

Genotypic and Environmental Effects on Oat Milling Characteristics and Groat Hardness

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ABSTRACT

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The production of oat bran involves the dehulling of oats, inactivation of their enzymes, and the subsequent grinding and sieving of the clean groats to isolate the larger bran particles. The bran yield from the oat groats may be related to their hardness, as it is in wheat. Groat breakage, which occurs during the dehulling process, reduces milling yield and may also be related to groat hardness. This study sought to investigate genotypic and environmental effects on oat dry milling and oat dehulling characteristics, and attempted to define properties associated with oat groat hardness. Significant genotypic differences in bran yield were largely attributed to groat composition, where higher β -glucan and oil

concentrations in the groat were associated with higher bran yields. Bran composition was largely dependent on a combination of the bran yield and the groat composition. Although groat breakage was correlated with bran yield and with groat β -glucan concentration, environmental factors appeared to be more influential. Locations that had suffered severe crown rust infestations exhibited higher rates of groat breakage during dehulling. Bran yield was not as strongly affected at the locations infested with crown rust, indicating that bran yield and groat breakage are manifestations of different types of groat hardness and are only partially related.

Oat bran production involves cleaning and dehulling of whole oats, heat treatments to inactivate enzymes, followed by grinding of the groats, and sieving of the flour to isolate the larger sized bran particles (Paton and Lenz 1993, Ganssmann and Vorwerk 1995). Oat bran is enriched in protein and β -glucan and contains less starch than whole groat flour (Marlett 1993). Interest in oat bran production has increased since the acceptance of oat bran as a food that can lower the risk of heart disease due to physiological effects of β -glucan on the mammalian digestive system, which lowers serum cholesterol (FDA 1996 1997).

The oat dehulling process, which involves mechanical stress delivered to the oat to release the groat from the hulls, can also break groats. Commercial oat mills use impact oat dehullers (Deane and Commers 1986) that eject oats through a spinning rotor, causing them to collide with the walls of a drum. Research laboratories more frequently use compressed-air oat dehullers (Kittlitz and Vetterer 1972) that subject oats to mechanical stress with a stream of compressed air. After dehulling, both methods of mechanical oat dehulling separate hulls from groats by an aspiration process where suction removes lighter hulls from the heavier groats. A study recently completed in this laboratory (Doehlert et al 1999) indicated that insufficient mechanical stress during dehulling resulted in incomplete dehulling, whereas too much mechanical stress resulted in increased groat breakage and loss of the broken groats by aspiration. It also indicated that insufficient aspiration failed to remove hulls efficiently, but excess aspiration removed many whole groats with the hulls. Thus, optimal dehulling conditions represent compromises between unfavorable extremes.

As indicated earlier, groats can break during the dehulling process, and broken groats decrease the milling yield. Very little is known about factors affecting groat breakage during dehulling. An earlier study from this laboratory (Doehlert et al 1999) indicated

those oat cultivars with higher groat percentages tended to have more groat breakage during dehulling. We suggested that thicker hulls might provide some protection to the groat during dehulling. Oats with high groat percentages (thinner hulls) may be more subject to groat breakage during dehulling.

Groat breakage may also be related to the hardness of the groat. Hardness of wheat and maize grain has been described in detail (Pomeranz et al 1988, Wu 1992). Hardness of these grains is generally attributed to specific classes of proteins (Simmonds et al 1973, Pratt et al 1995). Properties associated with oat groat hardness have not yet appeared in the literature.

Groat hardness may also be related to the bran yield during oat dry milling. Grinding clean groats and sieving to isolate the larger sized particles produces oat bran. A recent study from this laboratory described a number of milling conditions that affect bran yield (Doehlert and Moore 1997). Under consistent milling and sieving conditions, differences in bran yield of wheat are attributed to grain hardness. The proportion of particles held back by a sieve of a specific size is a measure of grain hardness and is referred to as the particle size index (Yamazaki and Donelson 1983). It is equivalent to what is called bran yield in oat milling. Harder kernels yield larger particles and thus have a larger particle size index and a larger bran yield. Some differences in oat bran yield among genotypes have been documented (Wood et al 1991), although no discussion about possible relationships between groat hardness and bran yield was offered.

Genotypic and environmental factors are expected to affect oat milling characteristics. This article reports results of two experiments on milling characteristics of a variety of genotypes in a number of environments. In the first study, six oat cultivars were grown in replicated plots in three environments, and the composition of the dry-milling fractions, derived from the cleaned groats from these oats, was analyzed. The objective of this study was to determine the effect of genotype on the composition of oat dry-milling fractions, including a finished bran fraction. Finished bran was previously shown to be more highly enriched in β -glucan than normal bran (Doehlert and Moore 1997). The second experiment involved 12 genotypes grown in a total of six environments. In this experiment, we determined the effects of genotype and environment on groat composition and oat bran yield and composition. We also evaluated oat dehulling characteristics, and groat hardness. Our objectives were to evaluate possible relationships between groat composition and bran yield and composition, and to develop the concept of groat hardness as measured by groat breakage, bran yield, and other hardness measures in relation to groat composition and other oat quality characteristics.

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MATERIALS AND METHODS

Plant Material

Two separate experiments are reported here. The first consisted of oat (*Avena sativa* L.) grain from six genotypes (cv. Hytest, Hazel, Jerry, Marion, Paul, and Whitestone) grown in replicated plots at three locations (Carrington, Prosper, and Minot) in North Dakota in 1994. The second experiment involved 12 genotypes (AC Marie, Bay, Hazel, Hytest, Jerry, Marion, ND880786, ND880946, Paul, Riel, Robert, and Whitestone) grown in replicated plots at three locations (Carrington, Prosper, and Minot) in North Dakota for two years (1995 and 1996). Prosper is in eastern North Dakota, Carrington is in central North Dakota, and Minot is in northwestern North Dakota. The soil type at Carrington is Heindahl (coarse, loamy, mixed Udic Haploborolls) and Emrick loams (coarse, loamy, Pachie Haploborolls). Soils at Minot are Williams (fine, loamy, mixed Typic Argiborolls) loam. Soils at Prosper are Perella (fine, silty, mixed, frigid, Typic Haploquolls) and Beardon (fine, silty, mixed frigid, Aeric Calcicquolls) silty clay loams. Nitrogen fertilizer in the form of urea was applied to bring the available soil nitrogen to 225 kg/ha for both years and all locations. The previous crop in Fargo in 1995 was maize (*Zea mays* L.) and the previous crop in 1996 was green fallow sudangrass (*Sorghum bicolor* (L.) Moench). The previous crop for the Carrington location was pea (*Pisum sativum* L.) for both years. Minot plots had been fallow in both previous years. A seeding rate of 2.47×10^6 kernels/ha was used for all experiments. Herbicide treatments consisted of preemergence application of 3.93 kg/ha propchlor (2-chloro-N-isopropylacetanilide) and postemergence application at the three-leaf stage with a tank mix of 0.14 kg/ha thifensulfuron {Methyl 3 [[(4-methoxy-6-methyl-1,3,5-triazin-2yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate}, 0.07 kg/ha tribenuron {Methyl 2-[[[N-(methoxy-6-methyl-1,3,5-triazin-2yl) methylamino] carbonyl] amino] sulfonyl] benzoate}, and 0.14 kg/ha¹ clopyralid (3,6-dichloro-2-pyridinecarboxylic

acid, monoethanolamine salt). In 1994, plots in Carrington, Minot, and Prosper were planted May 4, April 20, and May 9, and harvested August 8, August 11, and August 4, respectively. In 1995, plots at Carrington, Minot, and Prosper were planted May 5, May 3, and May 24, and harvested August 14, August 14, and August 15, respectively. In 1996, plots in Carrington, Minot, and Prosper were planted May 3, May 2, and May 28 and harvested August 8, August 20, and August 20, respectively. Experimental units consisted of four rows spaced 0.3 m apart and 2.4 m long. The two center rows were harvested with a two-row binder and threshed with a plot thresher. Seed was cleaned using an air-screen cleaner to remove chaff. Test weight was determined by weighing a fixed volume of grain. Plots at each location were grown in a randomized complete block design with three replicates.

Sample Preparation and Dehulling

Grain samples were stored in paper bags and envelopes. Whole oat samples were steam-treated in a vegetable steamer for 20 min to inactivate enzymes. Grain was dehulled with a laboratory oat huller (Codema Inc., Eden Prairie, MN). Dehulled groats were cleaned by hand to ensure that all hulls and broken groats were removed. Any groat with >10% of its mass broken off was considered broken. Broken groats were collected and weighed. Groat percentage was calculated as the mass of whole clean groats plus the broken groats as a proportion of the mass of the whole oat sample.

Oil concentration and groat weight were determined on whole groats. Groat samples to be tested for starch, protein, β -glucan, and ash concentrations were milled with a centrifugal mill with a 0.5-mm collar screen (Retsch model ZM-1, Brinkmann Instruments, Westbury, NY). Flour was stored in small sealing plastic bags in a desiccator at room temperature.

Roller Milling

Groats were conditioned and tempered before roller-milling by drying overnight at 40°C, determining moisture of the dried grain,

TABLE I
Composition and Yield (% , db) of Dry Milling Fractions Derived from Six Oat Genotypes

	Hazel	Hytest	Jerry	Marion	Paul	Whitestone	LSD ^a
Yield ^b							
Flour	60.4	62.0	65.3	57.9	58.5	63.3	1.8
Bran	40.2	37.3	32.4	42.8	41.9	37.0	2.2
Finished bran	65.5	64.9	66.5	64.8	66.9	65.2	ns
Starch (1.2) ^c							
Groat	56.2	56.9	61.5	58.2	57.1	61.6	1.3
Flour	66.8	69.0	72.9	70.2	69.1	73.9	1.3
Bran	44.2	41.9	44.8	46.5	42.1	46.4	1.3
Finished bran	33.9	31.1	33.8	36.6	33.3	36.4	1.3
Protein (0.4) ^c							
Groat	19.6	20.6	17.4	16.8	18.1	16.1	1.0
Flour	16.2	16.5	14.0	13.3	14.5	12.4	1.0
Bran	24.7	27.1	24.1	21.3	23.7	21.8	1.0
Finished bran	27.5	29.7	27.0	24.6	26.6	25.1	1.0
β -Glucan (0.28) ^c							
Groat	5.49	5.69	4.39	6.01	5.22	4.94	0.38
Flour	2.99	2.97	2.23	3.35	2.93	2.53	0.38
Bran	8.55	9.69	8.98	9.46	8.33	9.01	0.38
Finished bran	10.9	12.2	11.0	11.5	9.6	11.2	0.38
Lipid (0.15) ^c							
Groat	6.67	5.09	4.86	6.20	6.92	6.00	0.35
Flour	5.65	4.61	4.30	5.19	6.40	5.36	0.35
Bran	6.77	5.00	5.06	5.57	6.97	6.22	0.35
Finished bran	7.13	5.43	5.42	5.94	7.54	6.86	0.35
Ash (0.15) ^c							
Groat	2.22	2.14	2.00	2.11	1.95	1.96	0.14
Flour	1.19	1.09	0.98	1.10	1.08	0.96	0.14
Bran	3.22	3.25	3.40	2.98	2.93	3.10	0.14
Finished bran	4.12	4.26	4.32	3.84	3.68	3.96	0.14

^a Least significant difference ($P < 0.05$).

^b Yield of flour and bran are relative to the starting dry weight of the groats. Yield of finished bran is relative to the bran starting material

^c Critical value for comparing fractions in parentheses.

then adding water to samples to a 12% final moisture level. Groats were milled 20 min after addition of water, according to tempering protocols described in Doehlert and Moore (1997), with a laboratory roller mill (Quadrumat Jr., Brabender, South Hackensack, NJ). Milled samples were initially fractionated into bran and flour using a 60-mesh U.S. (0.25-mm) screen as described by Doehlert and Moore (1997). Portions of some oat bran fractions were additionally processed with a laboratory impact bran finisher (MCU-302, Buhler Corp., Minneapolis MN) to further separate flour particles from bran (Doehlert and Moore 1997).

Chemical Analysis

Moistures of flour samples were determined by heating a 2-g flour sample for 2 hr in a convection oven at 130°C. Samples were allowed to cool in a desiccator and reweighed. Moisture was proportional to the weight loss during the heat treatment. All chemical analyses are expressed on a dry weight basis.

Oil analysis was performed on whole groats and milling fractions with nuclear magnetic resonance (NMR) (Oxford 4000, Abingdon, England). Samples were dried at 130°C for 2 hr and allowed to cool in a desiccator before analysis to prevent interference from water. Calibration of the instrument had been established by comparison of signals with groats and bran samples of known oil concentration established by Soxhlet extraction with petroleum ether.

Starch was analyzed according to Approved Method 76-11 (AACC 1995). Protein was analyzed by combustion analysis with a nitrogen analyzer (FP-428, Leco Corp., St. Joseph, MI) at N × 6.25. Ash of a 2-g sample was determined in an ashing oven by initially incubating samples in crucibles for 1 hr at 350°C, then increasing the oven temperature to 450 and 590°C after 1 hr intervals, then maintaining 590°C for 18 hr. After ashing, crucibles were removed from the ashing oven and allowed to cool in a desiccator before measuring ash weight. Total (1→3), (1→4)-β-D-glucan (β-glucan) was determined by the method of McCleary and Glennie-Holmes (1985).

Other Characteristics

The groat hardness index was derived by analyzing clean groat samples with a single kernel characterization system (SKCS) (Perten Instruments, Inc., Springfield, IL) designed for analyzing wheat kernel characteristics (Martin et al 1993). The instrument was calibrated to measure wheat samples, which are much harder than oats. As a result, all oat hardness values were negative. Samples with higher hardness index values (less negative) represented harder groats.

Groat weight was derived from the number of kernels in the 10-g sample. Percent thins was determined from the proportion of the whole oats that passed through a 1.98- × 19.1-mm slotted sieve after 20 shakes on a strand sizer shaker (Seedburo Equipment Co., Chicago, IL).

TABLE II
Annual Location Mean Values for Test Weights, Groat Weights, and Dehulling Characteristics for 12 Genotypes of Oats Grown in North Dakota

Location	Year	Test Wt ^a (kg/m ³)	Groat Wt (mg)	Groat %
Carrington	1995	408	15.9	49.0
Carrington	1996	468	21.6	58.3
Minot	1995	517	22.7	66.5
Minot	1996	538	23.3	65.7
Prosper	1995	411	16.9	52.4
Prosper	1996	467	18.9	53.3
LSD ^b		40	0.8	2.7

^a Multiply value by 0.077 to obtain test weight as bu/acre. Multiply value by 0.1 to obtain test weight as kg/hl.

^b Least significant difference ($P < 0.05$).

Experimental Design and Statistical Analyses

Experimental plots were arranged in a randomized complete block design with three replicates. For the first experiment, composition of milling fractions were analyzed by a three-way analysis of variance (ANOVA) performed with the Statistix computer package (Analytical Software, Tallahassee, FL), where genotype and milling fraction were considered fixed and environments were considered random. Bran and flour yields were analyzed separately with a two-way ANOVA, where genotype was considered fixed and location was considered random. In the second experiment, test weight, groat weight, groat percentage, hardness, and bran yield data were analyzed with two-way ANOVA, where genotype was considered fixed and location was considered random. Groat and bran protein, oil, and β-glucan concentrations were combined for analysis in a three-way ANOVA, where genotype and milling fraction (groat or bran) were considered fixed, and environment was considered random. Homogeneity of variances was determined by the ratio of the largest to the smallest variances in a group. Variances were found to be homogeneous for all variables except broken groats. In order to apply ANOVA to the broken groats, data were transformed to square roots as discussed by Steel et al (1997). The variances of the transformed data were judged to be homogeneous, and a series of one way ANOVA analyses were performed, analyzing genotypic and environmental effects separately. Least significant differences (LSD, $\alpha = 0.05$) for all analyses were calculated with the Statistix computer package. Differences among means with the transformed broken groat data were compared with differences indicated by LSD on the untransformed broken groat data, and all differences indicated with the LSD on the untransformed data were also indicated with LSD from the transformed data. Because the LSD for the untransformed data are more useful for interpreting the results, and all differences indicated by them were validated from the transformed data, the LSD values for the untransformed data are presented. Pearson correlation matrices were calculated across all genotypes, except Paul, for each environment with the Statistix computer package and were pooled by the procedure described by Steel et al (1997). The cultivar Paul was excluded from these calculations because of biases introduced due to its hullless character. Chi-square tests (Steel et al 1997) indicated homogeneity of all r -values presented. Stepwise regressions were also performed with the Statistix computer package and also excluded the cultivar Paul. P values of <0.05 were required for entry into and exit out of the model.

RESULTS

In an initial experiment, cleaned groats of six oat cultivars grown at three locations in North Dakota were dry milled, and the bran was further processed with a bran finisher. ANOVA (not shown) indicated significant ($P < 0.05$) genotypic differences for all tested parameters, although the location main effect was not significant ($P > 0.05$) for starch, lipid, and β-glucan concentrations. Genotype × location interactions were significant ($P < 0.01$) for protein, lipid, and ash concentrations, and were attributed to differences in magnitude of genotypic means among locations. Genotype × location interactions (not shown) were not significant ($P > 0.05$) for starch and β-glucan concentrations. Bran yield range was 32–43% of the groat mass (Table I). As expected, starch concentration was increased in the flour relative to the groat and decreased in the bran. Protein, β-glucan, and ash concentrations were all increased in the bran and decreased in the flour in comparison with groats. Lipid was enriched in the bran relative to the flour in all cultivars. The extent of the fractionation of each component into bran and flour was significantly ($P < 0.05$) affected by genotype for all components. Additional processing of the bran with a bran finisher further decreased the starch concentration from that in the initial bran and increased the protein, β-glucan, lipid and ash concentrations for all genotypes tested.

A second experiment compared dehulling and dry-milling characteristics among 12 oat genotypes grown at three locations over two years. ANOVA (not shown) indicated significant genotype × environment interactions for all of the characteristics analyzed, except test weight. These interactions are largely attributed to differential crown rust (*Puccinia coronata corda* var. *avenae* W. P. Fraser & Ledingham) resistance among the cultivars. During this study, several environments, most notably Carrington 1995 and Prosper 1995, were characterized by severe crown rust infections. These infections appeared to strongly affect many quality characteristics of the oat grain, especially in those cultivars that were more susceptible to the prevalent races of crown rust at these locations. Cultivars that were more resistant to crown rust, such as Bay and Paul, were less affected.

Evidence suggesting a strong effect of the crown rust infection on oat quality characteristics can be derived from the environmental means (Table II). The Carrington 1995 and the Prosper 1995 locations, which were severely infested by crown rust, exhibited lower test weights, lower groat weights, and lower groat percentages than other locations. Environmental means for hardness, bran yield, and the composition of groats and bran are indicated in Table III. Although bran yield was the low at the Carrington 1995 location, the Prosper 1995 environment had a relatively high mean bran yield. Hardness (as determined by SKCS) values were not lower at Carrington 1995 or Prosper 1995, and were lowest at the Minot location, which was nearly rust-free. Environment appeared to have had very little effect on groat oil. Bran composition also showed effects of environment that appeared unrelated to crown rust infestations.

Groat breakage was highly variable among genotypes and environments (Table IV). Breakage was highest for most genotypes at the Carrington 1995 environment, which was heavily infested with crown rust. The genotypes Bay and Paul exhibited

lesser levels of groat breakage in this environment relative to the other genotypes and may have been more resistant to the crown rust (data not shown). The genotypic means appeared to be heavily influenced in the locations affected by crown rust. At relatively unaffected locations such as Minot 1995, Minot 1996, and Carrington 1996, Paul had higher rates of groat breakage than most other genotypes. At these locations, Marion and ND880786 usually had the lowest rates of groat breakage. The Minot location, which was relatively free of crown rust infection during these years, generated oats with mean test weights, groat percentage, and groat weights significantly higher than the other locations in both years (Table II). A significant amount of groat breakage was observed in samples from Minot in 1995 (Table IV), although these could not be attributed to crown rust infection.

Genotypic effects on oat dehulling and dry-milling characteristics are presented in Tables V and VI. Test weight and groat percentages were highest with Paul, a naked oat, because its grain threshes free of a hull and packs more densely. According to the hardness index (Table V), the breeding line ND880786 had the hardest groats and Paul had the softest. This is consistent with breakage rates observed at locations unaffected by crown rust (Table IV). However, ND880786 was particularly susceptible to rust, and at locations that were heavily infested with rust, ND880786 exhibited high rates of breakage. The breeding line ND880786 also had the highest bran yields (Table VI). Jerry had the lowest bran yield. The naked cultivar Paul had close to average bran yield. Bran protein was lowest in AC Marie, Marion, ND880786, and ND880946, all of which had relatively high bran yield. Cultivars with the highest bran protein levels included Bay, Hazel, Hytest, and Riel. These also had the highest groat protein concentrations. All genotypes exhibited enrichment in protein, β-glucan, and oil in the bran.

TABLE III
Annual Location Mean Values for Groat Hardness, Bran Yield, and Groat and Bran Composition (% , db) for 12 Oat Genotypes Grown in North Dakota

Location	Year	Hardness		Protein ^b		β-Glucan ^b		Oil ^b	
		Index ^a	Bran Yield (%)	Groat	Bran	Groat	Bran	Groat	Bran
Carrington	1995	-40.2	34.8	16.2	26.0	5.21	8.86	6.36	6.90
Carrington	1996	-32.6	34.7	16.6	22.9	4.72	8.86	6.34	7.23
Minot	1995	-42.2	40.6	19.0	21.5	4.93	8.65	6.50	6.60
Minot	1996	-36.1	35.5	18.4	25.5	4.47	8.60	6.36	7.26
Prosper	1995	-34.0	39.6	16.1	21.9	5.28	9.56	6.34	7.34
Prosper	1996	-34.4	36.5	15.8	21.8	4.63	8.65	6.59	7.54
LSD ^c		5.2	1.8	0.6		0.19		0.19	

^a Groat hardness index given in units derived from single kernel characterization system (SKCS).

^b Critical values for comparing groat and bran protein, β-glucan, and oil are 0.6, 0.17, and 0.12, respectively.

^c Least significant difference ($P < 0.05$).

TABLE IV
Broken Groats (% of total groats, db) Recovered After Dehulling for 12 Oat Genotypes Grown in Six Environments

Genotype	Carrington		Minot		Prosper		LSD ^a
	1995	1996	1995	1996	1995	1996	
AC Marie	28.8	0.125	2.89	0.764	3.93	0.096	4.27
Bay	3.5	0.219	2.83	0.782	0.71	0.083	0.86
Hazel	9.0	0.108	2.60	0.756	0.73	0.032	2.34
Hytest	26.8	0.223	2.54	1.203	5.29	0.145	2.52
Jerry	34.0	0.112	3.20	2.323	2.12	0.013	1.56
Marion	31.1	0.069	0.88	0.068	3.18	0.210	4.32
ND880786	27.6	0.012	0.87	0.074	4.02	0.099	3.84
ND880946	25.1	0.111	1.48	0.809	2.75	0.129	3.16
Paul	1.7	0.770	3.19	1.013	1.90	0.214	1.21
Riel	15.3	0.018	1.94	0.709	1.64	0.179	2.00
Robert	37.4	0.143	2.21	0.888	5.87	0.041	7.07
Whitestone	11.0	0.142	1.90	0.677	0.63	0.170	0.76
LSD	7.2	0.343	1.34	0.572	2.11	ns ^b	

^a Least significant difference ($P < 0.05$).

^b Not significant.

Correlation analyses (Table VII) indicated that the three measures of groat hardness employed here, groat breakage, bran yield, and hardness index, were correlated, but only at a moderate level. Broken groats were more highly correlated with the hardness index than with bran yield. Bran yield was highly correlated with certain components of groat composition, especially β -glucan and oil con-

centrations. Both broken groats and hardness were also significantly correlated with groat β -glucan. Test weight was significantly correlated with groat percentage, groat starch, groat protein and with bran yield.

Correlation analysis of bran protein with groat characteristics indicated significant correlations with test weight, groat weight, groat starch, groat protein, groat oil, groat β -glucan, and bran yield (Table VIII). Bran oil concentration was significantly correlated with test weight, groat oil, groat protein, and bran yield. Bran β -glucan concentration was neither correlated with groat β -glucan concentration nor with bran yield but was significantly correlated with groat protein and groat oil.

To describe the best combination of factors describing oat-milling characteristics, stepwise regressions were performed (Table IX). Bran yield was best described as:

$$\text{Bran yield} = -12.6 + 0.509 (\text{groat } \beta\text{-glucan concentration}) + 0.190 (\text{groat oil concentration}) - 0.161 (\text{broken groats}) + 0.037 (\text{groat starch concentration}) - 0.413 (\text{groat ash concentration})$$

Seventy-eight percent of the variation in bran yield was described by this equation (Table IX). Broken groats is taken as a measure of groat hardness. The best equation for broken groats described 62% of the variation and included the hardness index, groat weight, bran yield, and groat β -glucan concentration. Hardness index was described by an equation including broken groats, groat weight, groat starch, groat β -glucan, and bran yield, although only 53% of the variation was described. Regressions for bran composition indicated that one could predict a large proportion of the observed variation based largely on groat composition and bran yield.

TABLE V
Genotypic Mean Values for 12 Oat Genotypes Grown at Six Locations for Test Weight, Groat Weight, Hardness, and Groat Percentage

Genotype	Test Wt ^a (kg/m ³)	Groat Wt (mg/groat)	Groat %	Hardness Index ^b
AC Marie	422	20.0	55.9	-38.2
Bay	445	19.5	56.6	-33.1
Hazel	487	22.1	59.8	-35.7
Hyttest	527	22.6	63.2	-37.3
Jerry	495	20.1	58.8	-37.1
Marion	453	21.1	49.7	-36.1
ND880786	428	15.6	48.5	-29.3
ND880946	445	18.0	58.3	-35.4
Paul	591	21.3	84.8	-45.2
Riel	491	20.4	56.3	-36.2
Robert	419	21.6	49.5	-40.4
Whitestone	414	15.9	48.9	-35.1
LSD ^c	39	1.8	5.3	3.1

^a Multiply value by 0.077 to obtain test weight as bu/acre. Multiple value by 0.1 to obtain test weight as kg/hL.

^b Groat hardness index given in units derived from single kernel characterization system (SKCS).

^c Least significant difference ($P < 0.05$).

TABLE VI
Genotypic Mean Values of Bran Yield, Groat, and Bran Composition (% db) for 12 Oat Genotypes Grown in Six Different Environments in North Dakota

Genotype	Bran Yield (%)	Protein ^a		β -Glucan ^a		Oil ^a	
		Groat	Bran	Groat	Bran	Groat	Bran
AC Marie	39.2	14.8	18.9	4.69	8.07	7.90	8.22
Bay	34.6	19.6	26.7	4.98	9.84	4.71	5.61
Hazel	37.6	19.1	24.9	5.21	8.80	7.05	7.21
Hyttest	35.2	19.0	26.1	4.80	8.93	5.65	6.16
Jerry	32.1	17.2	25.0	4.23	8.98	5.12	6.06
Marion	41.2	16.1	21.1	5.53	8.81	6.82	7.25
ND880786	43.4	16.0	20.1	5.63	8.92	7.04	7.31
ND880946	39.7	15.7	20.8	5.12	9.19	6.75	6.98
Paul	36.8	18.2	25.2	4.75	8.48	7.28	7.95
Riel	33.1	17.4	25.5	4.53	8.82	6.06	6.74
Robert	33.9	15.4	22.9	4.30	8.62	6.19	7.07
Whitestone	36.9	15.8	22.1	4.70	8.90	6.43	7.34
LSD ^b	1.7	0.8		0.29		0.35	

^a Critical values for comparing groat and bran protein, β -glucan, and oil are 0.6, 0.17, and 0.12, respectively.

^b Least significant difference ($P < 0.05$).

TABLE VII
Phenotypic Correlations Among 11 Oat Genotypes^a Pooled from Six Environments

	Test Wt	Groat								
		Weight	Percent	Broken	Starch	Protein	Oil	β -Glucan	Ash	Bran Yield
Groat										
Weight	0.625*** ^b									
Percent	0.579**	0.564**								
Broken	0.146	0.013	0.026							
Starch	-0.388**	-0.241	-0.153	-0.079						
Protein	0.521**	0.348*	0.519**	-0.029	-0.373**					
Oil	-0.392**	-0.141	-0.236	-0.165	-0.037	-0.600**				
β -Glucan	-0.204	-0.222	-0.164	-0.339*	-0.319*	0.067	0.370*			
Ash	0.157	0.150	0.057	0.100	-0.618**	0.543**	0.013	0.428**		
Bran yield	-0.457**	-0.368*	-0.251	-0.311*	-0.068	-0.354*	0.683**	0.798**	0.226	
Hardness	-0.015	-0.479**	-0.154	-0.419**	-0.045	-0.126	-0.064	0.477**	-0.096	0.350*

^a Cultivar Paul was excluded from analyses because of biases introduced by its hullless character. All pooled correlation coefficients were homogenous according to a chi-square test.

^b *, ** = significant at $P < 0.05$, $P < 0.01$, respectively.

DISCUSSION

The results describe major environmental and genotypic effects, and genotype × environment interactions affecting oat dehulling and dry-milling characteristics. Interactions are largely attributed to differential resistance of genotypes to crown rust. The major environmental influence appeared to be the factors favorable to the incidence of crown rust infection, but additional environmental factors are certain to have had an influence. A major problem with the data presented here is that it appears to have been heavily affected by crown rust infection, yet no quantitative measure of rust infection can be offered. Therefore, only general inferences are made, based on the most severely affected location.

Of particular importance in this study was the analysis of groat breakage and groat hardness. Three separate measures of groat hardness were tested: groat breakage, bran yield, and hardness index. These measures were only moderately correlated (Table VII). They were not correlated at locations heavily infested with crown rust (data not shown). The very high breakage rates observed at the Carrington 1995 location (Table IV) were most likely due to the effects of the crown rust infestation and were not reflected by extreme changes in the bran yield or in the hardness index (Table III). Although all three characteristics were significantly correlated with groat β-glucan concentration, only bran yield was correlated with groat oil concentration (Table VII). Whereas these three measures appear to estimate related characteristics, they also appeared to be influenced by independent components. The hardness index was more highly correlated with groat breakage, although it was only moderately effective at predicting groat breakage. Therefore, hardness should be considered to be composed of several components. Some of these components would appear to affect each of the three measures to differing extents.

Groat composition appeared to have the strongest effects on bran yield. Regression equations constructed from groat compositional components accounted for >70% of the variation observed in bran yield (Table IX). Groat β-glucan and oil concentrations had particularly strong effects on bran yield.

Regression equations for the hardness index included bran yield and broken groats (Table IX). This observation enforces the concept of groat breakage and bran yield as measures of groat hardness.

Past studies have suggested that crown rust infections of oats can significantly affect groat protein concentration (Murphy 1936, Simons et al 1979, Singleton et al 1979). Studies on wheat and maize hardness have indicated that specific proteins are associated with hardness of these grains (Pratt et al 1995, Simmonds et al 1973). Disease may affect expression of specific proteins that affect hardness in oat groats. Locations with severe rust infection were observed to have lower protein than most (Table III). Detailed

TABLE VIII
Phenotypic Correlation of Bran Composition with Test Weight, Groat Weight, Bran Yield, and Groat Composition from 11 Oat Genotypes^a Pooled from Six Environments

	Bran		
	Protein	β-Glucan	Oil
Test weight	0.659** ^b	0.116	-0.463**
Groat			
Weight	0.404**	-0.231	-0.200
Protein	0.856**	0.423**	-0.698**
Oil	-0.801**	-0.556**	0.947**
β-Glucan	-0.333*	0.195	0.204
Bran yield	-0.724**	-0.141	0.571**

^a Cultivar Paul was excluded from analyses because of biases introduced by its hullless character. All pooled correlation coefficients were homogenous according to a chi-square test.

^b *, ** = significant at $P < 0.05$, $P < 0.01$, respectively.

protein analyses would be necessary to identify any specific protein associated with hardness in oat groats.

Most dehulling characteristics have already been treated in detail in a previous work from this laboratory (Doehlert et al 1999). In that study, breakage was positively correlated with groat percentage and it was postulated that thicker hulls protected the groat during the mechanically stressful dehulling process. In the current study, significant correlations between groat breakage and groat percentage were found at environments not heavily affected by crown rust, including Minot 1995 and Minot 1996 (data not shown). At locations with severe crown rust infection, negative correlations between groat percentage and groat breakage were observed (data not shown), suggesting that genotypes less severely affected by the disease exhibited higher groat percentage and less groat breakage. Therefore, when constructing a model to describe groat breakage, the level of crown rust infection appears to be an important component to include.

Bran composition appears to be easily and reliably predicted from the composition of the groats and the bran yield. Bran β-glucan concentration was the most troublesome to predict, being less dependent on bran yield and more dependent on groat oil. This is perhaps because groat β-glucan concentration was positively correlated with bran yield, yet increases in bran yield tended to decrease the bran β-glucan concentration (Doehlert and Moore 1997).

A regression equation developed for test weight suggested that a combination of groat percentage, groat starch, and groat weight described 68% of the variation in test weight observed in this study. The groat percentage and groat weight components of the equation suggest the importance of groat filling process in affecting test weight. Stress conditions that resulted in smaller groats and poorer groat percentage had strong negative effects on test weight.

TABLE IX
Stepwise Regression Results for Oat Quality and Milling Characteristics from Six Environments in 1995 and 1996

Dependent Variable	Independent Variable	Regression Coefficient	Student's <i>t</i> -Test	<i>R</i> ²
Bran yield	Constant	-12.6	-2.52	0.78
	Groat β-glucan	0.509	8.08	
	Groat oil	0.190	5.84	
	Broken groats	-0.161	-4.67	
	Groat starch	0.037	4.35	
	Groat ash	-0.413	-2.71	
Broken groats	Constant	-6.28	-0.57	0.62
	Hardness index	-0.989	-6.65	
	Groat weight	-1.10	-5.38	
	Bran yield	-1.04	-4.61	
Hardness index	Groat β-glucan	0.73	3.88	0.53
	Constant	1.02	0.10	
	Broken groats	-0.351	-5.45	
	Groat weight	-0.708	-4.99	
	Groat starch	-0.0457	-3.12	
	Groat β-glucan	0.355	2.91	
	Bran yield	-0.323	-2.06	
Groat %	Constant	17.95	2.08	0.74
	Groat protein	0.182	5.24	
	Groat weight	1.08	4.90	
	Groat ash	-0.768	-2.60	
Test Weight	Constant	373	3.63	0.68
	Groat %	3.48	3.96	
	Groat starch	-0.363	-2.38	
	Groat weight	5.23	2.28	
Bran protein	Constant	27.5	10.57	0.75
	Bran yield	-0.478	-10.04	
	Groat protein	0.0782	7.81	
Bran β-glucan	Constant	9.11	14.69	0.42
	Groat oil	-0.0449	-6.11	
	Groat β-glucan	0.0539	4.62	
Bran oil	Constant	2.98	7.62	0.76
	Groat oil	0.0828	13.60	
	Bran yield	-0.0655	-5.27	

The groat composition factor suggests that groat density also may have an influence on test weight. Groat starch concentration was negatively correlated with test weight, whereas groat protein was positively correlated with test weight (Table VII). Protein may make groats denser and starch may make them less dense, thus affecting test weight.

It is interesting that the naked cultivar Paul milled into bran much as did any hulled cultivar, indicating the suitability of naked oats in dry-milling applications.

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