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Success Stories: Breeding for Wheat Disease Resistance in Kansas

Ever since people have domesticated plants, they have noticed differences among varieties in their response to various stresses. One of the main stresses comes from attack by plant pathogens. About 300 B.C., the Greek philosopher Theophrastus (20) was one of the first to record observations about plant diseases. He noticed that plants differed with respect to their reactions to disease. However, one of the first demonstrations of the possible genetic manipulation of plant disease resistance didn't occur until 1905, when Biffen showed that resistance in wheat cultivars to stripe rust was simply inherited (3). Since then, there have been countless cultivars of plants bred for resistance to numerous pathogens. As a result, host resistance has become one of the primary control methods for reducing losses from plant diseases. This form of control is relatively inexpensive for plant producers to implement and is reported to be more "environmentally friendly" than some other control strategies.

The impact of resistant cultivars can be effectively demonstrated in research plots or extension demonstration strips. In these situations, visual differences and crop yields of resistant cultivars are dramatically higher than their susceptible counterparts when disease is a limiting factor. However, it is more difficult to accurately measure the economic impact of releasing resistant cultivars over a large area, such as an entire state. A program that facilitates such an assessment is an annual disease survey of commercial fields followed by a scientific estimation of the statewide losses that each disease causes. In 1976, such a survey program was begun in Kansas to quantify losses caused by wheat diseases (19). Shortly thereafter, a significant increase occurred in the development, release, and adoption of wheat cultivars with resistance to important wheat diseases. As a result of the annual disease survey and estimation of losses, the impact that resistant cultivars had on disease losses could be quantified. This paper describes the use of genetic resistance in wheat for control of diseases and related yield effects in Kansas during the past 25 to 30 years.

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Wheat Diseases in Kansas

Wheat disease losses are estimated by the combined effort of the Kansas Department of Agriculture, USDA, and the Kansas State University (KSU) Cooperative Extension Service. From these groups, there are five or six people who annually participate in a statewide survey of the Kansas wheat crop. Throughout the season, they randomly stop at fields and record the incidence and severity of diseases so that wheat in all nine crop-reporting districts in Kansas is surveyed several times. As a result, the location in the state, hectarage, and severity of wheat diseases are estimated. Combined with the survey information are data published by the Kansas Agricultural Statistics office that give the hectarages of each cultivar planted in each crop-reporting district. Additionally, the Cooperative Extension Service publishes cultivar ratings (1 to 9 scale) for important diseases (8). Based upon their rating, cultivars are grouped into the susceptible (MS-S) group (ratings of 7 to 9), intermediate (I) group (ratings of 4 to 6), and the resistant (MR-R) group (ratings of 1 to 3). Yield losses for the MS-S group are known from research experiments and fungicide trials. The I group is assigned a loss value half that of the MS-S group, and the MR-R group is given a loss value that is half that of the I group. Entering all of this information into a spreadsheet allows the estimation of losses first for each of the nine crop-reporting districts and then for the entire state.

During the past 25 years of estimates, wheat diseases collectively caused an average loss of 13.7% per year (Table 1). Because the average value of the Kansas wheat crop is about $1 billion, this represents about a $137 million loss to the state each year. Thirteen diseases have caused at least 1% loss in Kansas in a given year, with the maximum loss for a single disease at 13% for wheat streak mosaic in 1988 (Table 1). Because disease outbreaks are often localized, these statewide averages greatly underestimate the impacts on individual producers. A statewide loss of 1%, while sounding insignificant, still has a negative impact of about $10 million on the state. Clearly, control of losses due to wheat diseases is important to Kansas and has the potential to significantly add to the economy of the state. Therefore, one of the important attributes of a Kansas wheat cultivar to help protect its yield potential is its level of resistance to pathogens.

Economics of Wheat Breeding in Kansas

In most years, Kansas is the top wheat-producing state in the United States and one of the top wheat-producing areas in the world. Although the value of the crop to Kansas wheat farmers usually exceeds $1 billion, additional income is received by grain handlers, millers, bakers, and distributors. During 2000, about 70% of the state's hectares were planted with cultivars developed at Kansas State University. There are two wheat-breeding efforts at KSU, one located at the KSU Agricultural Research Center at Hays and the other on the Manhattan main campus. While the wheat breeder at each location is the focal point of the effort, scientists from several units play major supporting roles. These units include the departments of agronomy, entomology, grain science, and plant pathology, and the USDA/ARS. Because of the need for expertise from multiple disciplines to produce a modern wheat cultivar, current costs are about $4 million per year to operate the wheat-breeding program at KSU. These expenditures include salaries, research costs, and overhead. Wheat producers themselves, through the Kansas Wheat Commission, fund over 10% of the

Table 1. Percent yield loss estimates caused by wheat diseases in Kansas, 1976 to 2000

	Yield loss (%) by year												
Disease	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**
Leaf rust	1	1	1.5	1.5	T	1.5	2.8	2.5	1.5	5	9	4	2.5
Wheat streak mosaic	0.3	1	3.5	0.5	0.3	7	0.4	1.2	0.1	T	3	2	13
Septoria complex[a]	2	0.5	1	0.5	1	0.5	2.5	5.8	3.5	2.8	1	1.5	0.5
Soilborne mosaic[b]	5	5	3.5	1.6	3	2	1.7	1.2	2.5	2.4	1.4	1	1.5
Tan spot		3	1	1.5	3.5	0.7	1.3	1.8	2.5	2.5	1	3.5	1
Barley yellow dwarf	4.5	0.5	0.8	T	T	T	T	0.3	T	0	T	3.5	1.7
Take-all	3	1	2	0.5	0.6	0.7	0.4	1.1	1.2	2	1	0.4	1.3
Cephalosporium stripe	3	1	0.9	1.5	1.3	T	1.5	1	0.4	0.4	0.1	T	T
Root and crown rot			1.8	2			0.5	0.1	1	0.2	0.2	0.4	0.2
Powdery mildew	0.4	0.2	0.5	1	0.1	1.3	0.6	0.8	0.5	0.2	0.3	0.3	0.4
Scab			T		T		2.1	0.2	0.2	T	0.2	0.2	T
Stem rust	0.1	T[c]	T	0	0	0	0	0.1	0.1	0.1	4.6	0.1	T
Strawbreaker									0.8	1	0.1	T	T
Bacterial leaf blight								0.1	0.3	T		T	0.3
Bunt and loose smut	0.4	0.2	T	T	0.2	T	T	0.1	0.1	T	T	T	T
Stripe rust	0	0	0	0	0	0	0	0.1	T	T		T	T
American wheat striate													
Snow mold													
Total	19.7	13.4	16.5	10.6	10	13.7	13.8	16.4	14.7	16.6	21.9	16.9	22.4

[a] Includes Septoria tritici leaf blotch and Stagonospora nodorum leaf blotch.
[b] Includes wheat soilborne mosaic and wheat spindle streak mosaic.
[c] T = trace.

Table 2. Disease resistance at time of release in selected winter wheat cultivars

	Cultivar[a]					
Disease	**Scout 66**	**Eagle**	**Newton**	**Arkan**	**Karl**	**Jagger**
Leaf rust	S	S	R	R	R	R
Wheat streak mosaic	S	S	S	S	S	MR
Septoria tritici	S	S	S	MR	MR	MR
Stagonospora nodorum	S	S	S	S	MR	MR
Soilborne mosaic	S	S	R	R	R	R
Spindle streak mosaic	S	S	MS	MS	MR	R
Tan spot	S	S	S	S	MR	MR
Barley yellow dwarf	S	S	S	MS	MS	MS
Take-all	S	S	S	S	S	S
Cephalosporium stripe	S	S	MR	MR	MR	MR
Root and crown rot	S	S	S	S	S	S
Powdery mildew	MS	MS	MS	MR	MR	MS
Scab	S	S	S	S	MS	S
Stem rust	R	R	R	R	MS	R
Total MR and R reactions	1	1	4	6	8	9
Year of cultivar release	1967	1970	1977	1982	1988	1994

[a] S = susceptible, MS = moderately susceptible, MR = moderately resistant, R = resistant.

total (about 45% of the operating costs), while other funds come from federal, state, and USDA/ARS sources. A recent economic analysis of Kansas wheat breeding indicated that for each dollar invested in cultivar improvement at KSU, nearly $12 was earned by Kansas wheat producers (2).

The primary reason for this 12-to-1 return is the increase in grain yields from improved cultivars released from the program. However, numerous other factors enter into the success of a newly released wheat cultivar, including milling and baking quality, timing of maturation, straw strength, winter hardiness, and coleoptile length. Still, grain yield is the primary attribute by which a cultivar is judged.

Factors affecting yield potential of a cultivar include agronomic factors such as genetic yield potential, response to fertilizers, resistance to shattering, and resistance to abiotic stress factors (such as aluminum toxicity). However, resistance to biotic (insect and disease) stresses also profoundly affects the yield of a cultivar.

Prior to 1977, most winter wheat cultivars possessed resistance to relatively few diseases. Since then, there has been an increasing commitment from the KSU breeding program to incorporate genetic resistance to diseases of importance in Kansas (Table 2). As an example, the two cultivars Scout and Eagle, which were leading varieties in the 1960s and 1970s, possessed resistance to only one disease (stem rust) the year that they were released (Table 2). By comparison, Jagger, currently the most popular cultivar in Kansas, occupying 34% of the wheat hectarage in 2000, had resistance or moderate resistance to nine different diseases when it was released in 1994 (Table 2). Those nine diseases collectively accounted for 78% of the average total loss from disease (Table 1). Furthermore, Jagger had resistance to the seven most yield limiting of the 17 wheat diseases reported to cause measurable losses in Kansas (Tables 1 and 2). Therefore, during the past 25 years, there has been a dramatic increase in the efforts of KSU wheat breeders to incorporate disease resistance into their cultivars.

Selection for Disease Resistance

Several different techniques have been used by the KSU wheat breeding programs to identify accessions with useful levels of disease resistance. The most important has been visual ratings of the disease reaction of lines in breeding nurseries (Fig. 1). Breeders plant numerous nurseries (16 to 20 per year), each containing hundreds or thousands of different wheat lines, scattered across the state in several different environments. Because many diseases (such as leaf rust) naturally occur with regularity in many parts of the state, it is common to get sufficient disease pressure to make selections. Less widespread diseases usually occur to some degree in one or more of the many breeding nurseries planted throughout the state. Because 12 to 15 years are required from an initial cross to cultivar release, lines resulting in cultivars are evaluated over many location–years for reaction to disease and environmental influences. Therefore, during the developmental process, a new cultivar will probably have been evaluated several times

Table 1. (*continued*)

Disease	Yield loss (%) by year												
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	Avg.
Leaf rust	0.8	4	7.5	11.3	11	1	5	0.1	3.7	2.5	3.4	2.9	3.48
Wheat streak mosaic	3.5	1	4.5	0.3	0.5	0.9	0.6	T	0.6	0.3	1.5	0.9	1.88
Septoria complex[a]	T	T	2	1	3	0.6	7.4	1.5	0.1	0.6	0.4	0.04	1.6
Soilborne mosaic[b]	1	1.5	1	0.1	0.1	T	0.5	T	1	0.1	0.4	0	1.5
Tan spot	0.8	0.2	0.2	1.5	2.5	1.4	2	T	0.2	2.1	1.4	0.2	1.49
Barley yellow dwarf	0.4	1.5	0.2	4.5	0.2	2	3.3	0.1	0.2	0.2	2.3	5	1.25
Take-all	0.4	0.6	1.3	0.1	0.6	0.1	0.2	T	0.01	0.01	0.01	T	0.77
Cephalosporium stripe	0	T	T	0	T	0	0	0	0	0	T	0	0.44
Root and crown rot	1	0.1	0.1	0.3	0.1	0.1	0.1	0.2	0.01	0.01	T	T	0.42
Powdery mildew	0.3	1.3	0.5	0.2	0.1	T	0.1	0	0.01	0.05	T	0.05	0.37
Scab	0.1	0.8	0.2	T	1.3	T	1.2	0.1	T	T	0.2	T	0.34
Stem rust	T	0.1	0.7	T	0.1	0	T	0.1	0	T	T	T	0.25
Strawbreaker	0	0		0	T	0	T	0	0	0	T	0.3	0.14
Bacterial leaf blight	T	T	T	0	T	T	0.01	T	T	0	0	0	0.04
Bunt and loose smut	T	T	T	T	T	T	T	0.01	T	0.01	T	0.01	0.04
Stripe rust	0	0	0	0	T	0	0.01	0	0	T	T	0.05	0.01
American wheat striate					T	T	T	0	T	T	0	0	0
Snow mold					T	0	0	0	0	0	0	0	0
Total	8.3	11.1	18.2	19.3	19.5	6.1	20.4	2.1	5.8	5.9	9.6	9.5	13.7

for reaction to most of the important diseases.

In addition to the general evaluation nurseries, some breeding nurseries are established to produce a useful epidemic of a particular target disease. For example, short rows of advanced breeding lines are seeded into fields that have a history of severe soilborne mosaic. During the early spring, when virus symptoms are especially evident (Fig. 2), accurate assessments of breeding material can be made. Because resistance to soilborne mosaic is a high priority for central and eastern Kansas, only lines demonstrating resistance are advanced unless the lines are targeted for western Kansas. Thus, most cultivars released by KSU have high levels of resistance to this disease. In addition to soilborne mosaic, evaluation nurseries for other wheat diseases have been established (such as for Cephalosporium stripe and Fusarium head blight).

Breeders have successfully used another selection technique, called "green leaf duration," to identify resistant wheat lines. With this method, visual evaluations are made as plants approach maturity to identify lines that retain photosynthetic activity in their leaves (green leaves) longer than other lines in the nursery (Fig. 3). Notes on heading date must be taken along with green leaf duration to avoid selecting for late-maturing lines rather than true green leaf duration. The rationale is that the longer the plants photosynthesize, the greater the carbohydrate accumulation in the grain (higher yields). However, because leaf-spotting diseases (tan spot, Septoria complex) are important factors that significantly reduce green leaf duration, this method will indirectly select for resistance

Fig. 1. Typical winter wheat breeding nursery with short single rows of numerous wheat lines.

to those diseases. As a result, most modern KSU cultivars have greatly improved levels of resistance to the foliar, leaf-spotting fungi (Table 3).

Other important techniques to evaluate breeding lines are the numerous greenhouse evaluation procedures. Although each pathogen has its own unique procedure (such as tan spot; 15), they are all designed to mimic the infection process that occurs in the field. Procedures usually involve inoculating plant tissue with propagules of a pathogen, exposure of the

Fig. 2. Wheat soilborne mosaic screening nursery showing yellow (susceptible) and green (resistant) varieties of wheat.

Fig. 3. Research plots showing a wheat cultivar with improved green leaf duration (right) compared with a cultivar with poor green leaf duration (left).

inoculated material to a disease-conducive environment (such as a mist period to produce leaf wetness) that promotes infection, and then rating the disease reaction after an appropriate incubation period. For some of these diseases (leaf rust), large numbers of lines can be evaluated in the greenhouse in a relatively short amount of time. With others (such as tan spot), the number of lines that can be evaluated is much smaller than for field nurseries. Greenhouse tests in

Table 3. Reactions of selected Kansas winter wheat cultivars to leaf spotting diseases

Cultivar	Year of release	Leaf spotting disease[a] Tan spot	Septoria tritici leaf blotch	Stagonospora nodorum leaf blotch
Scout 66	1967	9	7	9
Eagle	1970	9	7	–
Newton	1977	9	9	8
Arkan	1982	7	8	9
Karl/Karl 92	1988	3	5	5
2163	1989	5	4	4
Jagger	1994	3	3	4
2137	1995	4	4	4
Betty	1998	3	3	4
Heyne	1999	4	4	3

[a] 1 = highly resistant, 9 = highly susceptible.

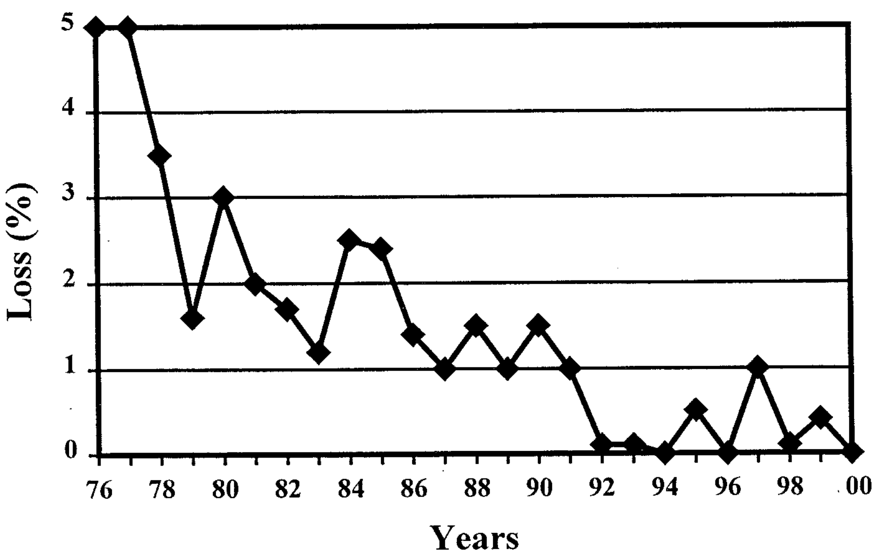

Fig. 4. Grain yield losses in Kansas from soilborne mosaic on winter wheat from 1976 through 2000 showing a significant (P = 0.0001) decline.

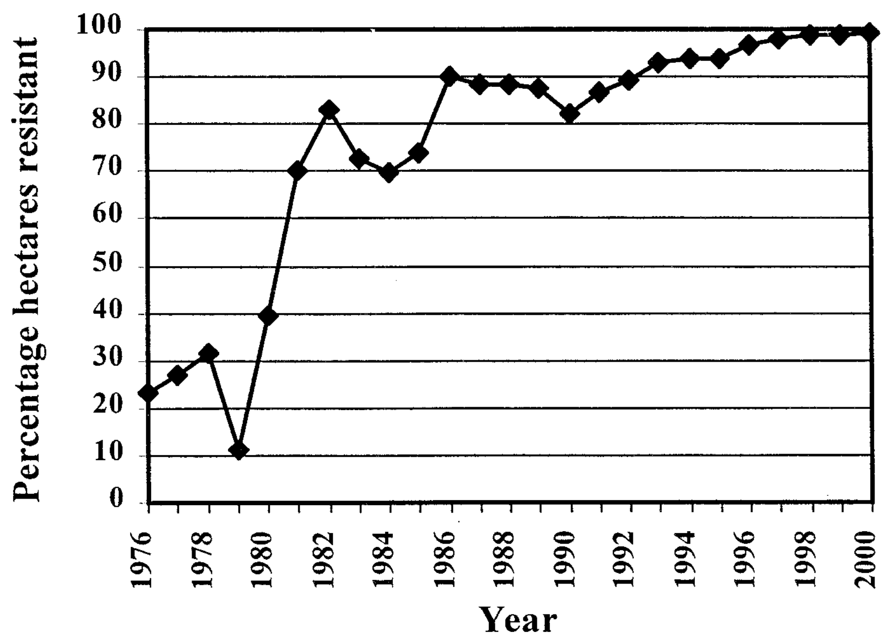

Fig. 5. Percentage of seeded hectares in the eastern two-thirds of Kansas that were planted to wheat cultivars with high levels of resistance to soilborne mosaic.

these latter cases mainly serve to corroborate ratings done in the field. As an example, it is sometimes very difficult to accurately determine whether a particular leaf spot in the field is caused by tan spot or by Stagonospora nodorum leaf blotch. Both diseases cause similar symptoms, and signs of the pathogen are frequently not visible in the field environment. Inoculations in the greenhouse, where the pathogen is known, can clear up this confusion.

Once a cultivar is released, its reaction to various diseases can be tracked by rating cultivar performance nurseries scattered across the state. Most counties in Kansas have locations where many popular commercial cultivars are planted in strips so that local wheat producers can observe how they perform in their own county. When diseases develop in these nurseries, symptoms can be used to evaluate the resistance of commercial cultivars in natural disease situations. Ratings from these evaluations are updated each year and published by the KSU Cooperative Extension Service as a “hard copy” (8) and on the World Wide Web. Such data are important to determine the durability of released resistance.

Deployment of Host Resistance

Four criteria must be met for successful resistance breeding: (i) a source of resistance to an important disease must be found; (ii) the resistance must be incorporated into an agronomically desirable cultivar; (iii) the resistant cultivar must be widely used in the state; and (iv) the resistance should be as durable as possible. In Kansas, useful sources of resistance have been identified and incorporated into adapted wheat cultivars for 10 important diseases in the state. These include leaf rust, wheat streak mosaic, Septoria tritici leaf blotch, Stagonospora nodorum leaf blotch, soilborne mosaic, spindle streak mosaic (=wheat yellow mosaic), tan spot, Cephalosporium stripe, powdery mildew, and stem rust (Table 2). For leaf rust, the lack of resistance durability in Kansas has limited long-term control of this disease by that method. For five others (wheat streak mosaic, Septoria tritici leaf blotch, Stagonospora nodorum leaf blotch, powdery mildew, and stem rust), it is too early to tell what impact deploying resistance will have on their statewide losses. There are two main reasons for this: (i) resistance has not been deployed sufficiently long or over a great enough area to measure its impact; and/or (ii) the diseases cause highly erratic losses from year to year and it is difficult to identify a statistically significant downward trend in their occurrence in a relatively short period of time. However, deployment of resistant cultivars has reduced losses caused by four important diseases in Kansas: soilborne mosaic, spindle streak mosaic, Cephalosporium stripe, and tan spot.

Success no. 1: Control of soilborne mosaic and spindle streak mosaic. The viruses that cause soilborne mosaic and spindle streak mosaic have the same vector, cause similar symptoms, and are favored by similar environmental conditions. Therefore, they are considered together when estimating losses in Kansas. However, resistance to these two diseases is under separate genetic control, and cultivars should have resistance to both pathogens. Nevertheless, from 1976 through 1979, the combination of soilborne mosaic and spindle streak mosaic was the most important wheat disease complex in Kansas (Table 1). During those years, these viral diseases caused an average of 3.8% loss, equivalent to about $38 million annually. Because of a major commitment by wheat breeders to incorporate high levels of resistance to these diseases into new cultivars, losses have dramatically declined and have averaged only 0.25% loss, or $2.5 million, during the past 9 years (Fig. 4). The decline in losses to these viruses resulted from the adoption of wheat cultivars that have high levels of resistance (Figs. 5 and 6). Therefore, incorporation of resistance to these two diseases has resulted in annual savings of about $35.5 million per year for the past 9 years, a benefit that will continue to accumulate as long as there is a commitment to breeding for resistance to this disease complex.

Fig. 6. Field comparison of a winter wheat cultivar with high levels of resistance to soilborne mosaic (left) with a susceptible cultivar (right).

Fig. 7. Intermediate levels of resistance to Cephalosporium stripe displayed by a winter wheat cultivar (bottom) compared with a typical susceptible cultivar (top). Plots on the left for each cultivar were not inoculated, while plots on the right were inoculated with *Cephalosporium gramineum*.

Success no. 2: Control of Cephalosporium stripe. From 1976 to 1983, Cephalosporium stripe caused an average of 1.3% loss statewide (Table 1). Although this is a small number, Cephalosporium stripe only occurred in an area of Kansas where less than 20% of the wheat was grown, and not every field had the problem. Therefore, in fields where it occurred, it was a major yield-limiting factor. Additionally, because Kansas produces so much wheat, 1.3% annual loss is equivalent to about $13 million.

Beginning in 1977, cultivars were released possessing intermediate to moderate levels of resistance to Cephalosporium stripe (Table 2; 4,14). Although these cultivars did not have high levels of resistance (Fig. 7), the disease declined to insignificant levels by 1987 and has since caused only trace losses in Kansas (Fig. 8). The intermediate levels of resistance in adapted cultivars result in poor carryover of the pathogen between seasons. As a result, when moderately resistant cultivars are grown in the same field for several years, the disease declines to inconsequential levels (17,18). Therefore, high levels of resistance are not always needed to control pathogens. Sometimes seemingly small advances in resistance may "tip the scales" to prevent a pathogen from increasing to damaging levels. Because of the commitment by wheat breeders to incorporate intermediate levels of resistance to Cephalosporium stripe into their cultivars, annual savings of about $13 million per year have been realized for the past 14 years.

Success no. 3: Control of tan spot. From 1977 to 1987, tan spot caused an average annual loss of 2.0% statewide, which is equivalent to about $20 million per year (Table 1). Beginning with the release of Karl in 1988, improved cultivars from the KSU breeding program have possessed moderate to high levels of resistance to tan spot (Fig. 9, Table 3). Resistance levels have been in the range of 3 to 5 on the KSU Cooperative Extension 1 to 9 scale, where 1 is highly resistant and 9 is highly susceptible. From 1976 to 2000, the hectarage planted to tan spot–resistant cultivars has gone from about 6% to over 60% (Fig. 10).

What effect do those levels of resistance have on losses caused by tan spot? The KSU extension leaf spot rating of a cultivar has been shown to be linearly related to its increase in yield after application of a foliar fungicide (5). According to the linear models, cultivars with a rating of 3 would average 150 kg/ha increase from fungicide, while cultivars with a rating of 9 would average 470 kg/ha increase. Using another method to measure the effectiveness of resistance, nonsprayed treatments of a cultivar were compared with those receiving multiple foliar fungicide applications to produce a "healthy" control. In these experiments, resistant cultivars sustained 1 to 9% yield loss, while susceptible cultivars sustained 18 to 27% yield losses (6). Therefore, currently available levels of resistance to tan spot are adequate to produce acceptable control but not at the "immune" level. Because there is room for improvement in resistance levels, and not all hectares are planted to resistant cultivars, losses from tan spot still occur (Fig. 11). However, there has been a substantial decline (63%) in severity of tan spot in recent years ($P = 0.0694$; Fig. 11), which is expected to continue.

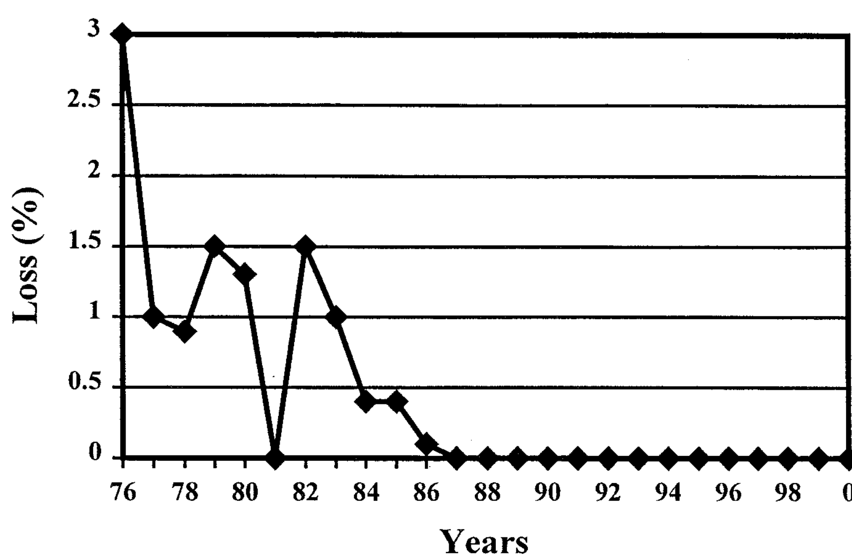

Fig. 8. Grain yield losses in Kansas from Cephalosporium stripe on winter wheat from 1976 through 2000 showing a significant ($P = 0.0001$) decline.

The decline in tan spot cannot be explained by the occurrence of a recent dry period. Tan spot is most important in the central one-third of Kansas and most active during the month of May. According to the May precipitation data for central Kansas (Fig. 11), there has been a nonsignificant increase in the amount of rainfall in May from 1976 to 2000, the opposite trend if dry weather was responsible for the decline in tan spot. Similarly, the decline cannot be explained by a shift in cropping practices. During the same period, the trend in Kansas has been toward reduced tillage, which should aggravate tan spot. We believe a major cause for the decline has been the commitment by wheat breeders to incorporate resistance to tan spot. This has resulted in annual savings of about $10 million per year, and that amount could increase to about $20 million per year with the incorporation of increased levels of resistance into improved cultivars (10) and increased adoption of resistant cultivars by wheat producers.

Overall Success: Reduction in Total Wheat Diseases in Kansas

As discussed above, partial to complete control of soilborne mosaic, spindle streak mosaic, Cephalosporium stripe, and tan spot has been achieved by producing and deploying host plant resistance. One would expect those successes to have an impact on the total annual losses from wheat diseases. In fact, there has been a measurable decline in total wheat disease losses (Fig. 12). Even though diseases cause highly erratic losses from year to year, the decline has been significantly linear ($P = 0.0676$). The linear model shows that average losses have declined from 17% in 1976 to only 10.5% in 2000, a 38% reduction. Several other factors could cause a decline in diseases, most notably nonconducive weather or a change in cropping practices. As mentioned above, however, the climate data (e.g., Fig. 11) and changes in cropping practices cannot explain the decline. We believe the major cause is the dramatic increase in the hectarage planted to cultivars with resistance to important diseases. Barring the appearance of new, damaging wheat diseases or more virulent strains of pathogens, we expect the decline to continue.

Potential Success Stories

Useful sources of resistance have been incorporated into wheat cultivars adapted for Kansas to wheat streak mosaic (12,16), the foliar diseases caused by the Septoria complex (Septoria tritici leaf blotch [8,9] and Stagonospora nodorum leaf blotch [8] [Table 3]), and scab (7). Because of the highly erratic occurrence of these diseases and the relatively short time that resistant cultivars have been available, the effect of resistance is till unclear. However, resistance to the Septoria complex has remained durable to this point, even though significant hectarage has been planted to resistant cultivars. For example, Karl and Karl 92 occupied over 20% of the hectares in Kansas from 1993 to 1997, and 2137 and Jagger together have occupied 30 to 55% of the hectares from 1998 to 2000. All of these cultivars rate 3 to 5 on the 1 to 9 scale for reaction to the Septoria complex and, to date, still maintain resistance. With data from several additional years, we expect to observe significant reductions in the losses from wheat streak mosaic, the Septoria complex, and scab.

Breeding for disease resistance in hard white winter wheat for Kansas has paral-

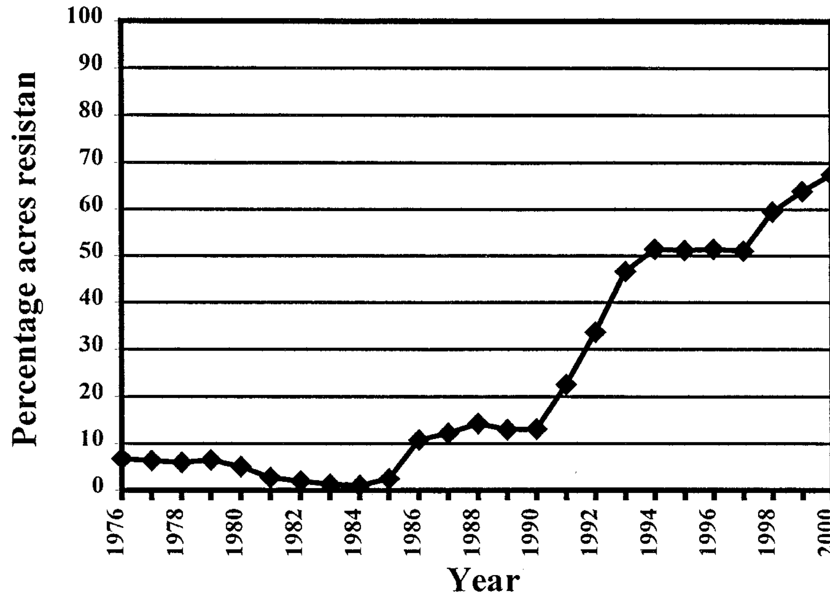

Fig. 10. Percentage of seeded hectares in Kansas that were planted to wheat cultivars with resistance to tan spot from 1976 through 2000.

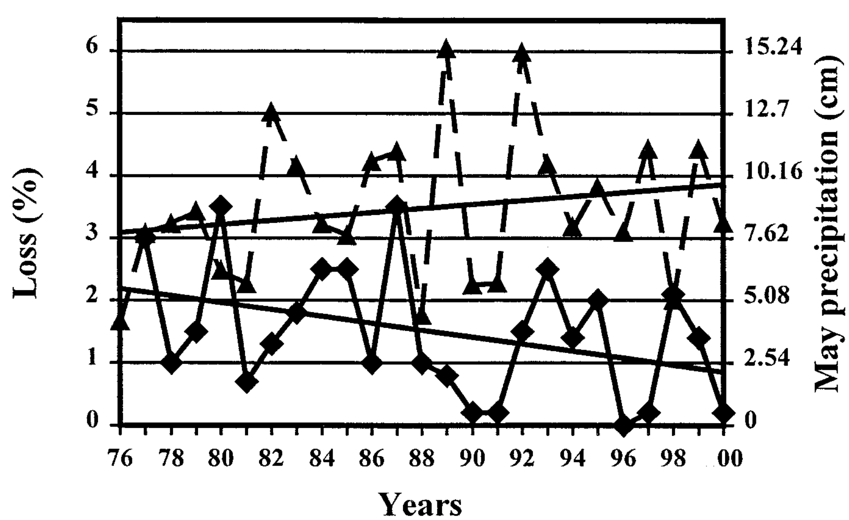

Fig. 11. Grain yield losses in Kansas from tan spot on winter wheat from 1976 through 2000 (diamonds) showing a significant ($P = 0.0694$) linear decline, and precipitation in May in the central one-third of Kansas (triangles) showing a nonsignificant ($P = 0.3389$) linear increase.

Fig. 9. Resistance to tan spot of a winter wheat cultivar (bottom) compared with a typical susceptible cultivar (top).

leled the situation for the hard red winter wheat cultivars. The first white winter wheat cultivars that were released had resistance to only a few diseases, but more recent white cultivars have resistance to as many diseases as the current red cultivars (Table 2). However, hard white winter wheat occupied only 0.2% of the Kansas hectarage in 2000. Nevertheless, if this class of wheat becomes more popular, the successes that have been observed for the red cultivars should continue.

Future Challenges

There still are several important diseases in Kansas where high levels of resistance have not been deployed in commercial wheat cultivars. These include barley yellow dwarf, root and crown rot, and take-all root rot. Although sources of resistance to barley yellow dwarf and common root and crown rot have been described elsewhere (1,11,13), they have not yet been utilized in the KSU breeding program. Unfortunately, no useful source of resistance to take-all has been reported. Nevertheless, utilizing existing resistance sources to these diseases, and potential advances from such areas as biotechnology, should allow for additional success stories for controlling wheat diseases in Kansas.

Another future challenge for resistance breeding in Kansas concerns the control of leaf rust. Despite the incorporation of high levels of resistance into popular cultivars, leaf rust has not been controlled successfully over time. The appearance of new strains of the pathogen has reduced the impact of the released resistance. For example, Karl was released in 1988 and was rated intermediate (4 on a 1 to 9 scale) for reaction to leaf rust through 1992. However, in 1993, it was assigned a rating of 7 (susceptible), followed by a rating of 8 in 1994 and a rating of 9 for 1995 to 2000. Clearly, a new race of the leaf rust fungus that could severely damage Karl appeared prior to 1993 and increased in frequency during 1993 to 1995. A similar occurrence was noted for the popular cultivar Jagger. It was released in 1994 and rated a 2 (resistant) for reaction to leaf rust until 1997, when it was rated 5 (intermediate). Since then, susceptibility ratings have increased each year, and it was rated 8 (susceptible) in 2000. Coinciding with the increase in planting of these two cultivars was their increase in susceptibility to leaf rust. Therefore, significant losses from leaf rust continue to occur (Table 1) and will continue until durable resistance to leaf rust is located and deployed.

In addition to the wheat diseases mentioned above, there is always the potential for the increase in importance of a previously minor pathogen. Also, the introduction from elsewhere of a pathogen that does not exist in Kansas is an increasing possibility with international commerce. The recent appearance of Karnal bunt in limited portions of Arizona caused a rapid increase in attention to this previously low-priority disease. The challenge for a breeding program is to anticipate which pathogens, as yet minor or alien, might become important and then to initiate research to develop screening techniques and find sources of resistance to such projected problems.

Conclusion

During the last 25 years, there has been a marked increase in the commitment of wheat breeding programs in Kansas to incorporate resistance to diseases. That commitment has been rewarded by the effective control of three major disease problems, soilborne mosaic/spindle streak mosaic, Cephalosporium stripe, and tan spot. Annual savings to Kansas wheat producers from controlling these diseases is probably about $58 million. Additionally, resistance to several other important diseases, including wheat streak mosaic, Septoria tritici leaf blotch, Stagonospora nodorum leaf blotch, and scab, has recently been incorporated into commercial wheat cultivars. Therefore, there should be future success in controlling these diseases. Finally, there is the potential for additional success in breeding for resistance to other diseases of importance in Kansas such a barley yellow dwarf, common root rot, take-all, and leaf rust. Due to its past success and future potential, disease resistance should continue to be a high priority for breeding programs that are developing wheat cultivars for Kansas.

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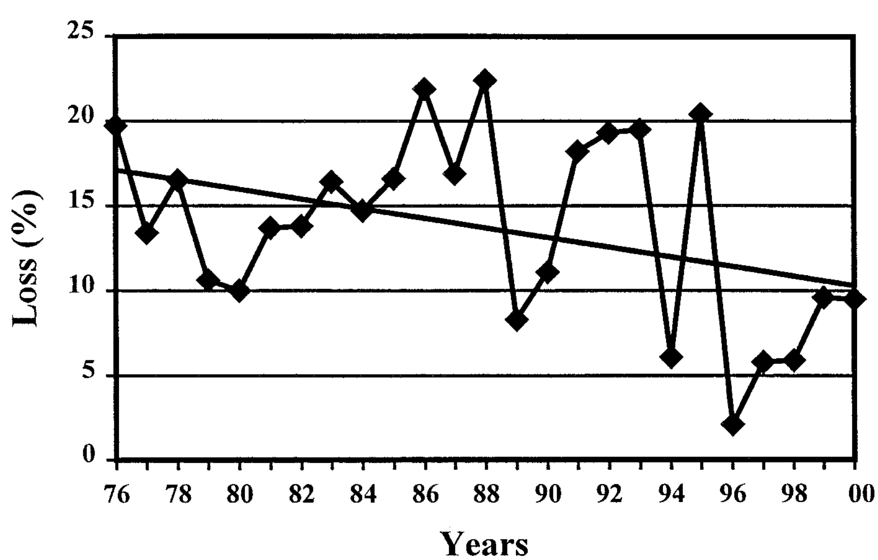

Fig. 12. Total grain yield losses in Kansas from all wheat diseases from 1976 through 2000 showing a significant (P = 0.0676) linear decline.

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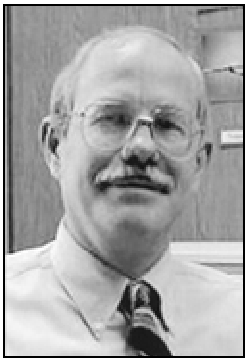

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Jon A. Appel

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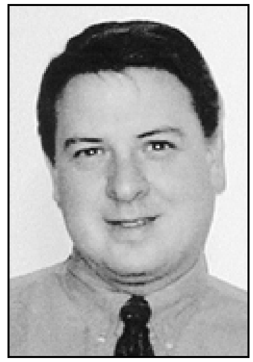

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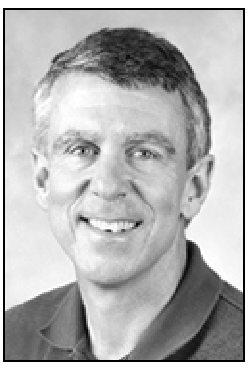
Bikram S. Gill

T. Joe Martin



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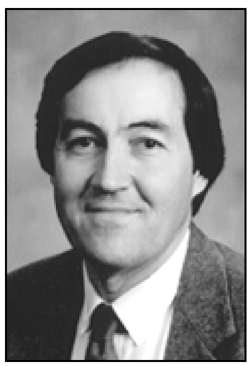

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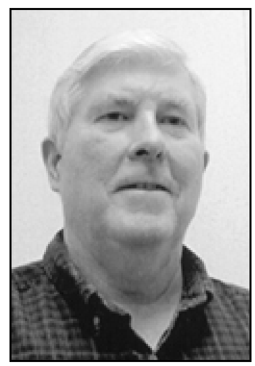

Merle G. Eversmeyer

Dr. Bockus is a professor of plant pathology at Kansas State University with research responsibilities in the area of applied aspects of soilborne and foliar fungal diseases of wheat. He received his Ph.D. in plant pathology in 1978 from the University of California, Davis, and joined the faculty at KSU the same year. Dr. Bockus has established a research program that focuses on the biology of wheat pathogens in the laboratory, greenhouse, and field and participates in the development of wheat germ plasm resistant to the wheat diseases. He also studies the effect of various cultural practices on the pathogens causing those diseases with particular attention to the effects of reduced tillage and crop rotations on disease severity.

Jon Appel serves as the plant pathologist for the Plant Protection and Weed Control Program for the Kansas Department of Agriculture and as an adjunct assistant professor with the Plant Pathology Department at Kansas State University. He received his M.S. in 1982 from Clemson University in South Carolina. Prior to filling the current position in 1989, he was employed by the University of Illinois at Urbana-Champaign, the Pennwalt Corporation, and the Division of Entomology of the Indiana Department of Natural Resources. His current responsibilities include detection and documentation of endemic and exotic plant diseases important to agriculture and native ecosystems in Kansas.

Dr. Bowden is an associate professor in the Department of Plant Pathology at Kansas State University. He received his Ph.D. in plant pathology in 1989 from the University of Wisconsin, Madison, and came to KSU in 1990. His responsibilities include extension and research efforts related to diseases of small grains and forage crops. Research interests include wheat and alfalfa disease management, crop loss assessment, chemical control, host plant resistance, and fungal genetics.

Dr. Fritz is an associate professor in the Department of Agronomy at Kansas State University. His program is responsible for development of new wheat varieties adapted to Kansas. Specific research interests include resistance to various wheat diseases, tolerance to abiotic stresses, and improvement of end-use quality. Prior to joining the faculty at KSU, he received his Ph.D. from Kansas State University in 1994 and was an assistant professor in the Department of Soil and Crop Sciences at Texas A&M University from 1997 to 2000.

Dr. Gill is a university distinguished professor and founder director of the Wheat Genetics Resource Center (WGRC) in the Department of Plant Pathology at Kansas State University. Dr. Gill has dedicated his research to the conservation, management, and utilization of wild wheat species in wheat improvement. Gill and his colleagues have made fundamental advances in the wheat genetic system, identifying individual chromosomes, developing chromosome deletion stocks, and constructing a molecular cytogenetic map of the wheat genome. Their group was the first one to identify gene-rich regions in the large genome of wheat. He is participating in two NSF-funded genomic projects ($12 million over 4 years) to map all the expressed genes in the wheat plant in chromosome bins and large DNA-contigs. The WGRC has developed 41 improved germ plasm lines containing 36 novel resistance genes effective against seven pathogens (fungal and viral) and four insects that have contributed to the release of commercial wheat cultivars in the United States and overseas. For further information check the KSU web site.

Dr. Martin is a professor of wheat genetics at the Kansas State University Agricultural Research Center-Hays, Hays, KS. His primary responsibility is the development of winter wheat cultivars with primary adaptation to production conditions in western Kansas. He received his Ph.D. in plant pathology from Michigan State University in 1974 and joined the KSU faculty the same year. Dr. Martin's breeding efforts are now centered on the development of hard white seeded cultivars that will meet the needs of the U.S. bread industry as well as the Asian noodle industry. Host plant resistance to diseases and insects is a major component of the breeding program. Among his current goals are the development of cultivars resistant to wheat streak mosaic virus, soilborne mosaic virus, leaf rust, stem rust, Hessian fly, and Russian wheat aphid.

Dr. Sears is a wheat breeder and co-manager for AgriPro Wheat. Prior to joining AgriPro Wheat in June 1999, he was a wheat breeder and professor in agronomy at Kansas State University. He has concentrated his efforts during the past 20 years toward developing winter wheat varieties with superior end-use quality combined with excellent disease resistance.

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