Fusarium Head Blight: Effect on the Milling and Baking of Some Canadian Wheats[1]

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ABSTRACT

Samples from the 1994 western Canadian wheat harvest of the hard red spring wheat cultivars Glenlea, Grandin, Roblin, and Taber that were downgraded predominately due to the presence of fusarium damaged (FD) kernels were composited at different FD levels. All samples were from southern Manitoba. As FD increased, deoxynivalenol (DON) levels increased. The ratio of DON to FD differed among cultivars, ranging from 0.6 to 2. Straight-grade flour yield was not related to increasing FD, but flour refinement (ash and color) was adversely affected. Gluten from hand-picked FD kernels contained a lower proportion of glutenins than did sound kernels. No qualitative or quantitative differences in gliadins attributable to FD were apparent. Flour from FD wheat showed relatively normal physical dough properties (mixograph and farinograph), but during remix baking, a long straight-dough procedure, dough became sticky and hard to handle. The effect of FD on loaf volume was cultivar dependent. Loaf volume of Glenlea was virtually unaffected by FD up to 7%, Grandin and Taber showed moderate declines, whereas Roblin showed a drastic decline.

Fusarium head blight (or scab) occurs worldwide on small grain cereals (Parry et al 1995). In Canada, fusarium head blight is caused primarily by *F. graminearum* Schwabe. Since 1984, this species has become increasingly common in southeastern Manitoba (Clear and Abramson 1986, Abramson et al 1987, Clear and Patrick 1990). In 1993 and 1994, conditions favorable to the disease resulted in the worst outbreaks of fusarium head blight ever in Manitoba (Canadian Grain Commission [CGC] 1993, 1994; Gilbert et al 1995).

Fusarium head blight outbreaks are a health concern because of the mycotoxins found in *Fusarium*-infected grain (Pomeranz et al 1990). There have been numerous studies focusing on the level of mycotoxins, particularly the trichothecene deoxynivalenol (DON vomitoxin) in infected wheat, flour, and processed products. Results have shown that DON is stable during wheat milling, although it becomes partitioned in varying concentrations among screenings, mill feed, and flour streams (Scott et al 1983, 1984; Seitz et al 1985; Lee et al 1987; Tkachuk et al 1991). DON is very stable during baking (El-Banna et al 1983, Young et al 1984, Tanaka et al 1986, Boyacioglu et al 1993). DON levels are reduced in cooked pasta and noodles because of leaching into the cooking water (Nowicki et al 1988), and in alkaline products such as tortillas due to decomposition (Abbas et al 1988).

The effects of fusarium head blight on the processing quality of wheat has not received much attention. According to Bechtel et al (1985), *F. graminearum* is an aggressive invader destroying starch granules, storage proteins, and cell walls. Boyacioglu and Hettiarachchy (1995) found that moderate *F. graminearum* infection causes significant compositional changes in carbohydrate, lipid, and protein. Meyer et al (1986) reported that German wheat infected by *F. culmorum* (W. G. Smith) Sacc. exhibited inferior baking quality, which they attributed to degradation of wheat gluten proteins. According to Seitz et al (1986), scab levels up to 3% did not significantly affect the baking quality of American hard red winter wheat.

Following the severe outbreak of fusarium head blight in southeastern Manitoba in 1994, there were reports from domestic processors that wheat from Manitoba containing fusarium-damaged (FD) kernels exhibited weaker dough properties than in previous years (*personal communications*). This study was initiated to determine the extent to which *F. graminearum* infection influences the processing performance of Canadian wheat.

MATERIALS AND METHODS

Wheat Samples

Wheat samples were commercially grown samples submitted by individual producers for CGC harvest surveys following the 1994 harvest. The samples selected had been downgraded primarily or exclusively due to the presence of FD, and would qualify for the milling grades in the absence of FD. All samples originated from southeastern Manitoba.

Samples of three red spring wheat cultivars, Glenlea (registered for the Canada Western Extra Strong class), Grandin (an American cultivar that was contract-grown in 1994 and marketed separately from the Canada Western Red Spring wheat class), and Taber (registered for the Canada Prairie Spring-Red class), originated from surveys of Canadian Wheat Board contract programs. Cultivar purity was ensured because cultivar was specified in the contracts. Roblin (registered for the Canada Western Red Spring class) samples were selected from the annual CGC Canada Western Red Spring wheat harvest survey. Samples downgraded due to FD were identified electrophoretically by cultivar by the method of Tkachuk and Mellish (1980). Those identified as pure Roblin, by far the most common cultivar identified, were selected.

Each individual sample was divided into two equal portions. Foreign material, dockage, and FD were removed by hand-picking from one portion to give a cleaned (CL) portion. Foreign material and dockage only were removed from the other portion to give an as is (AS) portion. Portions of CL and AS were blended 1:2 and 2:1 to give admixes at two intermediate levels of FD (AD1 and AD2). The size of resulting CL, AD1, AD2, and AS subsamples ranged from 50 to 150 g. Composites of 1.5 kg were prepared by blending 15 to 25 individual CL, AD1, AD2, and AS subsamples.

Grading and Determination of FD

Each composite, and the FD kernels removed during hand-picking, were examined by a CGC grain inspector. FD was determined according to standard CGC procedures. The Official Grain Grading Guide (CGC 1995) describes FD as "lifeless, thin, shrunken kernels affected by a whitish or pinkish fibrous mold.

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The presence of the mold on individual kernels is confirmed using a 10 power magnifier". A basic grade was assigned to each series exclusive of FD. The maximum FD tolerances for Canadian common wheat milling grades are 0.25% in No. 1 CWRS and 2% in all others.

Mycological Screening

Fungal analysis was performed on each CL and AS series and the hand-picked fusarium-damaged kernels (DK). Seeds (100) of each sample were chosen at random, surface-disinfected by soaking in a 0.3% sodium hypochlorite solution for 1 min, then air-dried in a laminar flow cabinet. Dried seeds were placed onto cooled potato dextrose agar in 100-mm petri dishes, with 10 seeds per plate. The plates were incubated for five days at room temperature (21–28°C) under a cycle of 12 hr of darkness and 12 hr of mixed UV and fluorescent light to induce sporulation of Fusaria and other fungi for identification.

Wheat Tests

Wheat moisture content, test weight, and kernel weight were determined by the methods described by Dexter and Tipples (1987).

Milling

The CL, AD1, AD2, and AS samples were prepared for milling and were milled in 1-kg lots by a five-stand mill (Allis-Chalmers) using procedures described by Dexter and Tipples (1987). The DK samples from all three replicates were combined, and a single 500-g lot was milled after the third replicate series.

Flour yields were calculated as the proportion of flour to wheat at first break on a constant moisture basis. Flour yields were adjusted to a constant ash content (ash score) and a constant flour grade color (color score) using relationships developed by Dexter et al (1989).

DON Determination

DON was determined in duplicate using Veratox enzyme-linked immunosorbent assay (ELISA) kits (Neogen Corporation, Lansing, MI) on 50-g samples of flour and ground wheat. Wheat samples (200 g) were ground in a Ditting coffee grinder (Elpack Ltd, Toronto, ON) at the 1.5 setting. The resulting grind is one in which 90% of ground material passes through a U.S. No. 20 mesh (850 μm) sieve. Extraction was at a 1:5 ratio with water at high speed in a blender. After settling, 30 ml of aliquot was centrifuged for 5 min at 3,000 rpm. Aliquots (100 μl) were used for the ELISA test.

Analytical Tests

Moisture contents of ground wheat and flour were determined with a Brabender rapid moisture tester (C. W. Brabender Instruments, South Hackensack, NJ) as outlined in the instruction manual. All wheat and flour analytical data are expressed on a 14% moisture basis.

TABLE I
Deoxynivalenol (DON) Levels in Whole Grain and Flour from Wheat Containing Fusarium-Damaged (FD) Kernels

Sample[a]	FD (%)	DON (ppm) Wheat	DON (ppm) Flour
Glenlea[b]			
CL	1.8	1.1	0.5
AD1	4.2	2.7	1.1
AD2	5.9	3.5	1.7
AS	7.3	4.9	3.3
DK	98	90	35
Grandin[c]			
CL	1.5	1.7	0.9
AD1	3.1	3.4	1.4
AD2	4.5	5.9	2.5
AS	7.3	8.0	4.6
DK	82	70	40
Roblin[d]			
CL	0.2	1.2	0.4
AD1	2.2	2.9	1.7
AD2	3.1	6.7	4.1
AS	5.9	9.5	5.9
DK	100	89	62
Taber[e]			
CL	2.5	2.5	1.6
AD1	5.1	5.7	2.7
AD2	8.9	8.6	4.9
AS	10.7	11	6.3
DK	100	85	51
P values[f]			
Wheat (W)	0.0001	0.0001	0.0001
FD	0.0001	0.0001	0.0001
W × FD	0.048	0.013	0.019
LSD ($\alpha = 0.05$)[g]	0.81	0.92	0.55

[a] CL = cleaned, sample hand-picked to lower FD; AD1 = admix 1, 2:1 blend of CL and AS; AD2 = admix 2, 1:2 blend of CL and AS; AS = as is, original sample; DK = damaged, FD kernels removed from AS sample.
[b] Canada Western Extra Strong class cultivar.
[c] Experimental cultivar.
[d] Canada Western Red Spring class cultivar.
[e] Canada Prairie Spring-Red class cultivar.
[f] Mean values of three replicates for CL, AD1, and AD2. Due to sample size limitations, DK results are means of duplicate analyses of single composite from all replicates.
[g] Least significant difference.

TABLE II
Properties of Fusarium-Damaged (FD) Wheat[a]

Sample[b]	TW (kg/hl)	KW (mg)	Ash (%)	PR (%)
Glenlea[c]				
CL	77.8	43.8	1.62	13.2
AD1	77.3	42.3	1.64	13.3
AD2	76.6	42.3	1.63	13.2
AS	75.7	41.1	1.62	13.2
DK	64.4	27.7	1.75	13.2
Grandin[d]				
CL	79.0	35.7	1.57	14.0
AD1	78.4	36.2	1.56	13.9
AD2	77.7	35.0	1.59	13.9
AS	76.7	34.5	1.57	13.7
DK	65.4	24.2	1.75	13.6
Roblin[e]				
CL	77.9	34.2	1.67	14.8
AD1	77.1	32.2	1.70	14.6
AD2	76.4	30.6	1.68	14.7
AS	75.0	29.7	1.65	14.7
DK	62.1	21.9	1.79	14.3
Taber[f]				
CL	77.0	36.4	1.67	11.6
AD1	76.3	35.7	1.66	11.7
AD2	75.5	35.3	1.58	11.6
AS	74.1	33.3	1.64	11.7
DK	64.4	24.4	1.86	11.6
P values[g]				
Wheat (W)	0.0001	0.0001	0.0001	0.0001
FD	0.0001	0.0001	0.64	0.92
W × FD	0.98	0.57	0.31	1.0
LSD ($\alpha = 0.05$)[h]	0.53	0.76	0.033	0.34

[a] TW = test weight, KW = kernel weight, PR = protein. Expressed as 14% mb.
[b] CL = cleaned, sample hand-picked to lower FD; AD1 = admix 1, 2:1 blend of CL and AS; AD2 = admix 2, 1:2 blend of CL and AS; AS = as is, original sample; DK = damaged, FD kernels removed from AS sample.
[c] Canada Western Extra Strong class cultivar.
[d] Experimental cultivar.
[e] Canada Western Red Spring class cultivar.
[f] Canada Prairie Spring-Red class cultivar.
[g] Mean values of three replicates for CL, AD1, and AD2. Due to sample size limitations, DK results are means of duplicate analyses of single composite from all replicates.
[h] Least significant difference.

Ash content, wet gluten content, and starch damage were determined by standard procedures (AACC 1995). Flour grade color was determined using a Colour Grader Series 4 (Satake UK, Stockport, UK) using flour testing panel method No. 007/4 (FMBRA 1991) and expressed in Satake international color grade units. Protein content (N × 5.7) was determined by the Kjeldahl procedure as modified by Williams (1973). The method of Kruger and Tipples (1981) was used to determine α-amylase content.

Protein Characterization

Gliadins, glutenins, and high molecular weight (HMW) glutenins were isolated from flour from the CL and DK composites by the sequential extraction procedure described by Marchylo et al (1989). The protein fractions were separated by reversed-phase high-performance liquid chromatography (HPLC) using a Waters HPLC and Waters 840 data and chromatography control station (Waters Associates Inc., Milford, MA) as described by Marchylo et al (1989), except that a Zorbax Rx300 C-8 HPLC column was used. Results are the average of five extractions with an average coefficient of variation of ≈8%.

Physical Dough Tests

Mixograph and farinograph curves were obtained by standard procedures (AACC 1995.)

Baking

Flours were baked by the remix-to-peak procedure (Kilborn and Tipples 1981). Loaf volumes were determined by rapeseed displacement. Bread scoring was as described by Preston et al (1982).

Experimental Design and Statistical Analysis

For each wheat cultivar, three independent series of CL, AD1, AD2, and AS composites were prepared as replicates. Each composite from each replicate was tested singly for physical, analytical, and milling properties, with the exception of the DK material, which was composited before testing because of sample size limitations.

All testing, except milling, was performed in randomized design. Each replicate series was milled in ascending order of FD, and a check sample free of FD was milled between series, to prevent spurious flour DON results that could arise because of cross-contamination of stocks from successive millings.

Due to sample size limitations, farinograph and remix-to-peak baking tests were performed on composites derived by blending flour from each CL, AD1, AD2, and AS replicate in equal proportion.

All statistics from replicated test results were calculated using general linear models procedures of the SAS (Cary, NC) software system v6.08 for Windows.

TABLE III
Milling Properties of Fusarium-Damaged (FD) Wheat[a]

Sample[b]	FY (%)	Ash (%)	AFY (%)	FGC[c]	CFY (%)
Glenlea[d]					
CL	74.2	0.56	71.2	0.1	73.1
AD1	73.7	0.55	71.2	0.3	72.0
AD2	74.1	0.57	70.8	0.7	71.2
AS	73.7	0.58	69.7	1.1	69.4
DK	72.3	0.84	55.3	7.8	48.0
Grandin[e]					
CL	75.0	0.50	75.2	0.1	73.9
AD1	74.8	0.50	74.8	0.3	73.1
AD2	75.0	0.51	74.4	0.7	72.0
AS	74.7	0.52	73.7	1.2	70.3
DK	72.7	0.84	55.7	7.2	50.2
Roblin[f]					
CL	74.1	0.49	74.4	–0.1	73.4
AD1	73.6	0.49	74.2	0.1	72.5
AD2	73.6	0.49	73.9	0.4	71.4
AS	73.5	0.52	72.3	0.9	69.8
DK	70.7	0.81	55.2	7.8	46.4
Taber[g]					
CL	73.8	0.47	75.1	0.1	72.9
AD1	73.8	0.48	74.9	0.7	70.8
AD2	73.8	0.48	74.8	1.2	69.4
AS	73.7	0.51	73.2	1.9	67.0
DK	71.9	0.89	52.4	9.5	42.5
P values[h]					
Wheat (W)	0.0001	0.0001	0.0001	0.0001	0.0001
FD	0.21	0.0006	0.0001	0.0001	0.0001
W × FD	0.97	0.91	0.92	0.44	0.37
LSD (α = 0.05)[i]	0.39	0.014	0.47	0.22	0.64

[a] FY = flour yield, AFY = FY corrected to constant ash content; FGC = flour grade color; CFY = FY corrected to constant FGC. Flour yields expressed as proportion of wheat to first break on constant moisture basis.
[b] CL = cleaned, sample hand-picked to lower FD; AD1 = admix 1, 2:1 blend of CL and AS; AD2 = admix 2, 1:2 blend of CL and AS; AS = as is, original sample; DK = damaged, FD kernels removed from AS sample.
[c] Satake international color grade units.
[d] Canada Western Extra Strong class cultivar.
[e] Experimental cultivar.
[f] Canada Western Red Spring class cultivar.
[g] Canada Prairie Spring-Red class cultivar.
[h] Mean values of three replicates for CL, AD1, and AD2. Due to sample size limitations, DK results are from single millings and means of duplicate analyses of single composite from all replicates.
[i] Least significant difference.

TABLE IV
Flour Properties of Fusarium-Damaged (FD) Wheat[a]

Sample[b]	PR (%)	WG (%)	α-A	SD
Glenlea[c]				
CL	12.5	31.7	3.8	8.9
AD1	12.5	32.4	4.0	9.0
AD2	12.5	31.6	4.5	9.4
AS	12.5	31.4	6.2	9.3
DK	12.3	28.7	24.5	7.7
Grandin[d]				
CL	13.2	34.6	20.3	8.3
AD1	13.2	34.2	18.5	8.3
AD2	13.3	34.4	21.0	8.1
AS	13.1	33.6	22.3	8.1
DK	12.6	26.1	26.0	7.2
Roblin[e]				
CL	14.5	38.0	2.7	7.7
AD1	14.4	37.8	2.8	7.3
AD2	14.4	37.9	3.3	7.0
AS	14.4	37.2	3.8	6.8
DK	13.9	32.0	20.0	5.8
Taber[f]				
CL	10.6	27.5	6.2	6.1
AD1	10.7	27.3	7.5	6.2
AD2	10.6	26.7	8.5	6.5
AS	10.6	26.5	13.5	6.4
DK	10.4	13.4	31.5	6.5
P values[g]				
Wheat (W)	0.0001	0.0001	0.0001	0.0001
FD	0.96	0.10	0.45	0.53
W × FD	1.00	0.98	1.0	0.72
LSD (α = 0.05)[h]	0.26	0.72	4.6	0.34

[a] PR = protein, WG = wet gluten; α-A = α-amylase activity (units/g); SD = starch damage (AACC units).
[b] CL = cleaned, sample hand-picked to lower FD; AD1 = admix 1, 2:1 blend of CL and AS; AD2 = admix 2, 1:2 blend of CL and AS; AS = as is, original sample; DK = damaged, FD kernels removed from AS sample.
[c] Canada Western Extra Strong class cultivar.
[d] Experimental cultivar.
[e] Canada Western Red Spring class cultivar.
[f] Canada Prairie Spring-Red class cultivar.
[g] Mean values of three replicates for CL, AD1, and AD2. Due to sample size limitations, DK results are means of duplicate analyses of single composite from all replicates.
[h] Least significant difference.

TABLE V
High-Performance Liquid Chromatography Gluten Protein Distribution from Cleaned and Hand-Picked Fusarium-Damaged (FD) Wheat[a]

Sample[b]	Total Recovery[c]	Gliadins (%)	Glutenins (%)
Glenlea[d]			
CL	100	61	39
DK	84	69	31
Grandin[e]			
CL	100	61	39
DK	82	72	28
Roblin[f]			
CL	100	59	41
DK	75	72	28
Taber[g]			
CL	100	64	36
DK	75	77	23

[a] Mean values from five extractions (avg. coefficient of variation = 8%).
[b] CL = cleaned, hand-picked to lower FD; DK = hand-picked FD kernels.
[c] Total integrated area from high-performance liquid chromatograms of CL flours normalized to 100%.
[d] Canada Western Extra Strong class cultivar.
[e] Experimental cultivar.
[f] Canada Western Red Spring class cultivar.
[g] Canada Prairie Spring-Red class cultivar.

The data were analyzed as a factorial experiment with two factors (both fixed effects). The analysis of variance (ANOVA) sources of variation were: FD, 3 df; cultivar, 3 df; cultivar to FD, 9 df; and error, 32 df; for a total of 47 df. Mean values for each treatment were compared by Fisher's protected least significant difference (LSD) test ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Mycology, FD Kernels, and DON Levels

Alternaria alternata was the fungus most often isolated from the CL and AS samples (results not shown). *F. graminearum* was the primary fungus in the DK composites, infecting over 90% of the seeds. In the AS samples, the frequency of kernels infected by *F. graminearum* ranged from a low of 38% for both Glenlea and Roblin, to a high of 50% for Taber.

Confirmation of FD with a magnifier was too tedious to be practical during the hand-picking, so the CL samples still contained some FD when officially graded by CGC grain inspectors, and the DK composites were <100% FD (Table I). Among the AS composites, Taber exhibited the greatest FD level, Roblin exhibited the lowest, and Grandin and Glenlea exhibited intermediate values.

TABLE VI
Farinograph and Mixograph Properties of Fusarium-Damaged (FD) Wheat[a]

	Farinograph				Mixograph	
Sample[b]	ABS (%)	DDT (min)	MTI (BU)	STA (BU)	DDT (min)	HGT (cm)
Glenlea[c]						
CL	59.8	7.0	20	7.0	18.0	6.5
AD1	59.6	7.5	20	7.5	20.0	6.2
AD2	60.2	7.75	20	7.75	16.7	6.6
AS	59.8	7.5	30	7.5	16.7	6.3
20% DK	59.8	5.75	45	9.0	nd[d]	nd
DK	58.3	1.25	75	1.25	11.0	5.0
Grandin[e]						
CL	62.4	4.5	40	8.0	9.5	5.8
AD1	62.4	4.75	40	8.0	10.7	5.4
AD2	62.3	4.25	35	7.5	9.9	5.9
AS	62.0	4.0	50	7.0	10.1	5.6
20% DK	62.0	3.75	40	7.0	nd	nd
DK	59.2	1.0	80	2.0	15.5	4.5
Roblin[f]						
CL	62.5	6.5	40	9.5	7.9	7.7
AD1	62.0	6.5	30	10.0	8.4	7.3
AD2	62.4	6.25	40	9.5	8.8	7.0
AS	62.0	5.75	40	9.0	8.8	6.8
20% DK	61.5	5.0	60	6.5	nd	nd
DK	59.6	2.75	90	4.5	8.8	5.8
Taber[g]						
CL	56.4	3.25	45	6.5	8.5	5.0
AD1	56.2	3.5	60	6.0	8.3	5.0
AD2	56.0	3.0	55	5.5	8.4	4.8
AS	55.9	2.75	65	5.5	8.8	4.7
20% DK	56.0	3.25	60	5.0	nd	nd
DK	53.8	1.0	130	2.0	16.0	2.5
P values[h]						
Wheat (W)					0.0001	0.0001
FD					0.052	0.056
W × FD					0.014	0.39
LSD ($\alpha = 0.05$)[i]					0.73	0.31

[a] ABS = water absorption (14% mb); DDT = dough development time; MTI = mixing tolerance index; STA = stability; HGT = maximum peak height.
[b] CL = cleaned, sample hand-picked to lower FD; AD1 = admix 1, 2:1 blend of CL and AS; AD2 = admix 2, 1:2 blend of CL and AS; AS = as is, original sample; 20% DK = 20:80 blend of flour from hand-picked FD kernels with flour from CL wheat. DK = damaged, FD kernels removed from AS sample. Due to sample size limitations, results are mean values for duplicate bakes of flours composited from replicate millings.
[c] Canada Western Extra Strong class cultivar.
[d] Not determined.
[e] Experimental cultivar.
[f] Canada Western Red Spring class cultivar.
[g] Canada Prairie Spring-Red class cultivar.
[h] Mean values of three replicates for CL, AD1, and AD2. Due to sample size limitations, DK mixograph results and all farinograph results are single results from composite flours from all three replicates.
[i] Least significant difference.

Within a wheat cultivar, DON values were strongly correlated to FD. Retention of DON in the flour for all cultivars averaged ≈50%, consistent with numerous previous reports (Pomeranz et al 1990 and references therein).

Experience at the CGC has shown that DON values from the ELISA test correlate strongly ($r > 0.8$) to values from the reference gas chromatograph-mass selection detection procedure described by Nowicki et al (1988). The ELISA results tend to be higher by as much as 50%, particularly when DON levels are well below 2 ppm.

It is interesting to note that determination of FD visually was only a rough predictor of DON levels in wheat because there were different ratios of DON to FD for individual cultivars. The ratio was near 2:1 for Roblin, near unity for Grandin and Taber, and near 0.6:1 for Glenlea. The cause may be environmental, although all of the samples came from southeastern Manitoba.

Wheat Properties

Exclusive of the DK samples, the wheat composites all met the requirements for the No. 1 or No 2 Canada Western grade for their class (not shown). Other than FD, the most frequent degrading factor cited was immaturity.

Test weight and kernel weight were strongly inversely related to FD because of the shriveled nature of FD kernels (Table II). However, neither wheat ash content or protein content were significantly ($P > 0.05$) affected by FD for the CL, AD1, AD2, and AS series. The DK samples also exhibited no change in protein content, but exhibited high ash content due to reduced endosperm content.

Milling Properties

Straight-run flour yield was not significantly affected ($P > 0.5$) by FD within the CL, AD1, AD2, and AS series, although the DK composites showed lower flour yield (Table III). However, when flour refinement was also considered, FD had a strong negative influence on milling performance. The DK composites gave a poorly refined flour as evident from high ash content and dark color. Within the CL, AD1, AD2, and AS series flour ash content generally rose, and flour color darkened with increasing FD.

When flour yield was calculated on a constant ash content basis, the decline in yield for CL to AS was highly significant ($P < 0.0001$). However, the absolute amount of flour yield decline was only moderate, ranging from 1.5 to 2% among the cultivars, equivalent to ≈0.25% for each 1% FD. When flour yield was calculated on a constant flour color basis, the effect on milling yield was more pronounced. Loss of yield ranged from 3.5 to 5% among cultivars, equivalent to >0.5% for each 1% FD.

Flour and Protein Properties

Within the CL, AD1, AD2, and AS series, FD had no significant effect ($P > 0.5$) on protein content, wet gluten, α-amylase activity, or starch damage (Table IV). However, the DK composites clearly indicated a moderate drop in protein content, a decline in wet gluten content (particularly for Taber), a moderate increase in α-amylase activity, and a decline in starch damage, indicative of softer kernel texture.

Although the CL to AS series did not exhibit a significant decline in wet gluten content, the handling properties of the wet gluten seemed to be moderately affected. For all cultivars, and in particular Roblin and Taber, the AS wet gluten was stickier than the CL gluten. In the case of DK samples, for all cultivars, the wet gluten was very sticky and difficult to handle.

During preliminary bulking of samples, no evidence of qualitative differences in gliadins were apparent between sound and FD kernels during polyacrylamide gel electrophoresis (PAGE) analysis to verify cultivar (results not shown). Similarly, there was no evidence of qualitative differences in gliadin profiles from HPLC chromatograms for corresponding DK and CL flours. Glutenin and HMW glutenin HPLC profiles of corresponding DK and CL flours were also identical.

According to HPLC analyses, the total quantity of gliadins per gram of flour was comparable for the DK and CL flours, but the data in Table V indicates that the proportion of glutenins in DK flour was less than for CL flour. These results are in agreement with those of Boyacioglu and Hettiarachchy (1995), who reported a decrease in glutenins in American hard red spring wheat infected by *F. graminearum*. *Fusarium* spp. have been shown to be aggressive invaders of wheat kernels, particularly the pericarp and aleurone regions (Bechtel et al 1985, Meyer et al 1986), and are known to invade the endosperm, leading to speculation that the fungus degrades gluten proteins. However, the absence of a quantitative effect on gliadins in DK flour in the current study implies that if degradation of gluten protein by *F. graminearum* is the primary cause of gluten quality deterioration, then the fungus must be specific to glutenins, which is unlikely.

An alternative (or additional) effect of *Fusarium* spp. infection on gluten properties is immaturity, brought on by incomplete development of the seeds by premature death of infected spikelets. In the absence of FD, the main degrading factor in the samples in this study is immaturity. Glutenins are synthesized more rapidly than gliadins during the later stages of the kernel maturation process (Huebner et al 1990). Simmonds (1968) estimates that in a FD kernel, development of the seed is halted by fungal invasion at about the early milk to early dough stage, depending upon the time of initial infection.

Physical Dough and Remix Bread Properties

Mixograph curves for the CL, AD1, AD2, and AS series were not significantly different ($P > 0.05$) for any of the wheat cultivars, but the DK curves were dramatically altered in both mixing time and height (Table VI). Similarly, farinograph curves for the CL, AD1, AD2, and AS series were not greatly affected. Farinog-

TABLE VII
Remix-to-Peak Baking Properties of Fusarium-Damaged (FD) Wheat[a]

Sample[b]	ABS (%)	RMT (min)	LV (cm^3)	BSI (%)
Glenlea[c]				
CL	61	3.1	905	111
AD1	60	3.3	925	113
AD2	60	3.5	935	114
AS	59	3.2	885	108
20% DK	57	1.9	800	98
Grandin[d]				
CL	60	2.0	920	106
AD1	60	2.3	905	105
AD2	59	2.3	885	101
AS	58	2.3	855	99
20% DK	56	1.7	700	81
Roblin[e]				
CL	61	1.2	690	72
AD1	61	1.1	575	61
AD2	61	1.2	550	58
AS	61	1.1	520	55
20% DK	59	1.1	470	50
Taber[f]				
CL	54	1.7	695	102
AD1	53	1.8	680	98
AD2	53	1.9	650	95
AS	51	1.5	610	89
20% DK	49	1.1	425	63

[a] ABS = water absorption (14% mb); RMT = remix mixing time; LV = loaf volume; BSI = baking strength index.
[b] CL = cleaned, sample hand-picked to lower FD; AD1 = admix 1, 2:1 blend of CL and AS; AD2 = admix 2, 1:2 blend of CL and AS; AS = as is, original sample; 20% DK = 20:80 blend of flour from hand-picked kernels with flour from CL wheat. Due to sample size limitations, results are mean values for duplicate bakes of flours composited from replicate millings.
[c] Canada Western Extra Strong class cultivar.
[d] Experimental cultivar.
[e] Canada Western Red Spring class cultivar.
[f] Canada Prairie Spring-Red class cultivar.

raph data for all the DK flours exhibited lower water absorption, shorter development time and shorter stability. When corresponding DK flour and AS flour were blended to an equivalent of 20% FD, the farinograph curves weakened significantly for all cultivars.

FD significantly affected baking quality, this is in agreement with previous reports (Meyer et al 1986, Seitz et al 1986, Moore 1994). In all cases, baking absorption showed a direct inverse relationship to FD (Table VII). Within the levels of FD examined, crumb color, and crumb structure were not affected (results not shown). The effect of FD on loaf volume was cultivar specific. Glenlea, which has extraordinarily strong gluten, actually exhibited slightly enhanced loaf volume up to ≈6% FD (AD2), followed by a moderate decline. The initial increase in loaf volume of Glenlea may be due to improved viscoelastic balance of the gluten at low FD due to a moderate increase in the proportion of gliadins.

Grandin and Taber exhibited a progressive decrease in loaf volume with increasing FD. Also, as FD increased the dough became progressively stickier and difficult to handle during sheeting and molding. For both cultivars, the loaf volume of the CL samples was within expectation, with a baking strength index near 100.

Roblin also exhibited a progressive decline in baking performance with increasing FD, but in contrast to the other cultivars, loaf volume of the CL sample was much lower than normal for Canada Western Red Spring (CWRS) wheat cultivars. The CL baking strength index was only 72, indicating that loaf volume was ≈30% below normal. Remix mixing time of the Roblin series was also much shorter than the usual 2–2.5 min typical of CWRS wheat.

The fact that the poor baking performance of the Roblin CL, AD1, AD2, and AS series was not evident from the farinograph curve is both curious and disconcerting. It is possible that proteolytic damage to the gluten proteins attributable to FD was incurred during fermentation. The relatively short time period for farinograph mixing would not show fermentation effects.

Regardless of the cause, the inability of the farinograph (and other standard tests like the mixograph and wet gluten properties) to predict the poor baking performance of the Roblin series is a concern from the practical standpoint of wheat marketing. FD wheat is sometimes cleaned on specific gravity tables before marketing (Tkachuk et al 1991, Trigo-Stockli et al 1995), and the poor baking performance of the CL Roblin shows that cleaning out FD may not guarantee good processing performance.

CONCLUSIONS

FD, within the levels encountered commercially in southeastern Manitoba in 1994, had significant wheat processing quality implications. Intrinsic flour yield was not affected, but flour refinement (ash and color) declined with increasing FD. The effect on flour color was equivalent to more than 0.5% flour yield for each 1% FD.

FD also had detrimental effects on baking performance. The extent of the effects appeared to be cultivar specific. Roblin exhibited unacceptable baking performance even after FD was removed. Grandin and Taber showed more moderate declines in baking performance with increasing FD, and Glenlea was less affected.

In terms of food safety, these studies showed that visual inspection for FD gave only a rough indication of DON levels. The ratio of DON to FD was cultivar specific, ranging from 2 for Roblin to ≈0.6 for Glenlea.

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