

# Effects of Genotype and Environment on the Starch Properties and End-Product Quality of Oats<sup>1</sup>

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## ABSTRACT

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Five Canadian oat genotypes were grown at six environments in Manitoba to assess the effects of genotype, environment, and genotype-by-environment interaction on oat starch properties and end-product quality. Genotypic variation was significant for total starch, amylose content, starch swelling volume (SSV), Rapid Visco Analyser (RVA) pasting viscosities, differential scanning calorimetry (DSC) thermal properties, and starch gel texture as well as the quality of flakes and cooked oatmeal made by laboratory-scale methodologies. Environment was the dominant factor contributing to the total variation of starch content, RVA pasting viscosities, SSV, and DSC thermal properties. Most measurements of starch

gel and oatmeal texture were not affected by growing environment. Cross-over analysis revealed that changes in the ranking of genotypes across environments occurred for starch RVA hot paste, breakdown and shear thinning viscosities, work of gel compression, flake hydration capacity, and the proportion of large flakes, indicating that breeding for these traits would require multiple testing sites. Trends were observed between oatmeal texture and several flake and starch gel properties, warranting further study. Results of this study indicated that there is a potential to breed Canadian oat cultivars with improved functional end-product quality for use in the milling and food manufacturing industries.

Canada is a major producer of oats (*Avena sativa* L.) destined for the milling and food processing industries (Agriculture and Agri-Food Canada 2000). Plant breeding programs have responded to the needs of these markets by selecting for desired nutritional composition, specifically high  $\beta$ -glucan and low oil contents, but further improvements could be achieved by breeding for superior processing and end-product quality. Criteria for food oat quality are typically set by millers and processors according to in-house standards as more research is required to understand the relationship between oat characteristics and end-product quality. A first step to defining specific breeding targets is to assess the variation in traits that affect functionality of oats during processing and end-product quality.

Starch swelling, pasting, and gelatinization are important properties in the processing of any oat end-product undergoing heat treatment in the presence of water, such as oat flakes (Deane and Commers 1986), oatmeal (Yui et al 1987; Zhou et al 1999a), and extruded ready-to-eat breakfast cereals (DesRochers 1998). Therefore, variability in the functionality of oat starch will affect end-product quality. For example, the Australian oat cultivar Yarran, which was identified as having poor milling and food processing quality, required more time and higher temperatures to reach peak pasting viscosity compared with commercially acceptable cultivars (Zhou et al 1999a,b). Other accounts of genotypic variation in oat starch (Wang and White 1994a; Hoover et al 2003) and wholemeal (Zhou et al 1998b, 1999b) pasting characteristics have been reported. A study conducted in Australia also found that growing location and genotype-by-location interactions had significant effects on wholemeal pasting characteristics (Zhou et al 1999b).

Genotypic variation in the temperature at which starch gelatinizes, as measured by DSC, has been reported for oats of Swedish

(Gudmundsson and Eliasson 1989), German (Tester and Karkalas 1996), U.S. (Wang and White 1994a), and Eastern Canadian (Hoover et al 2003) origin. Genotypic differences have also been found for the temperature and change in enthalpy associated with the disruption of amylose-lipid complexes (Gudmundsson and Eliasson 1989; Wang and White 1994a).

The proportion of amylose to amylopectin in oat starch has an important effect on starch functionality. Wang and White (1994a) observed a positive correlation between oat amylose content and gelatinization temperature, possibly due to an inhibition of swelling. Amylose content of oat starch also had a negative correlation with the clarity of oat starch paste (Wang and White 1994b). Amylose values for oat starch from various genotypes have been documented (MacArthur and D'Appolonia 1979; Paton 1979; Gudmundsson and Eliasson 1989; Wang and White 1994b,c; Tester and Karkalas 1996; Lásztity 1998; Hoover et al 2003) but environmental influences have not been addressed in studies to date.

Other evidence of variability in oat starch functionality comes from research conducted on oat starch gels. Paton (1977) observed variation in the strength, opaqueness, elasticity, and tackiness of gels made from two different Canadian oat genotypes as well as from the same genotype grown at three different locations.

Total starch content of oats may also be important to end-product quality, as suggested by a Finnish study in which a sensory evaluation panel described oatmeal made from flakes with higher levels of starch as being more slippery and less uniform (Lapveteläinen and Rannikko 1999). The total starch content of oat genotypes from diverse origins varies significantly (Paton 1977; Asp et al 1992; Zhou et al 1998a, 1999a). Growing year had a significant influence on total starch of 50 Swedish oat genotypes grown over three years (Asp et al 1992). Paton (1977) observed variation in starch content among growing locations and fertilization (0 vs. 500 kg N/ha) using a limited number of Canadian genotypes.

There are few published reports that have measured genotypic and environmental variation of oat end-products directly. Lapveteläinen et al (2001) studied the characteristics of oat flakes made from eight Finnish and Swedish genotypes grown over three years. They found that the amount of damaged material in a flake sample varied significantly among growing years but not genotypes, whereas the opposite trend was true for flake thickness. Water hydration capacity of flakes varied significantly with genotype, year, and genotype-by-year interactions. Trained sensory panelists found that the amount of oatmeal adhering to a spoon, the uniformity of the oatmeal, and its slipperiness were significantly influenced by genotype-by-year interactions. A Canadian study showed

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differences in end-product quality among flake types (large, quick, instant) but did not investigate genotypic variation (Ames and Rhymer 2003).

For plant breeders to assess the potential for improving specific oat starch and flake characteristics in newly developed Canadian cultivars, current information about how these traits vary among adapted genotypes grown at Canadian locations is needed. Traits that are highly controlled by genetics can be manipulated by the plant breeder relatively easily, whereas those that are strongly influenced by environmental factors such as weather and soil conditions cannot. Quantitative interactions between two main effects can also occur, such that the magnitude of the genotype response changes at different environments. Furthermore, cross-over interactions can greatly reduce the effectiveness of recurrent selection of the desired trait by changing the rank order of genotypes across environments (Gail and Simon 1985; Baker 1988; Kang 1990). Therefore, the objective of this study was to determine the relative effects of genotype, environment, and genotype-by-environment interactions, including cross-over effects, on the quality of oats grown in Manitoba (a leading oat-producing region in Canada). In this study, specific focus was given to oat starch properties, flake characteristics, and cooked oatmeal texture.

## MATERIALS AND METHODS

### Sample Set

Four registered oat genotypes (AC Assiniboia, CDC Boyer, AC Medallion, and Triple Crown) and one semi-dwarf breeding line (OT288) were grown at six environments in Manitoba, Canada, in a randomized complete block design with four replicates. The genotypes chosen were all commonly grown in the region or were important to breeding programs and oat processing companies but varied in origin, height, and disease resistance. Environments included three locations in 1998 (Glenlea, Morden, Silverton) and 1999 (Carman, Winnipeg, Silverton). They were diverse in soil type (Glenlea = Osborne Clay; Morden = Altona Light Sandy Loam; Silverton = Newdale Clay Loam; Carman = Almasippi Very Fine Sandy Loam; Winnipeg = Riverdale Silty Clay), seeding date, and soil nutrient content. Plots (40 m<sup>2</sup>) were seeded at a rate of 300 seeds/m<sup>2</sup>, adjusted according to each genotype's germination rate. Fertilizer (11-52-0) was applied to all plots at seeding at a rate of 23.5 kg/ha. Harvested oat grains were cleaned and the outer hulls were removed with a laboratory dehulling machine (model LH5095; Codema Incorporated, Vancouver, BC) to collect the groat portion (caryopsis, kernel) for analysis.

### Starch Extraction and Purification

Starch was extracted and purified according to the following procedure: 10 g of cracked groats was soaked in 100 mL of 0.02*N* hydrogen chloride at 4°C for 4 hr to soften the grain, neutralized to pH 7.0 with 0.2*N* sodium hydroxide, and centrifuged at 13,200 × *g* RCF for 15 min. The grist was ground in a mortar and pestle with 30 mL of Tris-HCl buffer and incubated at 35°C overnight with xylanase, lichenase, and protease K. Liberated starch was collected by passing through a 75-μm stainless steel sieve and further purified by layering over 78% cesium chloride and centrifuging at 28,400 × *g* RCF for 20 min. Following three water washes, the purified starch was recovered by filtering with a 45-μm nylon membrane and rinsed with 5 mL of acetone.

### Starch Analysis

Before all analyses, the purified starch was gently ground into powder with a mortar and pestle and dried in a forced-air oven at 38°C for 16 hr to achieve sample weights on a dry basis. Dried starch was stored in a desiccator until the time of analysis.

Starch swelling volume (SSV) was determined at 92.5°C using a ratio of 0.35 g of dried starch to 12.5 mL of water according to the method of Crosbie (1991).

Pasting properties of starch slurries (2.5 g of dried starch in 25 g of water) were assessed with a Rapid Visco Analyser (RVA) (Series 4; Newport Scientific Pty. Ltd., Warriewood, Australia) using Standard Method No. 162 (ICC 1995). The RVA viscosity parameters measured were defined by Newport Scientific Pty. Ltd. (1998) and Shim and Mulvaney (1999).

Upon completion of the RVA test, the hot sample surface was smoothed and the canister was stored at 4°C for 24 hr. The texture of the resulting starch gel was characterized by texture profile analysis (TPA) using a TA-XT2 texture analyser (Texture Technologies, Scarsdale, NY) equipped with a 25-kg load cell and a 3-mm diameter cylinder probe (TA 55, Texture Technologies, Scarsdale, NY). Detection of 5 g of force at the surface of the gel triggered the probe to descend 10 mm into the gel at a rate of 1 mm/sec. The probe then ascended back to the trigger point, paused for 5 sec before descending for a second time into the gel. This procedure was performed at five positions on each gel sample. The TPA parameters measured were previously defined by Epstein et al (2002).

Thermal properties of oat starch were measured with differential scanning calorimetry (DSC) (model 2010; TA Instruments, New Castle, DE). Hermetically sealed aluminum pans containing dried starch and deionized water (40% solids) were heated to 140°C at a rate of 10°C/min. The temperature and total energy change ( $\Delta H$ ) associated with the gelatinization of amylopectin and the melting of amylose-lipid complexes were measured against an empty reference pan.

Approved Method 76-13 (AACC 2000) was used to determine the total starch content of groats ground on a centrifugal mill (Retch model ZM100; Brinkman Instruments, Mississauga, ON). Starch amylose content was measured by potentiometric titration according to the method of Schoch (1964) and expressed as a percentage of iodine affinity. Lipids were removed from the starch with 1-propanol and water (3:1) (Morrison and Coventry 1985) before titration.

### Preparation of Oat Flakes

A laboratory-scale oat conditioning process was developed to mimic heat-moisture treatments used before flaking in the processing industry to inactivate enzymes that cause loss of quality during storage and to alter the functional properties and flavor of oats. Groats (70 g at 7.3–12.4% initial moisture content) were brought up to 17% moisture with the addition of boiling water in 500-mL glass jars, which were immediately closed and placed in a 100°C air oven (Isotemp Oven 300 series model 338F; Fisher Scientific, Nepean, ON) for 10 min. The lids were removed and the samples were returned to the oven for 45 min, resulting in a final groat-moisture content of ≈12%. Shaking was performed routinely throughout the procedure to ensure even dispersion of moisture and heat. The cooled, conditioned groats were tempered to 16% moisture overnight at room temperature to soften the kernels before flaking on a flaking machine (Marga Mulino, Marcato, Campodarsego, Italy), which had been modified by the addition of a 42 rpm motor set to a speed of 24 rpm. All samples were processed using the same gap distance between flaking rolls, which resulted in flake thicknesses similar to those of traditional, large commercial flakes. The resulting flaked oats were dried in a 35°C air oven for 1 hr to a final moisture content of ≈10% to prevent mold growth during storage at room temperature until the time of testing (≈1 month). Moisture content was determined according to Approved Method 44-15A (AACC 2000).

### Evaluation of Oat End-Product Quality

A sieve shaker (Ro-Tap model B, W.S. Tyler, Gastonia, NC), equipped with U.S. standard sieves (#5, 8, and 10), was used to separate flake samples into size categories to assess flake granulation. Each size category obtained after 2 min of shaking was weighed and calculated as a percentage of the starting sample

weight ( $\approx 70$  g). Water hydration capacity of 25 g of oat flakes soaked in 100 mL of water was measured according to Approved Method 56-40 (AACC 2000).

Cooked oatmeal was prepared by cooking 30 g of oat flakes with 120 mL of room temperature water in a microwave oven (Carousel model #311C(W)C; Sharpe Electronics of Canada, Mississauga, ON) on high power for 210 sec, stirring once at the midpoint in cooking time. The oatmeal was transferred to a metal canister (37 mm diameter  $\times$  68 mm high) and evaluated for textural characteristics using a TA-XT2i texture analyzer (Texture Technologies, Scarsdale, NY) equipped with a 5-kg load cell. After a trigger force of 0.005N was detected at the surface, a 1.9-cm ball probe (TA-18A, Texture Technologies, Scarsdale, NY) descended at a rate of 1 mm/sec into the sample canister for a distance of 40 mm and then ascended to its starting position. The parameters measured included peak force, adhesive force, and stringiness (a measure of the time that the sample was in contact with the ascending probe).

### Statistical Analysis

Uniformity of error variances among environments was confirmed using the F-Max test (Milliken and Johnson 1984) and data was pooled for analysis with one exception: the Winnipeg site was not pooled with the other data for DSC parameters associated with the amylose-lipid portion of the endothermic curve. All statistical analyses were performed with SAS software (v. 8, SAS Institute, Cary, NC) using PROC MIXED procedures. Analysis of variance (ANOVA) considered genotype, environment, and their interaction to be fixed, whereas the replicate effect was random.

Results of the ANOVA are presented as *F* values instead of mean squares due to the fact that the mixed model does not generate the ANOVA terms in a standard format. *F* values give a measure of confidence as to whether the effect was significant or not. A Tukey's Test was conducted to identify which genotype and environment means differed significantly. Cross-over analysis was performed to test for significant changes in the rank order of genotypes across environments (Baker 1988). Variance components were calculated considering all factors random, but the estimates apply only to the genotypes and environments used in this study.

## RESULTS AND DISCUSSION

### Starch Composition

The main effects of genotype and environment significantly affected wholemeal total starch and oat starch amylose content, expressed as percentage of iodine affinity (IA) (Table I). The range in genotype and environment means for IA values was narrow, but significant differences were found (Tables II and III). Genotypic variation found by other researchers also showed a narrow range (MacArthur and D'Appolonia 1979; Paton 1979; Gudmundsson and Eliasson 1989; Tester and Karkalas 1996; Lásztity 1998; Hoover et al 2003). Environmental effects have not been reported in the literature.

Estimated variance components for IA were similar for genotype and environment, whereas environment was the dominant factor contributing to the total variation for total starch (Table IV).

TABLE I  
Summary of ANOVA and Cross-Over Analysis for Oat Starch and End-Product Characteristics

Characteristic <sup>a</sup>	ANOVA <i>F</i> -Value <sup>b</sup>			Significant Cross-Over Effect ( <i>P</i> < 0.05)
	Genotype	Environment	G $\times$ E <sup>c</sup>	
TS	8.41***	10.12***	1.75	
IA	45.77***	12.53***	1.08	
SSV	5.28***	6.46***	2.87***	No
Starch DSC <sup>d</sup>				
AP <i>T</i> <sub>p</sub>	65.6***	27.16***	1.87	
AP $\Delta H$	10.24***	9.64***	1.20	
AM <i>T</i> <sub>p</sub>	7.01***	78.35***	1.17	
AM $\Delta H$	17.39***	65.72***	2.07	
Starch RVA				
Peak	56.05***	59.64***	1.53	
Final	17.19***	28.18***	1.91	
Trough	10.46***	55.62***	2.31**	Yes
Breakdown	8.26***	7.87***	2.55**	Yes
Setback	24.77***	14.95***	1.79	
Final – peak	13.72***	13.73***	1.82	
Shear thinning	5.12***	19***	2.94***	Yes
Gel texture				
Work of compression	76.77***	2.05	2.86***	Yes
Adhesiveness	3.89**	2.79	1.54	
Springiness	6.51***	0.61	0.98	
Gumminess	48.51***	2.44	0.93	
Resilience	7.92***	4.96**	1.21	
Flake granulation				
>4.00 mm	50.92***	10.18***	2.46**	Yes
<4.00, >2.36 mm	69.34***	13.42***	2.56**	No
<2.36, >2.00 mm	41.65***	8.01***	1.07	
<2.00 mm	61.77***	10.7***	1.73	
Flake hydration capacity	22.55***	6.54***	2.57**	Yes
Oatmeal texture				
Peak force	33.22***	2.23	0.84	
Adhesive force	28.63***	3.44	1.92	
Stringiness	12.5***	4.53**	1.81	

<sup>a</sup> TS, total starch; IA, iodine affinity; SSV, starch swelling volume; DSC, differential scanning calorimetry; AP, endotherm associated with disruption of amylopectin structure; AM, endotherm associated with the disruption of amylose-lipid complexes; *T*<sub>p</sub>, peak temperature;  $\Delta H$ , enthalpy of transition; RVA, Rapid Visco Analysis.

<sup>b</sup> Significant effect at *P* < 0.001 and *P* < 0.01 indicated by \*\*\* and \*\*, respectively.

<sup>c</sup> Genotype-by-environment interaction.

<sup>d</sup> Analysis of DSC AM parameters did not include the Winnipeg 1999 environment.

The lowest levels of total starch occurred at the 1998 Morden, 1998 Silvertown, and 1999 Silvertown environments (Table II), all of which had the highest residual soil nitrogen levels. This trend is opposite to that seen for protein content (data not shown) and supports previous reports of inverse relationships between protein and total starch contents (Paton 1977; MacArthur and D'Appolonia 1979; Lásztity 1998).

### Swelling, Pasting, and Gelatinization

Genotype and environment significantly affected all starch RVA and DSC parameters as well as SSV (Table I). Environment was the main contributor to total variation (Table IV). Variation in starch pasting characteristics between environments did not seem to be related to soil nutrients (Table III), as was observed by Paton (1977), but rather by growing year, suggesting a prevailing climatic factor. The same yearly trends were observed for DSC and RVA and SSV; the means for the 1998 locations were either higher or lower than all means for the 1999 locations (Table II).

For most parameters, genotype-by-environment interactions were not significant, indicating that consistent genotypic trends would allow for selection of the trait at any one of the locations. For example, CDC Boyer exhibited the lowest RVA peak viscosity at all environments, followed by AC Medallion. Triple

Crown required significantly lower temperatures for starch gelatinization at all environments, despite the fact that the range in genotype means (58.4–59.7°C) was narrow compared with four Swedish (57.0–61.2°C), six German (56.2–59.5°C), three U.S. (56.1–60.0°C), and six eastern Canadian (56.0–74.0°C) genotypes studied by Gudmundsson and Eliasson (1989), Tester and Karkalas (1996), Wang and White (1994a), and Hoover et al (2003), respectively. In contrast, genotype-by-environment interactions were significant for SSV and starch RVA trough, breakdown, and shear-thinning viscosities. The interaction effect contributed more than 10% of total variation in SSV, but no significant change in rank order of genotypes across environments occurred. Cross-over interactions were significant, however, for the three RVA parameters (Table I), indicating that multiple growing sites would be required to successfully breed for specific levels of these pasting properties. Zhou et al (1999b) found significant genotype-by-location effects for all wholemeal RVA parameters tested, but concluded that the main effects of genotype and location were consistently more important. In this study, variance components alone did not fully assess the impact of the genotype-by-environment interaction. For example, the component of variation due to interactions was relatively low for RVA trough (4.39%), reiterating the need to analyze for cross-over effects.

TABLE II  
Genotype and Environment Means for Oat Starch Differential Scanning Calorimetry (DSC) Characteristics<sup>a</sup>

	TS (%)	IA (%)	SSV (cm <sup>3</sup> )	AP		AM	
				T <sub>p</sub> (°C)	ΔH (J/g)	T <sub>p</sub> (°C)	ΔH (J/g)
Genotype <sup>b</sup>							
AC Assiniboia	64.37c	5.26b	5.67ab	59.73d	9.19b	93.40ab	103.49b
CDC Boyer	64.10bc	5.37c	5.54a	59.11b	9.15b	93.79b	103.27ab
AC Medallion	63.61a–c	5.14a	5.82ab	59.40c	9.08b	92.86a	103.09ab
OT288	63.40ab	5.25b	5.70ab	59.41c	9.17b	93.54ab	103.40b
Triple Crown	62.95a	5.28b	5.92b	58.36a	8.74a	93.19ab	102.83a
Environment <sup>c</sup>							
Glenlea 1998	64.74b	5.29ab	5.17a	60.32c	8.75a	104.71b	1.84a
Morden 1998	62.49ab	5.24a	5.33a	59.82bc	8.74a	104.15b	1.89a
Silvertown 1998	61.07a	5.21a	5.46ab	59.51bc	8.80a	103.98b	2.05a
Carman 1999	64.95b	5.22a	6.03ab	58.63ab	9.48b	101.76a	2.39b
Winnipeg 1999	65.18b	5.18a	6.44b	59.22b	9.47b	101.69	2.56
Silvertown 1999	63.69ab	5.41b	5.94ab	57.72a	9.15ab	101.48a	2.73c

<sup>a</sup> TS, total starch; IA, iodine affinity; SSV, starch swelling volume; AP, endotherm associated with disruption of amylopectin structure; AM, endotherm associated with the disruption of amylose-lipid complexes; T<sub>p</sub>, peak temperature; ΔH, enthalpy of transition.

<sup>b</sup> Means of four plot replicates and six environments, with the exception of DSC AM parameters, which excluded the Winnipeg environment. Genotype means followed by different letters are significantly different (*P* < 0.01).

<sup>c</sup> Means of four plot replicates and five genotypes. Note that the Winnipeg 1999 environment was not included in analysis of DSC AM parameters. Environment means followed by different letters are significantly different (*P* < 0.01).

TABLE III  
Rapid Visco Analysis (RVA) and Texture Profile Analysis of Starch Gel Texture

	RVA Viscosity (RVU) <sup>a</sup>				Gel Texture <sup>b</sup>			
	Peak	Final	F – P	Setback	AD (g/mm)	SP	GM	RE
Genotype <sup>c</sup>								
AC Assiniboia	179c	234ab	56a	101a	–29.1b	0.936a	11.94a	0.103a
CDC Boyer	160a	216a	56a	89a	–23.5a	0.954ab	16.6b	0.116a
AC Medallion	171b	249bc	79b	119b	–24.6ab	0.938a	11.90a	0.115a
OT288	180c	243bc	63a	101a	–23.8a	0.956b	13.30a	0.117a
Triple Crown	177c	260c	83b	119b	–23.3a	0.940a	15.96b	0.139b
Environment <sup>d</sup>								
Glenlea 1998	150a	187a	36a	79a	–31.75a	0.952a	14.88a	0.094a
Morden 1998	157ab	199a	42ab	85ab	–29.52a	0.947a	14.24a	0.098ab
Silvertown 1998	165b	226ab	61a–c	106a–c	–25.82a	0.922a	13.79a	0.117ab
Carman 1999	188c	263bc	75b–d	112bc	–20.25a	0.951a	13.35a	0.124ab
Winnipeg 1999	187c	278c	91cd	118c	–21.92a	0.941a	13.50a	0.131ab
Silvertown 1999	192c	289c	97d	135c	–20.12a	0.939a	13.92a	0.146b

<sup>a</sup> RVU, rapid visco units (1 RVU ≈ 12 cp).

<sup>b</sup> AD, adhesiveness; SP, springiness; GM, gumminess; RE, resilience.

<sup>c</sup> Means of four plot replicates and six environments. Genotype means followed by different letters are significantly different (*P* < 0.01).

<sup>d</sup> Means of four plot replicates and five genotypes. Environment means followed by different letters are significantly different (*P* < 0.01).

## Starch Gel Texture

Significant genotypic variation was observed in the texture of oat starch gels, as measured instrumentally by TPA, including adhesiveness, springiness, resilience, and gumminess (Table I). Starch gels made from AC Assiniboia were significantly more adhesive, followed by AC Medallion. CDC Boyer and Triple Crown starch gels were significantly gummier and Triple Crown was the most resilient. These results further extend previous observations that two oat genotypes produced starch gels with different properties (Paton 1977). Contrary to Paton's findings however, the environments used in this study did not significantly affect gel texture, with the exception of gel resilience. Oat starch from the 1999 Silverton environment produced gels that were significantly more resilient than those produced in this study from 1998 Glenlea (Table III). Environment means for gel adhesiveness showed a wider range than genotype means, but the effect was not significant due to high residual error. Genotype was a large contributor to the total variation for gel gumminess (Table IV).

The work of first compression of the gel was affected by a genotype-by-environment interaction, resulting in a significant cross-over effect (Table I). CDC Boyer had a significantly higher work of compression value than Triple Crown at the 1998 Glenlea and 1999 Winnipeg environments, but at 1998 Silverton, Triple Crown's value was significantly higher (Fig. 1). Triple Crown demonstrated an above average SSV at the Silverton 1998 site as well, which could be related to the observed stronger gel. All other changes in rank order of genotypes observed in Figure 1

were not significant. Overall, CDC Boyer and Triple Crown consistently produced starch gels that required the most work to compress, followed by OT288 with intermediate requirements. Gels from AC Medallion and AC Assiniboia required the least work to compress. Maintenance of these overall genotypic trends was reflected in the high genotype component of variation for gel work of compression (Table IV).

## Oat Flake Quality

Flake granulation was predominately influenced by genetics, as indicated by significant genotype effects (Table I) and a large genotype component of variation for all flake granulation size categories (Table IV). Triple Crown and OT288 had significantly fewer large flakes (>4.0 mm) than the other genotypes. Triple Crown also had the least amount of the smallest flakes (<2.36 mm) followed by CDC Boyer (Fig. 2). Desired granulation is dependant on end-use, but in general, flake pieces that pass through a 2.0-mm sieve are an indication of poor flake integrity. Lapveteläinen et al (2001) found that flake damage varied with growing year but did not vary among eight Swedish and Finnish oat genotypes. In this study, environment also had a significant impact on flake granulation but contributed less to total variation than genotype. Differences between genotypes were consistent across environments except for a significant cross-over interaction between AC Assiniboia and CDC Boyer for the largest flake size category. This cross-over effect indicates that several breeding test sites are required to ensure effective selection for large flake size.

TABLE IV  
Estimated Variance Components for Oat Starch and End Product Characteristics<sup>a</sup>

Characteristic <sup>b</sup>	Contribution to Total Variation (%)				
	Genotype	Environment	G × E <sup>c</sup>	Rep (E) <sup>d</sup>	Residual
TS	5.36	53.56	3.64	18.99	18.44
IA	37.02	36.06	0.51	8.02	18.39
SSV	2.40	41.77	10.22	25.50	20.12
Starch DSC					
AP $T_p$	20.06	63.26	1.57	8.17	6.94
AP $\Delta H$	11.59	43.73	0.94	12.50	31.23
AM $T_p$	2.24	86.83	0.35	2.97	7.60
AM $\Delta H$	14.65	61.20	5.14	0.00	19.01
Starch RVA					
Peak	15.26	74.09	0.88	3.68	6.09
Final	9.28	66.91	3.41	6.77	13.63
Trough	4.55	75.90	4.39	2.72	12.44
Breakdown	12.39	24.87	16.76	5.68	40.29
Setback	19.05	48.28	4.08	10.04	18.56
Final – peak	12.92	48.39	5.26	10.10	23.34
Shear thinning	3.85	46.05	15.98	3.35	30.77
Gel texture					
Work of compression	69.05	0.00	10.13	1.55	19.26
Adhesiveness	5.16	20.23	5.13	38.55	30.93
Springiness	15.25	0.00	0.44	24.78	59.52
Gumminess	67.45	2.59	0.12	0.58	29.26
Resilience	15.35	26.02	2.34	18.30	37.99
Flake granulation					
>4.00 mm	47.25	18.34	8.42	4.28	21.71
<4.00, >2.36 mm	52.94	19.28	7.26	3.05	17.47
<2.36, >2.00 mm	53.54	14.47	1.05	2.02	28.92
<2.00 mm	55.57	17.62	4.07	2.85	19.90
Flake hydration capacity	29.52	17.99	13.32	7.49	31.68
Oatmeal texture					
Peak force	59.86	3.14	0.00	0.00	37.01
Adhesive force	37.67	11.56	7.56	13.54	29.67
Stringiness	26.35	9.37	11.29	1.90	51.10

<sup>a</sup> Estimated variation applies only to genotypes and environments used in this study. Analysis of DSC AM parameters did not include the Winnipeg 1999 environment.

<sup>b</sup> TS, total starch; IA, iodine affinity; SSV, starch swelling volume; DSC, differential scanning calorimetry; AP, endotherm associated with disruption of amylopectin structure; AM, endotherm associated with the disruption of amylose-lipid complexes;  $T_p$ , peak temperature;  $\Delta H$ , enthalpy of transition; RVA, Rapid Visco Analysis.

<sup>c</sup> Genotype-by-environment interaction.

<sup>d</sup> Replicate within environment.

These genotype specific responses to some environmental conditions could be linked to grain filling during plant growth, as the size of the groat is likely to affect the ultimate size of the flake. Other researchers have reported that genotype-by-environment interactions affect the size of oat groats, but that genotype has the greatest control over morphology (Pietrzak and Fulcher 1995).

Oat flake hydration capacity was significantly affected by genotype, environment, and genotype-by-environment interactions (Table I). The hydration capacity of flakes made from CDC Boyer was particularly variable over environments and contributed to a significant cross-over effect involving Triple Crown, which was the most stable (Fig. 3). It appeared that flake granulation played a role in this interaction. CDC Boyer, grown at Glenlea, had a below-average hydration value for that genotype as well as a below-average proportion of small flakes between 2.00 and 2.36 mm. Conversely, at Morden, it had both the highest hydration capacity and the highest percentage of small flakes observed for that genotype. It is logical to assume that smaller flakes would take up water more rapidly than larger flakes. The interaction contributed almost as much to total variation as the main environment effect (Table IV), indicating that selection for breeding lines with specific flake hydration properties would require multiple test sites. These results are in agreement with Lapveteläinen et al (2001), who also found the hydration capacity of flakes made from Swedish and Finnish oats varied significantly with genotype, environment (in this case, year), and genotype-by-environment interactions.

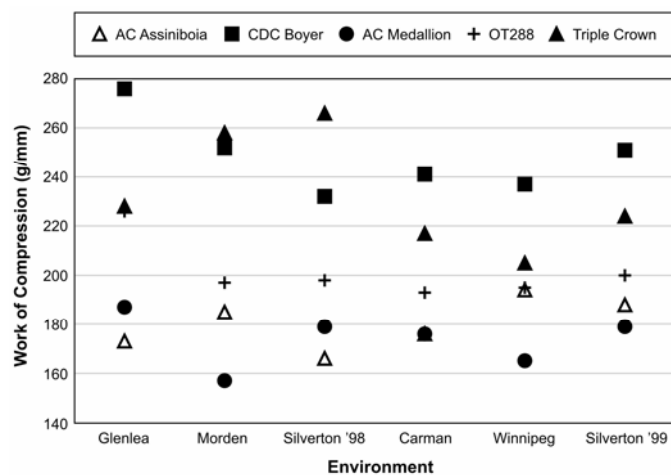


Fig. 1. Effect of genotype-by-environment interaction on oat starch gel texture (work of first compression). Points represent values averaged over four replicates.

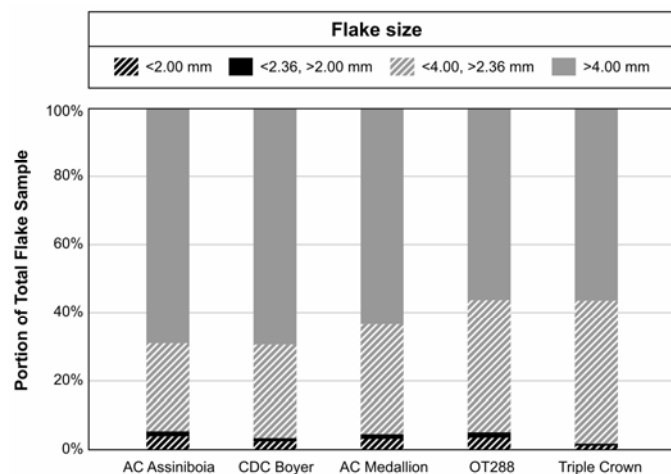


Fig. 2. Genotypic variation in oat flake granulation size. Bars represent values averaged over all environments and replicates.

### Cooked Oatmeal Texture

Instrumental evaluation of cooked oatmeal texture revealed significant genotypic variation (Table I). Figure 4 shows that Triple Crown and CDC Boyer required more force for the probe to descend into the oatmeal. These oatmeals appeared to be more fluid with two distinct phases: whole flakes and paste. These observations likely corresponded to the relative ease of the probe to travel through the weak paste followed by a rapid increase in force as the probe came in contact with flakes that had settled near the bottom of the canister. Alternatively, oatmeal that had relatively low positive force values and a gradual slope approaching the peak (AC Assiniboia, OT 288, and AC Medallion) appeared thicker, with flakes more uniformly dispersed throughout the samples. Genotypes also showed high (AC Assiniboia) and low (Triple Crown) degrees of oatmeal adhesiveness, as indicated by the negative portion of the texture curve.

Peak force and adhesiveness were not significantly affected by environment but stringiness was. Cooked oatmeal made from oats grown at 1999 Glenlea was significantly stringier (38.19 sec) than 1999 Silvertown (36.32 sec), but genotypic differences were consistent across all locations. Lapveteläinen et al (2001) found significant genotype-by-year interactions for oatmeal slipperiness, uniformity, and adherence as measured by a trained sensory panel.

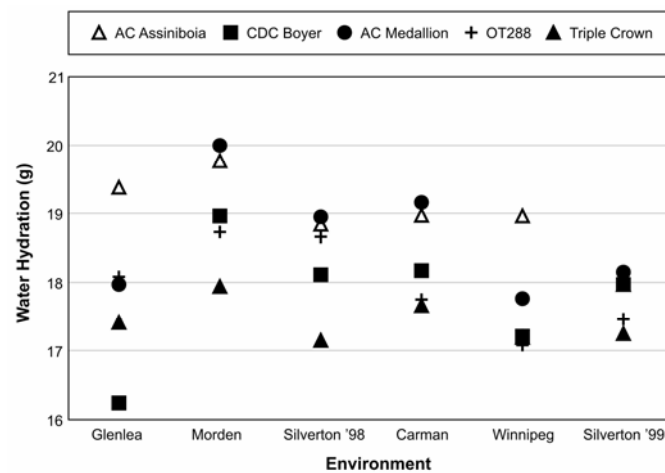


Fig. 3. Effect of genotype-by-environment interaction on oat flake hydration capacity. Points represent values averaged over four replicates.

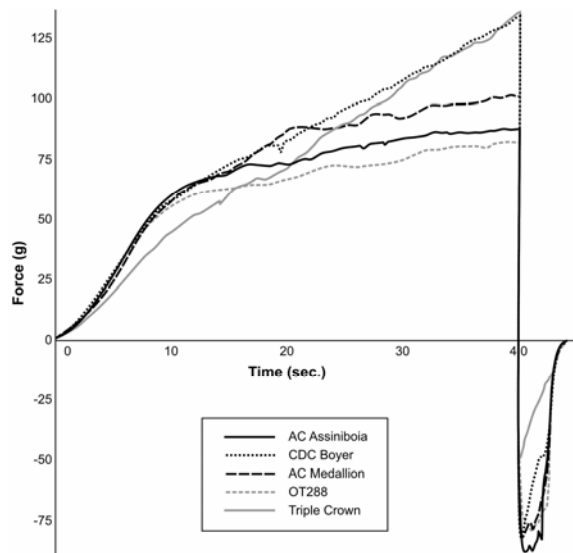


Fig. 4. Genotypic variation in oatmeal texture as measured by TAX-T2 texture analyzer. Curves represent an average of four replicates grown at Glenlea 1998.

The results from this study, however, indicate a strong potential for selecting breeding lines with specific oatmeal texture.

## CONCLUSIONS

This study found significant genotypic variation for several oat starch and end-product characteristics including total starch, amylose, SSV, starch RVA, DSC and gel properties, flake granulation and hydration, and cooked oatmeal texture. Growing environment also had an important influence on total starch content as well as starch swelling, pasting, and gelatinization characteristics, but further studies are required to investigate what specific environmental conditions were responsible for these differences. For the most part, interactions between genotype and environment contributed little to total variation, indicating a strong potential to breed for specific starch and end-product traits. However, selection for some aspects of starch pasting, gel texture, flake granulation, and hydration would require multiple testing sites, as genotypes did not rank consistently across environments for these characteristics.

Laboratory methodology developed for this study to test oat end-products provides a basis for future research and could lead to the incorporation of oat end-product quality screening into Canadian breeding programs. Working with oat millers, food processors, and consumers will be important to ensure that screening criteria are reflective of end-product quality characteristics desired by the industry. For example, relating instrumental texture data to sensory evaluation of oatmeal would validate its usefulness as a potential screening tool. As the food oat market continues to develop and oat research progresses in areas of human nutrition and food processing, there is a great opportunity for oat breeding programs to improve oat end-product quality.

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