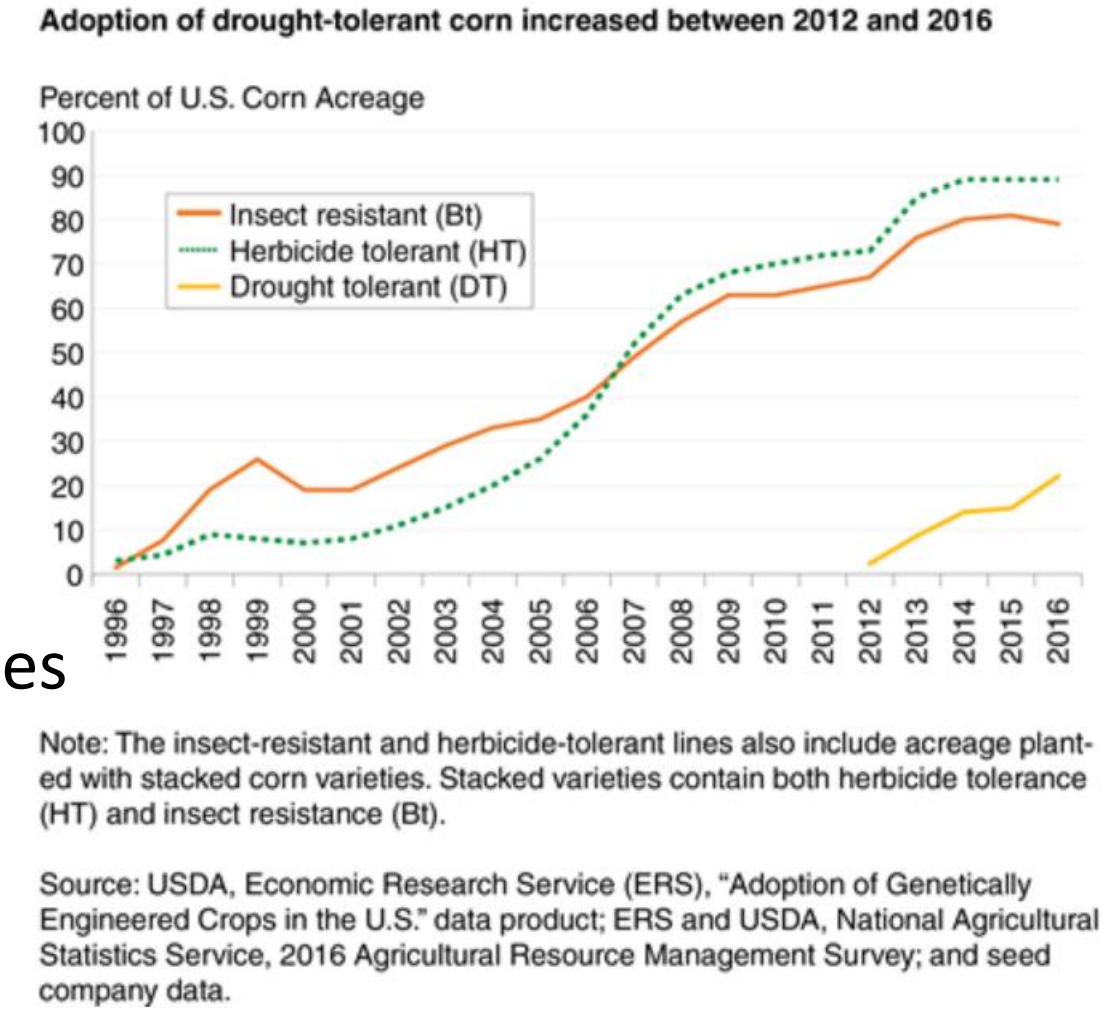
HaHB4 (**Helianthus annuus homeobox 4**)→wheat

MONSANTO

BAYER

DroughtGard

- **Cold shock protein** B gene
  - Gene CspB, from *B. subtilis*
- CSBs act as **RNA chaperones**
  - Bind and unfold tangled RNA molecules to promote normal function



CRISPR and drought resistance

- **ARGOS8** negatively regulates ethylene response
- Overexpression → reduced sensitivity to ethylene → **higher yield under drought**
- **CRISPR-Cas to obtain ARGOS8 with more active promoter → higher levels of ARGOS8 in all tissues**
- Higher level even under irrigation

DU PONT

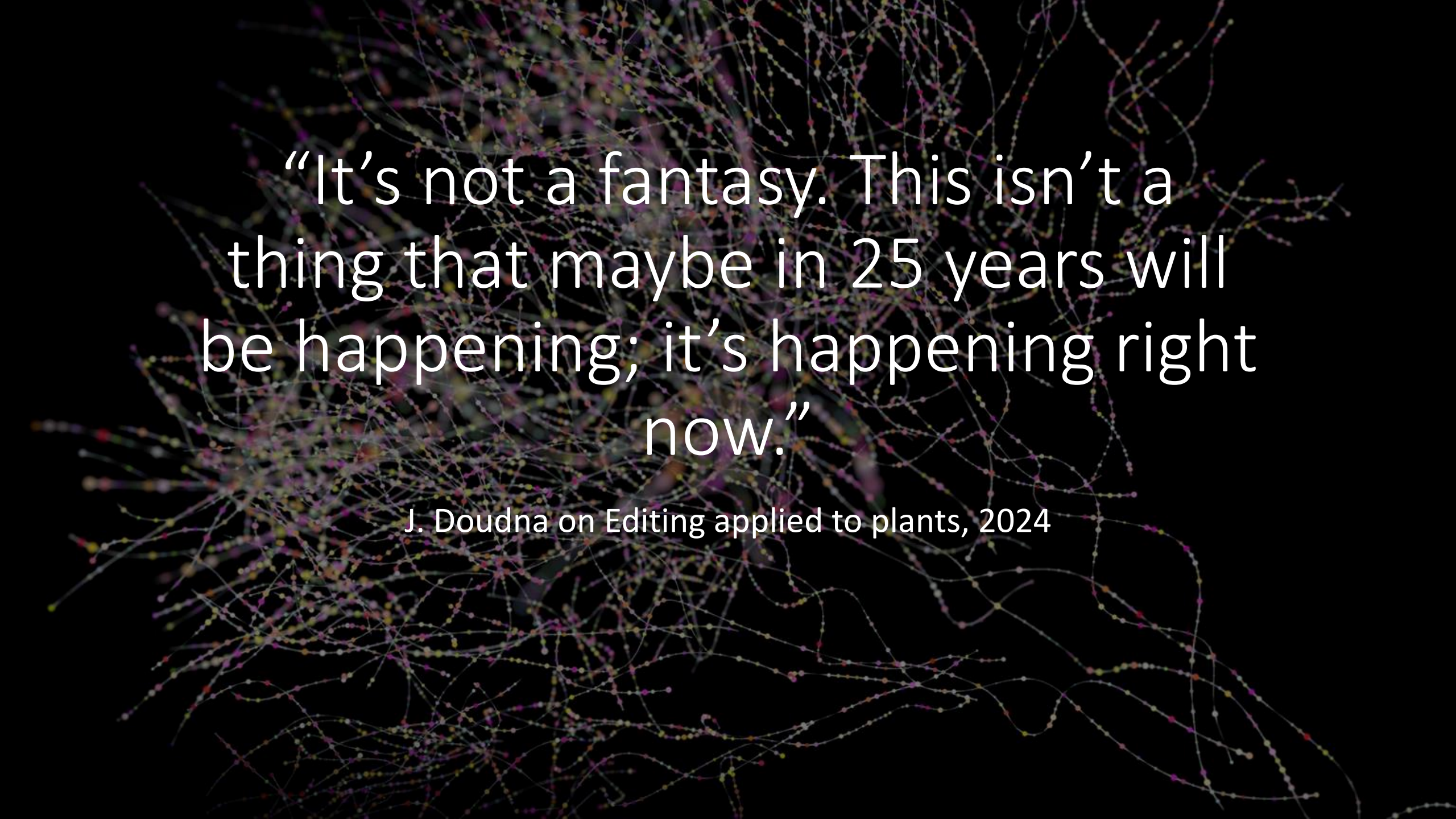
The breeder's equation

$$\Delta G = \frac{i * r * \delta_G}{L_g}$$

i	Selection intensity	Genome breeding
r	Selection accuracy/reliability	Genome assembly
δg	Genetic variance	Genome editing
Lg	Length of breeding cycle	

“Sometimes I feel unease thinking of the quality of data that are driving breeding innovation in maize”

(Maize breeder, private company, 2024)


“It’s not a fantasy. This isn’t a thing that maybe in 25 years will be happening; it’s happening right now.”
J. Doudna on Editing applied to plants, 2024

Some references

- 5Gs for crop genetic improvement (Varshney et al., 2020)
- Guo K., Yang J., Yu N., Luo L., and Wang E. (2023). Biological nitrogen fixation in cereal crops: Progress, strategies, and perspectives. Plant Comm. 4, 100499.
- Sub1 Rice: Engineering Rice for Climate Change. Emerick K, Ronald PC. Cold Spring Harb Perspect Biol. 2019 Dec 2;11(12):a034637. doi: 10.1101/cshperspect.a034637.
- Farrant JM, Hilhorst H. Crops for dry environments. Curr Opin Biotechnol. 2022 Apr;74:84-91. doi: 10.1016/j.copbio.2021.10.026. Epub 2021 Nov 19. PMID: 34808476.
- Zhang K, Mason AS, Farooq MA, Islam F, Quezada-Martinez D, Hu D, Yang S, Zou J, Zhou W. Challenges and prospects for a potential allohexaploid Brassica crop. Theor Appl Genet. 2021 Sep;134(9):2711-2726. doi: 10.1007/s00122-021-03845-8. Epub 2021 Jun 4. PMID: 34089067.
- Bohra A, Kilian B, Sivasankar S, Caccamo M, Mba C, McCouch SR, Varshney RK. Reap the crop wild relatives for breeding future crops. Trends Biotechnol. 2022 Apr;40(4):412-431. doi: 10.1016/j.tibtech.2021.08.009. Epub 2021 Oct 8. PMID: 34629170.
- Rewiring of the Fruit Metabolome in Tomato Breeding Cell, Volume 172, Issues 1–2, 11 January 2018, Pages 249-261.e12, Guangtao Zhu et al.
- Bhat, J.A., Yu, D., Bohra, A. et al. Features and applications of haplotypes in crop breeding. Commun Biol 4, 1266 (2021). https://doi.org/10.1038/s42003-021-02782-y
- Xiong, W., Reynolds, M.P., Montes, C. et al. New wheat breeding paradigms for a warming climate. Nat. Clim. Chang. 14, 869–875 (2024). https://doi.org/10.1038/s41558-024-02069-0
- Li, H., He, Z. Warming climate challenges breeding. Nat. Plants 7, 1164–1165 (2021). https://doi.org/10.1038/s41477-021-00996-w
- Farrant, J.M., Cooper, K., Hilgart, A. et al. A molecular physiological review of vegetative desiccation tolerance in the resurrection plant Xerophyta viscosa (Baker). Planta 242, 407–426 (2015). https://doi.org/10.1007/s00425-015-2320-6
- Koua AP, Siddiqui MN, Heß K, Klag N, Kambona CM, Duarte-Delgado D, Oyiga BC, Léon J, Ballvora A. Genome-wide dissection and haplotype analysis identified candidate loci for nitrogen use efficiency under drought conditions in winter wheat. Plant Genome. 2024 Mar;17(1):e20394. doi: 10.1002/tpg2.20394. Epub 2023 Oct 25. PMID: 37880495.
- Lu, Y., Xu, J., Yuan, Z. et al. Comparative LD mapping using single SNPs and haplotypes identifies QTL for plant height and biomass as secondary traits of drought tolerance in maize. Mol Breeding 30, 407–418 (2012). https://doi.org/10.1007/s11032-011-9631-5


That's all Folks!