

# Scab of Wheat and Barley: A Re-emerging Disease of Devastating Impact

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Scab can be a devastating disease affecting all classes of wheat and other small grains. This fungal disease, also called Fusarium head blight (FHB), has the ability to completely destroy a potentially high-yielding crop within a few weeks of harvest. Lush, green fields become blighted seemingly overnight (Figs. 1 and 2). Frequent rainfalls, high humidities, and/or heavy dews that coincide with the flowering and early kernel-fill period of the crop favor infection and development of the disease. Damage from head scab is multifold: reduced yields, discolored, shriveled "tombstone" kernels (Figs. 3 to 5), contamination with mycotoxins, and reduction in seed quality. The disease also reduces test weight and lowers market grade. Difficulties in marketing, exporting, processing, and feeding scabby grain are experienced.

In North America, *Fusarium graminearum* Schwabe (teleomorph *Gibberella zeae* (Schwein.) Petch; synonym = *G. saubinetii*) predominates among several *Fusarium* species that can cause scab (4,5,8,40,48,60). Other species may predominate in cooler climates or where crops other than wheat and corn are dominant (8,40,48,60). *F. graminearum* also is associated with stalk and ear rot of corn and may cause a root rot of cereals. The fungus persists and multiplies on infected crop residues of small grains and corn. The chaff, light-weight kernels, and other infected head debris of wheat and barley, returned to the soil surface during harvest, serve as important sites of overwintering of

the fungus. Continued moist weather during the crop growing season favors development of the fungus, and spores are windblown or water-splashed onto heads of cereal crops. Wheat and barley are susceptible to head infection from the flowering (pollination) period up through the soft dough stage of kernel development. Spores of the causal fungus may land on the exposed anthers of the flower and then grow into the kernels, glumes, or other head parts. Excellent descriptions of the disease cycle and spore stages of the causal fungi have been published (4,8,21,40,48).

Mycotoxins are frequently associated with the growth and invasion of cereal grains by scab fungi. The most common toxin associated with *F. graminearum*-infected grain is vomitoxin (deoxynivalenol). Vomitoxin is known to cause vomiting and feed refusal in nonruminant animals and poses a threat to other animals and humans if exposure levels are high (45). The presence of mycotoxins in infected grain further exacerbates the losses that scab can cause.

Recent articles have reviewed the epidemiology, management, and history of scab outbreaks in the United States, Canada, Europe, Asia, and South America

(5,40,45,48). As these papers indicate, numerous research and survey reports have described the worldwide occurrence and epidemic levels of scab during the past century. Yield loss reports have not always been based on replicated research trials, but extensive surveys of producers' fields have provided assessments of head blighting severity, which were translated into yield loss estimates. In the United States, scab was found in 31 of 40 states surveyed in 1917, with losses estimated at 288,000 metric tons (10.6 million bushels), primarily in Ohio, Indiana, and Illinois (4). Scab caused an estimated loss of 2.18 million metric tons (80 million bushels) of winter and spring wheat throughout the United States in 1919 (14). Extensive field surveys



**Fig. 1.** Field symptoms of scab in hard red spring wheat. Entire head infections or portions of heads infected are visible as prematurely whitened glumes and awns.



**Fig. 2.** Field symptoms of scab in spring barley. Discolored florets are symptomatic of scab infection. (courtesy Brian Steffenson, Department of Plant Pathology, North Dakota State University)

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showed additional large yield losses from 1928 to 1937 (15). In the 1980s, cool, wet weather in May and June led to epidemics in parts of Kansas (58), Nebraska, Missouri, Oklahoma, Iowa, southern Illinois (10), Indiana (44), and New York (9). In 1982, scab caused an estimated 4% reduction in total United States wheat production, or more than 2.72 million metric tons (100 million bushels) (10).

Scab infections have been reported worldwide from wherever cereal crops are grown. Scab is endemic in China, the world's largest producer of wheat, where losses in excess of 1 million metric tons (about 38 million bushels) have been reported (53). The severe losses caused by scab in barley in South Korea in 1963 threatened some of the population with starvation (52). Argentinean epidemics affecting durum wheat occurred in the 1960s, 1970s, and 1980s (36). Epidemics in Canada and Japan also have been severe, resulting in extensive studies on the epidemiology and control of the disease (38,48,60).

This article will describe economic and social impacts from some of the most recent scab outbreaks in North America, the causes leading to these outbreaks, and how scientists, producers, agencies, and industry are collaborating anew to develop effective strategies for managing scab. Although scab has been common, severe, and well documented in the past, recent epidemics have resulted in increased concern, greater public interest, and expanded research efforts.



Fig. 3. Scabby "tombstone" kernels mixed with healthy hard red spring wheat kernels. (courtesy Jim Miller, U.S. Department of Agriculture, Fargo, ND)

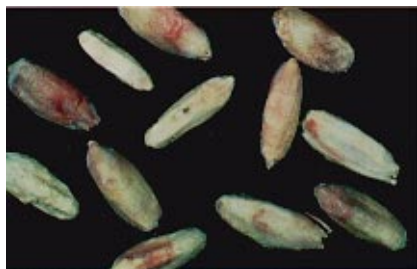


Fig. 4. Scabby durum kernels showing pinkish discoloration and chalky appearance. (courtesy Jim Miller, U.S. Department of Agriculture, Fargo, ND)



Fig. 5. Scabby barley kernels. Some show pinkish discoloration, others show blue-black perithecia of *Gibberella zeae*, the teleomorph of *Fusarium graminearum*. (courtesy Paul Schwarz, Cereal Science Department, North Dakota State University)

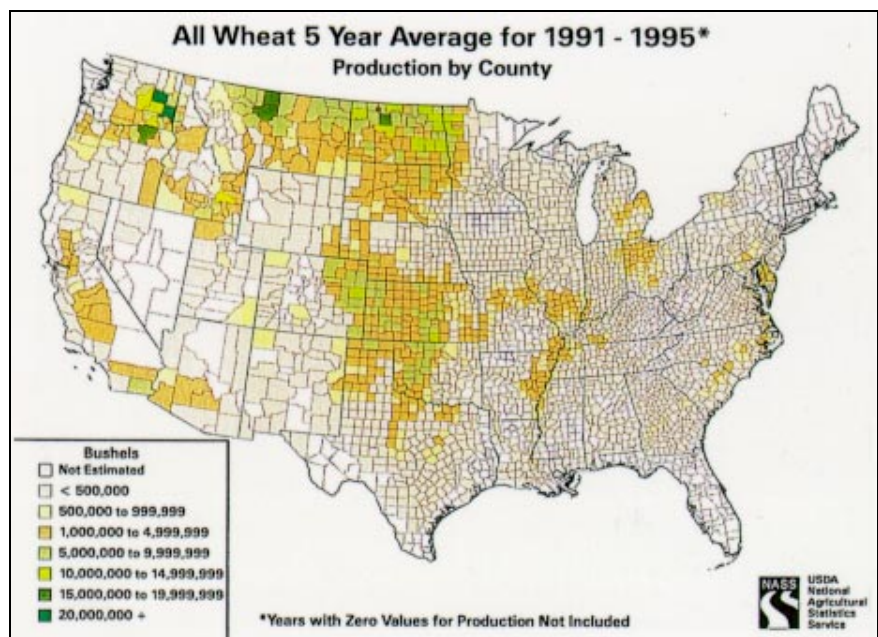


Fig. 6. Average wheat production per county in the United States, 1991 to 1995. Eastern half is primarily soft red winter wheat production and some white winter wheat (flour used for cookies, biscuits, cake mixes, cereals); western half is primarily hard red winter, hard red spring, and durum wheats, plus some white winter wheats (flour used in bread, pasta, cereals, noodles).

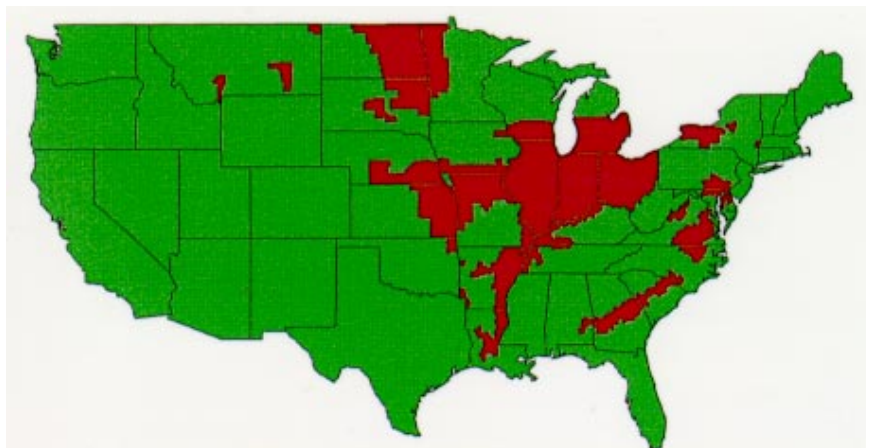


Fig. 7. Reported major outbreaks of scab on wheat and barley, United States, 1991 to 1996. (compiled from information provided by scientists who responded to a questionnaire)

## Re-emerging Disease

**1991 to 1996 epidemics in the United States and Canada.** Wheat production in the United States covers about 29.1 million hectares (72 million acres) each year (Fig. 6), with hectareage and production surpassed only by corn. Various classes of winter and spring wheats are grown, each used for specific milling or baking purposes such as bread, pasta, cookies, biscuits, noodles, cereals, and cake flour. Since 1991, scab outbreaks of varying intensity have been common and widespread across much of the eastern half of the United States, affecting yield and quality of wheat produced (Fig. 7). The locations of the recent scab outbreaks in wheat in the United States are reminiscent of those from 1928 to 1937 (Fig. 8), as described by Dickson (15). Historically, many of the outbreaks have been in areas of soft red winter wheat production, areas with high moisture (>500 mm rainfall) and abundant corn culture. But historic and recent epidemics indicate that when rainfall is above average, hard red winter and spring grain production areas of the eastern portions of the Great Plains (rainfall generally <500 mm) may also experience severe scab outbreaks.

The climatic conditions in the soft red winter wheat areas of the midwestern, southeastern, and mid-Atlantic states in 1991 favored development of scab and leaf diseases, with production dropping by about 25% or 2.72 million metric tons (100 million bushels) across 11 states and 6.1 million hectares (15 million acres) (24). In Arkansas, scab infection was the primary cause of average wheat yields dropping to 1.91 kl/ha (22 bu/ac) compared with the previous 5-year average of 3.73 kl/ha (42.8 bu/ac) (34). Localized epidemics of scab

also occurred in the upper Midwest in 1991, including areas of hard red spring wheat production in west central Minnesota (12) and in southeastern and east central North Dakota (29). In 1992, field surveys in Manitoba indicated an increased incidence of *Fusarium* head blight, with 25% of wheat fields surveyed having scab severities of 10% or greater (60). Illinois (26), Kansas (3), and Nebraska (54) reported significant levels of scab in eastern portions of their states in 1995.

In 1996, scab shook the soft red and soft white winter wheat trade, with epidemics in Iowa (37), Arkansas, Louisiana, Ohio, Indiana, Illinois, Wisconsin, Michigan, and New York, as well as in Ontario, Canada. The hardest-hit states were Illinois, Indiana, Michigan, and Ohio. For example, wheat producers in Ohio lost an estimated \$100 million in 1996 alone because of reduced yield, lower price received for remaining bushels, and cost of cleaning grain to achieve seed quality (P. Lipps, Ohio State University, *personal communication*). Wheat producers in both Illinois and Indiana suffered about a \$38 million loss in 1996 because of yield losses and price discounts due to scab (G. Shaner, Purdue University, *personal communication*). In Michigan, approximately one-half of the 1996 wheat crop was lost to scab, and the combination of reduced bushels and reduced quality resulted in an estimated \$56 million loss (P. Hart, Michigan State University, *personal communication*). Millers in these states paid high transportation costs to get unaffected grain and spent considerable resources in vomitoxin testing. Localized epidemics also occurred in 1996 in areas of north central and north-eastern North Dakota and in southern Manitoba.

In addition to the above epidemics from 1991 to 1996, scab devastated a large portion of the spring wheat and barley growing regions of North America in 1993 and 1994. An account of the 1993 epidemic follows, serving as an example of scab's potential to cause tremendous financial and human hardship. Following that account are descriptions of factors contributing to recent scab epidemics and of worldwide cooperative efforts to find answers for managing scab.

**1993 epidemic: One region's ordeal.** The tri-state areas of Minnesota, North Dakota, and South Dakota, and the Canadian prairie province of Manitoba produce hard red spring wheat, durum wheat, and spring barley. In 1993, scab struck this region (Fig. 9), an area traditionally near the top in North America in production of all wheat and malting barley (6,7). Yield and quality losses caused producers of this region to suffer an estimated \$1 billion loss (11), making it one of the greatest losses due to any plant disease in North America in a single year. Bushel losses were much greater than that recorded for any previous

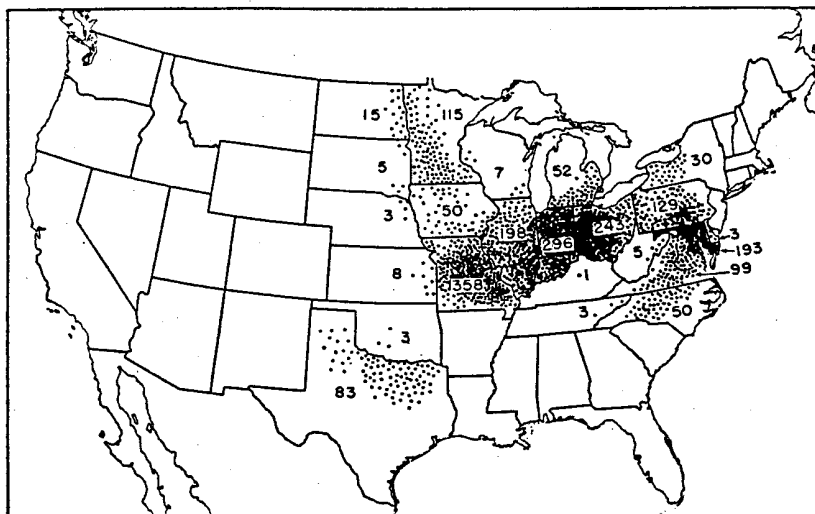


Fig. 8. Estimated average annual loss in bushels of wheat due to scab from 1928 to 1937, based on estimates by the Division of Mycology and Disease Survey, Bureau of Plant Industry, U.S. Department of Agriculture, and by annual scab surveys (15). Each dot = 1,000 bushel loss. Figures indicate the average annual loss in 1,000 bushels for each state.

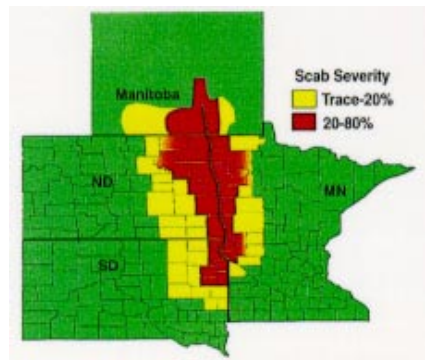


Fig. 9. Area and intensity of 1993 scab outbreak in hard red spring wheat, durum, and barley, Minnesota (MN), North Dakota (ND), South Dakota (SD), and Manitoba.

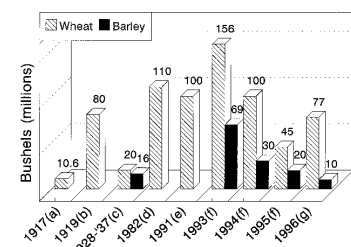
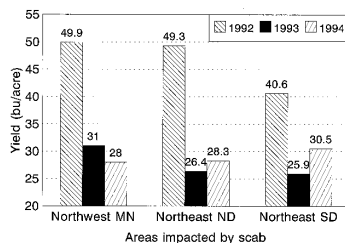


Fig. 10. Estimated wheat and barley losses (in million bushels) due to scab, United States, 1917 to 1996. Losses may have occurred in other years but were not recorded. a = Atanasoff 1920; b = Dickson 1929; c = Dickson 1942; d = Boosalis 1983; e = Kephart 1991; f = losses in North Dakota, Minnesota, and South Dakota as estimated by authors; g = personal communications (see Acknowledgments).

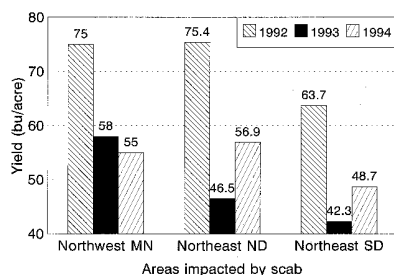
epidemic of scab in the United States (Fig. 10), and an estimated 4.0 million hectares (10 million acres) were affected.

**Yield losses.** Yields of wheat and barley plummeted in affected areas. For example, in northeastern North Dakota, average wheat yields dropped 45%, from more than 49 bu/harvested acre in 1992 to an average of 26.4 bu/harvested acre in 1993 (Fig. 11). Yield losses were estimated at 95 million bushels in North Dakota, 43 million bushels in Minnesota, and 18 million bushels in South Dakota. In Manitoba, scab caused an additional loss of 20 million bushels, for a total estimated wheat yield loss in the region of 176 million bushels (about 4.8 million metric tons) worth \$704 million. Barley losses were estimated at 56 million bushels in North Dakota, 12 million bushels in Minnesota and 1.6 million bushels in South Dakota, or a total of 69.6 million bushels (about 1.6 million metric tons) worth approximately \$122 million. In northeast North Dakota, for example, barley yields dropped from 75 bu/ac in 1992 to 45 bu/ac in 1993 (Fig. 12).

Yield losses due to scab were estimated or measured using field surveys by state and regional extension plant pathologists, by state departments of agriculture, and by county extension agents (6,12,17,19,23,32). The survey estimates correlated highly with each state's Agricultural Statistical Services yield estimates after harvest (1,7,20) and with yields from variety trials in the region. Field surveyors visually estimated number of heads infected (incidence) and amount of head infected (severity) (46). Incidence and head severity ranged from 5 to 80%.



**Fig. 11. Wheat yield comparisons in scab-affected areas: 1992 (no scab) versus 1993 and 1994 (severe scab).**



**Fig. 12. Barley yield comparisons in scab-affected areas: 1992 (no scab) versus 1993 and 1994 (severe scab).**

**Quality losses.** In addition to yield losses, the remaining harvested grain was low in test weight, high in percent damage due to scabby kernels, and high in vomitoxin content. Examination of over 1,000 field samples from eastern North Dakota revealed test weights as low as 44 lb/bu, scabby kernel contents as high as 70%, and vomitoxin levels as high as 44 ppm (47). Similar quality problems also were observed in Minnesota (12) and in South Dakota (50). The 1993 regional quality report for wheat (35) indicated that in affected crop reporting districts, average test weights were well below that required for number one dark northern spring wheat, and percent damage was well above the level allowed for this top wheat class (Table 1). The minimum standard required for number one dark northern spring wheat was 58 lb/bu, while the maximum percent damaged kernels allowed in 1993 was 2.0%. Scabby or tombstone kernels are included in damage.

**Vomitoxin discounts, wheat.** The scab infection in the 1993 crops resulted in high concentrations of vomitoxin, which further reduced marketability and price. Until the fall of 1993, the U.S. Food and Drug Administration (FDA) had "levels of concern" for vomitoxin that included a guideline of 2 ppm in raw grain. Average vomitoxin content in 1993 was well above this guideline in most areas (35). This forced the milling industry to seek scab-free wheat for blending and mixing purposes. The FDA tested for vomitoxin content among 1993 harvested wheat and barley samples across the United States (39). The Federal Grain Inspection Service (FGIS) assisted

the FDA in providing representative samples from wheat- and barley-growing regions. FDA results in wheat indicated an average vomitoxin content of 4.7 ppm across Minnesota (94 samples), 2.7 ppm across North Dakota (62 samples), and 3.7 ppm across South Dakota (37 samples), while Kansas averaged 1.3 ppm (73 samples). Vomitoxin levels also averaged above 2 ppm in several other states, but the sample size was much lower. These results were in contrast to 1991, when Illinois and Missouri averaged vomitoxin contents between 4 and 5 ppm, and Minnesota, North Dakota, and South Dakota levels were below 1 ppm (39).

Following the FDA analysis of vomitoxin levels in the 1993 crop, the "level of concern" for raw grain was dropped, but the guideline of "1 ppm for finished flour products" was maintained. The change in the FDA levels of concern for vomitoxin in the fall of 1993 shifted the consequences of vomitoxin contamination from the buying point to the marketplace.

The price of spring wheat on the Minneapolis grain exchange in the fall of 1993 reflected the extent of damage and vomitoxin levels (22) (Table 2). A number one milling quality, dark northern spring wheat was receiving \$5.36/bu, but if any vomitoxin was detected, the price was reduced by 96 cents. If the damage was high and the test weight was low, then the grade dropped to terminal grade (i.e., a grade below the top number one dark northern spring grade), and large additional discounts were given for the presence of vomitoxin. In truth, many producers had to sell at animal feed prices and were penal-

**Table 1. 1993 hard red spring wheat survey, grading information for areas affected by scab (35)**

Affected area	Test weight (lb/bu)	Damage (%) <sup>a</sup>	Grade <sup>b</sup>
NW Minnesota	56.1	4.6	3 DNS
NE N. Dakota	56.1	3.2	3 NS
EC N. Dakota	56.5	2.8	3 NS
NE S. Dakota	57.2	5.8	3 NS
Regional avg. 1993	58.2	2.0	2 DNS <sup>c</sup>
Regional avg. 1992	60.3	1.1	1 DNS

<sup>a</sup> Scabby kernels included in damage.

<sup>b</sup> DNS = dark northern spring wheat, 1 DNS = highest grade; NS = northern spring; 3 NS = lowest grade; test weight + damage + color influence grade.

<sup>c</sup> Regional average includes higher quality grain from less severely impacted districts within the three states.

**Table 2. Base prices and vomitoxin discounts for hard red spring wheat, Minneapolis Grain Exchange (22)**

Market/contract <sup>a</sup>	1993 contract price (\$/bu)	1993 vomitoxin discount (\$/bu)	1994 contract price (\$/bu)	1994 vomitoxin discount (\$/bu)
Milling	5.36	0.96	4.50	0.25
Terminal, 2 ppm	5.05	0.65	4.30	0.05
Terminal, 6 ppm	4.40	1.59	4.25	1.20
Feed	2.81	NA <sup>b</sup>	3.05	NA

<sup>a</sup> Milling = highest grade or 1 DNS; terminal = grades below 1 DNS.

<sup>b</sup> NA = not applicable.

ized with huge discounts. Wheat producers lost an estimated \$86 million due to vomitoxin discounts alone in 1993 (22). By 1994, familiarity with the disease and vomitoxin, plus increased supplies of clean wheat available for blending, resulted in somewhat smaller discounts based on vomitoxin levels. Net revenue per acre is never large for wheat producers in the northern Great Plains, but the yield and quality losses due to scab in 1993, and again in 1994, resulted in net losses (Fig. 13).

**Vomitoxin discounts, barley.** Average quality parameters for malting barley in the tri-state region were sufficiently good for malting grade in 1993, but vomitoxin levels in barley were high (6,42). FDA tests found an average of 5.5 ppm in samples from Minnesota and 4.8 ppm in samples from North Dakota, with a range of 0 to 28 ppm (39). The high levels of vomitoxin in barley were a concern for the malting, brewing, and feed industry. The major buyers of malting barley adopted a standard of less than 0.5 ppm in purchased grain, a standard that severely impacted barley growers in the affected region. The average barley price received by growers in affected areas was \$0.25 to \$0.30 per bu less than that received for malting barley (6).

**Tough harvesting-marketing-end-use decisions.** Producer decisions: Initially, many wheat and barley producers had to decide whether their crop was worth harvesting. Evaluations of fields in conjunction with Federal Crop Insurance representatives and with Farm Service Agency (formerly ASCS) agents led to decisions to either destroy the crop in the field or to try to salvage some yield. Many fields were not worth harvesting, based on near-zero yield potential. Approximately 18% of the wheat acreage in northwestern Minnesota was not harvested (1), and much of this acreage was eventually burned to destroy the residue. A Minnesota producer, Jerry Krueger, knew what was left of his 2,000 acres of wheat wasn't worth harvesting, but he still struggled emotionally with the decision. "I wasted my year, my family's work, my seed, my fertilizer... It's all down the tubes" (41).

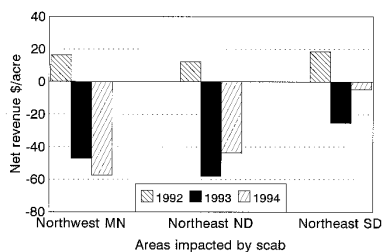


Fig. 13. Revenue per harvested acre, 1992 to 1994, for spring wheat producers in north central states affected by scab.

Producers who did harvest had to make tough decisions on whether to harvest as much grain as possible or turn up the fan speed on the combine to remove as many light, infected kernels as possible. Harvest was made doubly difficult because of the excessive soil moisture conditions that also accompanied harvest. Also, producers had to decide whether to try to sell their grain immediately, hold it and try to clean it with a gravity table to improve grade, or find alternative uses for severely infected grain, such as blending for feed or selling to alcohol plants. Producers who sold their grain immediately after harvest suffered the lowest prices, because the market was depressed.

**Elevator quandaries:** Elevator operators had a difficult time deciding whether to accept damaged grain, because the large cereal buyers were uncertain of what they would accept. Elevator operators did not want to ship a carload to Minneapolis and have it rejected, nor did a buyer want to ship a railroad car to port and have it fail to meet standards. Uncertainty about vomitoxin testing protocols and questions about the accuracy of testing procedures added to the initial confusion about vomitoxin levels and requirements for testing. By mid-autumn, establishment of and training with the ELISA quick test increased the accuracy and reliability of the vomitoxin testing procedures, and the test became an industry standard at the elevator. Overall, the elevator industry was severely affected because of the small amount of grain being delivered and the added cost of vomitoxin analysis.

**Market reactions:** Once the FDA relaxed the level of concern for raw grain, markets

stabilized, but the prices received by growers were much lower than the market price received in other regions because of the vomitoxin discounts and poorer quality (22). Ultimately, the epidemic resulted in higher wheat prices nationwide because of reduced supplies. The average price for good quality wheat in the region in 1993 was the highest (\$4.03/bu) since the 1988 drought (\$4.02/bu) and the highest in the previous 10 years (7). However, the farmers in the affected region had little to sell.

**Health concerns:** Great concern existed among grain and livestock producers, millers-handlers, brewers, and the general public, about the safety of affected grain for use as food, feed, or for bedding purposes. Consumers were concerned about the impact of this disease on the quality of their bread, cookies, and other wheat products. Calls were received on the safety of ready-to-eat cereals, how much vomiting would ensue, and also on air-quality issues. Although the impact of ingesting vomitoxin is not well documented for humans, the literature provided substantial evidence about negative impacts on swine and on some other nonruminant animals. Scabby wheat was analyzed for milling qualities, and some adverse effects on bread making were known (35). Durum and spring wheat millers had to make decisions on purchasing any of this grain, and on how much unaffected grain would be necessary for blending purposes to achieve the processed grain guideline of 1 ppm or less of vomitoxin content. Barley malters did not want scabby barley; the water-soluble toxin is extremely heat stable and the presence of the fungus in malt may cause gushing of the beer (43). Large malting plants in the

**Diseases ravage wheat**  
Grain/ Wheat scab is forcing farmers to abandon crops

**Valley grain diseased**  
To harvest or destroy crops? Disasters force tough choices on farms

**Wheat scab shocks Valley**  
• Disease is widespread, elevators expect discounts

**A blight on the land**  
• Lawmakers seek compensation to farmers for diseased wheat  
Crop scouts think harvests will be smaller than expected

**Farmers panic**  
Ruined wheat field

**Fields of disappointment**

**Crop disease, flood damage will be felt in the N.D. economy**

**Vomitoxin rears its ugly head**

**The Look, Why Summer**

Fig. 14. Regional newspaper headlines associated with 1993 scab epidemic.

region spent millions of additional dollars procuring enough noncontaminated grain for their malting production.

**Sociological impacts.** Producers and rural communities in affected regions suffered greatly in 1993 from the economic uncertainties caused by scab. At harvest, producers were surprised and alarmed to find severe scab infections and empty heads. Although preliminary warnings of scab infection had been provided to growers in late July via extension pest reports and news releases, the producers and the millers had been lulled by seemingly lush green crops and early predictions of another year of record yields. But when the magnitude of the epidemic became apparent, past histories and experiences with the disease were not adequate to handle its overwhelming nature. One of the largest cereal-producing areas in the world was in turmoil. Headlines from newspapers in the region and the nation during the late summer and fall of 1993 reflect despair, panic, and frustration (Fig. 14). Foreclosures and bankruptcies led to a ripple effect in small rural communities. The Wall Street Journal described the effect on the small town of Webster, South Dakota (population 2,417): "Car sales dropped 15% at Mid-West Motors as a salmon-colored mold spread through the flowering wheat fields. It was the final straw for the locally owned farm-equipment dealership, and merchants in Webster fretted that farm families had less reason to shop their Main Street" (25). The North Dakota, Minnesota, and South Dakota extension services established task forces to aid producers and businesses through some of the tough economic and psychological crises. The human experiences that resulted from this epidemic are difficult to summarize. They did, however, leave indelible marks.

**Recurrence.** Scab recurred in parts of the spring wheat and barley areas in 1994 through 1996 (18,23,31). In northwest Minnesota, scab losses in 1994 exceeded the 1993 losses (Figs. 11 to 13). Localized epidemics occurred in 1995 and 1996, with yield losses and price discounts resulting in an estimated \$200 million loss in North Dakota in 1996.

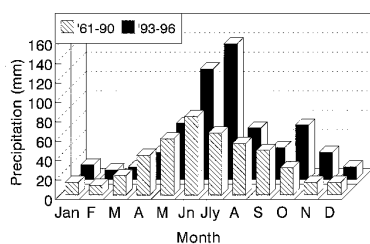


Fig. 15. Comparison of precipitation patterns in years of scab outbreaks versus long-term (30 year) normal precipitation, North Dakota (7).

## Why is Scab So Severe Again?

**Weather.** The very wet weather during 1993 led to severe flooding and associated problems in many areas of the United States. Areas of North Dakota, Minnesota, and South Dakota affected by scab in 1993 typically have relatively dry and cool climates, with annual rainfall ranging from 355 mm in the western edges to 500 to 635 mm in the eastern portions. Traditionally, the greatest precipitation occurs in June, based on the 30-year average from 1961 to 1990 (7,16) (Fig. 15), a time when spring-planted small grains are in leaf development stages. Spring grains in this region flower and develop kernels in July, a month generally characterized by lower rainfall and higher temperatures than June. But in 1993, July was characterized by some of the highest rainfall totals on record (16). Rainfalls averaged from 250 to 600% above normal in eastern North Dakota, northeastern and west central Minnesota, and northeastern South Dakota. In July 1993, measurable rainfall was recorded at Crookston, Minnesota, on 26 of the 31 days (55). Disease development was favored by moist weather lasting from 4 to 6 weeks, a time in which almost all of the wheat crop flowered and began grain fill, and when the barley kernels were filling. Conditions also were favorable for infection in Manitoba (19).

Above-normal precipitation in July in recent years (7) (Fig. 15) has contributed to recurring localized epidemics in North Dakota and Minnesota. Similarly, high rainfall and high soil moisture levels in May or early June have contributed to epidemics of scab in winter wheat growing areas in recent years (3,9,24,26,37,54).

**Other factors.** Although environment is important in the development of scab epidemics, other factors contribute, including high proportions of minimum tillage, high percentages of cultivated acres planted to susceptible host crops, and short rotation intervals between susceptible crops. These conditions occurred in 1993 and 1994 in the spring wheat and barley regions (23) and are similar to those reported favoring scab epidemics in other countries (28).

The causal fungus survives in the residue of host crops such as wheat, barley, and corn. Nationwide, the increase in con-

servation tillage within the last 10 years has been significant (2). Conservation tillage includes mulch or minimum till, no-till, and ridge till. Since corn is a host and an important reservoir of the scab fungus (48,59), an increase in conservation tillage acres, with possible concomitant increase in presence of infected corn residue on the soil surface, may be contributing to recent epidemics in the soft red winter areas. Acreage of conservation tillage corn overtook acreage of conventional tillage in 1993. States with the greatest no-till corn acreages are Iowa, Illinois, Nebraska, Indiana, and Ohio (2). In states such as North Dakota, where wheat is the primary crop, wheat residue on the surface has led to increased risk. North Dakota ranks among the top five states in mulch-till acres, and the acreage of no-till wheat has increased substantially in recent years (2).

Another factor possibly leading to increased levels of scab in recent years has been the U.S. Department of Agriculture's farm program. In states such as North Dakota, Minnesota, and South Dakota, this farm program encouraged producers to maintain high acreage of wheat and discouraged crop rotation because deficiency payments were tied to enrollment in the wheat program. For example, North Dakota had 96% of its 4.9 million hectares (12.1 million acres) of wheat enrolled in the Farm Program in 1993, Minnesota had 88%, and South Dakota had 93% (USDA report on acres in farm program, 1994, *personal communication from North Dakota Farm Service Agency*) (Table 3). Also, in 1991, farmers supported legislation to eliminate set-aside programs, which further limited the practice of crop rotation in wheat-intensive areas.

## Managing Scab The Search for Answers

We cannot control the weather; we cannot expect a large shift in tillage trends; and we will always grow large amounts of wheat and corn in the United States. We must search for other solutions for managing scab.

**Breeding for resistance.** In 1929, J. J. Christiansen, E. C. Stakman, and F. R. Immer (13) said that "the only effective method of controlling wheat scab (Fusar-

Table 3. Percent acreage enrolled in farm program in North Dakota, Minnesota, and South Dakota, 1993 (USDA Report on Acres in Farm Program, 1994, *personal communication from North Dakota Farm Service Agency*)

State	Crop	Base acres (millions)	Enrolled (%)
North Dakota	Wheat	12.1	96
	Barley	3.2	92
Minnesota	Wheat	3.2	88
	Barley	0.86	86
South Dakota	Wheat	4.5	93
	Barley	0.78	79

ium head blight) is to grow resistant varieties." Not much has changed since then, but we may have better ways to obtain those resistant varieties today: new sources of resistance have been identified (5,11,27,51,53); a better understanding of the kinds of resistance exists (33); the molecular tools for incorporating resistance are being developed (5); improved collaboration in the exchange and evaluation of breeding materials has occurred; and hopefully, a longer term commitment to research funding has evolved.

In the midst and aftermath of the 1993 scab epidemic, plant breeders and plant pathologists associated with agricultural universities, government agencies, or private companies screened existing hard red spring wheat, durum wheat, and barley cultivars in the field and after harvest for scab severity, kernel characteristics, yield, test weight, and vomitoxin levels (11,32,55). The widespread occurrence of the disease allowed evaluation of existing adapted cultivars to determine which had the most tolerance, and this information was widely disseminated to producers. Similar evaluations have been possible in soft red winter wheat areas (5,27). Greenhouse evaluations of breeding lines, using challenge inoculations of mixtures of isolates of *F. graminearum* and other scab inducing species, provide additional information on cultivar and advanced line susceptibility. In 1994, Uniform Regional Scab Nurseries were established in Manitoba, Minnesota, North Dakota, and South Dakota to allow testing of public and private breeding materials across a number of locations and environments. At each nursery, mist irrigation and supplemental inoculum were provided to assure infection. The North Dakota State University barley breeding and pathology programs established an additional field nursery in southeastern China, near Shanghai, to evaluate lines under the endemic infection levels present in China.

Genetic materials for all classes of wheat and also for barley are coming from all over the world, from research programs that have identified sources of resistance (5,11,21,33,36,40,45,51,53). In addition, interspecific crosses from other grass species also are being conducted. Of thousands of lines and crosses screened, much less than 1% have improved levels of resistance, and these lines then must be incorporated into cultivars that are adapted and have the yield and quality characteristics desired for the crop and region. Historically, breeders and pathologists have been able to identify and accumulate partial resistance to scab. The challenge for them is to develop effective screens, cooperatively standardize methods, and understand the inheritance of this partial resistance. Maintaining resistance in commercial wheats must not be at the expense of yield or quality. The alternative is that

resistance will be discarded when environmental conditions become unfavorable for scab.

**Cultural practices.** Crop rotations are a key to reducing the risk of severe scab. Although all producers in affected regions in 1993 suffered some degree of scab, no matter what their rotation, subsequent questionnaires indicated that those who did not have corn or wheat as the previous crop had less severe scab (30). The value of crop rotations in reducing scab has been demonstrated (4,14,15,23,30,38,40,48,49,59). The new "Freedom to Farm" Act in the United States may increase the flexibility of producers to try better crop rotations and alternative crops. Producers in the upper Great Plains certainly have new interest in crops such as carrot, crambe, canola, field peas, and lentils as alternatives to wheat and barley in their crop rotation sequence.

Although producers are interested in maintaining soil organic matter and soil moisture, those affected in the areas of heavier soils are looking at tillage rotation as an alternative to continuous no-till or minimum till. Previous and current studies are examining long-term effects of various tillage practices on residue and fungal survival.

**Crop protection chemicals.** We observed beneficial results from the use of seed treatment fungicides to limit damage caused by seedling blight, a potential problem when infected seed is planted. However, results with heading time application of fungicides to reduce scab have been variable (28,34,40,57). Inconsistent success with heading treatments may occur in part because of lack of disease forecasting information. This includes incomplete knowledge about inoculum development and movement. Fungicide costs in relationship to return per acre is another limiting factor in the use of fungicides for scab management. Improved application technology and disease forecasting information may allow producers to effectively use fungicides in conjunction with other disease management strategies (28). In addition to standard fungicides, we and others (40) are evaluating biological agents for their activity against *F. graminearum*.

**Networks of cooperation.** Recent epidemics have fostered a worldwide sense of urgency and cooperation in finding answers to scab. In addition to regional nurseries and cooperative research projects in the north central region, scab forums have been held annually from 1993 to 1996 in Moorhead, Minnesota; Fargo, North Dakota; Brookings, South Dakota; and Winnipeg, Manitoba, respectively. These forums provided the opportunity for input from producers, industry, research, and extension personnel, and resulted in discussion of research projects, results, and needs. In addition, researchers from other affected areas across North America and Mexico also attended. Similar conferences

were held in 1997 in Michigan and Ohio in response to the 1996 epidemic in that region. The 1993 scab epidemic led to establishment of the North Central Regional Research Committee in 1994 (NCR184), with chairmanship of the committee rotating among states. In October 1996, a discussion among 21 scientists from around the world working with scab was held at the CIMMYT headquarters in Mexico. An international seminar on Fusarium head blight and *Fusarium* mycotoxins will be held in the fall of 1997 in Szeged, Hungary. Today, Internet sources abound with information about this disease. Roy Wilcoxson, emeritus professor of plant pathology from the University of Minnesota, has collated a bibliography of all the known publications about this disease, available through the University of Minnesota Department of Plant Pathology, and he has compiled a list of references on chemical control of scab (57).

**Research funding.** At the first Regional Scab Forum, Roy Wilcoxson described the ebb and flow of scab research and its funding (56). As recent epidemics have created a greater public awareness of this disease and its potential severe impact, it is hoped that funding will be more long-term and more national in scope. The 1993 epidemics resulted in state legislative initiatives in North Dakota (\$357,000 over 2 years) and Minnesota (\$477,000 for 1993). These funds have been used to hire a regional small grain specialist and additional technical support, as well as for expenses involved in winter nurseries, greenhouse screening, and vomitoxin testing. Additional funding also has been received from local crop improvement associations and from state wheat and barley producer organizations. The American Malting Barley Association also made substantial financial contributions to the barley breeding, pathology, and cereal science programs. While some state and regional funding for scab research was provided, additional research support is needed. A long-term commitment at the national level to sustain current breeding and pathology efforts is needed. Michigan State University organized a meeting in Chicago in March 1997, in which scientists from states of the north central region developed a cooperative proposal for securing federal funding for scab research.

**Future outlook.** What is the outlook for wheat and barley producers with regard to future scab epidemics? While there is still much to be learned about this disease and its management, we know that weather will play a significant role. Cultivars, rotations, tillage practices, fungicide use, and other factors also will affect the disease. In the short term, we will have scab. The question is, how much and where will it strike? As newspaper cartoonist Trygve Olson so aptly illustrated (Fig. 16), there is a concern about a worldwide food short-



Fig. 16. Will wheat scab contribute to shortage of world food supply? Cartoon by Trygve Olson, May 6, 1996: THE FORUM (Fargo/Moorhead regional newspaper)

age. The cupboard should not be bare, nor should a disease such as scab contribute to such a shortage. We need to solve this problem so that wheat and barley producers worldwide can help provide a wholesome and abundant grain supply.

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