Accelerating Genetic Gains in Maize and Wheat

2022 Advanced Wheat Improvement Course

Breeding for durable rust resistance

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Rust menace- continuous fight with an old enemy

Global losses to rust diseases 4.5 -5 Billion USD/Yr

Yellow (stripe) rust
Puccinia striiformis

Black (stem) rust
Puccinia graminis

Brown (leaf) rust
Puccinia triticina

DID YOU KNOW THE ROMANS HAD A GOD FOR WHEAT RUST?

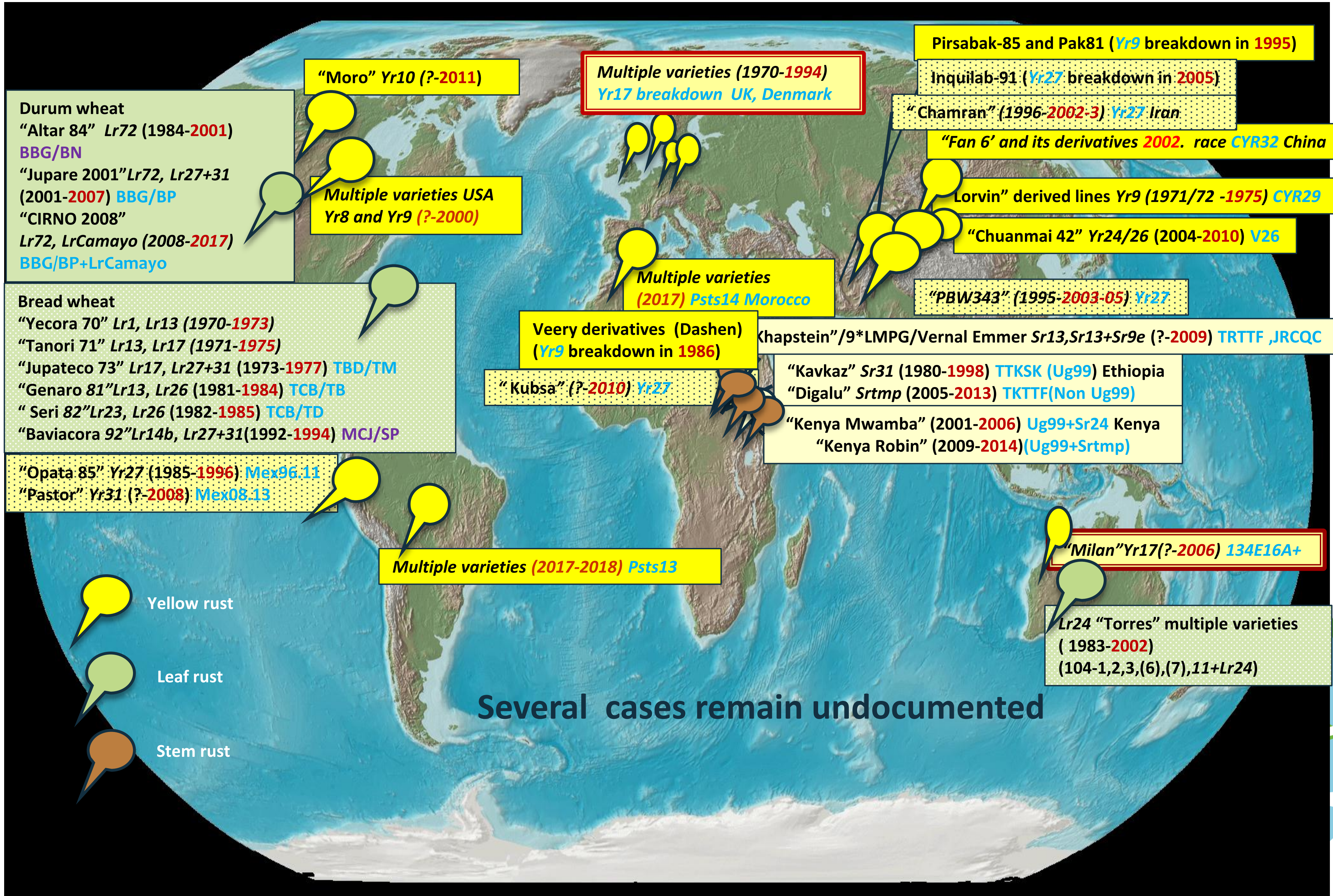
ROBIGALIA
AEDILES ‡ NOVAE ROMAE

Rust diseases of wheat have been a threat to food security since ancient times.

In the Roman Empire, April 25 was the day of the Robigalia festival, recognizing Robigus, the Roman god of wheat rust. It was thought that this cruel god was responsible for crop-destroying rust epidemics. On this day, a dog would be sacrificed in hopes that Robigus would be satisfied and allow a successful harvest.

- **Stem rust was and still continues to be one of the most feared diseases of wheat.**
- **Stem rust has been an ongoing problem dating back to Aristotle's time (384-322 B.C).**
- **References dating back to Biblical times relate to epidemics of cereal rusts and smut inflicted upon the Israelites as punishment for their sins (Chester, 1946).**
- **Fragments of stem rust-infected wheat from the Bronze Age have been discovered in Israel (Kislev, 1982).**
- **Numa Pompilius (715-672 BC) described the Roman festival of "Robigalia" that was established to protect cereal crops.**

Breakdown of “race specific genes”: some examples



Durum wheat
“Altar 84” *Lr72* (1984-2001)
BBG/BN
“Jupare 2001”*Lr72, Lr27+31*
(2001-2007) BBG/BP
“CIRNO 2008”
Lr72, LrCamayo (2008-2017)
BBG/BP+LrCamayo

Bread wheat
“Yecora 70” *Lr1, Lr13 (1970-1973)*
“Tanori 71” *Lr13, Lr17 (1971-1975)*
“Jupateco 73” *Lr17, Lr27+31* (1973-1977) TBD/TM
“Genaro *81”Lr13, Lr26* (1981-1984) TCB/TB
“ Seri *82”Lr23, Lr26* (1982-1985) TCB/TD
“Baviacora *92”Lr14b, Lr27+31*(1992-1994) MCJ/SP

“Opata 85” *Yr27* (1985-1996) Mex96.11
“Pastor” *Yr31* (?-2008) Mex08.13

“Moro” *Yr10* (?-2011)

Multiple varieties USA
Yr8 and Yr9 (?-2000)

Multiple varieties (1970-1994)
Yr17 breakdown UK, Denmark

Multiple varieties
(2017) Psts14 Morocco

Veery derivatives (Dashen)
(*Yr9* breakdown in 1986)

“ Kubsa” *(?-2010) Yr27*

Multiple varieties (2017-2018) Psts13

Pirsabak-85 and Pak81 (*Yr9* breakdown in 1995)

Inquilab-91 (*Yr27* breakdown in 2005)

“ Chamran” *(1996-2002-3) Yr27 Iran*

“Fan 6’ and its derivatives 2002. race CYR32 China

Lorvin” derived lines *Yr9 (1971/72 -1975) CYR29*

“Chuanmai 42” *Yr24/26* (2004-2010) V26

“PBW343” (1995-2003-05) Yr27

Khapstein”/9*LMPG/Vernal Emmer *Sr13,Sr13+Sr9e* (?-2009) TRTTF ,JRCQC

“Kavkaz” *Sr31* (1980-1998) TTKSK (Ug99) Ethiopia
“Digalu” *Srtmp* (2005-2013) TKTTF(Non Ug99)

“Kenya Mwamba” (2001-2006) Ug99+Sr24 Kenya
“Kenya Robin” (2009-2014)(Ug99+Srtmp)

“Milan”Yr17(?-2006) 134E16A+

Lr24 “Torres” multiple varieties
(1983-2002)
(104-1,2,3,(6),(7),*11+Lr24*)

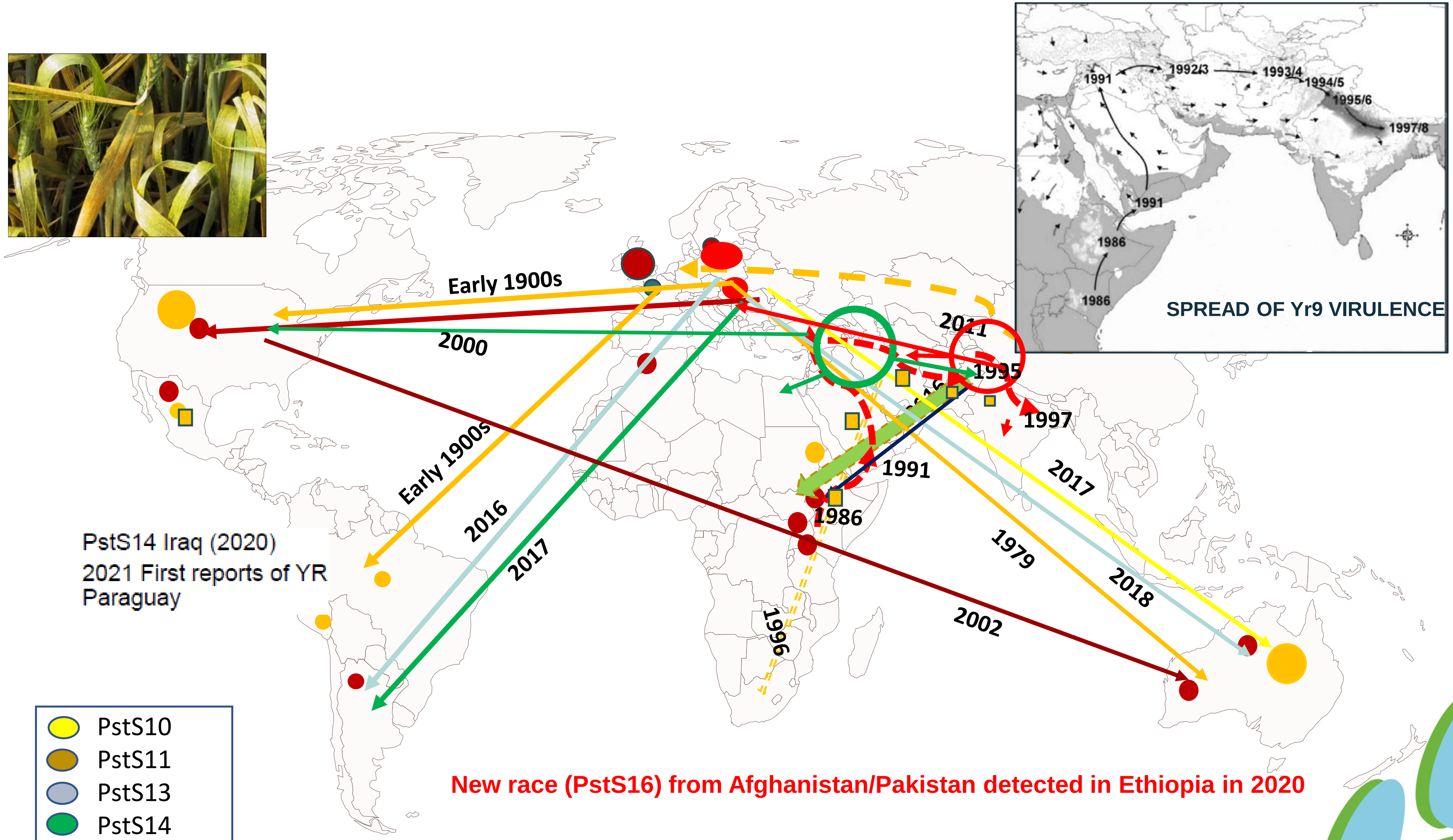
Yellow rust

Leaf rust

Stem rust

Several cases remain undocumented

Spread of aggressive *Puccinia striiformis* (yellow rust) races



SPREAD OF Yr9 VIRULENCE

PstS14 Iraq (2020)
2021 First reports of YR Paraguay

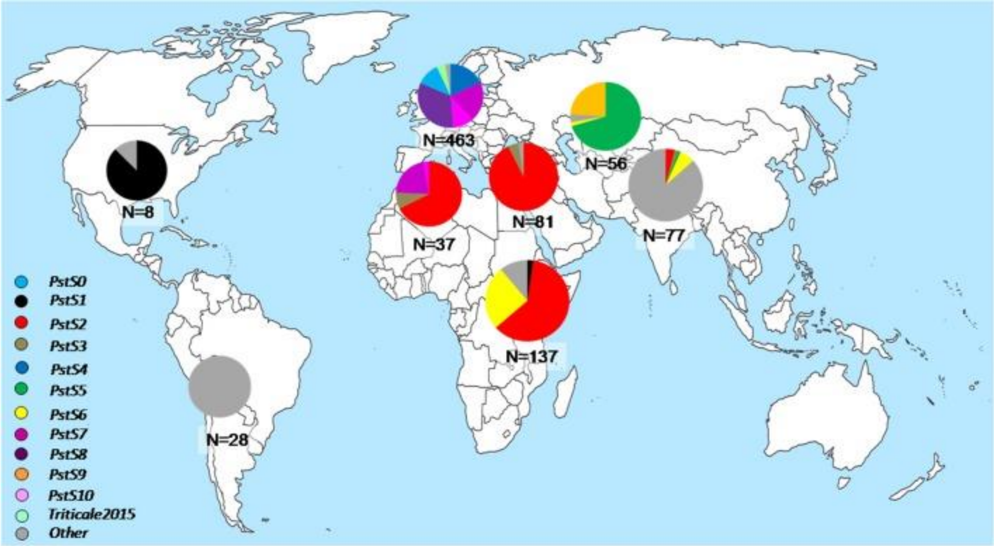
New race (PstS16) from Afghanistan/Pakistan detected in Ethiopia in 2020

- ● PstS10
- ● PstS11
- ● PstS13
- ● PstS14
- ● PstS1/S2
- ● PstS16

🟧 ***Yr27* breakdown (2002-2004)**

- **New emerging genetic groups of yellow rust**
- **Faster transcontinental spread**
- **Localized severe epidemics**

Source: Updated from Ali et al. (2014) PLoSPathog10(1): e1003903. doi:10.1371/journal.ppat.1003903



- In 2018, **PstS11** was detected in Kenya and Ethiopia, Rwanda and Tanzania, now being the most prevalent lineage in East Africa. **PstS11** was first detected in Afghanistan in 2012, (virulence phenotype: -,2,-,4,-,6,7,8,-,-,-,17,-,-,27,32,-,AvS,-),

- **PstS14,** containing only a single race, (virulence phenotype: -,2,3,-,-,6,7,8,9,-,-,17,-,25,-,32,Sp,AvS,-) dominated in Morocco, where it made up 100% of samples investigated. *PstS14* was detected in Europe at low frequency and in 2017 also in South America for the first time.

- **PstS1/PstS2*** was detected at multiple locations in CWANA, the most frequent race carrying virulence to Yr27. (-,2,3,-,-,6,7,8,9,10,-,-24,25,27,-,-, AvS,-) and also in West Asia

- In Uzbekistan, **PstS9** is by far the most prevalent group (most common virulence phenotype: 1,2,3,4,-,6,-,-,9,-,-,17,-,25,27,32,-,AvS,Amb), which was also the case in 2016-2017.

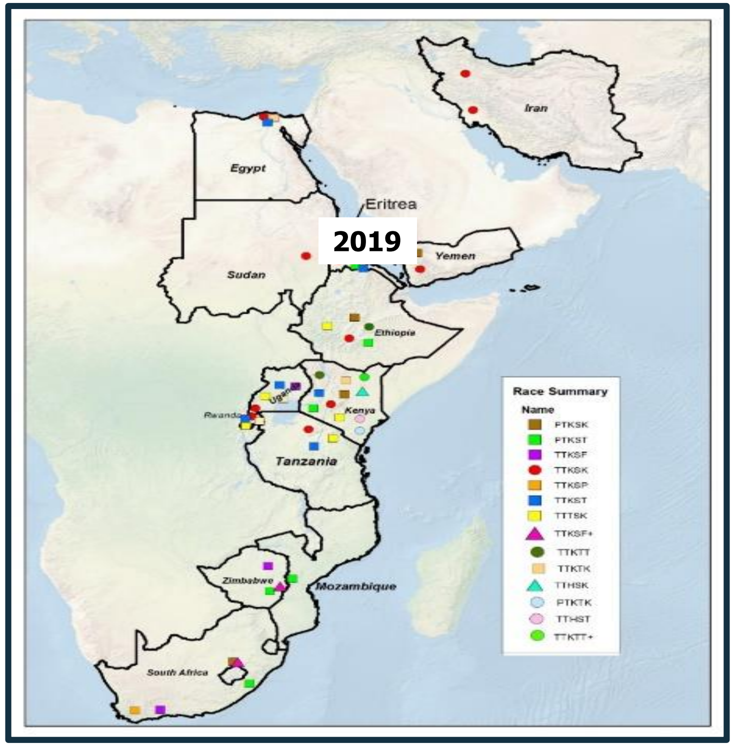
- Warrior race **PstS7** quite widely prevalent in Europe

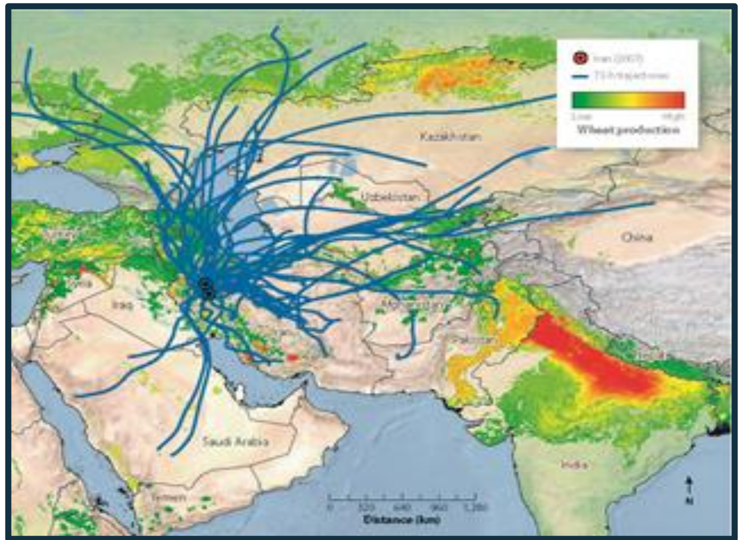
- A novel genotype was detected in Egypt, some relationship with **PstS1/PstS2, PstS13** and **PstS14**, but additional analyses and live samples are required to make a firm conclusion about origin and epidemic potential. It would be valuable to follow up, taking into account the yellow rust outbreaks observed in Egypt in 2018.

- In South America, **PstS13** was widespread in Argentina and Chile, where unusual severe and widespread epidemics of yellow rust affected wheat crops in many areas both in 2017 and 2018. (virulence phenotype: -,2,-,-,-,6,7,8,9,-,-,-,-,-,-,-,-,AvS,-). PstS13 has been detected in most European countries causing severe epidemics on Triticale and durum wheat severely.
- **GRRC annual report**

Different colors show different lineages identified from global samples during 2009-2015 at GRRC, Denmark Source: Ali et al. (2017) Front Plant Sci 8: 1057.

Stem rust Ug99: a global threat?





>80% of wheat varieties grown world wide found susceptible when tested in Kenya

Migrated from Uganda to 13 different countries (S. Africa - Middle East- Iran)

Highly aggressive - broad virulence spectrum

> 50% SR genes rendered ineffective including Sr31

Continuously evolving 17 races in identified in the Ug99 lineage

9 races evolved in Kenya (hot spot)

Predicted migration to other regions – S. Asia, East and central Asia and the pacific

Early epidemics with susceptible varieties can cause >70% losses

Effectiveness of Known *Sr* genes to TTKS (Ug99) Lineage

Origin of *Sr* genes	Ineffective	Effective
Triticum aestivum[f]	5, 6, 7a, 7b, 8a, 8b, 9a, 9b, 9f, 9h, 10, 16, 18, 19, 20, 23, 30, 41, 49, 54, McN, Wld-1, Tmp (or *Sha7*)[a,b]	15[a,b f], 28[a], 29[b,c], 42[a,b], 48, 55[b,d], 56[b,d], 57[b,d], 58[b,d], Huw234[a,b], ND643[b], Yaye[b]
T. turgidum	9d, 9e, 9g, 11, 12, 17	2[b,d], 13[a,b], 14[a,b]
T. monococcum	21	22, 35[a]
T. timopheevi	36	37[c]
Aegilops speltoides		32[c], 39[c], 47[e]
Ae. tauschii		33[b], 45[a,b], 46[a,e], TA10171[e], TA10187[a,e], TA1662[a,e]
Ae. searsii		51
Ae. geniculata		53
Dasypyrum villosum		52
T. comosum	34	
T. ventricosum	38	
T. araraticum		40[c]
Thinopyrum elongatum	24	25[a], 26, 43[a,c]
Th. intermedium		44[a,c]
Secale cereale	31	27[a], 50[a], 1RS(Amigo)[a,b]

a Virulence for the gene is known to occur in other races

b Level of resistance conferred in the field usually inadequate under high disease pressure

c Unsuitable for utilization due to linkage with undesirable traits in the translocation

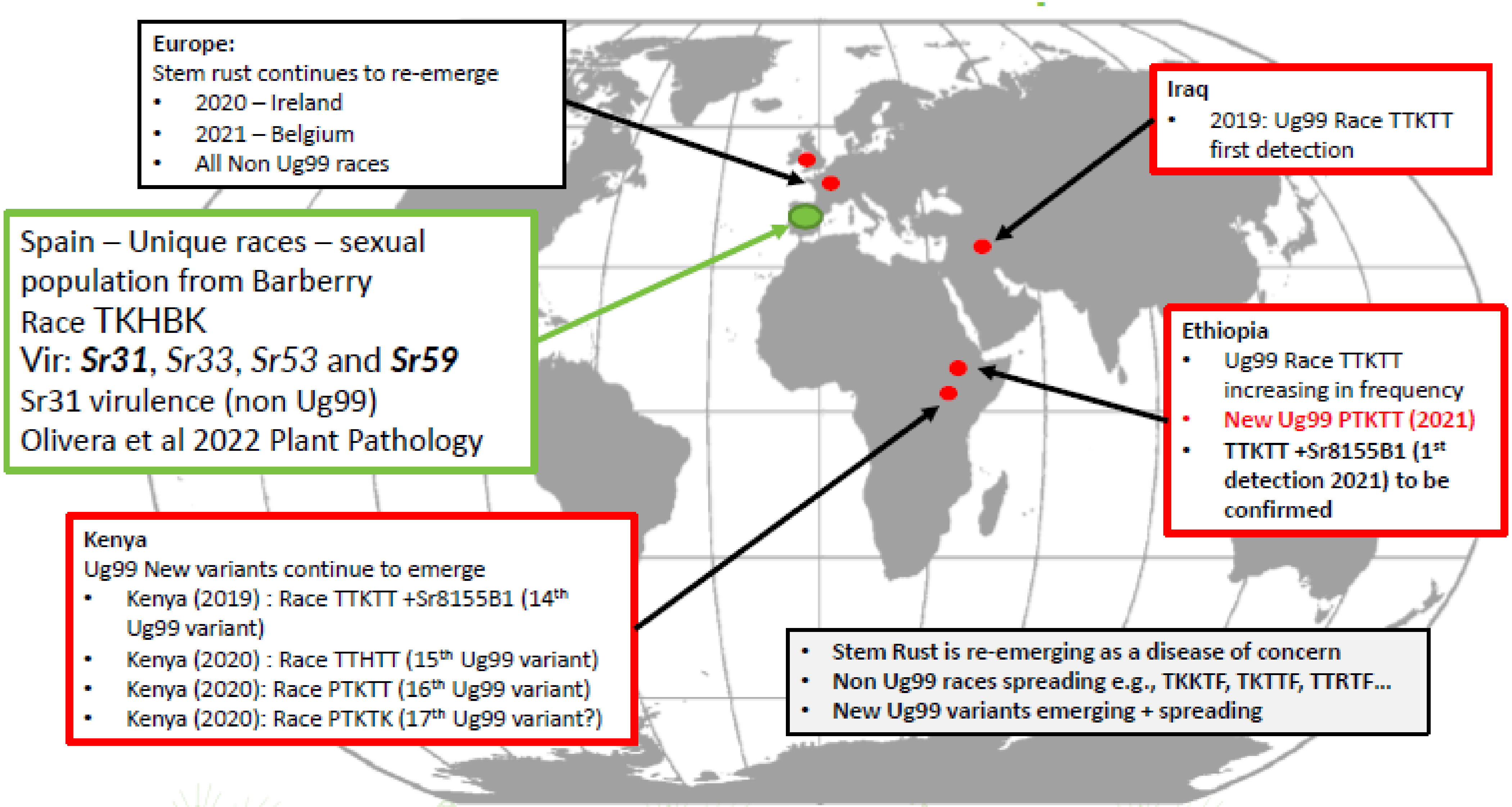
d Confers slow rusting adult plant resistance

e Not tested for resistance to Ug99 in field trials to determine effectiveness

f Data from multiple research groups are not consistent; initial studies determined Sr15 was ineffective however recent data shows avirulence in Ug99 lineage

(Singh et al 2015)

Stem rust races : recent update



Europe:
Stem rust continues to re-emerge
- 2020 – Ireland
- 2021 – Belgium
- All Non Ug99 races

Spain – Unique races – sexual population from Barberry
Race TKHBK
Vir: ***Sr31***, *Sr33*, *Sr53* and ***Sr59***
Sr31 virulence (non Ug99)
Olivera et al 2022 Plant Pathology

Iraq
- 2019: Ug99 Race TTKTT first detection

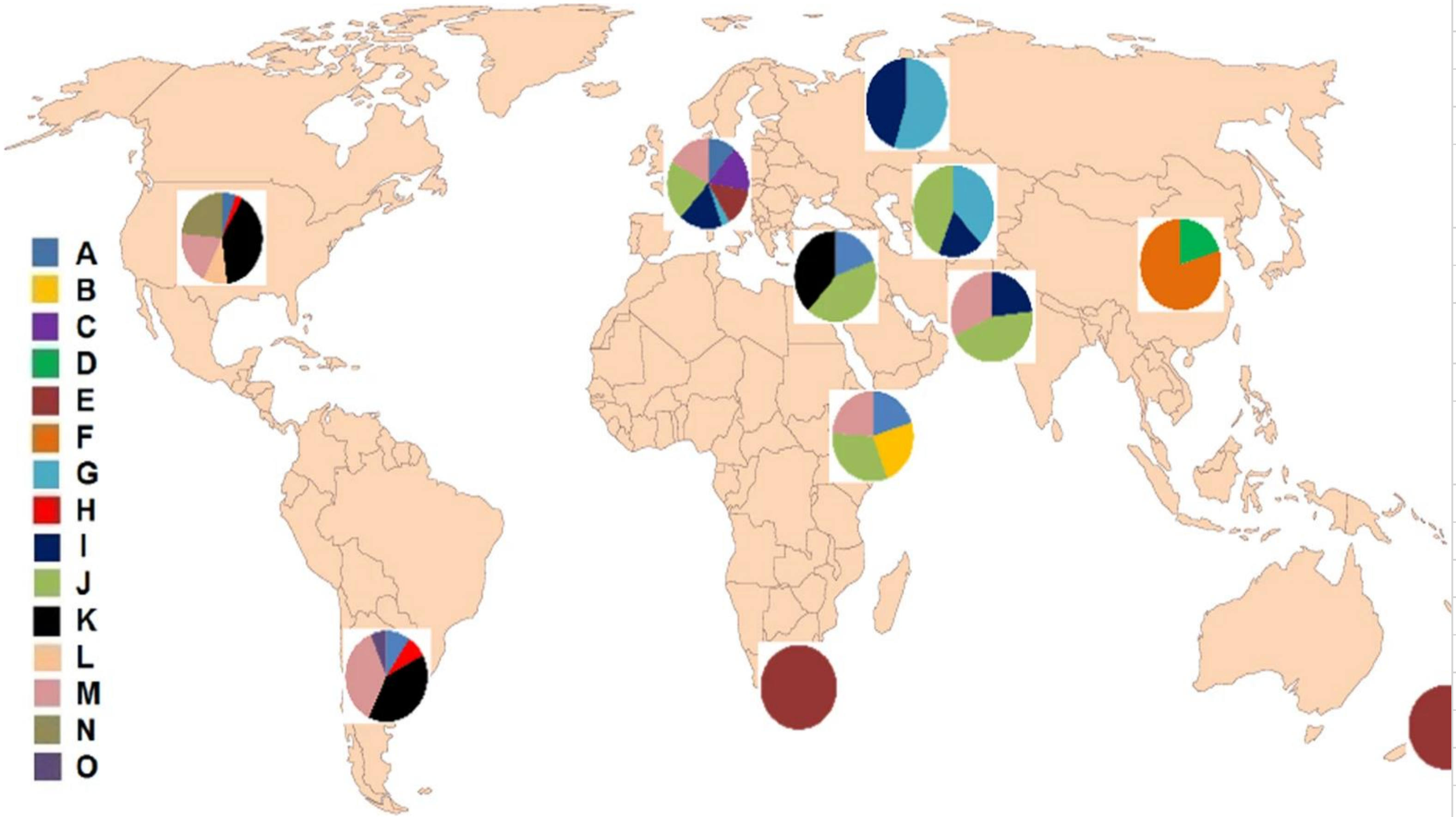
Ethiopia
- Ug99 Race TTKTT increasing in frequency
- New Ug99 PTKTT (2021)
- TTKTT +Sr8155B1 (1st detection 2021) to be confirmed

Kenya
Ug99 New variants continue to emerge
- Kenya (2019) : Race TTKTT +Sr8155B1 (14th Ug99 variant)
- Kenya (2020) : Race TTHTT (15th Ug99 variant)
- Kenya (2020): Race PTKTT (16th Ug99 variant)
- Kenya (2020): Race PTKTK (17th Ug99 variant?)

- Stem Rust is re-emerging as a disease of concern
- Non Ug99 races spreading e.g., TKKTF, TKTTF, TTRTF…
- New Ug99 variants emerging + spreading

USDA University of Minnesota GRRC GLOBAL RUST REFERENCE CENTER ICARDA EIAR CIMMYT

Diversity of *Puccinia triticina* isolates based on SNP genotype clusters (A-O) in 11 regional populations and different groups based on virulence diversity

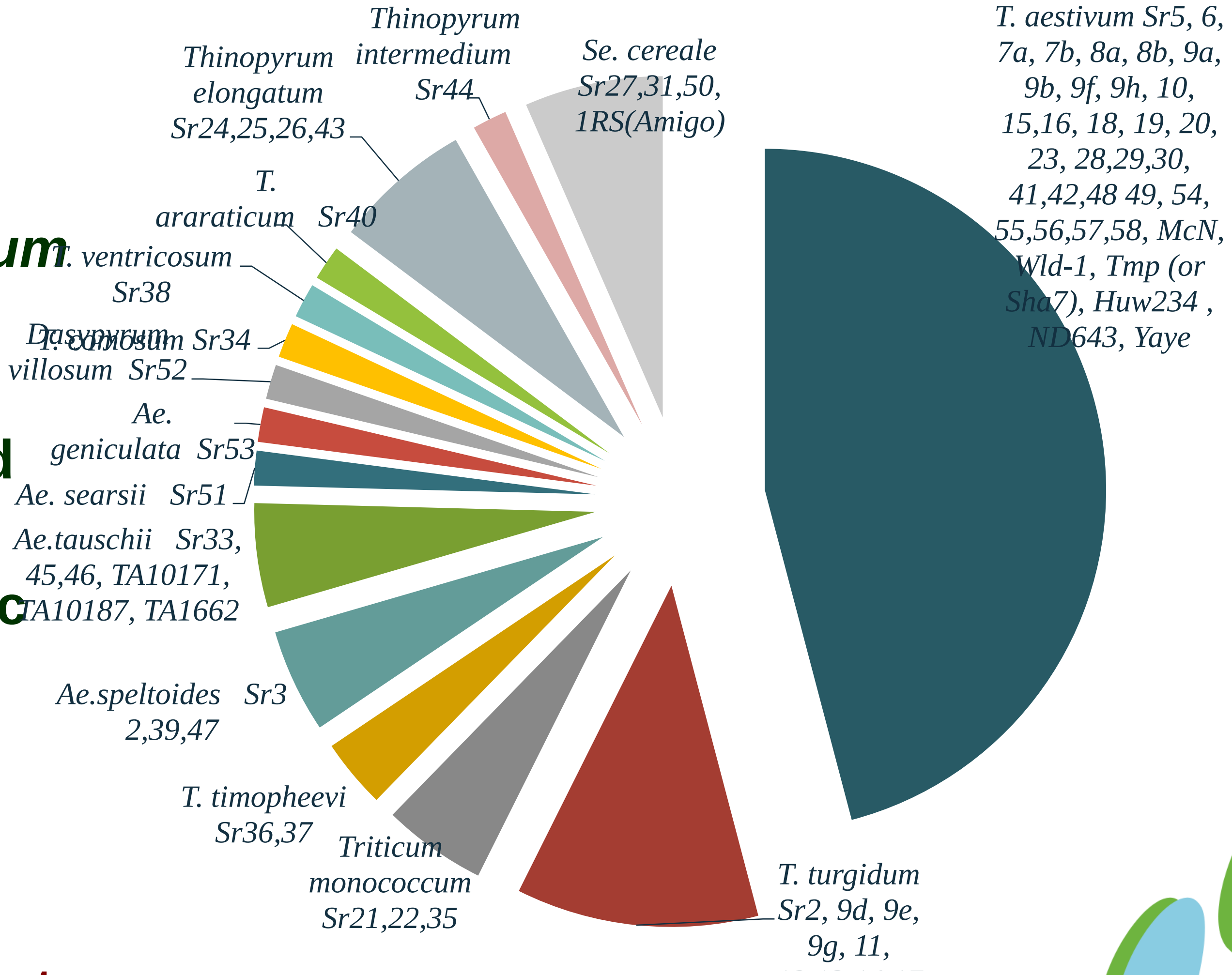


Group
CA-1
CA-2
CA-3
CA-4
Central Asia
CN-1
CN-2
CN-3
China
EA-1
EA-2
ETH-Durum
ETH-EEEEE
East Africa
EU-1
EU-2
EU-4
EU-5
EU-6
EU-7
EU-8
EU-Durum
Europe
ME-1
ME-2
ME-Durum
Middle East
North America
NZ
PK-1
PK-2
PK-3
Pakistan
RU-1
RU-2
Russia
SA-1
SA-2
SA-3
SA-4
SA-Durum
South America
South Africa

Kolmer et. al 2019, Heredity

Stem (black) rust- known resistance genes (63)

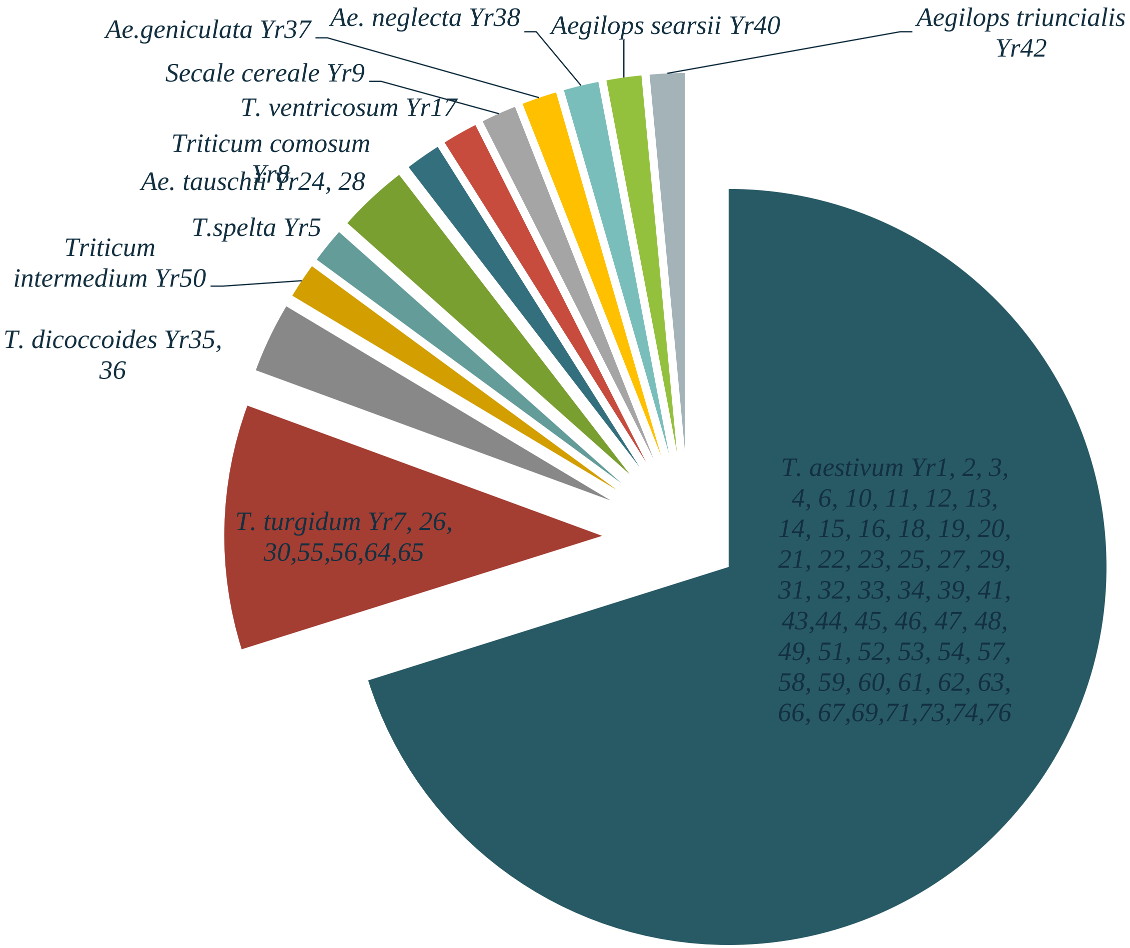
- **35 genes from *Triticum aestivum***
- **38 genes from 14 different species and genera**
- **Majority race-specific**
- **Some alien genes successfully used**



APR genes for stem rust

Sr2, Sr55, Sr56, Sr57, Sr58

Stripe (yellow) rust (83)



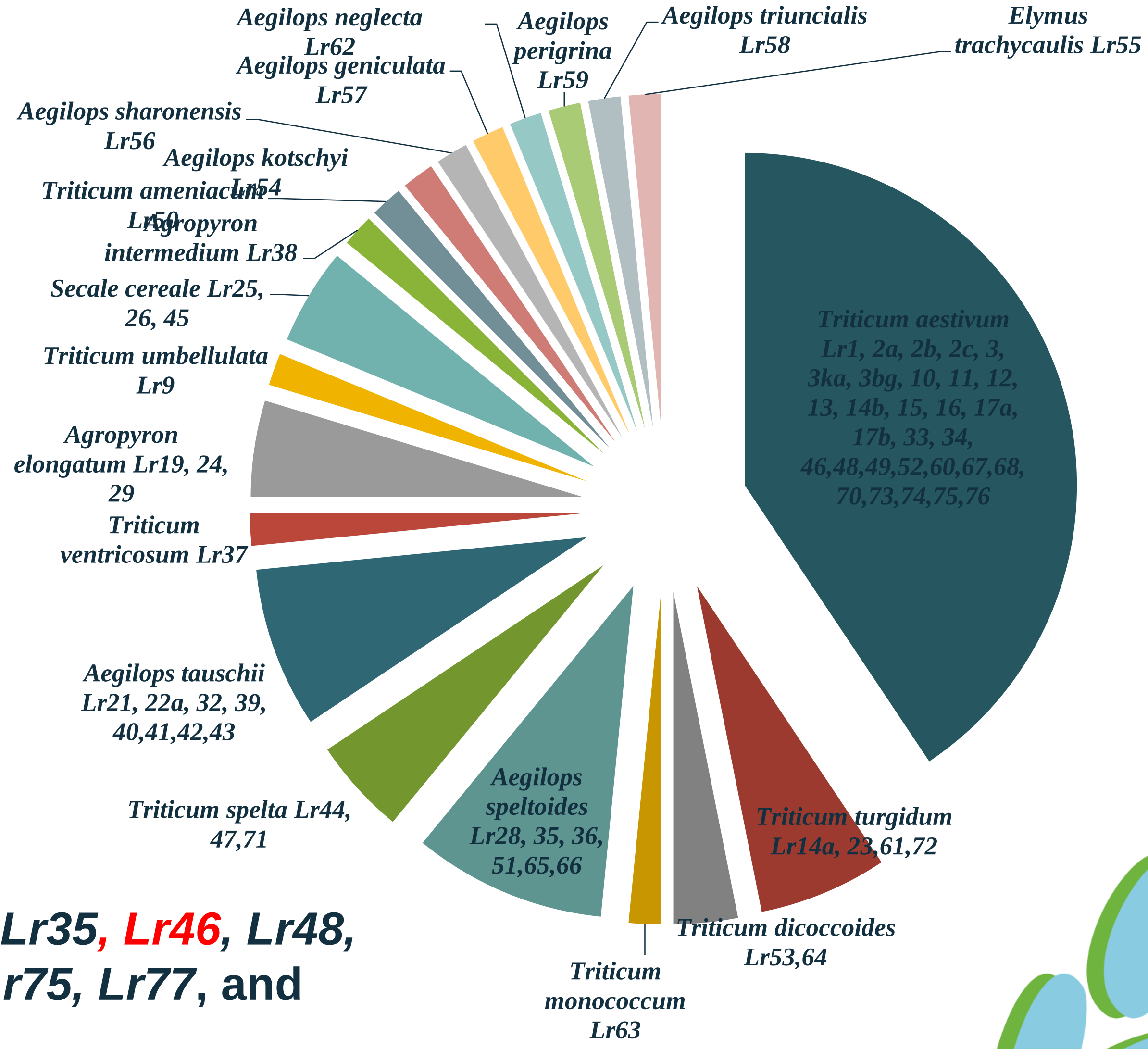
- 52 genes from *Triticum aestivum*
- 20 genes from 11 different species and genera

APR genes for YR

Yr11, Yr12, Yr13, Yr14, Yr16 (2DL), Yr18 (7DS), Yr29 (1BL), Yr30 (3BS), Yr34 (5AL), Yr36 (6BS), Yr39 (7BL), Yr46 (4DL), Yr48 (5AL), Yr49 (3DS), Yr52 (7BL), Yr54 (2DL), Yr56 (2AS), Yr58 (3BS), Yr59 (7BL), Yr60 (4AL), Yr62 (4BL), Yr68 (4BL), Yr71 (3DL), Yr75 (7AL), Yr77 (6DS), Yr78 (6BS), Yr79 (7BL), Yr80 (3BL), Yr82 (3BL)

Leaf (brown) rust (80)

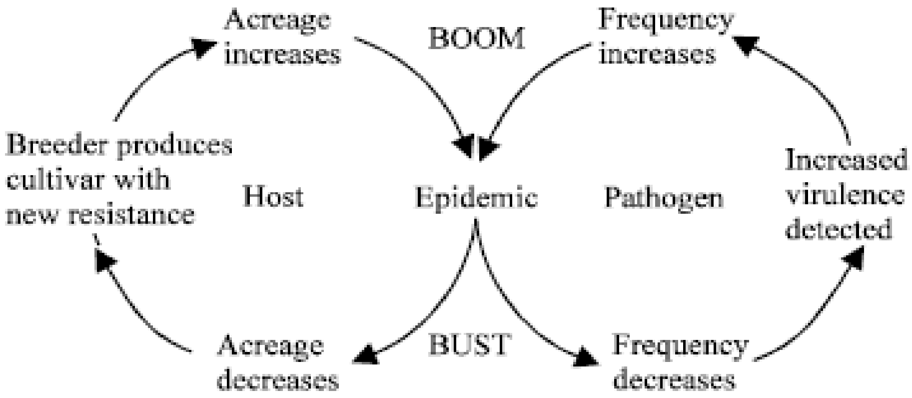
- 30 genes from *T. aestivum*
- 39 genes from 19 different species and genera



APR genes for leaf rust

Lr12, Lr13, Lr22a, Lr34, Lr35, Lr46, Lr48, Lr49, Lr67, Lr68, Lr74, Lr75, Lr77*, and *Lr78

Only *Lr46* has been reported in durum wheat



“Ug99” races evolved in Kenya

TTKSK
(Ug99)
2001

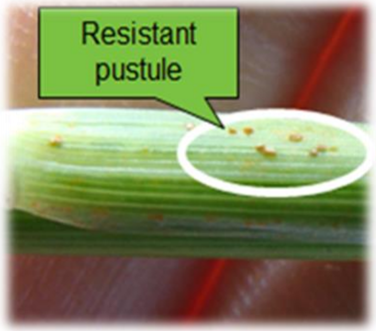
TTKST
(Ug99+Sr24)
2006

TTTSK
(Ug99+Sr36)
2007

TTKTK
(Ug99+Srtmp)
2014

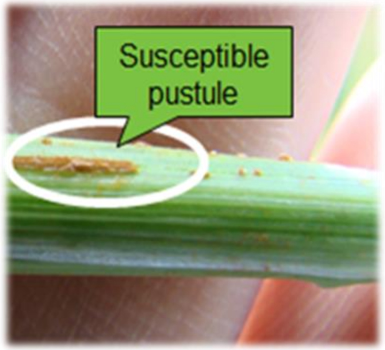
TTKTT
(Ug99+
Sr24+Srtmp)
2014

TTKTK
(Ug99+Srtmp+
Sr8155-B1 allele)
2018



BOOM

BUST



Priority Traits in Spring Bread Wheat Product Profiles

	Product Profile/Market Segment					
	Breeding Program 1		Breeding Program 2			
	1. Hard White- Optimum Environment	2. Hard White- Heat Tolerant Early Maturity	3. Hard White-Drought Tolerant Normal Maturity	4. Hard White-Drought Tolerant Early Maturity	5. Hard White- High Rainfall	6. Hard Red – High Rainfall
	HW-OE	HW-HTEM	HW-DTNM	HW-DTEM	HW-HR	HR-HR
Trait	2x	2x	1x	1x	0.75x	0.25x
High and stable yield potential	XXX	XXX	XXX	XXX	XXX	XXX
Water use efficiency/Drought tolerance	X	X	XXX	XXX	XX	XX
Heat tolerance	XX	XXX	XX	XXX	X	X
End-use quality	XXX	XXX	XXX	XXX	XXX	XXX
Enhanced grain Zn (and Fe) content (new mainstreaming trait)	XXX	XXX	XXX	XXX	XXX	XXX
Stem rust (Ug99 & other)	XX	XX	XX	XXX	XXX	XXX
Stripe rust	XXX	XX	XXX	XX	XXX	XXX
Leaf rust	XXX	XXX	XXX	XXX	XX	XX
Septoria tritici blotch	-	-	XXX	-	XXX	XXX
Spot blotch	X	XXX	-	X	-	-
Fusarium – head scab and myco-toxins	-	-	-	-	XX	XX
Wheat blast- new threat in South Asia	X	XXX	X	X	X	X
Maturity	Normal-late	Early	Normal	Early	Normal	Normal

Importance: X= low, XX= moderate, XXX= high

Rust Research at CIMMYT

Objective is to develop improved bread and durum wheat germplasm with durable resistance to the three rust (LR,YR,SR) diseases

- Understanding the genetic basis of resistance to the three rust diseases in a wide range of germplasm

- Identify and characterize new genes, QTL for resistance, developing diagnostic markers and implementing MAS (Marker Assisted Selection)

- Fine mapping of QTL regions, developing mutants for specific target genes and eventually clone them in collaboration with other ARI's to better understand their resistance mechanisms- CSIRO

- Pre-breeding to transfer new resistance genes identified from secondary and tertiary gene pools in to adapted genetic backgrounds to be used in breeding

- Coordinate rust phenotyping platforms ensuring reliable phenotypic data from hot spot environments with maximum pathogen diversity-

SR (OBREGON, KENYA, ETHIOPIA)
YR (TOLUCA,INDIA (Karnal, Ludhiana), KENYA, ETHIOPIA)
LR (OBREGON,URUGUAY)

- Improved survey and surveillance in partnership with global rust reference centers (CDL, GRRC, RRC) understanding virulence diversity and R gene deployment strategies

Why APR strategy to enhance durable resistance at CIMMYT?

- Huge diversity of rust races with **unknown virulence(s)**
- **Mutating** and **migrating** nature of rust pathogens
- **Annual virulence analysis and monitoring** required
- Most known race-specific genes **effective in one or more wheat growing regions**
- **Slow variety turnover** in many countries
- **Pleotropic effect** on other diseases
- Opportunity to break-out of **“Boom-and-Bust”** cycles and focus breeding for other important traits

Without durable resistance, stem rust—a formidable and evolving threat to global food security—could cause losses of

$1.12 BILLION

Origin and Chronology of slow rusting genes at CIMMYT

Notable sources of durable resistance to
SR include "Hope" (*Sr2,Sr7b,Sr9d,Sr17*) and "Thatcher"(*Sr5,Sr9g,Sr12,Sr16*)
LR "Americano 25", "Americano 44D", "Surpreza" (*Lr13; Lr34; Lr3,Lr20*), "Frontana (*Lr1,Lr13,Lr15; Lr10,Lr20,Lr28,Lr34*)", and "Fronteira"
YR "Wilhelmina", "Capelle Deprez" (*Yr16*), "Manella" (*Yr2, Yr14*), "Juliana" (*Yr14, Yr18*) and "Carstens VI" (*Yr12*).

Slow rusting adult plant resistance genes

- ***Lr34* [Syn.=*Yr18=Sr57=Pm38=Sb1=Bdv1=Fhb?=Ltn1*],**
- ***Lr46* [Syn.=*Yr29=Sr58=Pm39=Ts?=Ltn2*],**
- ***Sr2/Yr30/Lr,***
- ***Lr68***

were introduced to Mexican germplasm in the first two cultivars released by Dr. Borlaug

Frontera = Fronteira//Hope//Mediterranean
Supermo 211 = Supresa//Hope//Mediterranean
Supresa =Fronteira =Frondoso=Polissu/a.Chaves 6.21

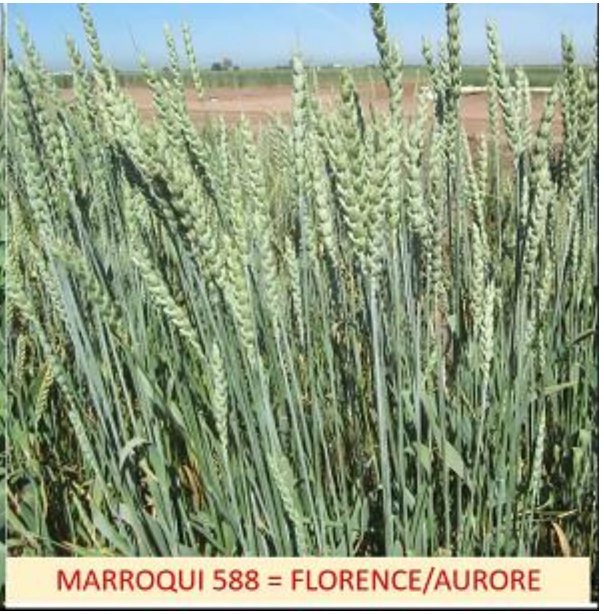
Additional ***Lr46+Lr68+Sr2*** gene combination was introduced through “**Egypt 101**” (= Kenya governor)

Dr. Borlaug introduced ***Lr67/Sr55/Yr46*** in to the Mexican breeding program through **Marroqui 588** (Florence/Aurora) in 1945 from Australia (Borlaug et al .,1949)

“Marroqui 588” is a cross made in 1922 in Australia and first released in Tunisia in 1925 (Wenholz et. al 1939

“Marroqui 588” carries ***Lr46/Yr29/Sr58, Lr67/Sr55/Yr46*** and ***Yr67***


EGYPT 101= KENYA GOVERNOR

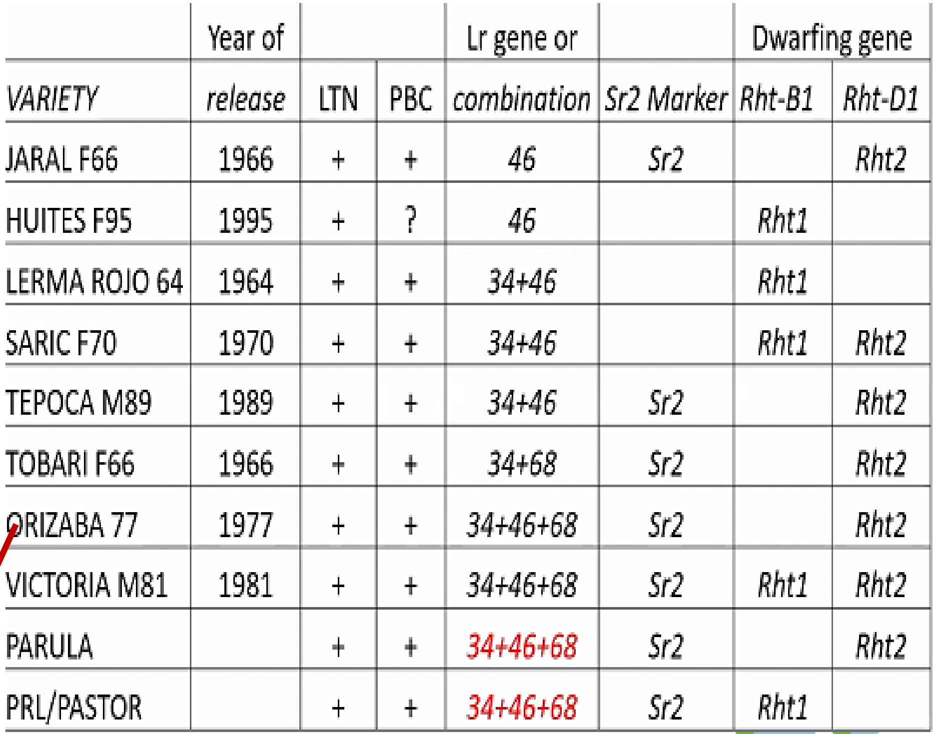

MARROQUI 588 = FLORENCE/AURORE

Additional sources of ***Lr34*** came to Mexico through **“Mentana”** from Italy
(Rieti/Wilhemina//Akagomughi=Ardito, a cross made in 1918)
and **“Frontana”** (Fronteria/Mentana) from Brazil

The first crosses carrying rust resistance were made by Dr. Borlaug in Mexico were **Marroqui588/Newtatch (Newtatch=Hope/3*Thatcher**) and released the following 5 varieties 1950’s
Yaqui 48, Chapingo 48, Nazas 48, Mayo 48 and **Yaqui 50**

‘Yaqui 50”, “Bonza 55”, “Torim 73”, and “Kavkaz” “Kalyansona” “Bluebird”,

“Pavon 76” and “Nacozari 76”, ‘Rayon 89’ and ‘Tarachi 2000”



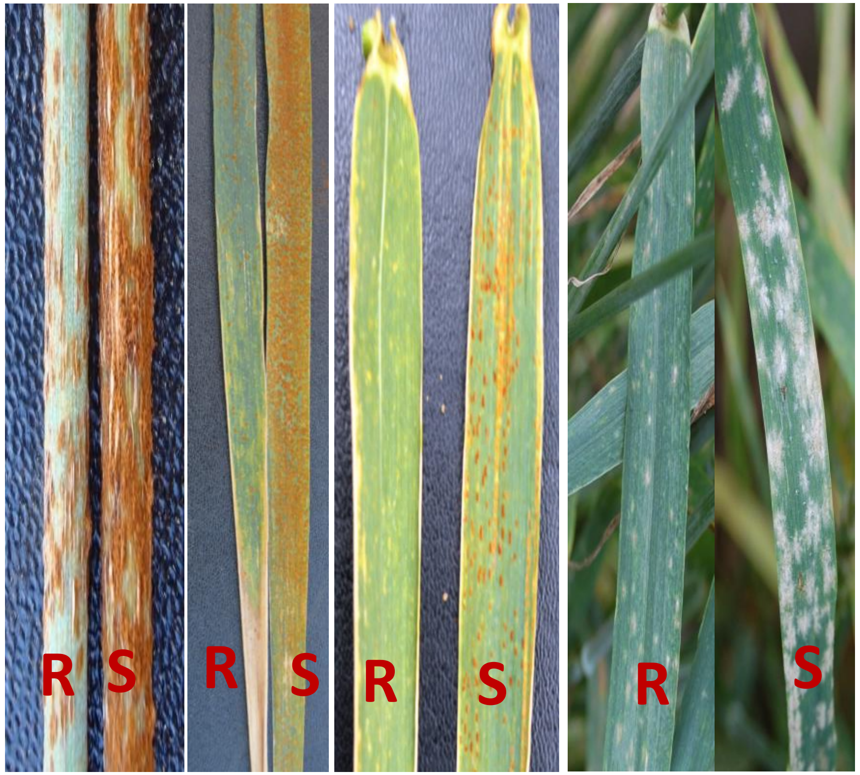
	Year of			Lr gene or		Dwarfing gene	
VARIETY	*release*	LTN	PBC	*combination*	*Sr2 Marker*	*Rht-B1*	*Rht-D1*
JARAL F66	1966	+	+	*46*	*Sr2*		*Rht2*
HUITES F95	1995	+	?	*46*		*Rht1*	
LERMA ROJO 64	1964	+	+	*34+46*		*Rht1*	
SARIC F70	1970	+	+	*34+46*		*Rht1*	*Rht2*
TEPOCA M89	1989	+	+	*34+46*	*Sr2*		*Rht2*
TOBARI F66	1966	+	+	*34+68*	*Sr2*		*Rht2*
ORIZABA 77	1977	+	+	*34+46+68*	*Sr2*		*Rht2*
VICTORIA M81	1981	+	+	*34+46+68*	*Sr2*	*Rht1*	*Rht2*
PARULA		+	+	*34+46+68*	*Sr2*		*Rht2*
PRL/PASTOR		+	+	*34+46+68*	*Sr2*	*Rht1*	

(CIANO-67(SIB)/SIETE-CERROS-66//CORRECAMINOS/TOBARI-66)

Slow rusting, adult plant resistance genes

Four catalogued genes confer pleotropic resistance to multiple pathogens (PAPR)

Lr67/Yr46/Sr55/Pm46



Lr34 [Syn. =*Yr18=Sr57=Pm38=Sb1=Bdv1=Fhb?=Ltn1*] chromosome 7DS

(leaf rust, yellow rust, stem rust, powdery mildew, spot blotch, barley yellow dwarf virus, fusarium head blight, leaf tip necrosis)

Lr46 [Syn.=*Yr29=Sr58=Pm39=Ts?=Ltn2*] chromosome 1BL

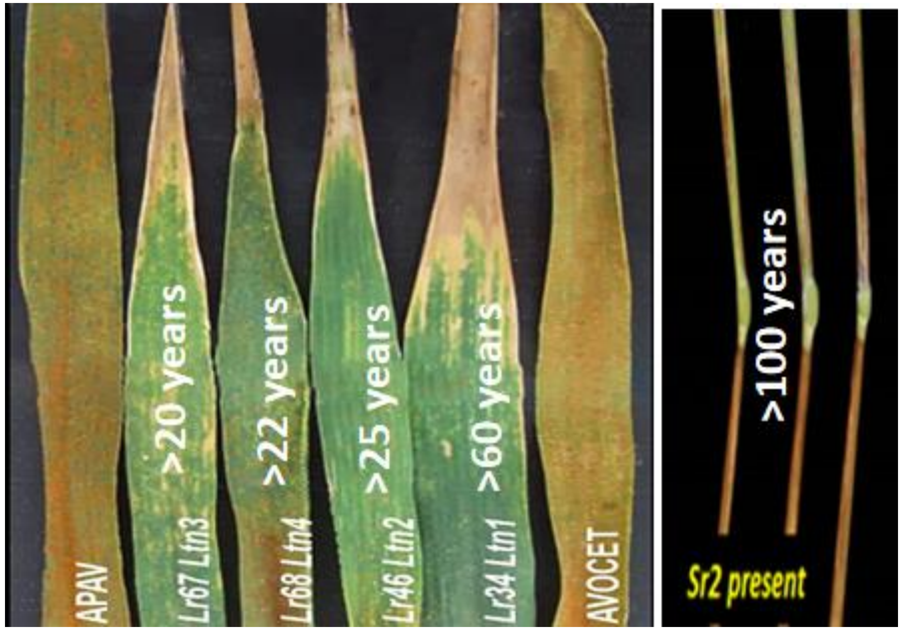
Lr67 [Syn.= *Yr46=Sr55=Pm46=Ltn3*] chromosome 4DL ("PI250413")

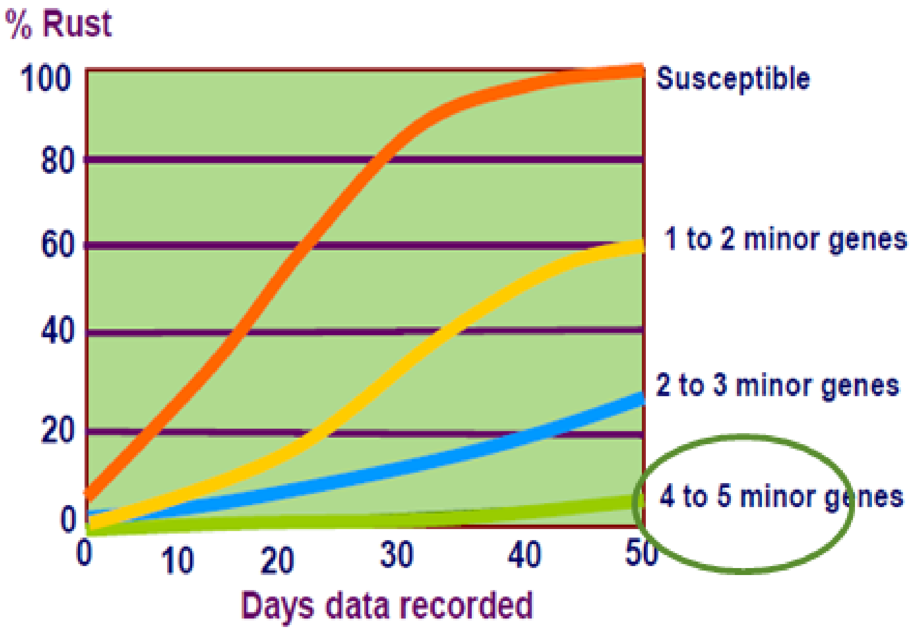
Sr2/Yr30/Lr chromosome 3BS

Lr68 chromosome 7BL

Various consistent QTLs, some with effects on multiple pathogens, e.g. on 1BS, 2AL, 2BS, 2DL, 5AL, 5BL, 6AL and 7BL (Li et al. 2014. Crop Sci. 54:1907-192)

New genomic regions on chromosomes 1BL, 2AS and 6BL in CIMMYT germplasm





- **Near-immunity (trace to 5% severity) achieved by combining (4-5 genes)**
- **A similar genetics for other leaf spotting diseases, fusarium head blight)**

F_3 Segregation Ratios

Genes With Minor/intermediate but Additive Effects on Disease Severity

No. of	Lines (%)			
Genes	HPTR	HPTS	SegI	SegS
2	6.3	6.3	37.5	50.0
3	1.6	1.6	56.3	40.6
4	0.4	0.4	68.0	31.3
5	0.1	0.1	76.2	23.6

HPTR = Homozygous Parental Type Resistant
HPTS = Homozygous Parental Type Susceptible
SegI = Segregating, or intermediate, but no completely susceptible plant
SegS = Segregating with completely susceptible plants

F_5 and F_6 Segregation Ratios

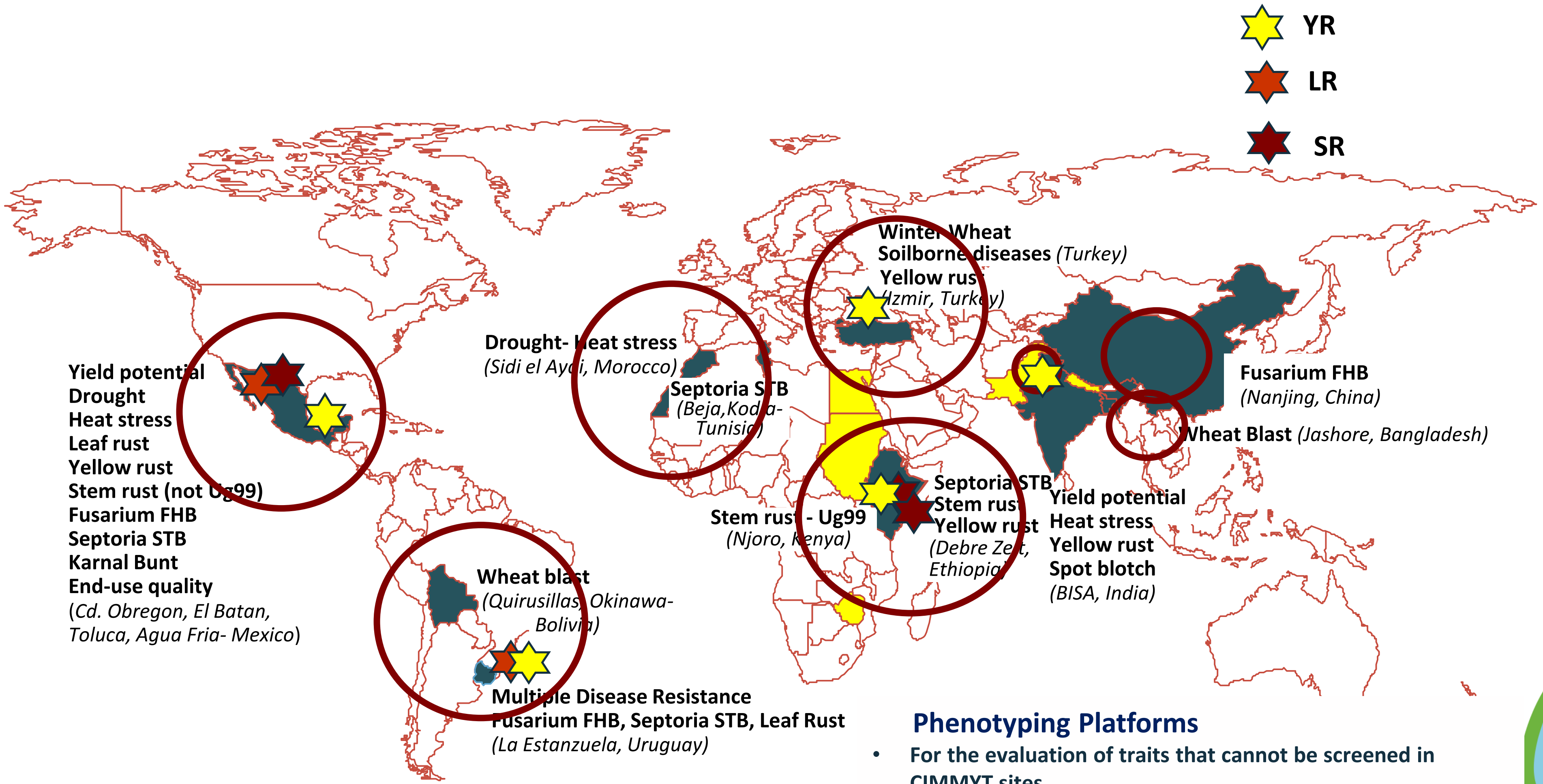
Genes With Minor/intermediate but Additive Effects on Disease Severity

No. of Genes	Generation	Lines (%) HPTR	Lines (%) HPTS	Lines (%) Other
2	F_5	19.1	19.1	61.8
	F_6	22.0	22.0	56.0
3	F_5	8.4	8.4	83.2
	F_6	10.3	10.3	79.4
4	F_5	3.7	3.7	92.6
	F_6	4.8	4.8	90.4
5	F_5	1.6	1.6	97.4
	F_6	2.3	2.3	95.4

HPTR = Homozygous Parental Type Resistant
HPTS = Homozygous Parental Type Susceptible
Other = Lines with intermediate levels of disease severities

Reliable phenotyping is Key!!!!!

International wheat disease phenotyping network)



★ YR

★ LR

★ SR

Yield potential
Drought
Heat stress
Leaf rust
Yellow rust
Stem rust (not Ug99)
Fusarium FHB
Septoria STB
Karnal Bunt
End-use quality
(*Cd. Obregon, El Batan,*
Toluca, Agua Fria- Mexico)

Drought- Heat stress
(Sidi el Aydi, Morocco)

Septoria STB
(Beja,Kodia-
Tunisia)

Winter Wheat
Soilborne diseases *(Turkey)*
Yellow rust
(Izmir, Turkey)

Fusarium FHB
(Nanjing, China)

Wheat Blast *(Jashore, Bangladesh)*

Septoria STB
Stem rust
Yellow rust
(Debre Zeit,
Ethiopia)

Stem rust - Ug99
(Njoro, Kenya)

Yield potential
Heat stress
Yellow rust
Spot blotch
(BISA, India)

Wheat blast
(Quirusillas, Okinawa-
Bolivia)

Multiple Disease Resistance
Fusarium FHB, Septoria STB, Leaf Rust
(La Estanzuela, Uruguay)

Phenotyping Platforms

- For the evaluation of traits that cannot be screened in CIMMYT sites
- Platforms hosted by NARs where environments are optimal for specific trait phenotyping
- Hubs for generating high quality phenotypic data, under defined good management practices
- Sites represent hotspots for pathogenic diversity facilitating both evaluation and selection

Mexico (Cd. Obregon-Toluca/El Batan)- Kenya International Shuttle Breeding

WINTER CYCLE

Cd. Obregon

39 masl

- High yield potential
- (irrigated)
- Water-use efficiency
- Heat tolerance
- Leaf rust
- Stem rust (not Ug99)

SUMMER CYCLE

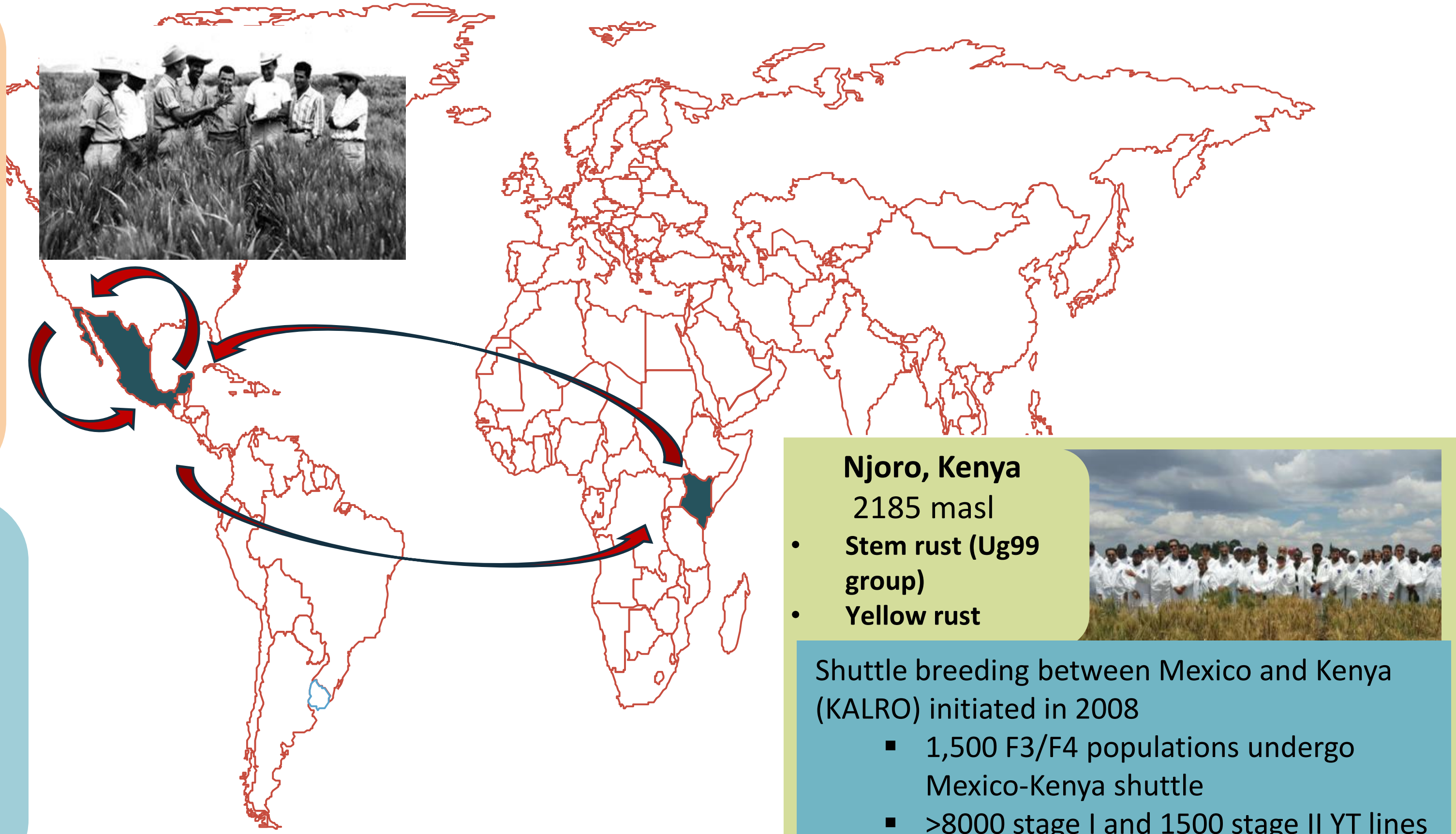
Toluca

- 2640 masl
- Yellow rust
- Septoria STB

El Batán

2249 masl

- Leaf rust
- Fusarium FHB



Njoro, Kenya

2185 masl

- **Stem rust (Ug99 group)**
- **Yellow rust**

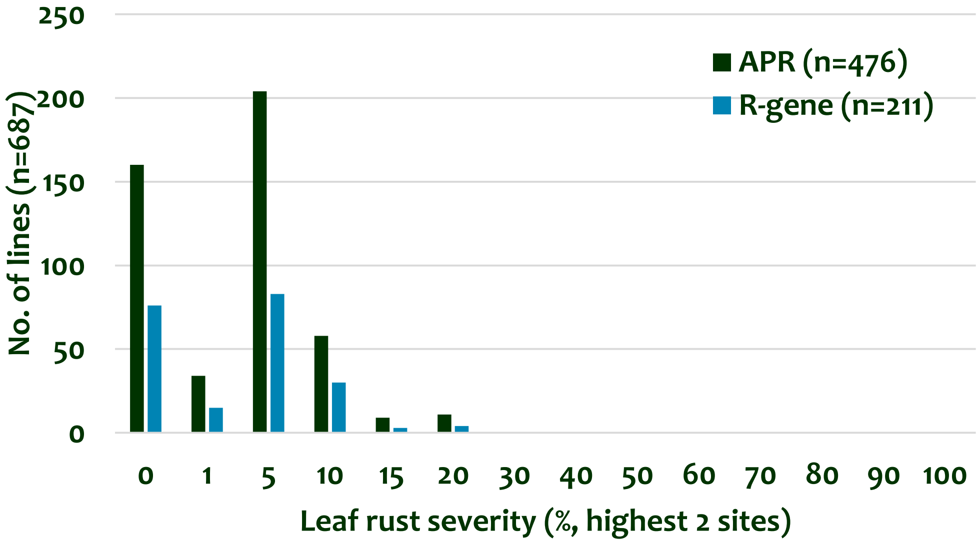
Shuttle breeding between Mexico and Kenya (KALRO) initiated in 2008

- 1,500 F3/F4 populations undergo Mexico-Kenya shuttle
- >8000 stage I and 1500 stage II YT lines evaluated every year
- High yielding, resistant lines distributed worldwide since 2011

Slow rusting adult-plant resistance to leaf rust in CIMMYT wheat germplasm

- **CIMMYT-derived varieties and breeding materials possess high levels of resistance**
- **Leaf rust under control for 25 years in countries growing CIMMYT- derived varieties**
- ***Lr46/Yr29* nearly fixed**
- **Excellent example of durability**

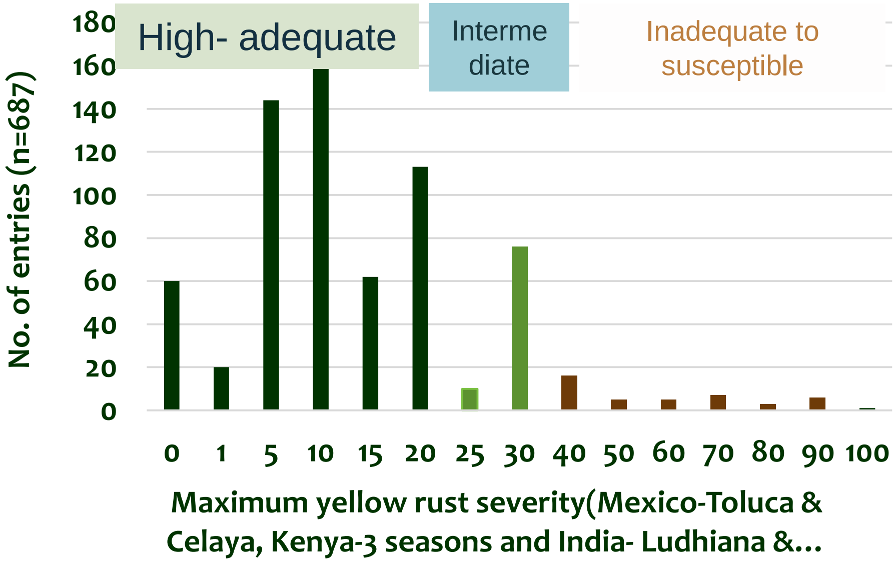
Leaf rust resistance in 687 wheat lines (international distribution in 2020) under high leaf rust pressures



Achieving all-stage near-immune, multi-genes based resistance to yellow rust

- **4-5 slow rusting genes based APR effective in most areas where infection begins at post stem elongation stages**
- **Early infections in some areas from aggressive races cause juvenile susceptibility**
- **High levels of all-stage resistance from interactions of slow rusting genes with small/ intermediate effect race-specific genes; e. g. *Yr48* (5AL), *Yr54* (2DL), *Yr60* (4BL), *Yr67* (7BL), etc.**
- **Simultaneous field-based selection for resistance with other agronomic traits increases genetic gains**

Highest yellow rust severity of 687 wheat lines at 5 field sites/environments under high disease pressures



- ➢ **Highly resistant lines in Mexico show varying resistance levels in Kenya and India due to presence to different races & environment**
- ➢ ***Phenotyping efforts increased in India and Kenya for culling***

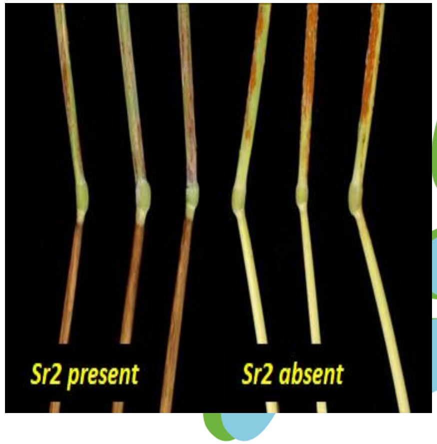
Progress in breeding Ug99 stem rust resistance in CIMMYT wheats: resistance in current international trials and nurseries

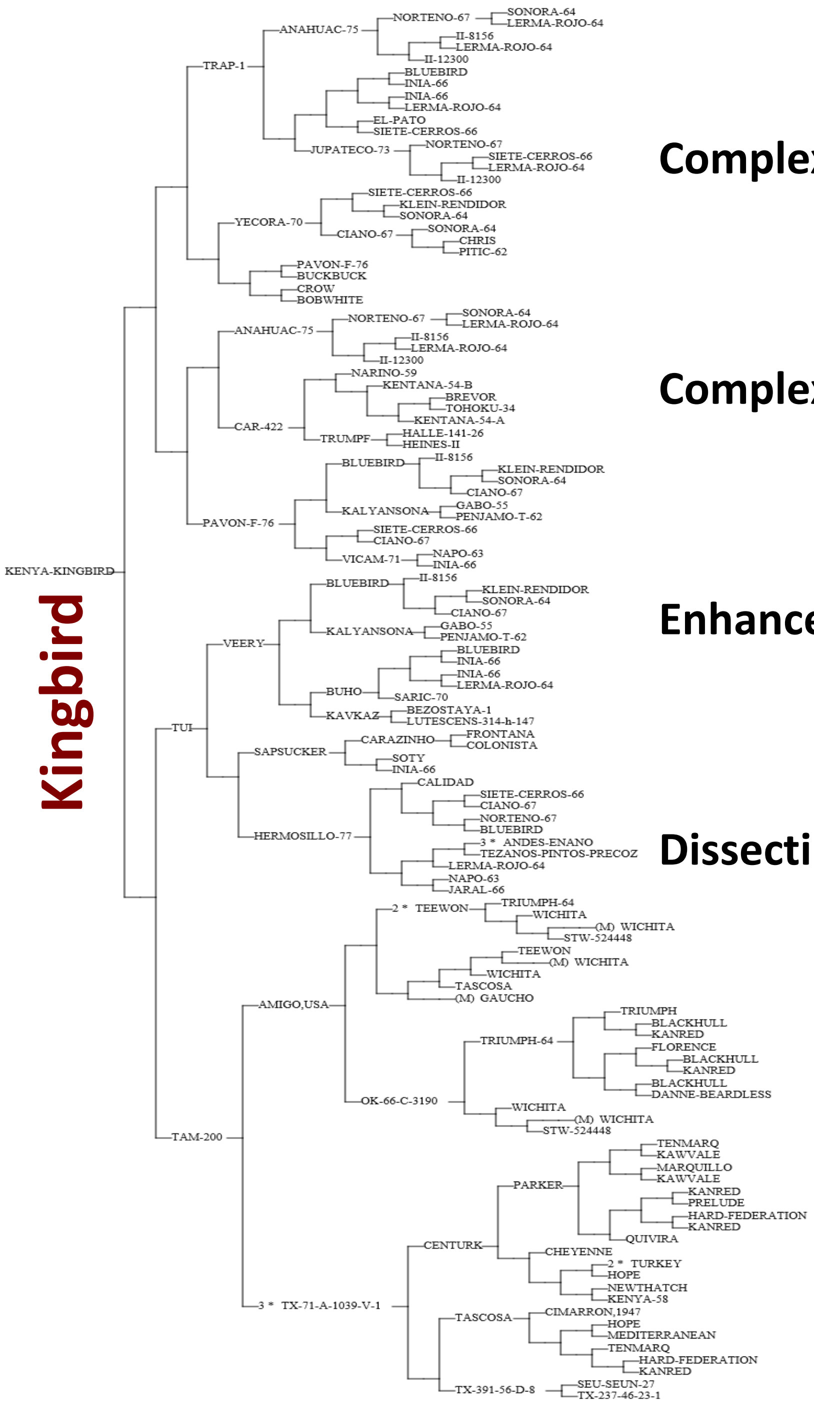
- **10-15%** lines with high levels of adult plant resistance
- **40-50%** lines with adequate adult plant resistance
- **20-30%** lines with at least 8 race-specific resistance genes (*Sr13a, Sr22, Sr25, Sr26, Sr50, SrND643, SrHuw234, SrNing*)
- **20-30%** lines with inadequate resistance

New lines with high yields and high levels of complex adult-plant resistance to stem rust (Njoro, Kenya 2021)

Sr2-Complex
(*Sr2* and other minor genes)

- *Sr2* transferred to wheat from ‘Yaroslav’ emmer in 1920s by McFadden
- Linked to pseudo-black chaff
- Confers only moderate levels of resistance (about 30% reduction in disease severity)



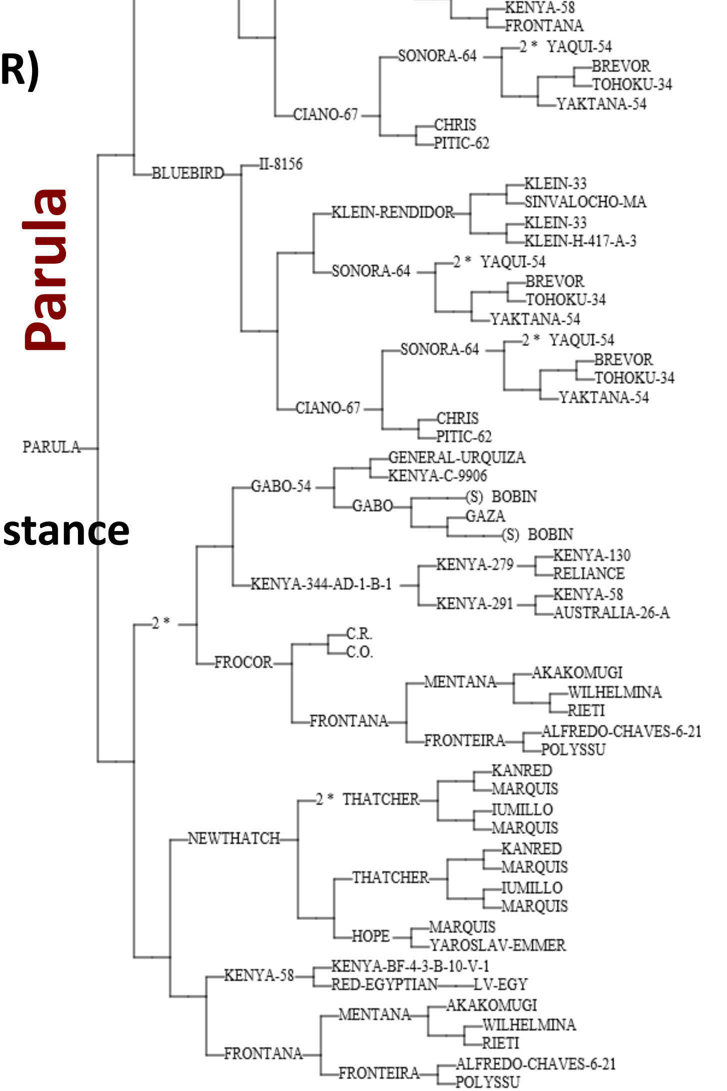


Complex pedigree

Complex resistance (APR)

Enhanced durability

Dissecting Complex resistance



Yr54 + slow rusting resistance genes for near-immune resistance to yellow rust

Introduced in CIMMYT breeding materials from a Kansas winter wheat germplasm carrying the *Ae. tauschii* gene *Lr42*

Mapping located the moderately effective APR gene *Yr54* on 2DS

Near-immune resistance achieved when *Yr54* combined with other slow rusting resistance genes, which is effective worldwide

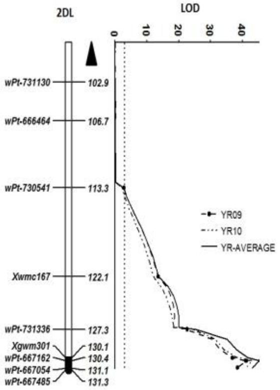
Varieties carrying *Yr54* released in Afghanistan, Ethiopia, India, Mexico, Kenya and Nigeria and resistance has remained effective

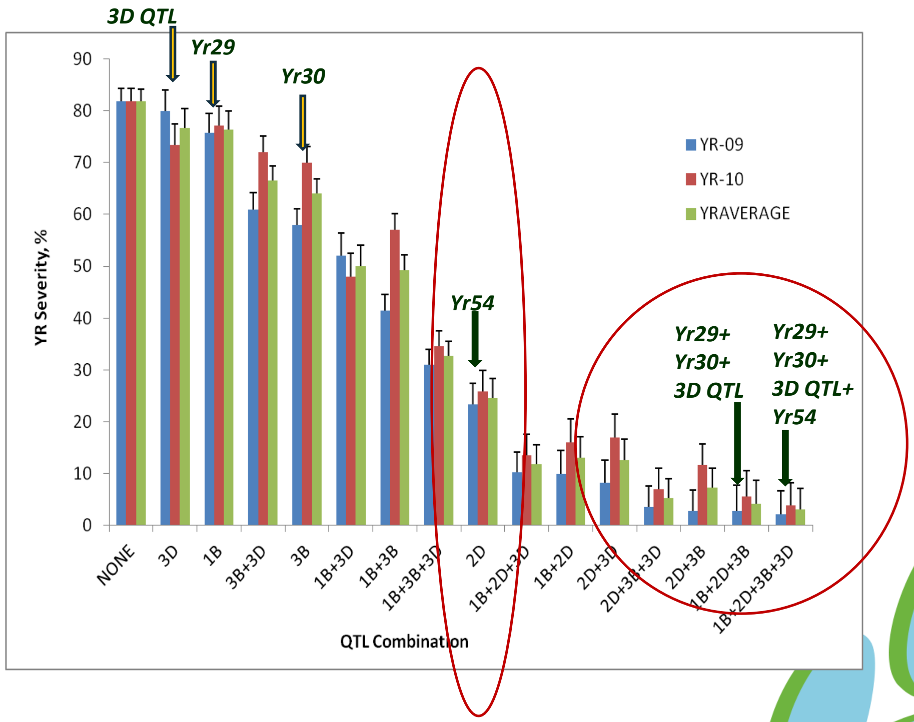
Mutants generated in Mexico & cloning underway in HZAU in C. Lan's Lab

Studies suggest *Yr54* may not belong to NBS-LRR gene family


Yr54


***Yr54* mutant**



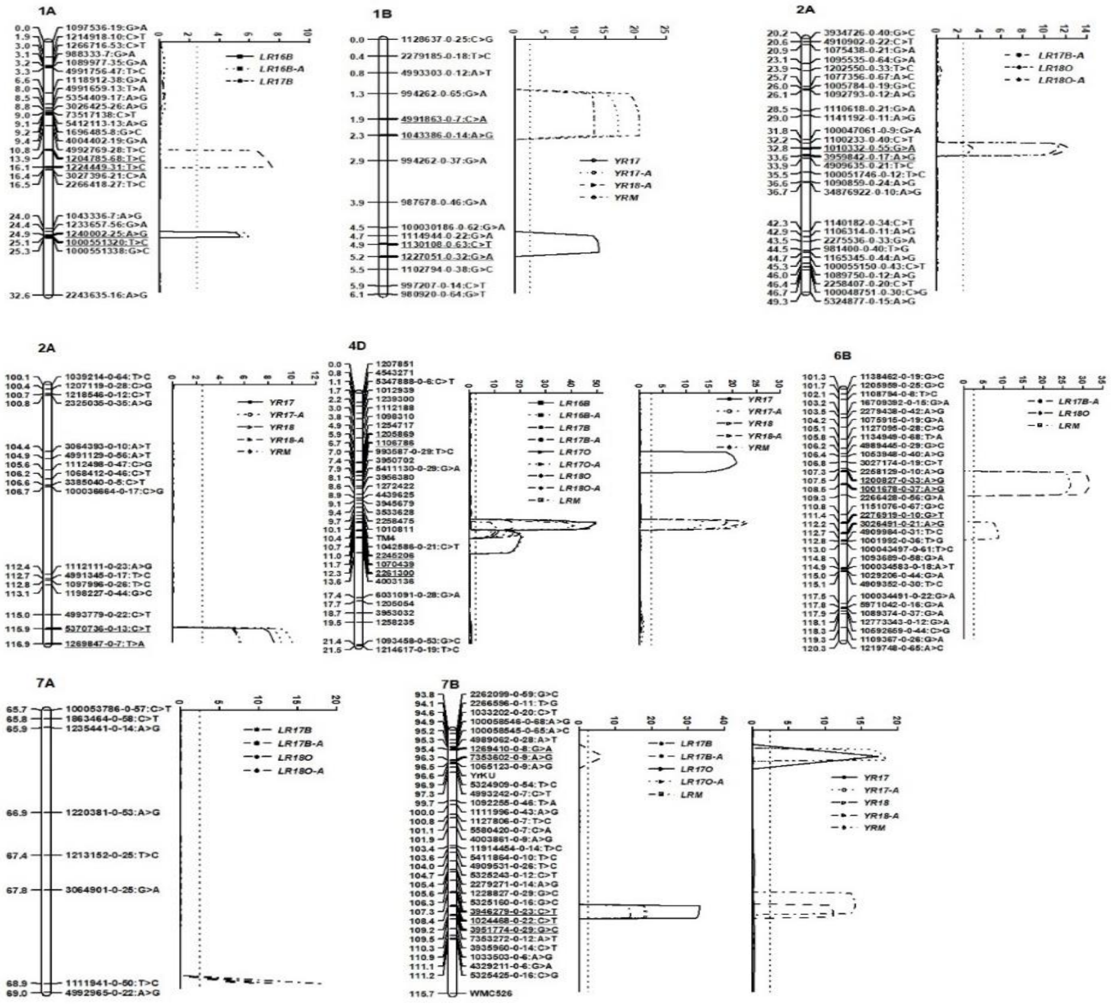


Yellow rust resistance of Avocet x Quaiu 3 RILs

Source: Basnet et al. Plant Dis. 2013

Mapping of leaf rust and stripe rust resistance in Afghanistan landrace “KU3067”

Bhavani et al. 2022

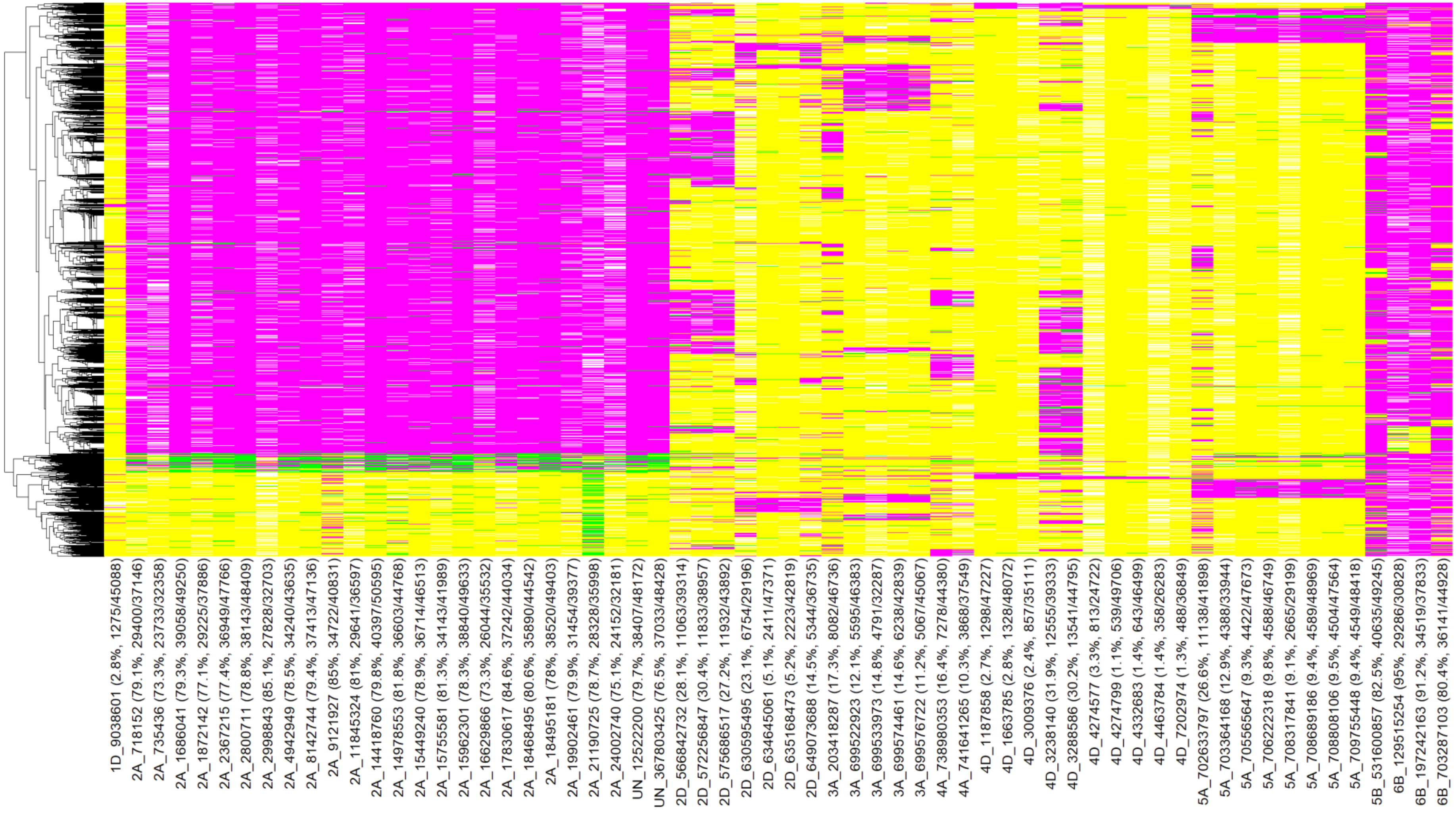


- **Six QTL for leaf rust** resistance on 1AS, 2AL, 4DL, 6BL, 7AL and 7BL
- **Four QTL for stripe rust** resistance on 1BS, 2AL, 4DL, and 7BL were detected.
- Pleiotropic gene **Lr67/Yr46**on 4DL with significantly large effect conferring resistance to both rusts.
- **QLr.cim-7BL/YrKU** showed pleiotropic resistance to both rusts and explained 7.5 - 17.2 % and 12.6 - 19.3% of the phenotypic variance for leaf and stripe rust, respectively (NOT Lr68) .
- **QYr.cim-1BS** and **QYr.cim-2AL** detected in all the stripe environments with PVE 12.9 - 20.5 % and 5.4 - 12.5%, respectively, might be new.
- **QLr.cim-6BL** region is likely to be new.

Line no.	**QTL combinations - Apav#1/ KU3067**	
	leaf rust	rust score
191	1A+Lr67+6B+7A+7B （No 2A)	5
210	1A+Lr67+6B+7A+7B （No 2A)	5
282	1A+Lr67+6B+7A+7B （No 2A)	10
	yellow rust	rust score
154	1B+2A+Lr67+7B	5
210	1B+2A+Lr67+7B	1
282	1B+2A+Lr67+7B	1

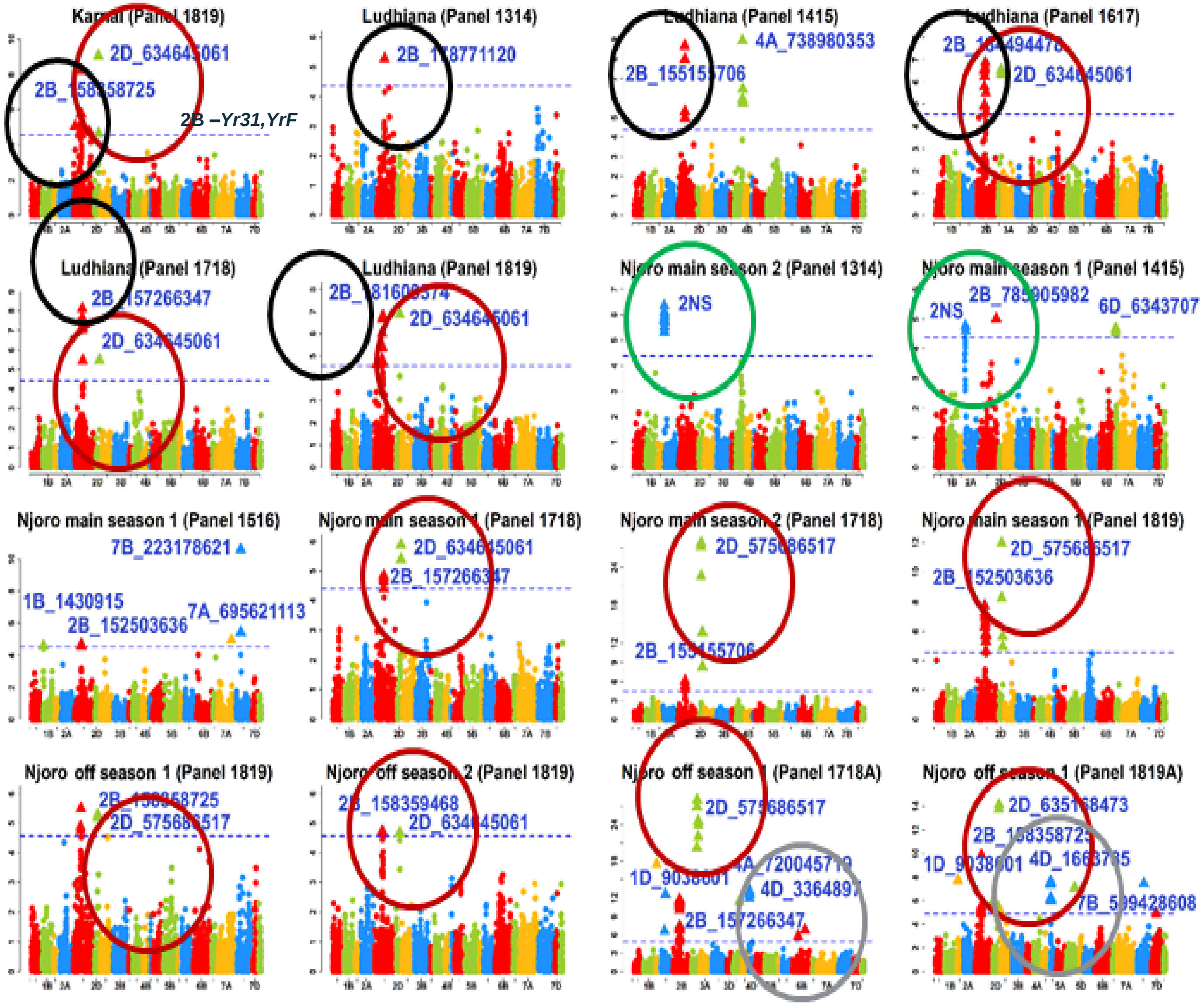
GRDC
Grains Research & Development Corporation

Allelic fingerprinting of stripe rust associated markers in 52,067 CIMMYT wheat lines for markers on chromosomes 1D, 2A, 2D, 3A, 4A, 4D, 5A, 5B and 6B



Juliana et al 2020

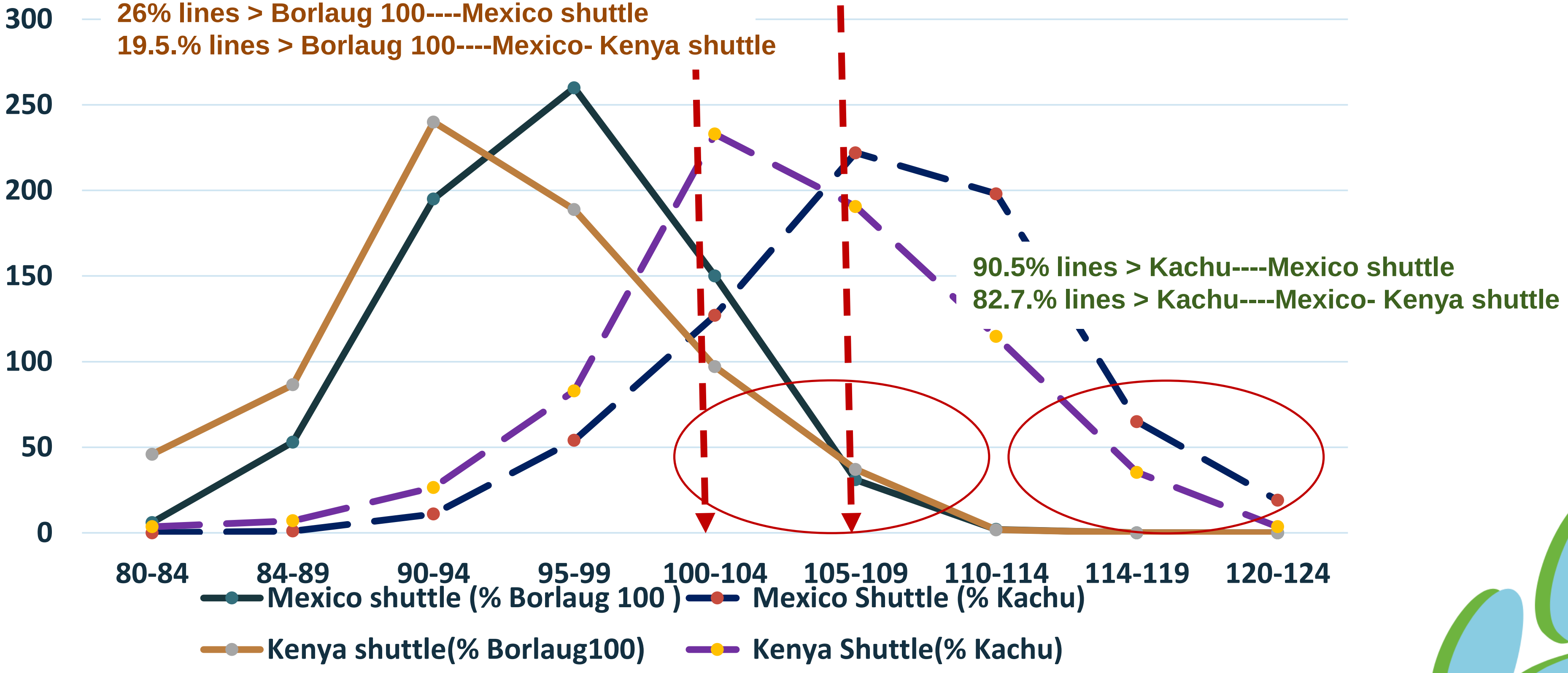
Genomic regions associated with stripe rust in India and Kenya



- *QYr.cim-2DL.2* on chromosome 2DL was associated with the highest number of datasets in India and Njoro and was 2.5 Mb away from the marker linked to the gene ***Yr54*** mapped from the CIMMYT spring wheat line QUAIU and it confers moderate resistance when present alone (Basnet, B. R. *et al.* (2014)).
- *QYr.cim-4DS.1* associated in the Njoro YT 1718 and 1819 was 0.42 Mbs away from marker *BS00108770_51* linked to gene ***Yr28*** that originated from synthetic wheat and confers moderate resistance

Juliana et al 2020

Comparison of grain yield performance of 697 EYT lines (Stage II) 2018-19 derived from Mexico Shuttle and Mexico Kenya Shuttle breeding schemes



26% lines > Borlaug 100----Mexico shuttle
19.5.% lines > Borlaug 100----Mexico- Kenya shuttle

90.5% lines > Kachu----Mexico shuttle
82.7.% lines > Kachu----Mexico- Kenya shuttle

APR based resistance works!!!

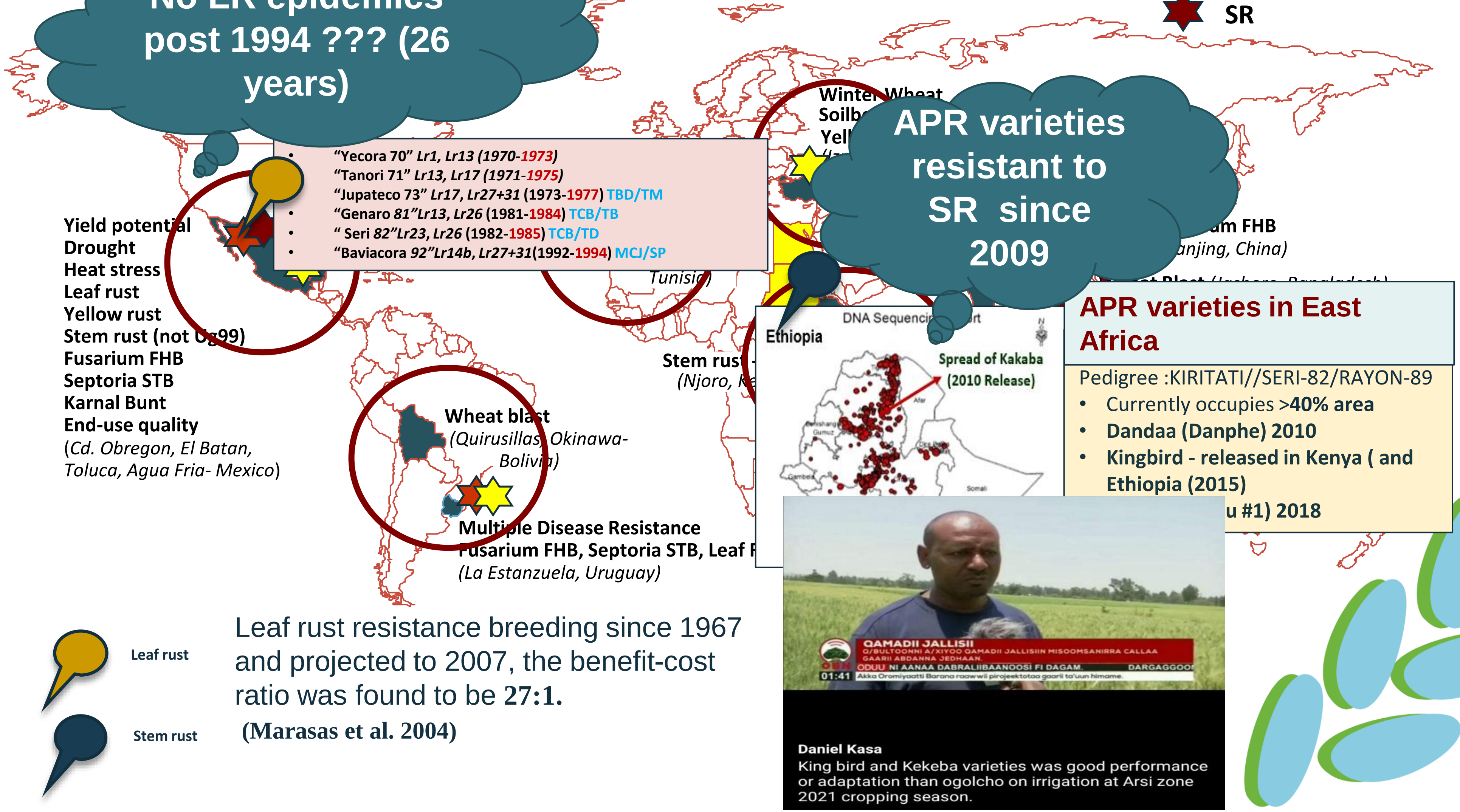
Reliable phenotyping is Key

International wheat phenotyping network & Disease phenotyping network

No LR epidemics post 1994 ??? (26 years)

- “Yecora 70” *Lr1, Lr13 (1970-1973)*
- “Tanori 71” *Lr13, Lr17 (1971-1975)*
- “Jupateco 73” *Lr17, Lr27+31* (1973-1977) TBD/TM
- “Genaro *81”Lr13, Lr26* (1981-1984) TCB/TB
- “ Seri *82”Lr23, Lr26* (1982-1985) TCB/TD
- “Baviacora *92”Lr14b, Lr27+31*(1992-1994) MCJ/SP

APR varieties resistant to SR since 2009



Daniel Kasa

King bird and Kekeba varieties was good performance or adaptation than ogolcho on irrigation at Arsi zone 2021 cropping season.

APR varieties in East Africa

Pedigree :KIRITATI//SERI-82/RAYON-89

- Currently occupies >**40% area**
- **Dandaa (Danphe) 2010**
- **Kingbird - released in Kenya (and Ethiopia (2015)**
- **u #1) 2018**

Leaf rust

Stem rust

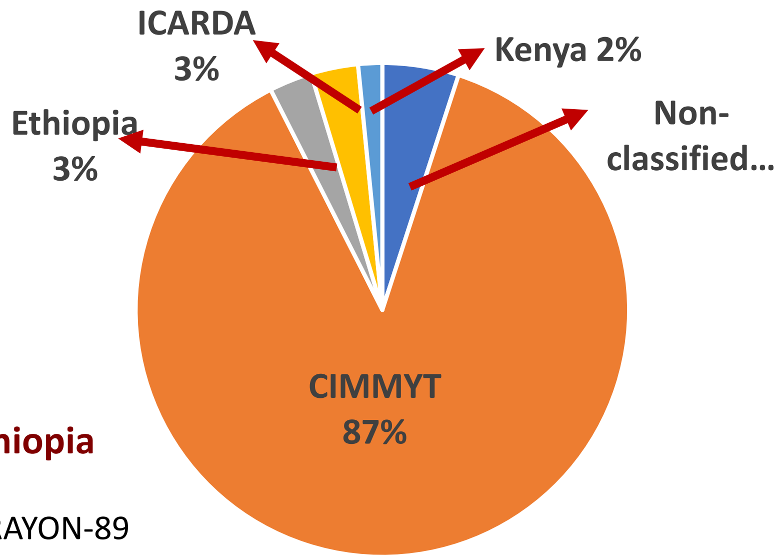
Leaf rust resistance breeding since 1967 and projected to 2007, the benefit-cost ratio was found to be **27:1.**

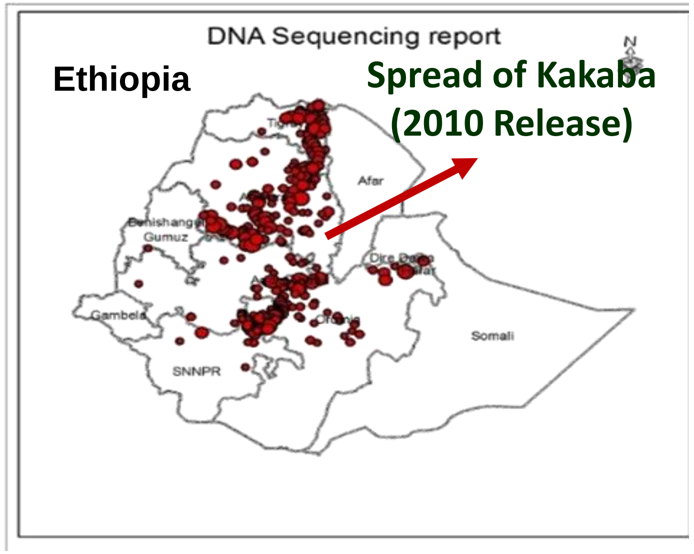
(Marasas et al. 2004)

Ethiopia: wheat Impact studies using DNA Fingerprinting

Ethiopia

- 89% of samples from all provinces CIMMYT derived varieties
- 55% of sampled households growing rust resistant varieties
- 45% of samples varieties released in last 10 years




DNA Sequencing report

Ethiopia

Spread of Kakaba (2010 Release)

APR based varieties in Ethiopia

Kakaba (Picaflor) 2010

Pedigree :KIRITATI//SERI-82/RAYON-89

Currently occupies >40% area

Dandaa (Danphe) 2010

Pedigree : KIRITATI//2*PBW-65/2*SERI-82

Kingbird 2015

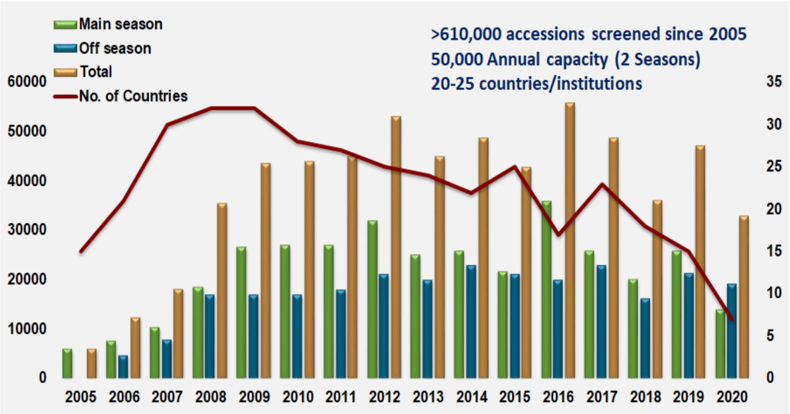
Pedigree : TAM-200/TUI/6/PAVON-76//CAR-422/ANAHUAC-75/5/BOBWHITE /CROW//BUCKBUCK/PAVON-76/3/YECORA-70/4/TRAP-1

Deka (Arableu #1) 2018

Pedigree Attila/3*Bacanora*2//Baviacora92/3/Kiritati/Weebil#1/4/Danphe

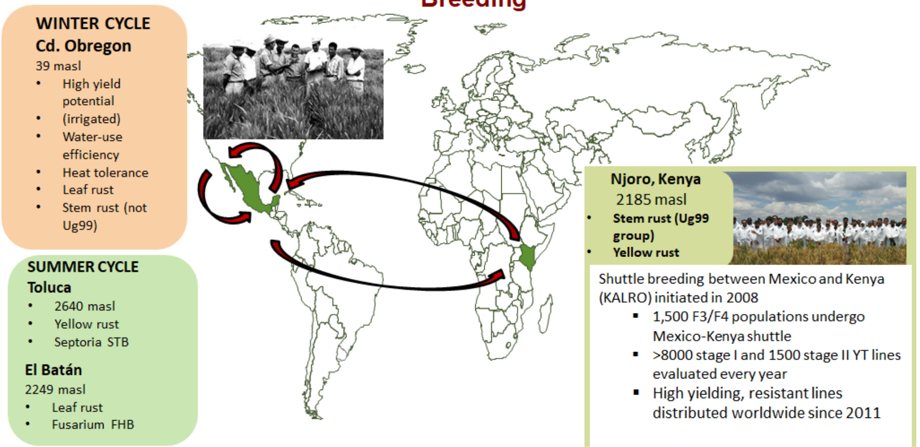
Mitigating the threat of stem rust: PP in Kenya and Ethiopia

Wheat accessions phenotyped during 2005-2020 for Ug99 resistance at Njoro (Kenya) and participating countries, in partnership with KALRO



>610,000 accessions screened since 2005
50,000 Annual capacity (2 Seasons)
20-25 countries/institutions

Mexico (Cd. Obregon-Toluca/El Batan)- Kenya International Shuttle Breeding



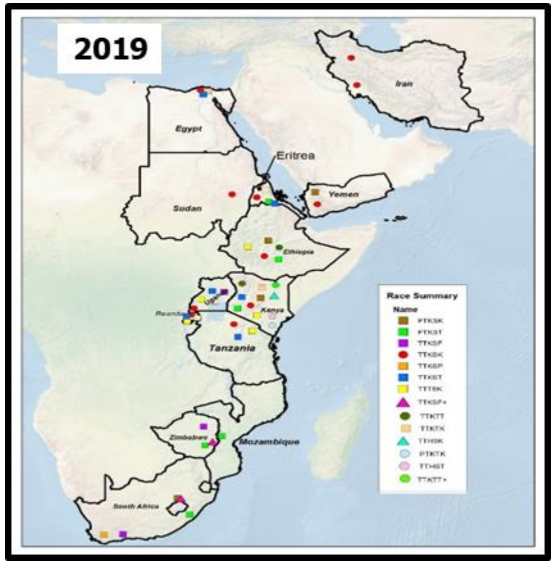
WINTER CYCLE
Cd. Obregon
39 masl
- High yield potential
- (irrigated)
- Water-use efficiency
- Heat tolerance
- Leaf rust
- Stem rust (not Ug99)

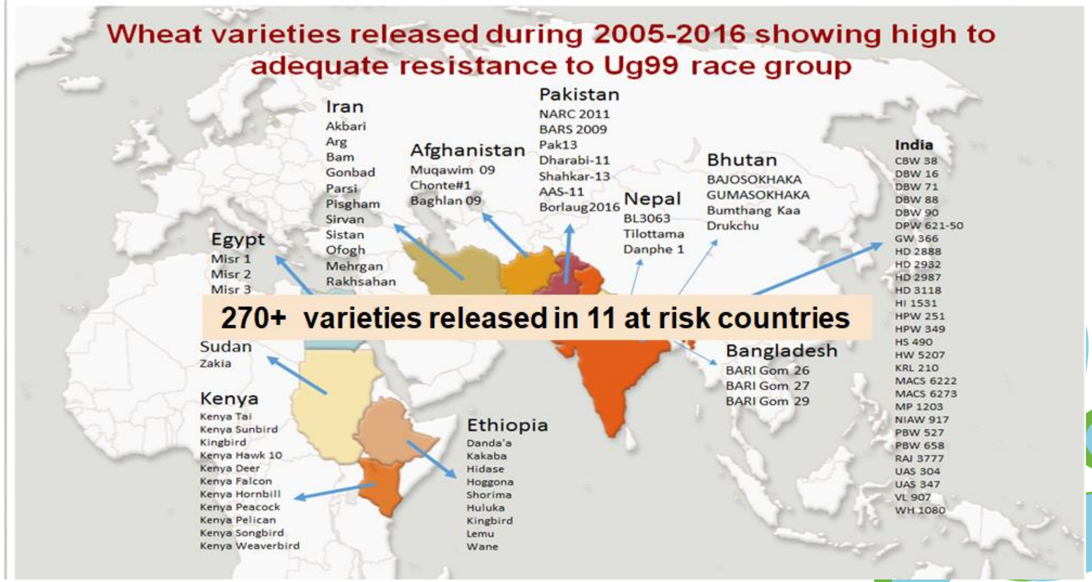
SUMMER CYCLE
Toluca
- 2640 masl
- Yellow rust
- Septoria STB

El Batán
2249 masl
- Leaf rust
- Fusarium FHB

Njoro, Kenya
2185 masl
- **Stem rust (Ug99 group)**
- **Yellow rust**

Shuttle breeding between Mexico and Kenya (KALRO) initiated in 2008
- 1,500 F3/F4 populations undergo Mexico-Kenya shuttle
- >8000 stage I and 1500 stage II YT lines evaluated every year
- High yielding, resistant lines distributed worldwide since 2011





Wheat varieties released during 2005-2016 showing high to adequate resistance to Ug99 race group

270+ varieties released in 11 at risk countries

Iran
Akbari
Arg
Bam
Gonbad
Parsi
Pisgham
Sirvan
Sistan
Ofogh
Mehrgan
Rakhsahan

Afghanistan
Muqawim 09
Chonte#1
Baghlan 09

Pakistan
NARC 2011
BARS 2009
Pak13
Dharabi-11
Shahkar-13
AAS-11
Borlaug2016

Nepal
BL3063
Tilottama
Danphe 1

Bhutan
BAJOSOKHAKA
GUMASOKHAKA
Bumthang Kaa
Drukchu

India
CBW 38
DBW 16
DBW 71
DBW 88
DBW 90
DPW 621-50
GW 366
HD 2888
HD 2932
HD 2987
HD 3118
HI 1531
HPW 251
HPW 349
HS 490
HW 5207
KRL 210
MACS 6222
MACS 6273
MP 1203
NIAW 917
PBW 527
PBW 658
RAJ 3777
UAS 304
UAS 347
VL 907
WH 1080

Egypt
Misr 1
Misr 2
Misr 3

Sudan
Zakia

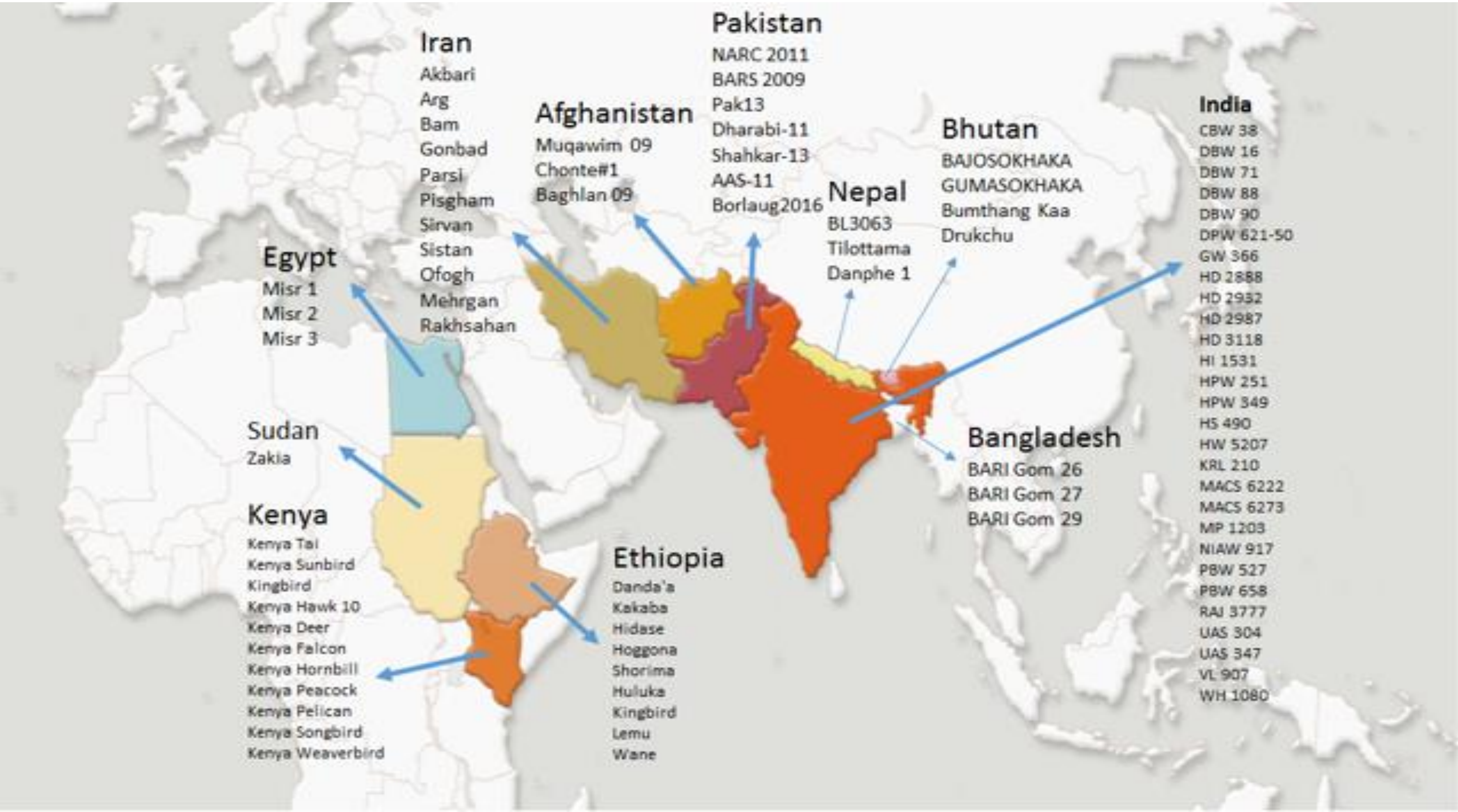
Kenya
Kenya Tai
Kenya Sunbird
Kingbird
Kenya Hawk 10
Kenya Deer
Kenya Falcon
Kenya Hornbill
Kenya Peacock
Kenya Pelican
Kenya Songbird
Kenya Weaverbird

Ethiopia
Danda'a
Kakaba
Hidase
Hoggona
Shorima
Huluka
Kingbird
Lemu
Wane

Bangladesh
BARI Gom 26
BARI Gom 27
BARI Gom 29

Rapid response to “UG99 “ threat

Some rust resistant wheat varieties released



Iran
Akbari
Arg
Bam
Gonbad
Parsi
Pisgham
Sirvan
Sistan
Ofogh
Mehrgan
Rakhsahan

Afghanistan
Muqawim 09
Chonte#1
Baghlan 09

Pakistan
NARC 2011
BARS 2009
Pak13
Dharabi-11
Shahkar-13
AAS-11
Borlaug2016

Nepal
BL3063
Tilottama
Danphe 1

Bhutan
BAJOSOKHAKA
GUMASOKHAKA
Bumthang Kaa
Drukchu

India
CBW 38
DBW 16
DBW 71
DBW 88
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DPW 621-50
GW 366
HD 2888
HD 2932
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HI 1531
HPW 251
HPW 349
HS 490
HW 5207
KRL 210
MACS 6222
MACS 6273
MP 1203
NIAW 917
PBW 527
PBW 658
RAJ 3777
UAS 304
UAS 347
VL 907
WH 1080

Egypt
Misr 1
Misr 2
Misr 3

Sudan
Zakia

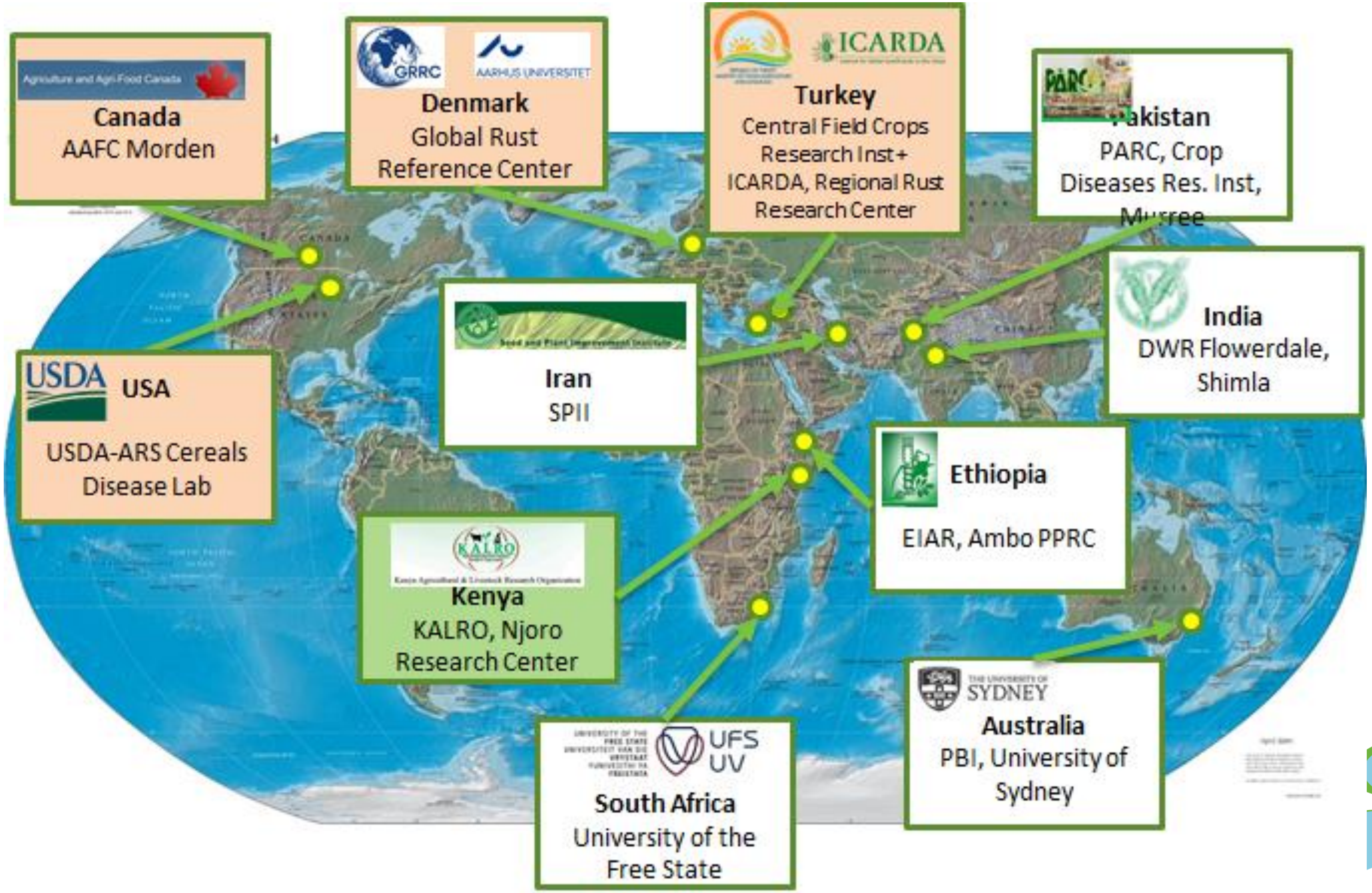
Kenya
Kenya Tai
Kenya Sunbird
Kingbird
Kenya Hawk 10
Kenya Deer
Kenya Falcon
Kenya Hornbill
Kenya Peacock
Kenya Pelican
Kenya Songbird
Kenya Weaverbird

Ethiopia
Danda'a
Kakaba
Hidase
Hoggona
Shorima
Huluka
Kingbird
Lemu
Wane

Bangladesh
BARI Gom 26
BARI Gom 27
BARI Gom 29

140+ wheat varieties with improved agronomic traits, climate resilience and disease resistance have been released and adopted by the BGRI in 11 at-risk countries in the past 10 years.

Rust Pathotyping Lab Network



Canada
AAFC Morden

Denmark
Global Rust
Reference Center

Turkey
Central Field Crops
Research Inst+
ICARDA, Regional Rust
Research Center

Pakistan
PARC, Crop
Diseases Res. Inst,
Murree

USA
USDA-ARS Cereals
Disease Lab

Iran
SPII

India
DWR Flowerdale,
Shimla

Ethiopia
EIAR, Ambo PPRC

Kenya
KALRO, Njoro
Research Center

South Africa
University of the
Free State

Australia
PBI, University of
Sydney

Enhancing the current genetic diversity in breeding materials

Incorporation of new SR, YR and PAPR genes through 'Marker Assisted Backcrossing' in

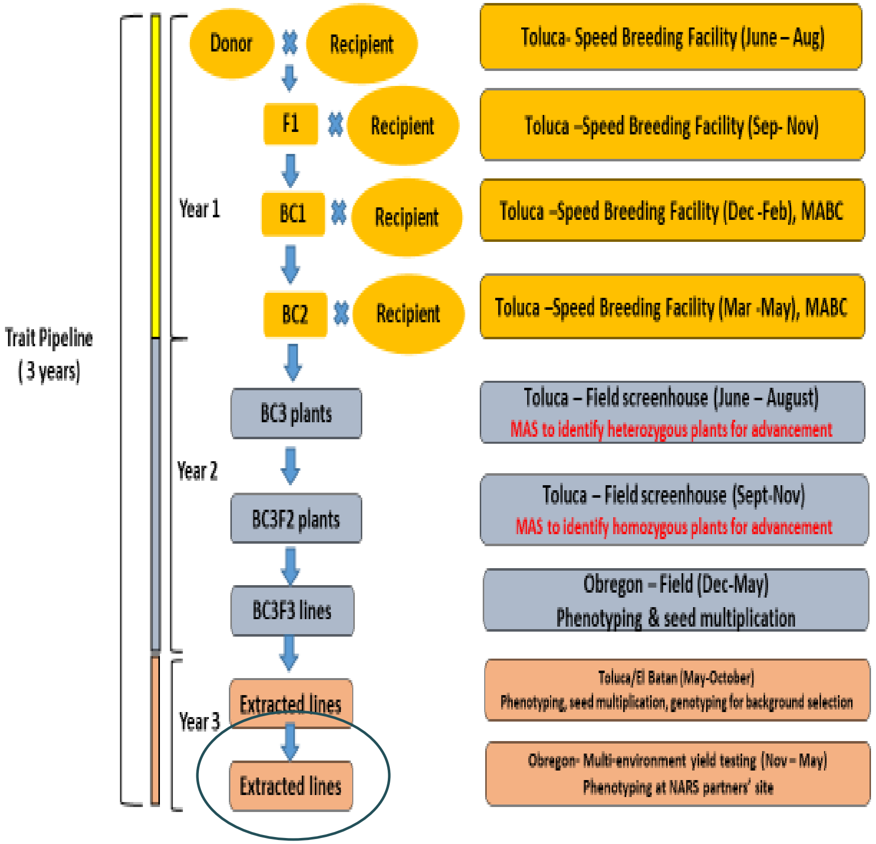
Trait pipeline

Pleiotropic APR
Lr67/Yr46/Sr55/Pm46
Lr67/Yr46/Sr55/Pm46 +YrSuj-7BL

H-S A/2*MUNAL #1	Sr2 + Fhb1
SWSR22T.B.	Sr22
KACHU/3/WHEAR//2*PRL/2*PASTOR	Sr25
SHORT SR26 TRANS./4/3*CHIBIA/…	Sr26
SR32	Sr32
W3763-SR35	Sr35
SR47	Sr47
SR50	Sr50

ALPOWA	Yr39
CHUAN NONG 19	Yr41
BLANCA GRANDE 515	Yr5 + Yr15
SUMMIT 515	Yr5 + Yr15
YR51#5515-1	Yr51
KOELZ W 11192:AE	Yr52
YR57#5474-6	Yr57
IRAGI	Yr59
LALBMONO1*4/PVN	Yr60

Trait integration pipeline for Rust resistance



Trait Pipeline
(3 years)

Year 1

Donor ✖ Recipient — Toluca- Speed Breeding Facility (June – Aug)

F1 ✖ Recipient — Toluca –Speed Breeding Facility (Sep- Nov)

BC1 ✖ Recipient — Toluca –Speed Breeding Facility (Dec -Feb), MABC

BC2 ✖ Recipient — Toluca –Speed Breeding Facility (Mar -May), MABC

Year 2

BC3 plants — Toluca – Field screenhouse (June – August)
MAS to identify heterozygous plants for advancement

BC3F2 plants — Toluca – Field screenhouse (Sept-Nov)
MAS to identify homozygous plants for advancement

BC3F3 lines — Obregon – Field (Dec-May)
Phenotyping & seed multiplication

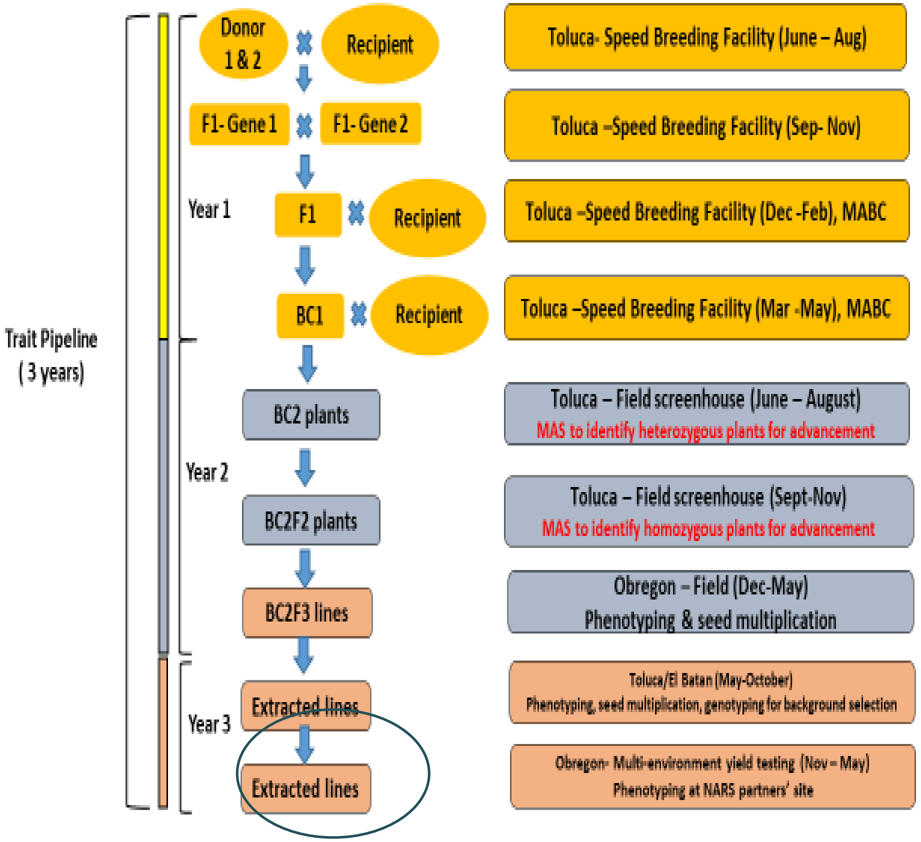
Year 3

Extracted lines — Toluca/El Batan (May-October)
Phenotyping, seed multiplication, genotyping for background selection

Extracted lines — Obregon- Multi-environment yield testing (Nov – May)
Phenotyping at NARS partners' site

Trait integration pipeline for incorporating single R-gene

Needs continuous trait discovery for deployment



Trait Pipeline
(3 years)

Year 1

Donor 1 & 2 ✖ Recipient — Toluca- Speed Breeding Facility (June – Aug)

F1- Gene 1 ✖ F1- Gene 2 — Toluca –Speed Breeding Facility (Sep- Nov)

F1 ✖ Recipient — Toluca –Speed Breeding Facility (Dec -Feb), MABC

BC1 ✖ Recipient — Toluca –Speed Breeding Facility (Mar -May), MABC

Year 2

BC2 plants — Toluca – Field screenhouse (June – August)
MAS to identify heterozygous plants for advancement

BC2F2 plants — Toluca – Field screenhouse (Sept-Nov)
MAS to identify homozygous plants for advancement

BC2F3 lines — Obregon – Field (Dec-May)
Phenotyping & seed multiplication

Year 3

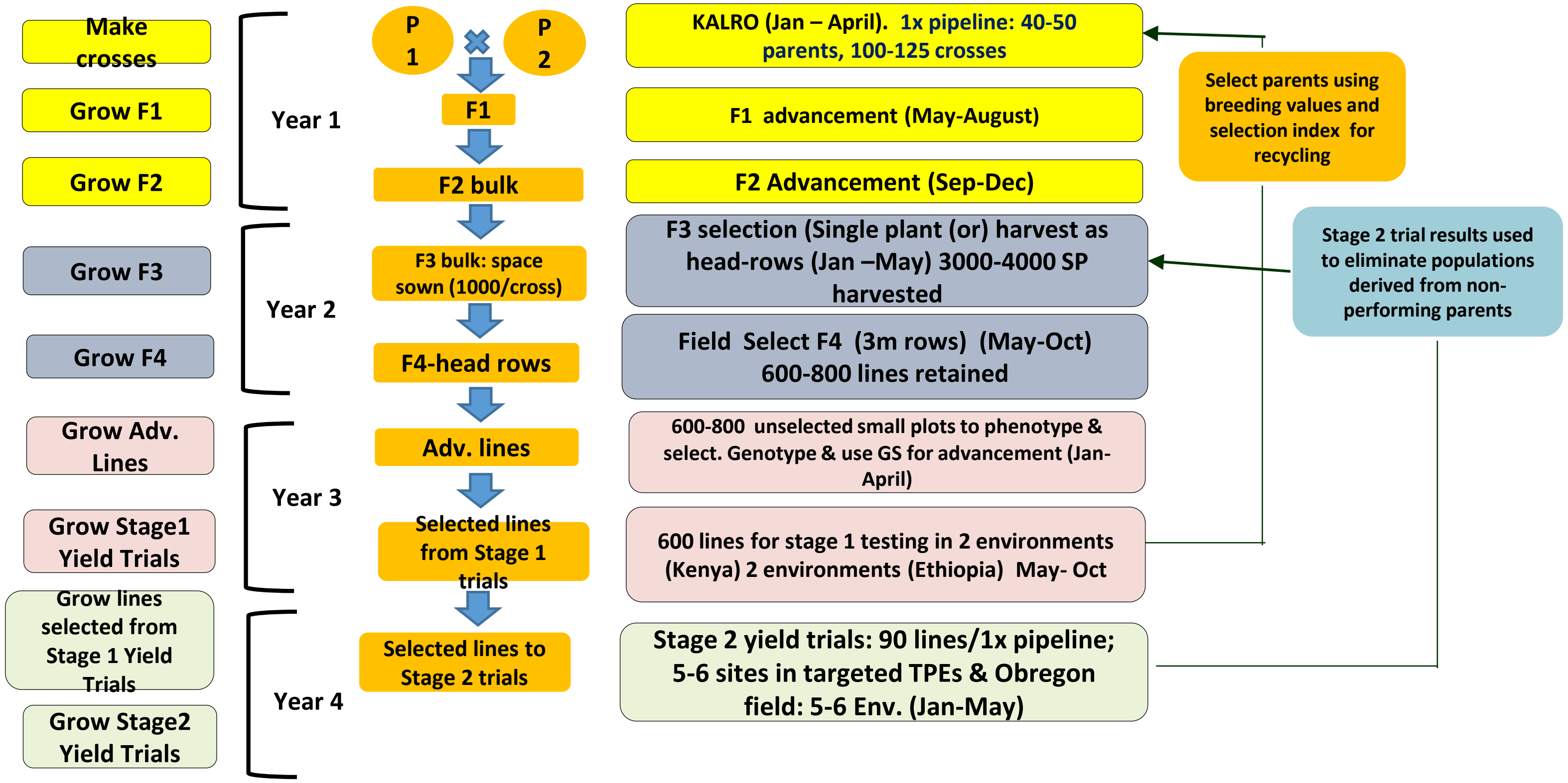
Extracted lines — Toluca/El Batan (May-October)
Phenotyping, seed multiplication, genotyping for background selection

Extracted lines — Obregon- Multi-environment yield testing (Nov – May)
Phenotyping at NARS partners' site

Trait integration pipeline for incorporating two R-genes

Integrating 2 or more genes usually associated with lower yields- linkage drag from alien origin

RBGA Scheme: 3 years breeding cycle- East African breeding pipeline



Year 1

- Make crosses — P 1 × P 2 — KALRO (Jan – April). 1x pipeline: 40-50 parents, 100-125 crosses
- Grow F1 — F1 — F1 advancement (May-August)
- Grow F2 — F2 bulk — F2 Advancement (Sep-Dec)

Year 2

- Grow F3 — F3 bulk: space sown (1000/cross) — F3 selection (Single plant (or) harvest as head-rows (Jan –May) 3000-4000 SP harvested
- Grow F4 — F4-head rows — Field Select F4 (3m rows) (May-Oct) 600-800 lines retained

Year 3

- Grow Adv. Lines — Adv. lines — 600-800 unselected small plots to phenotype & select. Genotype & use GS for advancement (Jan-April)
- Grow Stage1 Yield Trials — Selected lines from Stage 1 trials — 600 lines for stage 1 testing in 2 environments (Kenya) 2 environments (Ethiopia) May- Oct

Year 4

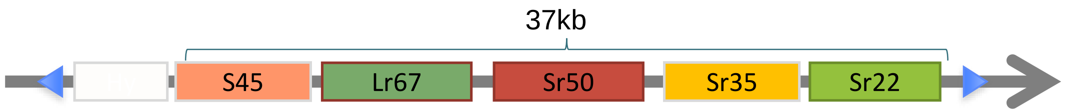
- Grow lines selected from Stage 1 Yield Trials — Selected lines to Stage 2 trials — Stage 2 yield trials: 90 lines/1x pipeline; 5-6 sites in targeted TPEs & Obregon field: 5-6 Env. (Jan-May)
- Grow Stage2 Yield Trials

Select parents using breeding values and selection index for recycling

Stage 2 trial results used to eliminate populations derived from non-performing parents

We can try out possibility of three cycles a year if that can be achieved as a small experiment in 2022 in parallel with a few croses

The “Big 5” Multi-Gene Cassette



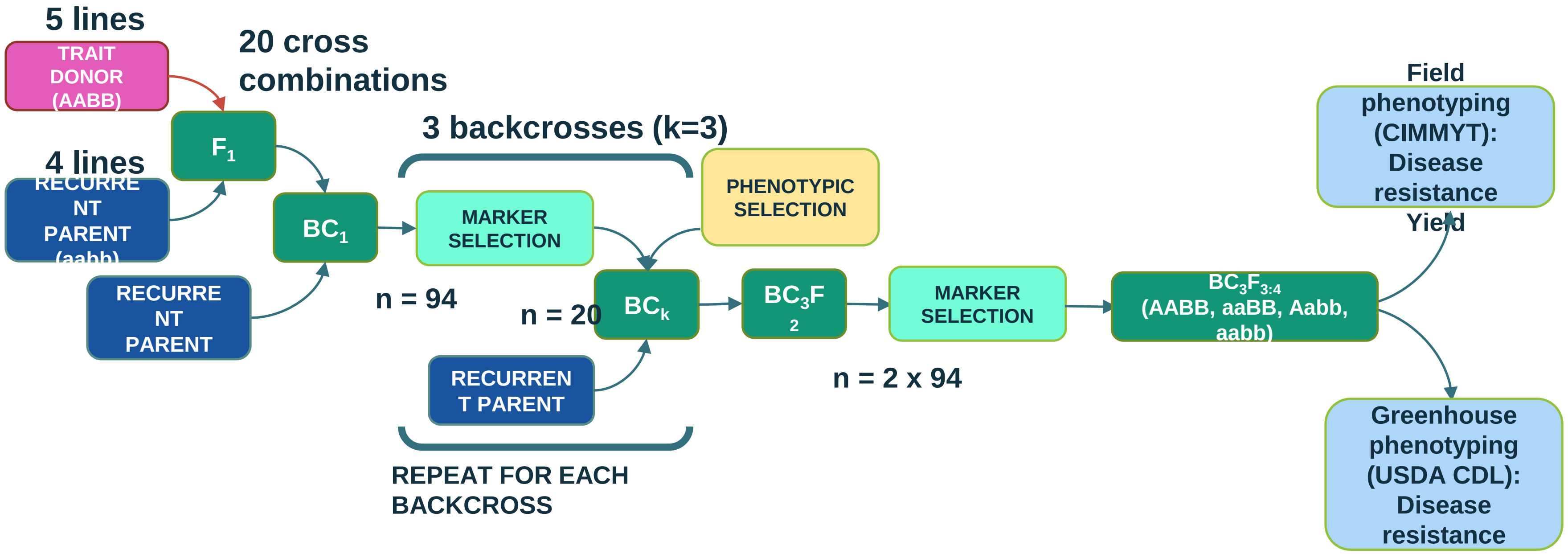
- ***Sr45* from *Aegilops tauschii***
- ***Lr67* (*Sr55*) from *Triticum aestivum***
- ***Sr50* from *Secale cereale***
- ***Sr35* from *Triticum monococcum***
- ***Sr22* from *Triticum boeoticum***

Multi-gene cassettes increase durability of resistance and segregate as a single locus simplifying breeding

Caution

Sicily race (TTRTF) had confimed virulence for 23 *Sr* genes (IT 3 or higher)
Sr5, *Sr6*, *Sr7a*, *Sr7b*, *Sr8a*, *Sr9a*, *Sr9b*, *Sr9d*, *Sr9e*, *Sr9g*, *Sr10*, *Sr11*, *Sr13b*, *Sr17*, *Sr21*, *Sr35*, *Sr36*, *Sr37*, *Sr38*, *Sr44*, *Sr45*, *SrTmp*, and *SrMcN*.
Sr50 Big “S” pustules observed on lines carrying *Sr50* in Kenya in 2019 *Ug99+Sr50* virulence ???
***Sr22* –** Virulence in Georgia, Egypt (2017 TKPTF), Kazakhstan, Germany (TKTTF)

CIMMYT introgression pipeline of Interactor/Enhancer loci



5 lines

TRAIT DONOR (AABB)

20 cross combinations

F_1

4 lines

RECURRENT PARENT (aabb)

BC_1

RECURRENT PARENT

3 backcrosses (k=3)

MARKER SELECTION

PHENOTYPIC SELECTION

n = 94

n = 20

BC_k

RECURRENT PARENT

REPEAT FOR EACH BACKCROSS

BC_3F_2

MARKER SELECTION

n = 2 x 94

$BC_3F_{3:4}$ (AABB, aaBB, Aabb, aabb)

Field phenotyping (CIMMYT): Disease resistance Yield

Greenhouse phenotyping (USDA CDL): Disease resistance

Collaboration with KSU, CDL and CIMMYT

YR- GRRC-Denmark, Izmir, India

Projects

Breeding

- AGG
- Zn Mainstreaming

Rust research

- GRDC-CSIRO Delivering genetic tools and knowledge required to breed wheat and barley with
- resistance to leaf rust, stripe rust and stem rust- Gene discovery and characterization -Evans

- GRDC-Univ. of Sydney Australian Cereal Rust Control Program:
- Delivering genetic tools and knowledge required to breed wheat and barley with
- resistance to leaf rust, stripe rust and stem rust

- CRP-WHEAT – Support rust research

- NMBU- Norway- Sustainable management of rust diseases in wheat

- Kansas State- New Sources of Genetic Disease Resistance through Host-Pathogen Mapping

- USAID- Resistance to rust diseases

- USDA – Phenotyping platforms Kenya and Ethiopia
- AAFC – Phenotyping platform Kenya

Conclusions and future outlook

- Rusts continue to remain the most important diseases for CIMMYT target environments.
- Resistance durability can be achieved deploying new varieties that possess complex adult plant resistance.
- Cloning will facilitate better understanding of resistance mechanisms, and gene based markers can enhance MAS, maintain genetic diversity
- Field phenotyping and selection are essential to make genetic and breeding progress.
- "Gene Cassettes" with 7 genes stacks available
- Area grown to susceptible varieties must be reduced for a better control of rust diseases.

"Rust Never Sleeps"

Dr. Norman Borlaug

Acknowledgements

BMGF & DFID/FCDO-UK through:
AGG project
DGGW project
HarvestPlus project
Zn Mainstreaming project

Governments:
ACIAR, Australia
BMZ, Germany
FFAR, USA
ICAR, India
USAID, USA

Farmers' organizations:
Agrovegetal, Spain
GRDC, Australia
Patronato-Sonora, Mexico

Thank you

The CGIAR Research Program WHEAT receives W1&W2
support from the Governments of Australia, Belgium, Canada, China, France, India, Japan, Korea, Netherlands, New Zealand, Norway, Sweden, Switzerland, U.K., U.S., and the World Bank.

Accelerating Genetic Gains
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Thank you

CGIAR

CIMMYT
International Maize and Wheat Improvement Center

Cornell University

BGRI
Borlaug Global Rust Initiative