Quality Parameters in Small Grains from Minnesota Affected by *Fusarium* Head Blight

R. K. Jones, Associate Professor and Extension Plant Pathologist, and C. J. Mirocha, Professor, Department of Plant Pathology, University of Minnesota, St. Paul 55108

ABSTRACT

Jones, R. K., and Mirocha, C. J. 1999. Quality parameters in small grains from Minnesota affected by *Fusarium* head blight. *Plant Dis.* 83:506-511.

Recent epidemics of *Fusarium* head blight (FHB) severely damaged the hard red spring wheat and barley crops in Minnesota. Samples of commercial grain were analyzed in 1993 and 1994 to determine the effects of FHB on several quality parameters. Wheat test weight (TW) averaged 832 kg m⁻³ (55.4 lb/bu), thousand kernel weight (TKW) averaged 27.4 g, and the proportion of visually scabby kernels (VSK) averaged 11.0%. Deoxynivalenol (DON) was detected in 493 of 500 samples (98.6%). The mean concentration was 8.3 µg/g (range = 0.0 to 44.7 µg/g). Scab in wheat could rapidly be estimated using easy-to-prepare visual comparison standards. Scores of percent VSK were correlated with DON concentration at $r = 0.897$ and 0.908 in 1993 and 1994, respectively. TW and TKW were less effective estimators of DON ($r = -0.622$ and -0.550 , respectively). DON was detected in 100 of 100 six-row barley samples collected during the survey and averaged 10.4 µg/g (range = 0.5 to 39.7 µg/g). DON concentration in barley could not be effectively estimated with grading parameters including TW, TKW, percent plump kernels, or a visual index of kernel discoloration. In 28 samples of oats, DON averaged 1.4 µg/g (range = 0.0 to 6.4 µg/g). Nivalenol was not detected in any of the 628 samples analyzed during the two-year study.

Additional keywords: barley, deoxynivalenol, *Fusarium graminearum*, *Gibberella zeae*, oat, wheat

Fusarium head blight or scab of wheat (*Triticum aestivum* L.) is occasionally destructive in the hard red spring wheat-production regions of the north-central United States and Canada. In Minnesota, *Fusarium* head blight (FHB) is caused primarily by *Fusarium graminearum* Schwabe Group 2 (teleomorph *Gibberella zeae* (Schwein.) Petch). This is supported by its frequency among species identified in regional surveys (1,8,40,41), chemotaxonomic grouping based on analysis of trichothecene-producing abilities of recovered isolates (11,13,19), and pathogenicity studies (31,40). Latitude, temperature, and the importance of susceptible rotational crops (particularly *Zea mays* L.) influence the pathogen's distribution (9,15,22), while the frequency and timing of summer rainfall appear to regulate disease

outbreaks (32,39). In other regions, other *Fusarium* spp. or other subgroups of *F. graminearum* can dominate or predominate as primary components of the FHB complex (21,30).

Wheat heads attacked by *G. zeae* produce seed that are reduced in size and quality (6,28). Yield loss results when primary infection of spikelets by ascospores of *G. zeae* is followed by rachis colonization and death (32). Susceptible cultivars have greater indices of spread in the rachis (37). In highly susceptible cultivars, 50 to 80% of developing spikelets may be killed or damaged prior to grain fill (5,24,25,37). Additional loss results during mechanical harvest because shrunken and light-weight seed produced in affected heads are not retained by combine fans and sieves (4,22).

Wheat heads with severe rachis damage may produce near-normal seed in asymptomatic spikelets. Seed produced in spikelets above those that have symptoms may be shriveled and exhibit reduced thousand kernel weight (TKW), but be otherwise unaffected (24). Seed produced in spikelets below those that show symptoms are often normal in color, size, quality, and quantity. Infected spikelets yield seed with characteristic visual symptoms including a pink, chalky white, or pale gray color and a "tombstone" (8,34) appearance. Tombstone

kernels have low densities and are reduced in size (34,39). In epidemics involving susceptible varieties, mixtures of seed of these types are brought to elevators and other buying points for grading and price determination.

Seed with symptoms of wheat scab are visually identified by grain inspectors and counted as damage but not dockage (2). The maximum limits for damaged kernels (total damaged kernels; TDK) in grades U.S. No. 1 to U.S. No. 5 hard red spring wheat (HRSW) are 2, 4, 7, 10, and 15%, respectively (2). Test weight, a measure of grain weight per unit volume, also factors into grade determination and influences market price. Test weight minimums for HRSW in grades 1 to 5 are 869, 854, 824, 794, and 749 kg m⁻³ respectively (2).

Deoxynivalenol (DON) is one of a family of substituted trichothecene mycotoxins produced by *Fusarium* spp. (27). This water-soluble toxin, also known as vomitoxin, is responsible for emesis and feed refusal in non-ruminant animals (10,38). Despite historic occurrences of feeding troubles associated with scabby wheat (14) and blighted barley (7), the chemical structure of DON was not elucidated until the early 1970s (43). Acetylated and diacetylated forms of DON have also been characterized (27,43). Globally, trichothecene mycotoxins are neither consistently nor uniformly regulated (30,36).

In addition to DON, nivalenol (NIV) has been identified in *Fusarium* spp.-damaged cereals, including those attacked by *F. culmorum* (Wm. G. Sm.) Sacc. (20,21,27,30,33). The health effects of NIV on animal systems are approximately 10-fold greater than those of DON (22). Ichinoe et al. (11) examined isolates of *G. zeae* from infested rice stubble collected in rotated wheat and barley fields throughout Japan. When grown in sterilized rice culture, derived isolates could be separated into one of two chemotaxonomic types; isolates produced either DON and 3-acetyldeoxynivalenol (DON-type) or NIV and 4-acetylnivalenol (NIV-type). Logrieco et al. (13) recovered the NIV-type of *G. zeae* in Southern Italy from FHB-affected barley and both NIV-types and DON-types from affected wheat. In the United States and Canada, isolates of *G. zeae* are of the DON-type; however, the North American

Corresponding author: R. K. Jones
E-mail: rogerj@puccini.crl.umn.edu

Published as paper No. 981,220,042 of the contribution series of the Minnesota Agricultural Experiment Station, based on research conducted under Projects 22-38 and 22-34H.

Accepted for publication 19 February 1999.

Publication no. D-1999-0401-01R
© 1999 The American Phytopathological Society

chemotype produces 15-acetyl DON instead of 3-acetyl DON as the primary monoacetate (18,19).

In 1982, following an outbreak of FHB in the Central Plains region of the United States, the Food and Drug Administration (FDA) issued an advisory to federal and state officials recommending a "level of concern" for DON of 2.0 µg/g for wheat entering the milling process and 4.0 µg/g for wheat and wheat milling by-products used in animal feed (29, citing Food Chem. News, 4 October 1982, pp. 3-4). Since that time, federal grain standards have been applied to discount scabby grain as damage (22). Samples exceeding 2% total damage (on a kernel count basis) fail to make standards for U.S. No. 1 milling wheat (2). Because there is no legal status to guidelines, and grain blending is allowed, market standards vary widely in their reaction to *Fusarium* spp. damage, and economic losses are difficult to calculate.

During small grain harvest in 1993, the U.S. FDA issued new guidelines for DON in wheat and barley that shifted advisory levels from raw grain at the buying point to quantities contained in finished products (16). New guidelines emphasized maximums for DON in bran, flour, and germ intended for human consumption at 1.0 µg/g; species-specific dietary maxima for

feed rations were also established. These guideline shifts resulted in an extraordinary increase in DON testing. Testing for sale purposes became routine, especially in barley, where malt quality was a concern and kernels affected by *Fusarium* spp. have fewer characteristic symptoms (26).

The purpose of this study was to examine and document the distribution and concentration of DON in HRSW samples collected from the 1993 and 1994 harvests and, to correlate with DON, the quality parameters, including test weight (TW), TKW, and percent scabby kernels in the harvested grain. A smaller number of barley and oat samples were analyzed in both years.

MATERIALS AND METHODS

Sample collection. A survey was conducted by personnel of the Minnesota Extension Service in August and September of 1993 and 1994. Collections began in southwest Minnesota, then continued northward to include all wheat-producing counties up to the Canadian border. Collection methods were established by protocol. Collection sites were distributed to provide representation of each county's acreage as a proportion of the state's total harvest over space and time. In fields, samplers collected 5 to 10 kg of grain at

spaced intervals directly off the combine as it was emptying (pouring stream samples). After mixing, sample volume was reduced to 2 kg by hand and placed in double-wrapped paper bags for shipment. Grain harvested from field edges (the first harvested) was avoided. High moisture samples were dried overnight in forced air ovens at 35°C prior to shipment. Samples were coded, identified as to variety, and shipped to St. Paul via rapid delivery service.

Determination of grain quality parameters. Upon arrival, sample volume was reduced to approximately 1 kg using a 16-chute riffle-divider with 2.5-cm openings (Model H-3987, Humboldt Testing Equipment, Norridge, IL) and grain was screened to remove chaff and weed seeds. TW was determined with a 473-ml kettle and standard methods (2). TKW of samples were determined. The percentage of visually scabby kernels (VSK) was estimated by comparing 1,000 kernel weight samples with comparison standards (Fig. 1). Three complete sets of comparison standards were created by mixing healthy seed of the HRSW cv. Norm with hand-selected scabby kernels (cv. Norm) to create ratios equivalent to 0, 1, 2, 4, 6, 8, 10, 15, 20, 25, 30, 35, 40, 45, and 50% on a 1,000-kernel count basis. Scabby kernels

Fig. 1. Visually scabby kernels (%) in comparison standards of the wheat cv. Norm.

were selected from grain produced in experimental plots subjected to a natural epidemic of FHB. Healthy seed were sound, bright seed produced in a scab-free area (Somerton, Arizona) and having a TW of 929 kg m⁻³. TKW of each of the standards also was determined. The TKW of the three 0% VSK standards were 40.98, 41.43, and 41.86 g. Regression analysis described the relationship between TKW and percent VSK in the three artificially constructed sets of comparison standards as linear ($y = 41.4 - 0.225x$) with a correlation of $r = 0.986$. Reader error variance was assessed using eight independent observers, blind samples of prepared standards (order randomized), and three unknowns of hand-counted commercial samples (cv. Norm) containing 3.5, 6.5, and 29.6% VSK. Standards and unknown samples were displayed in 115-mm plastic weighing dishes on a black laboratory bench top under consistent lighting. For survey samples, TKW and percent VSK were each determined twice and the average value reported. Samples exceeding 50% VSK were hand counted. The remaining portion of the TW sample was reduced to 100 g using a Boerner sample divider (model 34, Seedburo Equipment Company, Chicago) and ground for 2 min with a Stein Laboratory Mill (model M-2, Stein Laboratories, Inc., Atchison, KS) for mycotoxin analysis. Barley and oat samples were processed in a similar

fashion. TW and TKW were determined. Samples of both grains were scored for kernel discoloration (KD) on a 1 to 5 scale according to the method of Miles et al. (17). The percentage of plump kernels was determined for barley samples as the proportion of 200 g that would not pass through a 2.38- by 19.05-mm slotted screen (2).

Chemical analysis. All analyses were conducted in the Department of Plant Pathology at the University of Minnesota, St. Paul. Samples were analyzed for both NIV and DON. After thorough mixing, 25 g of the ground sample was extracted and processed according to the method of Romer (23) in 100 ml of solvent (acetonitrile: water, 84:16 vol/vol) and placed on a rotary shaker for 1 h. Extracts were filtered (Whatman #4) and 10 ml of the sample was passed through a Mycosep 213 clean-up column (Romer Labs Inc., Washington, MO). Clean-up columns were activated with 15 ml of extraction solvent prior to use. Following elution, columns were rinsed with 35 ml of the extraction solvent and the entire eluate was evaporated to dryness.

In 1993, samples were analyzed using high-performance liquid chromatography (HPLC; model SLC-6A, Shimadzu Ltd., Kyoto, Japan). The instrument was equipped with a C:18 column (300 by 3.9 mm i.d.) and a Shimadzu SPD-6AV Ultra-violet detector (wavelength = 229 nm).

Dried sample extracts were dissolved in 5 ml of 15% MeOH and 20 µl was injected onto the column. The flow rate of the mobile phase was 1 ml/min. Standards prepared from crystalline DON and crystalline NIV were injected every tenth sample. Concentrations of DON and NIV in samples were determined based on retention times and peak areas compared to standards. Detection limits for DON and NIV were 0.4 µg/g.

In 1994, samples were analyzed using gas chromatography and mass spectrophotometry (model QP-5000, Shimadzu Ltd.). The instrument was equipped with a DB-5 fused-silica capillary column (30 m by 0.25 mm i.d.). Sample preparation remained the same. Extraction protocols were identical except that Mycosep 215 cleanup columns (Romer Labs, Inc.) were substituted. DON was analyzed as its trimethylsilyl ether derivative using selected ion monitoring. Detection limits for DON and NIV were 0.1 µg/g. A reanalysis of 30 barley samples from 1993 with 1994 methods resulted in an average DON concentration of 8.0 µg/g, compared to 8.8 µg/g using Mycosep 213 columns and HPLC. The correlation coefficient between values for the different methods was $r = 0.953$.

RESULTS

A total of 260 samples of HRSW from the 1993 harvest were collected and analyzed. In addition, 40 samples of six-row malt barley and 12 samples of oats were examined. The geographic distribution of the HRSW samples represented the distribution of the 1993 HRSW crop with a sampling incidence of 1 per 3,500 ha. The survey included 20 counties that represented 95% of the state-wide harvest (Fig. 2).

HRSW samples contained an average DON concentration of 9.9 µg/g, with a range of 0 (none detected) to 44.7 µg/g. DON was detected in 257 of the 260 samples analyzed (98.8%). A total of 235 (90.4%) of the HRSW samples contained DON concentrations in excess of the 2.0 µg/g considered to be a "level of concern" by the U.S. FDA. A total of 195 (75.0%) exceeded the FDA's level of concern for animal feed (4.0 µg/g) and 38.1% of the samples contained more than 10.0 µg/g. NIV was not detected in any of the samples.

Samples contained an average of 12.2% scabby kernels (range = 0 to 65%). TW averaged 811 kg m⁻³ (range = 674 to 944 kg m⁻³) and TKW averaged 26.5 g (range = 17.8 to 34.3 g). The percent VSK was highly correlated with DON concentration in these samples ($r = 0.897$). TW and TKW were negatively correlated with DON ($r = -0.499$ and -0.418 , respectively) and positively correlated with one another ($r = 0.811$). Only 30 of 260 samples (11.5%) had TWs that met or exceeded Federal grain standards (2) for U.S. No. 1

Fig. 2. Mean concentration of deoxynivalenol in samples of hard red spring wheat surveyed in Minnesota during 1993 and 1994.

Table 1. Percent of 1993-94 hard red spring wheat survey samples placed in grade based on test weight (TW) and percent visually scabby kernels (VSK)^a

Grade	1993		1994	
	TW (g)	% VSK	TW (g)	% VSK
U.S. No. 1	11.5	9.4	24.9	17.5
U.S. No. 2	14.6	10.4	9.2	8.8
U.S. No. 3	29.2	23.1	25.4	15.0
U.S. No. 4	16.5	19.6	8.3	14.2
U.S. No. 5	15.8	11.2	7.5	8.8
U.S. sample	12.3	25.4	3.3	23.3

^a Visually scabby seed counted as damage for grade determination.

HRSW (868.8 kg m⁻³). TW values less than 749 kg m⁻³ were recorded for 32 samples (12.3%). Commercial lots of these grains would have been given "sample grade" designations by buyers (Table 1).

The average DON concentration from 240 HRSW samples examined following the 1994 harvest was 6.5 µg/g, with a range of 0 (none detected) to 29.4 µg/g. This survey included 21 counties that represented 94.3% of the state-wide harvest (Fig. 2). Samples contained an average of 9.7% VSK (range = 0 to 45%). TWs averaged 852 kg m⁻³ (range = 697 to 959 kg m⁻³) and TKW averaged 28.4 g (range = 18.6 to 41.4 g). The percent VSK in these samples was correlated with DON concentration ($r = 0.908$). TW and TKW were negatively correlated with DON ($r = -0.738$ and -0.665 , respectively) and positively correlated with each other ($r = 0.812$). In all, 137 samples (57.1%) had TW values that failed to meet federal standards for U.S. No. 1 HRSW. Eight samples (3.3%) had test weights placing them in the "sample grade" category (Table 1). NIV was not detected in any of the samples analyzed in 1994.

Eight cultivars of HRSW accounted for 452 of the 500 samples analyzed during the 2 years of this study. Among these, cvs. Marshall, 2375, Grandin, and Butte 86 each averaged less than 10% VSK and less than 10.0 µg/kg DON, while cvs. Vance, Bergen, Norm, and Gus averaged over 10% VSK and over 10.0 µg/g DON (Table 2). A total of 48 analyzed samples were classified as "other" and represented nine HRSW cultivars (36 samples) or samples for which cultivar information was missing or uncertain (12 samples). These samples averaged 10.0% VSK and 8.0 µg/g DON (Table 2). Based on sampling frequency, planting of highly susceptible cultivars (Vance, Norm, Bergen, and Gus) decreased from 37% in 1993 to 15% of the planted area in 1994. Despite this shift, quality parameters in the 1994 crop were severely reduced (Table 1), particularly in samples collected from a five-county area of northwest Minnesota where rainfall during anthesis and grain fill (July) was 7.7 cm above the 30-year average (39). Samples from these counties averaged 8.6 µg/g DON and 12.7% VSK.

Six-row malt barley samples contained an average DON concentration of 8.8 µg/g in 1993 and 11.5 µg/g in 1994 (Table 3). NIV was not detected in any of the 100 samples analyzed, but all samples contained detectable quantities of DON. The frequency of samples exceeding the FDA levels of concern were 95, 80, and 43% for the 2.0, 4.0, and 10.0 µg/g levels, respectively. DON concentration was correlated with KD scores ($r = 0.482$) and negatively correlated with TW ($r = -0.244$), TKW ($r = -0.313$), and percent plump kernels ($r = -0.255$). Regression analysis identified the linear relationship between DON concen-

tration and KD scores as significant ($P < 0.001$), but the relationships between DON concentration and the other parameters were not significant ($P = 0.05$). Three cultivars accounted for all barley samples analyzed in 1993 and 1994 (Table 3). Samples of the recently introduced cv. Stander contained higher concentrations of DON than the cvs. Excel or Robust ($P = 0.05$).

A total of 28 oat samples averaged 1.4 µg/g of DON (range = 0 to 6.4). Four samples (14.3%) exceeded the FDA's 2.0-µg/g "level of concern" and three samples exceeded 4.0 µg/g DON. TW, TKW, and KD values of oat samples averaged 530.4 kg/m⁻³, 25.7 g, and 1.7, respectively. Regression analysis failed to identify a significant linear relationship ($P = 0.05$) between DON and either TW, TKW, or KD among oat samples.

DISCUSSION

In 1993 and 1994, FHB was epidemic in the HRSW-producing areas of northwest and west-central Minnesota. Excessive rains combined with increased plantings of highly susceptible cultivars to create favorable conditions for FHB to develop (12). Production fell from 3.74 million metric tons (MMT) in 1992 to 1.90 MMT in 1993 and 1.91 MMT in 1994 (3). In 1993, 18.5% of plantings were declared unharvestable (3). Growers attempting to salvage the heavily damaged crop experienced significant reductions in grade and market price. Elevator operators and other

buyers refused to purchase this poor-quality wheat due to its scabby appearance and concerns over the presence of *Fusarium* spp.-related mycotoxins, including DON.

In 1993, spring wheat fields were surveyed at the soft-dough stage during the weeks of 26 July through 6 August. Symptoms were observed in each of more than 100 fields examined and the mean percentage of symptomatic spikelets varied from 5 to 80% on a field by field basis (R. K. Jones, unpublished data). Cultivar differences were observable. Harvested grain from 260 field-collected samples contained an average of 12.2% VSK and averaged 9.9 µg/g DON. The following year, rainfall was again well above average in the Red River Valley of northwest Minnesota. This, combined with heavily infected residues from 1993, created conditions for consecutive epidemics of FHB in this region. Field surveys conducted the weeks of 14 and 26 August estimated disease severity at 18% state-wide, with an estimated 38% severity in five northwestern counties (Marshall, Norman, Pennington, Polk, and Red Lake). These counties contained 43.7% of Minnesota's HRSW and 50.2% of the six-row malt barley plantings in 1994 (3). State-wide, samples contained 9.7% VSK and averaged 6.5 µg/g DON, while 116 samples from the five-county area averaged 13.9% VSK and 9.6 µg/g DON.

Several studies have attempted to examine grain quality parameters and mycotoxin contamination in relation to

Table 2. Deoxynivalenol (DON) concentration and quality parameters associated with 500 samples of hard red spring wheat collected in 1993 and 1994

Cultivar or year	n	DON (µg/g)	VSK (%) ^a	TW (kg m ⁻³) ^b	TKW (g) ^c
Marshall	28	5.3	8.1	829.4	25.6
2375	142	5.3	6.6	859.9	29.5
Grandin	115	6.2	8.9	838.1	27.8
Butte 86	36	5.5	5.4	844.7	28.1
Vance	50	14.0	17.3	801.5	26.3
Bergen	21	15.2	20.7	783.6	25.8
Norm	44	15.7	23.1	777.1	23.9
Gus	16	13.6	19.2	771.0	23.7
Other	48	8.0	10.0	836.6	26.8
1993	260	9.9	12.2	810.5	26.5
1994	240	6.5	9.7	852.5	28.4

^a Visually scabby kernels.

^b Test weight.

^c Thousand kernel weight.

Table 3. Quality parameters associated with samples of six-row barley collected in 1993 and 1994

Cultivar or year	n	DON (µg/g) ^a	KD index ^b	Plump (%) ^c	TW (kg m ⁻³) ^d	TKW (g) ^e
Excel	14	8.8	2.7	58.6	657.7	31.2
Robust	52	8.7	3.1	72.9	675.5	33.3
Stander	34	13.9	3.4	70.9	654.7	33.0
1993	40	8.8	3.2	71.1	656.2	32.6
1994	60	11.5	3.1	69.6	671.2	33.1

^a Deoxynivalenol concentration.

^b Kernel discoloration index (1 = bright, 5 = severe discoloration).

^c Percentage of kernels retained on standard 2.38- by 19.05-mm slotted screen.

^d Test weight.

^e Thousand kernel weight.

Fusarium spp. damage. Shotwell et al. (29) analyzed 161 samples of hard red winter wheat collected at elevators in Nebraska and Kansas following an outbreak of *G. zeae* in 1982. DON averaged 1.7 µg/g and the concentration in individual samples was found to correlate with *Fusarium* spp.-damaged kernels at $r = 0.75$. Tuite and Shaner (35) examined 75 samples of Indiana-grown soft red winter wheat in 1986. DON was detected in 88% of the samples and averaged 0.6 µg/g. DON concentration was correlated with the percentage of VSK at $r = 0.65$. In this study, we observed a higher correlation ($r = 0.897$) between DON and percent VSK. The higher correlation may have been the result of a wider range of DON concentrations and VSK percentages.

Comparison standards were a useful and non-destructive means of rapidly assessing the percentage of VSK in unknown samples. This method utilizes materials that are readily available and is much less laborious than individually counting *Fusarium* spp.-damaged kernels. In attempting to validate the system, eight individuals scored blind standards (15 samples each) and three hand-counted unknown samples within ± 1 incremental units of actual. We have successfully utilized this system to assess treatment effects from field experiments involving management practices (fungicide trials, tillage studies) and genotype evaluations (screening nurseries). If samples are representatively prepared with riffle dividers and sample splitters, they can be standardized on a weight (30 g) or volume (50 ml) basis and the linearity of the DON:VSK relationship remains. Heavily weathered samples are difficult to score and introduce greater variance. The system appears to work well for research purposes and can provide an inexpensive substitute for DON testing in routine genotype evaluations and certain other studies.

FHB and mycotoxin contamination of wheat have recently been reviewed (30). Tanaka et al. (33) surveyed the contamination of cereals with *Fusarium* spp.-produced mycotoxins in 19 countries. NIV, DON, and zearalenone were found to be distributed widely throughout the world. Few studies, however, have involved systematic surveys and none have approached the mean values for DON found in this report. Despite identifying samples with DON concentrations up to 44.7 µg/g and 65% VSK, NIV was not detected in any of the samples examined in this study. This suggests a limited or non-involvement of NIV-producing fungi (*F. culmorum* or *F. graminearum*, NIV-type) in the FHB epidemics of 1993 and 1994 in Minnesota.

Selected ion monitoring identified 15-acetyl DON present quantitatively at 2.2 to 5.0% of the DON concentration in 1994 field samples (data not shown). In separate analyses, zearalenone was recovered but

averaged less than 1.0 µg/g in commercial wheat and barley samples containing more than 10 µg/g DON. These findings are in agreement with previous studies (19) which suggest that North American isolates of *F. graminearum* are a chemotaxonomic group (15-Ac DON type) distinct from those that occur in Asia and Europe (3-Ac DON and NIV types). They also suggest that zearalenone production may be host regulated and represent a more significant problem in *Fusarium* spp.-damaged corn than in wheat or barley.

Since the epidemics of 1993 and 1994, FHB losses in Minnesota have failed to subside. Highly susceptible cultivars have been replaced by moderately susceptible cultivars, including 2375. This cultivar possesses additional unique resistance to FHB that is characterized by a non-proportional relationship between FHB severity on wheat heads (scored at the soft-dough stage) and percent VSK in the harvested grain. This tolerance to kernel damage reduces the financial impact of FHB on producers at harvest, but the cultivar is susceptible to initial infection, has a moderate index of spread in the rachis (ISR) (12), and appears to produce sufficient infected plant parts that primary inoculum is not being reduced over time. Additional resistance is much needed to further reduce losses in wheat and to reduce losses in the six-row barley that is often grown in rotation with wheat throughout the Red River Valley. Efforts are underway to enhance HRSW germ plasm with additional Type 2 resistance (25) from Chinese sources (4,5,37).

Losses in barley are difficult to characterize in relation to *Fusarium* spp. damage. Malt barley production in Minnesota dropped from 1.4 MMT in 1992 to 1.0 MMT in 1993 and 0.8 MMT in 1994 (3). Although losses were less catastrophic in terms of yield, they were most significant in terms of quality concerns relating to the presence of DON. DON concentrations in the 1993 to 1994 malt barley crop were the highest ever recorded in Minnesota. Malt barley infected with *F. graminearum* is readily contaminated with DON, and all commercial cultivars are considered susceptible (12). Most recently, maltsters have adopted a near-zero tolerance for DON (16) that critically threatens the industry in Minnesota.

Grading factors were not able to predict DON contamination in the six-row barley samples examined in this study. KD, which is primarily a darkening to olive brown associated with *Bipolaris* and *Alternaria* spp., was significantly correlated with DON ($P = 0.01$), but this relationship may have been coincidental and could be related to a similarity in environmental conditions favorable for these fungi and those for *F. graminearum*.

Epidemics of FHB seem to be increasing globally during the last two decades

(4,16,21,30). In Minnesota, weather conditions have included above-average summer rainfall and an above-average number of days with measurable precipitation in most years since 1990. In 1993, west-central and northwest Minnesota received July through August rainfall totals 7.4 and 12.5 cm above average, respectively (3). Measurable rainfall was recorded on 26 of 30 days during anthesis in 1993 at experimental sites in Crookston, Minnesota (39). However, rainfall alone does not fully explain the magnitude of the FHB epidemics that have resulted. The contributions of certain other practices need to be examined to understand fully the region's epidemics. These include the recent implementation of United States Department of Agriculture-directed conservation tillage programs which leave crop residue and thus primary inoculum on the soil surface, the elimination of set-aside acres that had been used for rotation and residue management, and the shift in acreage devoted to the production of newly-released high-protein spring wheats.

Mycotoxin testing may also be enhancing the severity of FHB-associated losses. Historic epidemics were not subjected to the present-day analytical capabilities brought on by advances in detection technology. Human health risks associated with outbreaks of *G. zeae* in the United States appear minimal according to many investigators (22,42), and recent animal studies fail to identify unmanageable health risks associated with DON. Our results suggest that factors used in grading can serve to keep excessive amounts of DON out of spring wheat milling channels. Marketing of visually damaged wheat into appropriate animal feeds and the establishment of reasonable quality standards for barley could help shift the focus away from the acute experience of recent epidemics. Efforts directed towards the identification and enhancement of genetic resistance represents an achievable goal that would not only prevent unnecessary exposure to *Fusarium* spp.-produced mycotoxins but would also reduce the devastating losses experienced by small grain producers.

ACKNOWLEDGMENTS

We thank personnel of the Minnesota Extension Service and wheat producers throughout the state who participated in the 1993 and 1994 surveys; and P. Golinski, H. Jelen, J.-P. Chen, and S. Gale for their assistance.

LITERATURE CITED

1. Abramson, D., Clear, R. M., and Nowicki, T. W. 1987. *Fusarium* species and trichothecene mycotoxins in suspect samples of 1985 Manitoba wheat. Can. J. Plant Sci. 67:611-619.
2. Anonymous. 1991. Inspecting Grain, Practical Procedures for Grain Handlers. U. S. Dep. Agric. Fed. Grain Inspect. Serv. U. S. Gov. Print. Office.
3. Anonymous. 1995. Minnesota Agricultural Statistics. Minn. Agric. Stat. Serv. St. Paul.
4. Bai, G., and Shaner, G. 1994. Scab of wheat:

- Prospects for control. *Plant Dis.* 78:760-766.
5. Bai, G., and Shaner, G. 1996. Variation in *Fusarium graminearum* and cultivar resistance to wheat scab. *Plant Dis.* 80:975-979.
6. Bechtel, D. B., Kaleikau, L. A., Gaines, R. L., and Seitz, L. M. 1985. The effects of *Fusarium graminearum* infection on wheat kernels. *Cereal Chem.* 62:191-197.
7. Christensen, J. J., and Kernkamp, H. C. H. 1936. Studies on the toxicity of blighted barley to swine. *Minn. Agric. Exp. Stn. Tech. Bull.* 113.
8. Clear, R. M., and Patrick, S. K. 1990. *Fusarium* species isolated from wheat samples containing tombstone (scab) kernels from Ontario, Manitoba, and Saskatchewan. *Can. J. Plant Sci.* 70:1057-1069.
9. Dickson, J. G., and Mains, E. B. 1942. Scab of wheat and barley and its control. *Farmers' Bull.* No. 1599. U. S. Dep. Agric.
10. Forsyth, O. M., Yoshizawa, T., Morooka, N., and Tuite, J. 1977. Emetic and refusal activity of deoxynivalenol to swine. *Appl. Environ. Microbiol.* 34:547-552.
11. Ichinoe, M., Kurata, H., Sugiura, Y., and Ueno, Y. 1983. Chemotaxonomy of *Gibberella zeae* with special reference to production of trichothecenes and zearalenone. *Appl. Environ. Microbiol.* 46:1364-1369.
12. Jones, R. K. 1994. Managing *Fusarium* head scab for 1995. *Plant Pest Newsl. PPST* 17:100-102. *Minn. Ext. Serv. Univ. Minn. St. Paul.*
13. Logrieco, A., Bottalico, A., and Altomare, C. 1988. Chemotaxonomic observations on zearalenone and trichothecene production by *Gibberella zeae* from cereals in Southern Italy. *Mycologia* 80:892-895.
14. Mains, E. B., Vestal, C. M., and Curtis, P. B. 1928. Scab of small grains and feeding trouble in Indiana in 1928. *Proc. Indiana Acad. Sci.* 39:101-110.
15. McInnes, J., and Fogelman, R. 1923. Wheat scab in Minnesota. *Minn. Agric. Exp. Stn. Tech. Bull.* 18.
16. McMullen, M. P., Jones, R. K., and Gallenberg, D. J. 1997. Scab of wheat and barley - A re-emerging disease of devastating impact. *Plant Dis.* 81:1340-1348.
17. Miles, M. R., Wilcoxson, R. D., Rasmussen, D. C., Wiersma, J., and Wames, D. 1987. Influence of genotype and environment on kernel discoloration of Midwestern malting barley. *Plant Dis.* 71:500-504.
18. Miller, J. D., Taylor, A., and Greenhalgh, R. 1983. Production of deoxynivalenol and related compounds in liquid culture by *Fusarium graminearum*. *Can. J. Microbiol.* 29:1171-1178.
19. Mirocha, C. J., Abbas, H. K., Windels, C. E., and Xie, W. 1989. Variation in deoxynivalenol, 15-acetyldeoxynivalenol, 3-acetyldeoxynivalenol, and zearalenone production by *Fusarium graminearum* isolates. *Appl. Environ. Microbiol.* 55:1315-1316.
20. Mirocha, C. J., Xie, W., Xu, Y., Wilcoxson, R. D., Woodward, R. P., Etebarian, R. H., and Bechele, G. 1994. Production of trichothecene mycotoxins by *Fusarium graminearum* and *Fusarium culmorum* on barley and wheat. *Mycopathologia* 128:19-23.
21. Parry, D. W., Jenkinson, P., and McLeod, L. 1995. *Fusarium* ear blight (scab) in small grain cereals—a review. *Plant Pathol.* 44:207-238.
22. Pomeranz, Y., Bechtel, D. B., Sauer, D. B., and Seitz, L. M. 1990. *Fusarium* head blight (scab) in cereal grains. *Adv. Cereal Sci. Technol.* 10:373-433.
23. Romer, T. R. 1986. Use of small charcoal/alumina cleanup columns in determination of trichothecene mycotoxins in foods and feeds. *J. Assoc. Off. Anal. Chem.* 69:699-703.
24. Schroeder, H. W. 1955. Factors affecting resistance of wheat to scab caused by *Gibberella zeae* (Schw) Petch. Ph.D. thesis, University of Minnesota, St. Paul.
25. Schroeder, H. W., and Christensen, J. J. 1963. Factors affecting resistance of wheat to scab caused by *Gibberella zeae*. *Phytopathology* 53:831-838.
26. Schwarz, P. B., Casper, H. H., and Beattie, S. 1995. Fate and development of naturally occurring *Fusarium* mycotoxins during malting and brewing. *J. Am. Soc. Brew. Chem.* 53:121-127.
27. Scott, P. M. 1990. Trichothecenes in grains. *Cereal Foods World* 35:661-666.
28. Seitz, L. M., and Bechtel, D. B. 1985. Chemical, physical, and microscopic studies of scab-infected hard red winter wheat. *J. Agric. Food Chem.* 33:373-377.
29. Shotwell, O. L., Bennett, G. A., Stubblefield, R. D., Shannon, G. M., Kwolek, W. F., and Plattner, R. D. 1985. Deoxynivalenol in hard red winter wheat: Relationship between toxin levels and factors that could be used in grading. *J. Assoc. Off. Anal. Chem.* 68:954-957.
30. Snijders, C. H. A. 1990. *Fusarium* head blight and mycotoxin contamination of wheat, a review. *Neth. J. Plant Pathol.* 96:187-198.
31. Stack, R. W., and McMullen, M. P. 1985. Head blighting potential of *Fusarium* species associated with spring wheat heads. *Can. J. Plant Pathol.* 7:79-82.
32. Sutton, J. C. 1982. Epidemiology of wheat head blight and maize ear rot caused by *Fusarium graminearum*. *Can. J. Plant Pathol.* 4:195-209.
33. Tanaka, T., Hasegawa, A., Yamamoto, S., Lee, U., Sugiura, Y., and Ueno, Y. 1988. World-wide contamination of cereals by the *Fusarium* mycotoxins nivalenol, deoxynivalenol, and zearalenone. 1. Survey of 19 countries. *J. Agric. Food Chem.* 36:979-983.
34. Tkachuk, R., Dexter, J. E., Tipples, K. H., and Nowicki, T. W. 1991. Removal by specific gravity table of tombstone kernels and associated trichothecenes from wheat infected with *Fusarium* head blight. *Cereal Chem.* 68:428-431.
35. Tuite, J., Shaner, G., and Everson, R. J. 1990. Wheat scab in soft red winter wheat in Indiana in 1986 and its relation to some quality measurements. *Plant Dis.* 74:959-962.
36. Van Egmond, H. P. 1989. Current situation on regulations for mycotoxins. Overview of tolerances and status of standard methods of sampling and analysis. *Food Addit. Contam.* 6:139-188.
37. Van Ginkel, M., Van Der Schaar, W., Zhuping, Y., and Rajaram, S. 1996. Inheritance of resistance to scab in two wheat cultivars from Brazil and China. *Plant Dis.* 80:863-967.
38. Vesonder, R. F., Ciegler, A., Jensen, A. H., Rohwedder, W. K., and Weislander, D. 1976. Co-identity of the refusal and emetic principle from *Fusarium*-infected corn. *Appl. Environ. Microbiol.* 31:280-285.
39. Wiersma, J. V., Peters, E. L., Hanson, M. L., Bouvette, R. J., and Busch, R. H. 1996. *Fusarium* head blight in hard red spring wheat: cultivar responses to natural epidemics. *Agron. J.* 88:223-230.
40. Wilcoxson, R. D., Kommedahl, T., Ozmon, E. A., and Windels, C. E. 1988. Occurrence of *Fusarium* species in scabby wheat from Minnesota and their pathogenicity to wheat. *Phytopathology* 78:586-589.
41. Wong, L. S. L., Tekauz, A., Leisle, D., Abramson, D., and McKenzie, R. I. H. 1992. Prevalence, distribution, and importance of *Fusarium* head blight in wheat in Manitoba. *Can. J. Plant Pathol.* 14:233-238.
42. Wood, G. E. 1992. Mycotoxins in foods and feeds in the United States. *J. Anim. Sci.* 70:3941-3949.
43. Yoshizawa, T., and Morooka, N. 1977. Trichothecenes from mold-infested cereals in Japan. Pages 309-321 in: *Mycotoxins in Human and Animal Health*. J. V. Rodricks, C. W. Hesseltine, and M. A. Mehlman, eds. Pathotox Publishers, Inc., Park Forest South, IL.