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Agronomic Characteristics, Malt Quality, and Disease Resistance of Barley Germplasm Lines with Partial Fusarium Head Blight Resistance

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ABSTRACT

Fusarium head blight (FHB), incited by *Fusarium graminearum* Schwabe, has caused devastating losses in both yield and quality of barley (*Hordeum vulgare* L.) produced in the northern Great Plains from 1993 to 2003. Thirty-five barley germplasm lines with partial resistance to FHB have been identified in exotic and unadapted germplasm lines. Little is known about their agronomic characteristics, malt quality, and reaction to other diseases as compared to adapted cultivars. This information is needed so barley breeders can make informed decisions when planning crosses involving the resistant germplasm lines. The objective of this study was to compare the agronomic performance, malt quality, and disease reaction of barley germplasm lines with partial FHB resistance to cultivars grown in the northern Great Plains. Agronomic and malting data were collected on the 35 germplasm lines and five check cultivars grown in five environments in North Dakota from 1998 to 2000. Data for FHB severity and deoxynivalenol (DON, a mycotoxin produced by *F. graminearum*) accumulation were obtained for the same 40 entries grown in FHB-epidemic nurseries in North Dakota from 1997 to 1999. Seedling responses to foliar pathogens common in the northern Great Plains were determined in the greenhouse during fall 1997. None of the FHB-resistant barley germplasm lines had acceptable malt quality for all traits. Kernel plumpness, grain protein concentration, and malt extract were the traits impacted most severely. The FHB-resistant barley germplasm lines headed significantly later than the adapted barley cultivars. Most FHB-resistant germplasm lines were susceptible to the common foliar diseases of the northern Great Plains. At least four cycles of breeding will probably be necessary to develop FHB-resistant germplasm lines acceptable to producers and the malting and brewing industry.

Fusarium head blight has caused devastating losses in both the yield and quality of barley produced in the northern Great Plains from 1993 to 2003. From 1993 to 1997, total losses due to FHB in the upper Midwest of the United States exceeded $200 million (U.S. GAO, 1999). Nganje et al. (2001) estimated losses of $136 million in the same region from 1998 to 2000. The greatest losses were due to reductions in yield and grain quality. Much of the reduced grain quality was due to the accumulation of the mycotoxin DON produced by the pathogen, *F. graminearum*. Depending on the purchaser of the grain, barley samples with DON concentrations as low as 0.6 $\mu g\ g^{-1}$ have been rejected. DON has been found to carry through malting and brewing into finished beer (Schwarz et al., 1995). Even beer with low DON levels poses a marketing problem for brewing companies because nobody wants to consume a "toxin" and DON has been associated with beer gushing (Schwarz et al., 1995). Beer gushing or overfoaming is the most easily identifiable consumer complaint associated with DON content.

Chemical and cultural management strategies for FHB in barley have been unsuccessful; thus, development of improved cultivars with genetic resistance to the disease offers the greatest potential for controlling this disease. The inheritance of FHB resistance is not well understood; however, some progress has been made in breeding for resistance to FHB in barley. Thirty-five six-rowed and two-rowed barley germplasm lines have been identified with partial resistance to FHB (Prom et al., 1996). Most of these accessions originate from eastern Asia and have the two-rowed spike morphology. Based on our initial evaluations of these lines, they appeared to be unadapted for growth in northern Great Plains of the United States and the western Prairie Provinces of Canada because of late maturity and tall, weak straw.

Many of these germplasm lines are being used as sources of genes for FHB resistance and low DON accumulation; yet, little is known about their agronomic and malt quality characteristics and their response to other foliar pathogens. Information in these areas is needed so barley breeders can make informed decisions when working with segregating populations developed from crosses to these resistant germplasm lines. The objective of this study was to compare the agronomic characteristics, malt quality, and reaction to foliar pathogens of 35 barley germplasm lines with partial FHB resistance to current cultivars grown in the northern Great Plains.

MATERIALS AND METHODS

Plant Materials

Forty barley germplasm lines (Table 1), 35 with partial resistance to FHB (B. Steffenson, personal communication, 1996; Prom et al., 1996), were used in this study. Susceptible checks used in the study for comparison purposes included the two-rowed adapted cultivars Logan and Conlon and the adapted six-rowed cultivars Foster, Morex, and Stander. Conlon, Foster, and Morex are on the "2004 List of Recommended Malting Barley Varieties" by the American Malting Barley Association (Milwaukee, WI) when grown in the northern Great Plains. Logan and Stander are high-yielding feed barley cultivars currently grown in North and South Dakota.

Agronomic and Fusarium Head Blight Evaluations

Trials for the agronomic comparisons were sown on 15 May 1998 and 4 May 2000 at Fargo, ND, in a fine, montmorillonitic, frigid Typic Haploboroll soil; on 18 May 1999 and 26 April

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Abbreviations: ASBC, American Society of Brewing Chemists; DON, deoxynivalenol; FHB, Fusarium head blight; RCBD, randomized complete block design.

Table 1. Barley germplasm lines evaluated for resistance to *F. graminearum* in North Dakota trials from 1997 to 2000.

Germplasm line	PI number	Source	Pedigree information	Origin	Row number
Aleli†	–	National Small Grains Collection	Unknown	Switzerland	2
Balder†	181149	National Small Grains Collection	Gull/Swedish landrace//Maja	Sweden	2
CIho 4196†	64275	K. Takeda, 1995	Unknown	China	2
Conlon‡	597789	J. Franckowiak, 1997	Bowman*2/Birgittamatt//ND10232	ND, USA	2
Daisen Gold†	–	B. Steffenson, 1997	Unknown	Japan	2
Dai Shan Er Leng Da Mai†	–	B. Steffenson, 1997	Unknown	China	2
Xiao Shan Ci Mang Er Leng Da Mai†	–	B. Steffenson, 1997	Unknown	China	2
F101-78	–	R. Horsley, 1997	Gobernadora/Foster//ND9712	ND, USA	2
F102-61	–	R. Horsley, 1997	Zhedar 1/Foster//ND9712	ND, USA	2
F103-53	–	R. Horsley, 1997	Zhedar 2/Foster//ND9712	ND, USA	2
F103-61	–	R. Horsley, 1997	Zhedar 2/Foster//ND9712	ND, USA	2
F103-105	–	R. Horsley, 1997	Zhedar 2/Foster//ND9712	ND, USA	2
Francks Hohenloher†	467513	National Small Grains Collection	Imperial/Bethge II	Germany	2
Fuji Nijo†	383928	K. Takeda, 1995	Plumage Archer/Nirasaki Wase 1	Kirin, Japan	2
Gobernadora†	–	J. Franckowiak, 1997	OC640/Mari//Pioneer/3/Maris Concord	Mexico	2
Horny Peseky†	–	K. Takeda, 1995	Unknown	China	2
Imperial†	61340	National Small Grains Collection	Mutant Imperial, CIho3197	Japan	2
Isaria†	321800	National Small Grains Collection	Bavaria/Danubia	Germany	2
Kombainesis†	–	K. Takeda, 1995	Unknown	Unknown	2
Kyoto Nakate†	–	K. Takeda, 1995	Selection from Svanhals	Japan	2
Logan‡	–	J. Franckowiak, 1997	ND7085/ND4994-15//ND7556	ND, USA	2
Maja†	184884	K. Takeda, 1995	Blinder/Gull	Denmark	2
Messidor†	174473	National Small Grains Collection	Selection from Svanhals	France	2
Mimai 114†	584962	National Small Grains Collection	Unknown	China	2
Misato Golden†	–	B. Steffenson, 1997	Unknown	Japan	2
CIho 7595†	161970	National Small Grains Collection	Bavaria/Danubia	Germany	2
Xiao Shan Er Leng Da Mai†	566203	National Small Grains Collection	Unknown	China	2
Primus II†	–	National Small Grains Collection	Bulked from Primus	SD, USA	2
Svanhals†	5474	K. Takeda, 1995	Selection from Besterhon Diamant	Sweden	2
Shyri†	–	J. Franckowiak, 1997	Lignee 640/Kober//Teran 78	Ecuador	2
Zao Shu 3†	466772	National Small Grains Collection	Unknown	China	2
Zhedar 1†	–	B. Steffenson, 1997	Unknown	China	2
Zhedar 2†	–	B. Steffenson, 1997	Unknown	China	2
Chevron	38061	R. Horsley, 1997	Unknown	Switzerland	6
CIho 16128†	–	B. Steffenson, 1997	Atsel/Chevron	MD, USA	6
Glenn	–	R. Horsley, 1997	Br5755-3/Trophy//NDB138	ND, USA	6
Hazen	483238	R. Horsley, 1997	Glenn/4/Nordic//Dickson/Trophy/3/Azure	ND, USA	6
ND15967	–	R. Horsley, 1997	Stander/3/ND9712//Foster/PI 452421	ND, USA	6
Foster‡	592758	R. Horsley, 1997	Robust/3/ND5570//Glenn/Karl	ND, USA	6
Morex‡	–	R. Horsley, 1997	Cree/Bonanza	MN, USA	6
Stander‡	564743	R. Horsley, 1997	Excel//Robust/Bumper	MN, USA	6

† Barley germplasm lines reported to possess partial resistance to Fusarium head blight (Steffenson, personal communication, 1996; Prom et al., 1996).
‡ Barley cultivars adapted for production in the northern Great Plains of the United States.

2000 at Osnabrock, ND, in a fine, montmorillonitic Udic Natriboroll soil; and on 27 April 2000 at Langdon, North Dakota in a fine, montmorillonitic Udic Natriboroll soil. Entries were assigned to experimental units using a randomized complete block design (RCBD) with two replicates. The experimental units consisted of three 3.38-m rows of barley spaced 0.83 m apart. To obtain a valid estimate of the agronomic potential of these germplasm lines under disease-free conditions, they were protected against FHB infection and other foliar diseases with foliar applications of the fungicide benomyl (0.5 kg a.i. ha^{-1}), beginning one week after heading and once a week for three consecutive weeks. The applications were done with a tractor-mounted sprayer using water at 159 L ha^{-1} at 207 kPa and a ground speed of 5.6 km h^{-1}.

Morphological and agronomic data were collected throughout the growing season. Days to heading were recorded as the number of days after 31 May when 50% of the spikes were fully emerged from the boot. Between maturity and harvest, data on plant height (stem plus spike-excluding awns), lodging (1 = no lodging, 9 = severe lodging), and spike row type (*vrs1vrs1Int-cInt-c* = sessile six-rowed, *Vrs1Vrs1int-cint-c* = normal two-rowed, and *Vrs1Vrs1Int-cInt-c* = hybrid two-rowed) were recorded.

At maturity, plots were harvested using a plot combine. Grain samples were dried in a forced dryer to approximately 100 g kg^{-1} moisture, de-awned, and cleaned. Yield of clean grain was recorded as megagrams per hectare (Mg ha^{-1}). Data were also recorded on test weight (kg hL^{-1}), kernel plumpness (g kg^{-1}), and grain protein concentration (g kg^{-1}). Grain protein concentration was determined on a dry matter basis by near infrared reflectance measurement using a Tecator Infratec 1226 grain analyzer (Perstorp Analytycal Inc., Silver Spring, MD) and expressed in milligrams per kilogram (mg kg^{-1}). Kernel plumpness was determined according to the method specified by the American Society of Brewing Chemists (ASBC, 1992). Kernels retained on a sieve with 0.2 by 1.9 cm slotted openings were considered plump. Kernel brightness was determined using a modification of the ASBC standard method, Barley-9 (ASBC, 1992), using the L-value obtained from a Pacific Scientific XL-800 series Gardner colorimeter with XL-845 circumferential sensor (Perstorp Analytical Inc., Silver Spring, MD).

Fusarium Head Blight and Deoxynivalenol Evaluations

The 40 barley germplasm lines also were grown in FHB-epidemic nurseries at Fargo and Langdon in 1997 and at Fargo, Langdon, and Osnabrock in 1998. The soil types at each location are the same as previously described. Experimental units consisted of one 1-m row. Germplasm lines were assigned to experimental units using a RCBD, and two replicates of each line were included at each location. Germplasm lines were inoculated four times with *F. graminearum*, beginning one week

before heading, and once a week for four consecutive weeks using the grain-spawn method described by Urrea et al. (2002).

Disease ratings were recorded at the soft dough stage (Zadoks 85) of development. Fifteen spikes within each row were harvested at random, and the number of infected kernels per spike was counted. The percentage of FHB severity was calculated by dividing the total number of infected kernels by the total of kernels and multiplying by 100. Deoxynivalenol content ($\mu g\ g^{-1}$) was determined using the methodology described by Schwarz et al. (1995). The threshold for DON detection by the method we used was 0.5 $\mu g\ g^{-1}$.

Foliar Disease Evaluations

The 40 germplasm lines were also grown in the greenhouse during fall 1997. Their responses to the wheat stem rust pathogen (*Puccinia graminis* Pers.:Pers. f. sp. *tritici*), leaf rust pathogen (*Puccinia hordei* G. Otth), net blotch pathogen (*Pyrenophora teres* Drechs.), spot blotch pathogen [*Cochliobolus sativus* (Ito & Kuribayashi) Drechs. ex Dastur], and the powdery mildew pathogen (*Blumeria graminis* DC. f. sp. *hordei* Ém. Marchal) were determined. Three to five seeds of each germplasm line were sown in 3.8 by 21 cm Ray Leach Conetainers (Stuewe & Sons, Corvallis, OR) with #1 Sunshine mix (3:1 peat moss/perlite) (Sun Gro, Bellevue, WA). Osmocote (14–14–14) (Scotts, Marysville, OH) was added to each cone at a rate of 1 g $cone^{-1}$. Additional water-soluble fertilizer was added as needed. Initial growing conditions in the greenhouse were 22 ± 2°C with supplemental lighting (430-W Agrosun bulbs, Hydrofarm Inc., Petaluma, CA) for 14 h day^{-1}. After inoculation with the respective pathogen at the first leaf stage for wheat stem rust and leaf rust and the second leaf stage for spot and net blotch, plants were placed in inoculation chambers at 20°C with a relative humidity near 100% and 16 h in the dark. Afterward, chamber doors were opened, and plants were allowed to dry for 4 h. Then, plants were returned to the greenhouse at 23 ± 2°C and 16-h photoperiod. For powdery mildew, plants were inoculated at the first leaf stage and returned back to the greenhouse as previously described.

A 0.7 mL rust suspension (3.5 mg urediniospores and 0.65 mL lightweight mineral oil) of *P. graminis* f. sp. *tritici* (pathotypes Pgt-MCC and Pgt-QCC) or *P. hordei* (race 8) was applied using a rust inoculator pressurized by an air pump (20 kPa). Inocula of *P. teres* (isolate NB89-19) and *C. sativus* (isolate SB85F) were applied to plants using an atomizer pressurized (Model 15, DeVilbiss Inc., Somerset, PA) by an air pump set at 60 kPa. One milliliter of the conidial suspension (5–8 conidia mL^{-1}) was applied per plant. Inoculum of *B. graminis* f. sp. *hordei* was applied by shaking heavily infected barley plants over the test entries. Disease ratings were assigned 1 wk after inoculation with each pathogen.

Infection types of wheat stem rust (Miller and Lambert, 1955) and leaf rust (Levine and Cherewick, 1952) were scored using a 0 to 4 rating scale, where a rating of 0 to 2 was indicative of low compatibility and 3 to 4 of high compatibility. Infection response caused by net blotch was scored using a 1 to 9 rating scale, where a rating of 1 to 4 was indicative of low compatibility, 5 was an intermediate compatibility, and 6 to 9 was indicative of high compatibility (Tekaus, 1985). Infection response caused by spot blotch was evaluated using a 1 to 9 rating scale, where a rating of 1 to 3 was indicative of a low compatibility, 4 to 5 was indicative of an intermediate compatibility, and 6 to 9 was indicative of high host–parasite compatibility (Fetch and Steffenson, 1999). Infection response caused by powdery mildew was evaluated using a 0 to 4 rating scale, where a rating of 0 to 2 was indicative of low compatibility and 3 to 4 was indicative of high compatibility (Torp et al., 1978).

Malt Quality Evaluations

In the experiments performed at Fargo in 1998 and Osnabrock in 2000, grain samples were collected from each experimental unit for malting in the Barley Quality Laboratory in the Department of Plant Sciences, North Dakota State University. Samples were malted using the methods described in Karababa et al. (1993). Data collected for each malt sample were moisture ($g\ kg^{-1}$), diastatic power (DP) (^{o}ASBC), α-amylase activity (20°C DU), wort viscosity (cP), wort protein ($g\ kg^{-1}$), fine- and coarse-grind extract ($g\ kg^{-1}$), and malt β-glucan content ($g\ kg^{-1}$). Moisture content was determined by heating 10-g samples of ground malt in a semi-automatic Brabender moisture tester (Karababa et al., 1993) at 130°C for 30 min. Diastatic power and α-amylase activity of malt samples were determined as described by Technican Industrial Method No. 424-76A (Bran and Luebbee, Inc., Tarrytown, NY) (Banasik, 1971). Wort viscosity at 20°C was determined according to ASBC wort method 13 (ASBC, 1992). Wort protein was determined according to the UV spectroscopic method of Pyler (Pyler, 1981). Fine- and coarse-malt extract were determined using a modification of ASBC Malt Method 4 (ASBC, 1992). In the modification, 20 g of malt was used rather than the 50 g described in the official method. Malt β-glucan content was determined according to the enzymatic method of McCleary and Nurthen (1986).

Statistical Analyses

Combined analyses of variance across environments were done using the PROC GLM procedure of SAS (Cary, NC) for the agronomic, FHB severity, DON accumulation, and malt quality data. In the combined analyses, environments were considered a random effect and germplasm lines a fixed effect. Thus, the environment × germplasm line mean square was used as the denominator of the *F*-test for the germplasm line source of variation, and the experimental error was used as the denominator of the *F*-test for the environment × germplasm line source of variation. *F*-tests were considered significant at $P \leq 0.05$. Mean separation was done using an *F*-protected LSD at $P \leq 0.05$.

RESULTS AND DISCUSSION

The 35 germplasm lines with partial FHB resistance evaluated in this study represent all the germplasm lines available to the barley improvement projects at North Dakota State University in 1996. The environment × germplasm line interaction was nonsignificant for all agronomic, malt quality, and foliar disease traits but plump kernels. Upon further investigation, the significance of this interaction was due to differences in magnitude between means from the different environments and not due to a "true" interaction. Hence, all discussion for the traits evaluated is based on means averaged across environments.

Based on the analysis of FHB severity and DON data (data not presented), 22 of the 35 germplasm lines previously reported to have FHB resistance had disease severities that were unacceptable for breeding purposes. Germplasm lines with mean FHB severity greater than 12.5% were deemed susceptible. The two-rowed cultivars judged susceptible were Maja, Balder, Kombainesis, Primus II, Isaria, Francks Hohenloher, Horny Peseky, Gobernadora, Shyri, Aleli, Fuji Nijo, Daisen Gold, Zao Shu 3, Mimai 114, and Misato Golden. The experi-

Table 2. Mean Fusarium head blight (FHB) severity,† deoxynivalenol (DON) concentration,‡ and agronomic performance§ of selected two-rowed barley germplasm lines grown in North Dakota trials from 1997 to 2000.

Germplasm line	FHB severity	DON	Days to heading	Plant height	Lodging	Yield	Test weight
	%	$\mu g\ g^{-1}$	days after 31 May	cm	(1–9)	$Mg\ ha^{-1}$	$kg\ hL^{-1}$
Xiao Shan Er Leng Da Mai	4.8	3.8	33.1	100.0	6.8	2.9	60.6
Zhedar 1	5.9	2.9	33.3	96.9	6.6	2.9	62.0
Dai Shan Er Leng Da Mai	6.1	2.5	32.9	99.3	7.2	2.6	60.6
Messidor	6.2	2.3	33.5	98.6	6.7	3.0	59.6
CIho 4196	6.6	2.7	33.6	95.9	7.4	2.6	60.7
Svanhals	6.7	2.9	32.7	97.7	6.9	3.0	59.2
Xiao Shan Ci Mang Er Leng Da Mai	6.9	3.8	33.3	96.2	7.4	2.7	61.8
Zhedar 2	7.4	5.0	33.6	99.5	5.9	3.1	61.1
Kyoto Nakate	7.9	4.3	32.2	98.5	6.4	2.7	60.5
CIho 7595	9.6	4.9	33.2	90.8	5.5	3.1	66.1
Imperial	9.6	6.0	33.3	97.2	4.4	3.3	64.7
Logan	24.9	12.8	27.8	83.5	1.7	4.6	65.9
Conlon	27.1	8.0	24.3	85.6	2.6	4.5	66.4
LSD (0.05)	5.1	5.4	1.7	5.6	1.1	0.7	2.2

† Fusarium head blight data were collected on germplasm lines grown in FHB nurseries in 1997 and 1998 at Fargo, Langdon, and Osnabrock, ND.
‡ Deoxynivalenol data were collected on grain grown in FHB nurseries in 1997 at Fargo, Langdon, and Osnabrock, ND; and in 1998 at Langdon and Osnabrock, ND.
§ Agronomic performance of selected germplasm lines grown in yield trials in 1998 at Fargo, ND; in 1999 at Osnabrock, ND; and in 2000 at Fargo, Langdon, and Osnabrock, ND. Germplasm lines were not inoculated with *F. graminearum* and were protected from FHB and foliar diseases using multiple applications of benomyl.

mental lines F102-61, F103-53, F101-78, and F103-105 also were deemed susceptible to FHB. The partial resistant six-rowed germplasm lines judged susceptible were Glenn, Hazen, and ND15967. To address the objectives of this study, discussions are limited to comparisons of two-rowed barley germplasm lines with partial FHB-resistance to Conlon and Logan, and six-rowed barley germplasm lines with partial FHB-resistance to Morex, Stander, and Foster.

Two-rowed Barley Comparisons

The two-rowed barley germplasm lines Xiao Shan Er Leng Da Mai, Zhedar 1, Dai Shan Er Leng Da Mai, Messidor, CIho 4196, Svanhals, Xiao Shan Ci Mang Er Leng Da Mai, Zhedar 2, Kyoto Nakate, CIho 7595, and Imperial were partially resistant to FHB (Table 2). Some of these germplasm lines actually are reselections from resistant germplasm lines. For example, Kyoto Nakate and Messidor are selections from Svanhals (Table 1). Kyoto Nakate originates from Japan and Messidor from France. FHB severity of this group of germplasm lines ranged from 4.8 to 9.6%, and DON concentration ranged from 2.3 to 6.0 $\mu g\ g^{-1}$ (Table 2). The FHB severities and DON concentrations of the germplasm lines within this class were not significantly different, but they were significantly lower than the North Dakota cultivars Logan and Conlon. Logan and Conlon had FHB severities and DON concentrations of 24.9% and 12.8 $\mu g\ g^{-1}$ and 27.1% and 8.0 $\mu g\ g^{-1}$, respectively.

Days to heading of the partially resistant germplasm lines on average were 8.4 and 11.9 d later than Logan and Conlon, respectively (Table 2). The significantly later maturity of the partially resistant germplasm lines as compared to the checks would be undesirable to growers. Growers prefer the relatively early maturity of barley because it allows them to harvest it before their other crops are mature. CIho 7595 was similar in height to Logan and taller than Conlon. The remaining partially resistant germplasm lines were all taller than Logan and Conlon (Table 2). Short plants often resist lodging better than tall plants, and plants that lodge are more likely to have greater levels of FHB and other foliar diseases. The partially resistant germplasm lines lodged more than Conlon and Logan (Table 2). There was no difference in resistance to lodging between Conlon and Logan. The lower FHB severity in the lodged resistant germplasm lines shows the importance of having genetic resistance. Conlon and Logan yielded significantly greater than all partially FHB-resistant germplasm lines (Table 2). Test weight of these germplasm lines was generally less than that of Conlon and Logan. Only Imperial and PI161970 had test weight similar to those of the checks.

All FHB-resistant two-rowed germplasm lines were susceptible to leaf rust, and most were susceptible to wheat stem rust, net blotch, spot blotch, and powdery mildew (Table 3). Messidor was resistant to pathotype Pgt-MCC of wheat stem rust and CIho 7595 was resistant to net blotch, spot blotch, and powdery mildew.

None of the partially FHB-resistant two-rowed germplasm lines had acceptable malt quality for the traits measured (Table 4). In general, kernel plumpness, grain protein concentration, and malt extract were the traits most severely impacted in the resistant germplasm lines. These germplasm lines had adequate levels of wort protein, diastatic power, and α-amylase activity

Six-rowed Barley Comparisons

Six-rowed barley germplasm lines CIho 16128 and Chevron were partially resistant to FHB (Table 5). CIho 16128 is a Chevron-derived germplasm line developed in the United States, and Chevron originates from Switzerland (Table 1). FHB severity of the two partially resistant germplasm lines ranged from 9.1 to 12.5%, and no DON was detected. Foster, Morex, and Stander had FHB severities and DON concentrations of 34.6% and 32.2 $\mu g\ g^{-1}$, 39.9% and 32.2 $\mu g\ g^{-1}$, and 41.1% and 28.9 $\mu g\ g^{-1}$, respectively (Table 5). The FHB severities and DON concentrations of the two partially resistant germplasm lines were not significantly different, and they had less FHB than Foster, Morex, and Stander.

Table 3. Greenhouse seedling response of selected barley germplasm lines to different foliar pathogens. Germplasm lines are ordered from most resistant to most susceptible to Fusarium head blight.

Germplasm line	Wheat stem rust†		Leaf rust race 8†	Spot blotch‡	Net blotch‡	Powdery mildew†
	MCC§	QCC¶				
Xiao Shan Er Leng Da Mai	2,3	3,2,3	3,3$^-$	8,7	8,9	3
Zhedar1	2,3$^-$	3,$^-$2	3	7,6	8,9	3
Dai Shan Er Leng Da Mai	3$^-$,2,3	2,3$^-$	3,3$^+$	5,6	8,9	3,4
Messidor	2,1,3$^-$	2,1	3$^-$,3	7,8	7,6	3,4
CIho 4196	3$^-$,2	2	3$^-$	7,6	8,9	3,4
Svanhals	3$^-$,2	3$^-$,2	3$^-$,3	6,5	8,9	3,4
Xiao Shan Ci Mang Er Leng Da Mai	3	2,3$^-$	3$^-$,2	7,6	8,7	3
Zhedar 2	3,3$^-$	3$^-$2,3	3$^-$,2	7,8	7,8	3
Kyoto Nakate	3$^-$,2,1	3$^-$,2	3,3$^+$	6,7	8,7	3
CIho 7595	3	3,$^-$2	3$^-$,2	3,2	3,2	1,2
Imperial	3,3$^-$	3$^-$,2	3,3$^+$	5,4	8,9	3,4
Logan	0,1	2,3$^-$	3$^-$,2	3,4	2,3	1
Conlon	1,0,2$^-$	3$^-$,2	3$^-$	5,4	2,3	0

† Germplasm lines exhibiting infection types 0 to 2 were classified as resistant, and those exhibiting infection types 3 and 4 were classified as susceptible.
‡ Germplasm lines exhibiting infection types 1 to 3 were classified as resistant, 4 and 5 as intermediate, and 6 to 9 as susceptible.
§ Pathotype Pgt-MCC.
¶ Pathotype Pgt-QCC.

All partially FHB-resistant six-rowed barley germplasm lines headed later and were taller than the six-rowed checks (Table 5). On average, the partially resistant germplasm lines headed 6.1 d later and were 15.3 cm taller than the susceptible checks. Chevron and CIho 16128 were more susceptible to lodging and yielded less than the susceptible checks; however, test weight of the partially resistant germplasm lines and susceptible checks was similar.

All partially FHB-resistant six-rowed germplasm lines were susceptible to leaf rust, pathotype Pgt-QCC of wheat stem rust, spot blotch, net blotch, and powdery mildew (Table 6). Chevron and CIho 16128 were resistant to wheat stem rust pathotype Pgt-MCC. None of the partially FHB-resistant germplasm lines had acceptable malt quality for all traits. Chevron and CIho 16128 had inadequate levels of kernel plumpness, malt extract, and α-amylase activity; excessive grain protein; and adequate levels of wort protein and diastatic power (Table 7).

Table 4. Malt quality of selected two-rowed barley germplasm lines grown at Fargo, ND, in 1998 and Osnabrock, ND, in 2000.

Germplasm line†	Plump kernels	Grain protein	Malt extract	Wort protein	Diastatic power	α-Amylase activity
	%	g kg^{-1}			°ASBC‡	20° DU§
Xiao Shan Er Ling Da Mai	59.0	150	759	510	107	50.3
Zhedar 1	63.0	151	757	510	113	53.1
Dai Shan Er Leng Da Mai	62.1	152	763	500	109	48.2
Messidor	60.2	138	769	490	106	54.5
CIho 4196	55.4	149	766	490	113	49.1
Svanhals	57.4	150	761	510	109	51.8
Xiao Shan Ci Mang Er Leng Da Mai	56.9	147	763	500	111	50.1
Zhedar 2	59.6	150	757	510	114	49.4
CIho 7595	62.4	147	771	460	111	50.5
Kyoto Nakate	63.2	152	755	510	116	50.3
Imperial	74.5	139	772	450	122	48.0
Logan	79.1	126	803	480	121	53.0
Conlon	85.5	125	812	520	104	56.0
LSD (0.05)	13.3	13.4	16.2	64	16.2	8.14

† Germplasm lines are ranked from most resistant to most susceptible to Fusarium head blight.
‡ °ASBC = Degrees American Society of Brewing Chemist.
§ 20° DU = Dextrinizing units at 20° DU.

Table 5. Mean Fusarium head blight (FHB) severity,† deoxynivalenol (DON) concentration,‡ and agronomic performance§ of selected six-rowed barley germplasm lines grown in North Dakota from 1997 to 2000.

Germplasm line	FHB severity	DON	Days to heading	Plant height	Lodging	Yield	Test weight
	%	μg g^{-1}	days after 31 May	cm	(1–9)	Mg ha^{-1}	kg hL^{-1}
CIho 16128	9.1	0.0	32.9	108.5	6.1	2.8	58.5
Chevron	12.5	0.0	33.7	103.3	6.3	3.0	60.1
Foster	34.6	17.5	27.3	88.8	3.3	4.4	55.8
Morex	39.9	32.2	26.3	90.9	3.3	4.2	55.9
Stander	41.1	28.9	28.0	88.0	1.9	4.6	58.1
LSD (0.05)	5.9	23.7	1.4	7.2	1.4	0.9	2.7

† Fusarium head blight data were collected on germplasm lines grown in FHB nurseries in 1997 and 1998 at Fargo, Langdon, and Osnabrock, ND.
‡ Deoxynivalenol data were collected on grain grown in FHB nurseries in 1997 at Fargo, Langdon, and Osnabrock, ND; and in 1998 at Langdon and Osnabrock, ND.
§ Agronomic performance of selected germplasm lines grown in yield trials in 1998 at Fargo, ND; in 1999 at Osnabrock, ND; and in 2000 at Fargo, Langdon, and Osnabrock, ND. Germplasm lines were not inoculated with *F. graminearum* and were protected from FHB and foliar diseases using multiple applications of benomyl.

Choice of Parents to Use for Introducing Fusarium Head Blight Resistance

Until we know if the partially resistant germplasm lines have different genes for FHB resistance, it would be difficult to recommend one germplasm line over another as a source of FHB resistance because of the deficiencies they have in agronomic traits, malt quality, and foliar disease resistance. Learning more about the genetics of FHB resistance in each of the partially resistant germplasm lines would take many years; however, a more timely method of determining if the germplasm lines may have similar FHB-resistance genes would be to determine via molecular markers the genetic diversity between the lines. The genetic diversity between germplasm lines that may have similar FHB-resistance genes would likely be less than that of lines with different genes.

Urrea (2000) reported on the genetic relationships

Table 6. Greenhouse seedling response of selected barley germplasm lines to different foliar pathogens. Germplasm lines are ordered from most resistant to most susceptible to Fusarium head blight.

Germplasm line	Wheat stem rust†		Leaf rust race 8†	Spot blotch‡	Net blotch‡	Powdery mildew†
	MCC§	QCC¶				
CIho 16128	0,1	3	3$^-$,3	5,6	5,6	3§
Chevron	0,1	3	3$^-$,3	6,7	8,7	3
Foster	0,1$^-$	3$^-$,2	3$^-$,2	4,3	7,8	3
Morex	0,1$^-$	3$^-$,2	3$^-$,3	5,6	7,8	3
Stander	1,0	2,3$^-$	3$^-$	4,3	7,8	3

† Germplasm lines exhibiting infection types 0 to 2 were classified as resistant, and those exhibiting infection types 3 and 4 were classified as susceptible.
‡ Germplasm lines exhibiting infection types 1 to 3 were classified as resistant, 4 and 5 as intermediate, and 6 to 9 as susceptible.
§ Pathotype Pgt-MCC.
¶ Pathotype Pgt-QCC.

Table 7. Malt quality of selected six-rowed barley germplasm lines† grown at Fargo, ND, in 1998 and Osnabrock, ND, in 2000.

Germplasm line†	Plump kernels	Grain protein	Malt extract	Wort protein	Diastatic power	α-Amylase activity
	%		g kg^{-1}		°ASBC‡	20° DU§
CIho 16128	14.6	164	733	530	174	53.0
Chevron	15.5	167	725	520	171	50.9
Foster	76.4	122	796	560	151	63.1
Morex	64.8	132	793	560	143	68.1
Stander	79.5	130	799	590	135	63.7
LSD (0.05)	7.8	11.4	19.1	81	35.2	13.5

† Germplasm lines are ranked from most resistant to most susceptible to Fusarium head blight.
‡ °ASBC = Degrees American Society of Brewing Chemist.
§ 20° DU = Dextrinizing units at 20° DU.

among the germplasm lines evaluated in this report using cluster analysis of genetic distance based on RAPD marker data. He found that all of the partially resistant two-rowed germplasm lines identified in this report appeared in the same cluster, except Imperial and CIho 7595. These two germplasm lines appeared together in a different cluster and had the highest FHB severity and DON accumulation of the partially resistant two-rowed germplasm lines (Table 2). Urrea (2000) found that Zhedar 1, Zhedar 2, Dai Shan Er Leng, and Svanhals were very similar based on his genetic diversity evaluation. Finally, he found the six-rowed germplasm lines Chevron and CIho 16198 were genetically similar and appeared in a different cluster than the two-rowed germplasm lines. The genetic similarity between Chevron and CIho 16198 is not unexpected since the pedigree of CIho 16198 is 'Atsel'/Chevron. Research is continuing on the determination of the genetic diversity among the resistant germplasm lines described in this study and additional resistant accessions identified by Scholz et al. (1999) using SSR and RFLP markers.

CONCLUSIONS

In general, germplasm lines with partial FHB resistance were taller, headed and matured later, and yielded less than cultivars adapted to the northern Great Plains of the United States. The partially resistant germplasm lines also tended to have unacceptable grain protein concentration, kernel plumpness, malt extract, and are susceptible to most other fungal pathogens that attack barley in this region. Fusarium head blight severity of the most resistant two-rowed germplasm lines was generally lower than that of the partially resistant six-rowed germplasm lines; however, DON content of these same germplasm lines was similar.

Improvements in malt quality, agronomic traits, and foliar disease resistance of germplasm lines derived from crosses to the accessions with partial FHB resistance have been made; yet, further improvements are needed before FHB-resistant cultivars will be acceptable to producers and the malting and brewing industry. The germplasm lines discussed in this report that are progeny from crosses to germplasm lines with partial FHB resistance have gone through at least two cycles of breeding. Our experience in working with unadapted germplasm tells us that at least four cycles of breeding will be necessary to develop FHB-resistant cultivars that are acceptable to growers and the malting and brewing industries.

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