CIMMYT Strategy for Adult Plant Resistance (APR)

Yellow (stripe) rust
P. striiformis f. sp. *tritici*

Black (stem) rust
P. graminis f. sp. *tritici*

Brown (leaf) rust
Puccinia triticina

The persistent pathogens

The three rust diseases, yellow (stripe) rust, black (stem) rust, and brown (left) rust occur in most wheat production environments, causing substantial yield losses and under serious epidemics, can threaten the global wheat supply. Although not all losses to rust pathogens are documented in literature and those reported correspond to records from developed countries, it is estimated that average annual losses to wheat rust pathogens can be around 15 million tons, valued at US$ 2.9 billion globally.

Durable control of wheat rusts can be achieved by developing and deploying wheat varieties with complex adult-plant resistance (APR)

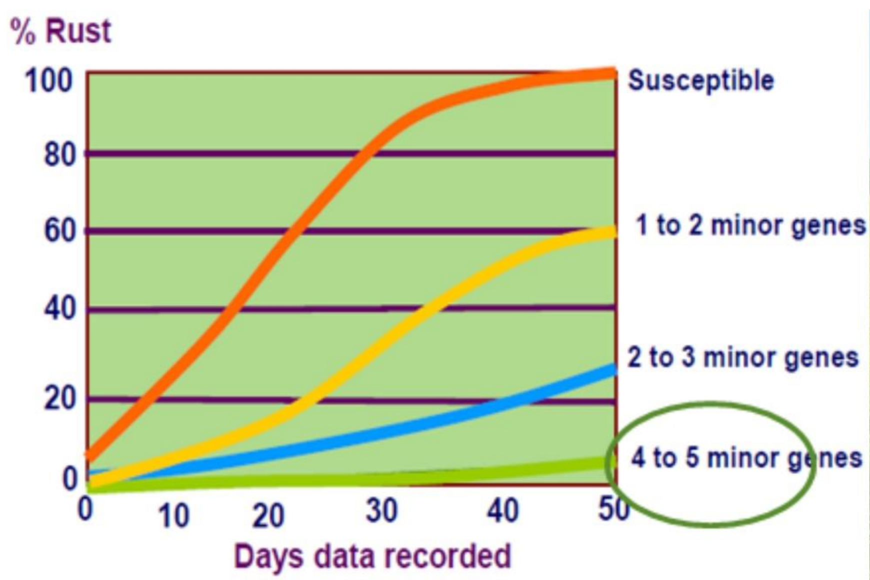
Resistance to wheat rust fungi is broadly divided into two classes: Race-specific genes (R-genes) and race-nonspecific adult plant resistance (APR). Commercially preferred R-genes usually have large effects against specific pathogen races and are often effective at all growth stages of plants. This makes them an easy choice for selection by breeding programs, both as both seedlings in the greenhouse and in the field, to develop resistant varieties. However, large-scale deployment of R-genes imposes a strong pressure to overcome virulent mutants in the populations of rust fungi, which can evolve within 3 to 5 years. Eventually, virulent mutants can break down the resistance genes, causing severe yield losses from widespread epidemics (a “boom and bust” cycle).

Because of this weakness in R-genes, CIMMYT has determined that deploying genetically complex and quantitative APR is undoubtedly the best choice for breeding varieties that have durable resistance. This is a decision that offers promise in protecting wheat, and indirectly, the livelihoods of millions of smallholder wheat farmers throughout Asia, Africa and Latin America.

In contrast to most R-genes, the level of resistance conferred by an individual APR gene is only partial, and has small or intermediate effects. However, by combining four or five APR genes, very high levels of resistance can be obtained and have shown to enhance durability. Some APR genes have even shown pleiotropic effects, or partial resistance to multiple pathogens. The distinct and diverse resistance mechanism and interactions of APR genes reduces the mutation and selection opportunity in the pathogen population, thus resulting in resistance durability.

Over the last four decades, rust research at CIMMYT has focused on characterizing, elucidating and selecting diverse APR genes in breeding populations. This has rejuvenated research on APR in and beyond CIMMYT while simultaneously providing elite lines with APR to national partners, resulting in the release of many varieties and their widespread cultivation. Even though breeding for quantitative APR is cumbersome initially, the additive and often pleiotropic effects of multiple minor APR genes enable selection of plants with high disease-resistance levels in-field, simultaneously with high grain yield-associated agronomic traits.

Pleotropic effect associated with *Lr67* (***Lr67/Yr46/Sr55/Pm46)***) on three rusts and powdery mildew (R= Resistant S= Susceptible) **Moore et al. 2015. Nature Genetics 47:1494-1498**



(a) Near-immunity (trace to 5% severity) achieved by combining (4-5 genes).

(b) New lines with high yields and high levels of complex adult-plant resistance to stem rust (Njoro, Kenya). A similar approach is now being used for other leaf spotting diseases, Fusarium head blight).

What genes are used and how are they selected?

Two pleiotropic, multi-pathogen APR genes *Lr34*/*Yr18*/*Sr57*/*Pm38*/*Sb1*/*Bdv1* and *Lr67*/*Yr46*/*Sr55*/*Pm46* were cloned and found to be both ABC (adenosine triphosphate–binding cassette) and hexose transporters. They belong to a different class of resistance genes than the majority of R-genes, which belong to the NBS-LRR (nucleotide-binding site, leucine-rich repeats) gene family or a variant of this family. These two genes, and other pleiotropic APR genes viz. *Lr46*/*Yr29*/*Sr58*/*Pm39*, and APR gene *Lr68* also have morphological marker LTN (leaf tip necrosis).

The stem rust APR gene, *Sr2*, is also likely pleiotropic and confers partial resistance to the yellow rust- *Yr30*, leaf rust, and powdery mildew- *Pm48* genes and the morphological marker PBC (pseudo-black chaff). These morphological markers can aid in selection, however, it is preferred to select plants that show minimum expression of these traits. Functional markers for the two cloned genes and tightly linked markers for the other two are available to facilitate marker-assisted selection. The characterized APR genes have conferred resistance in modern and improved tall varieties and landraces, possessing them for several decades and therefore have proven to be durable.

Studies on the expression of *Lr34* into transgenic barley and rice showed resistance to barley leaf rust, barley powdery mildew and rice blast. Similarly, recent reports of *Lr34* resistance, expressed in transgenic maize, showed increased resistance against common rust and northern corn leaf blight.

Demonstrated evidence that APR strategy works

Many CIMMYT-derived bread wheat varieties were no exception to the “boom-and-bust cycles” with leaf rust during the 1970-1990’s. These varieties carried either single R-genes or their simple combinations, thus succumbing to new races that caused substantial yield and monetary losses to wheat farmers in Mexico, requiring fungicide control and a search for new, resistant varieties. The problem of continuous evolution and migration of new rust races overcoming deployed R-genes, and the genetic knowledge generated on APR genes and their near-immune resistance levels, prompted CIMMYT wheat breeders to fully embrace and mainstream APR in the CIMMYT breeding program to enhance resistance durability.

The last breakdown of leaf rust resistance occurred in 1994 when wheat variety “Baviacora 92” became moderately susceptible to a new incursion of a leaf rust fungal race. Releases and widespread cultivation of APR varieties since then have stabilized the situation in Mexico for the last 26 years and in many other leaf rust-prone countries growing CIMMYT-derived varieties that possess four to five additive APR genes.

More recently, to combat “Ug99” and other races of the stem rust fungus in East Africa and new, more aggressive races of the yellow rust fungus, the Obregon-Toluca shuttle breeding scheme was further expanded to include a Mexico-Kenya shuttle breeding scheme in 2008 to identify and increase the frequency of resistance to the Ug99 race group within breeding materials. High emphasis was given to rebuilding APR based on *Sr2* and other minor resistance genes (*Sr55*, *Sr57*, etc.) to achieve resistance durability. The Mexico-Kenya shuttle has allowed scientists to drastically increase APR gene frequencies in combination with high yield potential through field-based selection. Moreover, breeding germplasm was also enriched with diverse R-genes for deployment in regions beyond eastern Africa as a preemptive measure.

The presence of different aggressive races of the yellow rust pathogen in Kenya also helped with the selection of APR gene combinations effective in the east African environment. Wheat varieties with APR that were released and grown in Kenya and Ethiopia include “Kingbird,” “Kakaba,” “Danda’a” and “Deka.” The first two, released in 2010, now occupy about 40% of Ethiopia’s wheat growing area and hold up well against stem rust.

Meanwhile, other R-gene-protected varieties, such as “Digalu,” have succumbed to a new race of stem rust. “Kingbird” has maintained the same level of APR in Kenya and Ethiopia since its identification in 2008 as APR variety, further proving the durability of APR. Deploying this strategy in CIMMYT-derived wheat varieties in different geographies has resulted in resistance durability and has eliminated the need to continuously introgress new R-genes in breeding germplasm already enriched with diverse, quantitative APR genes.

Controlled field epidemics remain the best tool for selecting/phenotyping slow rusting resistance in breeding populations at hot-spot sites for the three rust diseases

APR varieties released in Ethiopia

Photo: Daniel Kasa (EIAR), Bekele Abeyo, (CIMMYT, Ethiopia)

Importance of CIMMYT's APR strategy in the AGG project

Highly diverse populations of rust fungi with asexual and sexual evolution mechanisms, followed by new virulences, have resulted in serious localized epidemics in different wheat growing regions of the world. In addition to rapid pathogen evolution, local, regional and intercontinental migration of rust races has resulted in serious epidemics over the last two decades.

Yellow races that are more aggressive and adapted to warmer temperatures have migrated and spread across geographies and continents since 2000, resulting in the vulnerability of widely deployed cultivars. The disease impact is much higher than "normal" when sudden "exotic" incursions of strains from other continents occur. Thus, breeders and plant pathologists now need to not only focus on breeding for resistance to local yellow rust populations, but must also be prepared for any foreign incursions. In addition to pathogen diversity and transboundary migration, genetic uniformity has also contributed to plant vulnerability to rapidly evolving pathogens, threatening global wheat production.

To address these challenges and to continue delivering continuous genetic gain for other relevant traits, a concerted global effort must be made in using appropriate resistance breeding strategies to achieve durable disease resistance. Using APR is a preferred breeding strategy for CIMMYT's wheat breeding pipelines, which can be further rust-proofed in hot spot regions by incorporating additional, geographically targeted R-genes through trait integration pipelines.

CIMMYT is one of the largest providers of elite germplasm to national partners in over 80 countries through targeted international trials and nurseries. CIMMYT nurseries, in addition to being adaptive, high-yielding and high-quality, also carry resistance to several biotic and abiotic stresses. Disease resistance within breeding materials is completely under genetic control, so the concept of responsible gene deployment is fundamental to CIMMYT.

Advances in next-generation sequencing (NGS) technologies and bioinformatics tools have revolutionized wheat genomics in the recent decade. Significant progress in the field of wheat functional genomics and a growing number of genes controlling rust resistance have been identified and cloned. High-throughput genotyping platforms have not only reduced the cost, but wider genome coverage and density has enabled better estimation of genetic diversity, construction of the high-density genetic maps, dissecting polygenic traits, and understanding their interactions through GWAS (genome-wide association studies) and QTL (Quantitative trait loci) mapping studies. Deploying breeder-friendly KASP (Kompetitive allele specific PCR) has expedited the transfer of diverse APR genes in elite lines.

A combination of both conventional and modern technologies in mining and deploying APR will enable breeders to address the problem of rusts and other diseases and continue progress in delivering higher genetic gains, the main goal of the Accelerating Genetic Gains in Maize and Wheat (AGG) project.

Recommended reading

- Ali S, Gladieux P, Leconte M, et al (2014) Origin, Migration Routes and Worldwide Population Genetic Structure of the Wheat Yellow Rust Pathogen *Puccinia striiformis* f.sp. *tritici*. PLoS Pathog 10:. https://doi.org/10.1371/journal.ppat.1003903
- Bhavani S, Hodson DP, Huerta-Espino J, Randhawa MS, Singh RP, 2019. Progress in breeding for resistance to Ug99 and other races of the stem rust fungus in CIMMYT wheat germplasm. Frontiers of Agricultural Science and Engineering 6, 210–224.
- Chen X, Kang Z (2017) Stripe Rust. Springer Netherlands, Dordrecht
- Singh RP, Huerta-Espino J, Bhavani S, et al (2011) Race non-specific resistance to rust diseases in CIMMYT spring wheats. Euphytica 179:175–186
- Singh RP, Hodson DP, Jin Y, et al (2015) Emergence and spread of new races of wheat stem rust fungus: Continued threat to food security and prospects of genetic control. Phytopathology 105:872–884.
- Wellings CR, 2011. Global status of stripe rust: A review of historical and current threats. *Euphytica* **179**, 129–141
- William HM, Singh RP, Huerta-Espino J, Rosewarne G, 2007. Characterization of genes for durable resistance to leaf rust and yellow rust in Cimmyt spring wheats. In: Springer, Dordrecht, 65–70.