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Final report

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1 Acknowledgments

We acknowledge the support of our institutions, CIMMYT, ICARDA and University of Sydney for their support. Collaboration of numerous National Program Scientists and support from their respective institutions are also highly valued for the implementation of the project.

2 Executive summary

ACIAR funding supported ongoing, new research and capacity building activities at CIMMYT, ICARDA, and PBIC-Sydney University to ensure productivity and food security through sustainable control of wheat yellow rust, caused by Puccinia striiformis tritici (Pst), in Asia with spill-over effects in other regions. Yellow rust at present is the most important disease in Asia, Middle East and Africa where significant losses continue to occur. The goals of this project were combined with the goals of the "Borlaug Global Rust Initiative" especially to disseminate and breed spring wheat materials with durable resistance to all three rusts and training. This became necessary because Ug99 and its derivatives races of stem rust pathogen threaten wheat production in most of the countries within scope of the ACIAR project. The project had objectives: 1) To monitor the evolution and migration of new races of Pst in Asia; 2) To provide early warning to participating countries by advising significant changes in virulence or virulence frequency of Pst population in the region; 3) To identify the race-specific and adult plant resistance to Pst in popular cultivars; 4) To incorporate durable yellow rust resistance into adapted cultivars and promote their deployment; and 5) Scientific capacity building through training.

Existing and newly developed Avocet near-isogenic lines (NILs) were distributed worldwide and are now routinely used in many countries to determine changes in virulence in pathogen population through field based trap nurseries. Field samples can now be characterized at University of Aarhus, Denmark to identify the actual race. The key findings were 1) the worldwide spread of the highly aggressive race(s) adapted to warmer temperature, and its further evolution in different parts of the world to overcome additional resistance genes, including Yr27, a gene present in some of the mega-varieties in South Asia, Middle East and Africa; and 2) Identification of other races with virulences to some important resistance genes, such as Yr17, Yr27, Yr24 and Yr31, used in breeding programs. Pathogen monitoring allowed giving early warning to countries regarding the genetic vulnerability of some of the main varieties. Also studies on genetic resistance helped identify existing varieties and promising breeding materials that can be used for replacing the current varieties.

Development of high-yielding, adapted wheat germplasm with durable, adult plant resistance (APR) through shuttle breeding was undertaken in close collaboration with Sichuan and Yunnan Academies of Agricultural Sciences in China. Over 50 high-yield wheat germplasm adapted in Sichuan and Yunnan with high to adequate APR could be developed and some of these are at various stages of testing for release as varieties. More importantly several scientists in China are using these resistant materials in their breeding programs to develop future varieties. Incorporation of durable APR into popular facultative/winter wheat varieties was also initiated however finished products are expected to be available by 2012.

Multi-site testing of high yielding spring wheats with resistance to all three rusts (including Ug99 race of stem rust) were conducted since 2006-2007 wheat season. This resulted in the release of 3 varieties in Afghanistan, 2 in Egypt, 3 in Ethiopia and additional varieties are expected to be released in coming years in various other countries.

Various scientists were trained through intensive courses, specialized research activities, or short workshops. Training is expected to improve the quality of research, pathology and breeding done by these scientists.

Although significant progress was made during the project period, pathology, genetics, breeding, training and seed dissemination activities need to continue to ensure new research results reach farmers to enhance their income and contribute to food security.

3 Background

Of the total area (approximately 215 million hectares) sown to hexaploid and tetraploid wheat (Triticum aestivum and T. turgidum var. durum) worldwide, 44% (95 million hectares) is in Asia. Of this, 62 million ha is in just three countries: China, India, and Pakistan. However, food security and production stability are of paramount importance in most Asian countries, given that a majority of farmers are poor. The rust diseases of wheat have historically been one of the major biotic production constraints both in Asia and rest of the world including Australia. Yellow (or stripe) rust caused by Puccinia striiformis tritici (Pst) continues to pose a major threat to wheat production across a large area. Stripe rust could affect production on approximately 43 million ha in Asia (46% of the area), if susceptible cultivars are grown. Recent breakdowns of the yellow rust resistance gene Yr9 present in several cultivars grown in South, West and Central Asian countries and an unknown gene present in several Chinese cultivars have caused crop losses amounting to several million dollars and impacted the livelihoods of millions of poor farmers. Therefore, stripe rust is currently considered as the most important biotic constraint to sustainable wheat production in Asia.

Although the timely application of fungicides can provide adequate control, their use adds to production costs and pollutes the environment. Growing resistant cultivars is thus the most effective and efficient control strategy, as it has no cost to farmers and is environmentally safe. Significant variation for virulence to specific resistance genes in populations of highly specialized rust fungi, combined with the rapid evolution of new virulence through migration, mutation, or recombination and selection of existing virulences continue to complicate the control strategy.

Diversity of resistance in Asia can be maintained by growing cultivars that carry different resistance genes. However, there is a general tendency for farmers to grow only one or a few “choice” cultivars, which, as a result, come to occupy large areas. An example of this is cultivation of varieties ‘PBW343’ and ‘Inquilab 91’ on 7 and 6 million hectares in India and Pakistan, respectively. These cultivars are also grown in other countries under different names. Unfortunately, both cultivars are protected from stripe rust by the same resistance gene Yr27, for which virulence has been detected recently in Asia. Growing fewer cultivars that carry race-specific resistance genes thus leads to greater genetic uniformity and, consequently, greater disease vulnerability.

When stripe rust epidemics occurred in 1995 and 1996 in Pakistan, continuous wheat cropping from NWFP to Punjab was severely affected. Luckily the epidemic did not cross into the Indian side of the Punjab as the predominant cultivar in India was resistant. Similarly yellow rust epidemics in China have stretched from Gansu province to Yunnan Province. This experience clearly shows that if conditions are favorable then epidemics can stretch over a long distance. The environment (both temperature and relative humidity) in the northwestern wheat belt of India is very conducive for yellow rust epidemic during the months of December-mid March. Fungicides are not used as a standard crop management practice in South Asia. So if epidemics occurs, then the control will be difficult due to the lack of fungicides and knowledge of how and when to apply them. This means that losses will be high during the first year. During the 1995 and 1996 yellow rust epidemics in Pakistan, farmers did not use chemical control either due to high cost or lack of availability when they needed them. Chemicals were used in China over a large area to protect the wheat crop from yellow rust when a new race that had virulence for an undesignated resistance gene present in several popular cultivars caused major epidemics in the 2001-2002 season and subsequent years. The use of chemicals was successful only after the major epidemic during the first year when the governmental agencies mobilized the availability of fungicides. Manufacturing of generic fungicides in China has resulted in their low cost and thus enhanced acceptance by farmers in the affected areas as a routine crop management practice. Resistant cultivars are now replacing the susceptible cultivars and thus reducing the dependence on chemicals.The wheat crop can be protected from rust, or at least the occurrence of epidemics in Asia could be reduced, by emphasizing the following three strategies: 1) regional cooperation in monitoring the evolution and migration of new races of rust fungi, 2) enhanced information on the genetic basis of resistance in important wheat cultivars, and 3) a shift towards breeding and deploying wheat cultivars with durable resistance.

Regional cooperation in monitoring the evolution and migration of new races of rust fungi:

Monitoring the evolution and migration of new, virulent Pst races should be a high priority in Asia, especially because: 1) the spores of these fungi can move freely over long distances; 2) several currently grown cultivars carry race-specific resistance genes; 3) the same cultivars are being grown in more than one country; and 4) the same genes confer resistance to several cultivars grown in different countries. Political tensions in the region often do not permit scientists in some countries to collaborate and communicate with each other directly and hence the presence of a politically neutral institution such as CIMMYT or ICARDA is important to coordinate such efforts. It may also be necessary to test cultivars at hot-spot locations outside the region, as virulence for certain resistance genes may already be present in the pathogen population. Virulence for the stripe rust resistance gene Yr9 was known in China, Eastern Africa, Yemen and Central America in the mid 1980s, long before epidemics occurred on cultivars carrying Yr9 in West and South Asia. Similarly, virulence for gene Yr27, present in two leading cultivars in India and Pakistan, has been present in Mexico since the mid 1990s. Such testing is useful in determining the cultivars' level of susceptibility and identifying additional resistant cultivars at a low cost in a short time. This could alert national programs to a forthcoming problem.

Enhanced information on the genetic basis of resistance in important wheat cultivars:

Promoting cultivars that have distinct resistance genes can enhance genetic diversity in farmers' field. Generation of such information often has low priority, as conducting detailed genetic analysis is time consuming and often-considered academic. Several Asian countries lack proper greenhouse facilities, trained personnel, or the financial resources needed to conduct such research. A simple technique is to test cultivars as seedlings in the greenhouse with an array of diverse races of known avirulence/virulence combinations and use the host-pathogen interaction data to postulate the presence of known resistance genes. For some resistance genes, especially those transferred from alien sources to wheat, tightly linked DNA-markers are now available and can be used in gene identification. Further testing in the field of adult plants with known races at selected sites in Asia, outside the region, and at laboratories in advanced institutions could help determine the effectiveness of such seedling resistance genes and the presence of additional adult-plant resistance. Often this kind of testing, combined with pedigree information, may be enough to help enhance the genetic diversity, but genetic analysis may be necessary to confirm the gene postulations.

Shift towards breeding and deploying cultivars with durable resistance:

The phenomenon of the erosion of race-specific resistance genes, or their combinations, has led scientists to look for alternative approaches to resistance management. Van der Plank (1963) was the first epidemiologist to clearly define the theoretical basis of concepts of resistance. In the late 1960s and 1970s, there was a revival of the concept of general (race-nonspecific) resistance and its application in crop improvement (Caldwell, 1968). This approach was widely used for breeding stem rust resistance in wheat by Dr. N. E. Borlaug, leaf rust resistance by Caldwell (1968) and yellow rust resistance by Johnson (1988). The wide-scale application of such a concept in breeding for leaf rust resistance, commonly known as slow rusting, has dominated CIMMYT's bread wheat improvement for almost 30 years with major impacts (Marasas et al. 2004). Today, we understand better the genetic basis of durable resistance to yellow rust, and this knowledge is being applied in breeding at CIMMYT and PBIC. We firmly believe that deployment of durable resistance based on slow rusting resistance genes that have small to intermediate but additive effects will provide a long-term genetic solution to rust control in Asia and other countries.

4 Objectives

The aim of this project is to increase the food security and profitability of wheat production systems in several countries of Asia and to protect the environment and human health through strategies contributing to the sustainable control of yellow rust disease of wheat.

Objective 1: To monitor the evolution and migration of new races of Puccinia striiformis tritici (causal agent of yellow rust of wheat) in Asia.

Hypothesis

Field based monitoring using Avocet near-isogenic lines and popular cultivars is an effective tool to determine changes in pathogen populations.

Objective 2: To provide early warning to participating countries by advising significant changes in virulence or virulence frequency in the region.

Hypotheses

An early detection of new virulence when still in low frequency or just in one part of the region can prepare national programs for a forthcoming problem in coming years.

Resistant cultivars, existing and new, to the new race can be identified, multiplied and promoted to reduce losses even before the problem is widespread.

Objective 3: To identify the race-specific and adult plant resistance to Puccinia striiformis in popular cultivars.

Hypothesis

Information on the resistance genes present in cultivars is necessary to identify genetically diverse, resistant cultivars for promotion.

Objective 4: To incorporate durable yellow rust resistance into adapted cultivars and promote their deployment.

Hypotheses

Sources and breeding methodologies to incorporate minor gene based durable resistance are now available.

Incorporating durable resistance in popular wheat cultivars gives rise to derived resistant lines, which should maintain their adaptive traits and hence should be adopted easily by farmers.

Objective 5: To strengthen the network of collaborators in Asia through training at PBIC and CIMMYT.

Hypotheses

Plant Breeding Institute (Cobbitty), CIMMYT and ICARDA have expertise and facilities to conduct proper training in the area of rust epidemiology, genetics and breeding for resistance.

Better-trained scientists in various countries in the region will form an effective network.

5 Methodology

5.1 Development and distribution of Avocet NILs

Rationale: Development of Avocet near-isogenic lines carrying additional yellow rust resistance genes, both designated and those undesignated but present in common cultivars or in wheat germplasm, is an essential activity to fully characterize the variation in Puccinia striiformis tritici.

Specific tasks:

Identify important designated Yr resistance genes and other sources that are likely to carry previously unnamed genes, eg. Chinese and Indian yellow rust differentials, cultivars from China and new wheat lines that have synthetic wheats in their pedigree.

Understand the genetic basis of resistance and transfer these Yr genes into Avocet through repeated backcrossing (BC) into plants heterozygous for the resistance genes. The heterozygous plants identified either by testing their reaction to rust in the greenhouse or in the field (selfing BC plants will be necessary after two backcrosses for recessive resistance genes to identify plants that are homozygous for resistance gene). Selfed BC5 derived populations will be used for identifying NILs that are homozygous for resistance genes. New NILs distributed either directly or through the Global Rust Monitoring Nursery managed by CIMMYT and ICARDA.

The generation and distribution of NILs will be funded from the ACIAR project. Near-isogenic lines are now available for the following 18 resistance genes: Yr1, 5, 6, 7, 8, 9, 10, 11, 12, 15, 17, 18, 24, 26, 27, A, Sp and CV. Partially backcrossed (three backcrosses) lines are available for Yr28, 29, 30 and 31. Two to three additional backcrosses will be needed to complete the isogenic line generation. The additional genes proposed for developing NILs are the following designated genes: Yr2, 3, 4, 25, 33, 34, 35, and about six non-designated genes from synthetic, Chinese and Indian wheats.

For field based trap nurseries, it is also important to generate Avocet-lines that have combinations of genes of importance. We plan to develop between 6 to 10 combinations such as: Yr6+Yr7, Yr9+Yr27, Yr6+Yr17, YrA+Yr9, etc.

PBIC will be responsible for developing most of the new NILs and Avocet-lines with gene combinations, although some NILs will also be developed at CIMMYT or other institutions.

5.2 Pathogen monitoring through field based trap nurseries for an early warning system

Rationale: A majority of Asian countries do not have proper greenhouse facilities to determine pathogen variability. Field based trap nurseries are cheaper to operate and have been used by many to trap rust and determine the variation in the population.

Specific tasks:

Avocet NILs, important cultivars grown in the region and some other genotypes currently being used by CIMMYT and ICARDA will form the Rust Monitoring Nurseries for China, South Asia and West Asia/North Africa/Central Asia. New Avocet NILs will be incorporated as they become available.

Seeds of entries included in the monitoring nurseries will be multiplied at CIMMYT and ICARDA and distributed for planting in trap plots at key sites in each of the participating countries.

CIMMYT/ICARDA/PBIC scientists travel each year to selected countries and interact with NARS scientists to discuss the concept and use of data.

CIMMYT and ICARDA collect data back from NARSs, summarize, identify significant changes in pathogen populations and communicate results and the significance.

Any significant change used by NARSs as an early warning to withdraw susceptible cultivars.

The cost of the multiplication, distribution and analysis of data for the trap nurseries and the travel costs of the scientists will be absorbed by the ACIAR funds. CIMMYT will be responsible for the multiplication, distribution of nurseries and collection of data for South Asia and China, whereas ICARDA will be responsible for West and Central Asia. The yellow rust trap nursery will include between 60-80 lines depending on the sub-region.

5.3 Characterization of resistance in important cultivars grown in Asia

Rationale: Knowledge on the genetic basis of resistance in the cultivars currently grown or recommended can be used to enhance the genetic diversity in a country and the region.

Assemble a set (between 80 to 100) of wheat cultivars grown by the farmers or recommended for growing in Asian countries and test them with selected Pst races in the greenhouse at PBIC and CIMMYT to postulate the presence of known and unknown seedling effective resistance genes.

Evaluate the above set of cultivars in field trials at PBIC/CIMMYT/ICARDA and selected hot-spot sites within Asia and outside Asia under high rust pressure and determine the effectiveness of seedling resistance in field and identify cultivars which may carry additional adult-plant resistance.

Use DNA-markers linked to certain resistance genes to aid gene postulation.

Use the greenhouse, DNA-marker and field data to establish genetic diversity in these cultivars for yellow rust resistance.

Communicate this information to collaborating NARSs.

5.4 Incorporation of durable resistance in adapted cultivars

Rationale: Farmers in developing countries usually grow only a few cultivars. These “choice” cultivars have the best yield potential and yield stability. Incorporation of durable resistance in these cultivars is a fast way to provide a new derived adapted cultivar to farmers.

Specific tasks:

CIMMYT studies have shown that minor genes can be incorporated successfully into a cultivar by using a “single backcross- selected bulk” breeding scheme. Resistant derivatives of four important cultivars grown in South and West Asia were recently completed following the above scheme. These lines will be promoted for testing and release in various countries.

100 BC1 populations (400-500 seeds in each case) were obtained at CIMMYT during 2003 from the crosses of 20 spring wheat cultivars from China with five donor minor genes carrying lines. These populations will become part of the objective.

50 BC1-derived F5 populations from the cross of five Chinese cultivars and 10 donor lines were shipped back to China during 2003. A CIMMYT scientist will travel to China to assist in selection and discuss the importance of breeding for durable resistance.

Between 10-15 popular (but now susceptible to yellow rust) facultative/winter wheat cultivars from Central and West Asian countries will be crossed during the 2003-2004 and 2004-2005 seasons with 5-8 donors of durable resistance and backcrossed with the cultivars to achieve large BC1 populations. Selections will be carried out during the winter crop season (Nov-July) at the CIMMYT Toluca research station in BC1-F5 generations using the selected bulk scheme. The bulk selected F5/F6 populations will be distributed for final selection through CIMMYT's and ICARDA's regional offices.

Between 10-15 additional spring wheat cultivars will also be improved in a similar manner as described above, however, in this case advanced lines will be distributed through CIMMYT's seed distribution network after determining the yield potential at Cd. Obregon. Because two crop seasons are possible for spring wheat, expected advances are much faster than for winter wheats. NARS likely to release new cultivars after further testing from the above improved germplasm.

The 'single-backcross, selected-bulk' breeding scheme proposed for incorporating 4-5 minor genes in adapted wheat cultivars has been used very successfully at CIMMYT and results are documented (Singh et al. 2004). In response to a question of feasibility of the approach as raised by one of the reviewers, the following is offered: Resistance based on slow rusting, minor genes is additive, hence the F1 plants display intermediate levels of resistance and can be easily distinguished (Navabi et al. 2004). Assuming that the adapted cultivar does not carry any minor resistance gene, then when F1 plants are backcrossed with the adapted cultivar, 6.25% and 3.125% of BC1 plants carry all 4 and 5 additive genes, respectively in heterozygous conditions. In a population of 400 BC1 plants this translates to 25 and 12.5 plants, respectively. The number is usually much more because the adapted cultivars often carry 1-2 minor genes. The BC1F2 population is initiated selecting the most resistant heterozygous plants. In the BC1F2 generation 32% plants have all four genes at least in the heterozygous state. We grow about 1200 space-sown plants in the F2 generation and hence about 400 can have all the desired genes. We select many plants (100-200) with high emphasis given to retaining plants that have desirable agronomic features even though they may have intermediate resistance levels, and one spike is harvested from each selected plant as a bulk. This strategy allows retention of numerous plants that segregate in subsequent generation and give progenies of desired genetic makeup and agronomic features. Similar population sizes are maintained in subsequent segregating generations and eventually homozygous plants with high level of resistance and desired agronomic features are identified by the F6 generation. In Mexico we use two crop cycles per year for spring wheat improvement, hence in 4.5 years advanced lines are available for distribution after conducting yield tests in the F7 generation (with crosses initiated in 2005).

ACIAR funds will support about 40% of the above activity. The remaining 60% is currently being supported by Japan, GRDC and CAAS (China) funds.

5.5 To strengthen the network of collaborators in Asia through training.

Rationale: The capacity of many NARS to conduct significant research on rust pathology, resistance genetics and breeding has declined in recent years. Formal training of selected key scientists in these areas either at CIMMYT, ICARDA or PBIC should enhance the understanding and thus strengthen the quality of collaboration.

Specific tasks:

1 or 2 scientists will be identified annually for 3-4 months training at CIMMYT, PBIC or ICARDA.

These scientists will learn how to identify races and postulate resistance genes through seedling tests in the greenhouse. They will also be trained in the concept of durable genetic resistance and how to identify and select for it. Methodologies used in the greenhouse and field to improve the screening for rust resistance will also be taught.

Attempts will be made to enrol a few NARS scientists for a higher degree program at PBIC through external funding.

Our aim is to strengthen capacity in the following countries: China, India, Pakistan, Iran and Kazakhstan. Each of the above countries has reasonable facilities and scientists assigned for rust research. The needs are different in each country. For example, Iran now has well trained researchers with Ph.D. degrees and modern facilities to conduct rust research. India also has a well-established lab and program on surveillance. Their capacity will be strengthened by receiving the new NILs and links with institutions outside their countries. China at present does not have a coordinated effort on yellow rust monitoring. The efforts are fragmented. Our efforts for China will be to prepare three to four scientists in different provinces who can work together on monitoring. Scientists from Pakistan and Kazaksthan will need good training and some equipment. We expect that yellow rust surveillance by using the Avocet NILs and other important cultivars will become a routine exercise in countries such as China, India, Pakistan and Iran when scientists in the region understand how data from trap nurseries can be used. A uniform nursery will also enable scientists in the region to share information and compare results.

We have proposed 3-4 month visits to CIMMYT/PBIC/ICARDA by selected key scientists from Asia to provide a thorough training to those who will be the leaders of rust research in their respective countries in coming years and those who will conduct the rust surveillance. Our past experience at CIMMYT and PBIC has clearly demonstrated that such opportunities have developed scientists who have later contributed a lot in their respective countries. This type of training does not exclude short training courses of several scientists in a country in the region when we travel. Our objective will be to identify additional funds locally for this purpose.

Trial exit strategy: We will explore and promote the concept of a centralized laboratory in China that can provide/coordinate yellow rust surveillance at the national level and possibly provide a backup support to wheat breeders by providing sources of durable resistance or even facilities and staffing to be able to incorporate appropriate resistance in desired cultivars. The process is already under discussion in China under CIMMYT's guidance.

6 Achievements against activities and outputs/milestones

Objective 1: To monitor the evolution and migration of new races of Puccinia striiformis tritici (causal agent of yellow rust of wheat) in Asia.

Output: Better understanding of variation in Pst and resistance in wheat cultivars

no.	activity	milestones	completion date	comments
1.1	Multiply, distribute and grow yellow rust trap nursery (IC, PC)	Yellow rust trap nurseries grown each year at selected sites in Asia	Annual, last nurseries grown in 2009-2010 crop season	Avocet isolines together with additional lines carrying different resistance genes, or their combinations, were distributed annually Asia, Middle East and Africa for use in field and greenhouse studies. By 2008 an uniform Yellow Rust Trap Nursery was constituted, multiplied at ICARDA and distributed. Data on trap nurseries are now interpreted by the participating National Program Scientists to determine changes in virulence pattern locally. Data are also complied at ICARDA to determine changes or shifts in virulence frequency regionally. China and India have their own monitoring systems where extensive surveys are conducted in addition to trap nurseries and rust samples are studied in greenhouse on differential set to determine the predominant and new races. For countries where such greenhouse facilities are not available, ICARDA and CIMMYT have established a collaborative arrangement with Dr. Mogens Hollmover at the Univ. of Aarhus, Denmark to conduct race-analysis on selected samples. Such analyses were conducted from samples from Central Asia, Morocco, Pakistan, Nepal, Afghanistan, Eretria, and Kenya.
1.2	Develop Avocet isolines for additional Yr genes (A, IC)	Avocet isolines for 8-10 additional resistance genes available by Yr4, m12	2008, 2009	Several original Avocet isolines carried the adult plant resistance gene Yr18. This was established through the use of Yr18 molecular marker. This required their further crossing with the susceptible recurrent parent Avocet S and selection. These materials will be distributed in 2010. Isolines for Yr27, Yr28, Yr29, Yr30, Yr31, Yr32 and YrSp were completed and distributed through trap nurseries. Development of Avocet lines with combinations of resistance genes is under progress and first combinations are expected to be available in 2011.

IC = International Centre, PC = partner country, A = Australia

Objective 2: To provide early warning to participating countries by advising significant changes in virulence or virulence frequency in the region.

Output: Support for early warning systems to protect crops from new races of Pst

no.	activity	milestones	completion date	Comments
2.1	If a new virulence (race) is identified in the region, determine its relevance and migration path (IC, PC)	Presence or absence of a new race will be determined each year	Annual	Using trap plots and follow-up characterization of races from samples was very useful in determining changes in the pathogen population. Resistance gene Yr27, often present in combination with Yr9, is present in several important wheat varieties in South and West Asia, Middle East and Africa. Yr9+Yr27 virulence was first detected in Pakistan and Afghanistan and then in India, Iran and Central Asia. The other important virulences detected were for Yr17, Yr24 and Yr31. Virluences for Yr24 detected in 2009 in China is highly relevant as several varieties and breeding lines now carry this resistance gene.
2.2	Inform NARS about the significance of the new race in the region and which resistant cultivars can be grown (IC, PC)	If a new race is identified, NARS will be notified	Annual	NARS scientists and administrators were regularly informed through workshops and letters to reduce area under susceptible variety and increase the proportion of resistant varieties. However, in most cases varietal changes were seen only after significant losses occurred due to yellow rust epidemics.

IC = International Centre, PC = partner country, A = Australia

Objective 3: To identify the race-specific and adult plant resistance to Puccinia striiformis in popular cultivars.

Output: Better understanding of variation in Pst and resistance in wheat cultivars

no.	activity	milestones	completion date	comments
3.1	Determine the genetic basis of resistance in important cultivars (A, IC)	Seedling and field resistance of cultivars characterized by Yr3, m12	2007, 2008, 2009, 2010	Several independent studies were undertaken to determine the resistance in important commercial varieties and was combined with the training activities of scientists. In additional important varieties were also included in the trap nursery to determine their resistance at key sites to diverse population of yellow rust pathogen. Several graduate students at Chinese Academy of Agricultural Sciences were encouraged by CIMMYT Scientist posted in China to focus their research in identifying race-specific and adult plant resistance genes in Chinese germplasm.
3.2	Collect data, summarize and distribute report (PC, IC)	Data summarized and distributed each year	Annual	Resistance studies conducted by scientists under training were reported by them at conferences and other publications. Research conducted at CAAS, Beijing have resulted in various articles in international and Chinese journals. Yellow rust data shared annually with participating scientists.

IC = International Centre, PC = partner country, A = Australia

Objective 4: To incorporate durable yellow rust resistance into adapted cultivars and promote their deployment.

Output: Availability of locally/regionally adapted cultivars with durable resistance.

no.	activity	milestones	completion date	comments
4.1	Backcross durable resistance genes in about 30 spring wheat cultivars and select resistant plants in segregating populations and eventually achieve fixed advanced lines. Conduct yield trials to identify best yielding lines (IC, PC)	Fixed resistant versions of important cultivars provided to NARS for testing during Yr3, Yr4 and Yr5	Annual	The single-backcross breeding to incorporate complex adult-plant resistance was targeted to Chinese wheats from Sichuan and Yunnan Provinces. Because these wheats were resistant in Mexico, BC1-derived F2 and/or F3 populations developed in Mexico were grown in Sichuan and Yunnan provinces for selection. It is likely that two varieties will likely be released in Yunnan province in 2010. Several high-yielding, adult plant resistant derivatives were identified by participating scientists in China and distributed to other scientists in the region for use in future breeding. For South and West Asia, and Africa, the objectives of the yellow rust project were combined with the objectives of BGRI and advanced wheat lines that had shown high yield potential, yellow rust resistance and resistance to Ug99 and derivative races of stem rust pathogen, were distributed as special yield trials in 2006, 2007 and 2008. Some of the best yielding lines (5-10% higher yields than current cultivars) were released (2 varieties in Egypt, 3 in Afghanistan, 2 in Ethiopia) and others are under various stages of testing in Bangladesh, Nepal, India, Pakistan, Afghanistan, Iran, Turkey and Ethiopia. A seed project supported by the USAID is promoting the seed multiplication of resistant varieties in six countries (Bangladesh, Nepal, Pakistan, Afghanistan, Egypt and Ethiopia) and this will have major impact in reducing genetic vulnerability to stem rust and yellow rust.
4.2	Backcross durable resistance genes in 10-15 facultative/winter wheat cultivars and select resistant plants in segregating populations (IC, PC)	F4 or F5 populations distributed to NARS for making final selection during Yr5	2008, 2009	F4 populations were distributed to Turkey-CIMMYT-ICARDA program in 2008 and 2009. 2008 populations were distributed from Turkey to breeding programs in Central Asia after making a round of selection. Similarly, a second group of F4 populations were grown in Turkey. Advanced lines from the 1st group of populations were developed in Mexico and grown in 2009-2010 crop season. Unfortunately an unusual and prolonged frost period at flowering time destroyed all materials. We will need to re-plant the populations again to obtain the advanced lines.

IC = International Centre, PC = partner country, A = Australia

Objective 5: To strengthen the network of collaborators in Asia through training at PBIC and CIMMYT.

Output: An international alliance aimed at fostering the development of capability in rust pathology, resistance genetics and breeding to reduce losses.

no.	activity	milestones	completion date	comments
5.1	Train selected NARS scientists (A, IC)	5-6 better prepared NARS scientists by Yr5	Annual	Following approaches were undertaken for training: 1) participation in CIMMYT in-service training courses, 2) specialized training at PBI-Univ. of Sydney, 3) short training workshops, 4) Graduate studies on yellow rust resistance (especially in China). These activities as well as those supported by the BGRI have prepared several National Program scientists to conduct future research activities in their own countries.

IC = International Centre, PC = partner country, A = Australia

7 Key results and discussion

Objective 1: To monitor the evolution and migration of new races of Puccinia striiformis tritici (causal agent of yellow rust of wheat) in Asia, and

Objective 2: To provide early warning to participating countries by advising significant changes in virulence or virulence frequency in the region.

Field trap plots based monitoring of yellow rust is a practical solution for various National Programs because in place of conducting pathotype analysis in controlled greenhouse conditions that are not available in most countries. To conduct such monitoring PBI-Univ. of Sydney had developed isolines for various yellow rust resistance genes in the highly susceptible background of Australian variety 'Avocet S'. Advantage of Avocet isolines is that it grows well in most of the wheat growing environments. During the project period some of the isolines had to be purified. Additional isolines were also developed.

Table 1. Testing sites/countries and number of sites for 3nd IYRTN

No.	Country	No. of Sets	No.	Country	No. of Sets
1	Algeria	3	15	Lebanon	1
2	Armenia	2	16	Morocco	2
3	Azerbaijan	4	17	Nepal	4
4	Bangladesh	3	18	Pakistan	4
5	Bhutan	1	19	South Africa	2
6	Egypt	6	20	Sudan	2
7	Eritrea	2	21	Syria	7
8	Ethiopia	4	22	Tajikistan	1
9	Georgia	2	23	Tunisia	2
10	India	3	24	Turkey	4
11	Iran	4	25	Turkmenistan	1
12	Kazakhstan	1	26	Uruguay	1
13	Kenya	7	27	Uzbekistan	1
14	Kyrgyzstan	1	28	Yemen	6
	Total sets	43		Total sets	38
	Total	82			

Initially several trap nurseries were grown by the National Programs. During the course of the project we achieved one unified Yellow Rust Trap Nursery that is at present managed by an ICARDA scientist. The Trap Nursery consists Avocet isolines for available Yr genes, genetic stocks for additional Yr genes (not available in Avocet background), selected European yellow rust differentials, wheat varieties carrying combinations of important resistance genes, and important commercial varieties currently grown in Asia, Africa and Middle East. This nursery is now annually assembled at ICARDA headquarter in Aleppo and distributed to most wheat growing countries of Asia, Middle East and Africa. During 2008-2009 season 82 sets in 28 countries received the 3rd International Yellow Rust Trap Nursery (Table 1). Yellow rust data is compiled and important conclusions are then informed back to participating NARS partners. Chinese scientists have organized themselves and conduct their own disease surveys. Selected samples are then pathotyped at Plant Protection Institute of CAAS at Beijing or at various other institutes that now have good facilities.

Although several sets were distributed in different years, climatic conditions during years affect data recovery. For example 2007-2008 and 2008-2009 crop seasons were marked by dry conditions in Central Asia, West Asia and North Africa. In contrast 2009-2010 was an epidemic season in various countries. Data of trap nurseries over years has indicated that several known resistance genes have limited utility as host lines carrying them displayed susceptibility in all or some of the years. This included genes Yr1, Yr2, Yr6, Yr7, Yr8 and Yr9. Gene Yr27, present in several important cultivars (Inqualab 91, PBW343, WH542, Chamaran, Shirudi, Memof, Kubsa, etc) was initially effective in some areas, especially when present in combination with Yr9, however by 2010 became ineffective everywhere. Virulence for Yr17 was first detected in Afghanistan and Pakistan and but 2010 could be found in some other Central Asian countries and East Africa. Virulence for Yr17 was also detected in China in 2009. Yr17 is currently used in breeding in Indian and Chinese breeding programs but it is likely that resistant varieties, if released, will succumb soon as virulence already exists.

Avocet isolines for Yr3 and Yr4 are under development. We used European differential lines Vilmorin 23 and Hybrid 46 and these lines in field trials showed resistance at most sites. However, it is likely that the two lines also carry additional APR genes.

Yr5/6*Avocet S and Triticum spelta var. album were used as sources of Yr5. This gene continues to be effective at all locations. Effectiveness of Yr5 could be due to lack of its use in agriculture. Virulence for this gene has been detected in a greenhouse culture in Plant Breeding Institute (Cobbitty, Australia) indicating that this gene may not have value to be used in breeding programs.

Yr10/6* Avocet S and Moro were used as sources of Yr10. This resistance gene continues to be effective at most sites except in Tel Hadya and possibly in Kenya and Ethiopia. Yr15/6*Avocet S was used as source of Yr15 and this gene remains highly effective in all locations. Virulence for YrSp and Yr32 was recorded at some of the test sites indicating their limited usefulness.

Although slow rusting adult-plant resistance (APR) genes, Yr18 and Yr29, carrying lines were included in the nurseries. It was often difficult to differentiate whether higher severities recorded on the tester lines carrying them in some years/locations were due to the presence of corresponding virulence or the disease pressure. One thing was clear that these genes will not give sufficient resistance when present alone and it is important to use them in combination with other minor, APR genes. Similar results were observed with partially effective race-specific resistance genes Yr28 (derived from T. tauschii) and Yr31. Yr31 is present in some CIMMYT derived lines Bobwhite, Pastor and their derivatives. Because Pastor that carries Yr31 in combination with slow rusting resistance genes Yr29 and Yr30, showed high level of resistance in several areas, except in China and some Central Asian countries and since 2008 in Mexico, we interpret that virulence for Yr31 is present in various areas caution the utilization of Yr31 gene based resistance. It is recommended that resistance genes that confer only moderate levels of resistance when present alone should not be used in trap nurseries. It is better to use wheat lines with high levels of APR, such as Cook (used in the trap nursery), will be more beneficial to access changes in pathogen population.

Other lesson learnt was that despite new virulence was detected in a region and countries advised about the susceptibility of important varieties, it was not possible to influence replacement of these varieties due to unavailability of enough seed of resistant varieties, and due to the lack of interest of seed sector or farmers. This often resulted in localized or larger epidemics and chemical interventions to reduce the losses. National Program Scientists however were able to recommend resistant varieties for replacement in case of such events.

Objective 3: To identify the race-specific and adult plant resistance to Puccinia striiformis in popular cultivars.

Various studies were undertaken/encouraged and included testing of important varieties in multiple sites to determine the effectiveness of resistance to existing Pst populations, elaborate multi-pathotype seedling greenhouse and adult plant field tests on promising wheat germplasm, and genetic analyses and mapping studies. Several of these studies were conducted had a training component where National Program scientist conducted the work. Some of the key findings are summarized below.

Various commercial varieties from South Asia and CWANA region tested did not show adequate resistance at all sites. Some important varieties that showed resistance at most sites during the early phase of the project became susceptible in recent years due to shift in virulence in pathogen population. However, some varieties and breeding materials found to be resistant indicating the presence of new sources of resistance. Postulation of resistance genes often indicates the presence of defeated genes Yr1, Yr2, Yr6, Yr7 and Yr9 in most materials. Additional uncharacterized resistance genes, usually with only moderate/intermediate seedling resistance are also common and difficult to postulate. Different levels of adult plant resistance, however often inadequate, are also present in wheat varieties and germplasm.

Wide utilization of Yr24 (=Yr26) in China and to some extent Yr17 in China and other countries once again increases the genetic vulnerability. Chinese pathologists have shown the presence of virulence for these two genes in Pst population in 2009. In 2010 scientists in Sichuan province reported susceptibility of several resistant materials.

Graduate students in China were encouraged to work on the resistance to yellow rust, especially APR. CIMMYT, Australian and US scientists are playing important role in this mentoring and various their studies, published in international scientific journals, have identified new resistance genes that can be used in breeding. Studies also indicated that high frequency of older wheat materials possessed durable APR gene Yr18, whereas newer materials lack it. Slow rusting APR gene Yr29 was identified in a popular wheat variety Chuanmai 107.

Diversity of resistance in commercial cultivars is a cause of concern and all attempts are needed to enhance it. Identification of diverse slow-rusting, APR genes and their utilization in diverse combinations appears to be the best strategy for achieving resistance durability.

Objective 4: To incorporate durable yellow rust resistance into adapted cultivars and promote their deployment.

Three groups of breeding materials were included in this objective:

1. CIMMYT spring wheats that have adaptation in South Asia and CWANA region

2. Spring wheat varieties and germplasm from yellow rust prone areas of China with main focus on Sichuan and Yunnan provinces, and

3. Facultative and winter wheats varieties and germplasm from Central Asian countries.

CIMMYT spring wheats that have adaptation in South Asia and CWANA region

Project supported development and testing of promising wheat germplasm with durable adult plant resistance to yellow rust. These are traditional CIMMYT wheat germplasm. Although project initiated with yellow rust focus, soon it was clear to us that the germplasm to be promoted must also carry resistance to stem rust race Ug99 of stem rust pathogen. Funds from ACIAR and other projects supporting the Ug99 resistance breeding and testing were pooled towards a common objective. Breeding at CIMMYT has been focussing on identifying existing high yielding materials that have resistance to Ug99 and other two rusts with high emphasis on adult plant resistance. A shuttle breeding between Mexico and Kenya was established to enable selection for all three rusts. In addition to selection and testing of advanced lines in Mexico and Kenya under high disease pressure, hot-spot testing of advanced lines was done for yellow rust in Ecuador.

The best yielding lines with adequate resistance (in most cases APR) to all three rusts were distributed to selected National Programs as a special yield trials, 1st, 2nd, 3rd and 4thEBYT (Elite Bread Wheat Yield Trials) for growing during 2005-2006, 2006-2007, 2007-2008, 2008-2009 crop seasons, respectively for growing in multiple environments. These trials helped identify new wheat lines that have at least 5%, often 10% higher yield potential than the currently grown cultivars. Selected lines were promoted by National Programs for further testing and the outcome so far has been the release of 2 varieties in Egypt, 3 varieties in Afghanistan and 2 varieties in Ethiopia. Additional wheat lines from the 3rd and 4thEBWYT are also under further testing. We expect to see releases of additional varieties in Nepal, India, Pakistan, Afghanistan, Iran, Egypt and Ethiopia from the germplasm distributed through 2nd, 3rd and 4thEBWYTs.

Results of the 1st, 2nd and 3rd EBWYTs were reported in previous annual reports. As an evidence of progress results of the 4thEBWYT are presented here. Twenty-nine, high-yielding wheats identified to carry adequate levels of resistance to leaf rust and yellow rust in Mexico, and stem rust at Njoro in 2008 (both off- and main-seasons) were included in the 4th Elite Bread Wheat Yield Trial (4thEBWYT). Twenty-four entries had APR to stem rust whereas the resistance of 4 entries was based on Sr25 and one on SrHuw234. Fifty-one sets of the trial were distributed to various countries for planting during 2008-2009.

Twenty-eight entries on average yielded 100-114% of the local checks used at 10 sites in India. Five entries, including 'Munal#1' (CIMMYT check) yielded 10-14% higher than the checks. Ten sites represented diverse environments in the North-Western Plain Zone (NWPZ), North-Eastern Plain Zone (NEPZ), and Central and Peninsular Zone (CPZ). Considering only the NWPZ (6 sites), all entries yielded more than the local check and 11 entries were 10-19% higher yielding than the checks (PBW343 used at most sites). 'Wheatear/Sokoll' (entry 529) with Sr25 was the best yielder, 19% higher than the check in NWPZ. This was followed by 'Neloki#1' (entry 527) with 17% higher yield and APR to stem and yellow rust. NWPZ is the main wheat zone in India. The CIMMYT check Munal#1 has shown significant superiority over the checks in India for 3 years of testing and has potential to become a successful variety.

Trials were grown in Pakistan at 5 diverse sites from north to south. Four entries, 508, 515, 519 and 530, on average yielded 7-11% higher than the means of the local checks (different check at each site). Similarly, in Iran trials were grown at 5 diverse sites including those where facultative wheats are grown. On average eight entries had 100-108% yields compared to the checks. The best line was entry 527, Neloki#1, the entry rated 2nd in India.

Fifteen lines yielded 9-21% higher in Afghanistan based on means for three sites. One site data set was returned from Bhairahwa, Nepal, and 10 lines yielded 10-28% higher than the check. Munal#1 was the 2nd best yielder (24% higher yielding than the check) and Neloki#1, entry 527, yielded 28% higher than the check.

One site data set was returned from Kulumsa, Ethiopia. Eight entries had 9-31% higher yields than the highly popular cultivar ‘Kubsa’. The top two performers, Wheatear/Sokoll (entry 529) and Neloki#1 (entry 527) were also the top two performers in India. Munal#1 (entry 2), a derivative of Kubsa, had a 12% higher yield than Kubsa and is under seed multiplication in Ethiopia.

Entries included in the 4thEBWYT were selected based on visual agronomic and disease evaluations and grain-yield performance in a single yield trial at Ciudad Obregon in Mexico, the main breeding and testing site for the CIMMYT spring wheat program. Grain yield performance of new semidwarf wheat lines in various countries shows that significant progress in yield potential has been made over time. Varieties such as PBW343 in India, and Kubsa in Ethiopia, or Chamran in Iran were bred about 15 years ago in Mexico. We believe that changing to new higher yielding, triple rust resistant wheat varieties should enhance wheat productivity and farmers’ income in addition to genetic protection from all three rusts.

With the support from ACIAR and various other projects wheat breeding for rust resistance, yield, quality and other stresses at CIMMYT was strengthened and new wheat germplasm developed should further help enhance wheat productivity in many countries in the future. Some of the breeding progresses are documented below:

Fig. 1 summarizes the adult plant leaf rust severities of 360 recently developed advanced lines under high disease pressure in field trials at El Batan, Mexico, during 2009. Over 80% of lines had between 1 and 5% severities compared to the necrotic leaves of the susceptible checks. These near-immune lines were susceptible as seedlings in greenhouse tests with the same race as used in the field trial indicating that complex APR was the basis of resistance.

Fig. 1 Adult-plant leaf rust severities of 360 recently developed seedling susceptible wheat lines (effective race-specific resistance genes absent) evaluated at El Batan, Mexico, in 2009 when susceptible checks were defoliated by leaf rust

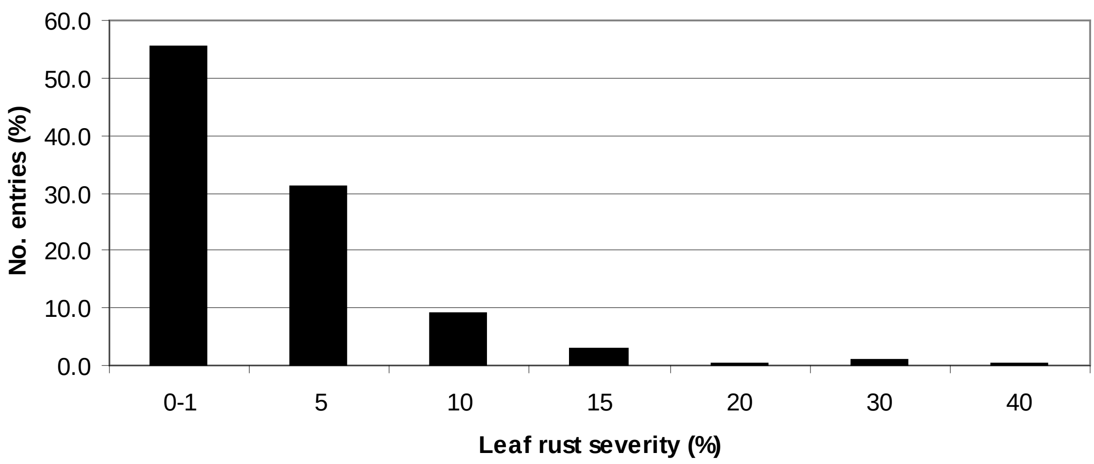
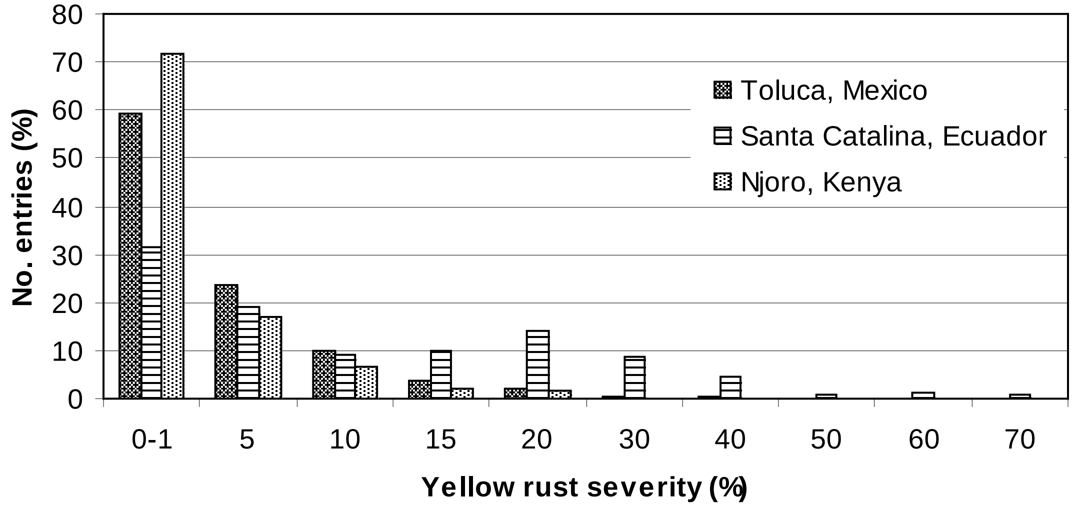


Fig. 2 Adult plant stripe rust severities of 504 recently developed advanced breeding lines at Toluca (Mexico), Santa Catalina (Ecuador) and Njoro (Kenya) in 2009. Data were recorded when the Avocet S check was defoliated in Mexico and Ecuador, and 80% severity in Kenya



A similar result was observed for the yellow rust responses of 504 recent advanced lines in field trials conducted in Mexico, Ecuador and Kenya (Fig. 2). Although seedling reaction data are not available, it can be predicted from the pedigrees that at least half of the lines showing 1 to 5% disease severity carry near-immune level of APR.

Fig. 3 summarizes the stem rust responses of 761 ‘Mexico-Kenya Shuttle Breeding’ advanced lines during the 2010 off-season at Njoro, Kenya, under high disease pressure. The parents of the lines lacked effective race specific resistance genes based on their pedigrees and field reactions. Around 25% of the lines derived from about 60 different crosses displayed near-immune levels of resistance with stem rust severities of 1-5% compared to 100% for the susceptible check Cacuke. An additional 25% of the lines displayed 10-15% stem rust severities.

Fig. 3 Adult plant stem rust responses of 761 ‘Mexico-Kenya shuttle breeding-2008’ wheat lines from crosses targeted for incorporating APR into high yielding wheat backgrounds and evaluated at Njoro, Kenya, during the 2010 off-season. Data were recorded ‘Cacuke’ displayed 100% stem rust severity

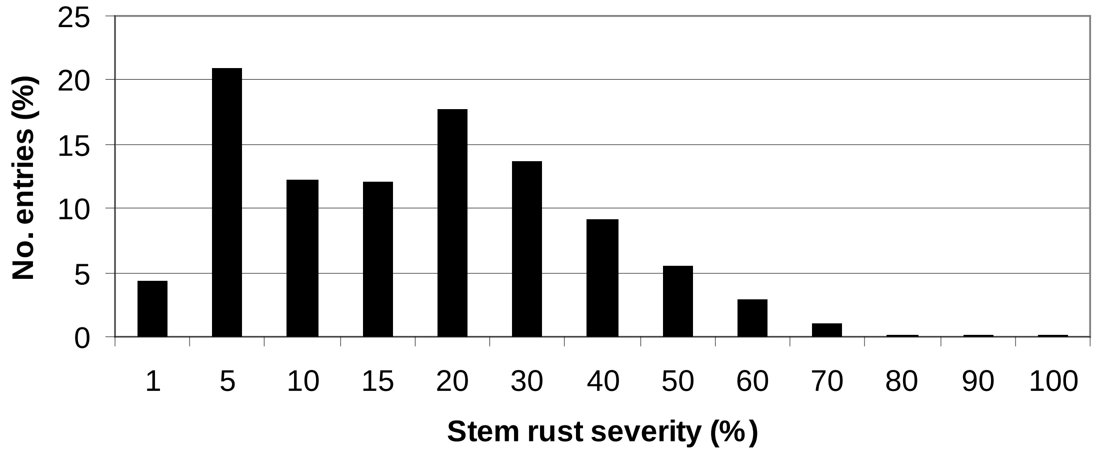
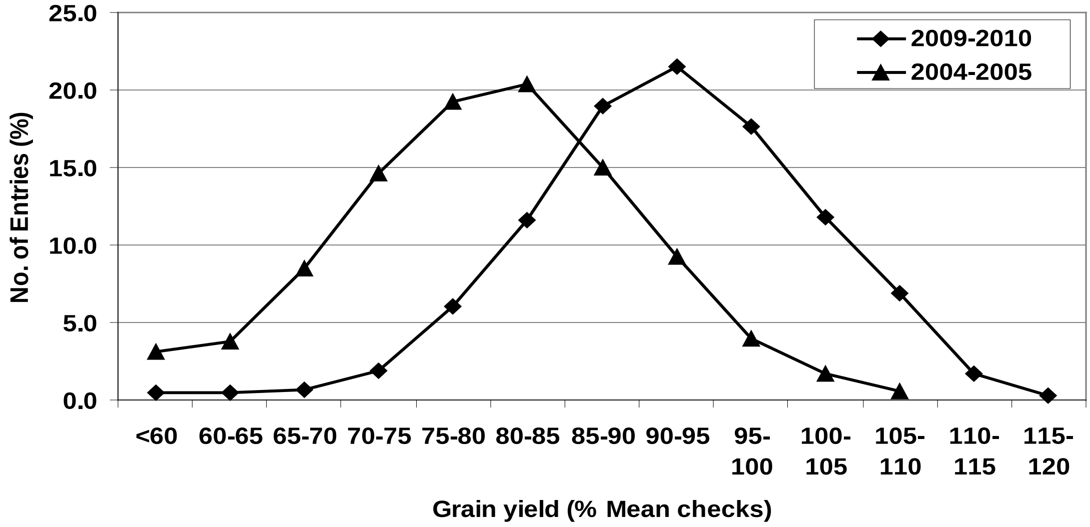


Fig. 4 Comparison of the progress in grain yield potential of breeding materials after one complete cycle of selection: performance of 4814 new lines tested at the beginning of the project (2004-2005 crop season data) and 4956 new lines at the end of the project (2009-2010 crop season data) at Cd. Obregon, Mexico



Progress in breeding for yield potential is shown in Figure 4 where grain yield performance of about 5000 new lines tested in 2004-2005 and 2009-2010 crop season are compared. The five year period represents a full breeding cycle for CIMMYT's 2-crop season/year breeding program. The best new lines in 2009-2010 showed about 10% higher yields than the best lines available in 2004-2005 crop season. We will test and promote the best yielding lines with durable APR to all three rusts in various countries in coming years.

Breeding wheat germplasm with APR to yellow rust and adaption in Sichuan and Yunnan provinces of China

A total of 257 BC1 derived segregating populations involving 25 Chinese varieties or promising breeding lines and CIMMYT wheat lines with high levels of APR were developed in Mexico and grown in Sichuan and Yunnan provinces from F2 or F3 generations onwards in most cases. R. Singh travelled to the two sites during most years and worked with Chinese wheat breeders and pathologists explaining and selecting the strategy to make selection of APR in segregating generations. Several advanced lines with high to adequate levels of APR were obtained. Selected resistant lines were also tested for grain yield performance and tested for yellow rust at multiple field sites by the Plant Protection Institute of Sichuan Academy of Agricultural Sciences. Yellow rust response data (Table 2) shows that each year lines with high and moderate (adequate) resistance could be found. Grain yield performances of 13 superior yielding lines are summarized in Table 3. The best yielding and resistant materials were distributed to other breeding programs by Prof. Y. Zhou. These new sources adult plant resistance in high yielding wheat backgrounds are expected to enhance genetic diversity of future wheat varieties.

We do not have data with us to report from Yunnan province however two lines have performed well in multi-site provincial trials and are at final stages of testing in large field trials before releases.

Table 2. Results of stripe rust resistance screening of adult plant resistant shuttle breeding lines in Disease Identification Nursery by Plant Protection Institute, SAAS in 2007 to 2009 (source: Prof. Y. Zhou)

	Lines	Resistant		Moderately resistant		Moderately susceptible		Susceptible	
Year	No.	lines	%	lines	%	lines	%	lines	%

2007	255	80	31.37	66	25. 88	71	27. 84	38	14. 90
2008	241	94	39. 00	110	45. 64	34	14. 11	3	1. 25
2009	173	19	10.98	70	40.46	69	39.88	15	8.67

Table 3. Grain yield expressed as % Check and stripe rust response of 13 shuttle breeding lines with 5% higher than the checks during 2007, 2008 and 2009 trials (source: Prof. Y. Zhou)

Line designation	Yield aa % Check	Yellow rust	Year tested
06RC579	106.9	MR	2007
06RC4117	105.2	R	2007
06RC2237	114.7	MR	2007
06RC2523	106.2	MR	2007
06RC4240	107.2	MR	2007
07RC3929	106.5	R	2008
08RC555	106.6	MR	2009
08GH 22	110.5	R	2009
08RC3157	107.8	S	2009
08RC1306	105.5	MR	2009
08SW29130	114.2	R	2009
08RC2525	115.6	MR	2009
08GH 37	107.2	R	2009

Incorporation of durable yellow rust resistance in facultative/winter wheats from Central Asian Countries

Seeds of 21 cultivars from Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Azerbaijan, Russia and Turkey were used for incorporating APR. In total 352 populations were developed and selected in Toluca by planting during winter season and under yellow rust pressure. F4 and F5 populations were sent to Turkey in 2008 and 2009 for conducting selection and distributing selected materials to Central Asian breeding programs. Materials were also advanced in Mexico and the first group of 2468 advanced lines were sown in 2009-2010 crop season at Toluca. Unfortunately these advanced lines and other segregating populations were lost due to an unusual frost that lasted for several nights during the flowering time. We shall plant the reserve seed again and continue the selection in Toluca to achieve yellow rust resistant advanced lines.

Objective 5: To strengthen the network of collaborators in Asia through training at PBIC and CIMMYT.

Following approaches were undertaken for training: 1) participation in CIMMYT in-service training courses, 2) specialized training at PBI-Univ. of Sydney, 3) short training workshops, 4) Graduate studies on yellow rust resistance (especially in China and Australia).

2006

Yellow Rust Training Workshop, Tashkent, 1-8 June 2006 (23 participants from CWANA region) organized by ICARDA.

Three months (1 August-30 October 2006) training of Mr. Huazhong Zhu, Wheat Breeder at the Sichuan Academy of Agricultural Sciences in Mexico. Mr. Zhu also working on a mapping population targeted to map APR to yellow rust and completed a PhD. Degree in China.

2007

Training activities in Australia

Dr Shynbolat Rysaliev, Senior Cereal Pathologist (Otar, Kazakhstan), spent 3 weeks at PBI Cobbitty for training in techniques and interpretation of data in yellow rust.

Trainees identified at the Tashkent regional yellow rust workshop in 2006 were followed up for further opportunities in specific training in cereal rust pathology:

(i) Mr Alexsandro Loladse was successful in applying for an international scholarship to begin PhD studies in the genetics of yellow rust resistance at The University of Sydney.

(ii) Mr Zafer Mert, Plant Pathologist with the Institute of Crop Protection in Ankara Turkey, spent 3 months at PBI in a collaborative research project on rust resistance sponsored by the Crawford Fund.

Training of scientists from India, Pakistan and Iran in Mexico

A three month (Feb 20-May 20, 2007) training course on “Breeding for yield potential, durable rust resistance and other traits” was conducted at El Batan and Ciudad Obregon, Mexico. This course was attended by 2 scientists from India, 1 from Pakistan and 2 from Iran among others. A similar two months course (September-October, 2007) at El Batan/Toluca, Mexico was attended by two scientists from India and one from Nepal among others. Funds from the Global Rust Initiative were used for supporting these courses.

Cereal Disease Management Training, Tunis April 2007

Training of 20 scientists in North Africa on crop improvement and breeding for disease resistance was conducted in Tunisia (April 2007). Emphasis was on leaf and yellow rust, main rust diseases that have impact on crop production in North Africa. The training was conducted in French language by “French speaking” scientists from ICARDA (A. Yahyaoui, M. Nachit), CIMMYT (E. Duveiller, K. Ammar, Y. Mannes), and National scientists from Research and teaching Institutions. Participants were from African French speaking countries. ICARDA and CIMMYT funds supported the training.

2008

Dr. Wanquan Chen, Institute of Plant Protection, Chinese Academy Agricultural Sciences, visited for 3 months research training at PBI Cobbitty from March-May 2008.

Dr. Yong Zhang, Institute of Crop Sciences, Chinese Academy of Agricultural Sciences (CAAS), Beijing 100081, China, spent 3 months (15 Feb-13 May 2008) at CIMMYT, Mexico in Ciudad Obregon and trained in Wheat Improvement.

Mr. Yang Ennian, Sichuan Academy of Agricultural Sciences, attended the training course for 2 months (5 August- 3 October) at El Batan and Toluca, CIMMYT, Mexico. Mr. Yang is now enrolled for a PhD program in China is working on the genetics of APR to yellow rust.

The costs of the trainings were co-shared (participants paid the travel cost and the ACIAR project paid the cost of stay in Australia and Mexico respectively for Dr. Chen and Mr. Ennian. Dr. Zhang expenses were covered by CAAS.

2009

Mr. Jun Li and Miss. Shizhao Li, two new young wheat breeders attended two months, 3 August - 2 October 2010, in-service wheat training course on wheat improvement. SAAS covered the travel expense whereas ACIAR project took care of the living expenses in Mexico.

These activities as well as those supported by the BGRI have prepared several National Program scientists to conduct future research activities in their own countries.

8 Impacts

The overall expected impact of the projects is the increased productivity and profitability of wheat in Asia by reducing the risks of losses from yellow rust epidemics through enhanced knowledge of variability in evolving population of yellow rust pathogen and by identifying and developing new wheat cultivars that have durable resistance to yellow rust and other diseases and superior yields than currently grown cultivars.

8.1 Scientific impacts – now and in 5 years

A proper monitoring of changes in virulence in yellow rust pathogen in many countries was not possible due to the lack of near-isogenic lines and lack of temperature controlled greenhouse facilities in many countries of Asia. The Avocet NIL set distributed is now being used by numerous scientists in both developing and developed countries for field based as well as greenhouse based identification of Pst races.

Application of durable resistance in wheat improvement was limited to CIMMYT and a few other breeding programs. Promoting the wheat germplasm with durable resistance and breeding scheme developed by the IARC for efficient utilization are now increasingly used/ adopted by various other breeding programs.

8.2 Capacity impacts – now and in 5 years

Project has focused on enhancing human capacity mainly in the following areas through hands on activities combined with lectures:

Monitoring changes in Pst populations and management of yellow rust disease.

Identification of resistance genes.

Breeding for durable yellow rust resistance in combination with other necessary traits.

Enrolling scientists for higher degrees.

It is common to see that scientists who have gone through the training program are using the knowledge gained in their pathology and breeding programs.

8.3 Community impacts – now and in 5 years

8.3.1 Economic impacts

It is expected that several wheat lines distributed will eventually be released by NARS as commercial varieties. Seed multiplication has already initiated in India, Pakistan, Iran, Afghanistan, Nepal, etc. for some lines that carry higher yield potential than currently grown cultivars and are resistant to all three rusts, including Ug99. Seed multiplication and sales of seed of new varieties in many developing countries also generates income as most seed sales occur between farmers.

8.3.2 Social impacts

Not available.

8.3.3 Environmental impacts

The environmental impact expected from the project include a reduction in the use of fungicides in yellow rust control by growing resistant varieties thus reducing negative impacts in environment and human health.

8.4 Communication and dissemination activities

Travel to the regions, working together with the scientists and presentations made during various conferences were the main methods of communication. Project scientists travelled extensively to China, South Asia and CWANA region during the crops season and interacted with National Program Scientists.

Project related publications:

Singh, R.P., J. Huerta-Espino, G. Rosewarne and H.M. William. 2005. Understanding and exploiting polygenic resistance to rust in wheat. P. 27. In: Program and Abstracts of Global Landscapes in Cereal Rust Control, 20-22 Sept 2005, Katoomba, NSW, Australia.

Singh, R.P. 2005. Global scenario of wheat rusts: an overview of the workshop "The cost to agriculture of recent changes in cereal rusts" P. 35. In: Program and Abstracts of Global Landscapes in Cereal Rust Control, 20-22 Sept 2005, Katoomba, NSW, Australia.

Wellings, C., R.A. McIntosh, R.P. Singh and A. Yahyaoui. 2005. International virulence monitoring using NILs in trap plots. P. 36. In: Program and Abstracts of Global Landscapes in Cereal Rust Control, 20-22 Sept 2005, Katoomba, NSW, Australia.

William, H.M., R.P. Singh, J. Huerta-Espino, G. Rosewarne. 2005. Characterization of genes for durable resistance to leaf rust and yellow rust in CIMMYT spring wheats. Page 7. In: Abstr. Of 7th International Wheat Conference: Wheat Production in Stressed Environments, Nov 27-Dec. 2, Mar de Plata, Argentina.

Singh, R.P. and J. Huerta-Espino. 2005. Application of durable resistance to leaf and yellow rusts in wheat breeding: success and challenges ahead. ASA-CSSA-SSSA meeting, Salt Lake City, USA. Ref. No. 49-5.

Wellings, C.R. (2005) Control Strategies for Wheat Stripe Rust in Australia: Outcomes Arising from Pathogen Incursion, Evolution and Host Resistance Studies. Symposium: Stripe Rust of Wheat; A Plan For Recovery, Proceedings of the Crop Science Society of America, Salt Lake City, Utah, 9-12 November 2005, Abstract 232-1.

Yahyaoui A., Abdalla O., and Rajaram S. 2005. Monitoring Wheat Rusts in the Caucasus, Horn of Africa, Central, and West Asia. 7th.International Wheat Conference, Mar del Plata, Argentina. Nov. 27 to Dec.2, 2005.

Yahyaoui A. 2005. Yellow Rust (Puccinia graminis fsp tritici): Epidemiology and Global Threat to Wheat Production. 7th. International Wheat Conference: GRI-Workshop, Mar del Plata Argentina. Nov. 28. 2005)

Wellings,C.R. (2006) Changing dynamics of Puccinia striiformis in Australia. Abstracts, The Second Central Asian Cereals Conference, Issyk-Kul, Kyrgyzstan, pp. 415-416, June 2006.

Park, R.F. and Wellings,C.R. (2006) The national cereal rust control program in Australia. Keynote address, Second Central Asian Cereals Conference, Issyk-Kul, Kyrgyzstan, June 2006.

Wellings, C.R. (2007) Puccinia striiformis in Australia: A review of the incursion, evolution and adaptation of stripe rust in the period 1979-2006. Australian Journal of Agricultural Research 58: 567-575.

Zhu H., R. Singh, J. Huerta and O. Banuelos. 2007. Genetic analysis of yellow rust resistance of Chuanmai 107 in Mexico. Southwest China J. of Agricultural Sciences 20:252-255.

Wellings,C.R. (2007) Stripe rust in Australia: a co-operative interagency approach to long term incursion management. Symposium “Rust Diseases: Threats to Global Food Security in the Context of Climate Change”, NSW Center for Animal and Plant Biosecurity, February 2007.

Yahyaoui A., Singh RP., Pretorius ZA., Hovmoller M., Fetch T., Welling C., Khoury W., Rajaram S. 2007. Implication of climate changes on trans-boundary rust diseases. 16th IPPC. Glasgow, Scotland UK. October 14-19, 2007

Yahyaoui A., Hodson D., Cressman K., De-Pauw E. Ward R. 2007. Global monitoring of rust movement. 16th IPPC. Glasgow, Scotland UK. October 14-19, 2007

Nazari, K., Wellings, C.R. and Park, R.F. 2008. Characterisation of seedling resistance to rust diseases in wheat cultivars from Central Asia and Caucusus. International Journal of Plant Breeding 2: 52-63.

Nazari, K. and Wellings, C.R. 2008. Inheritance of resistance in Cappelle Desprez/Avocet S DH population to stripe rust. International Wheat Genetics Symposium, Brisbane, September 2008.

Wellings, C.R. 2008. Monitoring changes in wheat stripe rust pathogens in Australia. China National Stripe Rust Conference, Lanzhou, December 2008.

Singh R.P. 2008. Durable resistance to rust diseases of wheat: from theory to breeding application. In G. Jellis and C. Edwards (eds): Papers from the BSPP Presidential Meeting on Cereal Pathosystems, Queen Mary, Univ. of London. Pages 1-11.

Wellings, C.R. and Kandel, K.R (2009) Mitigating Crop Losses Due to Stripe Rust in Australia: Integrating Pathogen Population Dynamics with Research and Extension Programs APPS Biennial Conference, Newcastle, 29 September-2 October 2009.

Snyman, J.E.,

Wellings, C.R., and Roake, J.E. (2009) A new pathotype of stripe rust affecting triticale in Australia. 12th International European and Mediterranean Cereal Rusts and Powdery Mildews Conference, 13-15 October, Antalya, Turkey.

Loladze, ., Druml, T. and Wellings, C.R. (2009) Differential Adaptation of Australian and New Zealand Stripe Rust Isolates to High Temperature. 12th International European and Mediterranean Cereal Rusts and Powdery Mildews Conference, 13-15 October, Antalya, Turkey.

Wellings, C.R. (2009) The Biology and Epidemiology of Stripe Rust in Australia – A National Integrated Disease Control Strategy. 12th International European and Mediterranean Cereal Rusts and Powdery Mildews Conference, 13-15 October, Antalya, Turkey.

Wellings, C.R. and Golegaonkar, P.G. (2009) Potential Vulnerability of Barley to an Undescribed Form of Puccinia striiformis in Australia. 12th International European and Mediterranean Cereal Rusts and Powdery Mildews Conference, 13-15 October, Antalya, Turkey.

Wellings, C.R. (2009) Monitoring Pathogen Dynamics in Puccinia striiformis: Alternative Methods and Approaches for Interpretation. 4th Regional Yellow Rust Conference for Central West Asia and North Africa 11-12 October, Antalya, Turkey.

Wellings, C.R. (2009) Breeding for stripe rust resistance in Australia. Stripe Rust Conference, North West Agricultural University, Yangling, Shaanxi, China

Wellings, C.R., Singh, R.P., Yayahoui, A., Nazari, K. and McIntosh, R.A. (2009) The development and application of near isogenic lines for monitoring cereal rust pathogens. Borlaug Global Rust Initiative 2009 Technical Workshop Proceedings. 17-20 March 2009. Cd. Obregon, Mexico: BGRI

9 Conclusions and recommendations

Yellow rust continues to be a major constraint in several wheat growing regions of the world. Wheat crop in developed as well as less developed countries suffer significant losses each year due to inadequate genetic resistance in commercial cultivars. Puccinia striiformis tritici, fungus causing yellow rust of wheat, has diverse population structure and evolves rapidly to overcome race-specific resistance genes. The spores of new races also travel short and long distances through prevailing winds, and occasionally through human errors. Proper use of genetic resistance, especially utilization of complex adult-plant resistance is likely to contribute to resistance durability. Project focussed on enhancing the knowledge on the variation for avirulence/virulence in pathogen population, resistance in important varieties and key parental materials used by the breeding programs, development and promotion of higher yielding wheat germplasm with durable resistance to rusts, and enhancing the human capacity of scientists in National Programs.

9.1 Conclusions

Although stem rust race Ug99 has received great attention as it has potential to destroy most of the world's wheat crop, yellow rust is at present the most devastating disease and causing significant yield losses in many countries of Asia, Middle East and Africa as well as USA and Australia. Monitoring of evolution and migration of new races is possible through trap nurseries and characterizing selected samples at recently established Yellow Rust Reference Centre at University of Aarhus, Denmark. Testing of released varieties and potential varieties at key sites within and outside of a region can give a good and fast assessment on the effectiveness of resistance to existing races. This information can be further strengthened by the knowledge on the resistance genes (race-specific or slow rusting adult plant resistance) present in them. Several varieties with inadequate resistance to yellow rust occupy large areas in farmers' field and must be replaced with resistant varieties to reduce losses and ensure food security. Breeding continues to generate new wheat germplasm that has resistance to all three rusts and higher yield potential. Strategies for the fast release and dissemination (through seed projects) of new higher yielding varieties with durable resistance should enhance productivity and food security in Asia, Middle East and Africa. This is only possible with a strong National Program or other agencies that have interest in enhancing wheat productivity and livelihoods of resource poor farmers.

9.2 Recommendations

We strongly recommend the following to ACIAR and other donors and National Programs interested in enhancing wheat productivity and reducing genetic vulnerability of wheat crops to rust diseases:

1. Establish and support a strong international rust monitoring system and participate

2. Establish and support a strong international germplasm testing system at key sites to determine the genetic vulnerability of released varieties and important breeding materials

3. Enhance the knowledge on the genetic resistance in germplasm used by the breeding programs and focus breeding and research towards durable genetic resistance

4. Update and strengthen human and infrastructure capacity to conduct better research, breeding and testing

5. Invest in seed systems and promotion of new varieties and other technologies to farmers.

10 References

10.1 References cited in report

10.2 List of publications produced by project

Navabi, A., J.P. Tewari, R.P. Singh, B. McCallum, A. Laroche and K.G. Briggs. 2005. Inheritance and QTL analysis of durable resistance to stripe and leaf rusts in Australian wheat cultivar Cook. Genome. 48:97-107.

Navabi, A., R.P. Singh, J. Huerta-Espino, and J.P. Tewari. 2005. Phenotypic association of adult-plant resistance to leaf and stripe rusts in wheat. Can J. Plant Pathol. 27:396-403.

Singh, R.P., J.Huerta-Espino and H.M. William. 2005. Genetics and breeding for durable resistance to leaf and stripe rusts in wheat. Turk. J. Agric. 29: 121-127.

Zhao, H., R.P. Singh, J. Huerta-Espino, Z. Yang and Q. Sun. 2005. Study of the adult-plant resistance at different growth stages to stripe rust in wheat. Agriculture Science in China 4:528-532.

Rosewarne, G.M., R.P. Singh, J. Huerta-Espino, H. M. William, S Bouchet, S Cloutier, H McFadden and E.S. Lagudah. 2006. Leaf tip necrosis, molecular markers and β1-proteasome subunits associated with the slow rusting resistance genes Lr46/Yr29. Theor Appl Genet. 112:500-508.

Mateos-Hernandez, M., R.P. Singh, S.H. Hulbert, R.L. Bowden, J. Huerta-Espino, B.S. Gill and G. Brown-Guedira. 2005. Targeted mapping of ESTs linked to the adult plant resistance gene Lr46 in wheat using synteny with rice. Functional and Integrative Genomics. Available online.

Li, Z.F., T.C. Zheng, Z.H. He, G.Q. Li, S.C. Xu, X.P. Li, G.Y. Yang, R.P. Singh and X.C. Xia. 2006. Molecular tagging of stripe rust resistance gene YrZH84 in Chinese wheat line Zhou 8425B. Genome. In Press.

8. Marais,G.F., Pretorious,Z.A., Wellings,C.R., McCallum,B.M. and Marais,A.S. (2005) Leaf rust and stripe rust resistance genes transferred to common wheat from Triticum dicoccoides. Euphytica 143:115-123.

Singh, R.P., J. Huerta-Espino, G. Rosewarne and H.M. William. 2005. Understanding and exploiting polygenic resistance to rust in wheat. P. 27. In: Program and Abstracts of Global Landscapes in Cereal Rust Control, 20-22 Sept 2005, Katoomba, NSW, Australia.

Singh, R.P. 2005. Global scenario of wheat rusts: an overview of the workshop “The cost to agriculture of recent changes in cereal rusts” P. 35. In: Program and Abstracts of Global Landscapes in Cereal Rust Control, 20-22 Sept 2005, Katoomba, NSW, Australia.

Wellings, C., R.A. McIntosh, R.P. Singh and A. Yahyaoui. 2005. International virulence monitoring using NILs in trap plots. P. 36. In: Program and Abstracts of Global Landscapes in Cereal Rust Control, 20-22 Sept 2005, Katoomba, NSW, Australia.

X. Xia, Z.F. Li, G.Q. Li, Z.H. He, Y.C. Niu and R.P. Singh. Seedling resistance to stripe rust in Chinese bread wheat cultivars and lines. P. 52. In: Program and Abstracts of Global Landscapes in Cereal Rust Control, 20-22 Sept 2005, Katoomba, NSW, Australia.

William, H.M., R.P. Singh, J. Huerta-Espino, G. Rosewarne. 2005. Characterization of genes for durable resistance to leaf rust and yellow rust in CIMMYT spring wheats. Page

7. In: Abstr. Of 7th International Wheat Conference: Wheat Production in Stressed Environments, Nov 27-Dec. 2, Mar de Plata, Argentina.

Li, Z.F., G.Q. Li, Z.H. He, R.P. Singh and X.C. Xia. Stripe rust resistance in Chinese bread wheat cultivars and lines. Page 9. In: Abstr. Of 7th International Wheat Conference: Wheat Production in Stressed Environments, Nov 27-Dec. 2, Mar de Plata, Argentina.

Singh, R.P. and J. Huerta-Espino. 2005. Application of durable resistance to leaf and yellow rusts in wheat breeding: success and challenges ahead. ASA-CSSA-SSSA meeting, Salt Lake City, USA. Ref. No. 49-5.

Wellings, C.R. (2005) Control Strategies for Wheat Stripe Rust in Australia: Outcomes Arising from Pathogen Incursion, Evolution and Host Resistance Studies. Symposium: Stripe Rust of Wheat; A Plan For Recovery, Proceedings of the Crop Science Society of America, Salt Lake City, Utah, 9-12 November 2005, Abstract 232-1.

Yahyaoui A., Abdalla O., and Rajaram S. 2005. Monitoring Wheat Rusts in the Caucasus, Horn of Africa, Central, and West Asia. 7th.International Wheat Conference, Mar del Plata, Argentina. Nov. 27 to Dec.2, 2005.

Yahyaoui A. 2005. Yellow Rust (Puccinia graminis fsp tritici): Epidemiology and Global Threat to Wheat Production. 7th. International Wheat Conference: GRI-Workshop, Mar del Plata Argentina. Nov. 28. 2005)

Mattews, K.L., S.C. Chapman, R. Trethowan, R.P. Singh, J. Crossa, W. Pfeiffer, M. van Ginkel and I. De Lacy. 2006. Global adaptation of spring bread and durum wheat lines near-isogenic for major reduced height genes. Crop Sci. 46:603-613.

William, H.M., R.P. Singh, J. Huerta-Espino, G. Palacios and K. Suenaga. 2006. Characterization of genetic loci conferring adult plant resistance to leaf rust and stripe rust in spring wheat. Genome 49: 977–990

Lillemo, M., H. Skinnes, R.P. Singh and M. van Ginkel. 2006. Genetic analysis of partial resistance to powdery mildew in bread wheat line Saar. Plant Dis. 90:225-228.

Rosewarne, G.M., R.P. Singh, J. Huerta-Espino, H. M. William, S. Bouchet, S. Cloutier, H. McFadden and E.S. Lagudah. 2006. Leaf tip necrosis, molecular markers and β1-proteasome subunits associated with the slow rusting resistance genes Lr46/Yr29. Theor Appl Genet. 112:500-508.

Mateos-Hernandez, M., R.P. Singh, S.H. Hulbert, R.L. Bowden, J. Huerta-Espino, B.S. Gill and G. Brown-Guedira. 2006. Targeted mapping of ESTs linked to the adult plant resistance gene Lr46 in wheat using synteny with rice. Functional and Integrative Genomics 6:122-131.

Lagudah, E.S., H. McFadden, R.P. Singh, J. Huerta-Espino, H.S. Bariana and W. Spielmeyer. 2006. Molecular genetic characterization of the Lr34/Yr18 slow rusting resistance gene region in wheat. Theor. Appl. Genet. 114:21-30.

Herrera-Foessel, S.A., R.P. Singh, J. Huerta-Espino, J. Crossa, J. Yuen and A. Djurle. 2006. Effect of leaf rust on grain yield and yield traits of durum wheats with race-specific and slow-rusting resistance to leaf rust. Plant Dis. 90:1065-1072.

Liang, S.S., K. Suenaga, Z.H. He, Z.I. Wang, H.Y. Liu, D.S. Wang, R.P. Singh, P. Sourdille and X.C. Xia. 2006. Quantitative trait loci mapping for adult-plant resistance to powdery mildew in bread wheat. Phytopathology 96: 784-789.

Li, Z.F., T.C. Zheng, Z.H. He, G.Q. Li, S.C. Xu, X.P. Li, G.Y. Yang, R.P. Singh and X.C. Xia. 2006. Molecular tagging of stripe rust resistance gene YrZH84 in Chinese wheat line Zhou 8425B. Theor. Appl. Genet. 112:1098-1103.

Joshi, A.K., R. Chand, B. Arun, R.P. Singh and R. Ortiz. 2007. Breeding crops for reduced-tillage management in the intensive, rice-wheat systems of South Asia. Euphytica 153:135-151.

Hysing S.C., S.L.K. Hsam, R.P. Singh, J. Huerta-Espino, L.A. Boyd, R.M.D. Koebner, S. Cambron, J.W. Johnson, D.E. Bland, E. Liljeroth and A. Merker. 2007. Agronomic performance and multiple disease resistance in T2BS.2RL wheat-rye translocation lines. Crop Sci. In Press.

Herrera-Foessel. S.A., R.P. Singh, J. Huerta-Espino, J. Crossa, A. Djurle and J. Yuen. 2007. Evaluation of slow rusting resistance components to leaf rust in CIMMYT durum wheats. Euphytica. Published online.

Herrera-Foessel, S.A., R.P. Singh, J. Huerta-Espino, M. William, G. Rosewarne, A. Djurle, and J. Yuen. 2007. Identification and mapping of Lr3 and a linked leaf rust resistance gene in durum wheat. Crop Sci. Accepted.

Singh, R. P., D. P. Hodson, Y. Jin, J. Huerta-Espino, M.G. Kinyua, R. Wanyera, P. Njau and R.W. Ward. 2006. Current status, likely migration and strategies to mitigate the threat to wheat production from race Ug99 (TTKS) of stem rust pathogen. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources. 1(No. 054), 13pp.

Singh, R.P., J. Huerta-Espino and M. William. 2006. Breeding for resistance to biotic stresses. Pages 310-322. In: K.R. Lamkey and M. Lee (eds.) Plant Breeding: The Arnel R. Hallauer International Symposium. Blackwell Publishing.

Singh, R.P. and R. Trethowan. 2007. Breeding Spring Bread Wheat for Irrigated and Rainfed Production Systems of Developing World. In: M. Kang and P.M. Priyadarshan (eds.). Breeding Major Food Staples. Blackwell Publishing. In Press.

Singh, R.P., J. Huerta-Espino, R. Sharma, A.K. Joshi and R. Trethowan. 2007. High yielding spring bread wheat germplasm for global irrigated and rainfed production systems. Euphytica Special Issue: Challenges to International Wheat Breeding. In Press.

Duvellier, E., R.P. Singh and J.M. Nicol. 2007. The challenges of maintaining wheat productivity: pests, diseases, and potential epidemics. Euphytica Special Issue: Challenges to International Wheat Breeding. In Press.

Chapman, S.C., K.L. Mathews, R.M. Trethowan and R.P. Singh. 2007. Relationship between height and yield in near-isogenic spring wheats that contrast for major reduced height genes. Euphytica Special Issue: Challenges to International Wheat Breeding. In Press.

Singh, R.P., M.G. Kinyua, R. Wanyera, P. Njau, Y. Jin and J. Huerta-Espino. 2006. Spread of a highly virulent race of Puccinia graminis tritici in Eastern Africa: challenges and opportunities. Proc. Of the 7th International Wheat Conference, Mar del Plata, Argentina.

Wellings,C.R. (2006) Changing dynamics of Puccinia striiformis in Australia. Abstracts, The Second Central Asian Cereals Conference, Issyk-Kul, Kyrgyzstan, pp. 415-416, June 2006.

Park, R.F. and Wellings,C.R. (2006) The national cereal rust control program in Australia. Keynote address, Second Central Asian Cereals Conference, Issyk-Kul, Kyrgyzstan, June 2006.

Singh, R.P., J. Huerta-Espino, R. Sharma and A.K. Joshi. 2006. High Yielding Spring Bread Wheat Germplasm for irrigated Agro-ecosystems In: Reynolds MP & Godinez D (Eds): Extended Abstracts of the International Symposium on Wheat Yield Potential “Challenges to International Wheat Breeding”March 20-24th, 2006 Cd. Obregon Mexico. CIMMYT, Mexico, D.F.

Singh, R.P., J. Huerta-Espino, and M. William. 2006. Breeding for resistance to biotic stresses In: pp 44-46 Science Week Extended Abstracts. CIMMYT headquarters, El Batan, Mexico 23-27 January 2006

Lillemo, M., Å. Bjørnstad, B. Asalf, R.P. Singh, J. Huerta-Espino, X.M. Chen, Z.H. He. 2006. Identification of molecular markers associated with partial resistance to powdery mildew, leaf rust and stripe rust in bread wheat line Saar. In: Abstracts of Eucarpia Cereal Congress: Cereal Science and Technology for Feeding Ten Billion People: Genomics Era and Beyond, Lerida, Spain 13-17 November, 2006. p128.

Huerta E.J., R.P. Singh, G. Leyva , H.E. Villaseñor M. y E. Espitia R. 2006. Virulencia innecesaria en aislamientos de Puccinia triticina. In: XXXIII Congreso Nacional de Fitopatologia y VIII Congreso Internacional de Fitopatoplogia, Manzanillo Colima México, 17 al 20 de Julio del 2006. C138.

5. Huerta-E. J., R.P. Singh, H.E. Villaseñor M., E. Espitia-R.y G. Leyva-M. 2006. Expresión de la resistencia del gene Lr14a a la roya de la hoja Puccinia triticina E. trigos cristalinos. In: XXXIII Congreso Nacional de Fitopatologia y VIII Congreso Internacional de Fitopatoplogia, Manzanillo Colima México, 17 al 20 de Julio del 2006. C139.

6. Sharma, R.C.,Singh, R.P., Joshi, A.K and Huerta-Espino, J. 2006. New CIMMYT-derived bread wheat Germplasm with High Yield potential and wide adaptation. In: Sophie Higman (ed.) Book of Poster Abstracts of International Plant Breeding Symposium. Mexico City, 20-25 August, 2006.