Recovery Plan

for

Leaf Rust, Stem Rust, and Stripe Rust of Wheat

caused by

Puccinia triticina, *Puccinia graminis, and*
Puccinia striiformis, respectively

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Contents page

This recovery plan is one of several disease-specific documents produced as part of the National Plant Disease Recovery System (NPDRS) called for in Homeland Security Presidential Directive Number 9 (HSPD-9). The purpose of the NPDRS is to insure that the tools, infrastructure, communication networks, and capacity required to mitigate the impact of high consequence plant disease outbreaks are such that a reasonable level of crop production is maintained.

Each disease-specific plan is intended to provide a brief primer on the disease, assess the status of critical recovery components, and identify disease management research, education and extension needs. These documents are not intended to be stand-alone documents that address all of the many and varied aspects of plant disease outbreak and all of the decisions that must be made and actions taken to achieve effective response and recovery. They are, however, documents that will help USDA guide further efforts directed toward plant disease recovery.

Executive Summary

Three fungal diseases of wheat, leaf rust, stem rust, and stripe rust, are commonly found on a world wide basis, including the United States. Wheat leaf rust, caused by *Puccinia triticina*, is the most common and widespread disease of wheat in the U.S. and world-wide. Stem rust of wheat, caused by *Puccinia graminis*, historically was one of the most important plant diseases worldwide. This disease has been brought under effective control through the use of host resistance in combination with the elimination of the alternate host, common barberry, from the wheat producing areas of the U.S. In 1999, a new stem rust race (Ug99) virulent on previously resistant wheat was reported in Uganda. Since then, there have been informal reports that similar virulence was occurring in Ethiopia and Kenya, suggesting that this new race may have spread into eastern and northern Africa. Stripe rust of wheat, caused by *Puccinia striiformis,* is most prevalent in cool regions of the world. In 2003, stripe rust struck the wheat crop in the Great Plains and caused yield losses of nearly 90 million bushels in the U.S.

Infections of wheat rusts become established on winter wheat in the southern Great Plains and southeastern states in the fall months. In the spring as temperatures begin to increase and wheat begins active growth, rust infections become active, producing reproductive spores that are wind dispersed over thousands of miles. Along the Gulf coast, rust infections are first observed from mid February to mid March; in the southwest infections are normally observed in early April, in Kansas the first infections are noticed from mid April to mid May, and in North Dakota the first leaf rust is observed on spring wheat during June.

The USDA has developed laboratories, located at Land Grant universities, with national mandates for the major wheat rust diseases. Among other duties, these laboratories provide a national service for identification of rust races and maintain substantial knowledge regarding rust resistance genes. At present, wheat stem rust and leaf rust are handled by the USDA Cereal Disease Laboratory at the University of Minnesota and wheat stripe rust by the Wheat Genetics, Physiology, Quality, and Disease Research Unit at Washington State University. Also, the Wheat Genetics Resource Center at Kansas State University has traditionally had a strong effort in identifying and characterizing resistance to the wheat rusts.

The front line defense in management of the wheat rust diseases has been and continues to be genetic resistance in wheat to the diseases. Durable rust resistance has been difficult to achieve because of variability and development of new races of the fungi. Thus, continued development of new wheat cultivars with genetic resistance to rust diseases is imperative. If genetic resistance breaks down, there is often a need for other management tactics while new genetic resistance is developed. There are presently several fungicides that provide acceptable control of the rust diseases, but long-term use of the fungicides as a stand-alone control tactic opens the door for fungicide resistance to develop.

Focused, national efforts on management of individual rust diseases clearly need to be continued. For example, wheat stem rust epidemics have been nearly eliminated in North America, but continuing research is now needed to protect against new stem rust races discovered in Africa.

Similarly, stripe rust efforts had been focused only on the Pacific Northwest, but the disease has now become a major issue in the Midwest, Southwest, and Southeast as well.

Leaf Rust, Stem Rust, and Stripe Rust of Wheat

caused by

Puccinia triticina, Puccinia graminis, and

Puccinia striiformis, respectively

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I. Introduction

Three fungal diseases of wheat, leaf rust, stem rust, and stripe rust, are commonly found on a world wide basis, including the United States. Wheat leaf rust, caused by *Puccinia triticina*, is the most common and widespread disease of wheat in the U.S. and world-wide (15). The disease is found annually in the soft red winter wheats grown in the eastern U.S., the hard red winter wheats grown in the southern Great Plains region, the fall-sown spring wheats in the southwest, and the hard red spring wheats grown in the northern U.S. Yield losses due to leaf rust can vary depending on the stage of crop development when the initial infections occur and the degree of genetic resistance in the wheat cultivars. Losses can vary from 10-20% if the flag leaves are defoliated due to leaf rust at the milk to soft dough stage of grain development (1). Losses can vary from 35-70% if the leaves are defoliated from jointing to flowering.

Stem rust of wheat, caused by *Puccinia graminis*, historically was one of the most important plant diseases worldwide. In the early 1900s, stem rust epidemics in spring wheat were frequent in the northern Great Plains of the United States and Prairie Provinces of Canada. Major epidemics that resulted in dramatic losses in the United States occurred in mid 1930s, and again in 1950s. Stem rust also caused significant yield losses in the hard red winter wheat in the southern and central Plains as well as in soft red and soft white wheat in the Midwest and Southeast United States. The disease has been brought under effective control through the use of host resistance in combination with the elimination of the alternate host, common barberry, from the wheat producing areas of the U.S. In 1999, a new stem rust race virulent on the resistance gene *Sr31* was reported in Uganda (Ug99). Since then, there have been reports that similar virulence was occurring in Ethiopia and Kenya, suggesting that this new race may have spread into eastern and northern Africa.

Stripe rust of wheat is caused by *Puccinia striiformis*. The disease is most prevalent in cool regions of the world. Because stripe rust is favored by low temperatures, the disease occurs earlier in the growing season than leaf rust and stem rust, and therefore, has potential to cause more damage. Stripe rust is an important disease of wheat in Asia, Europe, Africa, the Middle

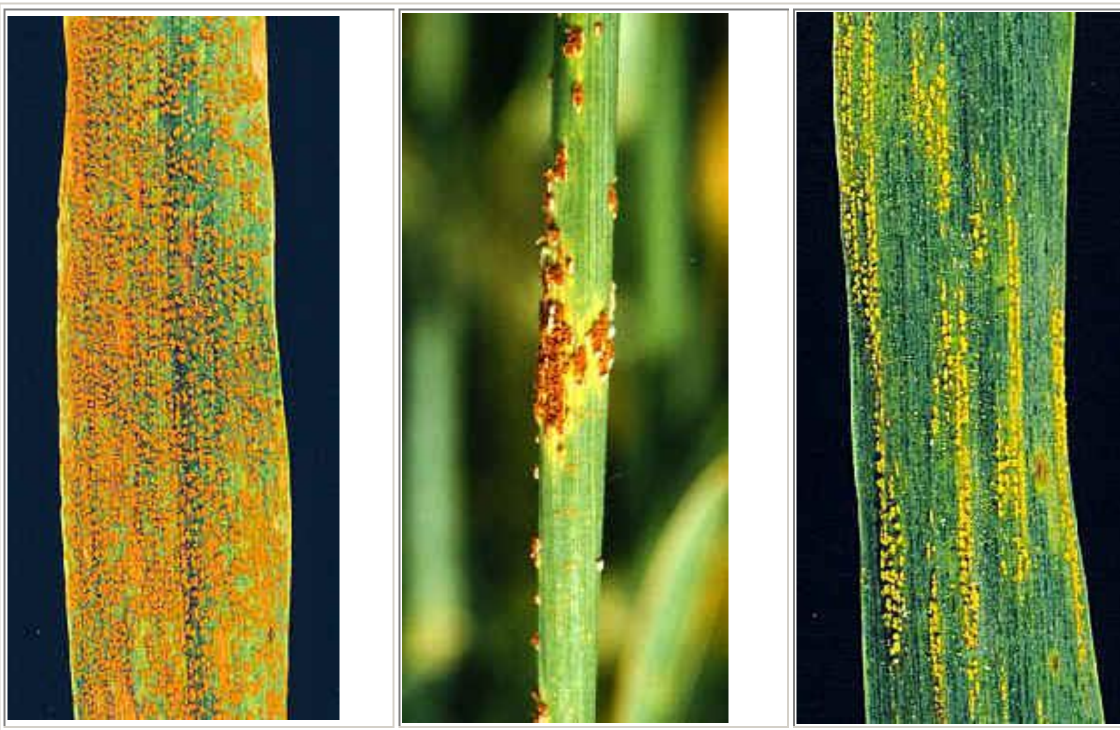
East, Australia, New Zealand, South America, and North America. In recent years, wheat stripe rust has caused major damage in Australia, China, Central Asia, Russia, and South Africa. In the U.S., the disease has been most destructive in the Pacific West (California, Oregon, Idaho, and Washington), but severe epidemics have occurred in the south central states and the Great Plains since 2000. In 2003, stripe rust struck the wheat production in the Great Plains and caused yield losses of nearly 90 million bushels in the nation, the highest yield loss in the record.

II. Biology and Spread

Infections of wheat rusts become established on winter wheat in the southern Great Plains and southeastern states in the fall months. In the spring as the mean temperatures begin to increase and the wheat breaks dormancy and begins active growth, rust infections become active, producing urediniospores (reproductive structures) that are wind dispersed over thousands of miles. Urediniospores are carried into the atmosphere by thermal updrafts and are often deposited onto the wheat crop by rainstorms. Wheat rust infections progress northward in the spring and early summer from the southern states on an annual basis. Along the Gulf coast, rust infections are first observed from mid February to mid March; in the southwest infections are normally observed in early April, in Kansas the first infections are noticed from mid April to mid May, and in North Dakota the first leaf rust is observed on the spring wheats during June (1).

III. Symptoms

Fig. 1. Comparison of the three rusts of wheat. (Photo from Kansas State Univ.)



leaf rust	stem rust	stripe rust

		(yellow rust)

IV. Survey and Detection

Records of wheat rust epidemics go back at least several centuries, and wheat rusts were the first diseases against which resistant crop cultivars were developed. There subsequently has developed an effective communication network among wheat rust pathologists and wheat breeders that is based on personal contacts and a longstanding history of cooperation. In addition to such informal interactions, the USDA has developed laboratories, located at Land Grant universities, with national mandates for the major wheat rust diseases. Among other duties, these laboratories provide a national service for identification of rust races and maintain substantial knowledge regarding rust resistance genes. At present, wheat stem rust and leaf rust are handled by the USDA Cereal Disease Laboratory (formerly the Cereal Rust Laboratory) at the University of Minnesota and wheat stripe rust by the Wheat Genetics, Physiology, Quality, and Disease Research Unit at Washington State University. Also, the Wheat Genetics Resource Center at Kansas State University has traditionally had a strong effort in identifying and characterizing resistance to the wheat rusts.

Several vehicles exist to facilitate communications among wheat rust workers in the U.S. The USDA Cereal Disease Lab conducts annual surveys of wheat, oat, barley, and rye stem rust, as well as wheat leaf rust and oat crown rust. Wheat stripe rust and barley stripe rust are cool weather diseases that thrive best in the Pacific Northwest, where the winters are mild and the summers are typically cool. Epidemics of stripe rust and changes in races of the stripe rust fungi are monitored by a USDA-ARS plant pathologist at Pullman, WA. Each year, scientists at the Cereal Disease Lab make seven survey trips through representative areas of the Great Plains and the Midwestern states from Missouri to Ohio to monitor rust development in the small grain crops and to collect rust samples. From the samples, they identify the rust races present in the infected crops.

Each year more than a thousand collections of rusted leaves and stems of wheat, oat, barley, and rye are processed at the Cereal Disease Lab. Rust fungi grow only as parasites, so isolates of rust for testing are maintained as infections in living plants. For long term storage, spores collected from infected plants are sealed in glass vials and placed in liquid nitrogen. For race identification, spores from single infections are collected and used to inoculate sets of small grain varieties with different specific genes for resistance. The pattern of varieties within the set that are susceptible to or resistant to each rust isolate determines its race identity. By testing samples collected in survey trips and samples sent to the Cereal Disease Lab from all over the United States, Cereal Disease Lab scientists are able to determine the frequency and distribution of rust races throughout the United States each year.

Results of the surveys and race identifications are distributed in the Cereal Rust Bulletin, Annual Wheat, Barley, and Oat Newsletters, and published in scientific journals. The Cereal Rust Bulletin is produced at 2-week intervals from April to August and is distributed to over 400 postal and e-mail addresses as well as being made available to thousands of American and

Canadian readers of various internet services. Subscribers include universities, state departments of agriculture, and more than 40 private corporations. The Cereal Disease Lab also compiles annual estimates of yield losses to rust diseases in wheat, barley, oat, and rye for all cereal-producing states in the United States. The yield loss estimates are distributed to scientists and university libraries throughout the U.S. Presumably, the recipient list for the Cereal Rust Bulletin could be used to contact wheat workers with a turnaround time of less than a week in the event of an emergency that required immediate reaction.

The USDA supports two Regional Education/Extension and Research Activity Committees (ERAs) with responsibilities that include wheat rusts, NCERA-184 and WERA-97. ERA members meet in person annually to discuss disease problems and visit experimental plots and commercial production fields. In addition to providing a forum for discussing strategic issues in cereal diseases, these meetings provide an opportunity to develop professional relationships between individuals. ERAs usually maintain some type of website to provide electronic communications among its members. Though, the ERAs have been very useful, it has sometimes been difficult to convince state experiment station directors to continue these efforts, and some state Experiment Stations allocate ERA travel funds into general budgets instead of travel support to annual meetings. More recently, establishment of the National Plant Diagnostic Network has provided an additional mechanism for diagnoses and rapid communication of time-sensitive issues in plant pathology.

Successes in developing wheat cultivars resistant to rust depend critically on national and international germplasm collections and exchanges among individual scientists. Wheat workers have a long tradition of free exchange of germplasm both nationally and internationally.

V. Compensation

The USDA Risk Management Agency (RMA) coordinates compensation for growers who sustain crop damage from several different types of perils. The following table from the USDA/RMA web site lists the most common crop insurance programs that may be considered for insuring against losses from wheat rust infestations as well as other types of risk.

WHEAT

Policy Name	Policy #	Ref #
GROUP RISK PLAN		
Wheat	00-111	3
MULTIPLE PERIL INSURANCE PROGRAM		
Wheat - Small Grains	04-011	2
Winter Coverage Endorsement	04-011A	2
CROP REVENUE COVERAGE (CRC) PROGRAM		

Wheat	04-CRC-WHEAT (ed. rev. 07/10/03)	4
Winter Coverage Endorsement	04-CRC-WWO (ed.05/28/03)	4
REVENUE ASSURANCE (RA) PROGRAM		
Wheat	04-RA-Wh (Ed. Rev. 07/25/03)	7
RA Winter Wheat Coverage Endorsement	04-RA-WWE	7

VI. Disease Management

The front line defense in management of the wheat rust diseases has been and continues to be genetic resistance in wheat to the diseases. Durable rust resistance has been difficult to achieve because of variability and development of new races of the fungi. Thus, continued development of new wheat cultivars with genetic resistance to rust diseases is imperative.

If genetic resistance breaks down, there is often a need for other management tactics while new genetic resistance is developed. There are presently several fungicides that provide acceptable control of the rust diseases, but long-term use of the fungicides as a stand-alone control tactic opens the door for fungicide resistance to develop.

The North Central Education/Extension and Research Activity Committee on Management of Small Grain Diseases (NCERA-184) has developed the following information on fungicide efficacy for control of certain foliar diseases of wheat for use by the grain production industry in the U. S

Table 1. Efficacy of fungicides for wheat disease control based on appropriate application timing.

Product	Fungicide(s)	Rate/A	Powdery mildew	Stagonospora leaf/glume blotch	Septoria leaf blotch	Tan spot	Stripe rust	Leaf rust	Head scab
Tilt 3.6 EC	**Propiconazole 41.8%**	**4 fl. oz.**	+++*	+++	+++	+++	+++	+++	+
PropiMax 3.6 EC	**Propiconazole 41.8%**	**4 fl. oz.**	+++	+++	+++	+++	+++	+++	+
Quadris	**Azoxystrobin**	**6.2 (to**	+(+)**	+++	+++	++++	++++	++++	

2.08 SC	**22.9%**	**10.8) fl. oz.**							
Quilt 200SC	**Azoxystrobin 7.0% Propiconazole 11.7%**	**14 fl. oz.**	+++	+++	+++	+++	+++	++	
Stratego 250 EC	**Propiconazole 11.4% Trifloxystrobin 11.4%**	**10.0 fl. oz.**	++	+++	+++	+++	+++	++	
Headline 2.09 EC	**Pyraclostrobin 23.6%**	**6.0 (to 9.0) fl. oz.**	++	+++	+++	++++	++++	++++	
Folicur 3.6 EC* **	**Tebuconazole 38.7%**	**4.0 fl. oz.**	++	+++	+++	+++	++++	++++	++

* the greater the number of + signs the greater the relative efficacy
** (+) indicates greater efficacy at higher application rates.
*** Folicur does not have a federal label, but may have Section 18 emergency registration in some states.

The following table lists the presently labeled fungicides for control of leaf, stem, and stripe rust of wheat by the U.S. Environmental Protection Agency.

Table 2. Fungicides labeled for use on wheat for control of leaf, stem, and stripe rust.

Active Ingredient Primary Tradename(s)	Tolerance Citation	Registered for Wheat and/or Small Grains?
Azoxystrobin Heritage, Abound, Quadris	40 CFR §180.507	**Yes**
Propiconazole Tilt, Orbit, Banner	40 CFR §180.434	**Yes**
Difenoconazole Dividend, Bargos, Bogard, Geyser, Score, Sico	40 CFR §180.475	**Yes**

Pyraclostrobin Insignia, Headline, Cabrio	40 CFR §180.582	**Yes**
Tebuconazole Folicur, Elite, Raxil	40 CFR §180.474	**Yes**

VII. Infrastructure and Experts Listing

To a great extent, protection against wheat rust diseases requires maintenance and strengthening of infrastructure that already exists. A few specific issues are discussed below.

1) Focused, national efforts on management of individual rust diseases clearly need to be continued. For example, wheat stem rust epidemics have been nearly eliminated in North America, due in great part to efforts by the Cereal Rust Laboratory. However, continuing knowledge is now needed to protect against new stem rust races discovered in Africa. Similarly, stripe rust efforts had been focused only on the Pacific Northwest, but the disease has now become a major issue in the Midwest, Southwest, and Southeast as well. The long-term USDA effort on stripe rust at Washington State University has been crucial to addressing this new stripe rust threat.

2) Support for ERAs that address wheat rusts need to be continued, and support funds need to be made available to the individual scientists involved.

3) Germplasm collection, characterization, and maintenance need to be supported and germplasm exchange needs to be kept free of political and legal restrictions (other than those truly necessary to avoid spread of seed-borne diseases).

4) Detection and immediate response to rust epidemics, regardless of origin, will best be met by well-trained field-oriented plant pathologists. The number of field-oriented pathologists has decreased substantially in recent decades, and this trend needs to be reversed.

5) The current combination of personal contacts, the Cereal Rust Bulletin, National Plant Diagnostic Network, and ERA web sites provide an appropriate level of communication of urgent information on disease progression, and these efforts all should continue. As the Cereal Rust Bulletin has a long history as a contact point for wheat rust issues, it may be useful (if not already the case) for that publication to be prepared to put out immediate, special notices in emergency situations.

Experts Listing

http://www.ars.usda.gov/Main/site_main.htm?modecode=36-40-05-00

The Cereal Disease Laboratory, A USDA/ARS facility located at the University of Minnesota, maintains a list of experts on cereal diseases. Please refer to the above website to contact the laboratory.

VIII. Wheat Rust Research Priorities

A. Continue development of genetic resistance to wheat rusts

1. *Introgress new resistance to wheat rusts from exotic germplasm*.
   Many rust resistance genes have been found in landraces of *Triticum aestivum* and in species related to cultivated wheat. Many of these genes have provided valuable protection, but proved to be race-specific, so that after deployment and widespread use, their effectiveness diminished. It is important to continue to find new genes to be used in place of those that are no longer effective. The search for new genes should place emphasis on genes that may provide more durable protection—genes that are expressed in adult plants and that confer phenotypes already known to confer durable resistance.
2. *Determine genetic basis of existing resistance to wheat rusts in U.S. wheat breeding programs.*
   Knowledge of what genes are currently deployed in U.S. cultivars is essential to determining which genes or gene combinations are providing durable protection. This knowledge will also alert pathologists and breeders to genetic vulnerability of the crop if, for example, it is determined that the same resistance gene is being used in cultivars that are grown over a wide area, especially over many degrees of latitude.

B. Locate molecular markers for important rust resistance genes to facilitate incorporating more durable resistance in wheat cultivars

Durable resistance is conferred by the action of several genes, many of which have small effects individually. Phenotypes of durable resistance are often more difficult to recognize than phenotypes of race-specific resistance because they are quantitative. Selection for a high degree of durable resistance based only on phenotypic selection is difficult and labor-intensive, and is possible only when the environment in the field is favorable for rapid rust development. Molecular markers would make is easier to assemble combinations of genes that confer a high degree of durable resistance.

C. Continue race surveys for rust populations to determine how races change over time and regions

Race-specific resistance is still widely used to protect wheat against rusts. The effective use of this resistance depends on accurate knowledge of the pathogens' population genetic structure. Race surveys serve as an early detection system for the appearance of a race that overcomes a widely-used resistance gene. Studies of race changes over time and space also provide essential information about the durability of different resistance genes or gene combination.

D. **Develop a set of stripe rust differentials that includes resistance genes found in winter wheat cultivars and breeding lines found east of the Rocky Mountains**

Differentials are most useful when they contain genes found in wheat cultivars being grown in an area. Stripe rust has become a greater problem in the southern U.S., and a sporadic problem in the Corn Belt states. If the resistance genes found in some eastern soft wheats are not represented in the current set of differentials, developed to study the stripe rust fungus in the western U.S., then these differentials are of little value for characterizing races in the eastern half of the U.S.

E. **Evaluate the impact of alternative hosts on rust population dynamics**

The rust fungi that infect wheat infect various other grasses. In some cases, the forms that infect other grasses do not infect wheat, but in other cases, the wheat forms do infect other grasses. Much of the work on host range for the three wheat rust fungi was done many years ago. Further studies should be conducted to determine if there have been changes in host range of the wheat-infecting forms of these fungi. These studies are especially important for *Puccinia striiformis* in the southern U.S., where the fungus may encounter grass species that do not grown in the Pacific Northwest.

F. **Determine the source of stripe rust primary inoculum and relate spore movement to weather patterns**

Most of the work in the U.S. on survival of *Puccinia striiformis* during the wheat-free period has been done in the Pacific Northwest and California. These regions differ greatly from the southern U.S., where stripe rust is becoming a chronic problem. In the Pacific Northwest, survival during a period of late summer, between harvest of the crop and planting of the new crop, is a critical issue. The period between harvest and planting in the southeastern soft wheat region is much longer, and characterized by hotter and wetter conditions than found in the Pacific Northwest. It is important to know how and where the stripe rust fungus survives between wheat crops in the South.

G. **Determine the effect of fungicide seed treatments on over-wintering stripe rust development**

Fungicide seed treatments may prevent the establishment of rust in a newly planted wheat crop. This would help break the overwintering cycle of the fungus in the South and lead to reduced or delayed development of rust disease in the northern areas.

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Appendix

Leaf Rust

The wheat leaf rust fungus, *Puccinia triticina*, is highly variable for virulence to leaf rust resistance genes in wheat. Although the alternate host of leaf rust, *Thalictrum speciossissum* is not present in North America, the population size of *P. triticina* is sufficiently large to provide ample opportunity for mutation and selection to occur. Every year 40-60 races that differ for virulence to leaf rust resistance genes are identified in the U.S. by the USDA-ARS Cereal Disease Laboratory (10). The widespread use of race specific resistance genes has resulted in regional populations of *P. triticina* that differ for frequency of virulence to leaf rust resistance genes. In the late 1980s -1990s hard red winter wheat cultivars with resistance genes *Lr11, Lr3ka, Lr24, Lr26,* and *Lr17* were grown in the southern Great Plains. Races of *P. triticina* with virulence to these genes rapidly increased and became widespread throughout the Great Plains region of the U.S. and Canada (5; 11; 12). Soft red winter wheat cultivars that are grown in the southeastern states with *Lr9, Lr11, Lr18, Lr24,* and *Lr26* have selected races with to these resistance genes (7; 9; 10). Virulence to *Lr2a*, and *Lr16* is common in the leaf rust population of the north central states since many hard red spring wheats have these two resistance genes (13).

New races of leaf rust have recently been introduced to North America. The use of molecular markers have made it possible to characterize distinct *P. triticina* populations in North America and world-wide (6; 8), thus making it possible to distinguish new races on a molecular basis. For many years the Great Plains population was dominated by a single group of races that had very little molecular variation between them, although they were quite diverse for virulence. In 1996 a group of races with virulence to *Lr17* was first detected in the Great Plains region. These races had been selected by the Kansas wheat cultivar Jagger, with *Lr17*. These races also differed in virulence to genes *LrB, Lr3bg,* and *Lr28.* The races with virulence to *Lr17* were also very distinct for AFLP variation (6) from the other races in the Great Plains region. These new races with virulence to *Lr17* were most likely introduced to the U.S. and Canada, possibly from Mexico. By 2002, these races had become widespread throughout the U.S. (9). In 2001 a new race of leaf rust with high virulence to durum wheat was observed in Mexico (17). By 2003 this race was present in the Imperial Valley of California, where it caused significant yield loss in durum wheats (J. A. Kolmer, unpublished data). Virulence testing has indicated that a single group of leaf rust with high virulence to durum wheats has recently become widespread throughout Europe, Mexico, and South America (J. A. Kolmer, unpublished data). Recently developed microsatellite markers for *P. triticina* (J. A. Kolmer, unpublished data) should make it possible to easily distinguish molecular genotypes of leaf rust, and thus more fully determine the migration patterns in North America and world-wide.

Long lasting or durable resistance to leaf rust has been difficult to achieve since *P. triticina* is so variable for virulence and that races with virulence to newly deployed resistance genes can become widespread in a very short period of time. Although over 50 *Lr* genes have been designated, distressingly few genes condition effective resistance to the predominant leaf rust races in the U.S. There are many examples of virulent leaf rust races increasing in response to wheat cultivars with specific seedling resistance genes. At present, many commonly grown wheat cultivars in all the wheat classes are susceptible to leaf rust. Genes that are most effective in the adult plant stage and condition a non-specific resistance have been the most durable over time. The most characterized of these genes is *Lr34* (2). This gene is found in wheat throughout the world, and is very common in the hard red spring wheats in the U.S. (4), and is likely also present in the soft red winter wheat germplasm (7). Cultivars with *Lr34* often have a moderate level of resistance, although high rust severity levels can occur if initial infections occur early in the crop development stage. *Lr34* also interacts with other leaf rust resistance genes to condition better resistance than either gene would if present singly (3). The gene *Lr46* (19) also conditions a non-specific adult plant resistance similar to *Lr34*. Wheat genotypes with combinations of *Lr34, Lr46* and other nonspecific resistance genes (18) may offer the best chances for developing cultivars with high levels of durable leaf rust resistance. Cultivars with *Lr34, Lr46* and other adult plant leaf rust resistance genes also have high levels of adult plant resistance to stripe rust, caused by *P. striiformis* (16).

In the future it will be essential to continue to monitor and characterize the *P. triticina* population in the U.S. and world-wide using virulence and newly developed molecular markers. Recent new introductions of leaf rust in Australia (14) and New Zealand, and North America have illustrated how rapidly new races of leaf rust can become established and comprise efforts to develop resistant cultivars. The emergence of other diseases such as Fusarium head blight (FHB) has complicated efforts to develop resistant cultivars, since the FHB resistant sources have poor leaf rust resistance, and less emphasis has been given to selection of leaf rust resistant germplasm. The development of diagnostic PCR based markers for genes such as *Lr34* and *Lr46* may facilitate the selection of these genes in breeding programs, however lines with these genes can also be selected by crossing adapted germplasm with lines known to have adult plant resistance genes and by testing with leaf rust races that have virulence to the seedling resistance genes in the parental materials.

Stem Rust

The stability of stem rust resistance in US wheat has been maintained by screening advanced breeding lines (conducted by the USDA-ARS Cereal Disease Laboratory in cooperation with breeders). In addition, the use of resistance in southern Plains and southeastern U.S. where stem rust overwinters, effectively reduces the amount of stem rust inoculum for the next crop season. The lack of virulence variation in the stem rust population has also contributed to the stability of resistance. In the last ten years, more than 90% of wheat stem rust isolates collected during the annual rust surveys across the United States belong to one of the two races, RCRS and QFCS. The large majority of US wheat cultivars possess adequate resistance to these two races. Stem rust resistance in wheat worldwide has also been effective and stable; largely due to the wide spread use of CIMMYT germplasm, with *Sr2* and *Sr31* resistance.

In the past several years, most of the CIMMYT wheat (released cultivars and elite breeding lines) grown in Kenya became susceptible to stem rust. The stem rust race identified from a collection from Uganda in 1999 and several isolates collected from Kenya in 2004 were identified to be race TTKS. Seedling evaluations of the various market classes of US wheat against race TTKS were conducted to identify resistance to this new race. Results from these evaluations indicated that more than 80% of the US hard red spring wheat (HRSW) cultivars and advanced breeding lines and 50% of durum cultivars from the northern Great Plains region were susceptible. Such a degree of susceptibility in HRSW is unprecedented and alarming. The most troubling pattern of susceptibility in the spring wheat was that nearly all newly released cultivars (released in the last five years) and currently grown cultivars included in the study were susceptible. Hard red winter wheat (HRWW) grown in the Great Plains was less susceptible comparing with the HRSW because many HRWW cultivars have *Sr24*, a stem rust resistance gene effective against TTKS. This was likely a result of the widespread use of *Lr24* for leaf rust resistance since *Lr24* has a tight linkage with *Sr24*. The stem rust resistance gene *SrTmp* (another gene conferring TTKS resistance) from Triumph 64 was also present in some HRWW lines. However, nearly 60% of released HRWW cultivars were susceptible. A high percentage of the soft winter wheat (>70%), primarily soft red winter, was susceptible to TTKS. There appears to be sufficient susceptibility in cultivars grown in the southern Great Plains and southeastern United States to allow the rust to overwinter, and become established in North America. If this new race was established in North America, it could easily spread, posing a threat to wheat grown in the central and northern Great Plains, and elsewhere in the Midwest.

Wheat developed by CIMMYT has been well known for rust resistance, and stem rust resistance in particular, has played an important role in the success of CIMMYT wheat worldwide. Most of the stem rust resistance genes, especially *Sr31*, used in CIMMYT have been distributed worldwide along with the wide dissemination of CIMMYT germplasm. Wheat breeding in many countries relies on CIMMYT germplasm for wheat improvement, including improvement for stem rust resistance. According to a recent report from CIMMYT (see http://www.cimmyt.org/: Impacts of International Wheat Breeding Research in Developing Countries, 1966-97), developing countries planted 69 million hectares (~170 million acres) of spring wheat in 1997, of which nearly 80% were planted to CIMMYT-related varieties. The implication of susceptibility in CIMMYT wheat to this new stem rust thus becomes obvious: a large portion of spring wheat planted in southwest Asia, Africa, and Latin America will be vulnerable to this new stem rust race; and more significantly, there will be little genetic resistance that could hinder the spread of this new race beyond eastern Africa.

Stem rust has been effectively controlled through the use of resistant cultivars in wheat for more than 50 years. Although this new African race has unprecedented virulence, effective resistance genes are available in adapted US wheat cultivars and elite breeding germplasm. CIMMYT germplasm with TTKS resistance was also identified. In addition to *Sr24*, *Sr36*, and *SrTmp*, we have found high levels of resistance conditioned by unknown genes in cultivars and breeding germplasm in all major classes of US wheat. Furthermore, a number of designated (but not utilized) stem rust resistance genes, including *Sr13*, *22*, *25*, *26*, *27*, *29*, *32*, *33*, *35*, *40*, and *44* are effective against TTKS. A rapid deployment of these resistance genes in breeding will lessen the vulnerability in US wheat to stem rust damage. Wheat improvement for stem rust resistance in developing countries, especially TTKS resistance, should also be promoted because the use of effective resistance in northern Africa, southwest Asia, the Middle East and South America will hinder the progress of this new race along its potential pathway of spread. A thorough survey of race composition and close monitoring of the development of new races worldwide will be necessary to understand fully the potential stem rust vulnerability in wheat.

Stripe Rust

In the U. S., stripe rust of wheat has existed for more than 100 years. A total of 115 races of the wheat stripe rust pathogen have been identified since 1960s and 72 races of the barley stripe rust pathogen have been identified since 1991. A new group of races that were first detected in south central states and California in 2000 has spread and become predominant throughout the U.S. In 2000, wheat stripe rust occurred in more than 20 states from the Pacific Northwest (PNW) and California to Virginia and from Texas to North Dakota. Another severe epidemic occurred in the Great Plains in 2001. The 2001 stripe rust epidemics caused about 40 million-bushel losses in the U. S. In 2002, severe stripe rust occurred on spring wheat crops in the PNW and winter wheat in south central U. S. Washington growers spent more than 2 million dollars for fungicide application. Without the use of fungicide, stripe rust could have caused losses from 26 to 32 million dollars in Washington alone. In 2004, stripe rust epidemic occurred mainly in California and the PNW; the yield losses was estimated about 12 million bushels in the country. In 2005, stripe rust of wheat has already occurring in Texas, Louisiana, Arkansas, Oklahoma, Alabama, Kansas, California, Oregon, and Washington.

Puccinia striiformis is a fungus in Uredinales of Basidiomycetes. Its lifecycle consists of the dikaryotic uredial and diploid telial stages in the nature. Teliospores can germinate to form haploid basidiniospores. Unlike the stem rust and leaf rust pathogens, the stripe rust pathogen does not have known alternate hosts for basidiniospores to infect, and thus, it does not have known sexual pycnial and aecial stages. Therefore, isolates of the fungus cannot be crossed through sexual hybridization, which makes it impossible to study the fungal genes through classic approach and linkage mapping. The fungus reproduces and spreads through urediniospores and survives as mycelium in living hosts. Because urediniospores cannot keep their viability for very long, living plants (volunteers of wheat and barley crops and grasses, or crops and grasses in cool regions in the summer and in warm regions in the winter) are essential to keep the fungus from season to season. Although the pathogen does not have known sexual reproduction, there is a high degree of variation in virulence and DNA polymorphism in the natural populations of the stripe rust pathogens.

Biology of the stripe rust fungus and epidemiology of the disease have been determined. Models for forecasting the disease have been established, especially for the western U.S. Numerous genes for stripe rust resistance have been identified and used in breeding programs. Molecular markers have been developed for some of the genes. Durable type resistance such as high-temperature, adult-plant (HTAP) resistance have been identified and successfully used in the PNW and have been started to use in other regions.