Plant Biotechnology: Current and Potential Impact For Improving Pest Management In U.S. Agriculture An Analysis of 40 Case Studies

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Fungal Resistant Barley

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36. BARLEY

Fungal Resistant

Production

Barley, a small grain cereal, is principally used in the US in malting and brewing. Malting barley is the basic ingredient for beer. Barley is also used as a feed grain. The malting process, during which barley grain is soaked in water to stimulate germination, produces enzymes in the grain which convert its starch, cellulose and proteins into sugar which are used in the fermentation process. After the barley grains are turned into malt, hops are added for more flavor, bitterness and aroma. Brewer's yeast is used in the fermentation process to convert the sugars to alcohol and carbon dioxide.

U.S. production of barley declined significantly in the 1990's- by approximately one-third (see figure 36.1) from 464 million bushels to 318 million bushels. While domestic use of barley for alcohol production remained relatively constant, US exports of barley have declined by two-thirds and imports doubled (see figure 36.2).

North Dakota is the number one state in the US in terms of barley production, producing approximately 30% of the nation's total annual barley crop [1]. The majority of the barley grown in North Dakota is spring planted, nonirrigated, malting varieties.

Barley acreage in North Dakota declined by 1 million acres (approximately a one-third reduction) since 1993 (Figure 36.3). As a result of the state's decline in acreage, the volume of North Dakota's barley production declined in the 1990's by approximately 25% (130 to 100 million bushels per year) while the value of the state's barley production fell by approximately 40% ($244 million/yr to $146 million/yr). The reduction in domestic barley acreage and production is largely attributed to recent epidemics of the disease Fusarium head blight in North Dakota [2, 5].

Fusarium Head Blight

Fusarium head blight (FHB), also called scab, is a fungal disease that affects barley and other small grains and grasses [2, 7]. The fungus is the same one that is frequently

associated with stalk rot of corn. Outbreaks tend to occur when high moisture conditions from rain, dew or humidity coincide with the flowering and grain-fill stages of barley development. The fungus overwinters in crop residue left over from corn and small grain harvests. In spring and summer, spores are carried by wind or splashing water to newly developing barley heads. In barley, infection generally occurs on exposed heads and spreads into kernels and other head parts. Fusarium spores frequently infect the barley kernel after flowering, after the grain head has emerged from the leaf sheath. Scab spores are distinctive; they are canoe-shaped.

Scab became so severe in barley in the first half of this century that it essentially eliminated barley production in the eastern and central corn belt of the U.S. where barley had been grown in rotation with corn [6].

Symptoms of head blight in barley start out as watery, brown lesions, which spread out and may cover single spikelets or the entire head [6]. The infected spikelets become prematurely bleached in color, contrasting with the green of healthy developing tissue. Infected kernels are shrunken and discolored, and their interior develops a floury texture. During prolonged wet weather, the fungus produces pink to salmon-colored spore masses on the barley heads. Under favorable conditions of high moisture and warm temperatures, head blight symptoms can develop within three days of infection. The disease has the ability to completely destroy a barley crop within a few weeks of harvest. Lush, green fields become blighted seemingly overnight [7]. Because disease development is influenced by temperature and moisture conditions during and after flowering, the severity of scab varies greatly from year to year [6].

Before the early 1990s, Fusarium head blight was rarely an economic problem in central and western barley production [6]. But in 1993 the first of a series of recent epidemics occurred in North Dakota barley and led to 500,000 planted acres being left unharvested (See Figure 36.1). Continued infestations in subsequent years have contributed to further reductions in barley acreage planted. Fusarium head blight is now the most serious fungal disease in North Dakota small grain [2].

The scab epidemics in North Dakota in 1993 through 1995 were associated with seasons of above average rainfall and the widespread adoption of conservation tillage practices that leaves abundant crop residues on the soil surface [6]. In 1990, federal farm legislation required the adoption of conservation plans that mandated a minimal requirement of 30% residue cover at the time of crop emergence for land classified as subject to soil erosion. This legislation led to the rapid adoption of reduced tillage practices throughout much of Minnesota and North Dakota. These practices contributed to significant increase in crop residues across much of the small grain production area of the region [10].

Economic losses occur in several ways. Production is decreased because of kernel shriveling, some kernels being so light that they are blown from the combine [6].
In addition to losses from discolored and shriveled kernels, damage from head blight in barley includes reduced yields, reduction of seed weight and quality, and contamination from a mycotoxin produced by the fungus [5, 7]. Significant concentrations of these toxins can be present in plump kernels and it is almost impossible to remove scabby barley kernels from healthy kernels with cleaning equipment [6]. However, the presence of FHB-infected grain does not automatically mean mycotoxins are present [17].
If the mycotoxin is consumed at high levels, it induces vomiting. Consequently, it is commonly known as vomitoxin. The chemical name for vomitoxin is deoxynivalenol, or DON. In addition to causing illness, DON reduces the quality of malting barley because it causes beer to produce too much foam. The water-soluble toxin is heat stable and it's presence in malt may cause gushing of the beer [7]. Elevated foam levels during the fermentation process may mean less beer is produced, and foamy beer that gushes from bottles and cans is not commercially desirable.

Because of strict grading standards, scabby barley is not used in the brewing industry [6]. Maltsters and brewers have reacted to the scab and vomitoxin damage by purchasing less barley from North Dakota farmers and more from Canada and other western states [5]. US imports of barley doubled between 1991 and 1999. Canadian production of malting

barley doubled between 1993 and 1997. In 1997, malting barley exports from Canada represented over 25% of all malting barley consumed in the US brewing industry [5]. In comparison, from 1988 through 1992, malting barley exports from Canada represented only about 5% of all malting barley consumed by the US industry [5].

The FDA established the following advisory levels for DON in food and feed in 1993 [17]:

- 1 ppm for finished grain products for human consumption
- 10 ppm for poultry, but contaminated feed can only be 50% of diet
- 5 ppm for swine, but contaminated feed can only be 20% of diet
- 10 ppm for cattle (over four months old), but contaminated feed can only be 50% of diet

Brewers and maltsters, the primary buyers of North Dakota's malting barley, develop pricing schedules based on DON contamination levels. Barley producers receive severe price discounts when these toxins are present [6].

An analysis of the economic impacts of head blight on barley in North Dakota, published by the US General Accounting Office, found that malting barley grain with 0.5 parts per million (ppm) was valued at premium prices and at 0.6 ppm or more DON, price discounts are applied [5]. The approximate level at which field tests can begin to quantify the amount of vomitoxin is 0.5 ppm [5]. Contamination levels between 0.6 ppm and 1.0 ppm reduce the price per bushel by approximately $0.50. After that, each additional increase of 1.0 ppm reduces the bushel price by another ten to fifteen cents. Barley grain with DON contamination levels of 3.1 ppm or more are valued at the feed grain price, approximately $0.80 below the premium malting barley price [5].

Before 1993, approximately 60-70% of annual North Dakota barley production went to premium malting markets, with less than 0.5 ppm DON [5]; from 1993 to 2000, the annual average was 26% [8].

Incidence and head severity of head blight in North Dakota barley during the 1993 epidemic were estimated to range from 5% to 80%, with an estimated 56 million bushels lost [7]. Examination of over 1000 field samples from eastern North Dakota revealed vomitoxin levels as high as 44 ppm [7]. FDA tests found an average of 4.8 ppm in samples from North Dakota with a range of 0 to 28 ppm [7].

Economic losses to head blight and DON contamination in 1993 were estimated at $62 million [5]. The GAO estimated that from 1993 through 1997 North Dakota barley farmers suffered revenue losses from scab and vomitoxin of about $200 million [5]. Crop insurance payments for scab and vomitoxin damaged barley covered less than 2% of these cumulative losses. About 70% of the losses were from reduced yields and from farmers leaving more barley unharvested. Between 1992 and 1997, average North Dakota barley yields dropped from 65 bushels an acre to 45 bushels an acre. Many producers in 1993 decided not to harvest their barley fields due to the presence of scab and likely low price that they would receive [7](see figure 36.3).
In 1993, North Dakota farmers harvested about 500,000 fewer barley acres than they planted [7]. Scab recurred in parts of the barley area in 1994 through 1996 with yield losses and price discounts resulting in a $200 million loss in North Dakota in 1996 [7].

Price discounts because of vomitoxin accounted for $61 million of total revenue losses from 1993 through 1997 [5]. Severity of head blight infestations were lower in the mid 1990s, but economic losses rose again in 1997 to an estimated $68 million [5]. From 1998 to 2000, an estimated $102.1 million in producer net revenue was lost to Fusarium head blight [9]. So prevalent was DON during the 1993-97 crop years and so severe the price discounts that many North Dakota producers shifted out of barley acreage [18].

The Farm Services Agency estimates that in the barley producing regions of North Dakota most affected by scab, 768 (or 14%) of the farmers stopped farming between 1996 and 1998 with scab as the primary reason they left farming [5].

Fusarium Head Blight Management

There are no commercial barley varieties with resistance to Fusarium head blight [17, 23]. Few sources of tolerance exist within the barley genome. Cultivars that have been traditionally bred for tolerance have been rejected by maltsters because they lack the specific enzymatic properties present in the elite cultivars preferred by maltsters and are not adapted to North Dakota [12].

Risk of Fusarium head blight infection can be reduced, though, by implementing cultural practices, such as rotating with non-host or broad leafed crops and deep tilling crop residue to bury it, therefore eliminating overwintering survival sites for the fungus. In areas concerned with soil erosion, however, deep tillage may not be a favorable management practice [5, 7]. Efforts to counteract the ill effects of drought and soil erosion, supported by federal legislation, led to widespread adoption of conservation tillage in the early 1990s. Shifting to conservation tillage requires investment in new tilling and planting equipment. Despite research showing that deep tillage may contribute to reductions in fusarium head blight [10], few growers already invested in conservation tillage are likely to revert back to deep tillage [12].

Although rotation and tillage may reduce the risk of Fusarium head blight within a barley field, infestation via airborne spores from offsite sources would still be a risk. Fungicide applications may reduce the incidence and severity of an infestation, but may not significantly reduce DON levels [11]. At best, fungicides may reduce disease levels by approximately 50%. If infestation is low to begin with, a 50% reduction may be an economic improvement. If, however, infestation is high, a 50% reduction may not be enough to reduce damage levels and bring DON levels down below those acceptable for malting barley [12]. The systemic fungicide tebuconazole has been available through emergency registration for use in North Dakota against Fusarium head blight in barley. Approximately 4,500 pounds of tebuconazole are applied to an estimated 40,000 acres (3%) annually [2]. The approximate cost of the tebuconazole applications is $360,000/yr ($80/LB AI). Fungicides used to manage other diseases in North Dakota barley (leaf,

spot, rust, and powdery mildew) are mancozeb and propiconazole. Approximately 25,000 lbs of these fungicides are used annually to control these diseases.

The severity of the Fusarium head blight epidemics in the 1990s and their widespread economic effects led to the establishment in 1998 of the US Wheat and Barley Scab Initiative, a multimillion dollar national research initiative involving university and USDA ARS scientists. In 2000, the US Congress appropriated $4.3 million to the Initiative, which involves 73 researchers in 23 states working on 104 projects [13]. Additional funds have been provided by state governments and by the American Malting Barley Association [7]. A major focus of the Initiative is research to determine the efficacy of fungicides and biological agents for control of FHB. This research also involves examining application methods to improve the efficacy of fungicides and increase coverage and redistribution on the grain kernels. The most effective protection against Fusarium head blight would be to plant resistant varieties [7]; therefore, a major focus of research on the disease is identifying tolerance or resistance traits and incorporating them into existing elite varieties [7, 13]. Many of the research projects rely on conventional breeding methods to develop more resistant varieties. Sources of resistance to FHB provide only partial protection and resistance is controlled by three or more genes, which make breeding for effective resistance difficult.

Because of many scientific and commercial requirements, it takes about 8 to 10 years to breed, test and release a new variety of barley [5]. A new variety of barley must not only be resistant to scab but also must meet the necessary malting and brewing qualities. For example, a new variety of barley must be uniform in size and have plump kernels (necessary for successful beer brewing) or millers and brewers will not be interested in buying it [5].

Transgenic Barley

Researchers with the USDA Agricultural Research Service in Fargo, North Dakota have transformed barley with two separate genes, and are testing those genes for effectiveness in controlling Fusarium head blight [14, 15]. One gene, *TRI101*, comes from another

Fusarium fungus closely related to head blight. The gene codes for an enzyme, which deactivates DON, protecting the fungus from its own toxin. This gene cues the fungus to make an enzyme that alters the structure of DON. The enzyme does this by placing a protective chemical group on the toxin [14]. The altered toxin apparently can not harm the fungus. DON is a protein inhibitor; the *TRI101* gene reduces protein inhibition, allowing a plant's defensive mechanism to be fully active [15]. Equipping the barley plants with a gene to deactivate the toxin made by the scab fungus might give the plants a form of protection [14]. With modifications, the *TRI101* gene has been introduced into barley and is expressed.

A second anti-toxin gene, *PDR5*, is also being incorporated into the barley genome and tested for efficacy against Fusarium head blight. The *PDR5* gene codes for a molecular pump, which transports toxins out of cells. The gene was found in yeast used to make bread and was modified for use in barley. The gene protects yeast from toxins by transporting the toxins out of the cells.

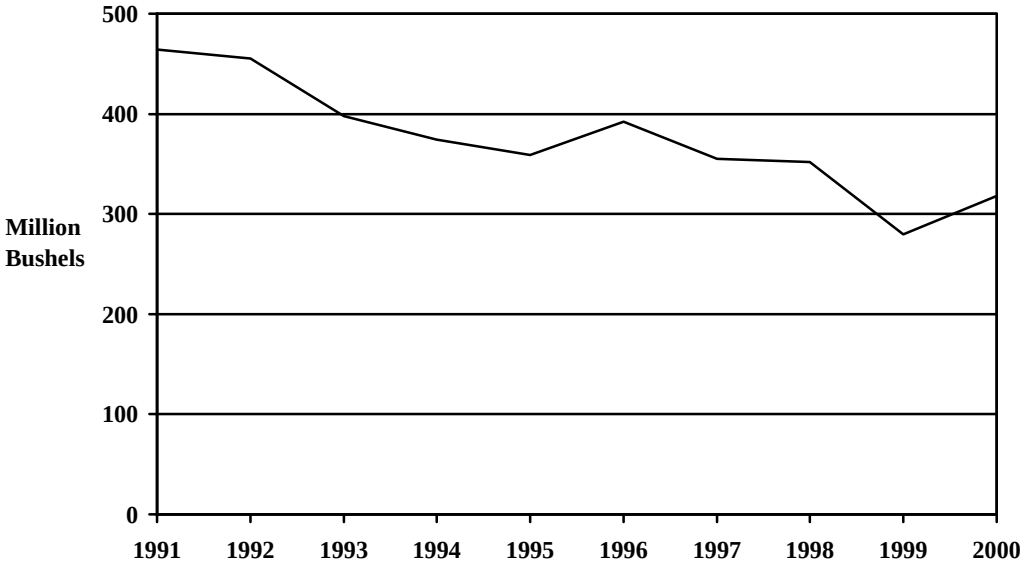
A commercial barley variety has been transformed through particle bombardment to contain both the *TRI101* and *PDR5* anti-toxin genes. Transgenic plants are being tested for gene expression and for performance when challenged with *Fusarium* infection [16, 19, 21]. Future goals include crossing elite lines with partial resistance being bred in by traditional methods to the transgenic cultivars to provide the FHB and DON free commercial cultivars that meet malting and brewing requirements.

Other research on Fusarium head blight resistance through biotechnology involve the use of anti-fungal protein genes which attack the *Fusarium* itself rather than the toxins produced by it [16, 20]. Barley naturally produces these antifungal toxins in the kernels, but researchers are trying to rebuild the genes so that the barley plants will produce the protein in the tissue outside the kernels, where *Fusarium* first attacks, to improve their efficacy. Other genes for antifungal proteins are being introduced into barley from *Fusarium* relatives. Barley plants transformed to produce antifungal proteins are being tested for resistance to Fusarium head blight.

Estimated Impacts

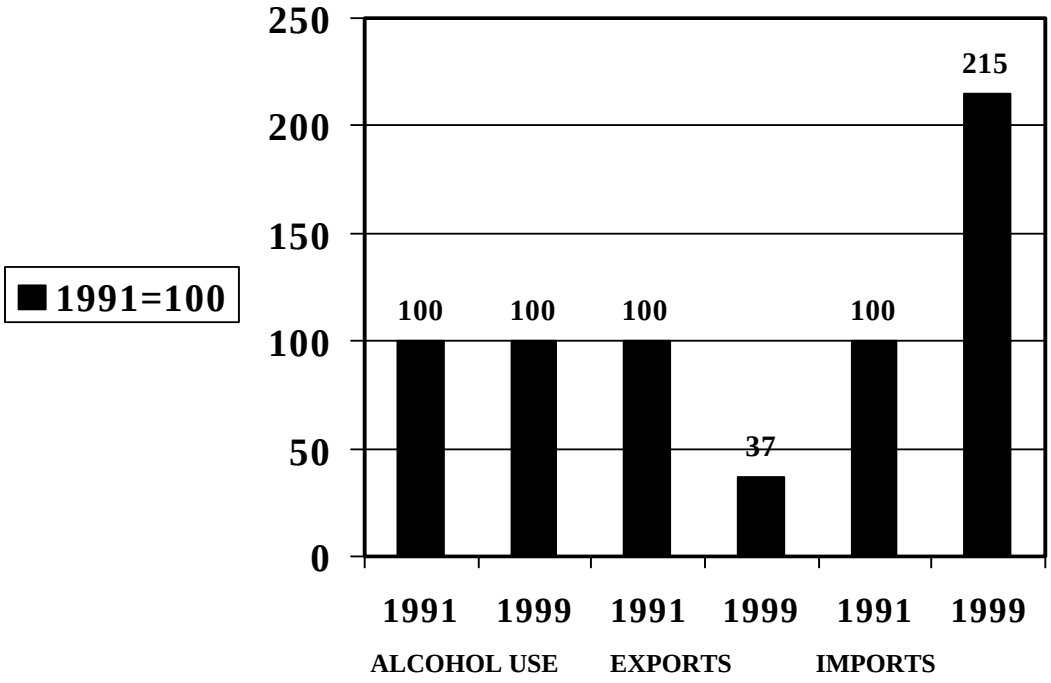
In North Dakota barley, the annual loss to Fusarium head blight and DON contamination is 30 million bushels (1.44 billion lbs. [48 lbs./bu.]) valued at approximately $100 million. In addition, approximately 40,000 acres are treated with 4,500 pounds of tebuconazole. Resistance to Fusarium head blight that a transgenic barley variety potentially offers could allow barley acreage and production to rebound to pre-1993 levels, as well as prevent both the annual economic losses to the disease and its mycotoxin byproduct. It would also eliminate the application of 4,500 pounds of fungicide with an associated cost of $360,000/yr.

FIGURE 36.1: US PRODUCTION: BARLEY



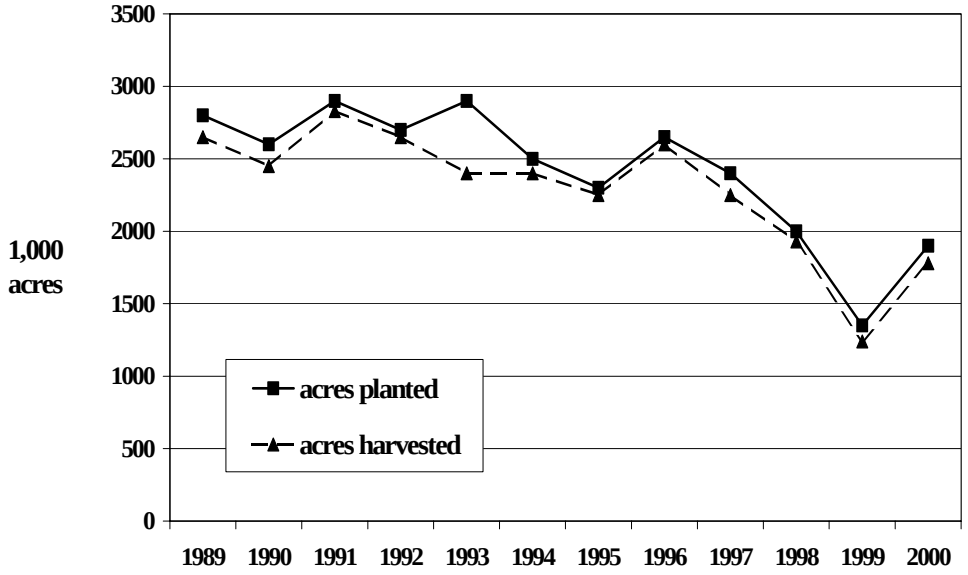
Source [1] [3] [4]

FIGURE 36.2: U.S. BARLEY INDICES



Source [1], [3], [4]

FIGURE 36.3. BARLEY ACREAGE IN NORTH DAKOTA, 1989 – 2000.



Source [1] [3] [4]

References

1. USDA, Small Grains 2000 Summary, National Agricultural Statistics Service, September, 2000.
2. USDA, Crop Profile for Barley in North Dakota, December, 2000.
3. USDA, Crop Production 1991 Summary, National Agricultural Statistics Service, January, 1992.
4. USDA, Field Crops Final Estimates 1992-1997, National Agricultural Statistics Service, December, 1998.
5. USGAO, Grain Fungus Creates Financial Distress for North Dakota Barley Producers, Resources, Community, and Economic Development Division, March, 1999.
6. Mathre, D.E., ed., Compendium of Barley Diseases, 2nd Edition, American Phytopathological Society, 1997.
7. McMullen, M.P., et al., "Scab of Wheat and Barley: A Re-emerging Disease of Devastating Impact", Plant Disease 81(12): 1340-1348, 1997.
8. Schwarz, P. and J. Barr, North Dakota State University. Personal Communication, August, 2001.
9. Nganje, E.W., et al., Economic Impacts of Fusarium Head Blight on Wheat and Barley, Agribusiness and Applied Economics Report, Department of Agribusiness and Applied Economics, North Dakota State University, Fargo, Forthcoming.
10. Dill-Mackey, R. and R.K. Jones, "The Effect of Previous Crop Residues and Tillage on Fusarium Head Blight of Wheat", Plant Disease 84(1): 71-76, 2000.
11. Pederson, J. and M. McMullen, "Evaluation of Fungicides for Control of Fusarium Head Blight (FHB) in Barley, 1998", Fungicide and Nematicide Tests 54:304, 1999.
12. McMullen, M., North Dakota State University. Personal Communication, July, 2001.
13. "Federal Lawmakers Boost FY2001 FHB Research", Scab News, US Wheat and Barley Scab Initiative, Spring, 2001. Available at www.scabusa.org.
14. Wood, M., et al., "Fighting Fusarium", Agricultural Research, USDA ARS, June, 1999.

15. Sayler, T., "Gene Transformation", Fusarium Focus, US Wheat and Barley Scab Initiative, www.scabusa.org/fusarium_gene.htm.
16. Dahleen, L. "Advancements in Biotechnology", Scab News, US Wheat and Barley Scab Initiative, Spring, 2001. Available at www.scabusa.org.
17. McMullen, Marcia P., and Robert W. Stack, Fusarium Head Blight (scab) of Small Grains, North Dakota State University, PP 804, December 1999 (revised).
18. Johnson, D. Dencey, and William Nganje, Impacts of DON on the Malting Barley Supply Chain: Aggregate Costs and Farm Level Risks, Department of Agricultural Economics, North Dakota State University, Misc Report No. 187, April 2000.
19. Dahleen, Lynn S., US Agricultural Research Service, Personal Communication, July 2001.
20. Dahleen, Lynn S., et al, "Transgenic approaches to combat Fusarium head blight in wheat and barley", Crop Science, May – June 2001.
21. Manoharan, M., et al, "Transformation of a commercial barley cultivar with genes for resistance to Fusarium head blight", ASA CSSA & SSSA Abstract, Annual Meeting 2001.
22. Skadsen, R.W., et al, "Transformation of barley with native anti-fungal genes – targeted expression and monitoring of Fusarium infection", Proc. 32nd Barley Improvement Conference, 1999.
23. Rudd, J.C., et al, " Host Plant Resistance Genes for Fusarium Head Blight: Sources, Mechanisms and Utility in Conventional Breeding Systems", Crop Science, May – June 2001