Rust research to enhance resistance durability

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CIMMYT

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

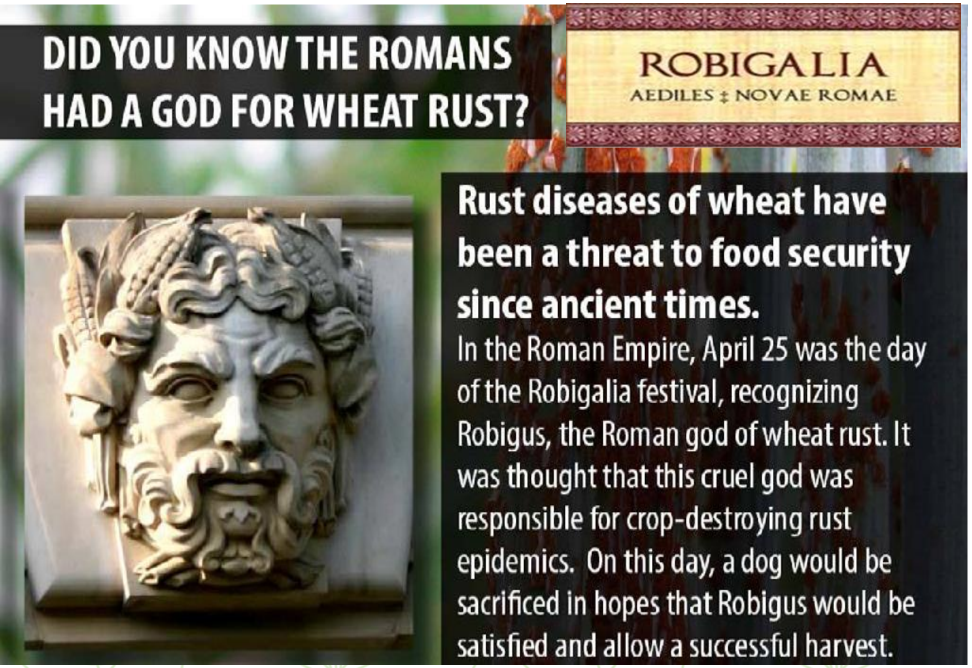
Rust menace- continuous fight with an old enemy

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



- 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.

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

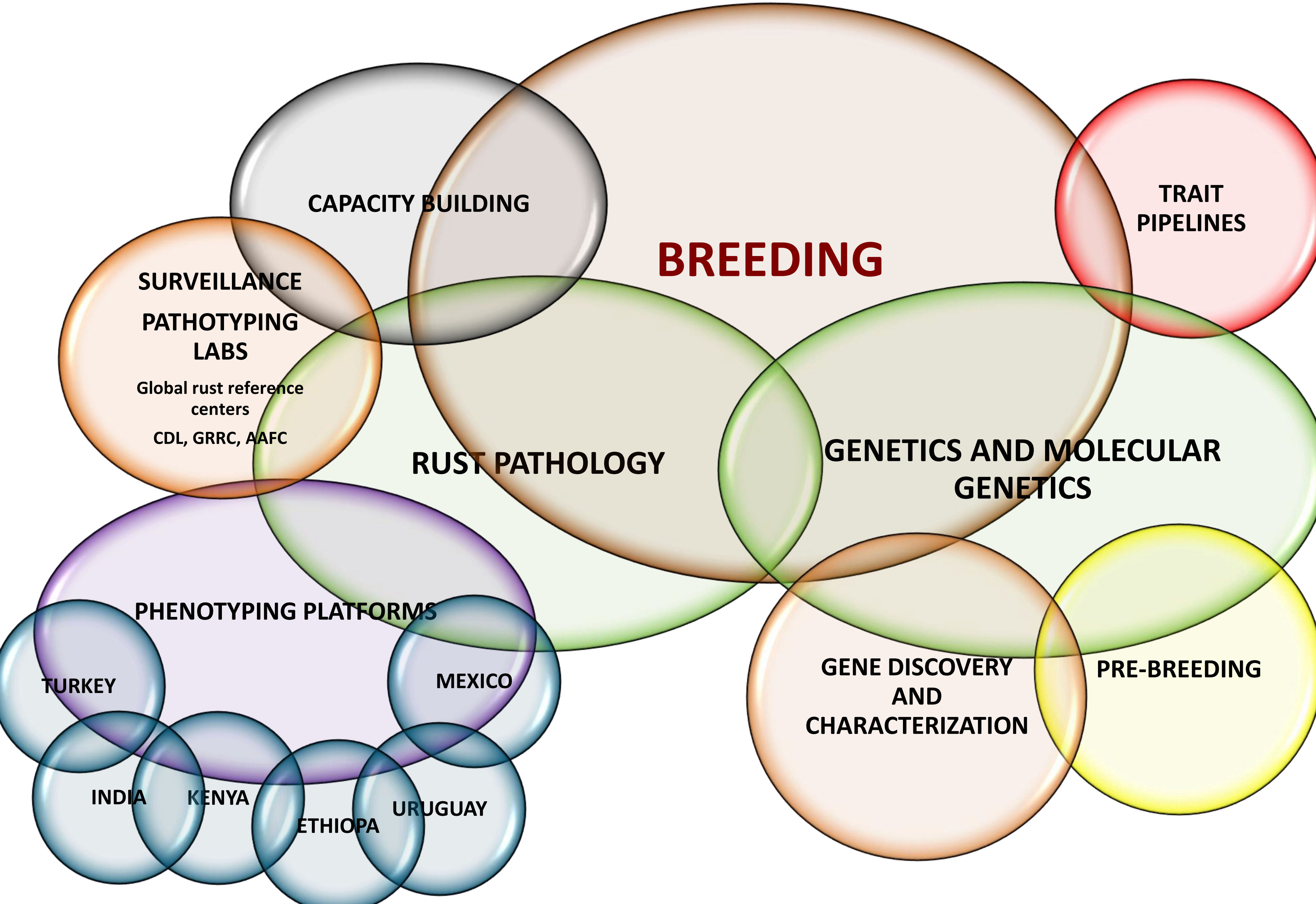
- Coordinate rust phenotyping platforms ensuring reliable phenotypic data from hot spot environments with maximum pathogen diversity-

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

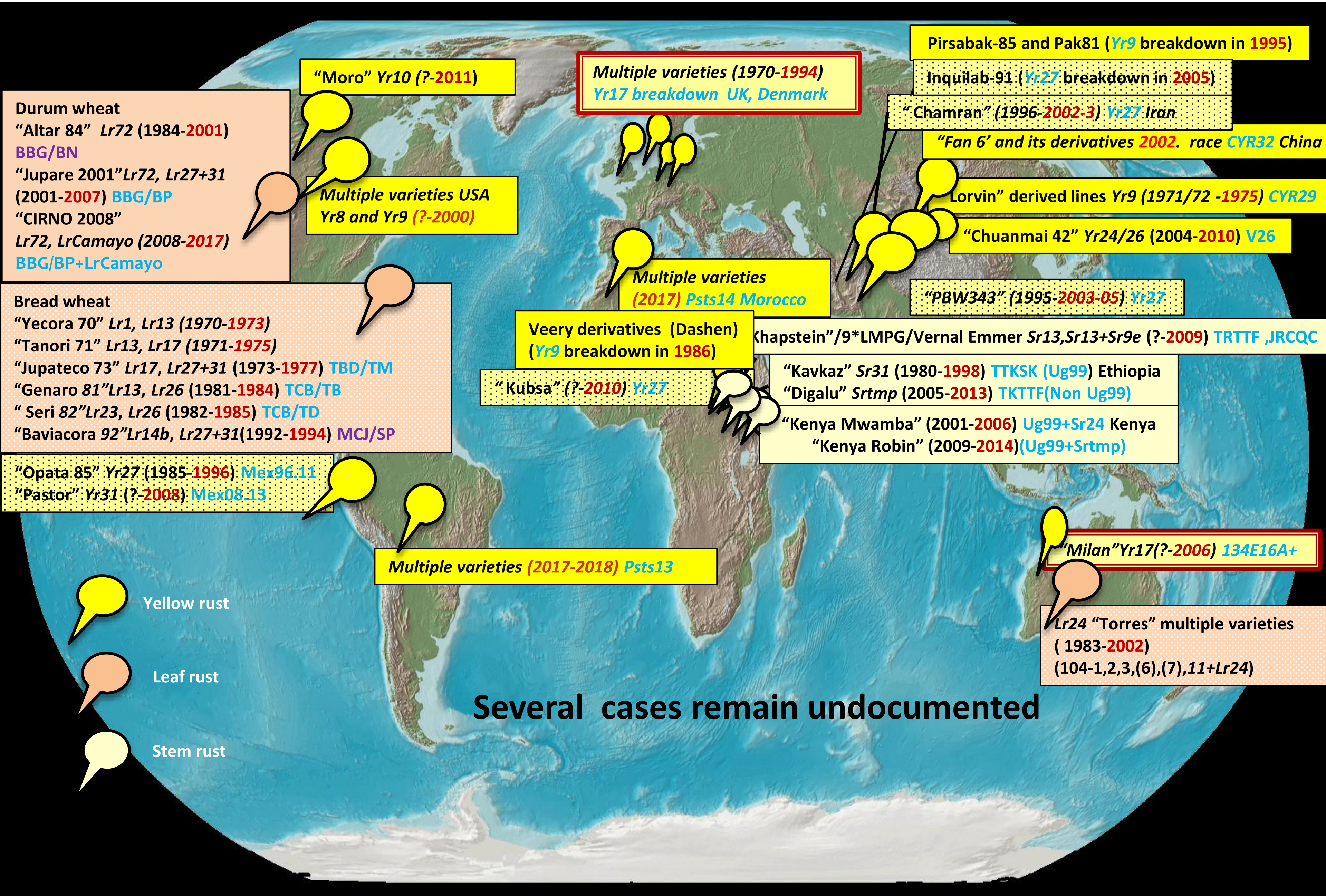
- Improved survey and surveillance in partnership with global rust reference centers (CDL, GRRC, RRC) understanding virulence diversity and R gene deployment strategies

CIMMYT[MR]

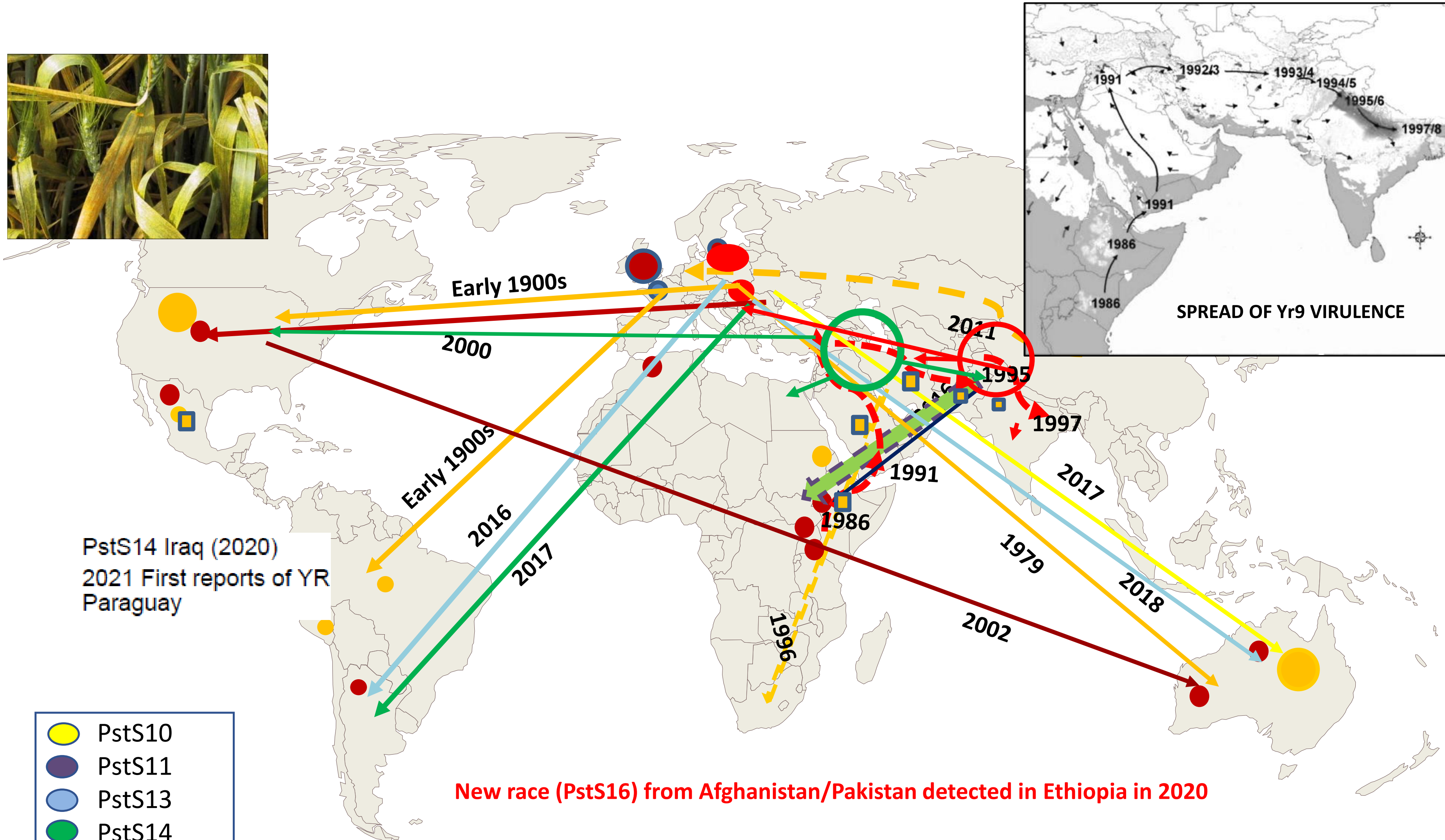
RUST RESEARCH –BW, DW, Physiology



Breakdown of “race specific genes”: some examples



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

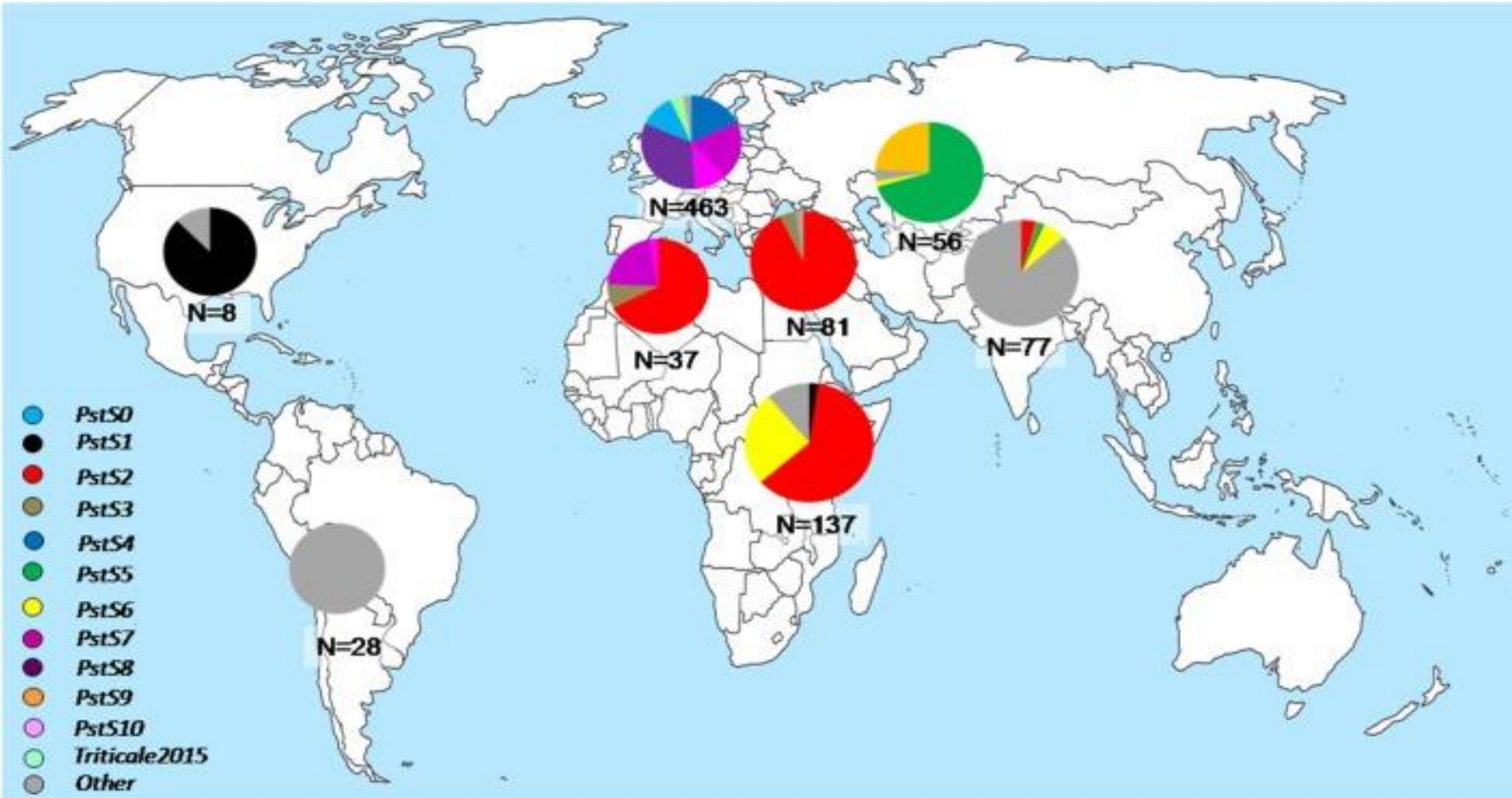


- PstS10
- PstS11
- PstS13
- PstS14
- PstS1/S2
- PstS16

***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



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.

- 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

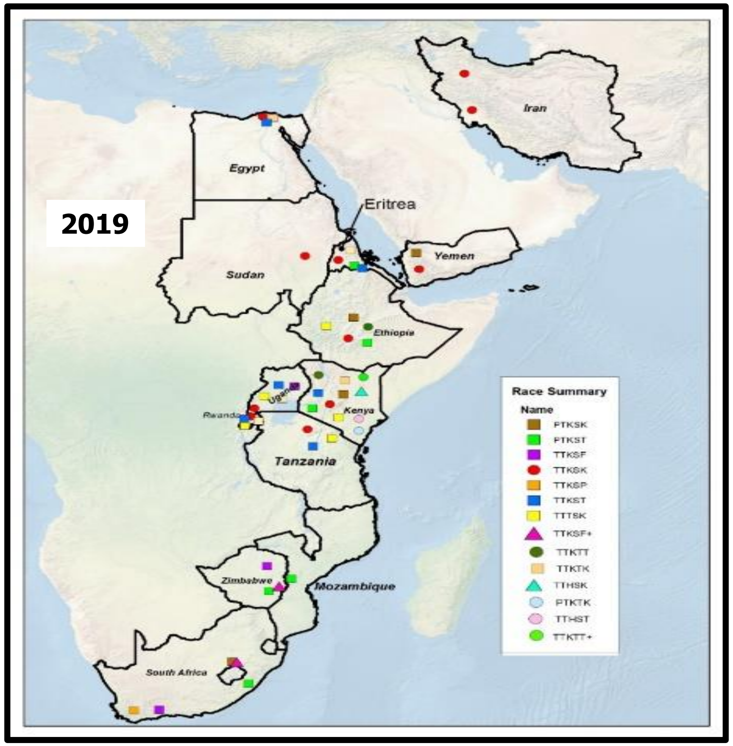
- In Uzbekistan, **PstS9** is by far the most prevalent group (most common virulence phenotype: 1,2,3,4,-,6,-,-,9,-,-,17,-,25,27,32,-,AvS,Amb), which was also the case in 2016-2017.

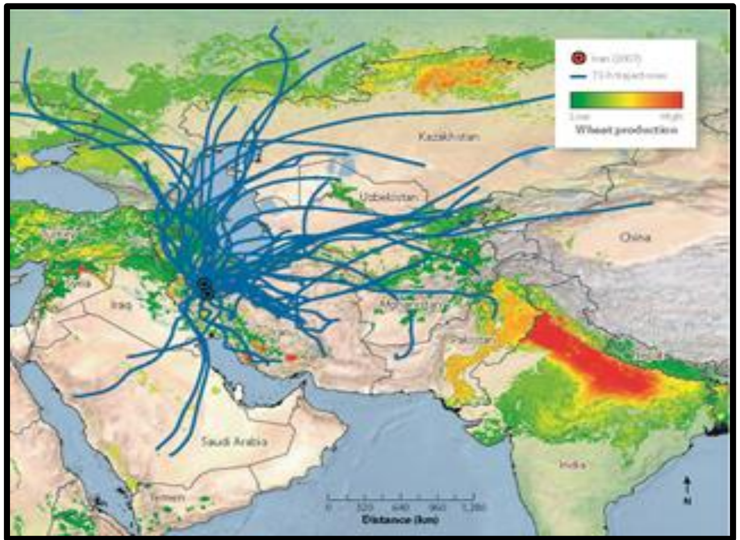
- Warrior race **PstS7** quite widely prevalent in Europe

- 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.

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 14 races in identified in the Ug99 lineage
- 7 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] Sr8115b	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]

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

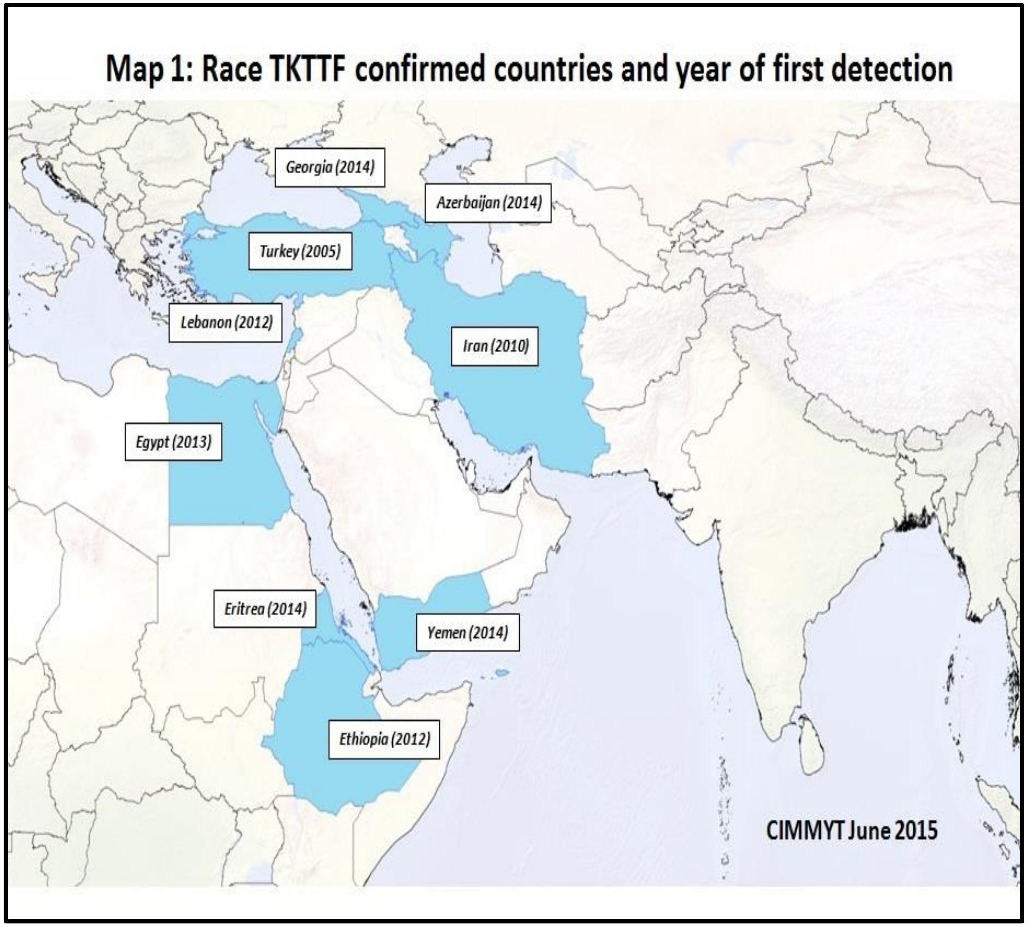
e Not tested for resistance to Ug99 in field trials to determine effectiveness

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

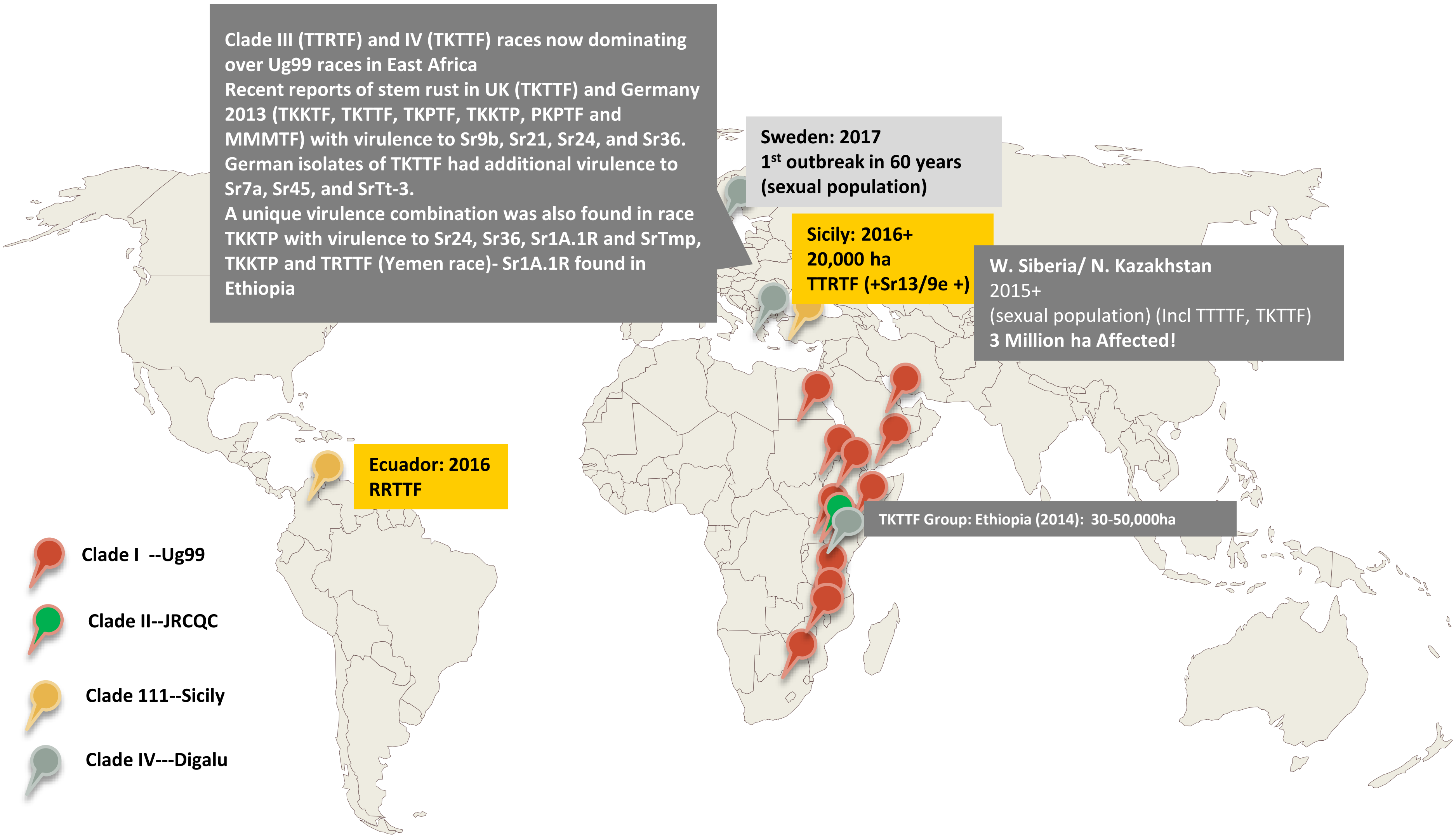
(Singh et. al 2015)

Race TKTTF (Digalu race)

- Digalu race (race TKTTF) not in Ug99 race group; genetically unrelated.
- In Turkey since at least 2005. Increasingly detected across a wide geographical range.
- Germany and Denmark detected TKTTF-like variants in 2013 (virulence on 4 additional Sr genes: *Sr33, Sr7a, SrTt-3, Sr45* (Olivera et al., 2015)).
- Race TKTTF was first detected in Ethiopia in August 2012 (trace). Epidemics in Ethiopia on cv Digalu 2013, 2014 and 2015
- 2 very distinct genotypes (type A and type B) (Olivera et al., 2015)
- New variants being detected – becoming the predominant race group in East Africa (replacing Ug99)



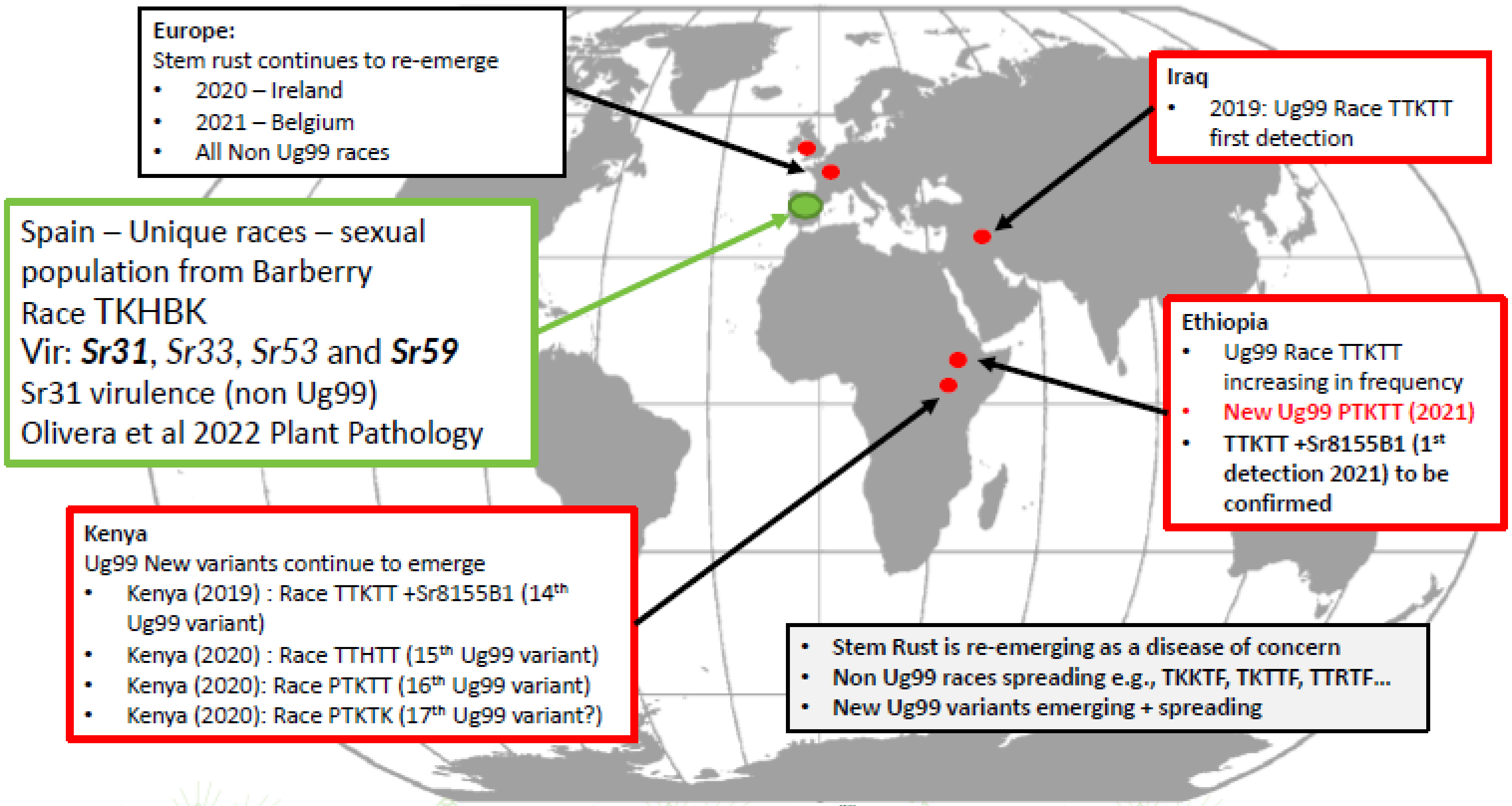
Stem rust races: evolution & spread



Sicily race (TTRTF) had confimed virulence for 23 *Sr* genes (IT 3 or higher)

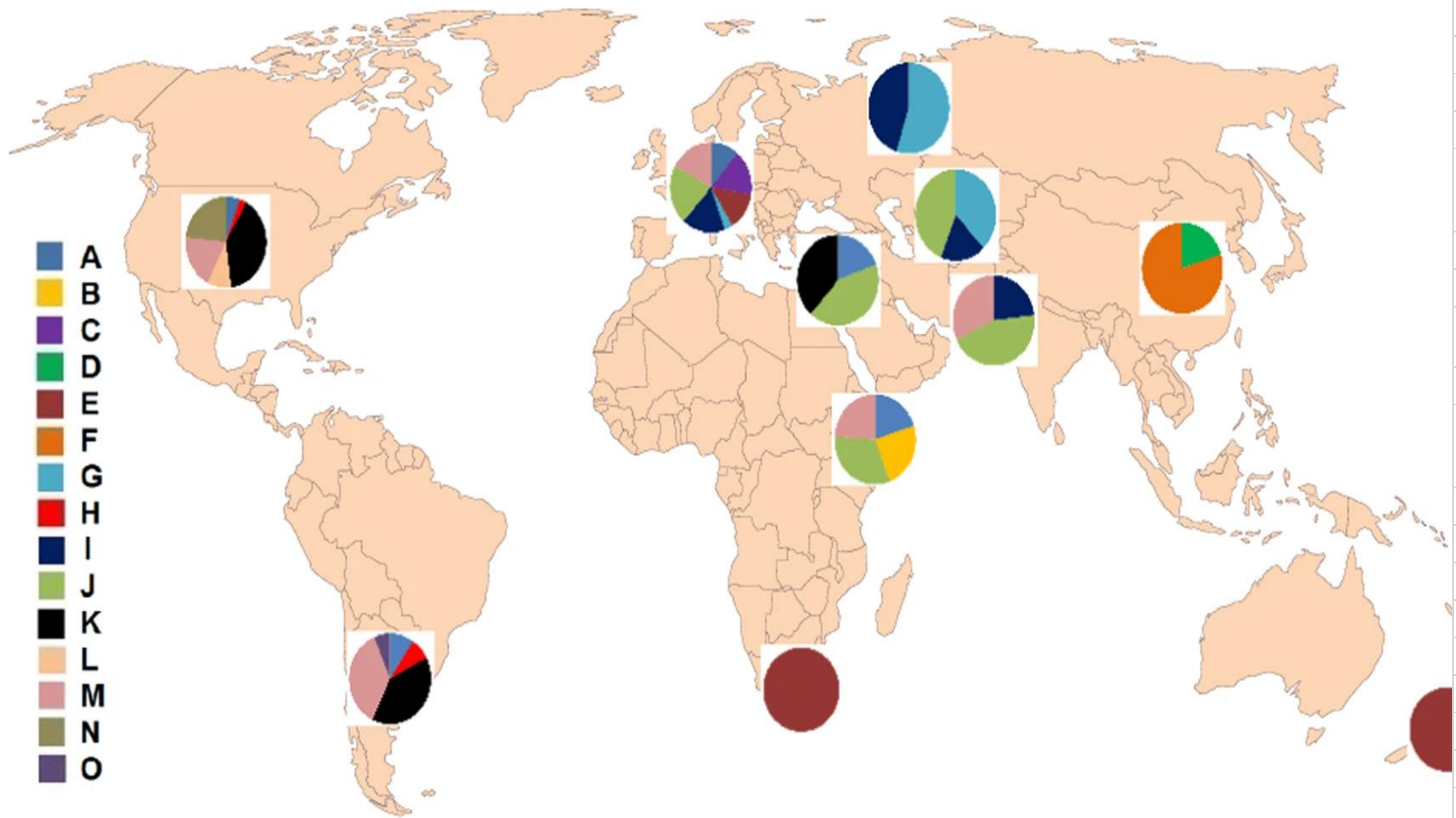
Sr5, *Sr6*, *Sr7a*, *Sr7b*, *Sr8a*, *Sr9a*, *Sr9b*, *Sr9d*, *Sr9e*, *Sr9g*, *Sr10*, *Sr11*, *Sr13 b*, *Sr17*, *Sr21*, *Sr35*, *Sr36*, *Sr37*, *Sr38*, *Sr44*, *Sr45*, *SrTmp*, and *SrMcN*.

Stem rust races : recent update



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

Diversity of leaf rust races in different parts of world

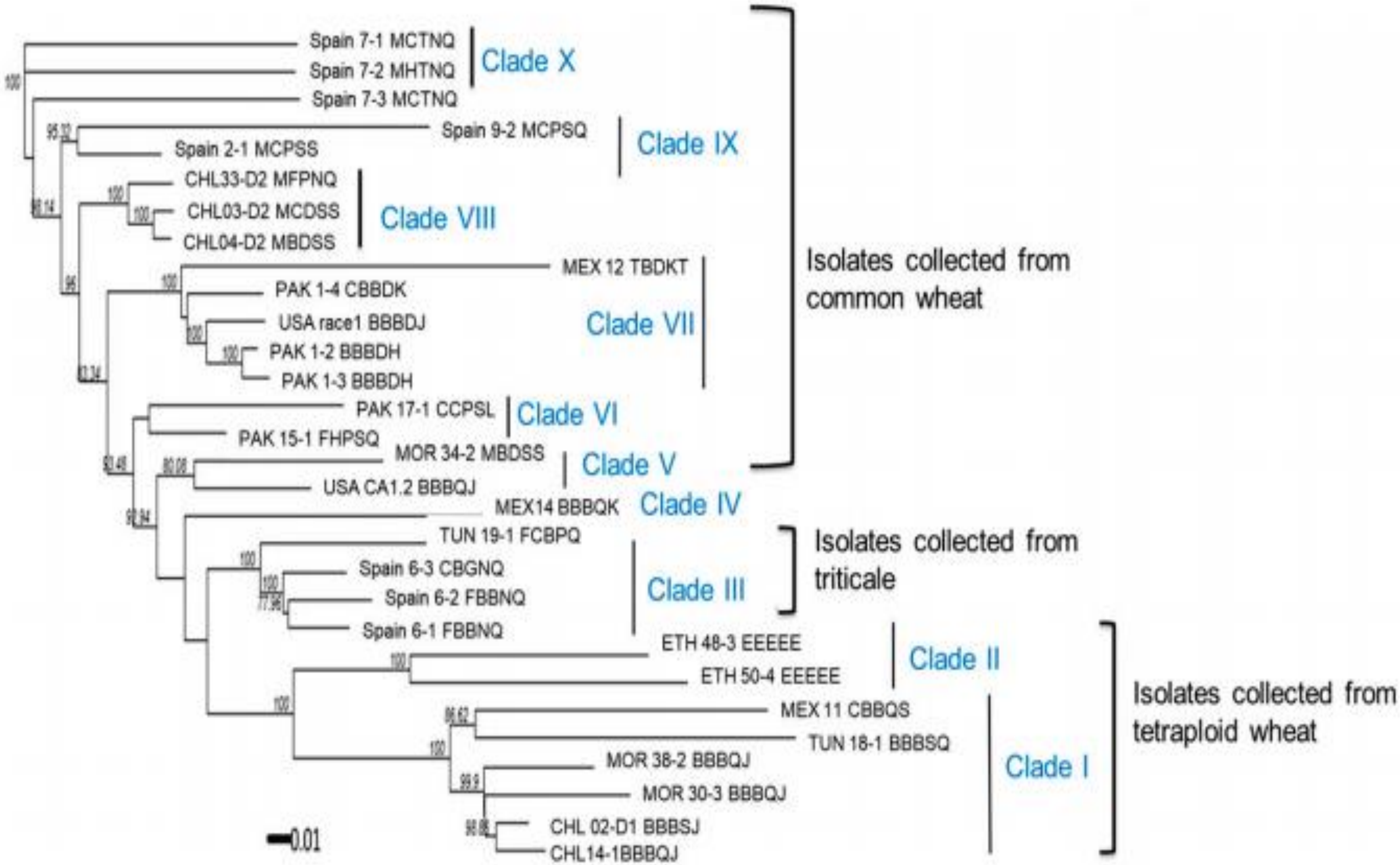


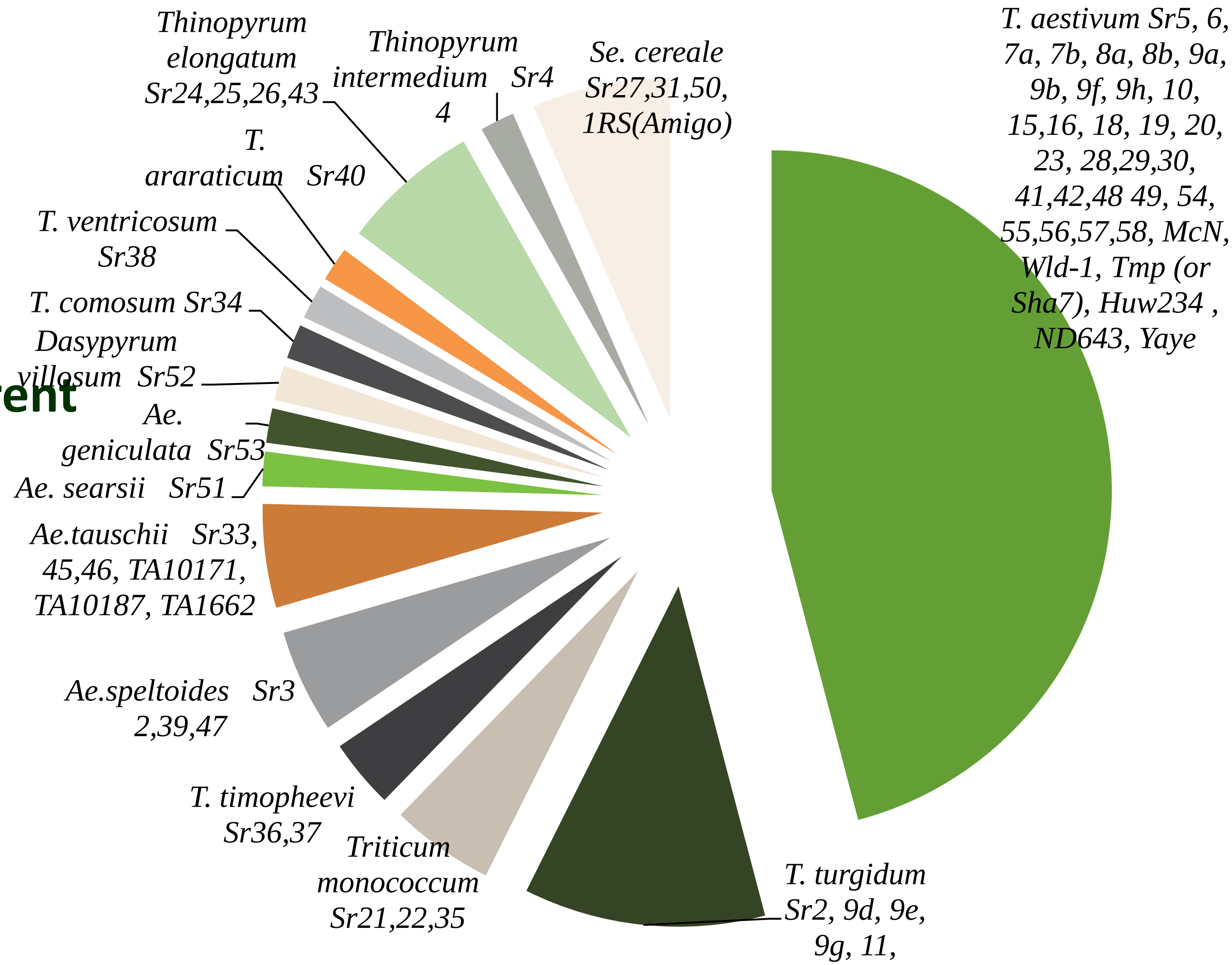
Fig. 1. Neighbor-joining phylogenetic tree of 30 *Puccinia triticina* isolates collected on durum wheat, emmer wheat, common wheat, and triticale, based on Nei's genetic distances, calculated using 2,125 single nucleotide polymorphism markers. Isolate name was based on country (USA = United States, CHL = Chile, MEX = Mexico, PAK = Pakistan, MOR = Morocco, TUN = Tunisia, and ETH = Ethiopia), collection number, and race-based virulence phenotypes on Thatcher differentials. Numbers along the nodes are bootstrap values >75% in 5,000 replicates.

Genotyping-by-Sequencing for the Study of Genetic Diversity in *Puccinia triticina*

Meriem Aoun,[1] James A. Kolmer,[2,3] Matthew Breiland,[1] Jonathan Richards,[1] Robert S. Brueggeman,[1] Les J. Szabo,[2,3] and Maricelis Acevedo[4,†]

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

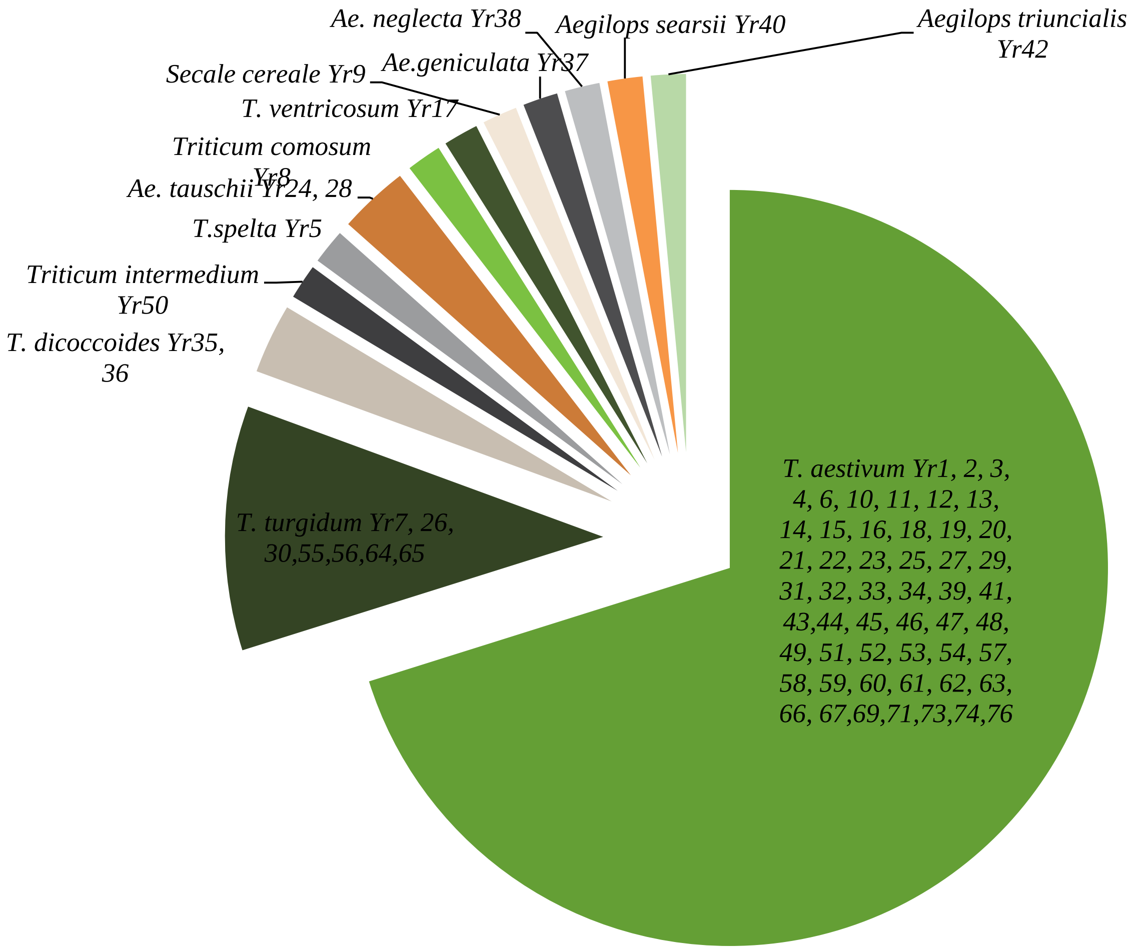
- 35 genes from *Triticum aestivum*
- 38 genes from 14 different species and genera
- Majority race-specific
- Some alien genes successfully used



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)

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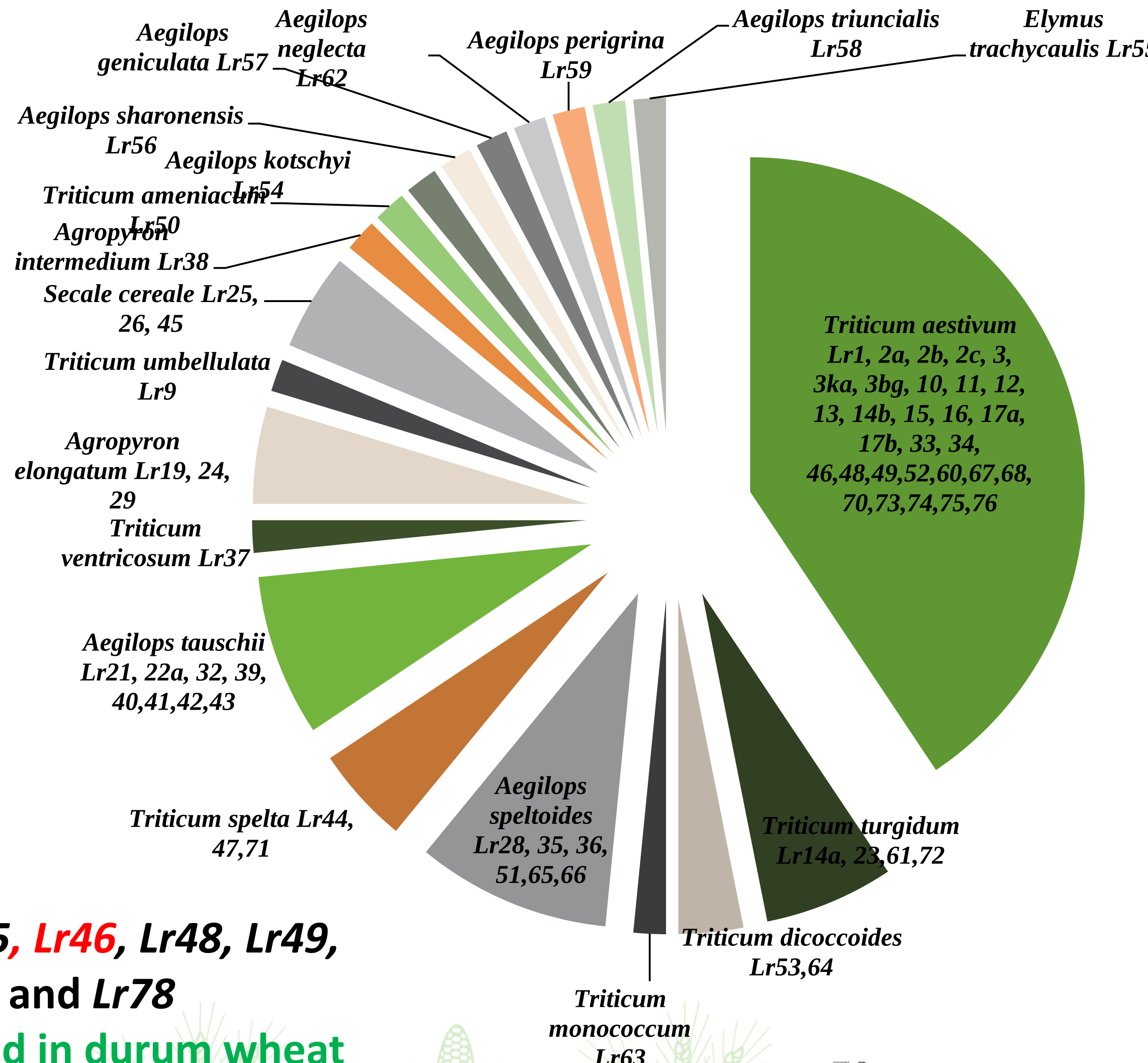
Leaf (brown) rust (80)

- 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

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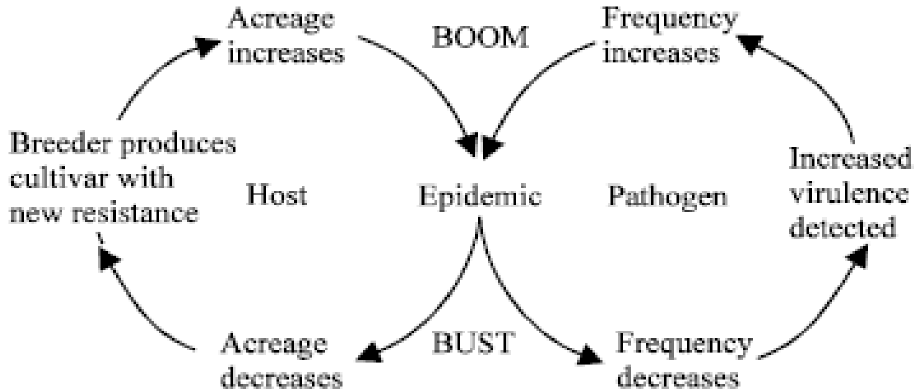

“Ug99” races evolved in Kenya

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

Variety Robin
2009
Resistant to “Ug99”

Variety Robin
2014
Susceptible to “Ug99+Srtmp”&
“Digelu” race

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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

CIMMYT

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

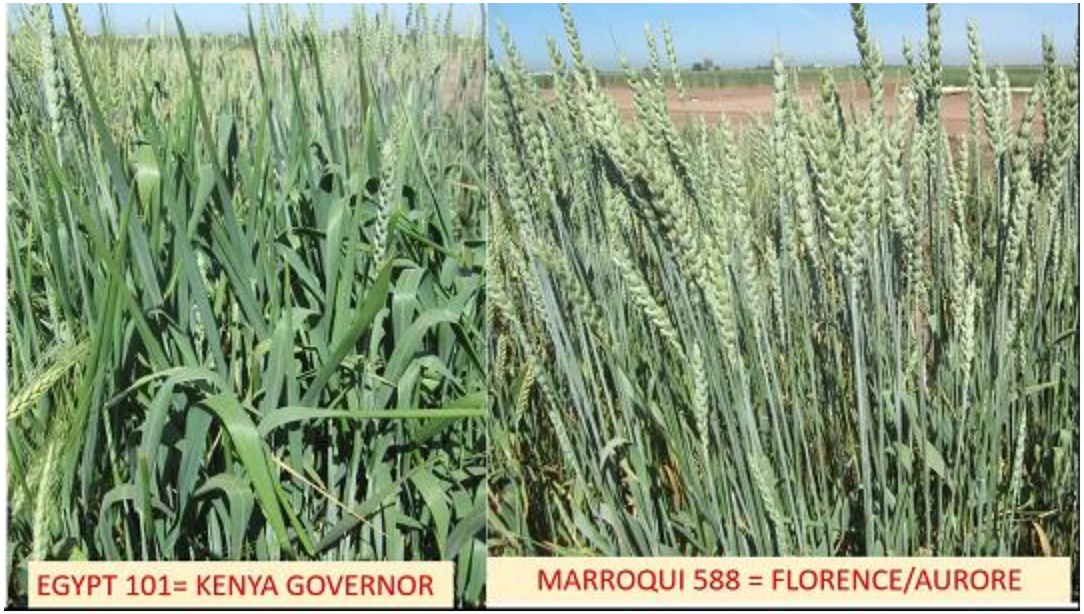
Supresa =Fronteira =Frondoso=Polissu/a.Chaves 6.21

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***



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"

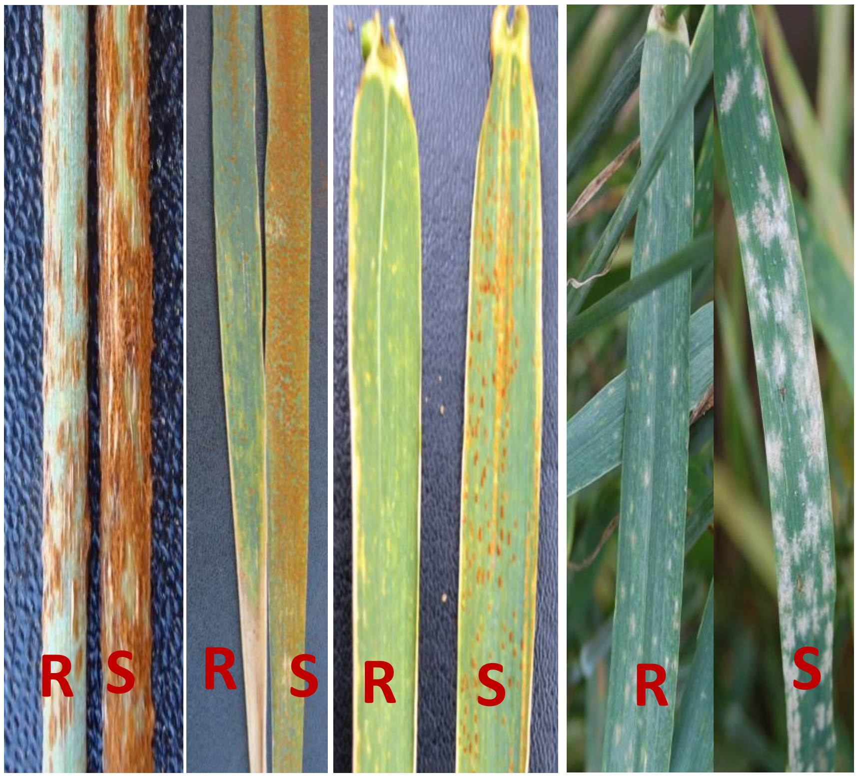
	Year of			Lr gene or		Dwarfing gene	
VARIETY	*release*	LTN	PBC	*combination*	*Sr2 Marker*	*Rht-B1*	*Rht-D1*
JARAL F66	1966	+	+	*46*	*Sr2*		*Rht2*
HUITES F95	1995	+	?	*46*		*Rht1*	
LERMA ROJO 64	1964	+	+	*34+46*		*Rht1*	
SARIC F70	1970	+	+	*34+46*		*Rht1*	*Rht2*
TEPOCA M89	1989	+	+	*34+46*	*Sr2*		*Rht2*
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

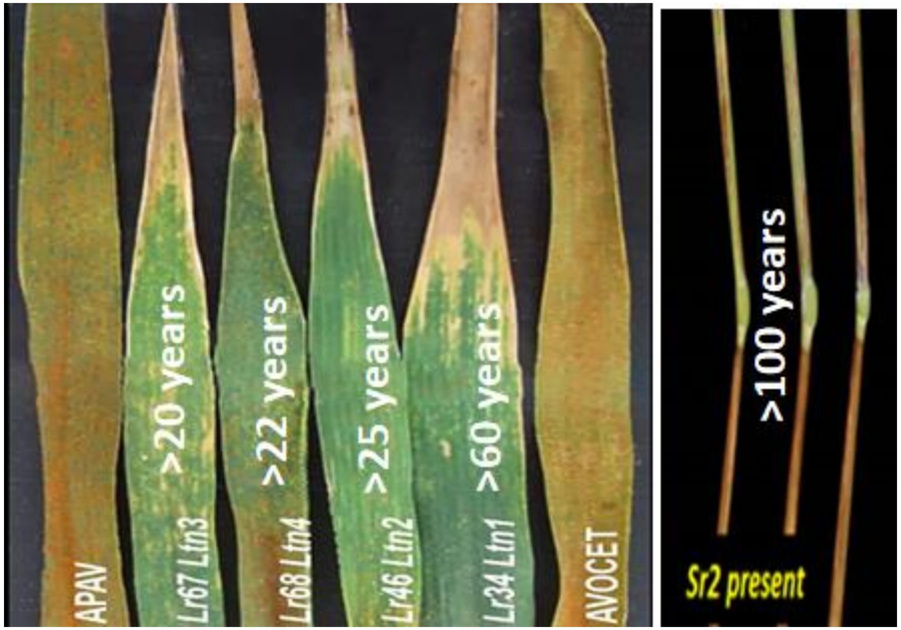
Four catalogued genes confer pleotropic resistance to multiple pathogens (PAPR)

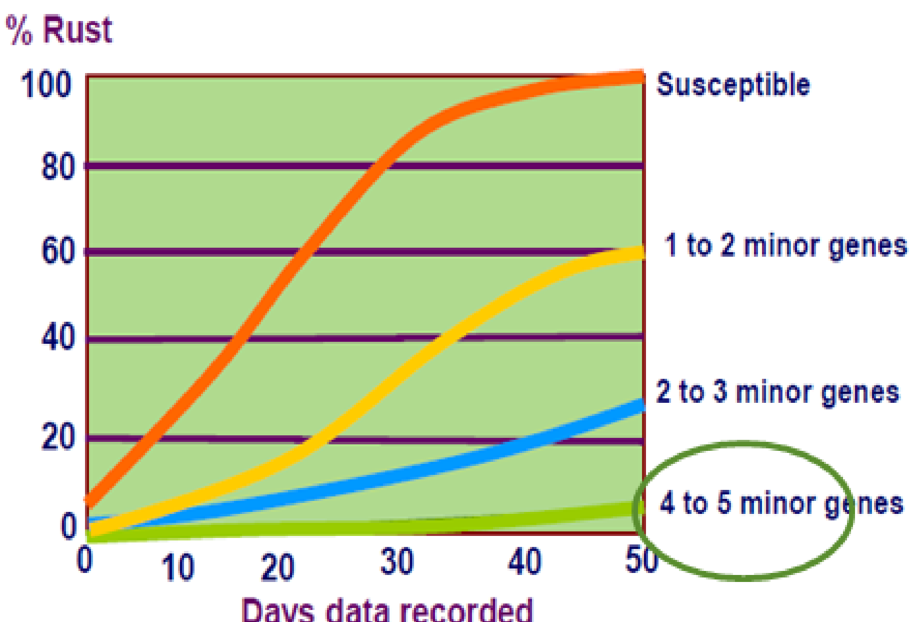
Lr67/Yr46/Sr55/Pm46



- *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**

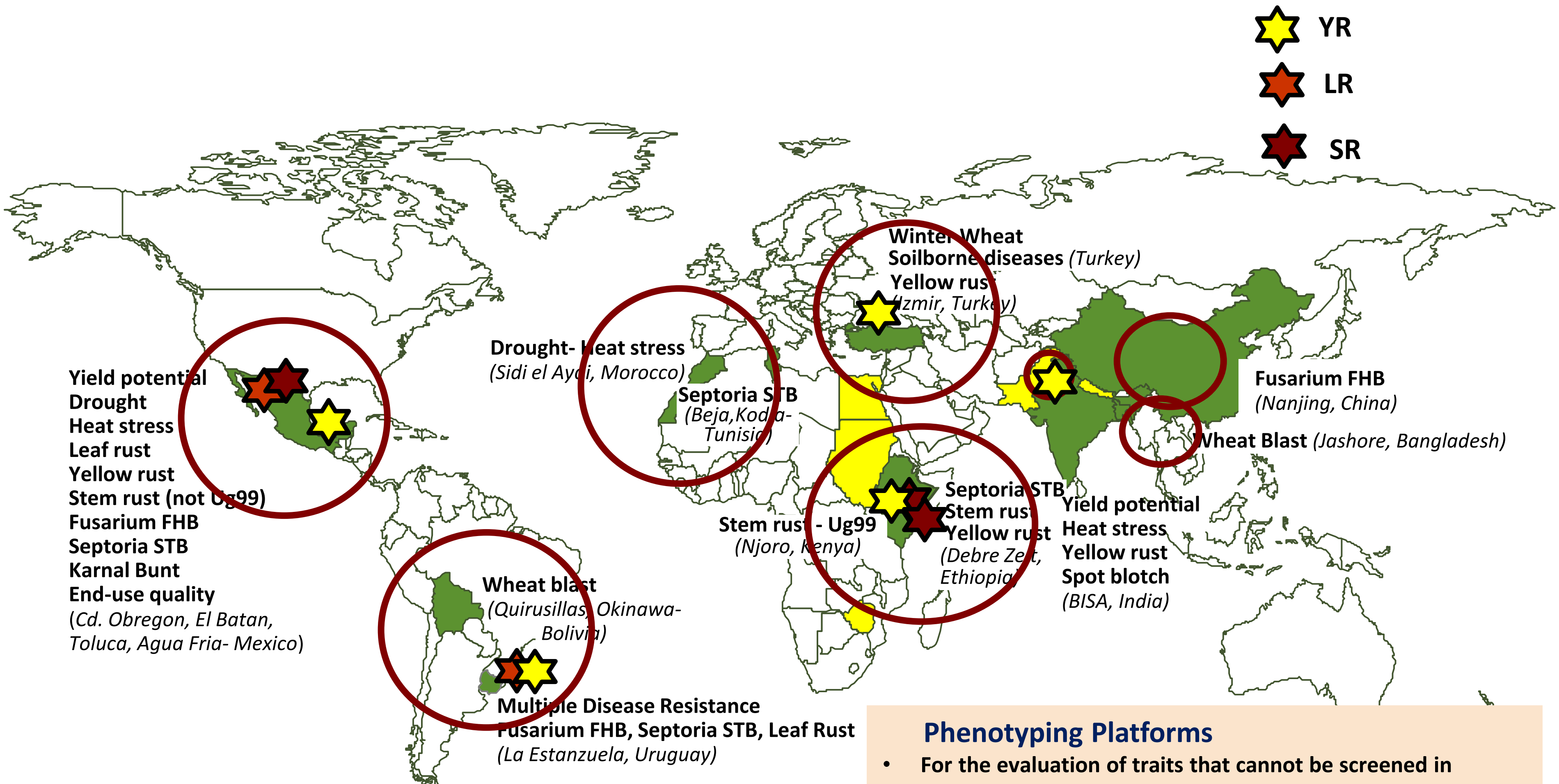




- **Near-immunity (trace to 5% severity) achieved by combining (4-5 genes)**
- **A similar genetics for other leaf spotting diseases, fusarium head blight)**

Reliable phenotyping is Key!!!!!

International wheat disease phenotyping network)

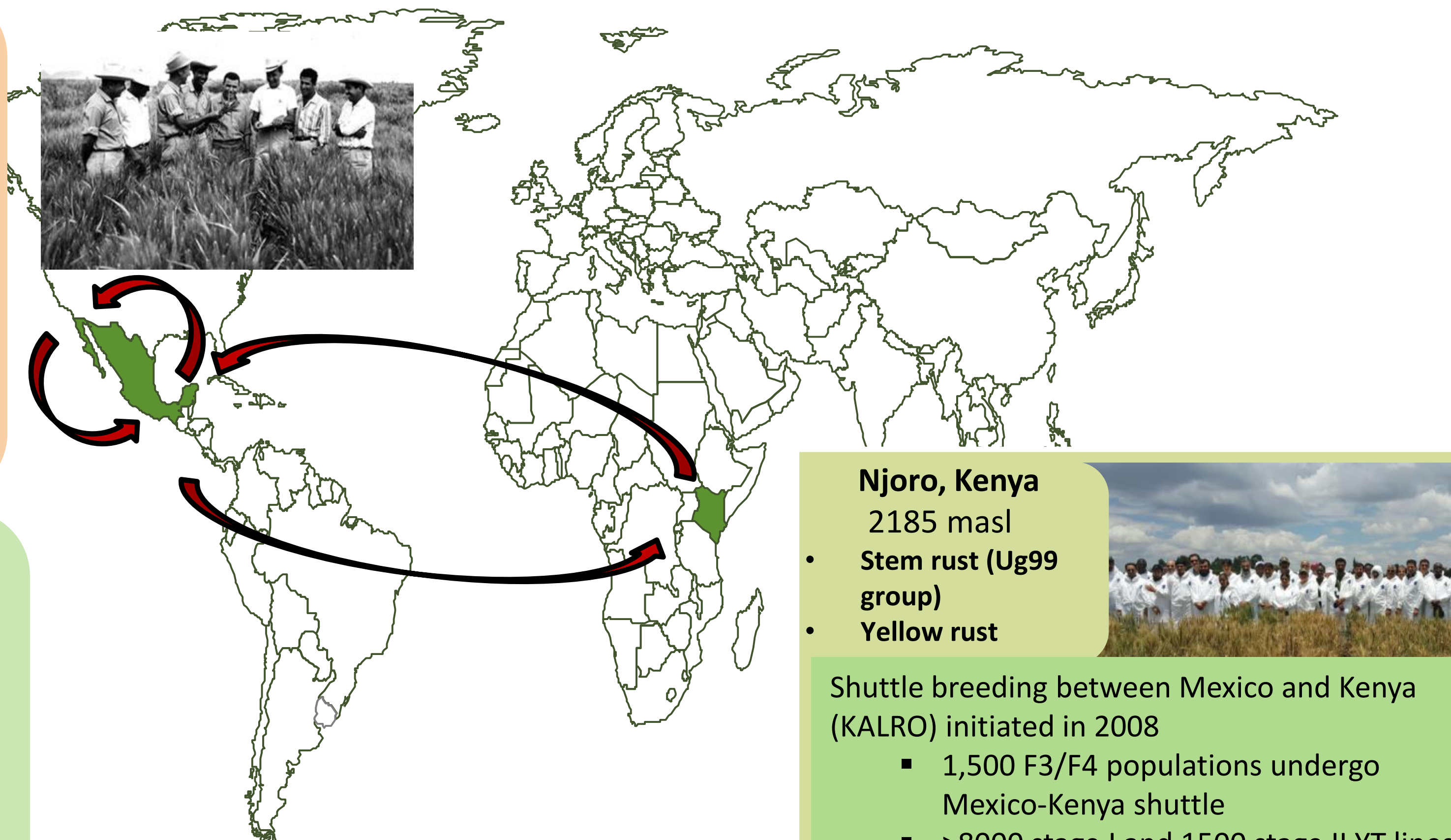


Phenotyping Platforms

- 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

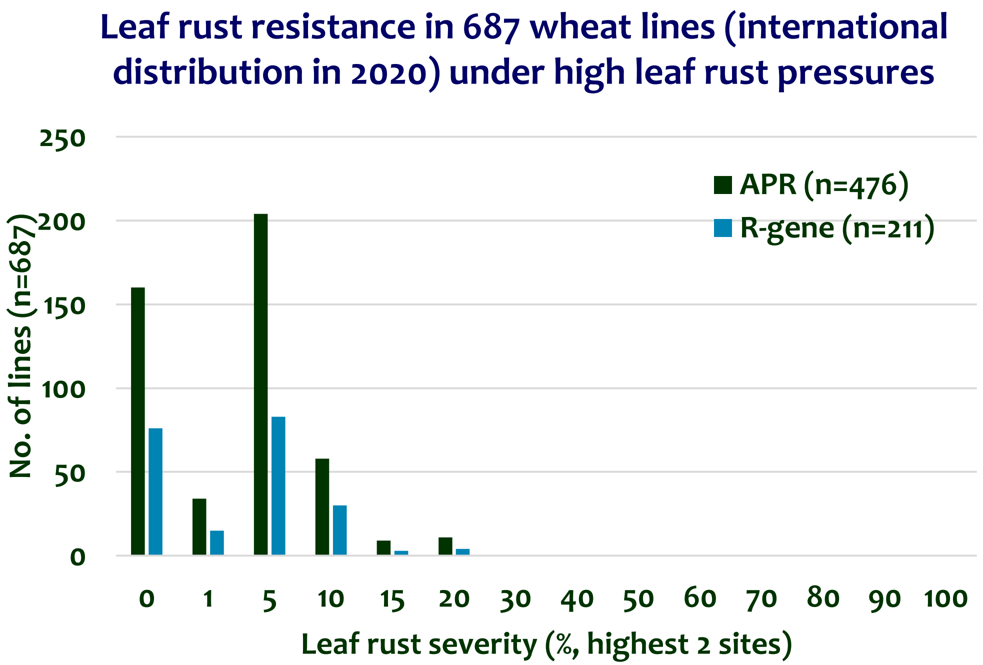
El Batán
2249 masl
- Leaf rust
- Fusarium FHB

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

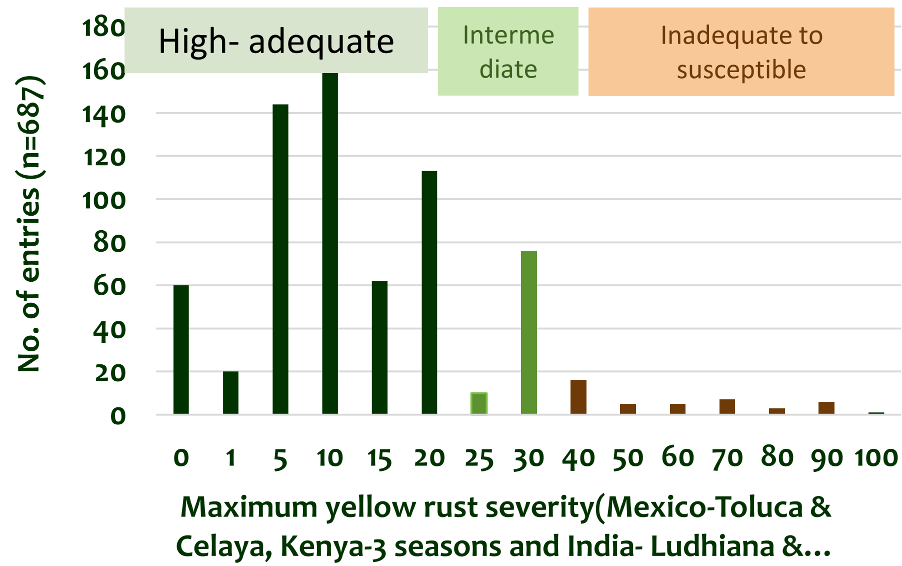
- CIMMYT-derived varieties and breeding materials possess high levels of resistance
- Leaf rust under control for 25 years in countries growing CIMMYT- derived varieties
- *Lr46/Yr29* nearly fixed
- Excellent example of durability



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***

CIMMYT

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

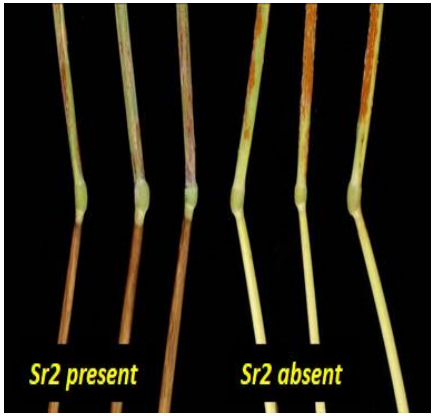
New lines with high yields and high levels of complex adult-plant resistance to stem rust (Njoro, Kenya 2018)

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

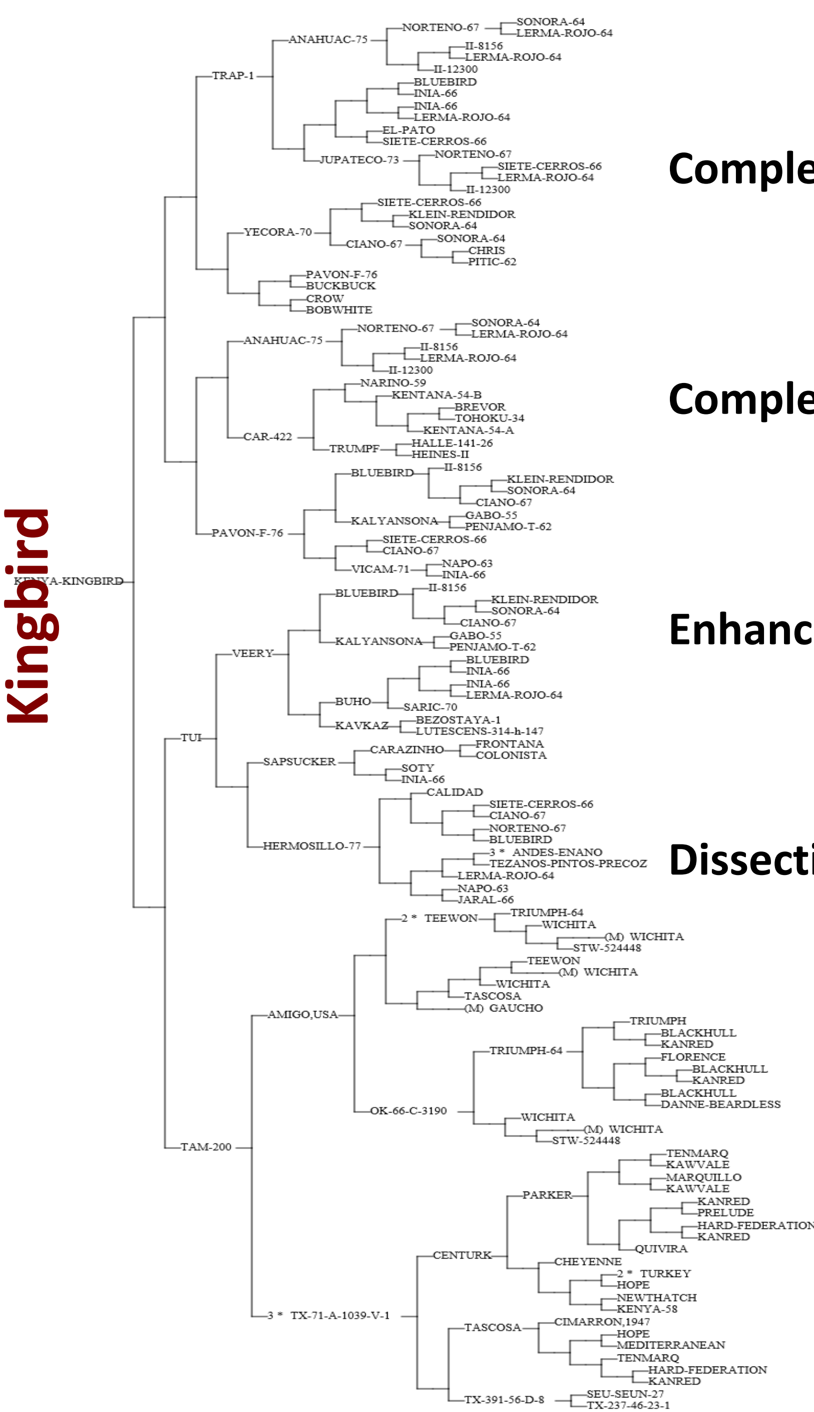
•*Sr2* transferred to wheat from 'Yaroslav' emmer in 1920s by McFadden

•Linked to pseudo-black chaff

•Confers only moderate levels of resistance (about 30% reduction in disease severity)



Kingbird



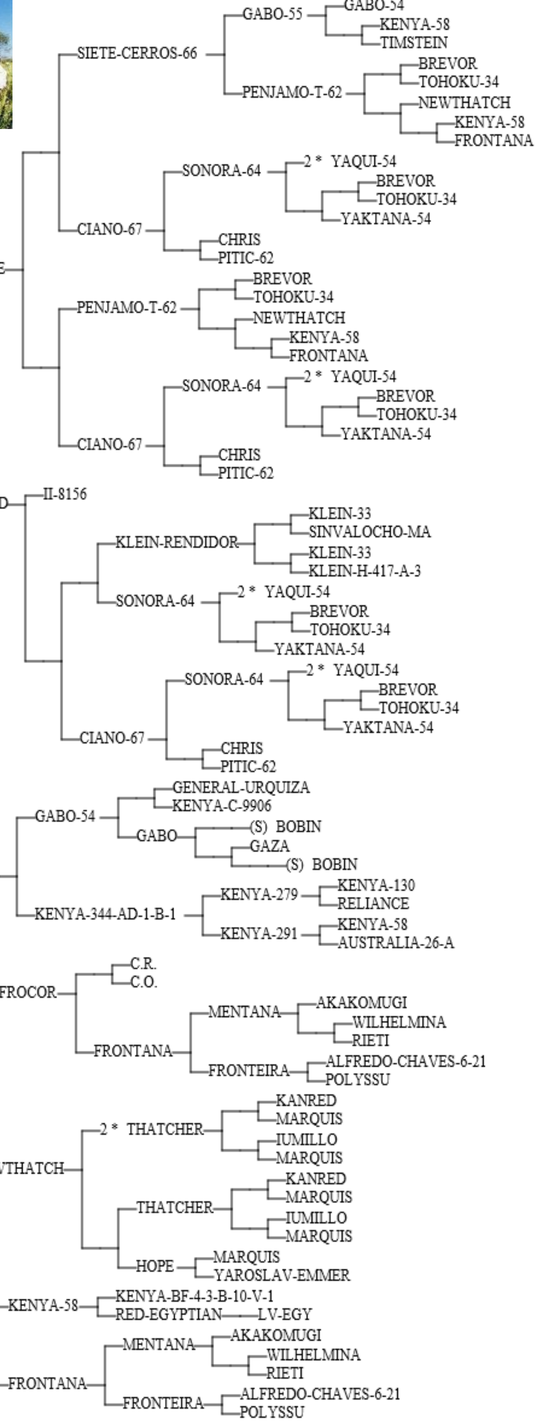
Complex pedigree

Complex resistance (APR)

Enhanced durability

Dissecting Complex resistance

Parula



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*

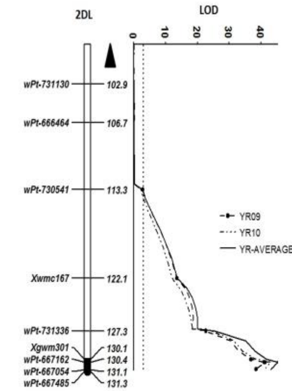
- Mapping located the moderately effective APR gene *Yr54* on 2DS

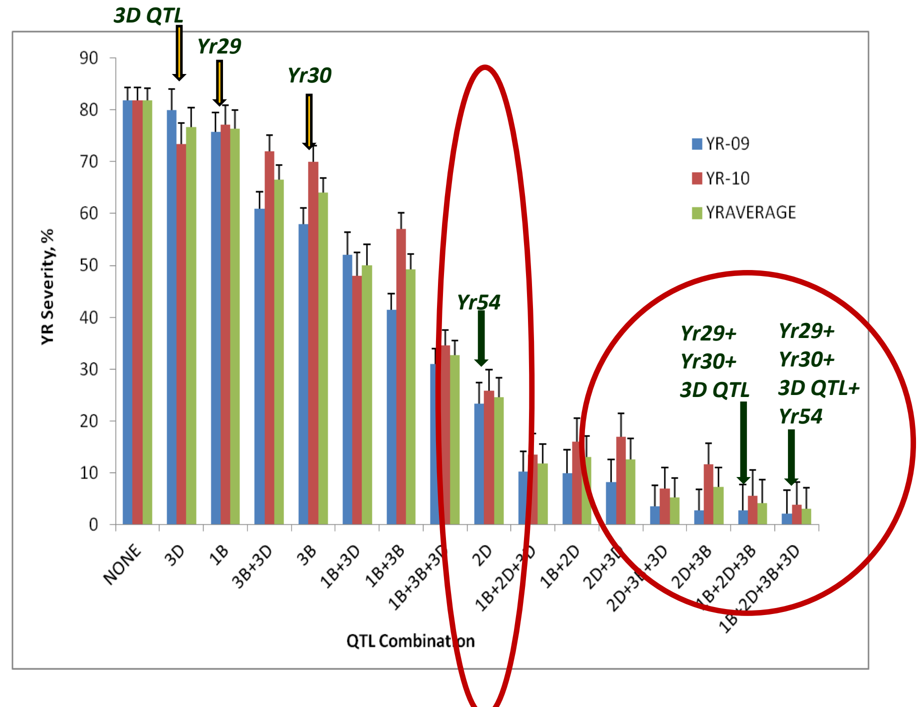
- Near-immune resistance achieved when *Yr54* combined with other slow rusting resistance genes, which is effective worldwide

- 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**



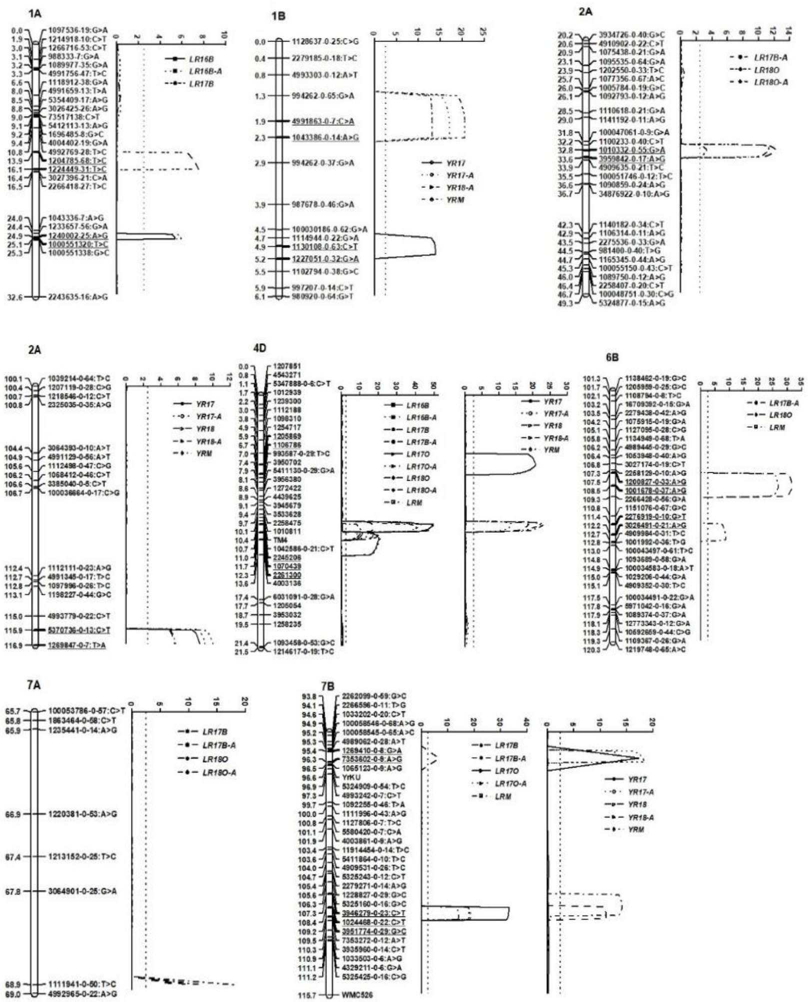


Yellow rust resistance of Avocet x Quaiu 3 RILs

CIMMYT

Source: Basnet et al. Plant Dis. 2013

Mapping of leaf rust and stripe rust resistance in Afghanistan landrace "KU3067"



- **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.

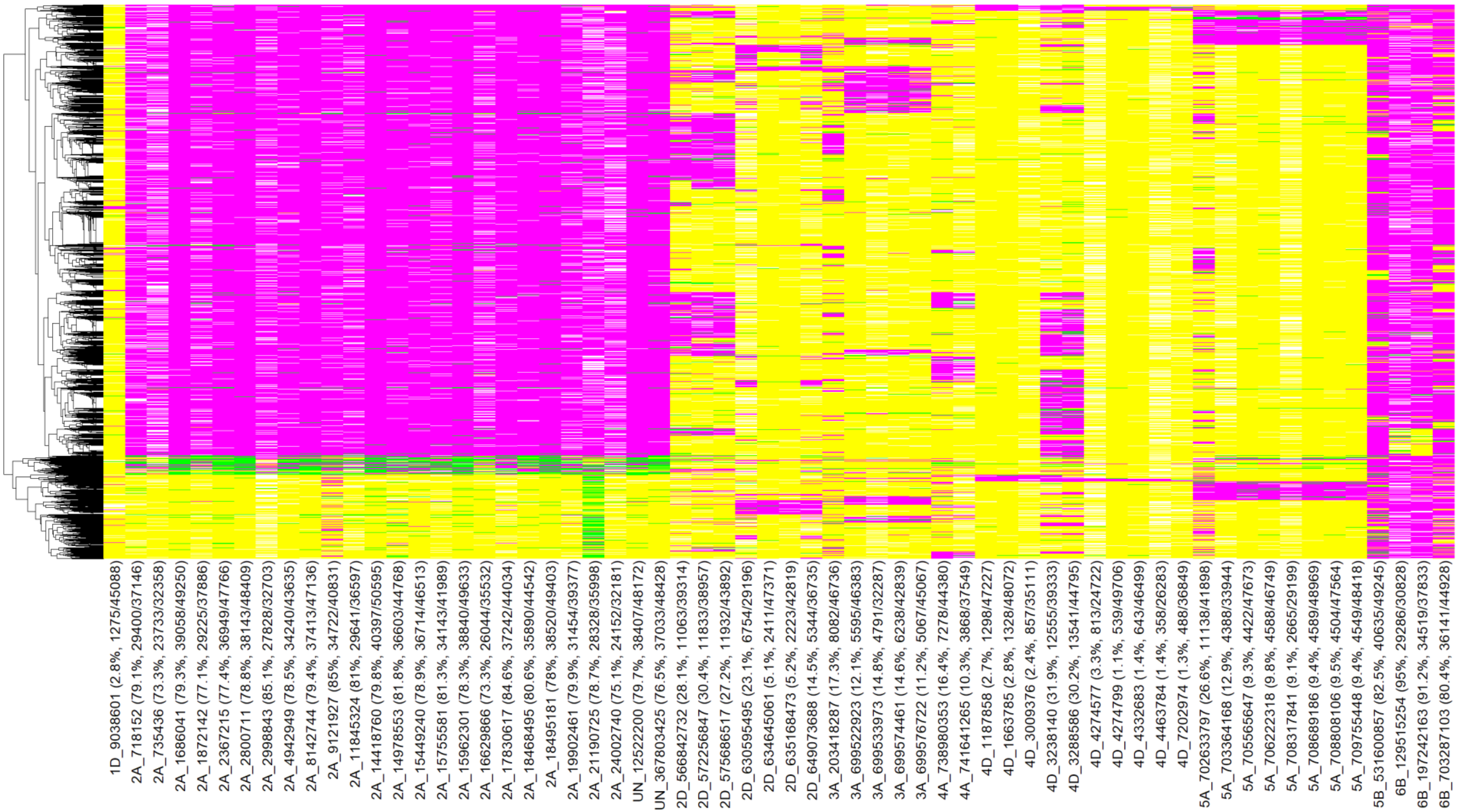
Line no.	**QTL combinations - Apav#1/ KU3067**	
	leaf rust	rust score
191	1A+Lr67+6B+7A+7B (No 2A)	5
210	1A+Lr67+6B+7A+7B (No 2A)	5
282	1A+Lr67+6B+7A+7B (No 2A)	10
	yellow rust	rust score
154	1B+2A+Lr67+7B	5
210	1B+2A+Lr67+7B	1
282	1B+2A+Lr67+7B	1

Grains Research & Development Corporation

Bhavani et al. unpublished data

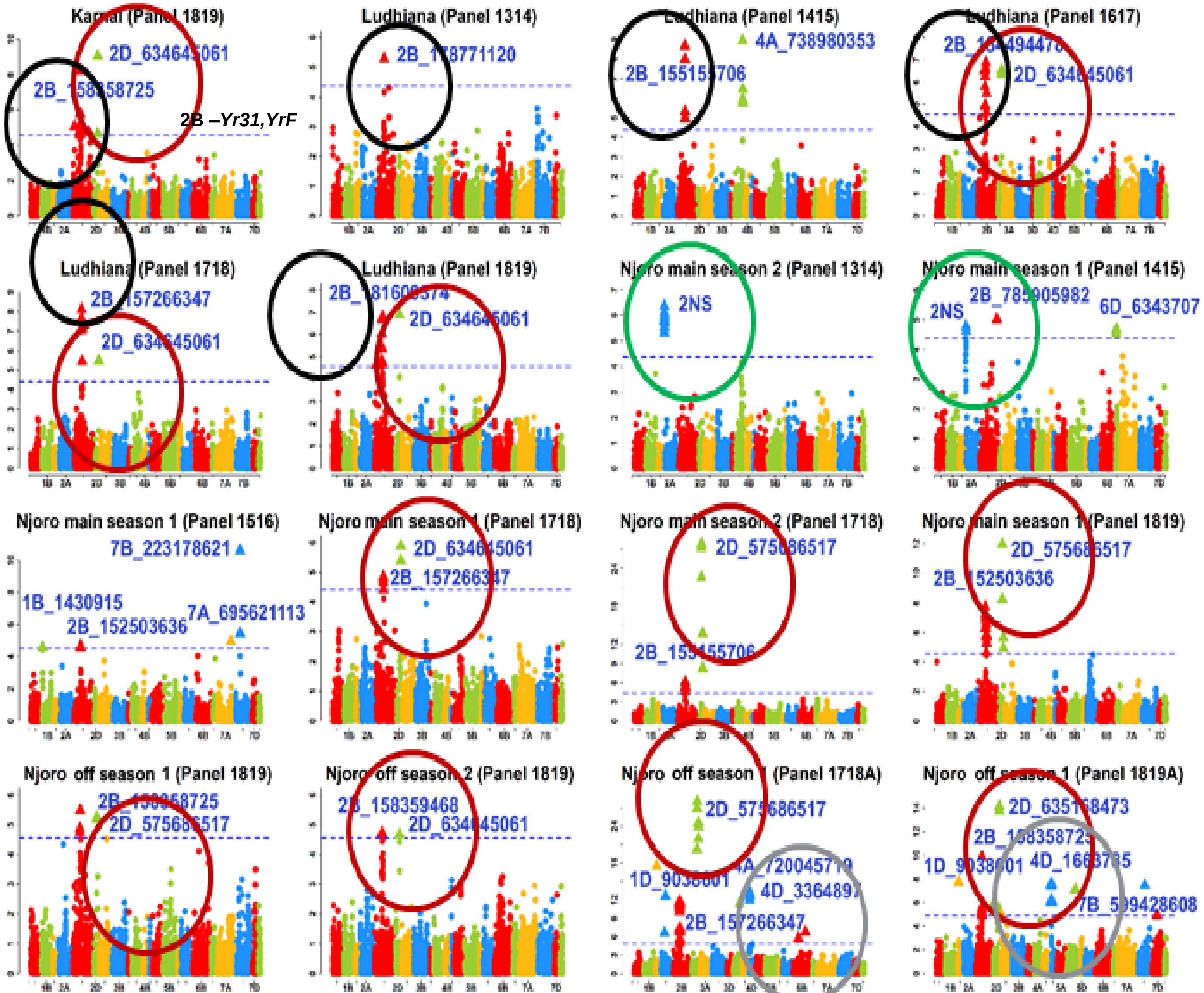
CIMMYT

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

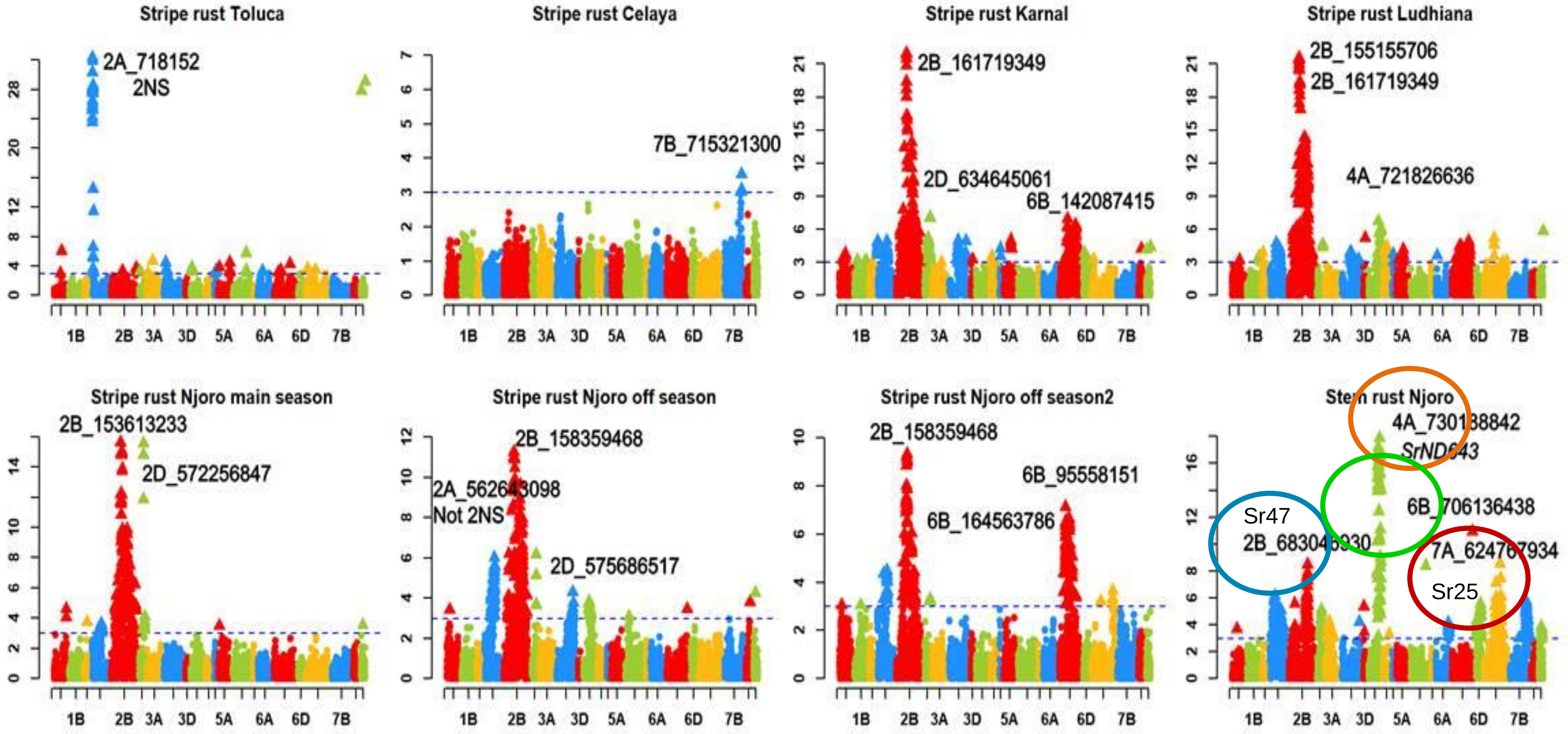
Genomic regions associated with stripe rust in India and Kenya



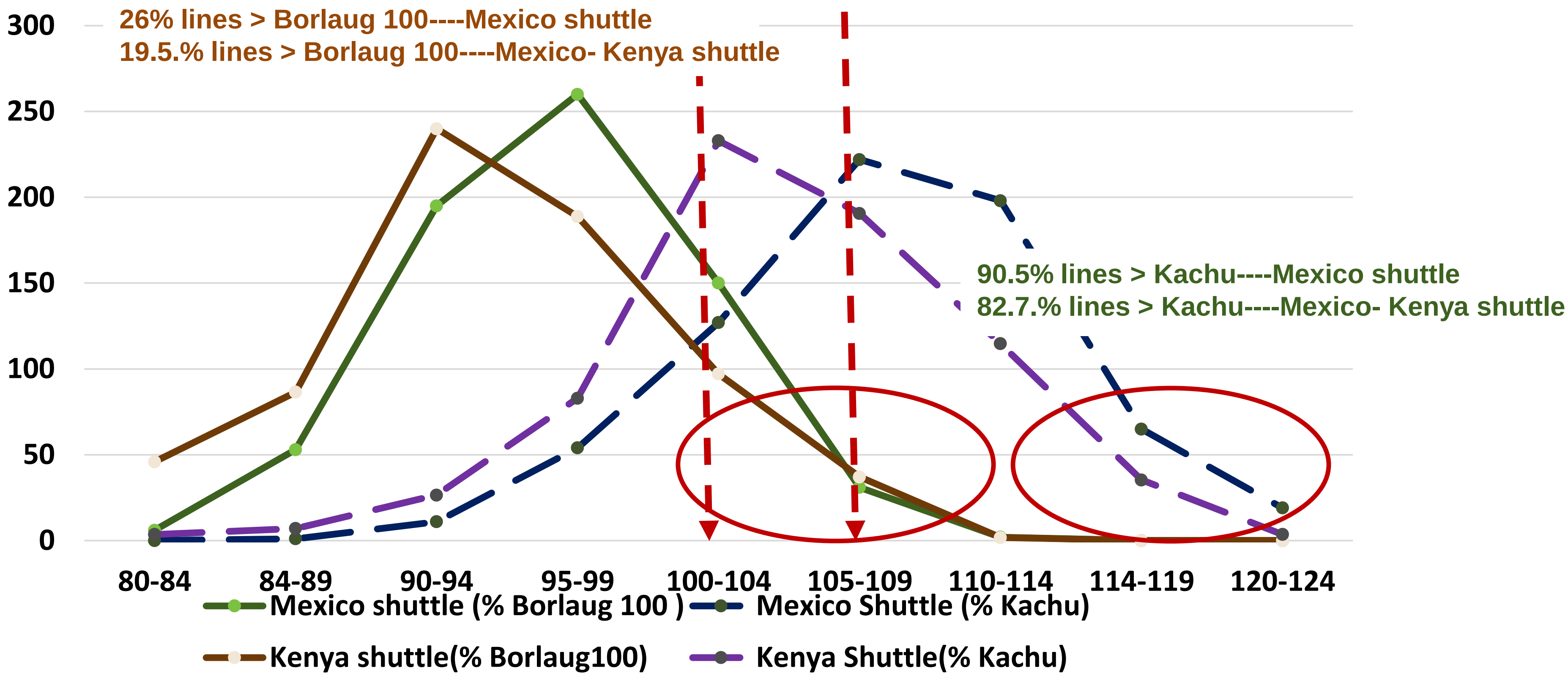
- *QYr.cim-2DL.2* on chromosome 2DL was associated with the highest number of datasets in India and Njoro and was 2.5 Mb away from the marker linked to the gene ***Yr54*** mapped from the CIMMYT spring wheat line QUAIU and it confers moderate resistance when present alone (Basnet, B. R. *et al.* (2014)).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

Genomic regions associated with stripe rust and stem rust EYT18-19



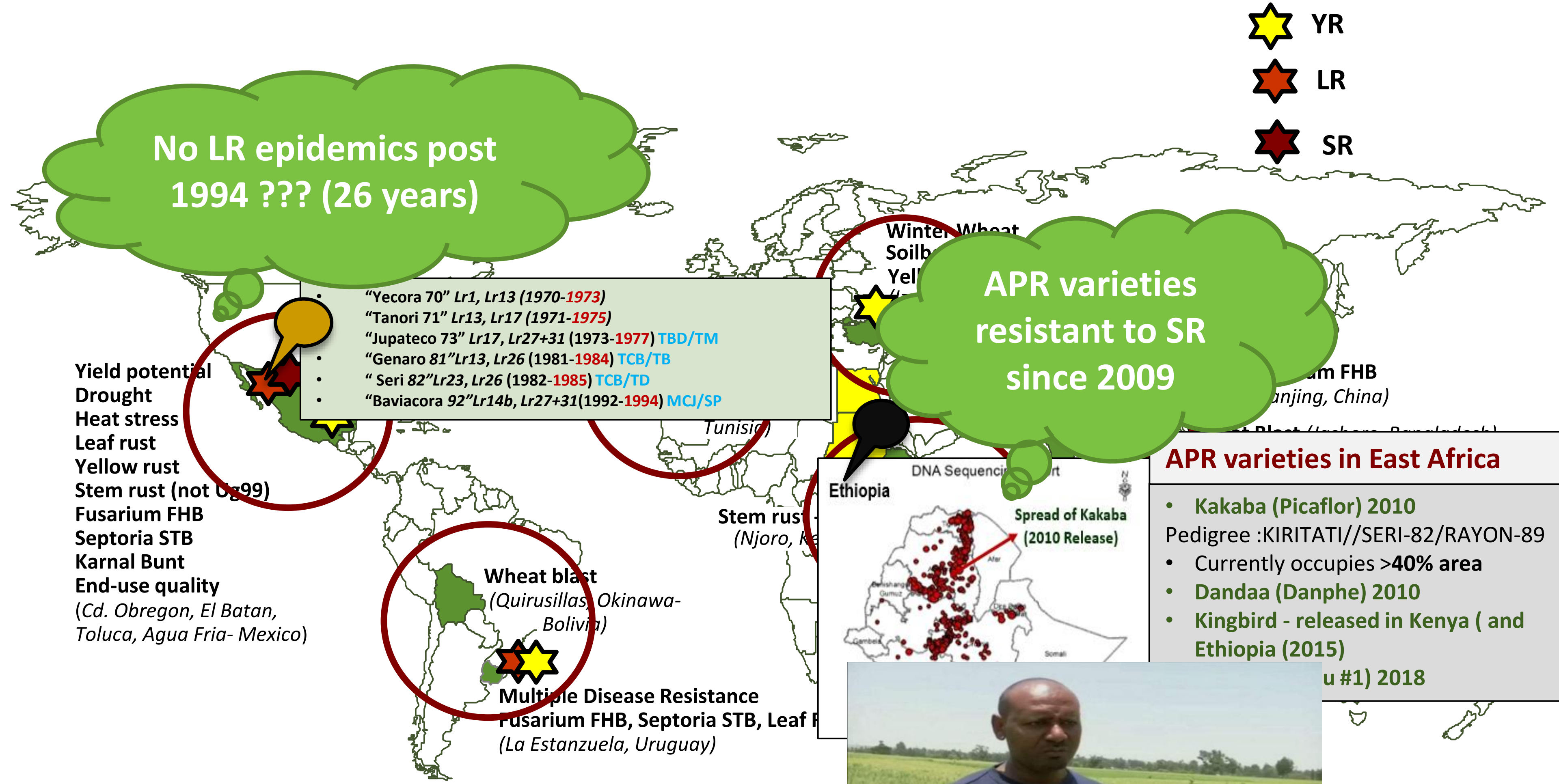
Comparison of grain yield performance of 697 EYT lines (Stage II) 2018-19 derived from Mexico Shuttle and Mexico Kenya Shuttle breeding schemes



APR based resistance works!!!

Reliable phenotyping is Key

International wheat phenotyping network & Disease phenotyping network



APR varieties in East Africa

- Kakaba (Picaflor) 2010
Pedigree :KIRITATI//SERI-82/RAYON-89
- Currently occupies >**40%** area
- Dandaa (Danphe) 2010
- Kingbird - released in Kenya (and Ethiopia (2015)

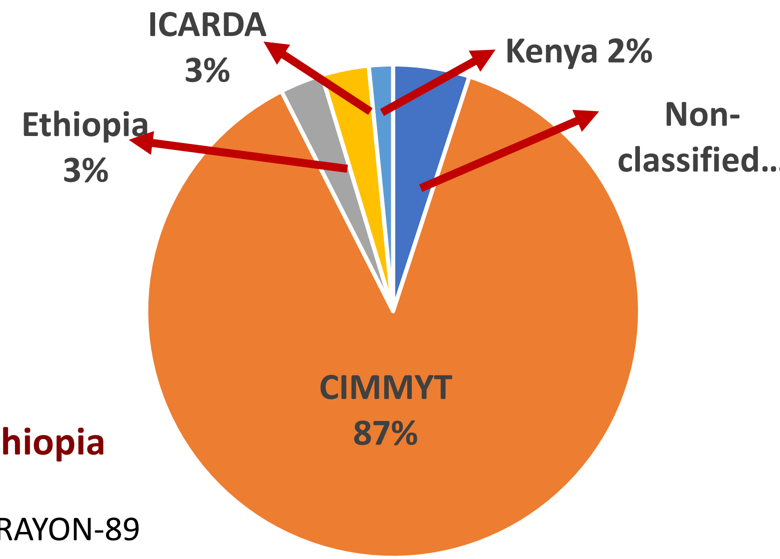
u #1) 2018

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

(Marasas et al. 2004)

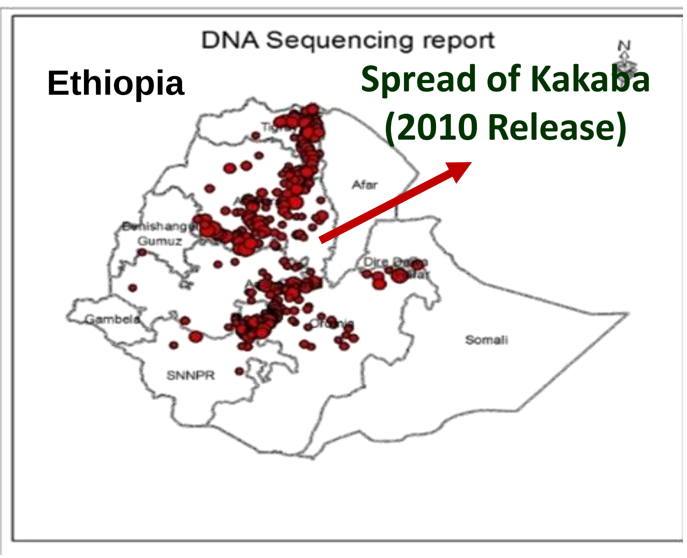
MMYT

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



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

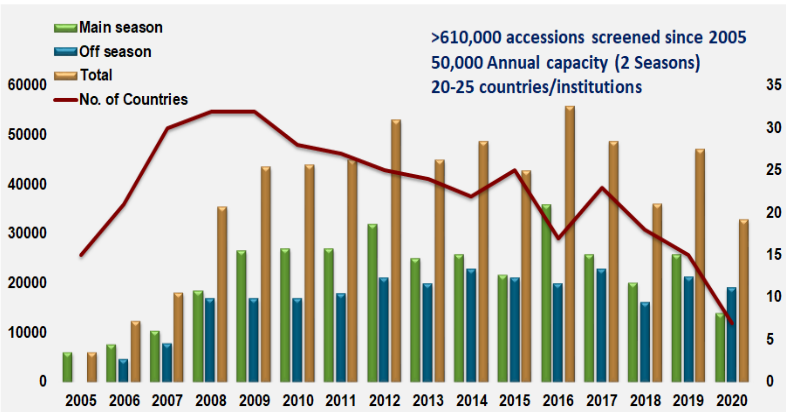
Pedigree : TAM-200/TUI/6/PAVON-76//CAR-422/ANAHUAC-75/5/BOBWHITE /CROW//BUCKBUCK/PAVON-76/3/YECORA-70/4/TRAP-1

Deka (Arableu #1) 2018

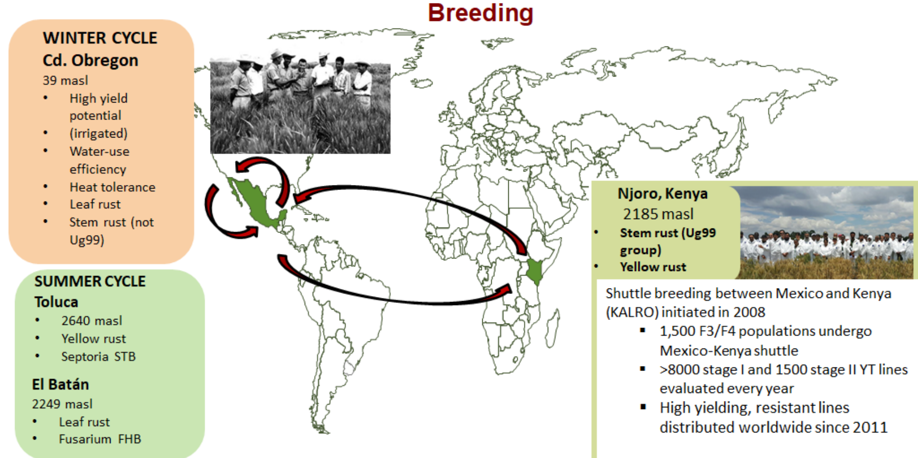
Pedigree Attila/3*Bacanora*2//Baviacora92/3/Kiritati/Weebil#1/4/Danphe

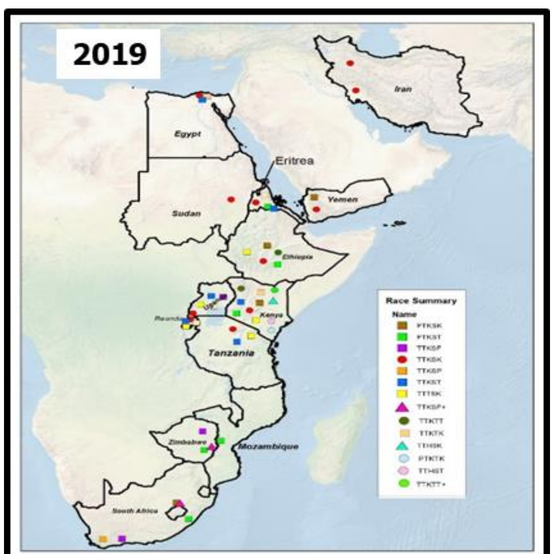
Mitigating the threat of stem rust: PP in Kenya and Ethiopia

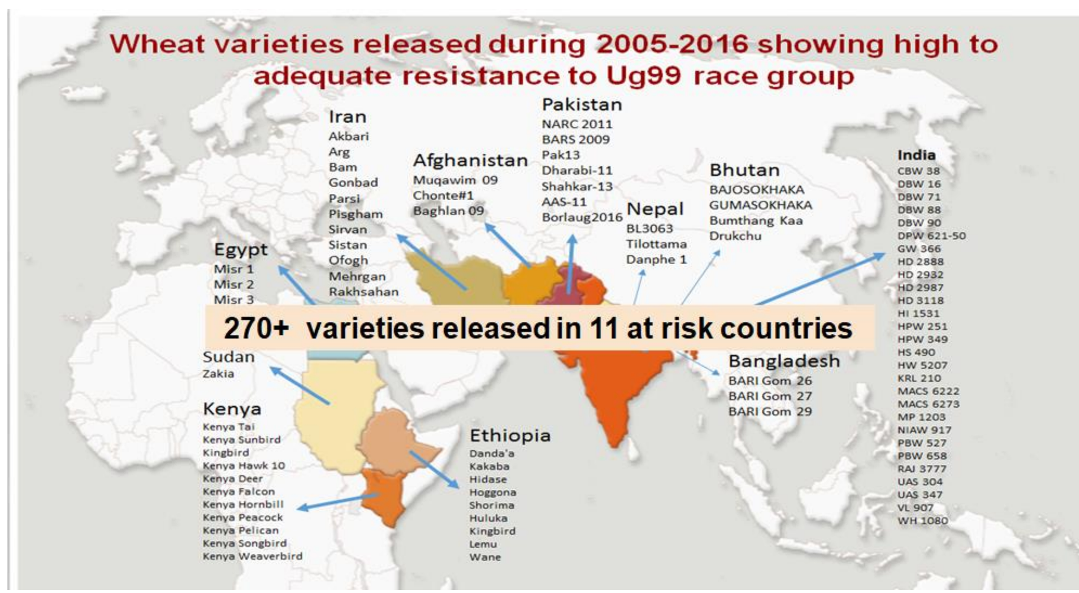
Wheat accessions phenotyped during 2005-2020 for Ug99 resistance at Njoro (Kenya) and participating countries, in partnership with KALRO



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

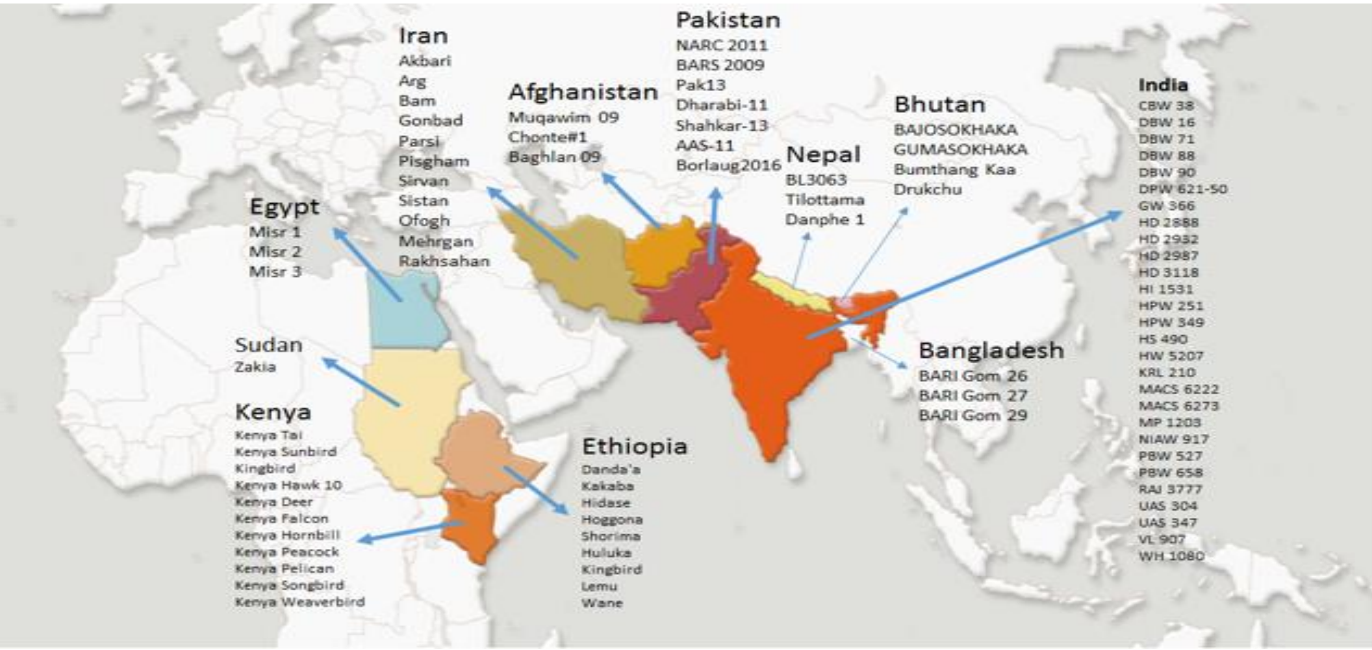






Rapid response to “UG99 “ threat

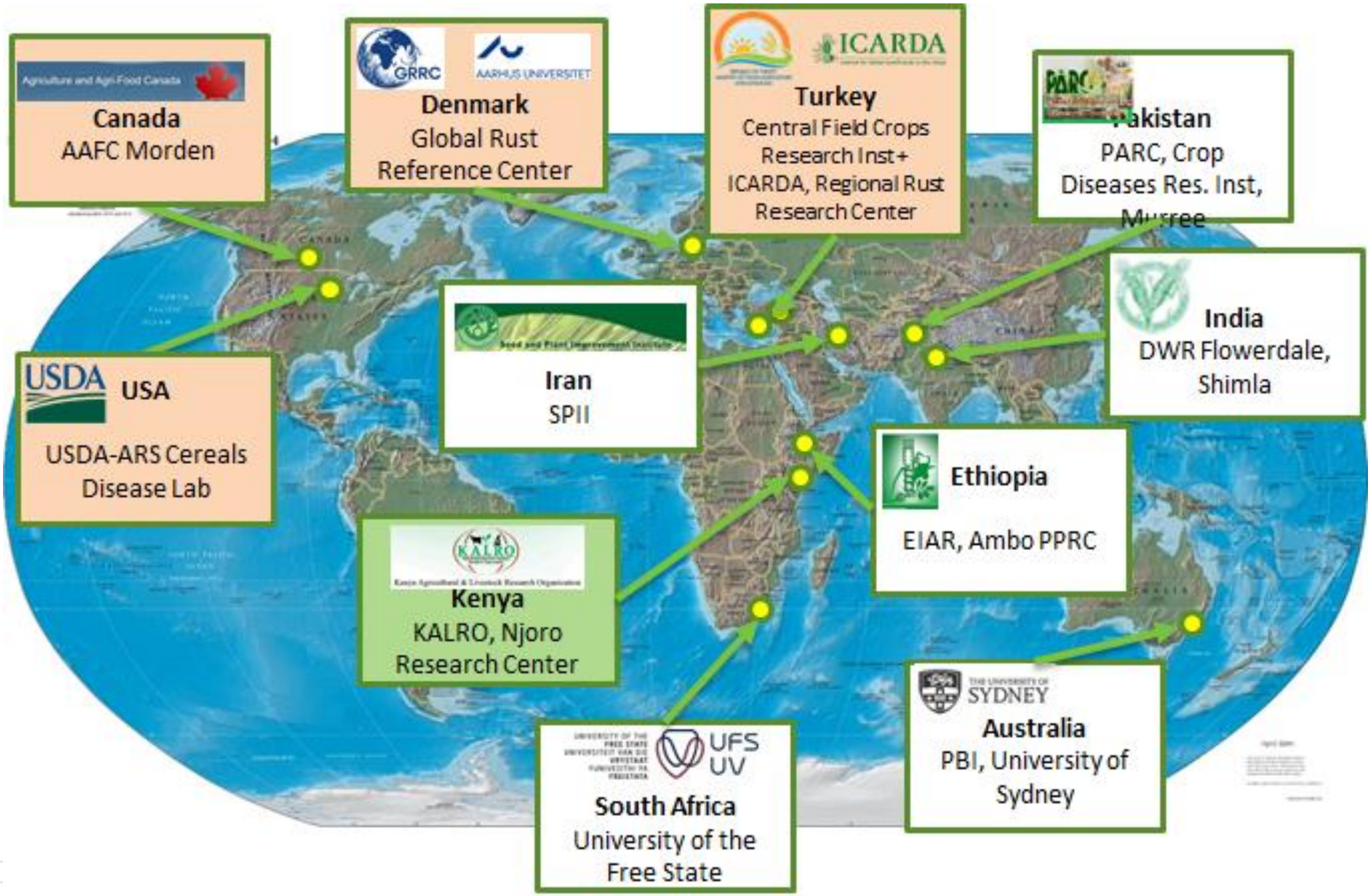
Some rust resistant wheat varieties released



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.

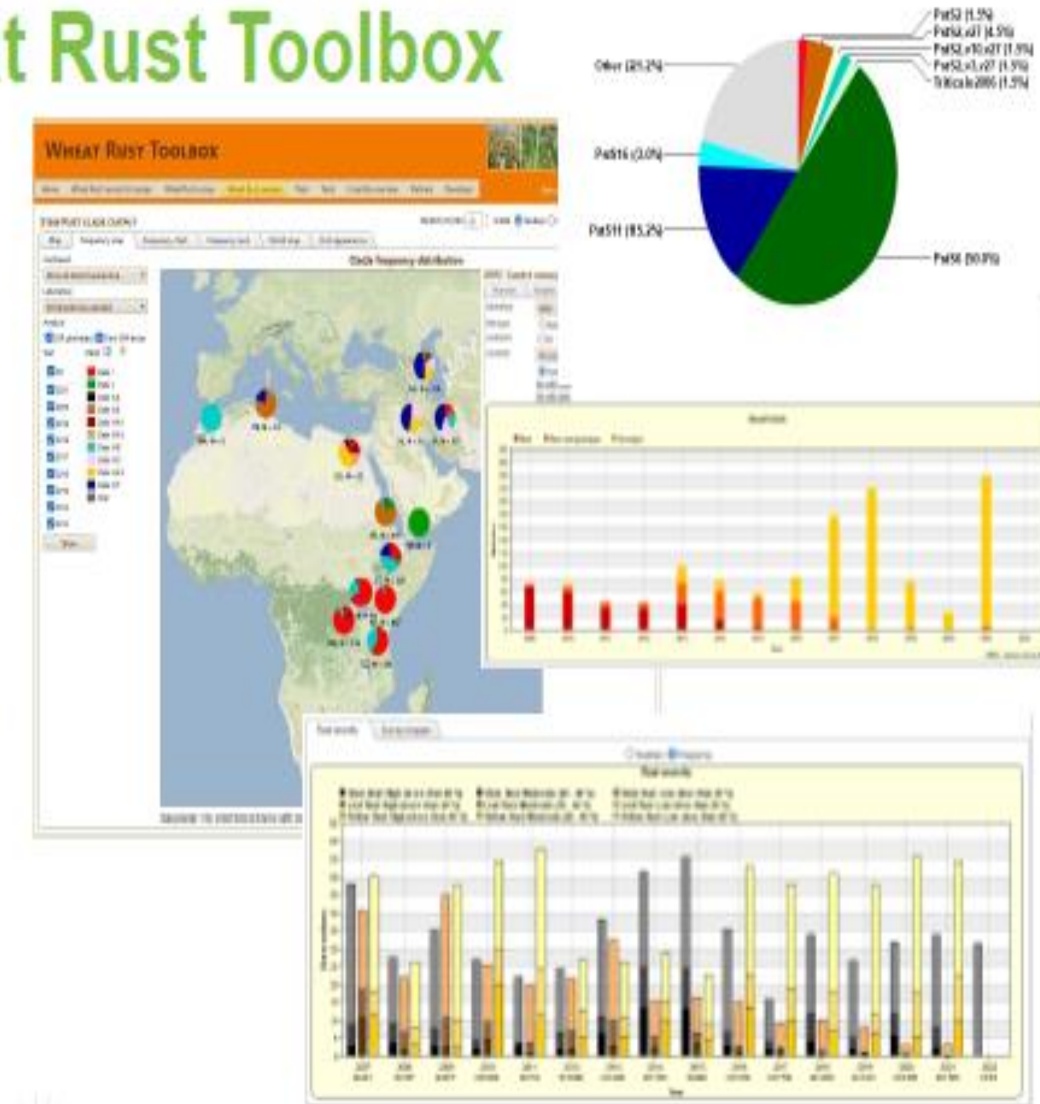
CIMMYT

Rust Pathotyping Lab Network



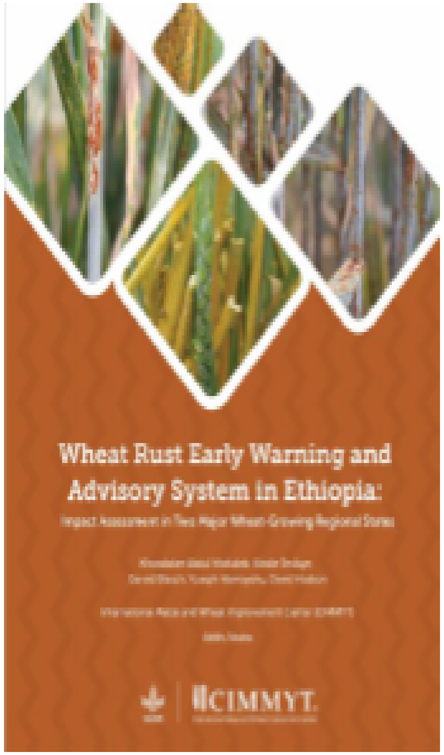
Wheat Rust Toolbox

- The wheat rust toolbox has been maintained and expanded.
- **One of the most comprehensive crop disease data resources**
- **55,000+ geo ref survey records from 43 countries**
- **10,000+ sample records (6700 YR, 3600 SR)**
- New display tools have been added:
  - frequency of races and genotypes
  - cultivar ranking on which races occur.
- A new module for the vulnerability mapping tool
- Automated ODK data feed to toolbox



Early Warning East Africa (Ethiopia, Kenya)

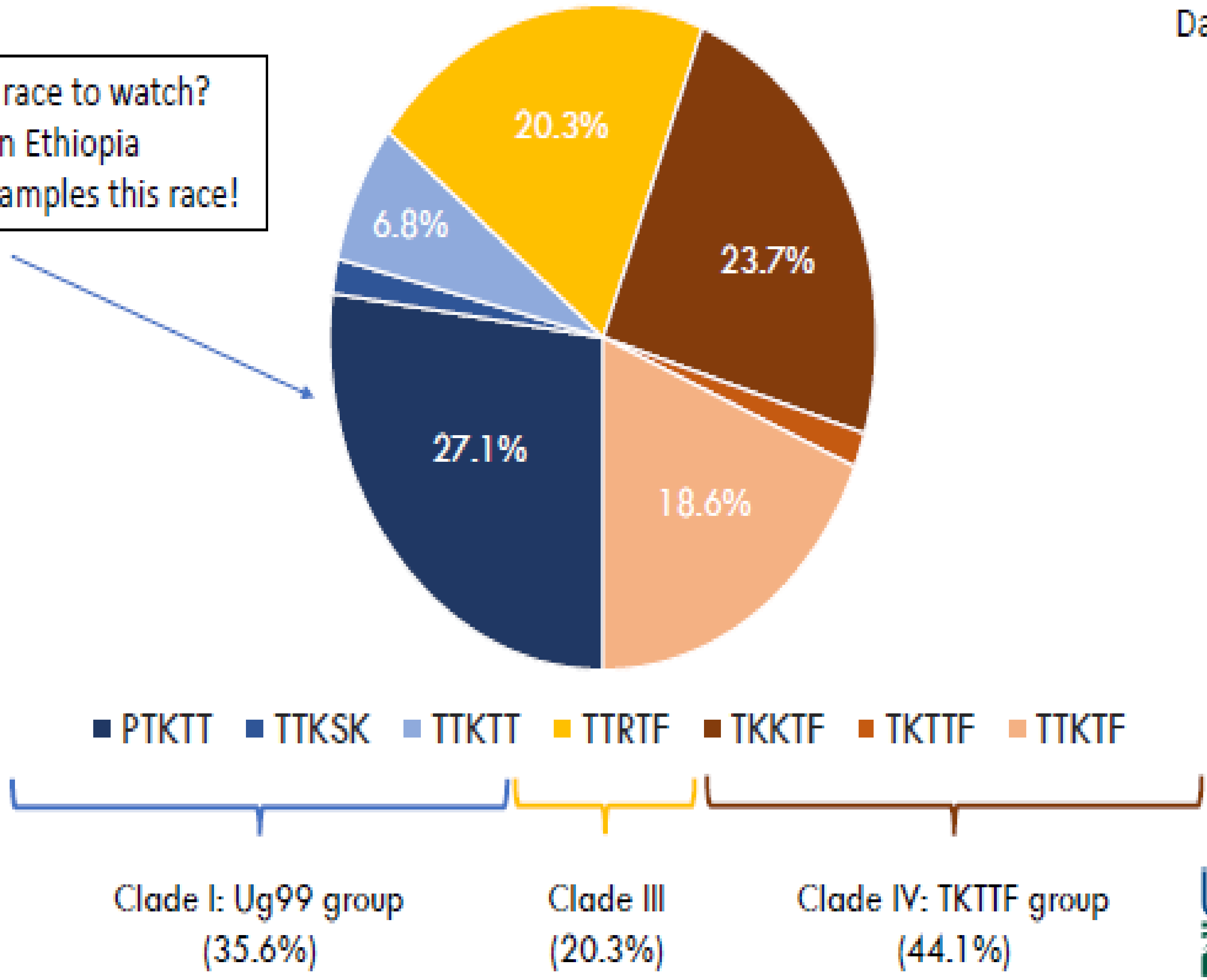
- Operational Early Warning Advisory System (EWAS) in Ethiopia – reaching 100,000's farmers
- Impact Assessment (ACES project) (Mottaleb et al 2021) – 1000+ farmers, Oromia & Amhara + repeat study in 2021/22 season
- Positive benefit from the wheat rust early warning system
  - farmer behaviour change in terms of fungicide use
  - increased awareness on rusts + ability to control
  - national policy changes e.g., reserve stocks of fungicides and creation of a dedicated desk in the national bank to facilitate import of fungicides.
- **2021/22 had extremely high risk for a yellow rust epidemic. It is extremely likely that the early warning and response prevented a major yellow rust epidemic in 2021 (Paper in prep)**
- EWAS now being expanded to Kenya – weekly advisories to KALRO



Races Ethiopia, 2021

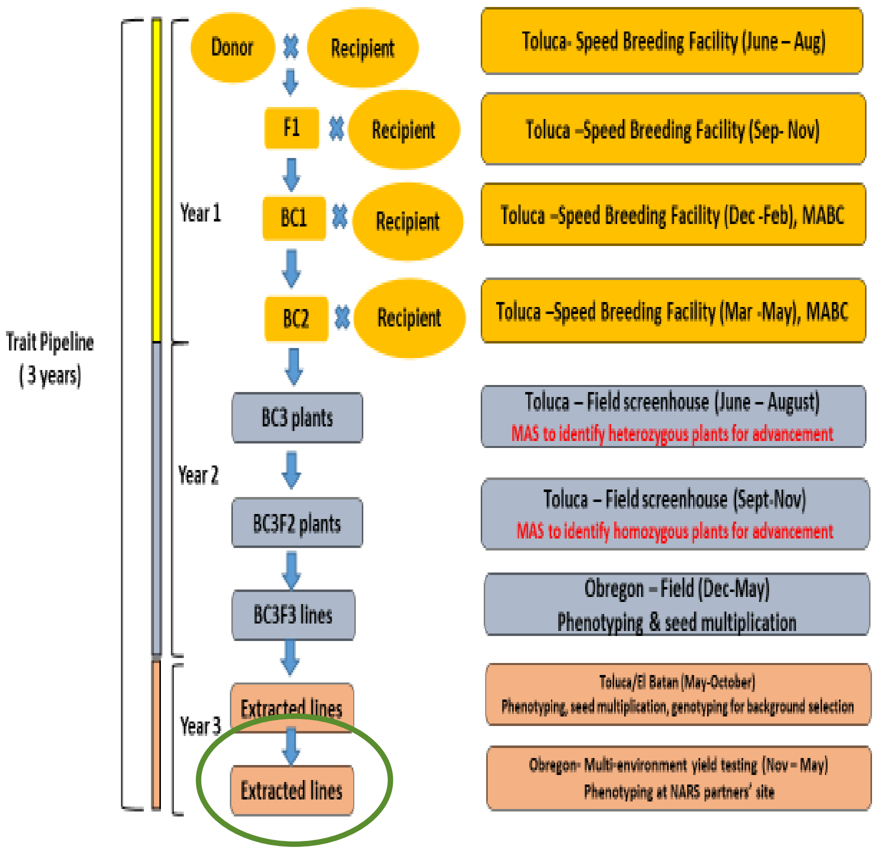
Data from Pablo Olivera

Race PTKTT – A race to watch?
First detection in Ethiopia
Nearly 30% of samples this race!

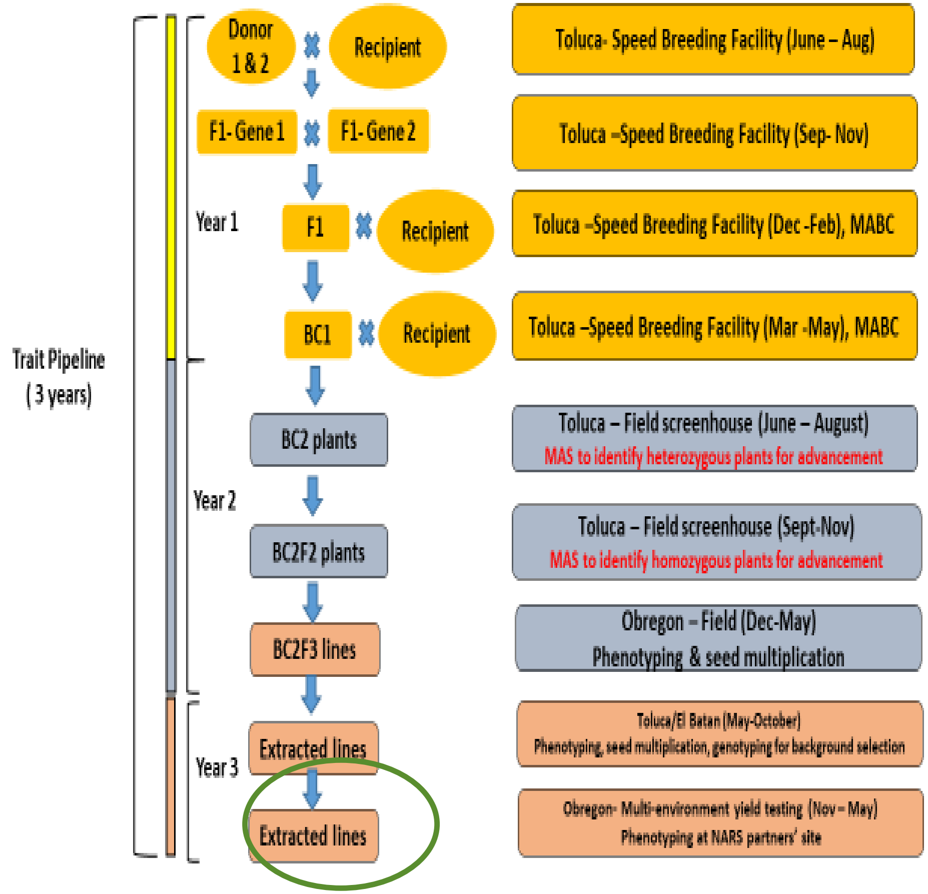


University of Minnesota

Trait integration pipeline for Rust resistance



Trait integration pipeline for incorporating single R-gene



Trait integration pipeline for incorporating two R-genes

Needs continuous trait discovery for deployment

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

CIMMYT

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

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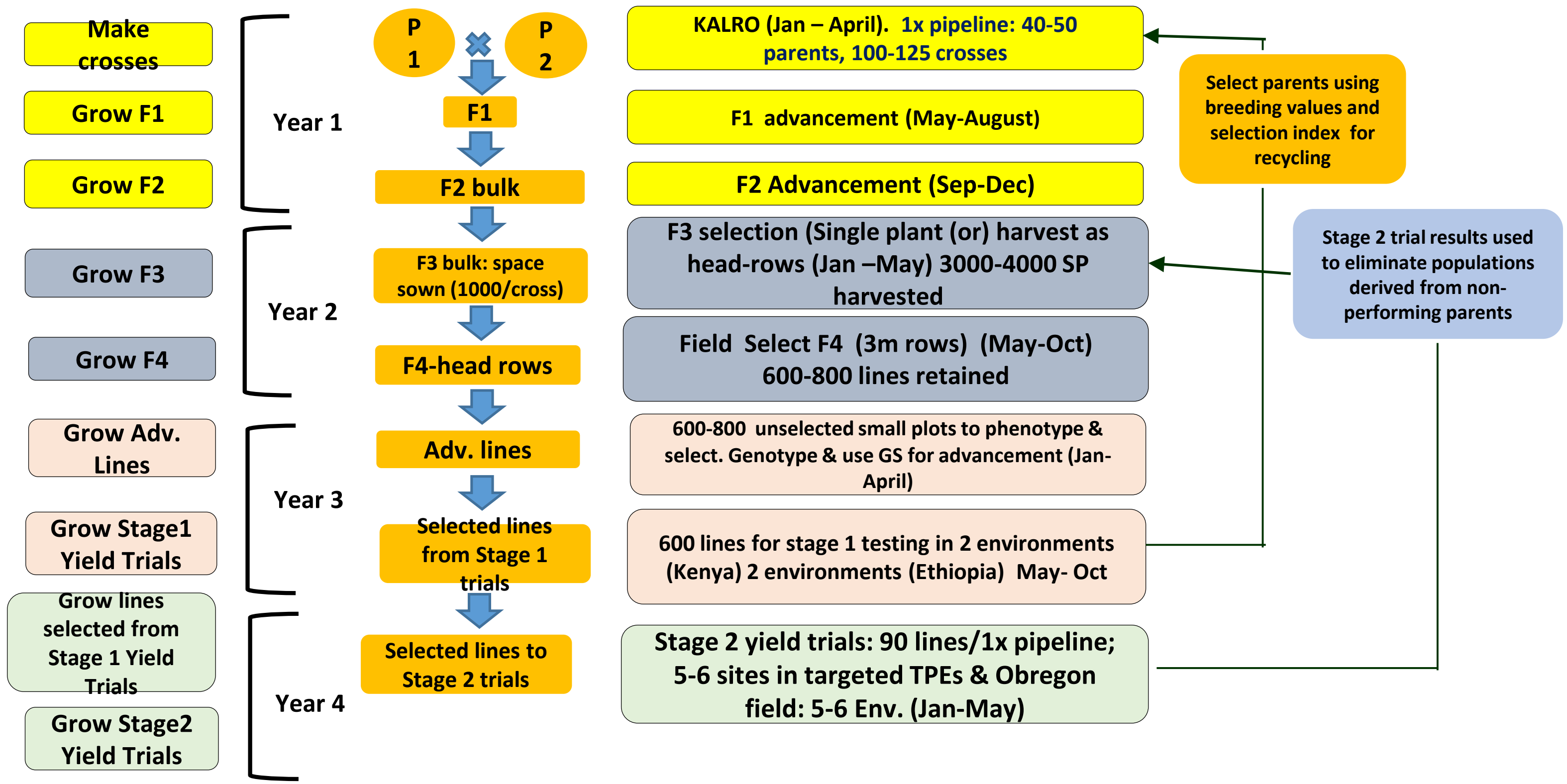
Number of lines with positive response for the markers in YTs

Gene	Y18-19	Y19-20
Sr35		11
Sr47		9
Sr50	14	22
Yr15	2	20
Yr41		5
Yr5	4	2
Yr5 + Yr15		2
Yr51		8
Yr57	2	17
Yr59	3	15
Yr52		3
Yr59		
Lr19/Sr25	8	
Yr60	5	
Sr26	2	
Lr67	2	
Sr22	11	
Fhb1	2	
Sr2	43	
Fhb1 + Sr2	15	

Pedigrees YT19-20
BLANCA GRANDE 515/3*CHIPAK
CHUAN NONG 19/3*BORL14
CHUAN NONG 19/3*MISR 1
IRAGI/3*BORL14
IRAGI/3*CHIPAK
IRAGI/MUCUY/3/2*MUTUS//ND643/2*WBLL1
SR47/4/3*KACHU*2/3/ND643//2*PRL/2*PASTOR
SR50/3*KENYA SUNBIRD
SR50/3/3*SWSR22T.B./2*BLOUK #1//WBLL1*2/KURUKU
SR50/3/3*SWSR22T.B./KACHU//2*KACHU
SR50/4/3*KACHU*2/3/ND643//2*PRL/2*PASTOR
SR50/4/3*KACHU/3/WHEAR//2*PRL/2*PASTOR
SR50/5/3*SHORTENED SR26 TRANSLOCATION/4/3*CHIBIA//PRLII/CM65531/3/MISR 2
SUMMIT 515/3*MISR 1
SUMMIT 515/3*NADI#2
W3763-SR35/3/3*SWSR22T.B./2*BLOUK #1//WBLL1*2/KURUKU
W3763-SR35/3/3*SWSR22T.B./KACHU//2*KACHU
W3763-SR35/4/3*KACHU*2/3/ND643//2*PRL/2*PASTOR
W3763-SR35/5/3*SHORTENED SR26 TRANSLOCATION/4/3*CHIBIA//PRLII/CM65531/3/MISR 2
YR51#5515-1/3*BORL14
YR51#5515-1/3*MISR 1
YR57#5474-6//SUP152/KENYA SUNBIRD/3/2*SUP152/CIRO16
YR57#5474-6/3*BAJ #1
YR57#5474-6/3*BORL14

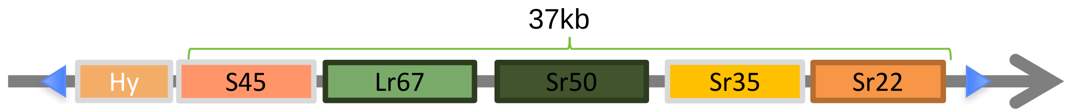
CIMMYT MR

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



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***

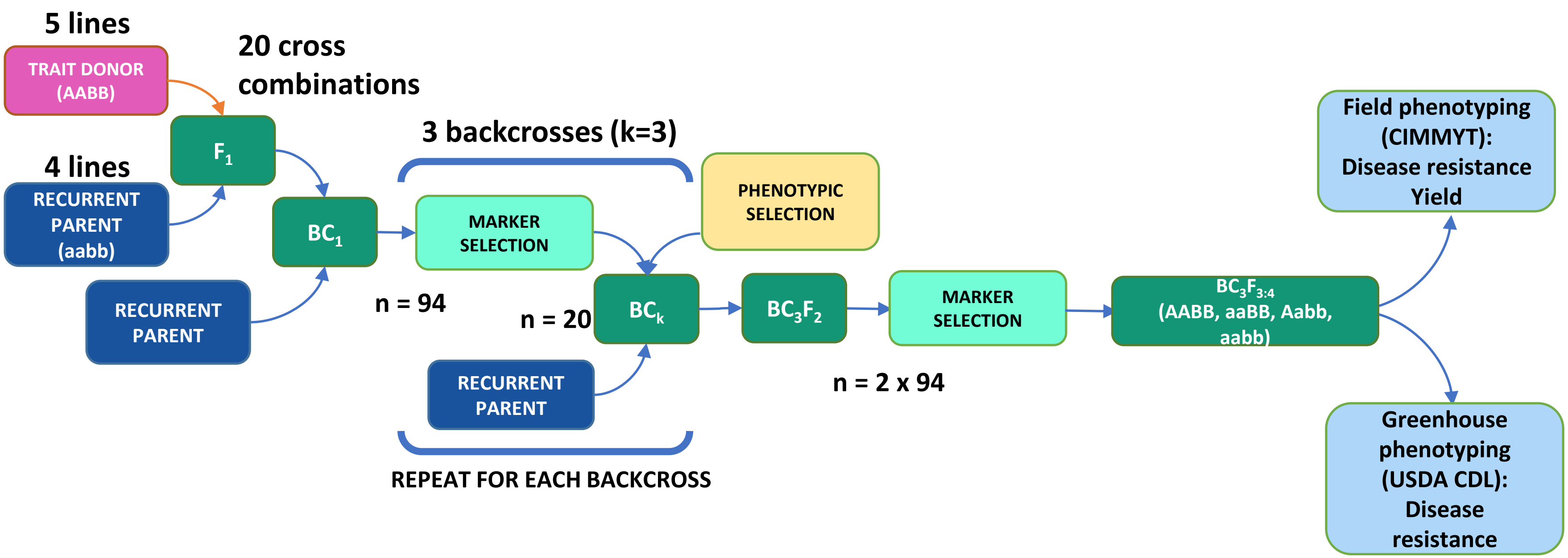
Multi-gene cassettes increase durability of resistance and segregate as a single locus simplifying breeding

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



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**

Outcome (6 years): 168 direct release of CIMMYT-derived spring bread wheat varieties by 24 partner countries (2015-2020); i.e., 28 varieties/year

Country	Name of variety
Afghanistan	Daima-17, Lalmi-17, Shamal-17, Garmser-18, Pakita 20, Jowzjan 20, Nasrat 20
Algeria	Ain El Hadjar, Bordj Mehis, El Hachimia, Nif Encer
Argentina	BIOCERES 1008, MS INTA 815
Australia	Borlaug100, SEA Condamine
Bangladesh	BARI Gom 31, BARI Gom 33, WMRI Gom 3
Bhutan	Bumthang kaa Drukchu
Bolivia	Cupesi CIAT, INIAF Tropical, Yotau, INIAF Okinawa
Egypt	Misr 3
Ethiopia	Amibara 2, Deka, Kingbird, Lemu, Wane, Bondena, Hadis, Hibist, Ga'ambo 2, Boru, Dursa
India	Ankur Shiva, DBW107, DBW110, DBW168, DBW93, HI1612, HI1605, HS562, PBW658, PBW677, PBW1Zn, Pusa Kiran, Pusa Vatsala, Super 252, Super 272, Super 404, WB2, WH1142, DBW187, HI1620, DBW222, NIAW3170, HI1628, HD3249, DBW252, HI1621, HUW711, Mucut, Tarak, VL Gehun 967, DBW303, WH1270
Iran	Baharan, Barat, Ehsan, Mehrgan, Rakhsahn, Sarang, Talaei, Tirgan, Torabi, Mearaj, Kelateh, Paya, Kabir, Sahar, Farin
Kenya	Kenya Deer, Kenya Falcon, Kenya Hornbill, Kenya Peacock, Kenya Pelican, Kenya Songbird, Kenya Weaverbird, Kenya Kasuku, Kenya Jakana
Jordan	Ghweir 1
Mexico	Bacorehuis F2015, Conatrigo F2015, Ñipal F2016, Ciro NL F2016, RSI Glenn, Noroeste F2018, Noeheli F2018, Hans F2019
Nepal	Chyakhura, Danphe, Munal, Tilottama, Zinc Gahun 1, Zinc Gahun 2, Bheri-Ganga, Himganga, Khumal-Shakti, Borlaug 2020
Nigeria	Lacriwhit 9, Lacriwhit 10
Pakistan	Anaaj-17, Barani-17, Borlaug 2016, Ihsan-16, Israr-shaheed-2017, Khaista-17, Kohat-17, NIFA-Aman, Pakhtunkhwa-15, Pasina-2017, Pirsabak-15, Shahid-2017, Sindhu-16, Ujala-16, Wadaan-2017, Zincol 2016, Ghazi 19, Markaz 19, Bhakkar 19, Gulzar 19, Fahim 19, NIFA Awaz, Aghaz 2019, Umeed-e-Khass 2019, Akbar 19
Paraguay	Caninde 31, Itapua 90
Peru	INIA 440 K'ANCHAREQ
Rwanda	Cyumba, Gihundo, Keza, Kibatsi, Majyambere, Mizero, Nyangufi, Nyaruka, Reberaho, Rengerabana
Spain	Tujena, Santaella, Montemayor, Setenil
Sudan	Ageeb, Akasha
Tajikistan	Haydari, Roghun
Turkey	Altinoz, Ekinoks, Kayra, Koc 2015, Nisrat, Polathan, Karmen, Kirve, Sahika, Simge

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

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