The use of synthetic hexaploid wheat in the CIMMYT Global Wheat Program

Susanne Dreisigacker and Masahiro Kishii

Genetic diversity in plant breeding germplasm

- Genetic uniformity creates vulnerability
- Genetic uniformity leads to reduced genetic gains
- Resilience require options and options require diversity

Genetic diversity is a requisite for breeding and food security

Sources of genetic diversity used in the CIMMYT Global Wheat Program

- Elite cultivars from different genepools

  Australian cultivars, UK winter wheat cultivars,..

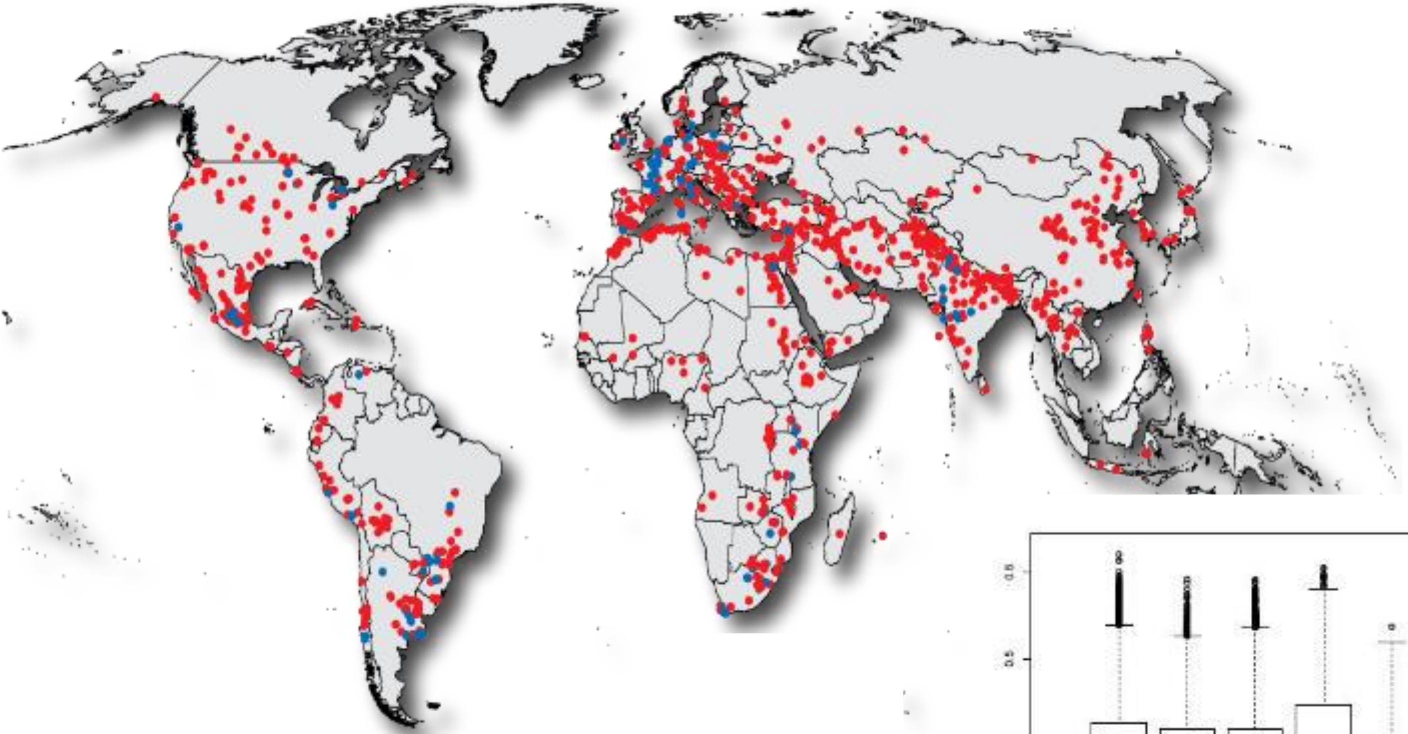
- Genetic stocks

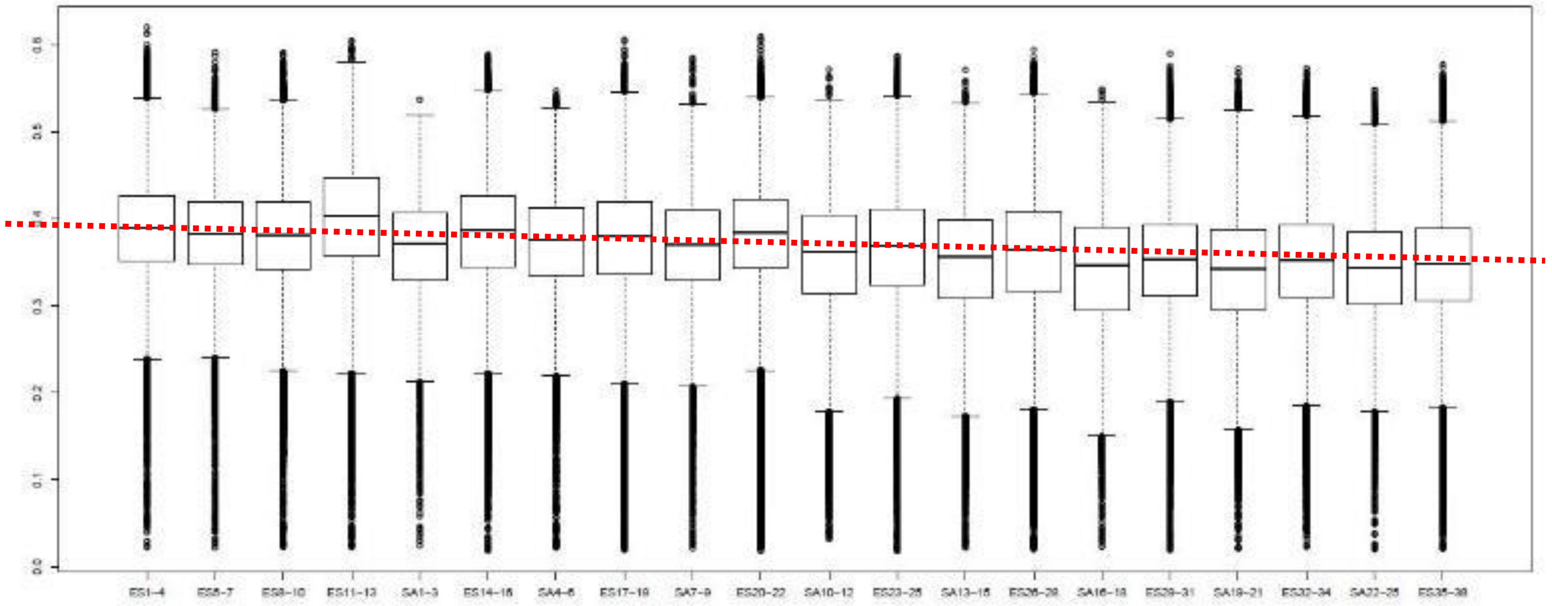
  - Translocation lines

  - Gene introgression lines

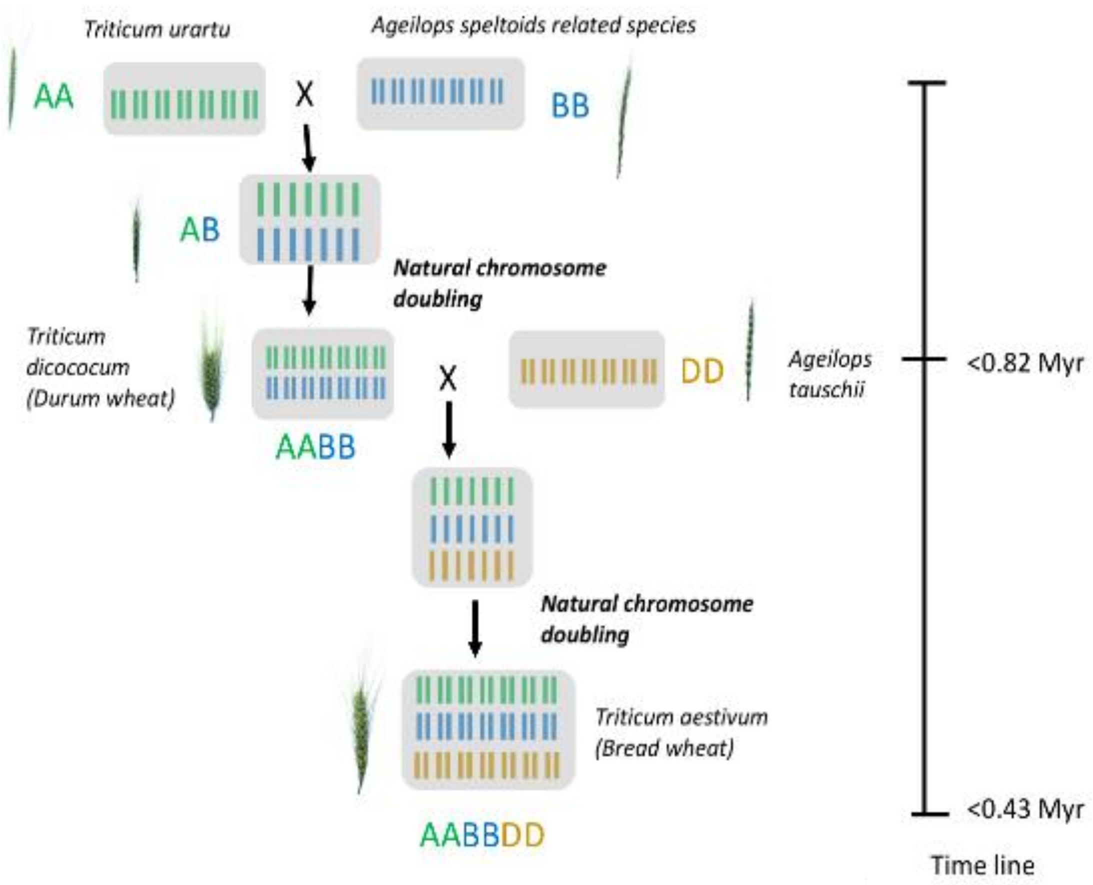
- Landraces
- Synthetic hexaploid wheat
- Wide crosses

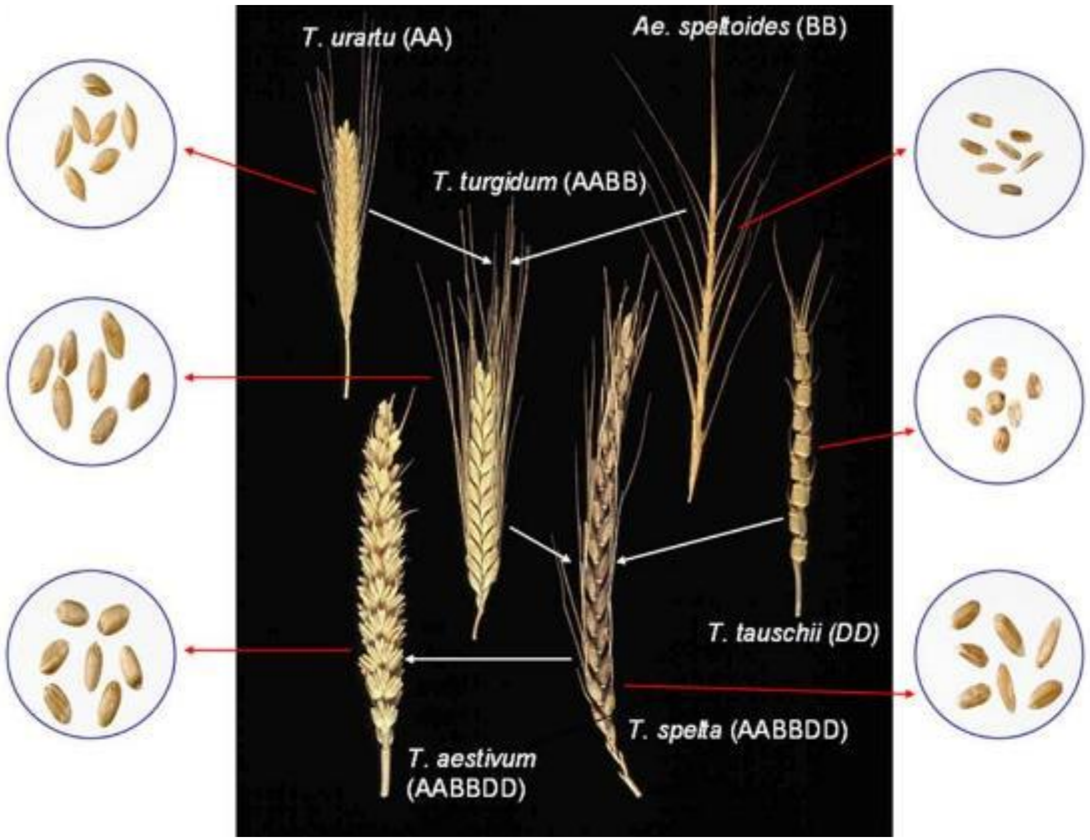
Genetic diversity in CIMMYT international trails, ESWYT and SAWYT across 40 years



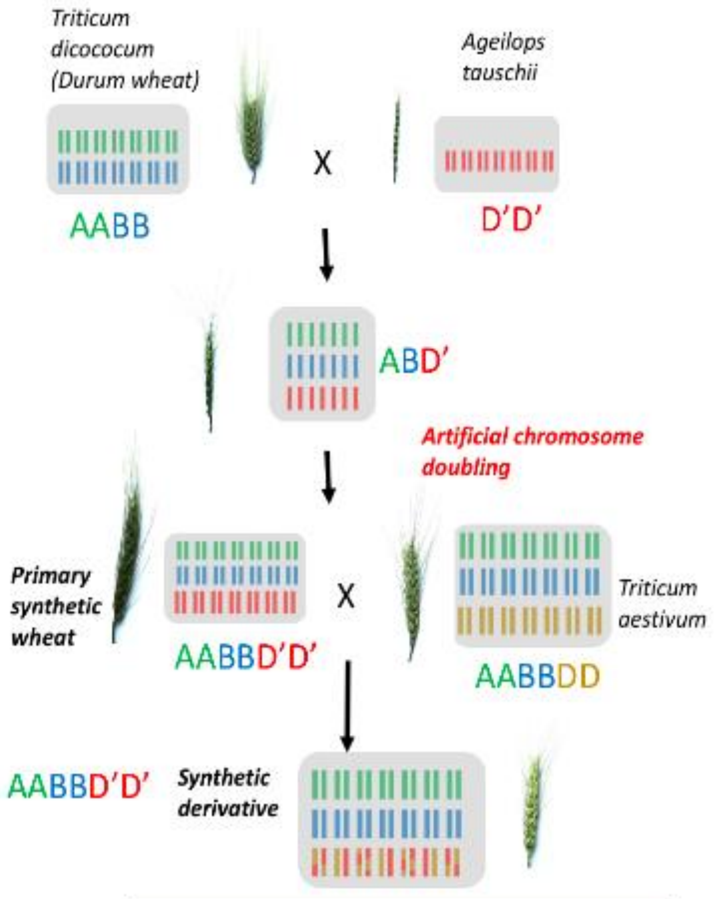


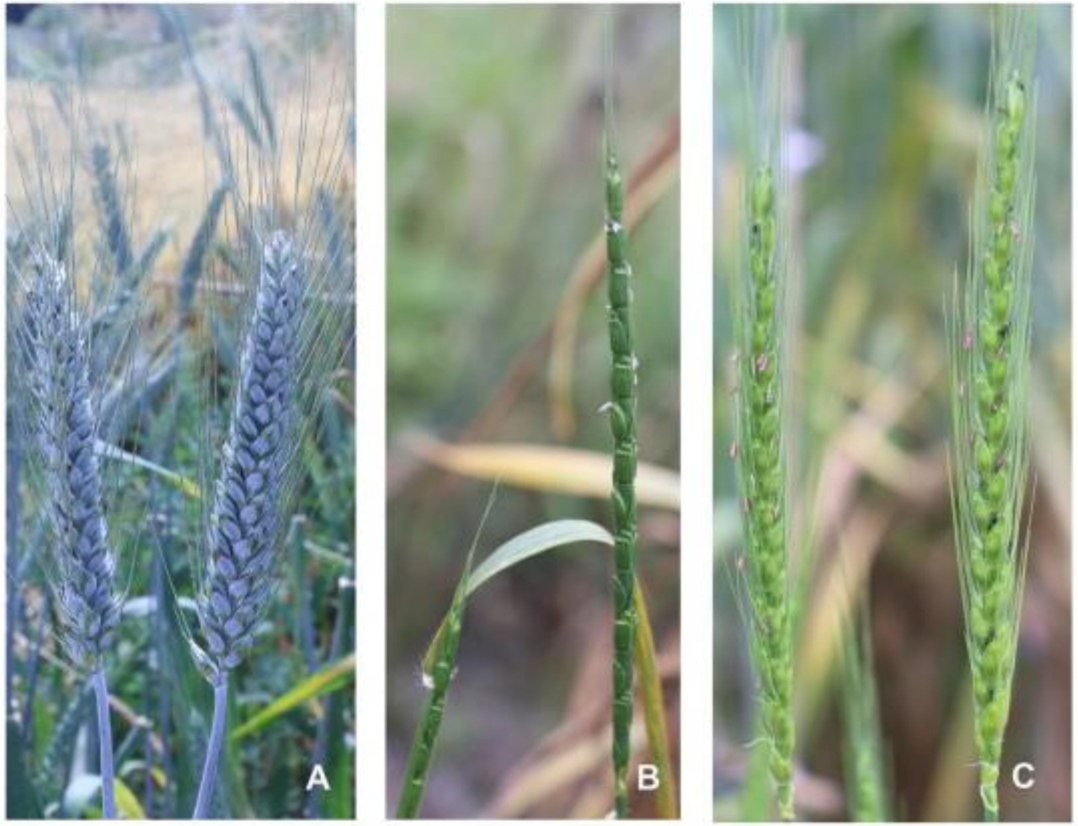
Natural evolution of hexaploid wheat





Development of synthetic hexaploid wheat (SHW)





T. turgidum AS2255 (AABB, 4*x*) x *Ae. tauschii* AS60 (DD, 2*x*) → Synthetic wheat SHW-L1 (AABBDD)

Production of SHW at CIMMYT

- The development of synthetic hexaploid wheat in CIMMYT started in 1986 (Dr. Mujeeb Kazi)
- The use of elite durum varieties was important for initial success. Crosses to wild tetraploid wheat species have been performed, but have increased undesirable agronomic properties
- A total number of 1,100 synthetic hexaploid wheat were generated in 2005
- The first synthetic derivative lines appeared in the international nurseries in 1997
- In 2008 the production of winter wheat synthetic hexaloid was initiated
- To date, 1,524 CIMMYT derived synthetic hexaploid wheat exist

SHW: source for biotic stress resistance
Disease resistance genes for leaf, stem, and stripe rust

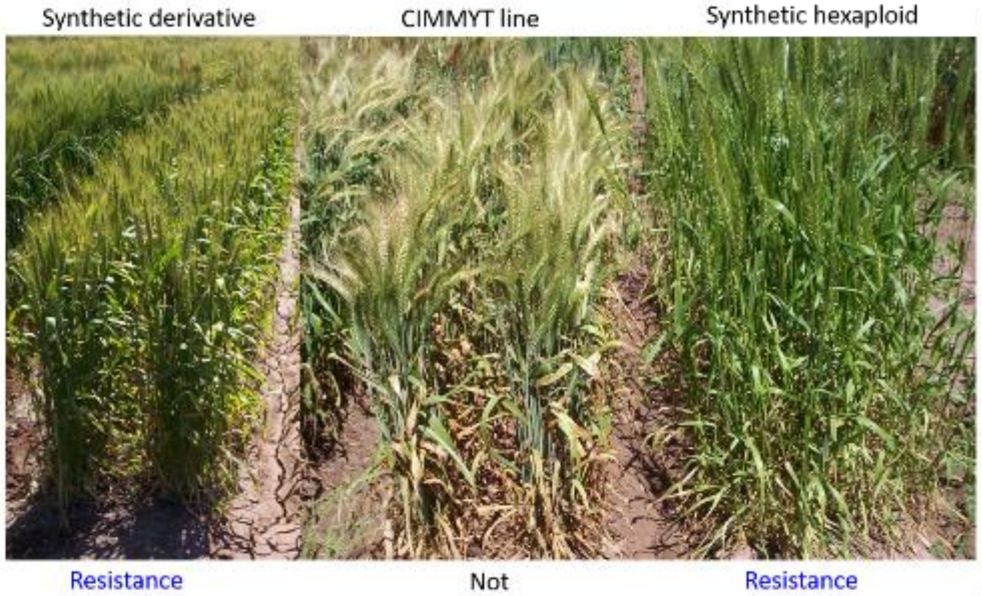
Seedling stage resistance to leaf rust
Observed in *Ae. tauschii* accession RL5289 on chromosome 1D.

Seedling stage resistance to leaf rust on chromosome 3DS
Transferred through synthetic hexaploid wheat RL5713, virulence detected in South Africa

Effective against several races including UG99. Transferred to chromosome 1DS in wheat. Linked to *Sr45*

Effective against prevalent races in Australia, India, South Africa and UG99. Transferred through synthetic hexapoid wheat RL5406. Linked to *Sr33*

Adult stage resistance to stripe rust. Observed in synthetic derivative line Soru #1 on chromosome 4DS, together with Yr24/26 from durum wheat.



SHW: Source for biotic stress resistance

Disease resistance genes for other globally important diseases

Septoria tritici blotch

Stb5, Stb17

Powdery mildew

PM2, PM18

Green bug tolerance

GB3, GB7

Hessian fly resistance

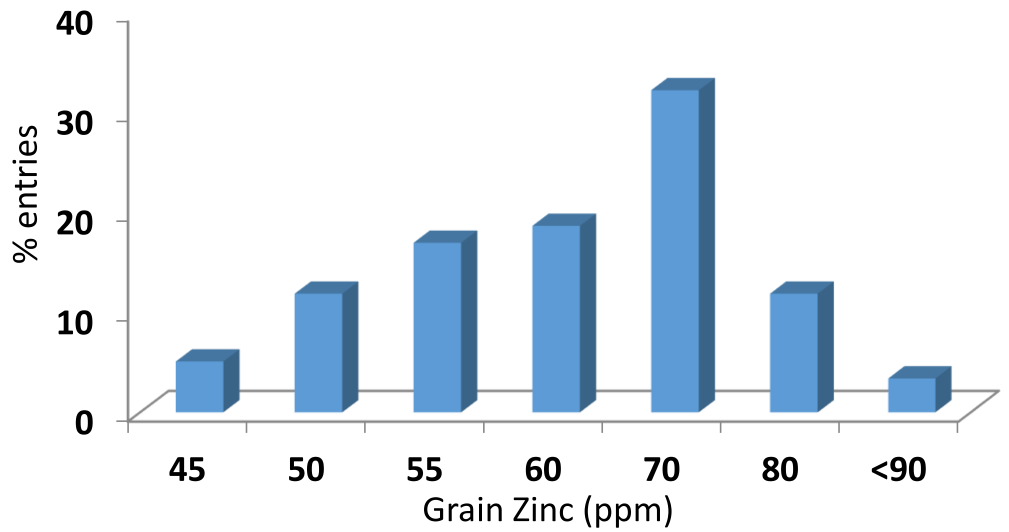
H13, H26

Nutritional quality from synthetic derivatives:

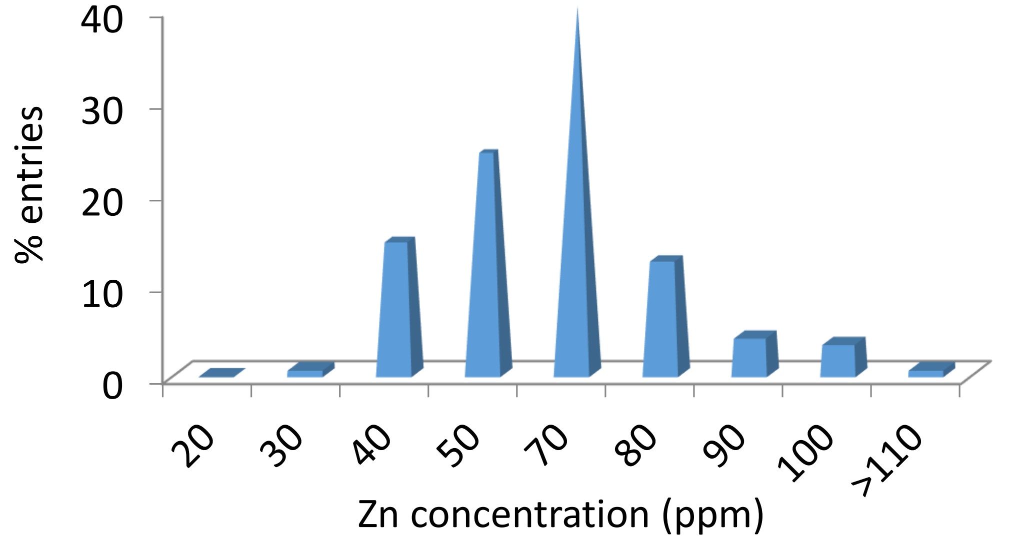
Sources for high zinc and iron

- Limited diversity in improved wheat germplasm for Zn and Fe in the grain
- High Zn & Fe present in accessions of genetic resources e.g., *T. dicoccum, T. dicoccoides)*
- Development of synthetic hexaploid wheat using tetraploids accessions with high Zn & Fe
- Various registered varieties derived from synthetics e.g., Zinc Shakti, WB-02, HPBW 01

T. dicoccum based synthetic hexaploid wheat with 90 ppm Zn



3-4 fold variation for Zn content in *T. dicoccoides derivatives* from Israel (>300 accessions) in Zn-enriched area



Slide: Velu Govindan

Synthetic derivative lines to improve drought tolerance

CROSS	Drought 2006 t ha^{-1}
T.DICOCCON PI225332/AE.SQUARROSA (895)//WEEBILL1/3/2*WEEBILL1	2.62‡
T.DICOCCON PI225332/AE.SQUARROSA (895)//WEEBILL1/3/2*WEEBILL1	2.45
T.DICOCCON PI225332/AE.SQUARROSA (895)//WEEBILL1/3/2*WEEBILL1	2.24
T.DICOCCON PI225332/AE.SQUARROSA (895)//WEEBILL1/3/2*WEEBILL1	2.22
T.DICOCCON PI225332/AE.SQUARROSA (895)//WEEBILL1/3/2*WEEBILL1	2.21
T.DICOCCON PI225332/AE.SQUARROSA (895)//WEEBILL1/3/2*WEEBILL1	2.16
T.DICOCCON PI225332/AE.SQUARROSA (895)//WEEBILL1/3/2*WEEBILL1	1.94
T.DICOCCON PI225332/AE.SQUARROSA (895)//WEEBILL1/3/2*WEEBILL1	1.86
PASTOR	1.76
WEEBILL1	1.79

Synthetic wheat

Drought tolerant wheat line

Reynolds et al., 2007, Lopes and Reynolds, 2011

- New variation of drought-adaptive traits in SHW and synthetic derivatives

Dreccer et al., 2007

- Synthetic backcross derivatives outperformed local benchmark varieties in Australia

Pradhan et al., 2012

- Synthetic hexaploid wheat least effected by drought and heat stress

Song et al., 2017

- Drought resistance in Northern Winter Wheat region in China

Trethowan et al., 2008

Synthetic derivative lines to improve drought tolerance

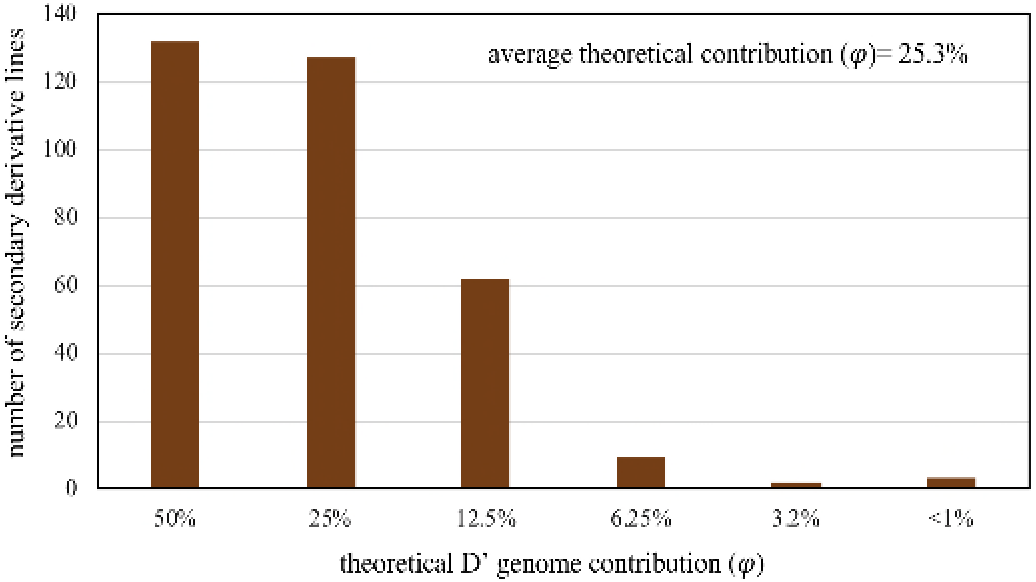
Trait variation in SHW that might benefit drought tolerance

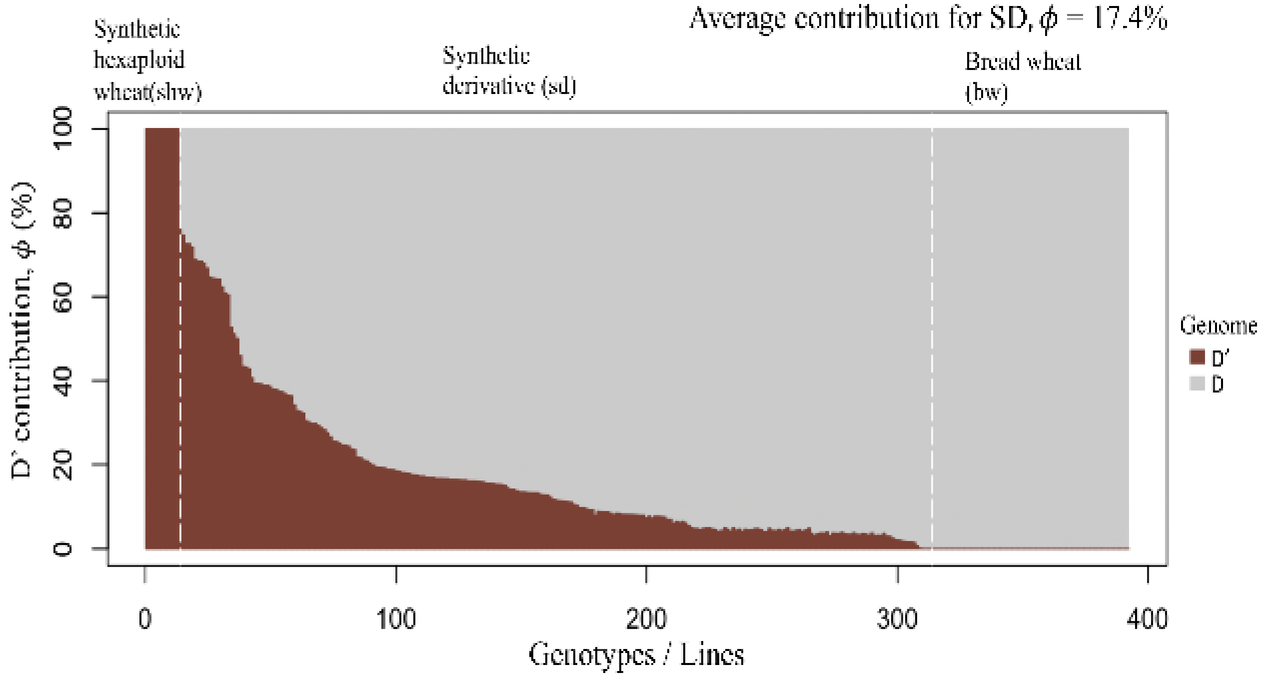
- Deep root biomass (larger amounts of small diameter roots at depth)
- Root depths
- Water extraction capacity, water use efficiency
- Novel diversity in ABA responsiveness for better plant adaptation
- Stomatal density and aperture
- Antioxidant enzyme activities

Cross	Yield % to the BW parentes
CROC_1/AE.SQUARROSA (518)//SUP152	122%
CPI8/GEDIZ/3/GOO//ALB/CRA/4/AE.SQUARROSA (637)/5/2*KACHU	114%
CPI8/GEDIZ/3/GOO//ALB/CRA/4/AE.SQUARROSA (637)/5/2*KACHU	112%
CROC_1/AE.SQUARROSA (518)//NAVJ07	111%
CROC_1/AE.SQUARROSA (518)//2*NAVJ07	108%
CROC_1/AE.SQUARROSA (518)//SUP152	108%

Data: Masahiro Kishii

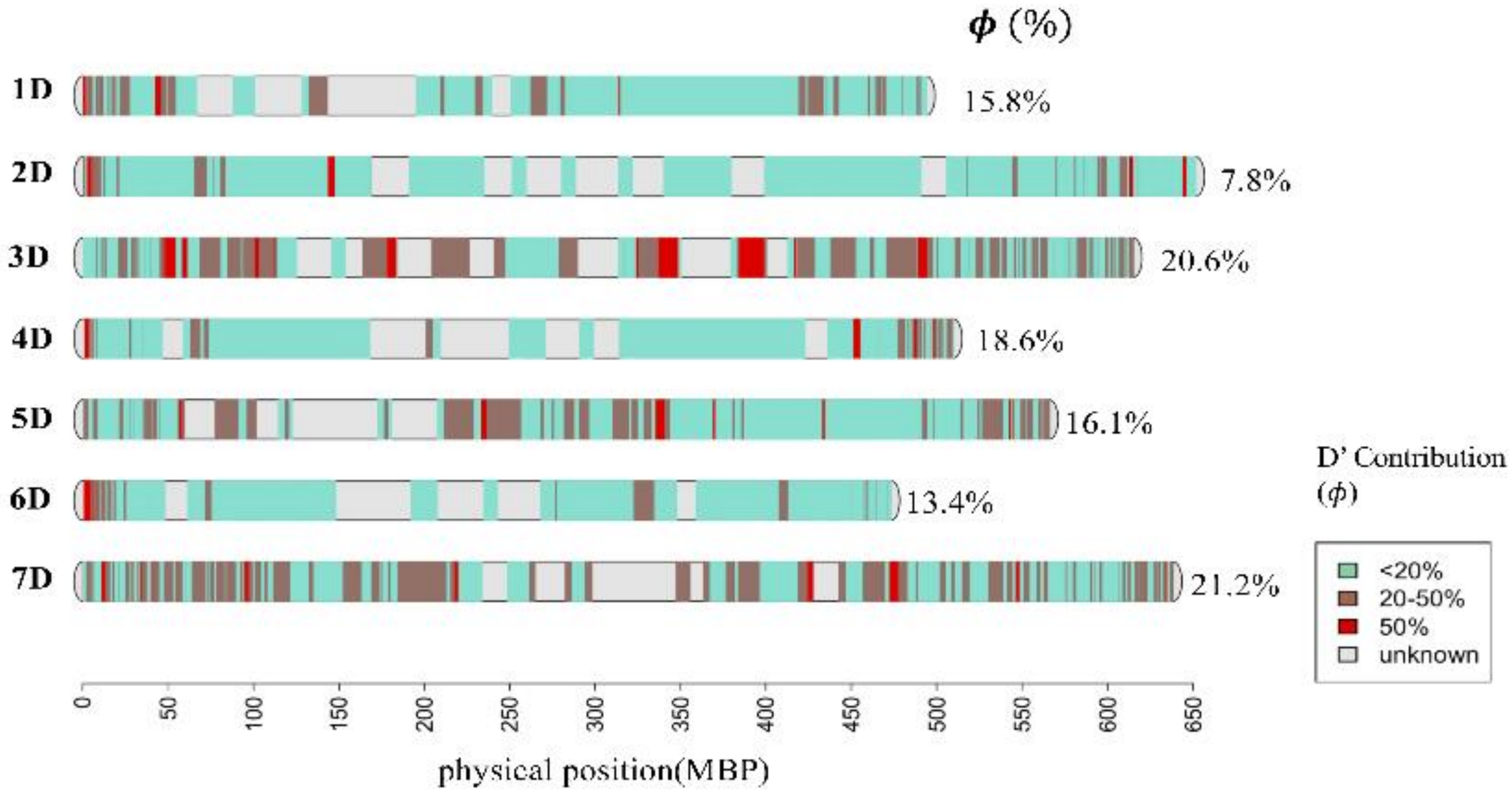
Genetic contribution of the D‘ genome estimated via pedigree and GBS marker data





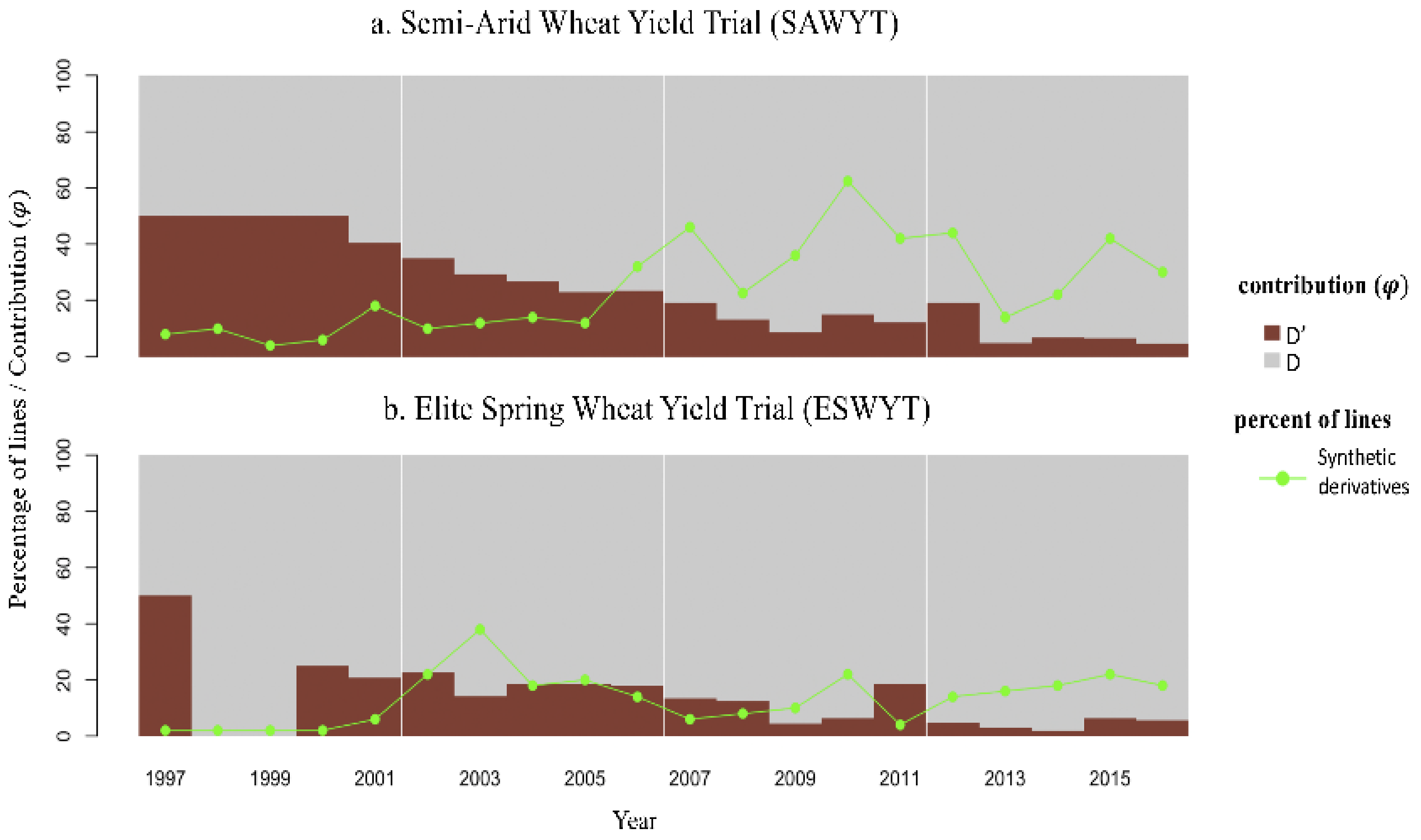
Rosyara et al., 2019

Genomic regions most likely contributed by the D‘ genome



Rosyara et al., 2019

Number of synthetic derivative lines in CIMMYT international yield trials ESWYT and SAWYT



Rosyara et al., 2019

Actual number of deployed synthetic hexaploid wheat

- 25 different synthetic hexaploids wheat in the international yield trails

- ±15 different synthetic hexaploid wheat in the pedigrees of released cultivars

1-2% of synthetic hexaploid wheat deployed after thousand of crosses

SN	Yield trial	Primary Synthetics	Number of SD	Average D' Contribution φ	Nursery Number
1	SAWYT	ALTAR 84/AE.SQ	4	14.1	9,14,18,19
2	SAWYT	ALTAR 84/AE.SQUARROSA (191)	1	6.3	15
3	SAWYT	ALTAR 84/AE.SQUARROSA (205)	2	3.3	16
4	ESWYT	ALTAR 84/AE.SQUARROSA (211)	1	12.5	26
5	SAWYT	ALTAR 84/AE.SQUARROSA (219)	2	12.5	18
6	ESWYT	ALTAR 84/AE.SQUARROSA (221)	3	2.1	28,33,34
6	SAWYT	ALTAR 84/AE.SQUARROSA (221)	1	25.0	12
7	SAWYT	ALTAR 84/AE.SQUARROSA (224)	1	12.5	13
8	ESWYT	ALTAR 84/AEGILOPS SQUARROSA (TAUS)	12	9.2	31,36,37
8	SAWYT	ALTAR 84/AEGILOPS SQUARROSA (TAUS)	90	16.6	5–10,13–15,17–20,22–24
9	ESWYT	CENTURY/(TR.TA)TA-2450*	31	3.7	24,29–31,33–36
9	SAWYT	CENTURY/(TR.TA)TA-2450*	10	4.8	17,19,21–23
10	ESWYT	CHEN/AE.SQ	1	1.6	30
10	SAWYT	CHEN/AE.SQ	13	10.7	9,14–17,21,23,24
11	ESWYT	CHEN/AEGILOPS SQUARROSA (TAUS)	21	19.8	22–26,29–31
11	SAWYT	CHEN/AEGILOPS SQUARROSA (TAUS)	10	18.0	10,11,15,18,19,23
12	ESWYT	CNDO/R143//ENTE/MEXI_2/3/AEGILOPS SQUARROSA (TAUS)	13	9.8	23,24,26,30,31,33,35,36
12	SAWYT	CNDO/R143//ENTE/MEXI_2/3/AEGILOPS SQUARROSA (TAUS)	24	20.4	5,6,8,10–13,15–18,20–23
13	ESWYT	CROC_1/AE.SQUARROSA (205)	22	20.7	18,23–27,31,34,37
13	SAWYT	CROC_1/AE.SQUARROSA (205)	16	17.3	6,9,10,15–18,22,24
14	ESWYT	CROC_1/AE.SQUARROSA (213)	8	9.8	27,28,33,37
14	SAWYT	CROC_1/AE.SQUARROSA (213)	11	15.9	12,14,18,21,23,24
15	ESWYT	CROC_1/AE.SQUARROSA (224)	9	11.3	25,26,31,32,36,37
15	SAWYT	CROC_1/AE.SQUARROSA (224)	37	24.4	9,10,12–17,19–21,24
16	ESWYT	CROC-1/AE.TA(WX-224)	2	25.0	25,29
16	SAWYT	CROC-1/AE.TA(WX-224)	6	20.8	19,20,21,22
17	ESWYT	D67.2/PARANA 66.270//AE.SQUARROSA (320)	2	28.1	32,36
17	SAWYT	D67.2/PARANA 66.270//AE.SQUARROSA (320)	9	32.6	15,18,20,24
18	ESWYT	DVERD_2/AE.SQUARROSA (214)	1	25.0	21
19	ESWYT	DVERD_2/AE.SQUARROSA (221)	1	25.0	28
20	ESWYT	KS-8010-71/(TR.TA)TA-2470	4	6.3	24
21	SAWYT	SCA/AE.SQUARROSA (409)	1	25.0	15
22	SAWYT	T.DICOCCON PI225332/AE.SQUARROSA (895)	1	18.8	20
23	SAWYT	T.DICOCCON PI94625/AE.SQUARROSA (372)	1	12.5	19
23	SAWYT	T.DICOCCON PI94625/AE.SQUARROSA (372)	8	18.0	16,17,19,20
24	ESWYT	WICHITA/TA-1675(TR.TA)	2	4.7	24
25	SAWYT	YAR/AE.SQUARROSA (783)	1	6.3	24

Current number of deployed SHW and synthetic derivatives

- 53IBWSN, 38 SAWSN, 31HRWSN (697)

  14% synthetic derived lines, 15 different SHW

- Candidates 7th SATYN, 9th WYCYT (208)

  89% synthetic derived lines, 12 different SHW

- Harvest Plus (preliminary yield trails, 252)

  71% synthetic derived lines, 17 different SHW

MANKU/6/CROC_1/AE.SQUARROSA (444)/3/T.DICOCCON PI94625/AE.SQUARROSA (372)//3*PASTOR/4/T.DICOCCON PI94625/AE.SQUARROSA (372) //3*PASTOR/5/KIRITATI/4/2*BAV92//IRENA/KAUZ/3/HUITES

KACHU*2/5/WBLL1*2/TUKURU/3/T.DICOCCON PI94624/AE.SQUARROSA (409)//BCN/4/WBLL1*2/TUKURU/6/CROC_1/AE.SQUARROSA (444) /3/T.DICOCCON PI94625/AE.SQUARROSA (372)//3*PASTOR/4/T.DICOCCON PI94625/AE.SQUARROSA (372) //3*PASTOR/5/KIRITATI/4/2*BAV92//IRENA/KAUZ/3/HUITES

ALTAR 84/AE.SQUARROSA (221)
ALTAR 84/AOS
CHEN/AE.SQ
CHEN/AEGILOPS SQUARROSA (TAUS)
CPI8/GEDIZ/3/GOO//ALB/CRA/4/AE.SQUARROSA (208)
CROC_1/AE.SQUA
CROC_1/AE.SQUARROSA (205)
CROC_1/AE.SQUARROSA (210)
CROC_1/AE.SQUARROSA (213)
CROC_1/AE.SQUARROSA (224)
CROC_1/AE.SQUARROSA (444)
D67.2/PARANA 66.270//AE.SQUARROSA (320)
D67.2/PARANA 66.270//AE.SQUARROSA (465)
ENTE/MEXI_2/3/AEGILOPS SQUARROSA (TAUS)
GAN/AE.SQUARROSA (741)
KATERE (LAHN/AE.SQUARROSA (210))
KUTZ (LAHN/AE.SQUARROSA (205))
MANKU (T.DICOCCON CI9309/AE.SQUARROSA (409))
MAYIL (T.DICOCCON CI9309/AE.SQUARROSA (409))
MUCUY (LAHN/AE.SQUARROSA (224))
SCOOP_1/AE.SQUARROSA (634)
SHAKTI (LAHN/AE.SQUARROSA (210))
SOKOLL (GALLARETA/AEGILOPS SQUARROSA (TAUS))
SORA/AE.SQUARROSA (323)
T.DICOCCON CI9309/AE.SQUARROSA (409)
T.DICOCCON PI272533/AE.SQUARROSA (458)
T.DICOCCON PI94624/AE.SQUARROSA (409)
T.DICOCCON PI94625/AE.SQUARROSA (372)
T.DICOCCUM IG88725/AE.SQUARROSA (224)
VOROBEY (LAHN/AE.SQUARROSA (224))
YAR/AE.SQUARROSA (783)

Varieties released based on synthetic derivatives

From 2003 to 2018:
At least 85 synthetic derivatives released worldwide

First registrations in 2003 in Spain and China ‘Carmona‘ and ‘Chuanmai 42‘

Releases in overall 21 countries

18 cultivars in China covering 25% or the wheat area in Southwest China

10 Cultivars in India covering 30 million ha (12%) in 2018.

Dr. Hafid Aberkane, Li et al., 2018

More targeted introgression strategies for SHW deployment

1) Systematic phenotyping of genetic resources

E.g. prescreening of *T. dicoccum* for drought tolerance

No significant correlation of the traits expressed in the wild relatives with their corresponding SHW lines

Low predictabilty due to genome alternations

- Progenitor-dependent meiotic irregularities, e.g., incomplete homologous pairing leading to aneuploidy
- Loss and gain of DNA segments, coding and non coding sequences
- DNA methylation repatterning
- Differential expression patterns and gene regulations

2) Systematic phenotyping at the hexaploid (SHW) level

Screening for disease resistance (Fusarium head blight, Tan spot, Spot blotch and Septoria nodorum blotch)

Synthetic hexaploid wheat panel (160 entries). Screening for yield potential, drought and heat tolerance

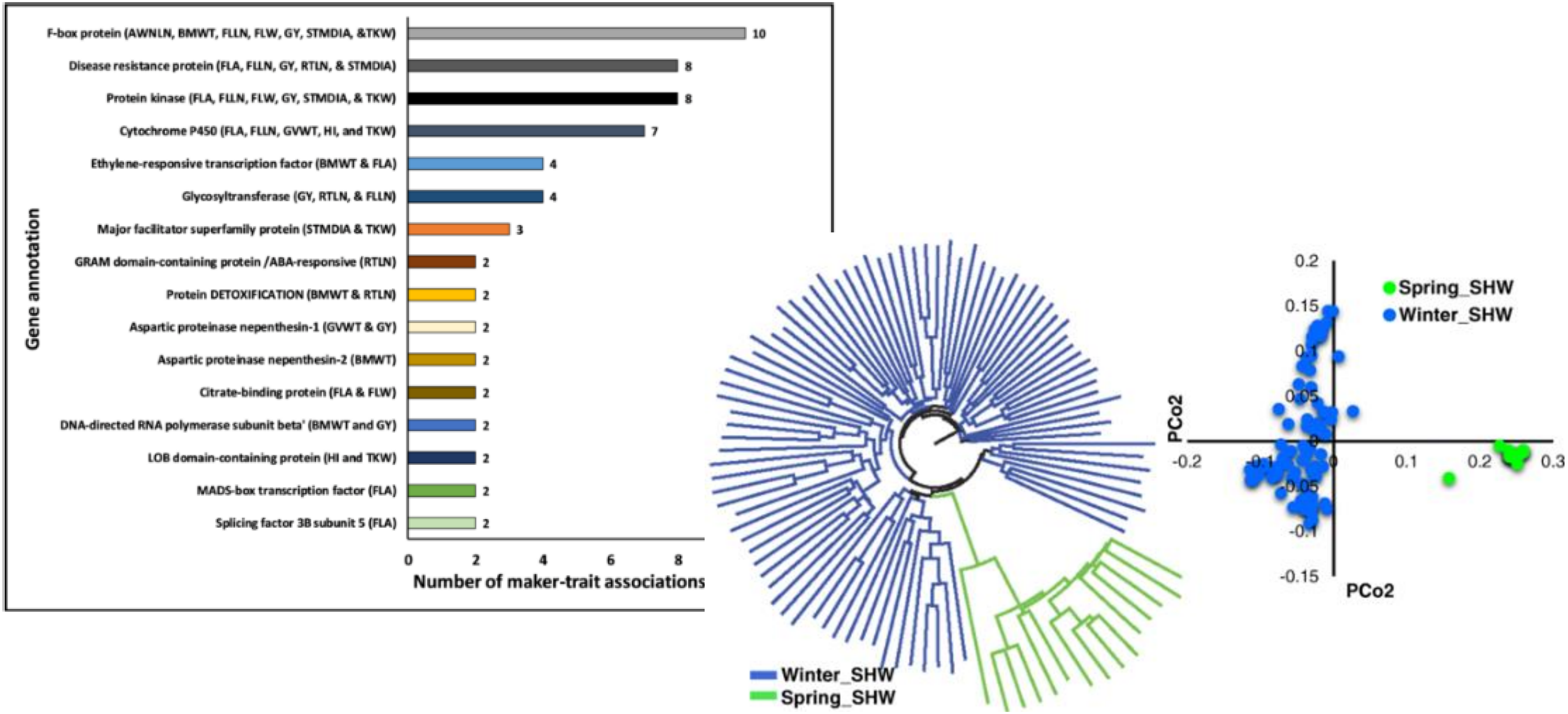
Nerida Lozano, Pawan Singh, Matthew Reynolds

3) Make use of recently available genomic tools

- Trace QTL from the wild relatives during SHW development
- Sytematically phenotype and genotype SHW to identify QTL at the hexaploid level, select the QTL carriers and trace the QTL during crossing with elite lines
- For more complex traits, predict the SHW x BW peformance using high-density genetic markers to be able to reduce total number of crosses

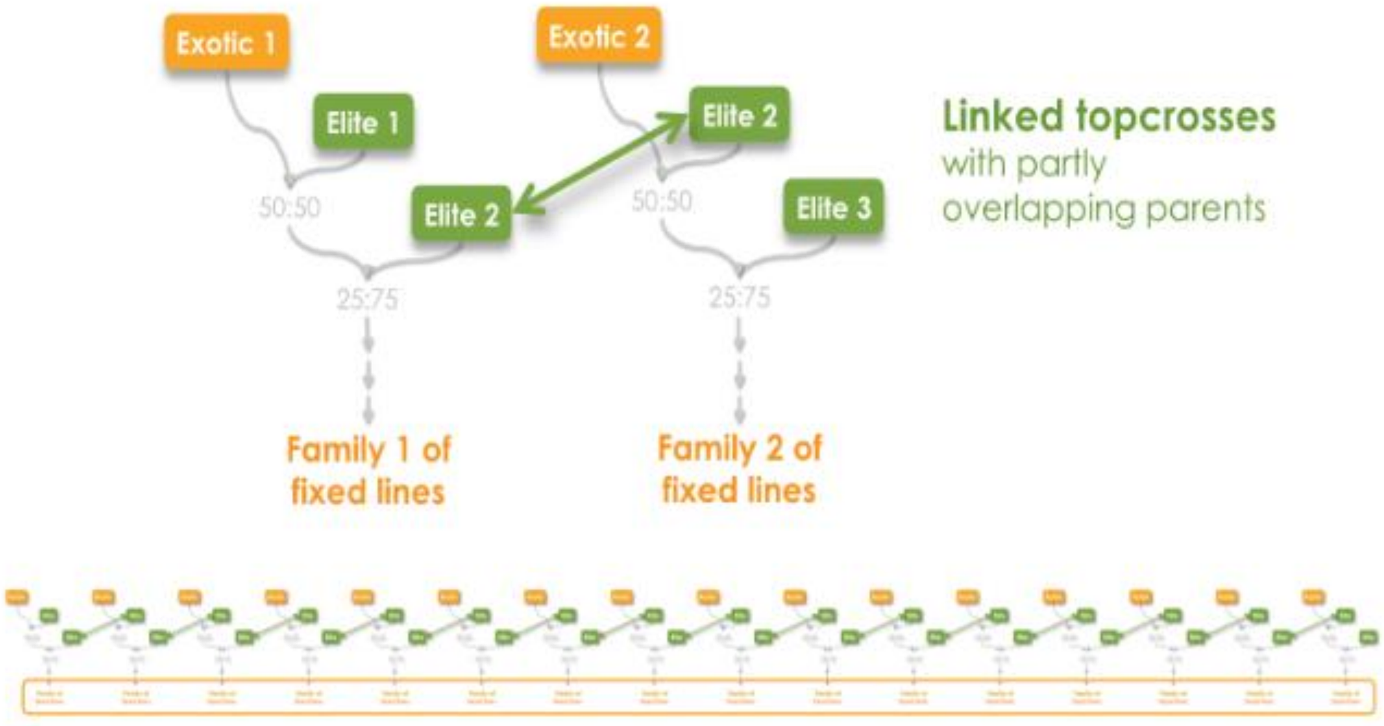
Background selection for targeted QTL introgression required to eliminated undesired alleles or ‘genetic load’

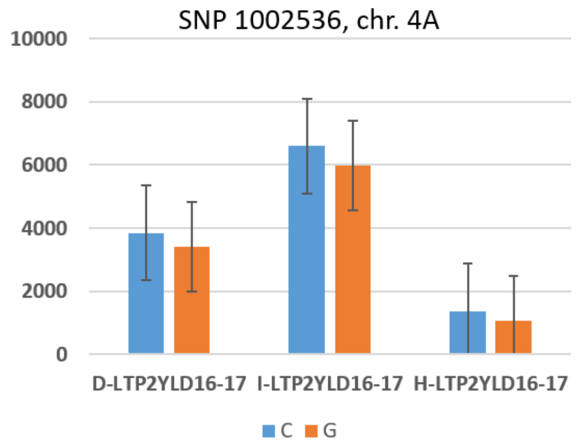
Example: 45 marker-trait associations in annotated genes with projected role in drought stress in CIMMYT winter wheat synthetics



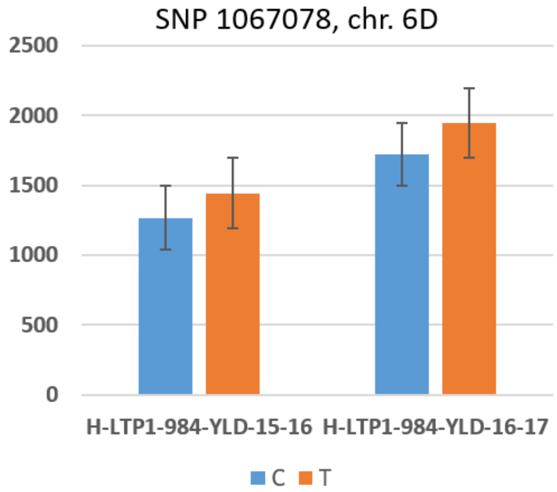
Bhatta et al., 2018

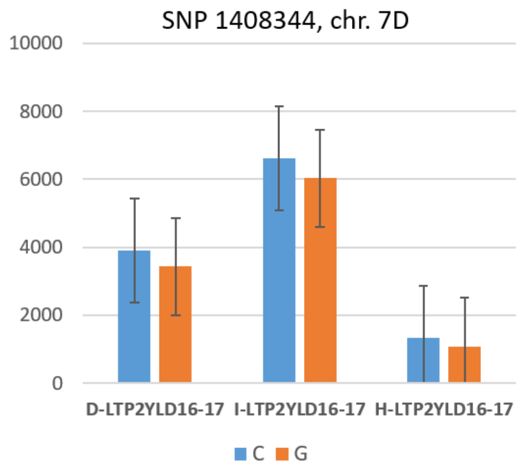
Example: QTL from SHW identified in linked topcross populations





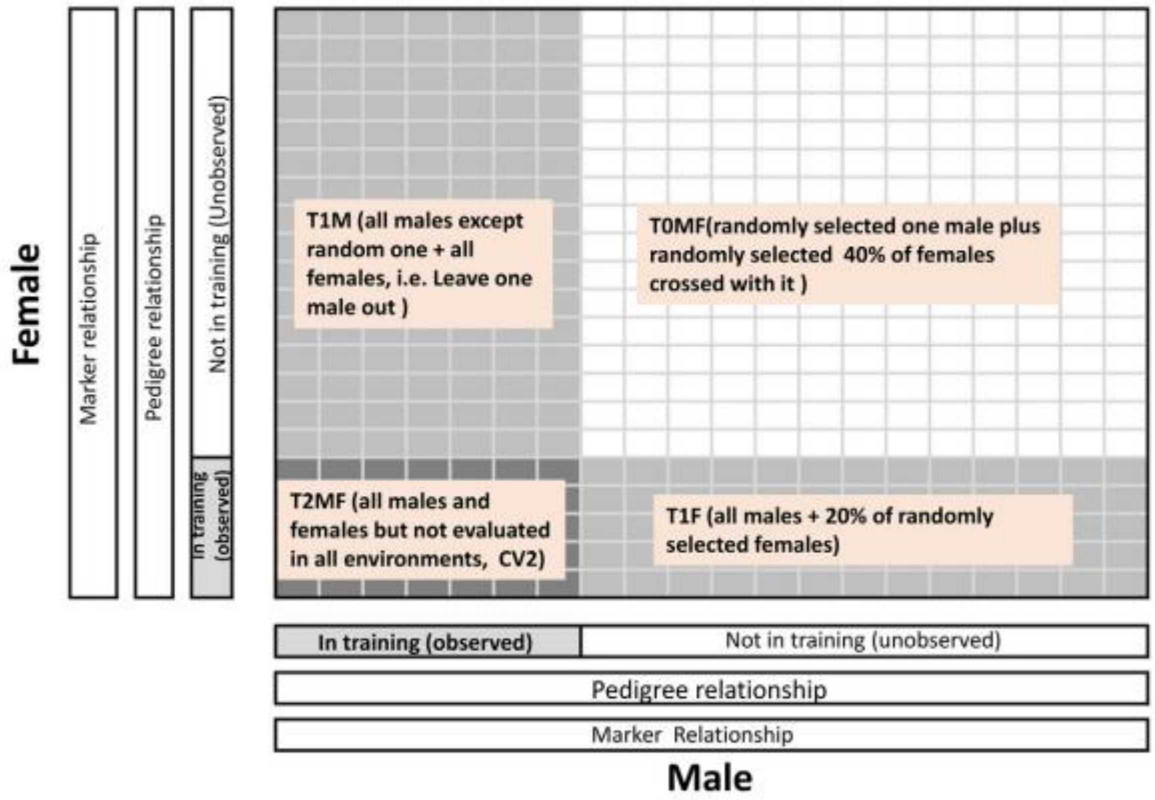
Three QTL derived from SHW (durum and *Ae. tauschii* parents) related to heat and drought tolerance





Sehgal et al., unpublished

Good prediction abilities when predicting wheat hybrids



Possible prediction problemes of tested and untested male and females

T2MF

	Model				
	M1	M2	M3	M4	M5
GY	0.62 (0.04)	0.64 (0.03)	0.61 (0.04)	0.64 (0.04)	0.65 (0.04)
DTH	0.80 (0.02)	0.81 (0.02)	0.80 (0.02)	0.82 (0.01)	0.82 (0.02)
DTF	0.79 (0.02)	0.80 (0.02)	0.80 (0.02)	0.81 (0.02)	0.81 (0.02)
DTM	0.52 (0.05)	0.63 (0.03)	0.54 (0.05)	0.66 (0.04)	0.66 (0.03)
PHT	0.47 (0.05)	0.55 (0.04)	0.45 (0.04)	0.53 (0.04)	0.55 (0.04)

T1F

	Model				
	M1	M2	M3	M4	M5
GY	0.53 (0.08)	0.54 (0.08)	0.49 (0.06)	0.52 (0.05)	0.55 (0.07)
DTH	0.49 (0.07)	0.49 (0.06)	0.46 (0.06)	0.47 (0.08)	0.52 (0.06)
DTF	0.47 (0.07)	0.47 (0.07)	0.46 (0.05)	0.47 (0.06)	0.50 (0.06)
DTM	0.34 (0.05)	0.40 (0.06)	0.39 (0.06)	0.44 (0.07)	0.45 (0.08)
PHT	0.32 (0.04)	0.37 (0.06)	0.30 (0.06)	0.34 (0.06)	0.38 (0.06)

Basnet et al., 2019

Summary

- SHW bridge wild relatives and bread wheat and are thus important genetic resources for future wheat breeding
- SHW provide an opportunity for further improvement of complex traits in wheat required under rapidly changing climatic conditions
- SHW significantly contribute to maintain the genetic diversity in the CIMMYT Global Wheat Program
- SHW significantly contribute to CIMMYT genetic gains in wheat
- Routine targeted introgression strategies are required for a higher success rate of SHW deployment

Acknowledgements

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