Effects of Nitrogen Fertilization, Genotype and Environment on the Quality of Oats (*Avena sativa*) Grown in Manitoba

by

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A Thesis
Submitted to the Faculty of Graduate Studies
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ABSTRACT

Manitoba is a major producer of high quality oats (*Avena sativa*) destined for milling and food processing in domestic and export markets, particularly the United States. Strengthening the demand for Canadian oats requires continued improvement of oat cultivars to meet the changing needs of the agricultural and food industries. In order for plant breeders to achieve this, more information is needed regarding what factors affect variation in the milling, nutritional, functional and end-product quality of oats grown in western Canada. The objective of this study was to determine the relative effects of genotype, environment, nitrogen fertilization and their interactions on the quality of oats destined for human food. Replicated field tests were grown at each of six environments using a split plot design. Five genotypes were the main plots and four nitrogen fertilization treatments (0 to 120 kg/ha) were applied to the sub-plots. Hull content was significantly affected by a qualitative genotype-by-environment interaction, indicating the need for multiple testing sites. Growing conditions also had a strong influence on groat breakage, protein, and oil (36, 73, and 49 % of total variation respectively) but differences between genotypes remained consistent across environments. Genotype was the main factor affecting β-glucan content (78 % of total variation). Nitrogen fertilization had a greater impact on oat composition than on milling characteristics and in many cases the effect of nitrogen was dependant on the location. At sites where residual nitrogen was low (less than 36 kg/ha), fertilization resulted in increased levels of protein and β-glucan (by as much as 4.4% and 1 % respectively), while oil decreased slightly (less than 1 %). The effect of nitrogen on wholemeal pasting

properties was also dependant on location. Investigation of oat starch characteristics and wholemeal pasting properties revealed many significant differences between genotypes, suggesting potential for the genetic improvement of oat functionality in food systems. Several of these properties also varied with environment, but for most, the ranking of genotypes across environments was stable. A laboratory scale oat conditioning and flaking process was developed, which allowed for the measurement of genotypic and environmental influences on flake granulation, water hydration capacity and cooked oatmeal texture. Overall, the results of this study indicate that the processing quality of Canadian produced oats can be optimized with plant breeding and crop management efforts.

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CHAPTER 1

INTRODUCTION

Oat (*Avena sativa*) production in Canada has a substantial economic influence on the agricultural industry. The estimated area seeded to oats was 1.82 million hectares in the year 2000 (Agriculture and Agri-Food Canada, 2001), making it the fourth most seeded crop in Canada. Currently, the majority of Canadian oat production occurs in western Canada. The end of the Western Grain Transportation Act in 1995 resulted in a shift in oat production from Alberta to eastern Saskatchewan and Manitoba due to their close proximity to markets located in the mid west United States (Agriculture and Agri-Food Canada, 2000). Seeded area to oats in Manitoba was 384 500 hectares in 2000 and the predicted seeded acreage was similar for 2001 at 374 300 hectares (Manitoba Agriculture and Food, 2001).

Dramatic increases in oat exports since the 1980's have made Canada a leader in oat export markets. Canadian oats satisfied an estimated 60 % of world demand in the 1999-2000 crop year. This share was considerably greater than that of other major oat producing countries like Sweden (14 %), Finland (8 %), and Australia (7 %). Canadian producers continue to grow more oats, which is helping to satisfy demands from the largest importer of oats in the world, the United States. An estimated 95 % of Canadian oat exports go to the north central United States; other customers include Japan. Relatively low transportation costs to the United States and supply of high quality oats are the main reasons why Canada has dominated world oat exports (Agriculture and Agri-Food Canada, 2000).

Oats have traditionally been used for animal feed, which remains the primary use today. However, the proportion of the world oat supply destined for human consumption has doubled to 24 % of total consumption since 1960 (Agriculture and Agri-Food Canada, 1998). Demand for oat based foods is expected to stay strong and increase, particularly as there are a growing number of consumers seeking functional foods with the ability to reduce the risk of chronic diseases. The cornerstone of this functional food market for oats is the health claim that states oat β-glucan lowers cholesterol and reduces the risk of cardiovascular disease. This health claim has increased the demand for milled oat products such as cut groats, flakes and flour, which are used in a wide range of products including hot cereals, granola, extruded cereals, cookies, muffins, breads, crackers, snacks, baby food, meat extenders and even beverages (Can-Oat Milling, 1998). Between 60 and 70 % of Canadian oats exported to the United States are for milling (Agriculture and Agri-Food Canada, 2000). Canadian millers also export groats, flakes, and meal. Manitoba's exports of these products were valued at approximately $36 million in 1999 (Manitoba Agriculture and Food, 2001). For example, Can Oat Milling Inc., located in Manitoba and Saskatchewan, has become the largest industrial supplier of oats in the world. It can process approximately 10,000 cwt of finished product per day, 95 % of which is exported to the United States, South and Central America, the Caribbean and Australia (Can-Oat Milling, 1998). There are also other potential uses of oats for food such as oat oil for cooking (Branson and Frey, 1989; Erazo-Castrejón et al., 2001) and oat extracts for use in functional foods. For example, Ceapro Inc., located in Alberta, uses fractionation technology to concentrate oat components such as β-glucan

and antioxidants for use in nutraceuticals and non-food products (Agriculture and Agri-Food Canada, 2000). Oat β-glucan is thought to improve the health of skin and is used in the treatment of wounds. Oat preparations are used in a variety of lotions and cosmetics and in veterinary shampoo (Paton and Fedec, 1996). As innovative uses for oats are created and human consumption continues to increase, the demand for high quality oats will strengthen. Successful competition in domestic and international markets requires continued improvement of Canadian oat cultivars to meet the changing needs of the agricultural and food industries.

Oat breeding programs are in place in Canada to ensure the availability of cultivars that possess the characteristics desired by producers, millers, food and non-food manufacturers and consumers. Quality traits that have long been a priority to breeders include agronomic performance, disease resistance, yield, test weight and hull content. Traditionally, oats with high oil and protein were desired for high energy animal diets (Burrows, 1986). However, increased human consumption of oats has shifted breeding priorities to include the development of cultivars high in β-glucan and low in oil in order to meet low energy requirements for human diets. As food oat markets develop and oat research progresses in the areas of human nutrition and food processing, there is an opportunity for oat breeding programs to evolve even further. For example, it is essential to the success of a cultivar for it to perform well in an end-product. This concept is demonstrated in the breeding programs of other cereal crops, such as wheat, where achieving high bread loaf volume is an integral part of the screening process (Peterson et al., 1997). Currently, no end-product testing system exists for Canadian oat breeding.

Part of the reason lies in the lack of small scale methodology and equipment needed to process oats as is done in the industry. Prior to flaking or milling, oats are subjected to moist heat treatments and then dried down in a kiln. This conditioning process is controlled to inactive enzymes and alter the sensory qualities of the oats. Oats are briefly treated again with steam before flaking to impart resilience to the groat and thus reduce the production of fine particles under the pressure of rolling (Deane and Commers, 1986). Methodologies that mimic these complex processes need to be developed for use in genetic screening of oat end-product quality. Furthermore, this technology would open the door to studies on factors affecting the quality of oat foods and may justify the need to breed for specific oat starch and functional characteristics.

Successful introduction of novel or improved traits into adapted cultivars requires a good understanding of the factors that control the expression of the trait. For example, 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, like weather and soil conditions, cannot. Quantitative interactions can occur between the genotypic and environmental factors controlling a trait, meaning that the magnitude of the genotype response changes with different environments. Breeders are more interested in qualitative (also called cross-over) interactions, which are characterized by a change in the rank order of a number of genotypes when they are grown in different environments. This type of interaction would cause the choice of superior genotype to be different depending on the growing environment, thus greatly reducing the effectiveness of recurrent selection of the desired trait (Gail and Simon, 1985; Baker, 1988; Kang, 1990).

In order to assess relative effects of genetic and environmental factors, studies need to be conducted in the target growing region using genotypes of interest.

In addition to genetic improvement, controlling quality at the crop production stage may help provide the food industry with superior food oats. Specific environmental conditions, such as soil fertility, are largely controlled by the producer. For example, nitrogen fertilization is a common agricultural practice used to increase yield and test weight. The effect of nitrogen fertilization on other oat characteristics that are important to millers and the food industry need to be examined. Companies sourcing oats may be able to ensure desired oat quality by providing producers with specific nitrogen fertilization recommendations. Furthermore, breeders will benefit from information regarding interactions between genotype and nitrogen effects.

The goal of the research presented in this thesis was to provide oat breeders, millers and manufacturers of oat products with information regarding the variation that exists in the quality of oats grown in Manitoba. The specific objectives of the study were as follows:

1. To determine the relative effects of genotype, environment and genotype-by-environment interaction on a) the composition and physical attributes of whole and/or milled oats, b) the characteristics and functionality of oat starch and wholemeal and c) the quality of oat end-products processed by laboratory scale methodologies and equipment.

2. To determine the relative effects of nitrogen fertilization rate, genotype, environment and interactions amongst these factors on whole and/or milled oat physical attributes, composition and wholemeal pasting characteristics.

CHAPTER 2

REVIEW OF LITERATURE: FACTORS AFFECTING VARIATION IN OAT QUALITY CRITERIA

2.1 PHYSICAL OAT PROPERTIES

Physical oat properties, such as hull content and test weight, have long been a measure of oat quality at grain elevators and mills. The increasing usage of oats for human foods has strengthened the need for oats with superior milling quality. In addition to traditional quality parameters, newly studied traits such as groat breakage are beginning to shape the definition of high quality milling oats.

2.1.1 Hull Content

Whole oats, in the state they are harvested, consist of a caryopsis, or groat, enclosed in a fibrous covering called a hull, which is made up of the lemma and palea. Although the hull protects the groat from damage during seed development and grain handling, it is of minor economic value to millers compared to the groat because it is inedible. Thus, the first step of the oat milling process is removal of the hull from the groat. Naturally, whole oats that have a minimum proportion of hull to groat content provide millers with a greater recovery of usable product. Oats with high proportions of hull can be bulky, thereby increasing storage space and transportation requirements. Hull content is also negatively correlated with test weight (Asp et al., 1992; Doehlert et al., 1999), which is an important grading factor. Oats receiving a low grade due to low test weight at the point of sale earn a reduced price for producers and are generally used for animal feed rather than enter the food market. Due to the economic importance of this

characteristic, reducing the hull content of registered oat cultivars is a major goal of Canadian oat breeding programs.

Hull content is measured as the ratio of the weight of the hull compared to the weight of the whole grain sample and is expressed as a percentage. Conversely, groat percentage of an oat sample can be measured, in which case a high value is desirable. Based on these definitions, it follows that the physical basis for a change in hull percent can be due to a change in the quantity or thickness of the hull, the plumpness of the groat, and the occurrence of tertiary or bosom kernels, which tend to have relatively high amounts of hull. The most accurate measurements of hull content are achieved with hand separation but more practical mechanical methods are available. Compressed air and impact dehulling machines are useful for larger sample sizes especially when followed by removal of remaining hulls in the final groat sample (Doehlert et al., 1999).

Hull and groat percentages of oats vary significantly with genotype as well as the environmental conditions in which the oats are grown. For example, one hundred Swedish oat samples showed a range in hull content from 23.2 to 35.0 % (Asp et al., 1992). Oat genotypes originating from Australia (Zhou et al., 1998b; Zhou et al., 1999a), Canada (Humphreys et al., 1994a; Ronald et al., 1999) and the United States (Doehlert et al., 1999) also varied significantly ($P \leq 0.01$) in hull and groat content. Three growing locations in North Dakota, USA resulted in significantly different ($P \leq 0.01$) groat percentages (Doehlert et al., 1999) as did eight locations in New South Whales, Australia (Zhou et al., 1999a). Zhou et al. (1999a) also found that the mean groat percentage for eight genotypes was different depending on the growing year and that location influenced

groat percentage more than genotype in both of the two growing years. In contrast, Ronald et al. (1999) studied the heritability of hull content in oats derived from three crosses between Canadian cultivars grown in several locations and found genotype to be the dominating influence on hull percentage. Location effects were significant ($P \leq 0.001$) but the component of variation for genotypes was greater. Genotype-by-environment interaction effects were found to be significant in all three studies. Doehlert et al. (1999) and Zhou et al. (1999a) thus concluded that multiple growing sites would be required for breeding purposes. However, Ronald et al. (1999) determined that the interaction effect contributed little to total variation compared to the effects of genotype, location and experimental error, indicating that few growing sites would be required to breed for hull content using the genotypes in the study. These findings, in addition to broad-sense heritability estimates of 0.35 to 0.90 (towards high range with more diverse parents), indicate confidence in the ability to select for oats with low hull content.

The effects of agricultural management practices, such as nitrogen fertilizer application, on oat hull and groat content have also been studied. An experiment involving five Australian cultivars and six nitrogen fertilizer rates ranging from 0 to 100 kg/ha found no significant effect of fertilizer rate on groat percentage (Zhou et al., 1998b). Another study conducted in Eastern Canada examined the effect of applying 40 kg/ha of nitrogen fertilizer at seeding versus the same treatment plus 20 kg/ha at a later stage in the crop's development. An observed decrease in hull percent with the higher level of nitrogen was thought to be associated with the observed increase in plump grain and decrease in bosom grain (double kernels high in hull content). Further study is

required to confirm this finding, considering that the decrease in hull content observed with nitrogen fertilization was so small (25.7 to 25.2 % hull) and was only significant ($P \leq 0.05$) at one out of four growing environments studied (Humphreys et al., 1994a).

2.1.2 Groat Breakage

Another physical oat characteristic that affects milling product recovery upon dehulling is resistance to breakage. The mechanical stress that oats are subjected to during removal of the hull causes some of the groats to break. Broken groats cannot be processed into end products such as bran and whole flakes and thus represent an economic loss to millers.

It is only recently that research into the factors that cause oat groat breakage has been published. Doehlert et al. (1999) measured the breakage of ten oat genotypes (including some Canadian cultivars) grown at three locations in the United States. The type of hull removal system influenced the overall level of groat breakage, but within the range of each, there were significant differences among the genotypes and growing environments. Significant genotype-by-location interactions were observed in which the genotype response to environment varied in magnitude and resulted in rank order differences. Furthermore, Doehlert and McMullen (2000) reported that interaction effects may have been influenced by disease resistance since they observed higher breakage levels (up to 20 %) at a location heavily infected with crown rust. In both of these studies, oats with low amounts of breakage also tended to have high hull content suggesting that the hull provided protection against breakage. Breakage was also found to be influenced by the hardness of the groats (Doehlert and McMullen, 2000), which

may be due to high amounts of bran or strengthened internal bonds due to the presence of phenolic compounds such as ferulic acid (Engleson and Fulcher, 2001).

2.2 OAT COMPOSITION

Major components in oats include β-glucan, protein, oil and starch. The levels of these components desired in a registered cultivar depend on the end-use. For example, oats used for animal feed ideally contain high fat and low fibre for maximum feed efficiency. Now that more oats are being milled for human consumption, it is necessary to develop cultivars that contain nutrients in proportions that are conducive with the low fat, high fibre diets recommended by nutrition authorities (Health and Welfare Canada, 1990). In other cases, it may be desirable to have levels of certain nutrients above dietary requirements in order to fractionate for use in nutraceutical and non-food industries and to blend with sources of oats having low levels of desired nutrients.

2.2.1 β-Glucan Content

The majority of the soluble dietary fibre fraction in oats is comprised of the unbranched polysaccharide (1→3)(1→4) β-D-glucan. This component is highly desirable in oats destined for human consumption because it is believed to be responsible for lowering total and low density lipoprotein cholesterol without decreasing high density lipoprotein cholesterol in both animals and humans (Klopfenstein, 1988; Wood et al., 1989; Mälkki et al., 1992; Newman et al., 1992; Kahlon et al., 1993; Braaten et al., 1994). This information prompted the United States Food and Drug Administration to allow health claims regarding the ability of oat soluble fibre to reduce the risk of cardiovascular disease to be printed on food packaging. To qualify for this claim, the food product must

contain a minimum of 0.75 g/serving of β-glucan from oat bran, rolled oats or whole oat flour. This amount is based on oat bran containing at least 5.5 % β-glucan and the rolled oats and whole oat flour containing at least 4.0 % (Food and Drug Administration, 1996). Oat products meeting these requirements may satisfy increasing consumer demands for functional foods that help prevent heart disease. There is no Canadian counterpart to the US health claim on oats as of yet, but groups in Canada are pursuing such legislation (Fitzpatrick, 2001). Regardless, the majority of Canadian oats are exported to the United States, therefore it is essential from a competitive standpoint that newly registered Canadian oat cultivars meet industry specifications for high β-glucan content.

A survey of the literature reveals that oat β-glucan content can range from as low as 1.8 % (Miller et al., 1993b) to greater than 7.0 % (Peterson, 1991). Variation in β-glucan content of oat genotypes from several origins have been reported by many researchers (Asp et al., 1992; Lim et al., 1992; Cho and White, 1993; Miller et al., 1993b; Humphreys et al., 1994b; Lee et al., 1997). Peterson (1991) tested the β-glucan content of 12 oat genotypes grown at ten locations in the United States. He found that genotype, location and genotype-by-location interaction effects were all significant ($P \leq 0.01$) but that the variance ratio for the interaction effect was less than that of the main effects. This was in agreement with a study by Miller et al. (1993a) who found a significant genotype-by-location interaction to be of little practical importance. Furthermore, they determined that genotypic variation among a group of six Canadian cultivars and seven breeding lines to be greater than the variation observed among five growing sites in Eastern Canada in two out of three growing years. Brunner and Freed (1994) did not find

a significant location effect, likely because the two US sites used were not sufficiently diverse to cause differences in oat β-glucan content. However, they did find that growing year (n = 3) significantly effected β-glucan content as did Saastamoinen et al. (1992). In contrast, Lim et al. (1992) did not see a significant main effect of growing year (n = 2) but genotypes responded differently to the different growing years. The highest and lowest ranking genotypes were consistent across years and therefore would not likely have influenced breeder selections. These discrepancies in results reiterate the need for studies testing the effects of location and year to be designed to achieve maximum environmental diversity.

Several reports have indicated that low precipitation and high temperatures are possible environmental factors responsible for increased β-glucan content (Peterson, 1991; Miller et al., 1993a; Brunner and Freed, 1994). High β-glucan may be associated with smaller seed size and weight (characteristics of low precipitation and high temperature growing conditions), suggesting that the physical properties of the kernel can influence the proportion of the β-glucan rich subaleurone layer in the groat (Peterson, 1991; Saastamoinen et al., 1992). It would therefore follow that a negative correlation between β-glucan content and characteristics such as thousand kernel weight, test weight and possibly yield would exist but this is may not always be the case (Asp et al., 1992; Brunner and Freed, 1994; Miller et al., 1993b). Correlations between β-glucan content and other kernel characteristics also seem to be inconsistent. Miller and colleagues (1993b) found a negative correlation (r = -0.54) between protein and β-glucan whereas Brunner and Freed (1994) found a positive correlation at five out of six sites (r values

ranged from 0.17 to 0.72). Asp and colleagues (1992) also found a weak but significant correlation between β-glucan and oil content (r = 0.33).

The effect of nitrogen fertilizer on the β-glucan content of oats has also been investigated. Brunner and Freed (1994) applied three nitrogen fertilization rates (0, 37, 74 kg/ha) to five oat genotypes grown at two locations in the United States over three years. Nitrogen effects were not significant in their overall analysis due to year-by-nitrogen and location-by-nitrogen interactions. These interactions indicated that the fertilizer did not have a consistent influence on β-glucan content at all environments. However, higher rates of nitrogen resulted in significantly higher β-glucan contents (by 0.8 % β-glucan on average) at three out of the six growing sites. It was suggested that heavy precipitation at the other sites caused nitrogen leaching, thus eliminating the effects of the fertilizer. Another study conducted in Eastern Canada (Humphreys et al., 1994b) found that adding additional nitrogen at a later stage of plant development did not significantly affect β-glucan content, suggesting that β-glucan synthesis occurs at the early stages of groat development. Neither study reported on the possibility that high initial soil nitrogen levels at some test sites lead to the non-significant effect of fertilizer on β-glucan content.

2.2.2 Protein Content

Oat protein is nutritionally valuable because it is reported to have a good amino acid profile (Hischke et al., 1968; Robbins et al., 1971; Wu et al., 1972; Wu et al., 1973). Zarkadas et al. (1995a, 1995b) compared the amino acid content of five Canadian cultivars to the amount of essential amino acids recommended for a 2 to 5 year old child

by the Food and Agriculture Organization/World Health Organization. They found that oat groats exceeded the recommendations for the nine essential amino acids except lysine, which was the first limiting amino acid, and threonine. Oats do however, have a high lysine content compared to other cereal grains such as wheat, barley and rye (Tkachuk and Irvine, 1969; Wu et al., 1972). Wu et al. (1973) found that oats, especially those of high protein content, are suitable for nutritional supplemented food products because of the resulting bland taste and acceptable hydration capacity and emulsion stability.

Factors that may lead to higher protein content in oats have been investigated. Differences in whole oat and groat protein content among genotypes are well documented (Hischke et al., 1968; Wu et al., 1972; Wu et al., 1973; Ohm, 1976; Welch and Yong, 1980; Asp et al., 1992; Peltonen-Sainio and Peltonen, 1993; Humphreys et al., 1994b; Zarkadas et al., 1995a; Zarkadas et al., 1995b; Zhou et al., 1998b). Reports for groat protein have ranged from 12.4 % (Asp et al., 1992) to 24.4 % protein (Robbins et al., 1971) for domesticated oat genotypes and as high as 33.7 % for a non-domesticated oat (Miller et al., 1993b). Peltonen-Sainio and Peltonen (1993) found a highly significant ($P \leq 0.001$) effect of growing year on the protein content of whole oats, although only two years were studied with their overall means differing by only 0.6 % protein. They attributed the lower protein values in one year to lower levels of precipitation and higher temperatures, which resulted in poor groat development. In another study, Ohm (1976) found variation in the response of three US genotypes to different growing years with respect to groat protein content.

Nitrogen fertilizer is perhaps the most studied environmental influence on oat groat protein content. Addition of 100 kg/ha nitrogen fertilizer increased groat protein content by an average of 1.6 % compared to an addition of 0 kg/ha. This resulted in a significant ($P \leq 0.01$) effect of nitrogen fertilizer and a significant correlation between nitrogen fertilizer and groat protein content ($r = 0.90$) (Zhou et al., 1998b). In the same study, the genotype-by-nitrogen interaction was not significant, indicating that the five Australian genotypes tested did not differ in their response to the fertilizer, which is in agreement with other studies (Humphreys et al., 1994b; Welch and Yong, 1980). Although nitrogen effects were significant, genotype was responsible for greater variation in protein content. Ohm (1976) observed even greater increases in groat protein (0.82 to 3.77 %) with application of 110 kg/ha but they were dependent on genotype ($n = 21$ US genotypes).

Other researchers studied the effects of applying nitrogen fertilizer at different stages of plant growth. Welch and Yong (1980) found that adding 125 kg/ha of nitrogen at heading resulted in a significantly higher whole oat protein content (16.3 %) than if the same rate had been applied at the two to three leaf stage (14.6 %). Adding 125 kg/ha at both stages (double the amount) did not significantly increase protein content (16.6 %) compared to the single application at heading. All fertilizer treatments resulted in significantly higher protein than if no fertilization occurred (13.5 %). Humphreys et al. (1994b) compared treatments of 40 kg/ha of nitrogen fertilization at seeding verses 40 kg/ha at seeding plus an additional 20 kg/ha at the boot stage (plant development stage just prior to head emergence). The effect of additional nitrogen was significant at three

out of four growing sites and only increased groat protein on average by 0.6 %. These studies show a potential for nitrogen fertilization to increase the protein content of oats but indicate that the response is variable depending on the rates used, the genotypes involved and the environments in which the oats are grown.

2.2.3 Oil Content

The oil content of oats is relatively high compared to other cereal grains. A high or low oil content is desirable depending on the end-use. In many food applications a high oil content is undesirable because it can decrease storage stability due to lipid oxidation. In addition, some food manufacturers desire a low oil content to ensure they achieve an oat product that can be labeled as low fat. For example, in order for an oat based food product to meet the criteria for the heart healthy claim in the United States, it must not contain more than 3 g of fat per serving. Development of low oil oat cultivars would help millers and food manufacturers meet consumer demands for low fat, high fibre foods.

On the other hand, oat oil has a beneficial fatty acid composition; it is high in unsaturated fatty acids such as oleic, linoleic and linolenic acids. The later two fatty acids are essential in the human diet. In addition, oat oil is rich in bioactive compounds such as tocopherols and other antioxidants (Lásztity, 1998). In particular, α-tocopherol, a component of Vitamin E, is thought to be important in the protection of lipids in cell membranes from peroxidation with free radicals (Burton and Traber, 1990). This activity may have potential for cancer prevention. Oat oil is also rich in tocotrienols, which are also components of Vitamin E. Consumption of tocotrienols has been shown to

significantly reduced total and low density lipoprotein cholesterol in hypercholesterolemic animals and humans and is thought to be a powerful inhibitor of cholesterol synthesis (Qureshi et al., 1986; Qureshi et al., 1991a; Qureshi et al., 1991b). Thus, these compounds may have implications for prevention of cardiovascular disease. Antioxidants also help prevent lipid oxidation and thus impact the storage stability of the oats themselves and potentially other products containing oat antioxidants. For example, the ability of a specific antioxidant compound extracted from oats, Δ^5-avenasterol, to prevent deterioration of soybean frying oil has been demonstrated (White and Armstrong, 1986). High oil oats are a possible source of edible oil and concentrated extracts for use as food ingredients and nutraceuticals.

Reports on groat oat oil content typically fall within the range of 3.1 to 14.4 % (Brown et al., 1966; Brown and Craddock, 1972; Asp et al., 1992; Humphreys et al., 1994b; Zhou et al., 1999b) with the majority between 5 and 9 % (Brown and Craddock, 1972). Significant genotype effects have been documented in oat groats from eastern Canada ($n = 4$) (Humphreys et al., 1994b) and Australia ($n = 5$, $n = 8$) (Zhou et al., 1998b; Zhou et al., 1999b) and whole oats from Finland, Sweden and Norway ($n = 29$) (Peltonen-Sainio and Peltonen, 1993). Zhou and colleagues (1999b) found the variation in oil between eight genotypes to be slightly greater than the variation in groat oil content caused by eight different growing locations, although the location effect was also significant ($p \leq 0.01$) in both of two growing years. Genotype-by-location interaction effects were also significant in both years. Highly significant ($p \leq 0.001$) location (Saastamoinen et al., 1990) and year effects (Saastamoinen et al., 1990; Peltonen-Sainio

and Peltonen, 1993) have also been observed by other researchers for whole oat oil contents. Environmental variation in oat oil content is likely to be, at least in part, a result of prevailing temperature, as several researchers have noted a strong relationship between low growing temperature and high oil content and vice versa (Saastamoinen et al., 1989; Saastamoinen et al., 1990; Peltonen-Sainio and Peltonen, 1993). Saastamoinen et al. (1990) estimated that 76.8 % of the variation in whole oat oil content observed for 21 genotypes grown at eight locations for three years could be explained by growing temperature.

Other environmental factors that may impact oat oil content is availability of nitrogen. Humphreys et al. (1994b) studied the effect of applying 40 kg/ha of nitrogen fertilizer at seeding verses the same treatment plus an additional 20 kg/ha at a later stage of development. They found that nitrogen had a significant effect at two out of four sites studied. However, at one site the decrease in oil content with the heavier fertilizer rate was minimal (average 6.27 verses 6.16 %). One genotype actually showed an increase in oil with more nitrogen at one of the sites (5.93 verses 6.25 %). In another study, six nitrogen fertilizer rates ranging from 0 to 100 kg/ha did not significantly effect the oil content of five Australian genotypes (Zhou et al., 1998b). A general trend was observed showing an increase in oil with an increase in nitrogen fertilization. The overall genotype-by-nitrogen interaction effect was not significant in either study.

Despite the effects of environment on oat oil content, the strong genotype component for this trait has been proven by the success of recurrent selection for high oil content. Branson and Frey (1989) carried out trials of three cycles of recurrent selection

for high oil content at a single location in Iowa, United States. The mean oil content increased from 8.5 to 11.3 % in the three cycles. More recently, Frey and Holland (1999) were able to increase the mean oil content of oats from 9.8 to 15.9 % in nine cycles of recurrent selection conducted at three environments. They found that groat percentage was not affected by selection for high oil but that yield decreased. Plants with exceptionally high oil (>15 %) also experienced greater problems with lodging and disease. Based on correlations found by other researchers between oat oil content and protein (Brown et al., 1966; Saastamoinen et al., 1990; Asp et al., 1992; Zhou et al., 1999b), starch, β-glucan and test weight (Asp et al., 1992), it is possible that other quality characteristics could be indirectly altered by selection for high or low oil content in oats.

2.3 OAT STARCH QUALITY

Starch is the most abundant component in oat groats and thus has a great potential to affect the quality of oat products. Heating starch in the presence of water during the production and preparation of oat products brings about pasting and gelatinization. Pasting is characterized by the swelling of starch granules and disruption of their crystalline structure as they take up water. Thickening of the paste occurs as amylose is preferentially leached into the surrounding continuous phase in most cereal starches, but in oat starch amylose and amylopectin are co-leached from the granule (Doublier et al., 1987; Hoover and Vasanthan, 1992; Wang and White, 1994a). Gelatinization is marked by the irreversible disruption of the granule structure, signified by the loss of the birefringent light scattering property of the intact granule.

Several researchers have found oat starch to be unique in that it exhibits greater swelling and solubility as well as reaches higher peak viscosities than other cereal starches (MacArthur and D'Appolonia, 1979; Doublier et al., 1987; Gudmundsson and Eliasson, 1989; Hoover and Vasanthan, 1992). In addition, hot oat starch pastes show greater reductions in viscosity under shear stress (MacArthur and D'Appolonia, 1979). Although there is a need for more research to determine how these and other starch characteristics impact oat processing and end product quality, it is first important to investigate what variation exists for these properties. Determining the variation among oat starches from different genotypes and understanding what factors impact the variation may be helpful in the future development of oat cultivars with superior starch characteristics.

2.3.1 Total Starch Content

Starch yield is important for the purification of oat starch for non-food uses such as talc and cosmetics (Paton and Fedec, 1996). The amount of starch in oats is also important because of its function in pasting and gelatinization in processed food products. The total starch content of oat groats from genotypes of several origins have been shown to vary significantly, with reports ranging from 39.3 to 72.7 % (Paton, 1977; Asp et al., 1992; Zhou et al., 1998a; Zhou et al., 1999a). Environmental effects are less well studied. Asp et al. (1992) grew 50 Swedish oat genotypes over three years. They found significantly different total starch contents between years, however, it was not clear whether the same genotypes were grown each year. Paton (1977) found only a 1.3 % range in total starch content of the oat variety Hinoat when it was grown in Ottawa over

three years. A greater range was observed for Rodney oats grown in one year at three sites in Manitoba and Saskatchewan (range 48.5 to 60.0 % total starch). Paton also found that a heavily fertilized oat sample had yielded less starch than one grown under lack of added nutrients (43.7 verses 47.2 %), which was inverse to its effect on protein content. Other researchers have also reported negative correlations between protein and starch content, indicating that conditions favoring the synthesis of one compromises the other (MacArthur and D'Appolonia, 1979; Lásztity, 1998).

2.3.2 Amylose Content

The proportion of amylose to amylopectin in oat starch is recognized as having an important impact on starch functionality. Some amylose occurs in a free form but the majority is bound to lipid. The later portion is particularly high in oat starch relative to other cereal starches (Doublier et al., 1987; Gudmundsson and Eliasson, 1989). High proportions of amylose and lipids have been shown to inhibit swelling of cereal starches perhaps by diluting amylopectin, the main component responsible for swelling (Tester and Morrison, 1990; Tester and Karkalas, 1996). Wang and White (1994a) observed a positive correlation ($r = 0.97$; $P < 0.01$) between oat amylose content and gelatinization temperature, possibly due to the inhibition of swelling. Amylose content of oat starch also had a negative correlation with the clarity of oat starch paste ($r = -0.99$; $P = 0.0001$) (Wang and White, 1994b).

Amylose values for oat starch vary drastically between studies encompassing a range from 16.0 to 33.6 % (MacArthur and D'Appolonia, 1979; Paton, 1979; Gudmundsson and Eliasson, 1989; Wang and White, 1994b; Wang and White, 1994c;

Tester and Karkalas, 1996; Lásztity, 1998). Such a wide range may be due to large differences between genotypes of broad origin but is likely influenced by methodology, thus making it difficult to interpret genotypic variation. Comparing genotypes within a study shows a more narrow range in amylose values, but could still have functional significance. MacArthur and D'Appolonia (1979) analyzed oat starches from three U.S. genotypes and found a range from 25.5 to 27.9 %. Slightly higher values were found for four Swedish genotypes (27.3 to 29.4 % amylose) (Gudmundsson and Eliasson, 1989) and six German genotypes (27.5 to 29.8 % amylose) (Tester and Karkalas, 1996). The highest reports of oat amylose content (30.3 to 33.6 % amylose) are from US oats (Zhou et al., 1998a). The lowest reported values were 3.19 to 3.54 % IA for two Canadian genotypes measured by iodine affinity, which converted to amylose content assuming an iodine binding capacity of pure oat amylose of 19.5 g/100g becomes 16 to 18 % amylose (Paton, 1979). Environmental influences on oat starch amylose content have not been addressed in studies to date.

2.3.3 Pasting and Gelatinization Properties

Starch swelling, pasting and gelatinization are important events in the processing of any oat end-product undergoing heat treatment in the presence of water such as oatmeal (Zhou et al., 1999a) and extruded ready to eat breakfast cereals (DesRochers, 1998). However, defining desired pasting and gelatinization characteristics is more difficult than with oat composition and milling properties because there is a lack of published research on the relationship between pasting and the quality of various end-products. According to Zhou et al. (1999a, 1999b) the Australian cultivar Yarran has

been distinguished as a poor variety for millers and food manufacturers. They found it to have a unique pasting curve as measured with a Rapid Visco-Analyser, including a long time and high temperature to reach peak viscosity compared to commercially acceptable cultivars. Low gelatinization temperatures would be preferred by food manufacturers due to faster processing times. Zhou et al. (1999a) also speculated that pasting parameters measured by a Rapid Visco-Analyser would also describe the cooking quality of oatmeal. They equated a high peak viscosity to the need for stirring during cooking and a high temperature at peak to the likelihood of burning if not well stirred. The time to peak viscosity indicates the cooking time required for the oatmeal and the final viscosity at 40 °C would be a measure of the thickness of the oatmeal at the time of consumption. Although these are theoretical definitions, it cannot be denied that differences in the way starch behaves during cooking will affect the end product texture. For example, Yiu et al. (1987) altered the progression and extent of starch swelling, pasting and gelatinization by preparing oatmeal by a rapid and a slow cooking method. The slow cooked oatmeal had a more viscous and creamier texture, presumably due to a greater degree of starch granule disruption and starch leaching. Furthermore, one may expect oats with different starch characteristics to also result in cooked oatmeals with varying texture. For example, starch with relatively high swelling capacity would reduce the volume of water and increase the concentration of solutes in a food system, thus increasing viscosity. Other pasting characteristics such as the increase in viscosity that occurs as a hot paste is cooled (setback) are associated with end-product quality. High setback is typically thought to correlate positively with starch retrogradation, which could impact the staling and freeze-

thaw stability of a product. However, Paton (1979) did not find that the gels from high setback oat starch pastes showed the visual signs of high retrogradation (syneresis).

Genotypic variation in the temperature at which oat starch gelatinization occurs has been evaluated by Differential Scanning Calorimetry, which involves measuring the energy flow that occurs when hydrated starch is heated to temperatures over 100 °C. Gudmundsson and Eliasson (1989) observed a range in gelatinization temperatures of 57.0 ° to 61.2 °C for starches from four Swedish oats. The corresponding change in enthalpy associated with the disorganization of the starch crystalline structure ranged from 10.4 to 12.1 J/g. Similar ranges in gelatinization temperature were observed for six German genotypes (56.2 to 59.5 °C) (Tester and Karkalas, 1996) and three US genotypes (56.1 ° to 60.0 °C) (Wang and White, 1994a). 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).

Oat starch pasting characteristics have been measured using a Brabender Visco-Amylograph. This apparatus measures viscosity of a starch and water slurry during heating to 95 °C and cooling to 50 °C with constant stirring. Genotypes have been shown to differ in their peak starch paste viscosity, the susceptibility of the swollen granules to rupture with shearing at a holding period at 95 °C, and the change in viscosity that occurs upon cooling the paste to 50 °C (Wang and White, 1994a). Furthermore, when Paton (1977) cooled pastes made from two different genotypes to room temperature and stored them at 2 °C for 24 hours, the resulting gels exhibited differences in strength, opaqueness, elasticity, and tackiness. These characteristics also varied for gels from one oat genotype

grown at three different sites. In addition, Paton observed differences in starch pasting characteristics for the same oat cultivar grown under high and low fertilization.

Two recent studies have focused on the effects of genotype and environment on the pasting properties of oat wholemeal (ground groat) and water slurries. A Rapid Visco-Analyser was used to measure the maximum (peak) and minimum (hot paste) viscosities attained at 90 °C, the difference between them (breakdown), the final viscosity after cooling to 40 °C, and the difference between the hot paste and final viscosities (setback). In the first study (Zhou et al., 1998b), five Australian oat genotypes were grown under six nitrogen fertilization regimes (0 to 100 kg/ha). Genotype was the main contributor to variation found in all pasting parameters. The response to nitrogen fertilizer differed among genotypes with respect to peak viscosity and breakdown, but overall, increasing the nitrogen fertilizer rate had a small but significant ($P \leq 0.05$) decreasing effect on peak viscosity. In a second study (Zhou et al., 1999b), genotype ($n = 8$), growing location ($n = 8$) and genotype-by-location interaction significantly affected all pasting characteristics measured with the Rapid Visco-Analyser. Relative contributions of genotype and location depended on the growing year, but both effects were consistently more important than genotype-by-location interactions, indicating that multiple breeding sites are not needed.

2.4 OAT END-PRODUCT QUALITY

Millers and food manufacturers largely rely on in-house quality specifications for products such as flakes and oatmeal that are defined by the varying preferences of their customers. In order to breed for superior oat end-product quality, efforts need to be taken

to formulate a universal end-product quality definition that can be used to assess oats destined for food use. Until this is achieved, continued research into the factors affecting end-product quality will help reveal the possibilities for oat improvement. Researchers in Finland have begun to look at the quality of oat end-products made from different genotypes.

2.4.1 Oat Flake Quality

The physical characteristics of oat flakes are of economic importance to millers. Granulation specifications depend on individual products, but in general, a low percentage of very small flakes that stay directly above and/or go through a US #10 sieve (2 mm) is desirable (Can-Oat Milling, 1998). This characteristic can be related to flake integrity, or the tendency for flakes to remain intact during handling. Lapveteläinen and colleagues (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. Flake granulation is also influenced by the surface area of the flake, which is naturally affected by the size of the original groat, and the thickness of the flake. The same study found that flake thickness differed significantly among genotypes but did not vary with year.

The desired functional characteristics of oat flakes are also largely dependant on the end-use. For example, flakes destined for granola bars are rolled thicker to prevent breaking and thus have reduced surface area. It is desirable for these flakes to have a high water hydration capacity to enable them to bind ingredients despite their greater

thickness. On the other hand, lower flake hydration may be desirable in a cookie formulation where excessive water uptake would dry out the dough. The water hydration capacity of flakes has been shown to vary significantly with genotype in addition to year and genotype-by-year interactions (Lapveteläinen et al., 2001).

2.4.2 Cooked Oatmeal Quality

The properties of oat flakes are important to the end-product they will be used in. For example, the sensory characteristics of oatmeal cooked from Finnish and Swedish oat genotypes have been studied (Lapveteläinen and Rannikko, 1999; Lapveteläinen et al., 2001). Trained 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. Thick oat flakes tended to make oatmeal that was more coarse and slippery and less uniform and adherent (Lapveteläinen et al., 2001). Thinner flakes demonstrated greater water binding capacities, which in turn were associated with thicker oatmeal (Lapveteläinen and Rannikko, 1999). The starch content of the flakes was also associated with increased oatmeal slipperiness and decreased uniformity.

CHAPTER 3

EFFECT OF GENOTYPE, ENVIRONMENT AND GENOTYPE-BY-ENVIRONMENT INTERACTION ON THE QUALITY OF OATS GROWN IN MANITOBA

3.1 INTRODUCTION

A significant portion of Canadian oat production is used to meet the increasing world demand for high quality oats for food processing. Plant breeders require an understanding of what factors influence oat physical characteristics, composition, functionality and end-product quality in order to provide industry with superior cultivars. Researchers have studied the effects of genotype and environment on a number of oat quality traits. The majority of this research has focused on characteristics such as yield, test weight, hull percent and β-glucan (Ohm, 1976; Brinkman and Rho, 1984; Powell and Phillips, 1984; Marshall et al., 1987; Frensham et al., 1988; Anderson and McLean, 1989; Welch and Lloyd, 1989; Peltonen-Sainio, 1990; Peterson, 1991; Welch et al., 1991; Asp et al., 1992; Lim et al., 1992; Saastamoinen et al., 1992; Cho and White, 1993; Miller et al., 1993b; Brunner and Freed, 1994; Humphreys et al., 1994a; Humphreys et al., 1994b; Lee et al., 1997; Zhou et al., 1998b; Doehlert et al., 1999; Ronald et al., 1999; Zhou et al., 1999a), which are important to producers, millers and food manufacturers. Where interactions between factors are reported, distinction between quantitative effects (genotypes respond differently to environments) and qualitative effects (rank order of genotypes changes across environments) are often not considered. The literature is lacking in studies designed to assess genotypic and environmental variation in the quality of oat starch and end-product functionality, which also impact the use of oats for human

consumption. Furthermore, new cultivars must be adaptable to the region intended for growth, therefore it is important that tests for genotypic and environmental effects are conducted in the target region (e.g. Manitoba, a major oat producing province in western Canada) with the genotypes of interest (e.g. those important to current breeding programs and industry).

The objective of this research was to determine the relative effects of genotype, environment and genotype-by-environment interaction on a) the composition and physical attributes of whole and/or milled oats, b) the characteristics and functionality of oat starch and wholemeal and c) the quality of oat end-products processed by laboratory scale methodologies and equipment. Where genotype-by-environment interaction effects were found to be significant, the nature of the interaction was determined (I.E. quantitative or qualitative).

3.2 MATERIALS AND METHODS

3.2.1 Sample Set and Experimental Design

Five oat genotypes (AC Assiniboia, CDC Boyer, AC Medallion, Triple Crown and OT 288) were grown in four replicated test plots at each of six sites in Manitoba, Canada. All of the genotypes are registered cultivars recommended for production in Manitoba with the exception of OT 288, which is a semi-dwarf breeding line. These genotypes were chosen because they are important to breeders, millers and food manufacturers, and they exhibit a range in agronomic characteristics (Table 3.1).

Table 3.1: Description of genotypes.

Genotype	Origin	Status	Height	Hull Colour[1]	Rust Resistance[1]	
					Crown Rust	Stem Rust
AC Assiniboia	Canada	Registered	Tall	Tan	Very Good	Very Good
AC Medallion	Canada	Registered	Tall	White	Very Good	Very Good
CDC Boyer	Canada	Registered	Tall	White	Poor	Very Good
Triple Crown	Sweden	Registered	Tall	White	Very Good	Poor
OT 288	Canada	Breeding Line	Semi-Dwarf	White	Very Good	Very Good

[1] Source of information is the Manitoba Co-operator (1999) except for OT 288.

The environments tested were Silverton, Glenlea and Morden in 1998 and Silverton, Carman, and Winnipeg in 1999. These growing sites were diverse in their soil type, initial soil nutrients and seeding dates (Table 3.2). Plots (40 m^2) were seeded at a rate of 300 seeds/m^2, adjusted according to each genotype's germination rate and kernel weight. Fertilizer (11-52-0) was applied to all plots at seeding at a rate of 23.5 kg/ha.

3.2.2 Sample Preparation

3.2.2.1 Whole Oats. The oat plots were harvested with a Wintersteiger small plot combine (Glenlea 1998, Morden 1998 and Carman 1999), a Hege combine (Silverton 1998), or hand harvested and threshed with a Hege combine (Winnipeg 1999 and Silverton 1999). The grain was cleaned and the whole oats were stored in paper bags at ambient temperature until the time of testing (up to 7 months).

3.2.2.2 Groats. The hulls were removed from a 70 g sample of whole oats with a Codema laboratory dehulling machine (Model #LH5095; Codema Incorporated, Vancouver, BC.) The machine was set as follows: air adjustment sleeve open 1.15 cm, air blast gate open 1.5 cm, initial air pressure 103 psi. The oats were subjected to impact for 1 min and the loosened hulls were removed with air for the following 10 sec. Small amounts of hull remaining in the groats were removed by hand. Groat samples were stored in polyethylene re-sealable bags at -40 °C until testing (up to 12 months).

3.2.2.3 Wholemeal. A 10 g sample of groats (broken pieces removed) was dried at 60 °C for 17 hrs and milled into a wholemeal flour using a Retch Centrifugal Mill (Model #ZM100; Brinkman Instruments, Mississauga, Ont.) equipped with a

Table 3.2: Description of environments.

Year	Environment	Soil Type	Seeding Date	Estimated Available Soil Nutrients (kg/ha)[1]			
				N	P	K	S
1998	Glenlea	Osborne Clay	May 26	35	65	1122	28
	Morden	Altona Light Sandy Loam	May 19	144	38	278	156
	Silverton	Newdale Clay Loam	May 21	441	22	444	119
1999	Carman	Almasippi Very Fine Sandy Loam	May 28	36	67	1044	94
	Winnipeg	Riverdale Silty Clay	May 19	20	76	934	22
	Silverton	Newdale Clay Loam	May 25	172	13	464	179

[1] Soil nutrient evaluations were conducted at Norwest Labs (Winnipeg, Manitoba).

0.5 mm screen. The mill speed was set to 14 000 rpm. Wholemeal samples were stored in polyethylene re-sealable bags at -40 °C until testing (up to 12 months).

3.2.2.4 Starch. Groats were cracked in a Buhr Mill (Model #WKM90-60; Groschoppu Co., Viersen/Rhld.) at setting #10 for 1.5 min. A 10 g sample of this coarsely ground material was soaked in 100 ml of 0.02 N hydrogen chloride (HCl) at 4 °C for 4 hrs to soften the grain and then neutralized to pH 7.0 with 0.2 N sodium hydroxide. The supernatant was removed after centrifugation at 9000 rpm and the grist was ground in a mortar and pestle with 30 ml of Tris-HCl buffer. The enzymes xylanase (30 µl), lichenase (30 µl) and protease K (5 mg) were added to each sample and incubated at 35 °C overnight. The liberated starch was collected by passing through a 75 µ stainless steel sieve and washed with water. The starch was purified by layering over 78 % cesium chloride and centrifuging at 14 000 rpm for 20 min. This was followed by three water washes. The purified starch was recovered by filtering through a 45 µ nylon membrane and rinsed with 5 ml of acetone. Starch samples were dried at ambient conditions overnight, ground into powder and re-dried in a forced air oven at 38 °C for 16 hrs.

3.2.2.5 Defatted Starch. The fat was removed from a 0.5 g portion of the starch with a propanol and water solution according to the method of Morrison and Coventry (1985). Defatted starch was allowed to air dry overnight before it was ground with a mortar and pestle and dried in a forced air oven at 38 °C for 16 hrs.

3.2.2.6 Oat Flakes. A laboratory scale oat conditioning process was developed to mimic heat-moisture treatments used prior to flaking in the processing

industry to inactivate enzymes and alter the functional properties and flavour of oats. The moisture content of 70 g of groats (broken pieces removed) was brought to 17 % with the addition of boiling water in a 500 ml glass mason jar. The jars were immediately closed and the sample was mixed by hand shaking before placing in a 100 °C air oven (Isotemp® Oven 300 Series Model #338F; Fisher Scientific, Nepean, Ont.) for 10 min. Shaking took place during this period at 2 and 6 min to ensure even dispersion of the water and heat. The lids were removed after the 10 min of high moisture heating and the jars were returned to the oven for 45 min with shaking at 5, 10, 20, 30 and 40 min. The lids were returned while the jars were allowed to cool at room temperature for 45 min with periodic shaking. The conditioned groats were then transferred to plastic jars and stored at 10°C. Approximately 70 g of these conditioned oat groats were tempered to 16 % moisture content overnight to soften the kernels prior to flaking on a Marga Mulino flaking machine (Marcato; Campodarsego, Italy). This small scale flaking machine had been modified by the addition of a 42 rpm motor so that a consistent roller speed could be used for all samples. The rollers were set to the smallest gap and a speed of 24 rpm was used. The resulting rolled oats were spread out in two plastic petri dishes (150 mm dia x 15 mm ht) and dried in a 35°C air oven for 1 hr. Fine particles able to pass through a US Standard #10 sieve were removed from the rolled oat samples.

3.2.3 Analytical Methods

3.2.3.1 Hull Content. Hull content was determined using the Codema dehulling machine (see 3.2.2.2) and expressed , in percentage, as the ratio of hull weight to whole oat weight. A single analysis was performed for each sample.

3.2.3.2 Groat Breakage. The groats recovered after dehulling (3.2.2.2) were sorted by hand into whole groats and broken pieces. Groat breakage was calculated as the ratio of broken groat weight to total recovered groat weight and expressed as a percentage. A single analysis was performed for each sample.

3.2.3.3 β-Glucan Content. The total (1-3) (1-4)-β-D-glucan content of oat wholemeal was determined by the AACC Standard Method #32-23 (American Association of Cereal Chemists, 1995). Modifications to this method include the use of a magnetic hot plate and stir bars to achieve continuous stirring in addition to vortex mixing during incubation with lichenase (McCleary and Mugford, 1997). The average of duplicate analyses was calculated for each sample and presented as a percentage on a dry weight basis.

3.2.3.4 Protein Content. Protein content of 200 mg of wholemeal was determined using the Dumas combustion method (Sweeney and Rexroad, 1987) (Model #FP-528; Leco Corporation, St. Joseph, MI). A factor of 6.25 was used to convert amount of nitrogen to protein, which was expressed as a percentage on a dry weight basis. A single analysis was performed for each sample.

3.2.3.5 Oil Content. Oil content of whole oats was measured by Near Infrared (NIR) Scanning (Model #6500; NIR Systems Inc., Silver Spring, MD). NIR calibrations were determined by oat oil data from Nuclear Magnetic Resonance.

3.2.3.6 Total Starch Content. Total starch content of oat wholemeal was determined by the AACC Standard Method #76-13 (American Association of Cereal

Chemists, 1995). A single analysis was performed and presented as a percentage on a dry weight basis.

3.2.3.7 Starch Amylose Content. Amylose content of defatted oat starch was measured by potentiometric titration according to the method of Schoch (1964). A single determination was made for each sample and the results expressed as a percentage of iodine affinity (higher IA indicates higher amylose content).

3.2.3.8 Starch Swelling Volume. Starch swelling volume (SSV) was determined at 92.5 °C using a ratio of 0.35 g of undefatted starch to 12.5 ml of water according to the method of Crosbie (1991). Centrifugation of the tubes resulted in a slanted gel surface, therefore the minimum and maximum gel heights were measured and the average was used to calculate starch swelling volume in cubic centimeters.

3.2.3.9 Pasting Characteristics of Wholemeal and Starch. Pasting properties of oat wholemeal and starch were assessed with a Rapid Visco Analyzer (RVA) (Series 4; Newport Scientific Pty. Ltd., Warriewood, Australia). Either 3.5 g of wholemeal or 2.5 g of starch were mixed with 25 ml of room temperature deionized water in a standard aluminum RVA canister. The RVA profile involved heating the slurry from 50 °C to 95 °C in 4.7 min. The temperature was held at 95 °C for 2.5 min before dropping back to 50 °C and holding for 2 min. The stirring rate was 960 rpm for the first 10 sec and 160 rpm for the remainder of the 13 min test period. The RVA parameters measured included peak (maximum viscosity at 95 °C), hot paste (minimum viscosity at 95 °C), final (viscosity at end of 50 °C hold period), breakdown (peak minus hot paste),

final minus peak and setback (final minus hot paste). Another parameter defined by Shim and Mulvaney (1999) called shear thinning was calculated as peak minus hot paste, expressed as a percentage of the peak viscosity. Viscosity is expressed in RVU (1 RVU is equivalent to 12 centipoise). An example of a typical RVA curve is shown in Figure 3.1.

3.2.3.10 Starch Gel Texture. Preparation of the oat starch gel for textural analysis was achieved by using the samples that underwent starch RVA testing. The RVA mixing paddle was immediately removed from the canister. Upon completion of the pasting test the surface of the hot starch paste was gently smoothed with a spatula. The canister (37 mm dia x 68 mm ht) was covered with plastic wrap and placed under refrigeration for 24 hrs. The texture of the resulting starch gel was characterized by texture profile analysis 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, following the same path as the first puncture. This procedure was performed at five positions on each gel sample. Parameters measured include gel strength for the first and second compressions (area of work under each of the positive peaks), adhesiveness (area of work for the negative peak), cohesiveness (ratio of gel strength for the second compression to that of the first compression), springiness (ratio of second to first time difference from peak onset to maximum force), gumminess (ratio of maximum force at first peak to cohesiveness) and resilience (ratio of area of first peak

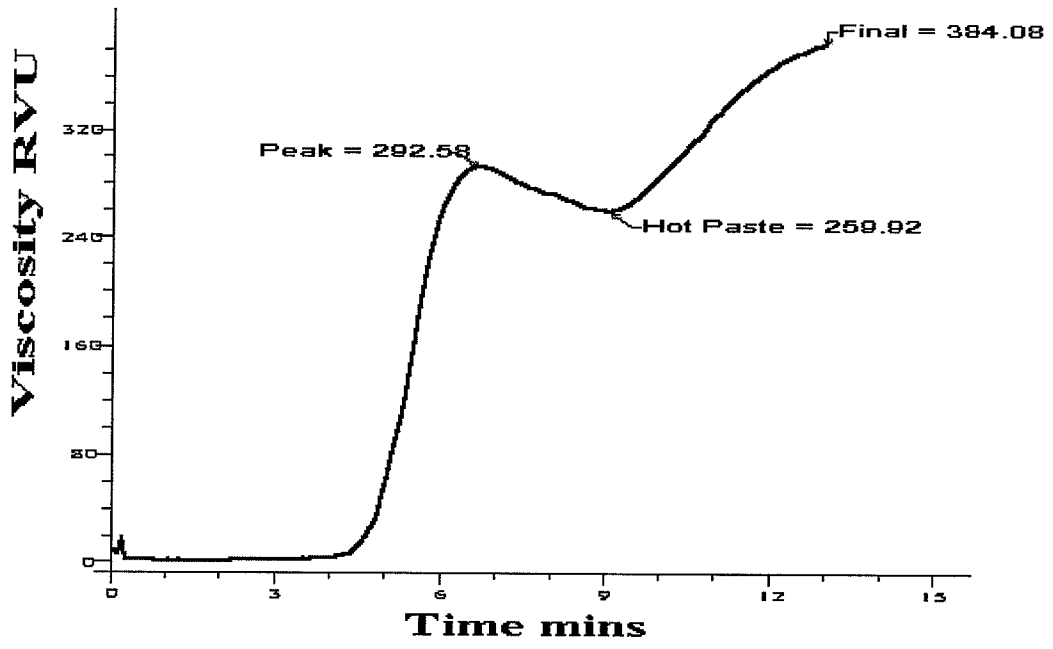


Figure 3.1: Example of an RVA oat starch pasting curve.

after maximum force to area before maximum force). A typical texture profile analysis curve is shown in Figure 3.2.

3.2.3.11 Thermal Properties of Starch. Thermal properties of oat starch were assessed using a Differential Scanning Calorimeter (DSC) (Model #2010; TA Instruments, New Castle, DE). Hermetically sealed aluminum DSC pans containing starch and deionized water (40 % solids) were heated to 140 °C at a rate of 10 °C/min. The change in enthalpy as a function of temperature was recorded, resulting in two endothermic peaks, the first corresponding to the melting of the starch crystalline structure (gelatinization of amylopectin) (AP) and the second peak corresponding to the melting of the amylose-lipid complex (AM). The parameters measured include the onset temperature, peak temperature and ΔH (total energy change) associated with each of the endothermic peaks. A typical oat starch DSC curve is shown in Figure 3.3.

3.2.3.12 Oat Flake Granulation. A Ro-Tap equipped with US Standard #5, 8 and 10 sieves was used for 2 min to separate each rolled oat sample into sizes that were larger than #5 (> 4.00 mm), between #5 and #8 (< 4.00, >2.36 mm), between #8 and #10 (<2.36, >2.00 mm), and smaller than #10 (<2.00 mm). The weight of each size class was calculated as a percentage of the starting sample weight (approximately 70 g).

3.2.3.13 Oat Flake Hydration Capacity. Water absorption of the rolled oat samples was measured by the AACC method #88-10 (Lane et al., 1997) with the following modification: the sample size was scaled down by one half to a ratio of 25 g of rolled oats to 100 ml of water. The hydration capacity was therefore expressed in grams of water/25 g of groats.

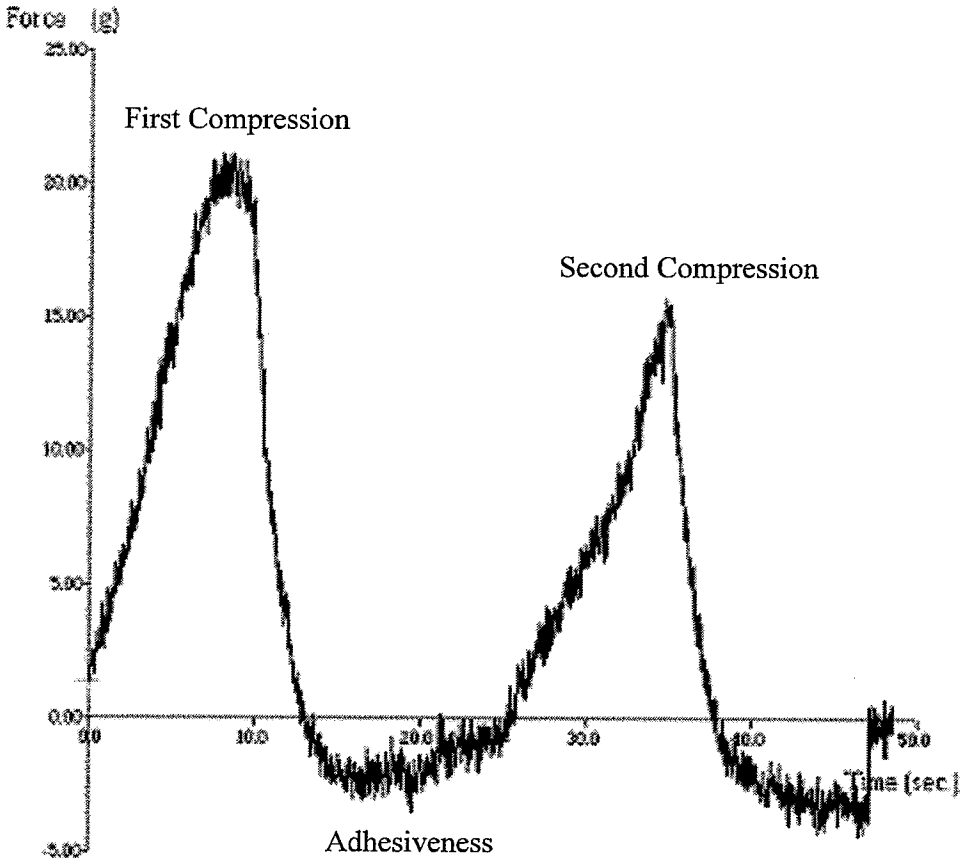


Figure 3.2: Example an of oat starch gel texture curve.

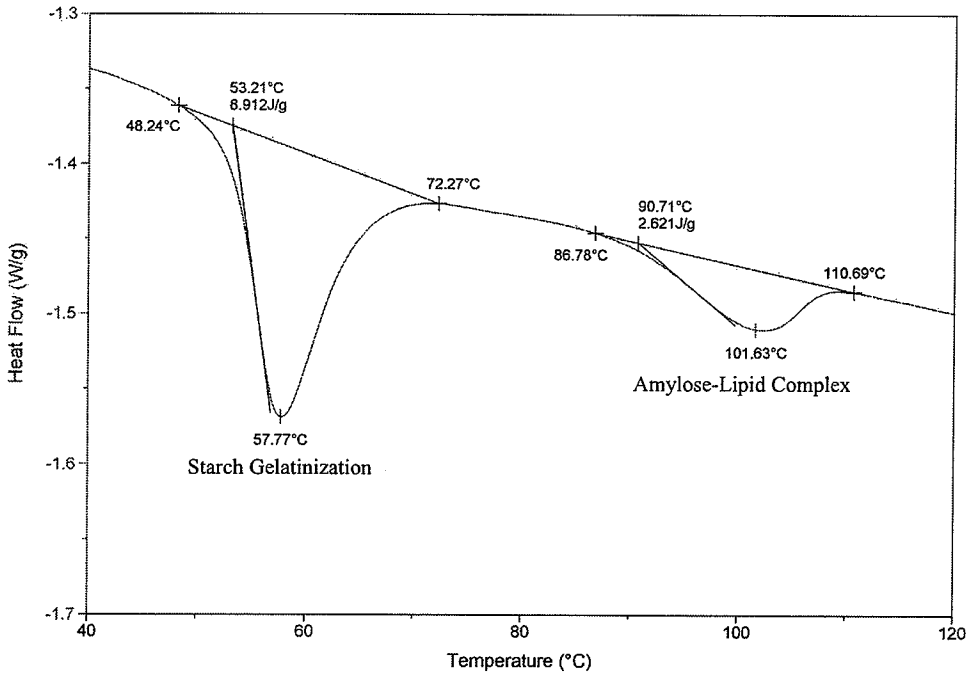


Figure 3.3: Example of an oat starch DSC curve.

3.2.3.14 Cooked Oatmeal Texture. Cooked oatmeal was prepared by combining 30 g of rolled oats with 120 ml of room temperature deionized water in a 1.6 L glass bowl. The mixture was cooked uncovered in a microwave oven (Carousel Model #311C(W)C; Sharpe Electronics of Canada, Mississauga, Ont.) on high power for 210 sec, stirring once at the midpoint in cooking time. The oatmeal was stirred again, covered with aluminum foil, and allowed to stand for 1 min at which point it was transferred to a metal canister (37 mm dia x 68 mm ht) and leveled off flush with the top. One minute after the end of the stand time, the texture of the oatmeal was evaluated using a TA-XT2*i* Texture Analyser (Texture Technologies, Scarsdale, NY) equipped with a 5 kg load cell. A ¾ inch ball probe (TA-18A; Texture Technologies, Scarsdale, NY) was positioned 7.5 cm above a base plate (TA-90A; Texture Technologies, Scarsdale, NY) and the sample was centered under the probe using a cardboard template to ensure consistent positioning. The probe descended at a rate of 1 mm/sec into the sample canister for a distance of 40 mm after a trigger force of 0.005 N was detected at the surface. The probe then ascended to its starting position. During the test, oatmeal was displaced by the probe and allowed to overflow the canister to create a back extrusion style test. The parameters measured include peak force, adhesive force and stringiness (length of time oatmeal is in contact with the ascending probe). An example of a typical cooked oatmeal texture analysis curve is shown in Figure 3.4.

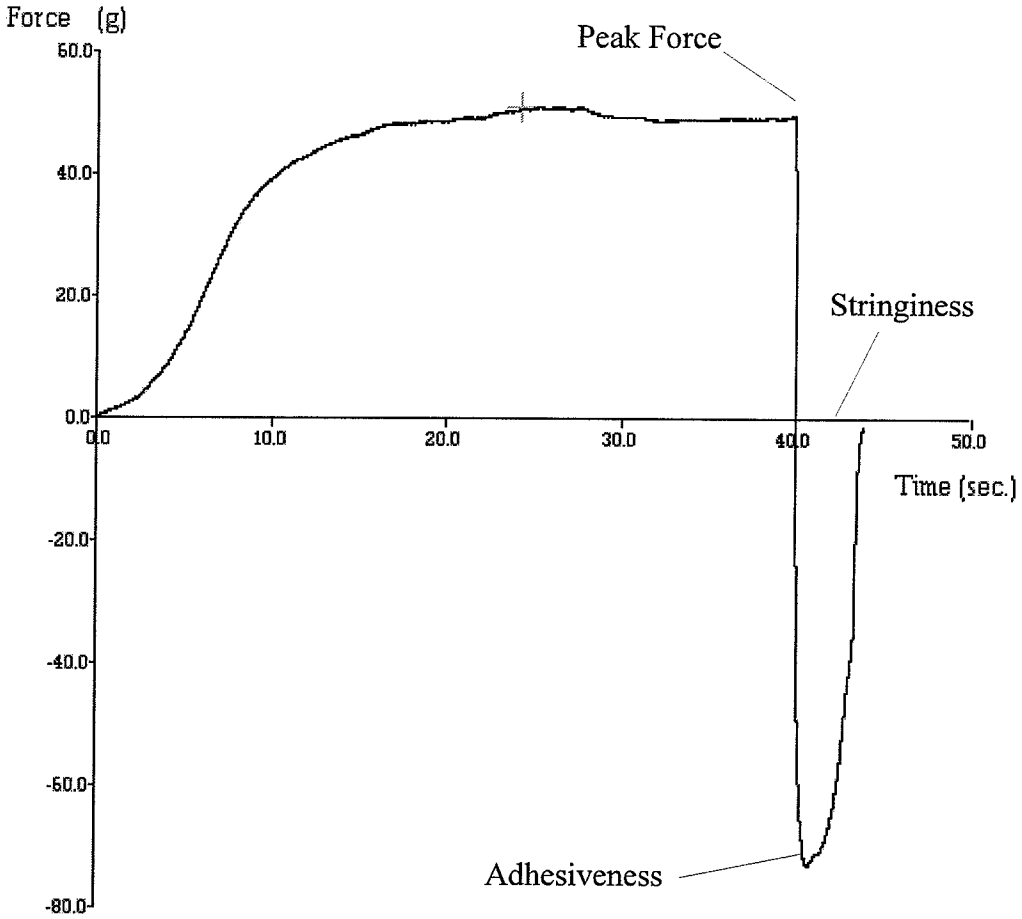


Figure 3.4: Example of an oatmeal texture curve.

3.2.3.15 Moisture Content. Moisture content analysis of wholemeal required to present β-glucan, total starch, and protein contents on a dry weight basis was performed according to the AACC method #44-15A (American Association of Cereal Chemists, 1995) using approximately 1 g of sample. Groat and rolled oat samples were ground with a coffee grinder and weighed immediately for moisture content analysis by the same method as above.

3.2.4 Statistical Analysis

Prior to any statistical analysis, uniformity of error variances among environments was tested using the F-Max test to determine if data could be pooled (Milliken and Johnson, 1984). Pooling environments for analysis without achieving homogeneity of error variances would have either over or underestimated the error variance resulting in inaccurate analysis of variance (ANOVA) testing. This test of homogeneity involved calculating the error variance for each of the six environments and dividing the largest by the smallest. If the ratio was less than a critical value (1 % probability level), the environments were pooled for analysis. There were a few parameters for which the ratio exceeded the critical value (Table 3.3). In these cases, an attempt was made to identify outlying data points that had residual values greater than three times the square root of the mean square error. Failing this, log and square root transformations were performed and the F-max was repeated on the transformed data. None of these efforts successfully solved the heterogeneous error variance problem. It was decided to group environments with homogeneous error variances to create smaller pools of data. The Carman and Winnipeg sites were analyzed separately from the other environments for hull content.

Table 3.3: Summary of F-Max test for homogeneity of environment error variances.

Quality Parameter	Environmental Error Variance			Homogeneous Error Variances (if ≤ 8.2)
	Minimum	Maximum	Ratio Max/Min	
Hull Content	0.344	3.180	9.2	NO
Groat Breakage	3.634	14.707	4.0	YES
Protein	0.192	1.302	6.8	YES
β-Glucan	0.027	0.148	5.6	YES
Oil	0.007	0.031	4.4	YES
Total Starch	0.393	1.231	3.1	YES
Iodine Affinity	0.002	0.004	2.0	YES
Starch Swelling	0.032	0.138	4.3	YES
Starch RVA				
Peak	8.426	60.696	7.2	YES
Hot Paste	55.262	158.732	2.9	YES
Final	187.226	637.819	3.4	YES
Breakdown	29.152	92.197	3.2	YES
Final - Peak	149.450	462.239	3.1	YES
Setback	73.824	331.312	4.4	YES
Shear Thinning	9.870	30.459	3.1	YES
Starch Gel Texture				
Gel Strength (1st Compression)	0.711×10^{-5}	3.228×10^{-5}	4.5	YES
Gel Strength (2nd Compression)	0.008	0.050	6.2	YES
Adhesiveness	3.824	30.693	8.0	YES
Cohesiveness	0.813×10^{-4}	5.077×10^{-4}	6.3	YES
Springiness	29.468	142.317	4.8	YES
Gumminess	0.475×10^{-3}	1.821×10^{-3}	3.8	YES
Resilience	0.572	3.213	5.6	YES

Table 3.3 Continued: Summary of F-Max test for homogeneity of environment error variances.

Quality Parameter	Environmental Error Variance			Homogeneous Error Variances (if ≤ 8.2)
	Minimum	Maximum	Ratio Max/Min	
Starch DSC[1]				
AP Onset Temp.	0.020	0.157	7.8	YES
AP Max. Temp.	0.039	0.177	4.5	YES
AP ΔH	0.026	0.128	4.9	YES
AM Onset Temp.	0.084	1.644	19.5	NO
AM Max. Temp.	0.057	0.359	6.3	YES
AM ΔH	4.821×10^{-3}	49.319×10^{-3}	10.2	NO
Wholemeal RVA				
Peak	31.725	428.436	13.5	NO
Hot Paste	17.667	266.191	15.1	NO
Final	30.992	381.118	12.3	NO
Breakdown	12.558	73.118	5.8	YES
Final - Peak	20.467	147.753	7.2	YES
Flake Hydration	0.124	0.573	4.6	YES
Flake Granulation				
> 4 mm	6.894	33.397	4.8	YES
< 4 mm, > 2.36 mm	7.193	26.532	3.7	YES
< 2.36 mm, > 2 mm	0.056	0.134	2.4	YES
< 2 mm	0.204	0.731	3.6	YES
Oatmeal Texture				
Peak Force	55.805	462.591	8.2	YES
Adhesive Force	71.690	189.420	2.6	YES
Stringiness	0.572	2.092	3.7	YES

[1]AP refers to the enthalpy peak associated with the gelatinization of amylopectin; AM refers to the enthalpy peak associated with the melting of the amylose-lipid complex.

The 1998 Silverton site was excluded from the pooled analysis for all wholemeal RVA parameters. The Winnipeg site was analyzed separately only for the amylose-lipid portion of the DSC curve.

All statistical analyses were performed using SAS software (Version 8, 1999-2001; SAS Institute, Cary, NC, USA). The analysis of variance (ANOVA) and cross-over procedures (PROC MIXED) considered genotype, environment and their interaction to be fixed whereas the replicate effect was random. A Tukey's Test was also conducted to identify which genotype and environment means differed significantly. The cross-over analysis was performed to test for significant changes in the rank order of genotypes across the different environments (Baker, 1988). This analysis involved calculating t-values (difference/standard error) for ten possible genotype comparisons at each of the six environments. The largest and smallest t-values for a given genotype pair were then compared to a critical t-value. If there was a negative and a positive t-value, and both were larger in absolute value than the critical t-value, then a significant ($P \leq 0.05$) cross-over effect had occurred. This meant that, for example, Genotype 1 was significantly lower than Genotype 2 for a particular parameter when grown at one or more environments, but that Genotype 1 was also significantly higher than Genotype 2 at one or more other environments.

Component of variation analysis (PROC MIXED) was performed to gain a better understanding of the relative effects of the factors under study. The calculation of the variance components (expressed as a percentage of total variation for a given parameter) required that all factors be considered random effects. It is therefore important to note

that the variance components presented are only estimates and that they apply only to the genotypes and environments used in this study. Pearson correlation coefficients were computed (PROC CORR) using genotype means.

3.3 RESULTS AND DISCUSSION

ANOVA summary tables are presented in Appendix 1. Appendix 2 contains a correlation matrix for all quality parameters.

3.3.1 Hull Content

Heterogeneous error variances between the six environments prevented a completely pooled statistical analysis of hull content across all environments. Instead, selected environments with homogeneous error variances (Silverton 1998, Morden 1998, Glenlea 1998, Silverton 1999) were pooled and analyzed separately from the remaining two sites (Winnipeg 1999, Carman 1999). Significant ($P \leq 0.01$) genotype, environment and genotype-by-environment interaction effects were found for both environmental groupings.

The group of data which pooled all environments except Winnipeg and Carman was used to test for cross-over effects. Two out of sixty possible genotype comparisons across environments contributed to significant cross-over effects. Both pairs involved OT 288. In the first case, AC Assiniboia showed a large increase in hull content at the Silverton 1998 site, as did all other genotypes except OT 288 (Figure3.5). OT 288's response to this environment was not as pronounced, leading to a significant change in rank order with AC Assiniboia. The second significant cross-over also occurred at

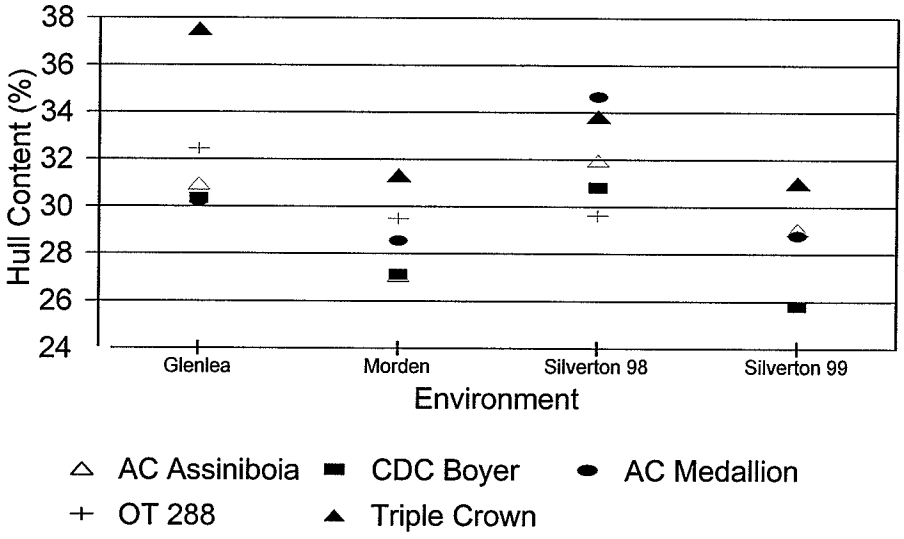


Figure 3.5: Change in rank order of genotypes across environments for oat hull content.

Silverton 1998 where OT 288 had significantly less hull content than AC Medallion as opposed to at Glenlea, where its hull content was significantly higher. The cause of these significant changes in rank order of genotypes across environments needs to be investigated further. Burrows (1986) indicated that lodging, for which tall cultivars are particularly at risk, can result in shrunken groats and high hull contents. OT 288's inherently short height may be indirectly linked to its low hull content at the Silverton 1998 site. Environmental conditions leading to lodging at this site may have lead to poor grain filling and thus high hull content in tall cultivars with less of an impact on OT 288. If this were the case, breeding for both low hull content and short plant height would be important. If the reason for these cross-over interactions cannot be determined, breeding at multiple sites to ensure accurate selection for low hull content would be necessary. Other than in the two cases discussed, there were no significant changes in rank order of the genotypes across the four environments.

Genotype means calculated across replicates and the four pooled environments ranged from 28.52 % (CDC Boyer) to 33.43 % (Triple Crown). Environment means calculated across replicates and genotypes showed a similar range from 28.69 % (1999 Silverton) to 32.18 % (Silverton 1998). The average coefficient of variation among genotypes was only slightly less (6.39 %) than for environments (6.83 %). CDC Boyer and Triple Crown also had respectively the lowest and highest hull contents at the Carman and Winnipeg sites (Table 3.4). Winnipeg, on average, resulted in the highest hull content of all sites studied.

Table 3.4: Genotype and environment means for oat hull content (Carman and Winnipeg locations).[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Carman	30.23	28.32	31.68	32.29	36.01	2.55	31.71
Winnipeg	34.16	29.66	33.76	35.44	38.39	2.82	34.28
Std[2]	1.97	0.67	1.04	1.58	1.19		
Mean	32.20	28.99	32.72	33.87	37.20		

[1] Values are expressed in percentage.
[2] Std = Standard Deviation

Variance component analysis (also excluding Carman and Winnipeg sites) showed that environment contributed the most variation in hull content (30.72 % of total variation) followed by genotype (24.28 %) (Figure 3.6). The contribution of the genotype-by-environment interaction effect to total variation was slightly over half of that of the environment (16.60 %). These results are in agreement with other studies showing large effects of genotype and location on hull and groat percent (Ronald et al., 1999; Zhou et al., 1999a). Discrepancies between studies with regards to whether genotype or location effects are greater, are likely a function of the diversity of genotypes and environments used in each study. In this study large environmental effects on hull content could have been confounded by the use of different threshing machines for different sites, which can influence the amount of hull remaining in a grain sample. The large effect of environment suggests that it is important for millers to consider location when identifying sources of oats with low hull content. For example, Ronald et al. (1999), suggested that drought stress causes the hull content of oats to increase.

3.3.2 Groat Breakage

Groat breakage was also significantly affected ($P \leq 0.01$) by genotype, environment and genotype-by-environment interaction effects. The significant interaction effect indicates that the genotypes varied in their response to different environments but cross-over analysis detected no significant change in their rank order between the six growing sites (Figure 3.7). Breeders could successfully select for low breakage at any of the environments. Triple Crown exhibited the least groat breakage at all environments with

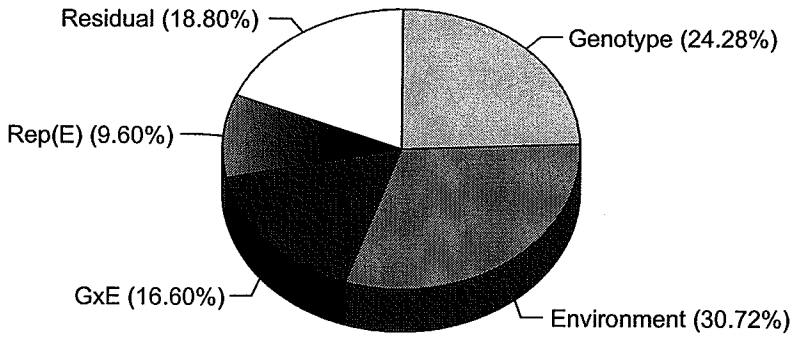


Figure 3.6: Relative contributions of factors to total variation in oat hull content.

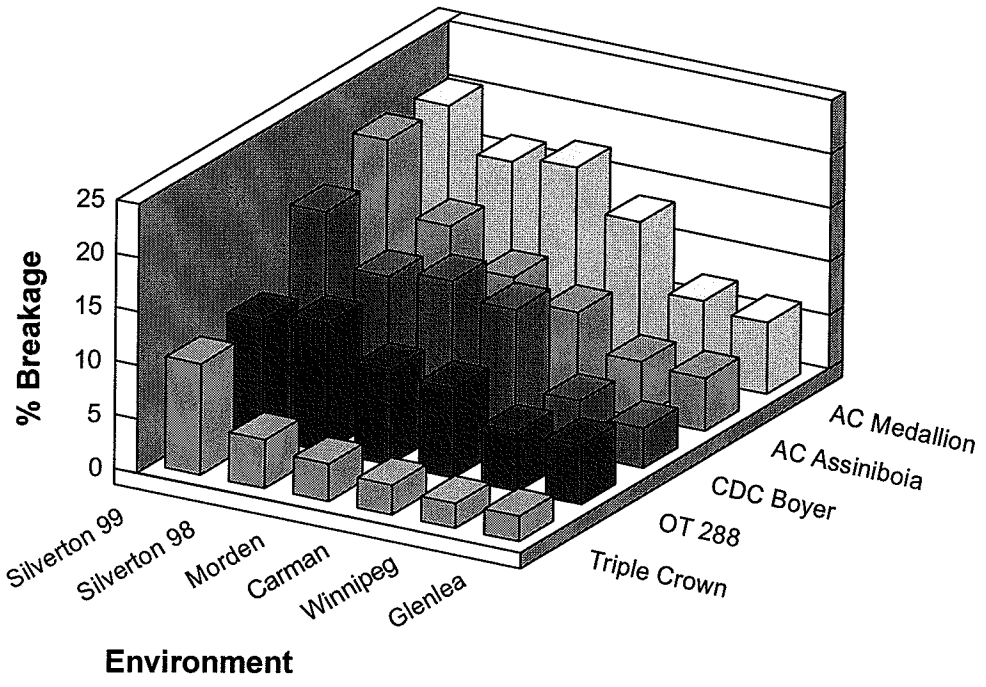


Figure 3.7: Effect of genotype and environment on oat groat breakage.

an overall mean of 4.31 % (Table 3.5). The overall mean for the other genotypes ranged from 9.67 % (OT288) to 13.14 % (AC Medallion). Rossnagel (1999) also designated Triple Crown as a low breakage type. Doehlert et al. (1999) typically found lower breakage values using a compressed air dehuller (1.5 to 3.7 %) than were found in this study, but discrepancies are likely due to machine settings and to the different environments studied. Despite differences in the range of values, they also found that AC Medallion tended to have higher breakage (3.7 %) than AC Assiniboia (1.6 %).

The 1999 Silverton growing site produced oats with the highest susceptibility to groat breakage, in some cases up to 20 %. Oats grown at Glenlea showed the least breakage (overall mean 5.28 %) (Table 3.6). Doehlert and McMullen (2000) also found large differences in breakage among growing sites and attributed some of the worst breakage to sites infected with crown rust. Other environmental factors must also play a role in groat breakage since the crown rust resistant genotypes in the present study did not necessarily fare better than CDC Boyer (poor crown rust resistance) at environments with high mean breakage values.

Component of variation analysis (Figure 3.8) confirmed the small role of the genotype-by-environment interaction in total variation (6.20 %). Environment was the largest contributor to variation (36.08 %). Genotypic variation was also high (26.95 %) which indicates that breeder selection for low breakage types is possible at only a few environments showing extreme values in breakage. In the meantime, millers wishing to minimize economic loss due to groat breakage should consider contracting low breakage

Table 3.5: Genotype means for oat groat breakage.

	Genotype				
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown
Mean[1]	10.33 b	12.17 bc	13.14 c	9.67 b	4.31 a
Std[2]	5.26	5.08	4.40	2.34	2.90

[1] Values represent a mean across six environments and are expressed in percentage. Values followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard deviation for genotype across six environments.

Table 3.6: Environment means for oat groat breakage.

	Environment					
	Glenlea	Morden	Silverton '98	Carman	Winnipeg	Silverton '99
Mean[1]	5.48 a	9.93 ab	12.29 ab	8.99 a	6.14 a	16.71 b
Std[2]	2.13	4.16	4.27	3.65	2.08	4.04

[1] Values represent a mean across five genotypes and are expressed in percentage. Values followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard deviation across five genotypes within each environment.

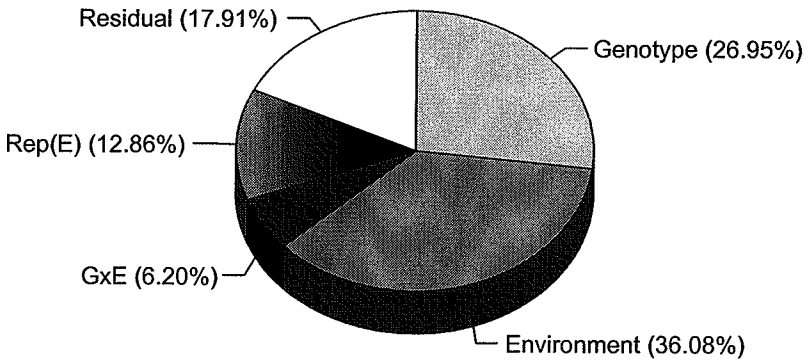


Figure 3.8: Relative contributions of factors to total variation in oat groat breakage.

genotypes such as Triple Crown, but be aware that environmental conditions could still result in high breakage.

It should be noted that Triple Crown exhibited the lowest level of breakage and the highest hull content. The trend between these two characteristics was quite high although the correlation coefficient was not significant ($r = -0.85$; $P = 0.0699$). Although this is a contradiction in terms of quality it is possible that these two parameters may be directly related. Other researchers have also found this relationship suggesting that thicker hulls protect the groats from damage during dehulling (Doehlert et al., 1999; Doehlert and McMullen, 2000).

Components in the groats may also impact breakage. In this study, the correlation between protein content and breakage was significant ($r = -0.91$; $P = 0.0346$), which is supported by Doehlert and McMullens' observation that when protein was affected by crown rust damage, breakage increased. Preliminary work by Rossnagel (1999) did not show a relationship between breakage and protein. Other researchers have reported that low groat breakage is negatively correlated to oil (Rossnagel, 1999) and slightly, but significantly, negatively correlated to β-glucan content (Doehlert and McMullen, 2000). In the present study, a weak trend between low groat breakage and high β-glucan ($r = -0.57$; $P = 0.3108$) and low oil content ($r = 0.73$; $P = 0.1654$) was found. More intense investigation is required to better understand the role, if any, that these components play in groat breakage and to pinpoint the environmental factor or factors leading to increased groat breakage. Analysis of other components, such as bran yield

and phenolic acids, may also help explain variation in groat breakage (Engleson and Fulcher, 2001).

3.3.3 β-Glucan Content

The β-glucan content of oat wholemeal varied significantly ($P \leq 0.01$) with genotype. Genotype means calculated across replicates and environments showed a range from 4.33 % (OT 288) to 5.69 % β-glucan (Triple Crown) (Table 3.7). There are currently no published reports on the β-glucan content of the genotypes used in this study but the values observed are within the range obtained for other registered cultivars (Peterson, 1991; Asp et al., 1992; Lim et al., 1992; Saastamoinen et al., 1992; Cho and White, 1993; Miller et al., 1993b; Brunner and Freed, 1994; Lee et al., 1997).

The effect of environment on β-glucan content was not significant at a 1 % probability level. Environment means calculated across replicates and genotypes ranged from 4.66 % (Winnipeg) to 5.04 % (1998 Silverton). Peterson (1991) found a slightly larger range in average β-glucan content (5.4 to 6.1 %) between nine environments in the United States. Low precipitation and high temperatures have been implicated as possible factors leading to high β-glucan content (Peterson, 1991; Miller et al., 1993a; Brunner and Freed, 1994). Temperature and precipitation records were not available for the sites used in this study, making it difficult to assess whether or not conditions expected to affect β-glucan were extreme enough in the six sites studied to maximize environmental differences.

Table 3.7: Genotype and environment means for oat wholemeal β-glucan content.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	4.27	5.29	4.73	4.22	6.01	0.67	4.90 a
Morden	4.46	4.94	4.82	4.46	5.54	0.40	4.84 a
Silverton '98	4.62	5.12	4.97	4.51	5.98	0.52	5.04 a
Carman	4.34	5.02	4.71	4.27	5.42	0.43	4.75 a
Winnipeg	4.27	5.02	4.46	4.02	5.55	0.55	4.66 a
Silverton '99	4.31	5.24	4.94	4.49	5.65	0.49	4.93 a
Std[2]	0.13	0.13	0.17	0.18	0.22		
Mean	4.38 a	5.11 c	4.77 b	4.33 a	5.69 d		

[1] Values are expressed in percentage. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

The genotype-by-environment interaction effect on β-glucan content was not significant indicating that breeder selection of superior genotypes could be done consistently at any of the six environments studied. Triple Crown had the highest β-glucan content at all environments and AC Assiniboia and OT 288 consistently had the lowest. Component of variation analysis (Figure 3.9) supported the lack of practical significance of the genotype-by-environment interaction and showed that genotype played a much greater role in total variation (78.46 %) than environment (2.92 %), which is in agreement with the findings of Miller et al. (1993a) and Peterson (1991).

Once again, there is evidence of Triple Crown possessing the most desirable characteristics (high β-glucan and low breakage) along with poor qualities (high hull content). Breeders may be concerned that selecting for a desirable trait that is genetically linked to an undesirable one, may result in a genotype with an unbalanced quality profile. The data showed evidence of a trend between high β-glucan and high hull content ($r = 0.51$, $P = 0.3849$). A more favorable trend from a quality perspective indicated that if β-glucan increased, breakage tended to decrease ($r = -0.57$; $P = 0.5936$). Previous research has found both positive (Brunner and Freed, 1994) and negative (Miller et al., 1993b) correlations between β-glucan and protein. No significant correlation between these two parameters was found in this study ($r = 0.35$; $P = 0.5650$) nor was there a correlation between β-glucan and oil content ($r = -0.66$; $P = 0.2220$). This finding did not

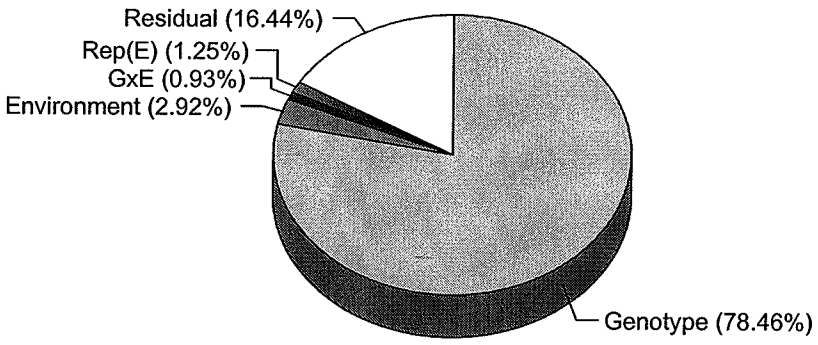


Figure 3.9: Relative contributions of factors to total variation in oat wholemeal β-glucan content.

agree with that of Asp and colleagues (1992) who observed a positive correlation between these two traits. Neither the current study nor previous research gives any strong evidence that selecting for high β-glucan content would concurrently result in detrimental effects on other quality characteristics.

3.3.4 Protein Content

Oat wholemeal protein content was significantly ($P \leq 0.01$) affected by genotype as has been well documented in the literature (Welch and Yong, 1979; Peltonen-Sainio and Peltonen, 1993; Humphreys et al., 1994b; Zhou et al., 1998b). There was a difference of 0.85 to 2.33 % protein content among genotypes depending on the growing site. Overall, Triple Crown had the highest protein content (15.04 %) and AC Medallion had the lowest protein content (14.10 %) (Table 3.8).

The effect of environment was also highly significant ($P \leq 0.01$) . Mean protein content for the six environments ranged from 12.81 % (1999 Carman) to as high as 17.83 % (1999 Silverton) (Table 3.9), thus contributing to environment as the dominant factor contributing to total variation (Figure 3.10). Other researchers observed different protein values depending on the growing year, which suggests the influence of weather conditions such as temperature and moisture (Peltonen-Sainio and Peltonen, 1993). The geographic diversity of the environments in this study likely exposed the test plots to different weather conditions, thus contributing to differences in protein content. Another likely explanation for the large environmental variation is the difference in soil nitrogen levels at the six sites. Morden, 1998 Silverton and 1999 Silverton all had soil nitrogen

Table 3.8: Genotype means for oat wholemeal protein content.

	Genotype				
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown
Mean[1]	14.39 ab	14.32 ab	14.01 a	14.85 ab	15.04 b
Std[2]	1.64	2.03	2.04	1.99	1.80

[1] Values represent a mean across six environments and are expressed in percentage. Values followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard deviation for genotype across six environments.

Table 3.9: Environment means for oat wholemeal protein content.

	Environment					
	Glenlea	Morden	Silverton '98	Carman	Winnipeg	Silverton '99
Mean[1]	13.45 a	16.12 bc	17.83 c	12.81 a	12.82 a	14.20 ab
Std[2]	0.79	0.55	0.41	0.32	0.50	0.69

[1] Values represent a mean across five genotypes and are expressed in percentage. Values followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard deviation across five genotypes within each environment.

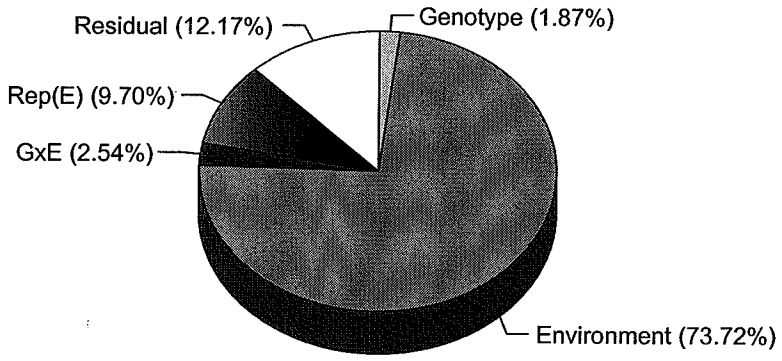


Figure 3.10: Relative contributions of factors to total variation in oat wholemeal protein content.

levels greater than 144 kg/ha, producing oats with mean protein contents of 16.12, 17.83 and 14.20 % respectively. In contrast, the other three sites, which had soil nitrogen levels of 20 to 35 hg/ha, produced oats with lower mean protein contents (12.81 to 13.45 %). This association between high nitrogen availability and high protein content suggests that soil fertility plays an important role in the variability of oat protein content.

The genotype-by-environment interaction on protein content was not significant at the 1 % probability level indicating that selection for high or low protein would be successful at any of the sites (Figure 3.11). Ohm (1976) found a significant genotype-by-environment interaction effect on protein but gave no indication as to whether or not the rank order of the genotypes changed.

There was a trend towards increasing protein content as total starch decreased ($r = -0.70$; $P = 0.1873$) as was found by Asp and colleagues (1992). This is in keeping with the concept that the two major components in the groat are protein and starch, so that as one component increases, the other will generally decrease. Similarly, several researchers have suggested that the growing conditions that promote high protein also tend to result in low oil (Brown et al., 1966; Saastamoinen et al., 1990; Zhou et al., 1999b). The current study found a weak trend between high protein and low oil contents ($r = -0.38$; $P = 0.5238$).

3.3.5 Oil Content

The values for oil content as measured by NIR analysis are at the low end (< 5 %) of the typical range in values reported by other researchers. For example values of 3.1

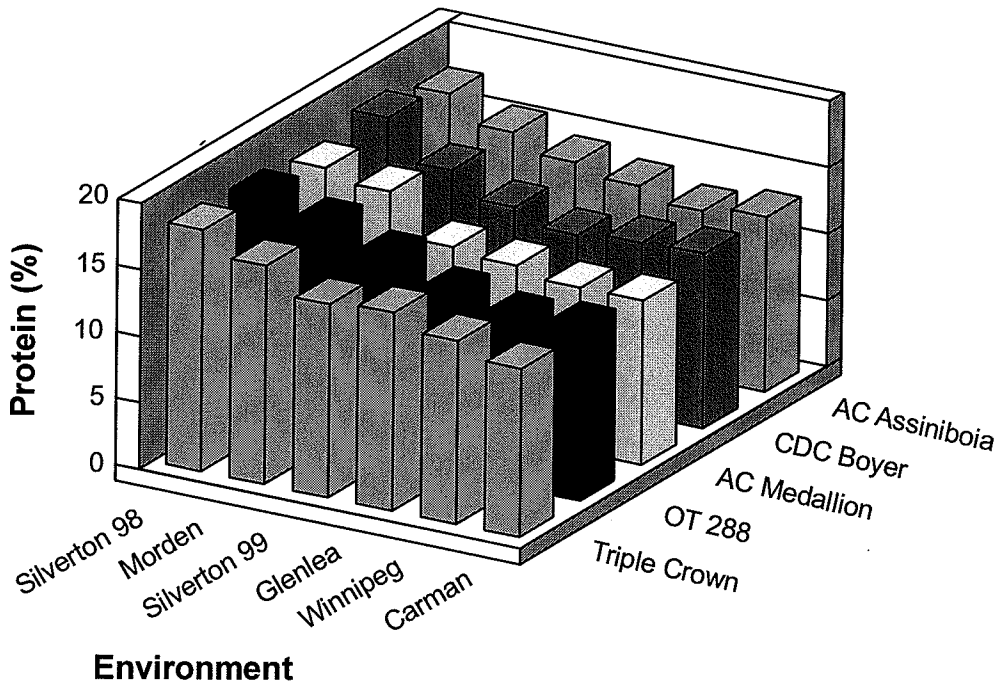


Figure 3.11: Effect of genotype and environment on oat wholemeal protein content.

to 11.6 % oil were reported by Brown and Craddock (1972). The low values obtained in the present study are likely due to the fact that whole oats were tested as opposed to groats. The hull contains less than approximately 3 % of the total oil content (Youngs, 1978) and therefore contributes to a diluting effect on the majority of the oil found in the groat. Whole oat oil values between 4 and 5 %, once corrected for hull content (example 30 % hull), would result in groat oil contents between 5.7 and 7.1 %, which are in closer agreement with values found in the literature. The results for whole oat oil content still show the relative differences between the treatments examined in this study.

Oat oil content was significantly affected by both genotype and environment despite the relatively small range in variation observed for this trait. Genotype means across replicates and environments showed less than a 1 % range in oil content as did the overall environment means (Table 3.10). It is possible that the use of a chemical analysis method for measuring groat oil content would have detected a larger range in values, while NIR was only able to show relative differences.

The genotype-by-environment interaction effect on oil content was not significant. For example Triple Crown consistently had the lowest oil content at all environments. This lack of interaction between genotype and environment was in contrast to the findings of Zhou et al. (1999b) that showed significant differences in the response of Australian genotypes grown at different locations.

Variance components for whole oat oil content (Figure 3.12) showed a small contribution of the genotype-by-environment interaction effect to total variation (1.13 %)

Table 3.10: Genotype and environment means for whole oat oil content.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	4.24	4.42	4.56	4.49	4.06	0.18	4.35 a
Morden	4.09	4.35	4.06	4.24	3.98	0.13	4.14 a
Silverton '98	4.29	4.30	4.37	4.49	4.06	0.14	4.30 a
Carman	4.48	4.55	4.80	4.85	4.42	0.17	4.62 b
Winnipeg	4.51	4.68	4.74	4.91	4.35	0.19	4.64 b
Silverton '99	4.58	4.78	4.91	4.99	4.45	0.20	4.74 b
Std[2]	0.17	0.17	0.29	0.27	0.19		
Mean	4.37 b	4.51 c	4.57 cd	4.66 d	4.22 a		

[1] Values are expressed in percentage. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

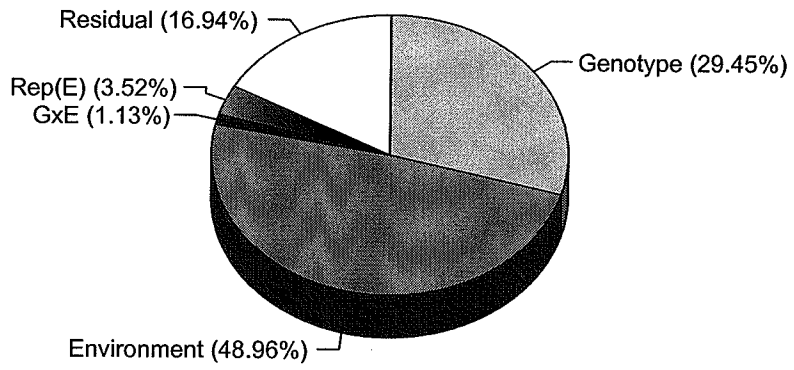


Figure 3.12: Relative contributions of factors to total variation in whole oat oil content.

and a somewhat higher contribution of environment (48.96 %) compared to genotype (29.45 %). Large environmental effects on oil content were found in other studies (Saastamoinen et al., 1989; Saastamoinen et al., 1990; Peltonen-Sainio and Peltonen, 1993; Zhou et al., 1999b) although for the genotypes and environments studied by Zhou et al. (1999b), genotype effects were slightly more predominant. The results of this study indicate that growing site should be an important consideration in sourcing oats with either high or low oil content. Due to a low contribution of genotype-by-environment interaction and a significant genotypic influence, breeder selection for high or low oil genotypes should be successful using only a few locations. This is in agreement with findings by Branson and Frey (1989) and Frey and Holland (1999).

3.3.6 Total Starch Content

Total starch content of oat wholemeal ranged from 60.68 to 66.41 % depending on the genotype and environment, which were both significant ($P \leq 0.01$) effects. The genotype-by-environment interaction effect was not significant at a 1 % probability level.

Overall genotype means ranged from 62.95 % (Triple Crown) to 64.37 % (AC Assiniboia) and the overall environment means ranged from 61.07 % (1998 Silverton) to 65.18 % (Winnipeg) (Table 3.11). The three environments where the lowest total starch contents occurred also had the highest residual soil nitrogen levels and vice versa. This trend is opposite to what was observed for protein content and supports previous research by Paton (1977) who also found a decrease in total starch and an

Table 3.11: Genotype and environment means for oat wholemeal total starch content.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	65.01	65.63	64.80	65.26	63.00	0.91	64.74 a
Morden	63.55	63.18	61.76	62.16	61.78	0.74	62.49 ab
Silverton '98	61.89	60.79	61.20	60.68	60.78	0.45	61.07 a
Carman	65.19	65.11	65.27	64.67	64.52	0.30	64.95 b
Winnipeg	66.41	65.32	64.63	65.51	64.03	0.81	65.18 b
Silverton '99	64.20	64.54	63.97	62.13	63.61	0.84	63.69 ab
Std[2]	1.42	1.68	1.56	1.83	1.30		
Mean	64.37 c	64.10 bc	63.61 abc	63.40 ab	62.95 a		

[1] Values are expressed in percentage. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

increase in protein with a highly fertilized environment. In addition, some environments resulted in greater differentiation between genotypes than others. The degree of differentiation between genotypes at a given site for total starch was not related to soil nitrogen but did match the same trend for protein; ranking of coefficients of variation among genotypes at the six sites was nearly identical for both total starch and protein. Component of variation analysis showed relatively low contributions of genotype-by-environment interaction and genotype effects to total variation (3.64 and 5.36 % respectively) compared to environment (53.56 %) (Figure 3.13).

3.3.7 Starch Amylose Content

IA values for oat starch were significantly affected ($P \leq 0.01$) by genotype and environment but the interaction was not significant. Values ranged from as low as 5.07 % to as high as 5.51 % IA depending on the genotype and environment (Table 3.12). An estimation of the range in amylose content, assuming an IA of pure oat amylose to be 19.5 g/100g, is 25.35 to 27.55 %. These values are much higher than those reported by Paton (1979) who also measured starch from two Canadian oats using IA (3.19 to 3.54 %). The IA values in this study are closer to those of Wang and White (1994b) who found a range of 4.33 to 5.07 %. CDC Boyer had the highest amylose content at all growing sites and AC Medallion consistently had the lowest. All genotypes had above average amylose content at the 1999 Silverton site. This site was also characterized by producing oats with high oil and breakage values, suggesting that there is potentially a common environmental factor influencing these traits.

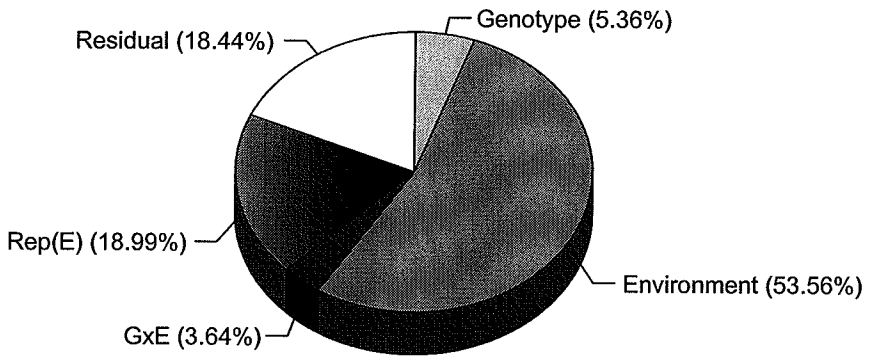


Figure 3.13: Relative contributions of factors to total variation in oat wholemeal total starch content.

Table 3.12: Genotype and environment means for oat starch iodine affinity.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	5.27	5.43	5.15	5.32	5.28	0.09	5.29 ab
Morden	5.24	5.36	5.09	5.21	5.28	0.09	5.24 a
Silverton '98	5.21	5.32	5.11	5.22	5.18	0.07	5.21 a
Carman	5.21	5.33	5.07	5.24	5.27	0.09	5.22 a
Winnipeg	5.22	5.25	5.07	5.17	5.20	0.06	5.18 a
Silverton '99	5.41	5.51	5.33	5.36	5.45	0.06	5.41 b
Std[2]	0.07	0.08	0.09	0.07	0.09		
Mean	5.26 b	5.37 c	5.14 a	5.25 b	5.28 b		

[1] Values are expressed in percentage. Higher iodine affinity values indicate higher levels of amylose in the starch. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).

[2] Std = Standard Deviation

Variance components for genotype and environment were similar in magnitude (37.02 and 36.06 % of total variation respectively) whereas the genotype-by-environment interaction effect contributed less than 1 % (Figure 3.14). These results indicate that oat starch amylose content does vary in the five Canadian genotypes studied and is affected by growing conditions. The range in IA values was narrow, but ranking was consistent across environments indicating that cultivar improvement would be the best way to control oat starch amylose content. Further research is needed to determine the functional significance of this narrow range in oat amylose content.

3.3.8 Starch Swelling Volume

The SSV of oat starch was significantly affected ($P \leq 0.01$) by genotype, environment and genotype-by-environment interactions. Genotypes responded differently to the six growing sites. There was a low degree of differentiation between genotypes at Glenlea, Morden and 1998 Silverton except for Triple Crown, which demonstrated a large increase in SSV at the former location. This unusually high SSV value was not accompanied by a particularly low amylose value. This sample did however, have a somewhat low DSC ΔH for the amylose-lipid complex compared to the means for that location. It is possible that this sample exhibited a large SSV due to the relative lack of pasting inhibition that can result from amylose-lipid complexing (Tester and Morrison, 1990). Despite these responses, there was no significant change in rank order of genotypes across environments.

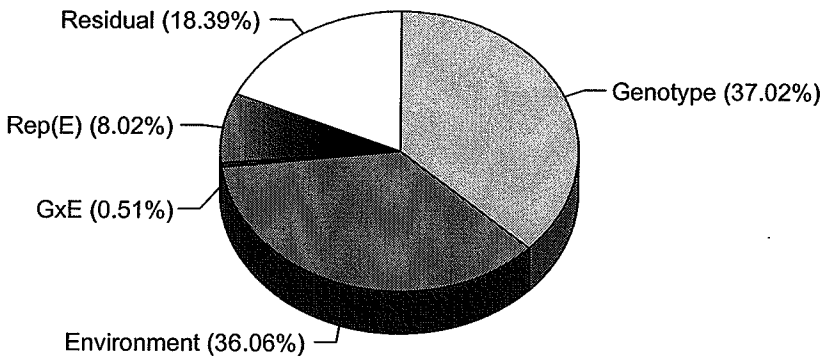


Figure 3.14: Relative contributions of factors to total variation in oat starch iodine affinity.

Overall genotype means ranged from 5.54 cc (CDC Boyer) to 5.92 cc (Triple Crown) (Table 3.13). Overall environment means showed a greater range (5.17 to 6.44 cc). Oat starch from the Winnipeg site consistently swelled to a greater degree than from other sites. This location also produced oats with the lowest average amylose content. This trend is in keeping with the fact that swelling is primarily a property of amylopectin (Tester and Morrison, 1990), so that one would expect to see higher swelling with lower amylose. In this study, the correlation coefficient between these two parameters was not significant ($r = -0.58$; $P = 0.3086$).

Component of variation analysis confirmed that environment played the largest role in total variation of SSV (41.77 %) and that the genotype-by-environment interaction effect contributed more (10.22 %) than genotype (2.40 %) (Figure 3.15).

3.3.9 Starch Pasting Characteristics

The viscosity of oat starch slurries as they are stirred and heated to 95 °C and cooled to 50 °C was measured with an RVA. All RVA parameters were significantly affected by genotype and environment. CDC Boyer had the lowest peak viscosity at 95 °C for all environments (overall mean 160RVU) followed by AC Medallion (overall mean 170 RVU) (Table 3.14). Triple Crown, AC Assiniboia and OT 288 all showed the highest peak viscosities (177 to 180 RVU). Overall, the range in peak viscosities observed was fairly narrow. This range cannot be compared to previous research because the available reports show genotype differences in oat starch viscosity using the

Table 3.13: Genotype and environment means for oat starch swelling volume.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	5.20	5.14	5.22	5.34	4.94	0.13	5.17 a
Morden	5.28	5.42	5.09	5.50	5.37	0.14	5.33 a
Silverton '98	5.30	5.09	5.34	5.44	6.13	0.35	5.46 ab
Carman	5.79	5.89	6.20	5.87	6.38	0.23	6.03 ab
Winnipeg	6.70	6.25	6.63	6.16	6.47	0.21	6.44 b
Silverton '99	5.74	5.45	6.43	5.87	6.20	0.34	5.94 ab
Std[2]	0.51	0.41	0.62	0.29	0.56		
Mean	5.67 ab	5.54 a	5.82 ab	5.70 ab	5.92 b		

[1] Values are expressed in cubic centimeters. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).

[2] Std = Standard Deviation

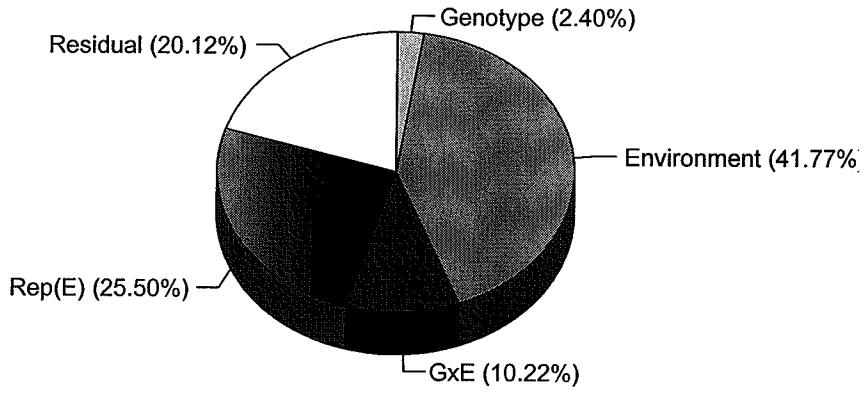


Figure 3.15: Relative contributions of factors to total variation in oat starch swelling volume.

Table 3.14: Genotype and environment means for oat starch RVA peak viscosity.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	156	135	147	158	155	8.47	150 a
Morden	165	145	150	169	155	9.00	157 ab
Silverton '98	174	152	163	170	168	7.58	165 b
Carman	190	176	189	193	193	6.31	188 c
Winnipeg	192	178	183	189	194	5.91	187 c
Silverton '99	198	175	191	202	194	9.27	192 c
Std[2]	15.28	16.93	18.02	15.49	17.71		
Mean	179 c	160 a	171 b	180 c	177 c		

[1] Values are expressed in RVU. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Brabender (Paton, 1977; Wang and White, 1994a) or RVA results for oat flour pasting (Zhou et al., 1998b; Zhou et al., 1999a; Zhou et al., 1999b). Genotype means for final viscosity at 50 °C did not follow the same trend as peak viscosity. CDC Boyer was again the least viscous (216 RVU) but was not significantly different than AC Assiniboia (Table 3.15). Triple Crown had the highest final viscosity (260 RVU). AC Medallion and OT 288 were significantly higher than the other three genotypes for setback viscosity and the final minus peak viscosity values (Tables 3.16 and 3.17). Environmental effects on starch paste viscosity were also apparent with the Carman, Winnipeg and Silverton 1999 sites generally showing higher peak, final, setback and final minus peak viscosities.

Genotype-by-environment interactions were significant at a 1 % probability level for hot paste, breakdown and shear thinning viscosities and significant cross-over effects occurred for all three parameters. Only one pair of genotypes significantly changed rank order for hot paste (CDC Boyer and AC Medallion at Morden and 1999 Silverton) (Figure 3.16) and shear-thinning (OT 288 and Triple Crown at Glenlea and 1998 Silverton) (Figure 3.17). Five significant cross-over effects involving two genotype pairs occurred for breakdown viscosity (AC Medallion and Triple Crown at Glenlea, Morden and 1998 Silverton and OT 288 and Triple Crown also at Glenlea and 1998 Silverton) (Figure 3.18). This indicates that multiple testing sites would likely be required to successfully breed for genotypes with specific levels of these pasting properties.

Table 3.15: Genotype and environment means for oat starch RVA final viscosity.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	177	168	194	192	203	12.58	187 a
Morden	198	192	182	215	206	11.34	199 a
Silverton '98	216	209	243	218	244	14.60	226 ab
Carman	244	239	276	261	297	21.28	263 bc
Winnipeg	279	250	284	272	305	17.81	278 c
Silverton '99	292	237	316	297	303	27.21	289 c
Std[2]	41.55	29.03	48.29	36.72	44.09		
Mean	234 ab	216 a	249 bc	243 bc	260 c		

[1] Values are expressed in RVU. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.16: Genotype and environment means for oat starch RVA setback viscosity.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	70	66	86	73	99	12.12	79 a
Morden	81	77	88	85	92	5.24	85 ab
Silverton '98	102	96	126	97	110	11.07	106 abc
Carman	97	95	123	109	135	15.32	112 bc
Winnipeg	117	100	127	110	137	12.89	118 c
Silverton '99	137	100	161	132	143	19.89	135 c
Std[2]	22.10	12.91	25.63	18.98	19.86		
Mean	101 a	89 a	119 b	101 a	119 b		

[1] Values are expressed in RVU. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.17: Genotype and environment means for oat starch RVA final minus peak viscosity values.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	21	33	46	34	48	9.81	36 a
Morden	33	47	32	46	51	7.78	42 ab
Silverton '98	43	57	80	49	76	14.63	61 abc
Carman	54	63	87	69	104	17.92	75 bcd
Winnipeg	88	72	100	83	112	13.83	91 cd
Silverton '99	94	62	126	95	109	21.08	97 d
Std[2]	27.06	12.59	31.65	21.55	26.63		
Mean	56 a	56 a	79 b	63 a	83 b		

[1] Values are expressed in RVU. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

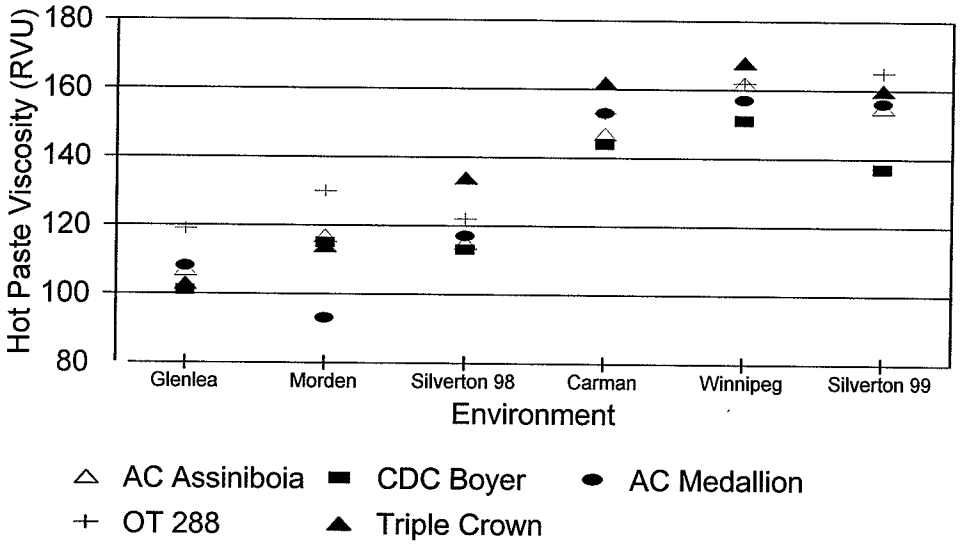


Figure 3.16: Change in rank order of genotypes across environments for oat starch RVA hot paste viscosity.

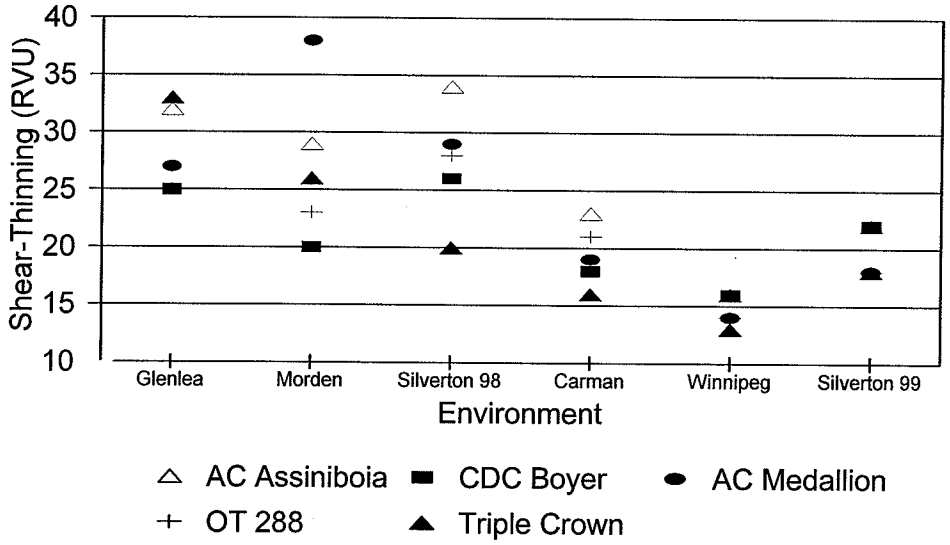


Figure 3.17: Change in rank order of genotypes across environments for oat starch RVA shear thinning viscosity.

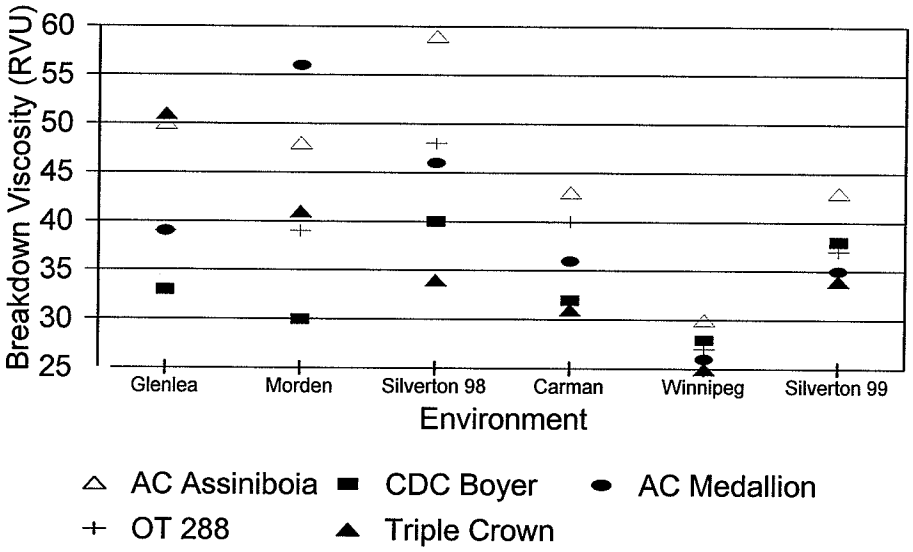


Figure 3.18: Change in rank order of genotypes across environments for oat starch breakdown viscosity.

Component of variation analysis revealed that the environment caused the most variation for all starch RVA parameters except breakdown (Table 3.18). Second to environment, genotype contributed more to variation relative to other factors for peak viscosity and setback. The contributions of genotype-by-environment interactions to total variation were highest for breakdown and shear-thinning, which were also greatly affected by factors other than those defined in the statistical model. A trend was observed for most parameters where environmental means for sites within a year were similar to each other but different from the other year. This grouping by year was particularly noticeable for peak, final, hot paste and shear thinning viscosities. It is likely that analysis within each year would result in a relatively higher influence of genotype compared to environment.

3.3.10 Starch Gel Texture

Variation was observed in the texture of cooled, gelled oat starch pastes as measured instrumentally by texture profile analysis. Genotypic variation was significant ($P \leq 0.01$) for strength (for both the first and second compressions), adhesiveness, springiness, resilience and gumminess. Cohesiveness, which is the ratio between the force required to compress the gel the second time and the force of the first compression, did not differ significantly among genotypes. Environment did not significantly affect gel texture except for gel resilience.

Gel strength at the first compression was significantly affected by a genotype-by-environment interaction, resulting in a significant change in rank order of the genotypes

Table 3.18: Relative contributions of factors to total variation in oat starch pasting properties.

	Variance Component[1]				
Viscosity Measurement	Genotype	Environment	GxE[2]	Rep(E)[3]	Residual
Peak	15.26	74.09	0.88	3.68	6.09
Final	9.28	66.91	3.41	6.77	13.63
Hot Paste	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

[1]Values are expressed as a percentage of total variation.
[2] GxE = Genotype-by-environment interaction
[3] Rep(E) = Replicate within environment

across environments. Only one genotype pair was involved; CDC Boyer was significantly firmer than Triple Crown at Glenlea and Winnipeg, but at 1998 Silverton, Triple Crown was firmer (Figure 3.19). It was noted previously that Triple Crown demonstrated an uncharacteristically high SSV for the 1998 Silverton site. A higher degree of starch swelling could have lead to a firmer gel. A trend between high SSV and high starch gel firmness was observed but there was no significant correlation ($r = 0.85$, $P = 0.0664$). Overall, CDC Boyer and Triple Crown consistently produced starch gels that were firmer than the other genotypes and gels from AC Medallion and AC Assiniboia were the least firm.

Genotype means across environments for firmness at the second compression ranked the same as for the first compression (Figure 3.20). The least firm gels, AC Assiniboia and AC Medallion, were also the most adhesive (Figure 3.20). There was a very narrow range in springiness values (ratio of time to peak for the second compression relative to that of the first compression) but differentiation between genotypes was still observed (Figure 3.21). Starch gels made from OT 288 were significantly more springy than all of the other genotypes except CDC Boyer. Gumminess, which is calculated as the gel strength divided by its cohesiveness, was greatest for CDC Boyer and Triple Crown (Figure 3.22). Cohesiveness as a measurement alone did not differ significantly with genotype or environment. Despite the low range in gel cohesiveness values, it was correlated with IA ($r = -0.91$; $P = 0.0324$), in which samples with high levels of amylose

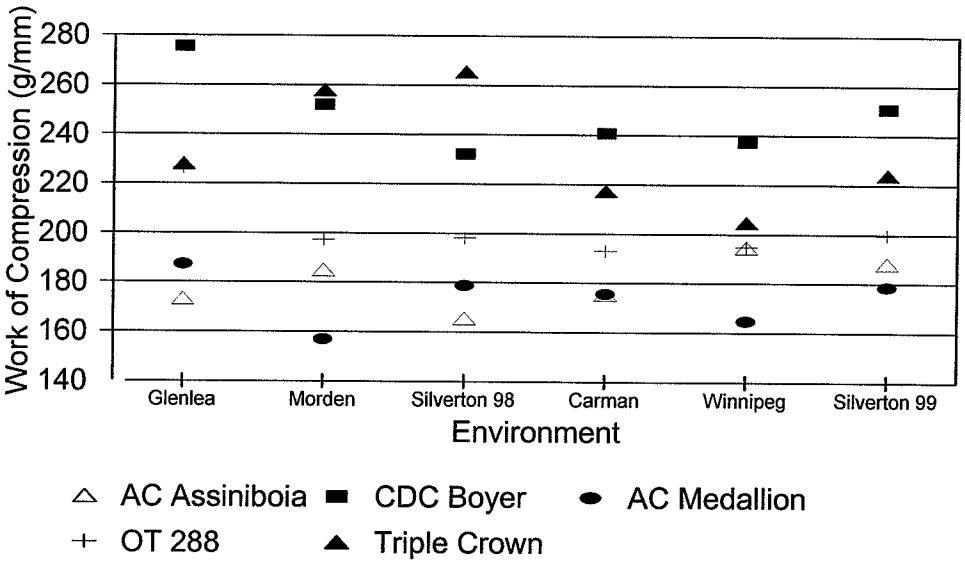
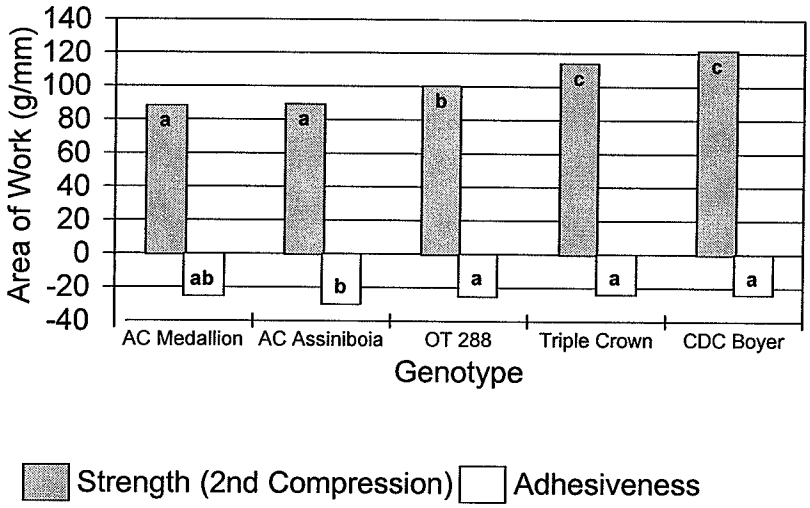
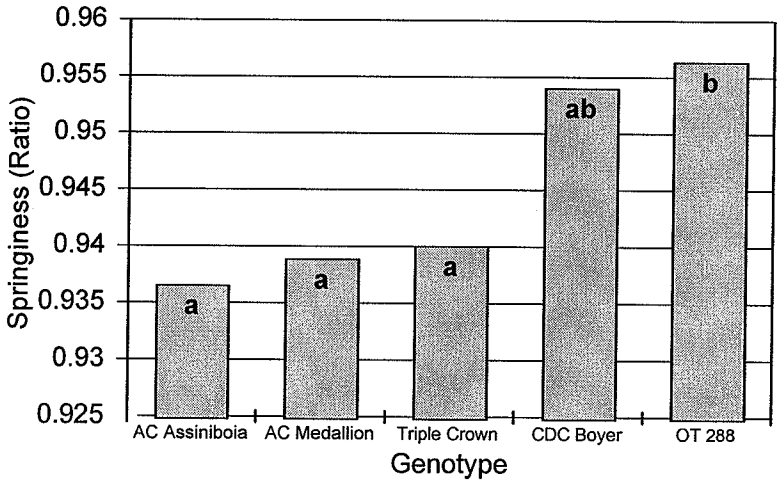


Figure 3.19: Change in rank order of genotypes across environments for oat starch gel strength (1st compression).



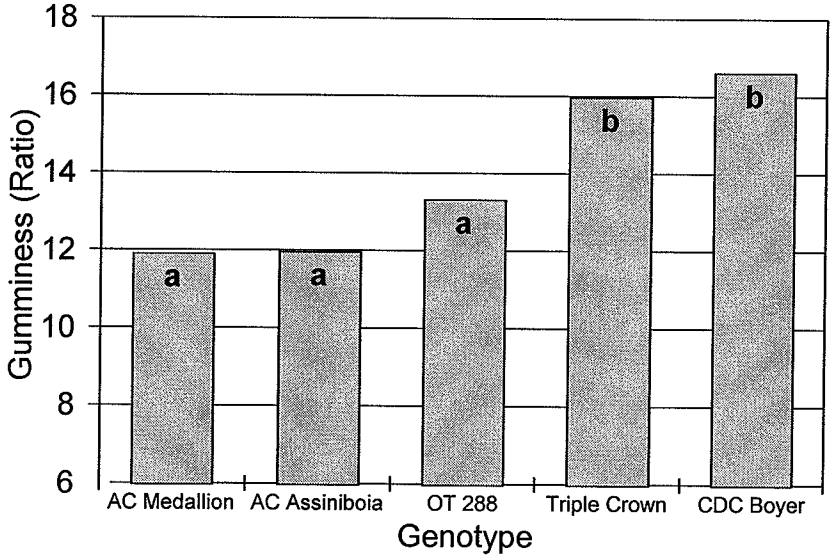
Bars within a parameter marked by the same letter are not significantly different ($P \leq 0.01$).

Figure 3.20: Genotypic variation for oat starch gel strength and adhesiveness.



Bars marked by the same letter are not significantly different ($P \leq 0.01$).

Figure 3.21: Genotypic variation for oat starch gel springiness.



Bars marked by the same letter are not significantly different ($P \leq 0.01$).

Figure 3.22: Genotypic variation for oat starch gel gumminess.

were the least cohesive. In general, the firmer the gel, the less cohesive it was ($r = -0.92$; $P = 0.0263$) and the more gummy it was ($r = 0.99$; $P = 0.0005$).

Resilience (ratio of the area after the peak relative to that before the peak for the first compression) was the only gel texture parameter for which the main effect of environment was significant. Oats grown at the Glenlea site produced starch gels with less resilience than those at the Silverton 1999 site (Table 3.19).

Genotype was the major contributor to total variation for gel firmness and gumminess (Table 3.20). Environment played a greater role than genotype only for adhesiveness and resilience, however for these measurements as well as for springiness and cohesiveness, replicate and residual effects dominated. These high residual effects would explain why ANOVA did not indicate significant environment effects for adhesiveness when both the range in environmental means and contribution to total variation were greater than those for genotype. Contrary to these results, Paton (1977) found the starch gel from one oat genotype to differ in strength and tackiness when grown at three growing sites. Several factors including different genotypes, environments and methodology could explain these different findings.

Gel firmness did not seem to be related to starch RVA peak or final viscosities ($r = -0.52$; $P = 0.3677$ and $r = -0.30$; $P = 0.6190$ respectively). Both gel firmness and adhesiveness did however, show closer trends to starch RVA breakdown ($r = -0.84$; $P = 0.0718$ and $r = -0.92$; $P = 0.0286$ respectively) and shear-thinning viscosities

Table 3.19: Genotype and environment means for oat starch gel resilience.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0.078	0.092	0.101	0.099	0.098	0.008	0.094 a
Morden	0.089	0.115	0.073	0.100	0.112	0.015	0.098 ab
Silverton '98	0.086	0.120	0.111	0.114	0.153	0.021	0.117 ab
Carman	0.103	0.117	0.121	0.125	0.152	0.016	0.124 ab
Winnipeg	0.134	0.126	0.129	0.113	0.152	0.013	0.131 ab
Silverton '99	0.127	0.127	0.155	0.151	0.168	0.016	0.146 b
Std[2]	0.021	.0.12	0.025	0.018	0.025		
Mean	0.103 a	0.116 a	0.115 a	0.117 a	0.139 b		

[1] Values represent a ratio of area after maximum force to before maximum force for the first compression. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).

[2] Std = Standard Deviation

Table 3.20: Relative contributions of factors to total variation in oat starch gel texture.

	Variance Component[1]				
Characteristic	Genotype	Environment	GxE[2]	Rep(E)[3]	Residual
Gel Strength (1st Compression)	69.05	0.00	10.13	1.55	19.26
Gel Strength (2nd Compression)	66.72	0.00	2.39	3.96	26.93
Adhesiveness	5.16	20.23	5.13	38.55	30.93
Springiness	15.25	0.00	0.44	24.78	59.52
Cohesiveness	0.00	0.00	14.96	26.80	58.23
Resilience	15.35	26.02	2.34	18.30	37.99
Gumminess	67.45	2.59	0.12	0.58	29.26

[1]Values are expressed as a percentage of total variation.
[2] GxE = Genotype-by-environment interaction
[3] Rep(E) = Replicate within environment

($r = -0.82$; $P = 0.0862$ and $r = -0.91$; $P = 0.0322$ respectively). These parameters are measures of loss in viscosity due to stirring at a constant high temperature, where shear thinning is expressed as a percentage of the peak viscosity. Starch from AC Assiniboia and AC Medallion exhibited the greatest decrease in viscosity upon stirring at high temperature and also made the least firm gels. The gelatinization temperatures of AC Assiniboia and AC Medallion starches also tended to be high but AC Medallion was not significantly different from OT 288, which had medium gel strength and adhesiveness properties. AC Assiniboia, AC Medallion, and OT 288 tended to have lower IA values as well as high ΔH values for the amylose-lipid complex enthalpy ($r = -0.93$; $P = 0.0225$ for correlation between gel strength and ΔH). Both higher gelatinization temperatures and larger proportions of amylose-lipid complexes could contribute to incomplete gelatinization and thus weaker gels. At any rate, there is evidence that some chemical and/or physical difference exists among AC Assiniboia and AC Medallion starches that cause them to be weaker during hot stirring and as a cooled gel. It does not however appear to be affecting these starches' ability to reach a high paste viscosity at 95 or 50 °C.

3.3.11 Starch Thermal Properties

The Winnipeg location was not included in a pooled analysis of the results for the second enthalpy curve due to unequal error variances. Separate ANOVA of the thermal parameters associated with the amylose-lipid complex, for this location, found significant genotypic differences for onset temperature and ΔH but not for the peak temperature.

Pooled ANOVA for all other results indicated that genotype and environment significantly ($P \leq 0.01$) influenced all starch DSC parameters. Genotype-by-environment interactions were not significant at a 1 % probability level for any of the DSC parameters.

Starch isolated from Triple Crown was significantly distinct from the other genotypes in that it gelatinized at a lower temperature (onset = 53.60 °C; peak = 58.36 °C) (Tables 3.21 and 3.22) and required less total energy (ΔH = 8.74 J/g) at all growing sites (Table 3.23). In contrast, AC Assiniboia had the highest overall means for onset (54.77 °C) and gelatinization temperatures (59.73 °C) as well as for ΔH (9.19 J/g). However, the values for AC Assiniboia were not necessarily significantly different from CDC Boyer, OT 288 and AC Medallion for these three parameters. Similar ranges in the gelatinization temperature of oat starch were observed by Tester and Karkalas (1996) (56.2 to 59.5 °C), Wang and White (1994a) (56.1 to 60.0 °C) and Gudmundsson and Eliasson (1989) (57.0 to 61.2 °C). Gudmundsson and Eliasson (1989) used the same solids content (40 %) for DSC testing as was used in the present study, but found higher ΔH values (10.4 to 12.1 J/g) for four Swedish oat genotypes.

The onset of the melting curve associated with the amylose-lipid complex was, overall, significantly higher for CDC Boyer (93.57 °C) than AC Medallion (92.63 °C); the other genotypes were not significantly different from either of these two genotypes (Table 3.24). The peak temperature at which this enthalpy change occurred was lowest for Triple Crown (102.61 °C) and highest for AC Assiniboia (103.23 °C) (Table 3.25).

Table 3.21: Genotype and environment means for oat starch DSC onset temperature for melting of amylopectin.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	55.95	56.00	55.58	55.54	54.65	0.48	55.54 d
Morden	55.61	55.57	55.14	55.52	54.57	0.39	55.28 cd
Silverton '98	54.93	54.71	54.52	54.39	53.70	0.42	54.45 bc
Carman	54.17	53.82	54.09	54.14	53.26	0.34	53.90 b
Winnipeg	54.43	54.13	54.30	54.51	53.17	0.49	54.11 b
Silverton '99	53.52	53.13	52.77	52.94	52.25	0.42	52.92 a
Std[2]	0.83	0.99	0.89	0.88	0.83		
Mean	54.77 c	54.56 bc	54.40 b	54.51 bc	53.60 a		

[1] Values are expressed in degrees Celsius. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).

[2] Std = Standard Deviation

Table 3.22: Genotype and environment means for oat starch DSC maximum temperature for melting of amylopectin.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	60.76	60.50	60.50	60.37	59.45	0.45	60.32 c
Morden	60.20	59.78	59.83	60.09	59.21	0.34	59.82 bc
Silverton '98	60.16	59.39	59.94	59.40	58.65	0.52	59.51 bc
Carman	59.16	58.38	58.85	58.91	57.83	0.47	58.63 ab
Winnipeg	59.58	59.02	59.70	59.76	58.05	0.64	59.22 b
Silverton '99	58.50	57.59	57.60	57.91	56.98	0.49	57.72 a
Std[2]	0.74	0.94	0.94	0.82	0.84		
Mean	59.73 d	59.11 b	59.40 c	59.41 c	58.36 a		

[1] Values are expressed in degrees Celsius. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.23: Genotype and environment means for oat starch DSC enthalpy change for melting of amylopectin.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	8.74	8.84	8.76	8.85	8.58	0.10	8.75 a
Morden	8.78	8.71	8.73	9.11	8.35	0.24	8.74 a
Silverton '98	9.06	8.94	8.59	8.79	8.62	0.18	8.80 a
Carman	9.56	9.53	9.59	9.52	9.21	0.14	9.48 b
Winnipeg	9.78	9.75	9.61	9.32	8.91	0.33	9.47 b
Silverton '99	9.20	9.14	9.20	9.44	8.78	0.21	9.15 ab
Std[2]	0.38	0.37	0.41	0.28	0.27		
Mean	9.19 b	9.15 b	9.08 b	9.17 b	8.74 a		

[1] Values are expressed in joules per gram of starch. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).

[2] Std = Standard Deviation

Table 3.24: Genotype and environment means for oat starch DSC onset temperature for melting of the amylose-lipid complex.[1]

	Genotype						
Environment	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown	Std[2]	Mean
Glenlea	95.42	96.02	94.36	95.62	95.10	0.56	95.30 d
Morden	94.76	94.43	94.59	94.54	94.67	0.11	94.60 cd
Silverton '98	94.29	93.97	93.77	95.10	94.43	0.46	94.31 c
Carman	92.15	92.56	91.40	91.85	90.94	0.57	91.78 b
Silverton '99	90.40	91.97	90.20	90.60	90.82	0.62	90.80 a
Std[2]	1.86	1.43	1.75	1.96	1.90		
Mean	93.40 ab	93.79 b	92.86 a	93.54 ab	93.19 ab		

[1] Values are expressed in degrees Celsius. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.25: Genotype and environment means for oat starch DSC maximum temperature for melting of the amylose-lipid complex.[1]

	Genotype						
Environment	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown	Std[2]	Mean
Glenlea	104.84	104.57	104.55	104.98	104.60	0.17	104.71 b
Morden	104.50	104.16	104.16	104.15	103.80	0.22	104.15 b
Silverton '98	104.51	103.61	103.86	104.20	103.71	0.33	103.98 b
Carman	102.14	102.07	101.55	101.85	101.17	0.36	101.76 a
Silverton '99	101.47	101.92	101.34	101.80	100.89	0.36	101.48 a
Std[2]	1.40	1.08	1.36	1.32	1.51		
Mean	103.49 b	103.27 ab	103.09 ab	103.40 b	102.83 a		

[1] Values are expressed in degrees Celsius. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

The mean ΔH value for CDC Boyer (1.9 J/g) was significantly lower than the other genotypes whereas AC Medallion demonstrated the top of the range in mean ΔH values observed (2.37 J/g) (Table 3.26). Gudmundsson and Eliasson (1989) found similar peak temperatures (102.4 to 103.9 °C) but slightly higher ΔH values (2.8 to 3.9 J/g) for four Swedish oat genotypes. Wang and White (1994a) found lower peak temperatures (91.0 to 92.4 °C) and ΔH values (0.42 to 0.72 J/g) for three oat genotypes using a 50:50 starch to water ratio in the DSC pans.

Environmental differences in starch thermal properties were also found, evidence of which has not been investigated by other researchers. The 1999 Silverton site exhibited the lowest temperature at the onset of the first enthalpy curve for all genotypes, whereas Glenlea and Morden had the highest values (Table 3.21). The trend for environmental differences in peak gelatinization temperature was similar (Table 3.22). All three 1998 sites had similar ΔH means that were significantly lower than the Carman and Winnipeg sites with Silverton 1999 being not significantly different from either group (Table 3.23). Environments differed in the thermal properties of the amylose-lipid complex as well. The 1998 sites were significantly different than the 1999 sites for all three parameters studied (Tables 3.24 to 3.26), including the Winnipeg site, which was analyzed separately (Table 3.27). A similar trend was also noted for starch and wholemeal pasting characteristics, SSV, as well as wholemeal oil content, suggesting that some environmental condition prevalent in 1999 caused a change in the plant's synthesis. Factors such as amylose and amylopectin chain length and molecular weight, which were

Table 3.26: Genotype and environment means for oat starch DSC enthalpy change for melting of the amylose-lipid complex.[1]

	Genotype						
Environment	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown	Std[2]	Mean
Glenlea	1.91	1.62	2.03	2.13	2.01	0.17	1.94 a
Morden	1.92	1.62	2.17	1.97	1.77	0.19	1.89 a
Silverton '98	2.29	1.96	2.22	2.03	1.77	0.19	2.05 a
Carman	2.37	2.06	2.46	2.51	2.56	0.18	2.39 b
Silverton '99	2.91	2.33	2.96	2.92	2.54	0.25	2.73 c
Std[2]	0.37	0.27	0.33	0.36	0.35		
Mean	2.28 bc	1.92 a	2.37 c	2.31 bc	2.13 b		

[1] Values are expressed in joules per gram of starch. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).

[2] Std = Standard Deviation

Table 3.27: Genotype means for oat starch DSC properties associated with melting of the amylose-lipid complex (Winnipeg location).

Environment	Genotype					Std[1]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Onset Temp.[2]	91.49	92.47	91.43	91.99	91.31	0.43	91.74
Max. Temp.[2]	101.91	101.96	101.38	101.76	101.46	0.23	101.69
ΔH[3]	2.86	2.32	2.56	2.53	2.54	0.17	2.56

[1] Std = Standard deviation
[2] Onset and maximum temperatures are expressed in degrees Celsius.
[3] ΔH represents the enthalpy change associated with the melting of the amylose-lipid complex and is expressed in joules per gram of starch.

not measured in this study, could be responsible for the observed differences in starch properties.

Environmental differences contributed the most to total variation for all DSC parameters (43.73 to 86.83 %) (Table 3.28). Despite large environmental variation, consistent differences between genotypes indicate that breeders could select for specific oat starch thermal properties. Further research is required to determine if there is an optimum oat starch gelatinization temperature that would help industry process superior quality oat end-products.

3.3.12 Wholemeal Pasting Properties

Results for oat wholemeal pasting characteristics were similar to those for starch in that genotype and environment effects were also significant ($P \leq 0.01$) for all RVA parameters. Triple Crown had the highest peak viscosity at all environments (Table 3.29). Triple Crown and CDC Boyer were the most viscous after cooling to 50 °C (final viscosity) (Table 3.30). CDC Boyer did, however, have one of the lowest peak viscosities, which lead to its high final minus peak values (Table 3.31). OT 288 was characterized as having low peak, hot paste (Table 3.32), final, and final minus peak viscosities, whereas AC Assiniboia and AC Medallion tended to have low or intermediate values in comparison to the other genotypes.

The Glenlea and Morden environments had significantly lower peak viscosities (301 and 292 RVU respectively) than all other locations (318 to 324 RVU) (Table 3.29).

Table 3.28: Relative contributions of factors to total variation in oat starch thermal properties.

	Variance Component[1]				
Thermal Property[2]	Genotype	Environment	GxE[3]	Rep(E)[4]	Residual
AP Onset Temp.	15.21	68.76	1.40	8.86	5.77
AP Maximum Temp.	20.06	63.26	1.57	8.17	6.94
AP ΔH	11.59	43.73	0.94	12.50	31.23
AM Onset Temp.	1.71	82.68	1.64	0.00	13.97
AM Maximum Temp.	2.24	86.83	0.35	2.97	7.60
AM ΔH	14.65	61.20	5.14	0.00	19.01

[1]Values are expressed as a percentage of total variation.
[2] AP refers to the enthalpy peak associated with the gelatinization of amylopectin; AM refers to the enthalpy peak associated with the melting of the amylose-lipid complex; ΔH = total enthalpy change.
[3] GxE = Genotype-by-environment interaction
[4] Rep(E) = Replicate within environment

Table 3.29: Genotype and environment means for oat wholemeal RVA peak viscosity. [1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	303	293	295	292	321	10.81	301 a
Morden	298	287	290	285	302	6.53	292 a
Carman	324	312	304	318	336	10.85	319 b
Winnipeg	323	312	320	321	342	9.93	324 b
Silverton '99	319	308	312	325	325	6.85	318 b
Std[2]	10.78	10.40	10.93	16.39	13.82		
Mean	312 b	302 a	304 a	308 ab	324 c		

[1] Values are expressed in RVU. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.30: Genotype and environment means for oat wholemeal RVA final viscosity.[1]

	Genotype						
Environment	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown	Std[2]	Mean
Glenlea	353	378	361	337	379	15.82	362 b
Morden	312	343	320	281	340	22.41	319 a
Carman	325	354	322	310	356	18.35	333 a
Winnipeg	330	353	339	328	358	15.96	342 ab
Silverton '99	325	356	335	316	355	15.96	337 a
Std[2]	13.40	11.51	14.73	19.15	12.47		
Mean	328 b	356 c	335 b	314 a	357 c		

[1] Values are expressed in RVU. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.31: Genotype and environment means for oat wholemeal RVA final minus peak viscosity values.[1]

	Genotype						
Environment	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown	Std[2]	Mean
Glenlea	50	85	66	45	58	14.05	61 b
Morden	16	57	30	-5	38	20.86	27 a
Carman	2	42	18	-7	20	16.83	15 a
Winnipeg	7	41	20	8	16	12.31	18 a
Silverton '99	7	48	23	-9	31	19.62	20 a
Std[2]	17.40	16.23	17.77	20.20	14.91		
Mean	17 b	55 d	32 c	7 a	33 c		

[1] Values are expressed in RVU. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.32: Genotype and environment means for oat wholemeal RVA hot paste viscosity.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	169	197	174	161	183	12.37	177 b
Morden	157	178	153	137	176	15.28	160 a
Carman	178	193	169	166	196	12.21	180 b
Winnipeg	176	189	183	176	189	5.82	183 b
Silverton '99	173	195	178	170	193	10.30	182 b
Std[2]	7.45	6.74	10.29	13.43	7.17		
Mean	170 a	190 b	171 a	162 a	187 b		

[1] Values are expressed in RVU. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Glenlea was also unique in that final viscosity and final minus peak values were consistently higher than at all other sites for all genotypes (Tables 3.30 and 3.31). Oats grown at Morden exhibited significantly lower hot paste values (Table 3.32).

Breakdown was the only parameter that had significant genotype-by-environment and cross-over effects. AC Medallion and Triple Crown significantly changed rank order at Morden compared to Glenlea and Winnipeg (Figure 3.23). Despite the genotype-by-environment interaction, some consistent trends were observed. For example, CDC Boyer had the lowest breakdown values at all locations.

Component of variation analysis for breakdown confirmed these observations; genotype contributed the most to total variation, but the interaction effect played more of a role than environment (Table 3.33). In contrast, variance components showed that environment resulted in greater variation in peak viscosity than genotype but that genotype played a larger role in hot paste and final viscosities. Final minus peak viscosity values were influenced equally by genotype and environment. Zhou et al. (1999b) also found location to be more important in determining the peak viscosity of eight Australian genotypes for one year of testing but that genotype and environment were equal in another year.

The 1998 Silverton environment was analyzed separately due to its high error variance. The wholemeal RVA results for oats grown at this location were quite distinct, giving further support to the importance of environmental effects (Table 3.34). Overall,

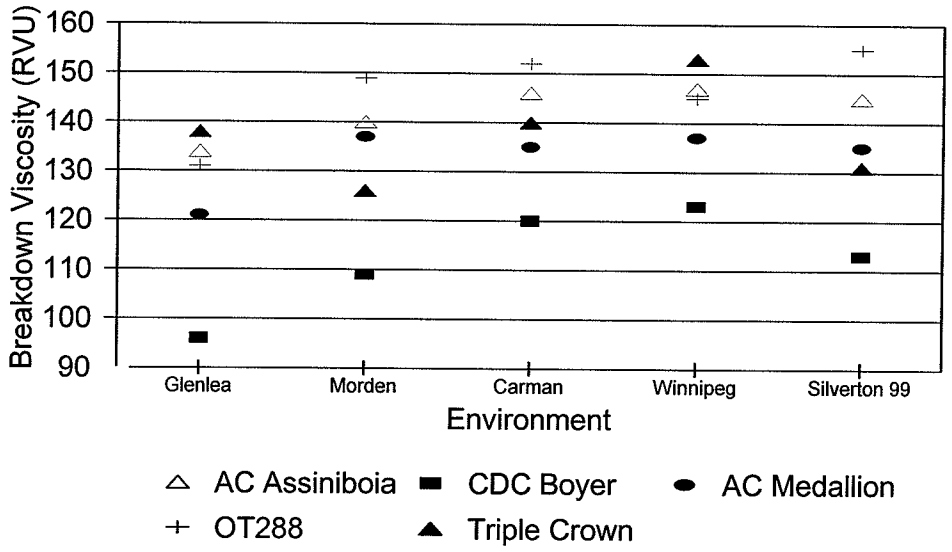


Figure 3.23: Change in rank order of genotypes across environments for oat wholemeal breakdown viscosity.

Table 3.33: Relative contributions of factors to total variation in oat wholemeal pasting properties.[1]

	Variance Component[2]				
Viscosity Measurement	Genotype	Environment	GxE[3]	Rep(E)[4]	Residual
Peak	22.87	52.62	3.78	2.72	18.02
Final	47.85	30.54	0.13	4.61	16.87
Trough	46.04	24.56	3.29	4.20	21.91
Breakdown	59.57	10.65	11.21	6.31	12.27
Final-Peak	42.04	42.84	1.73	4.28	9.09

[1] Analysis does not include the 1998 Silverton location.
[2] Values are expressed as a percentage of total variation.
[3] GxE = Genotype-by-environment interaction
[4] Rep(E) = Replicate within environment

Table 3.34: Genotype means for oat wholemeal pasting properties (1998 Silverton location).[1]

RVA Parameter	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Peak	278	251	251	280	266	13	265
Hot Paste	127	117	107	131	112	9	119
Final	282	279	265	280	252	11	272
Breakdown	151	133	145	149	155	8	147
Final-Peak	5	2	14	0	-15	9	1

[1] Values are expressed in RVU.
[2] Std = Standard Deviation

peak, final and hot paste viscosities tended to be much lower than the average of those at the other locations, and breakdown viscosities were higher. Genotype differences were not significant at this location except for final minus peak viscosity values. The genotypes ranked the same as the means for the other sites with respect to final minus peak values with the exception of Triple Crown. Triple Crown exhibited fairly high positive final minus peak values at all other sites except 1998 Silverton, where its value was -15 RVU. The genotype-by-environment interaction for the combined analysis was not significant for final minus peak values ($P = 0.0767$) but the additional information from the Silverton 1998 site suggests that genotypes respond differently to different conditions.

The unique wholemeal pasting properties observed at the 1998 Silverton site were not mirrored in the corresponding starch RVA curves nor did they appear to be related to DSC, amylose or starch swelling volume. This site was unique in its high protein and low total starch contents, which may be responsible for the overall lower wholemeal viscosity. The trend between total starch and wholemeal RVA peak viscosity was not significant when calculated over genotype means ($r = -0.53$; $P = 0.3578$), but would likely have been much stronger had it been calculated across environmental means. The environmental means for total starch and wholemeal peak viscosity ranked almost exactly the same from lowest to highest.

3.3.13 Oat Flake Granulation

Oat flake granulation was significantly ($P \leq 0.01$) affected by genotype and environment. Significant genotype-by-environment interactions also occurred for the proportion of largest flakes (> 4.00 mm) and medium sized flakes (< 4.00 and > 2.36 mm) ($P \leq 0.01$). These interaction effects only resulted in significant changes in rank order of the genotypes at the six environments for the proportion of largest flakes. AC Assiniboia had a significantly greater proportion of flakes that did not pass through the 4.0 mm sieve than CDC Boyer at the Glenlea site, however this trend was reversed at the 1999 Silverton site (Figure 3.24). These genotype specific responses to some environmental conditions could be linked to grain filling, as the size of the groat is likely to be related to the ultimate size of the flake. Other researchers have reported genotype-by-environment effects on the size of oat groats, but that genotype had the greatest control over morphology (Pietrzak and Fulcher, 1995). The percentage of largest flakes was very similar for AC Assiniboia and CDC Boyer at all of the other sites. In addition, the overall means across environments for these two genotypes were significantly greater than AC Medallion, which was in turn was greater than Triple Crown and OT 288.

The proportion of medium sized flakes increased as the proportion of the largest sized flakes decreased. Thus the trends for genotype and environment effects on flakes size 2.36 to 4.00 mm (Table 3.35) were similar but opposite in direction to those for the flakes greater than 4.00 mm. Triple Crown had the smallest proportion of flakes and/or particles between 2.00 and 2.36 mm (Table 3.36) and those passing through the smallest

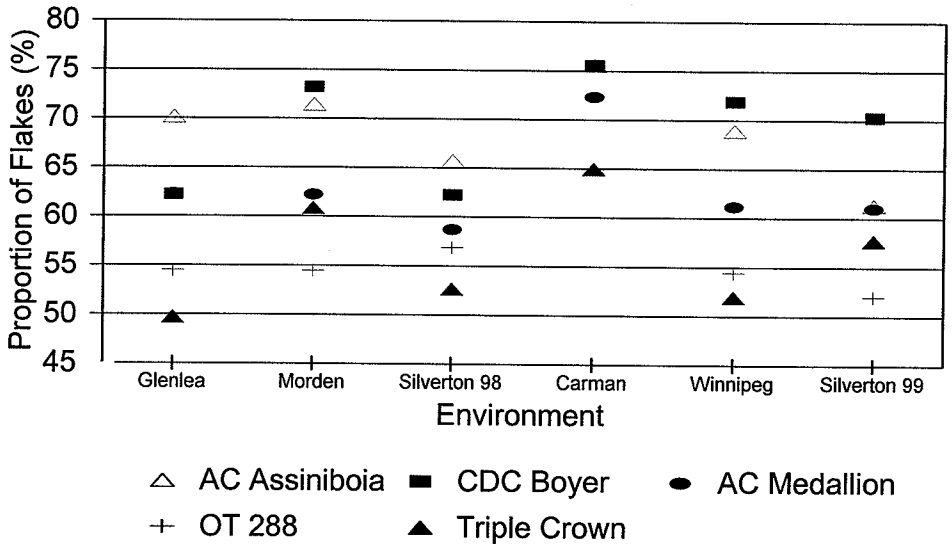


Figure 3.24: Change in rank order of genotypes across environments for oat flakes sized greater than 4.00 mm.

Table 3.35: Genotype and environment means for the proportion of oat flakes sized between 2.36 and 4.00 mm. [1]

	Genotype						
Environment	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown	Std[2]	Mean
Glenlea	24.96	35.58	31.15	40.55	48.45	8.01	36.14 b
Morden	22.03	21.79	30.34	39.00	36.83	7.19	30.00 ab
Silverton '98	29.45	34.17	36.62	37.83	45.21	5.15	36.66 b
Carman	19.24	20.44	23.73	29.97	33.19	5.42	25.31 a
Winnipeg	26.29	25.23	35.26	41.50	46.51	8.32	34.96 b
Silverton '99	31.58	25.66	33.72	42.19	39.68	5.89	34.57 b
Std[2]	4.18	5.77	4.21	4.09	5.50		
Mean	25.59 a	27.14 a	31.80 b	38.51 c	41.65 c		

[1] Values are expressed in percentage. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.36: Genotype and environment means for the proportion of oat flakes sized between 2.00 and 2.36 mm. [1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	1.30	0.66	1.07	1.51	0.50	0.38	1.01 a
Morden	1.60	1.29	2.00	1.78	0.58	0.49	1.45 bc
Silverton '98	1.17	0.85	1.27	1.46	0.59	0.31	1.07 ab
Carman	1.35	1.06	1.12	1.67	0.53	0.38	1.15 abc
Winnipeg	1.31	0.82	1.24	1.36	0.44	0.35	1.03 ab
Silverton '99	2.12	1.23	1.68	1.88	0.84	0.46	1.55 c
Std[2]	0.32	0.23	0.33	0.18	0.13		
Mean	1.48 c	0.99 b	1.40 c	1.61 c	0.58 a		

[1] Values are expressed in percentage. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

sieve (< 2.0 mm) (Table 3.37). OT 288, AC Medallion and AC Assiniboia had the largest proportion of material in the smallest size ranges. High amounts of small flake material may be due to broken flakes, which is an indication of poor flake integrity. Triple Crown, which had the least amount of flake material passing through the smallest sieve, was also the genotype exhibiting the least groat breakage after dehulling. Similarly, the three environments that resulted in oats with the most groat breakage also had the highest means for flake material passing through the smallest sieve. It is possible that some of the same factors influencing groat breakage could also impact flake integrity. There was a trend between increasing groat breakage and the increasing proportion of smallest flake material. Highly significant correlations were found between β-glucan content and the amount of small flakes above ($r = -0.98$; $P = 0.0026$) and passing through the smallest sieve ($r = -0.98$; $P = 0.0032$). Further research is needed to determine if this is a coincidence or if β-glucan plays a structural role in preventing flakes from breaking.

Genotype contributed the most to variation in flake granulation for all size categories (47 to 55 % of total variation) indicating potential to control this trait through plant breeding (Table 3.38).

3.3.14 Oat Flake Hydration Capacity

The capacity of oat flakes to hydrate with water was significantly ($P \leq 0.01$) affected by genotype, environment and genotype-by-environment interactions. A significant change in rank order occurred between CDC Boyer and Triple Crown at the Glenlea and Morden sites (Figure 3.25). Overall means across environments for these

Table 3.37: Genotype and environment means for the proportion of oat flakes sized less than 2.00 mm. [1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	3.38	1.39	2.32	3.26	1.10	0.93	2.29 a
Morden	4.73	3.52	5.18	4.50	1.41	1.34	3.87 b
Silverton '98	3.41	2.45	3.13	3.57	1.19	0.87	2.75 a
Carman	3.66	2.68	2.60	3.27	1.11	0.87	2.66 a
Winnipeg	3.34	1.86	2.22	2.54	0.85	0.822	2.16 a
Silverton '99	4.79	2.56	3.40	3.75	1.54	1.10	3.21 ab
Std[2]	0.63	0.67	1.00	0.59	0.22		
Mean	3.89 d	2.41 b	3.14 c	3.48 cd	1.20 a		

[1] Values are expressed in percentage. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.38: Relative contribution of factors to total variation in oat flake granulation.

	Variance Component[1]				
Size Category	Genotype	Environment	GxE[2]	Rep(E)[3]	Residual
> 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

[1] Values are expressed as a percentage of total variation.
[2] GxE = Genotype-by-environment interaction
[3] Rep(E) = Replicate within environment

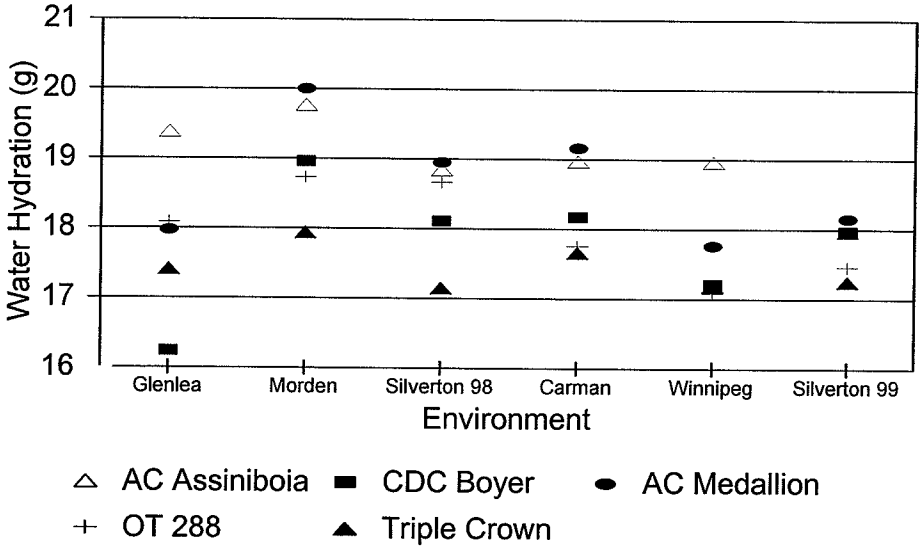


Figure 3.25: Change in rank order of genotypes across environments for oat flake water hydration capacity.

two genotypes were not significantly different (17.78 and 17.43 g, respectively); they both showed lower hydration capacities than AC Assiniboia and AC Medallion. However, CDC Boyer was the most variable over environments (CV = 4.81), especially compared to Triple Crown (CV = 1.63), thus increasing the likelihood of a cross over effect. The interaction effect contributed almost as much to total variation (13.32 %) as the main effect of environment (17.99 %). Genotype contributed slightly more at 29.52 % (Figure 3.26).

The Morden location resulted in the highest water absorption capacity for all genotypes. Morden also showed the highest mean for fine particles passing through the smallest sieve, which were removed from the sample prior to testing hydration. However, if this trait is an indicator of poor flake integrity, it may suggest that flake samples from Morden were very delicate and could have incurred more breakage during the minimal handling of the test, thus resulting in greater hydration.

There was a relatively large source of variation for this trait that could not be explained by the factors in the model. Variation in flake size that was not strongly linked to genotype could have contributed to this high residual effect. Additional experimental error could have been introduced by scaling down the method from 50 g to 25 g of flakes. A collaborative study on the AACC Method #88-10 determined that duplicate samples of whole oat flakes tested in the same laboratory should not differ by more than 3.4 percentage points (Lane et al., 1997). However, replicates were tested from each sample by the scaled down method in this study, resulting in coefficient of variation values of

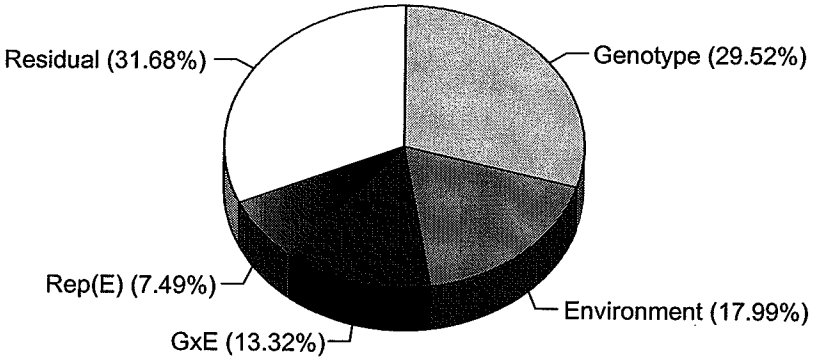


Figure 3.26: Relative contributions of factors to total variation in oat flake water hydration capacity.

5 % or less.

There appeared to be a relationship between increased hydration and an increase in the percentage of small flakes between 2.00 and 2.36 mm. For example, the CDC Boyer sample grown at Glenlea, which was involved in the cross over interaction, had a below average hydration value for that genotype as well as a below average proportion of small flakes and particles. Conversely, when grown at the Morden location it had both the highest hydration capacity and the highest percentage of small flakes observed. It is logical to assume that smaller flakes would take up water more rapidly than larger flakes.

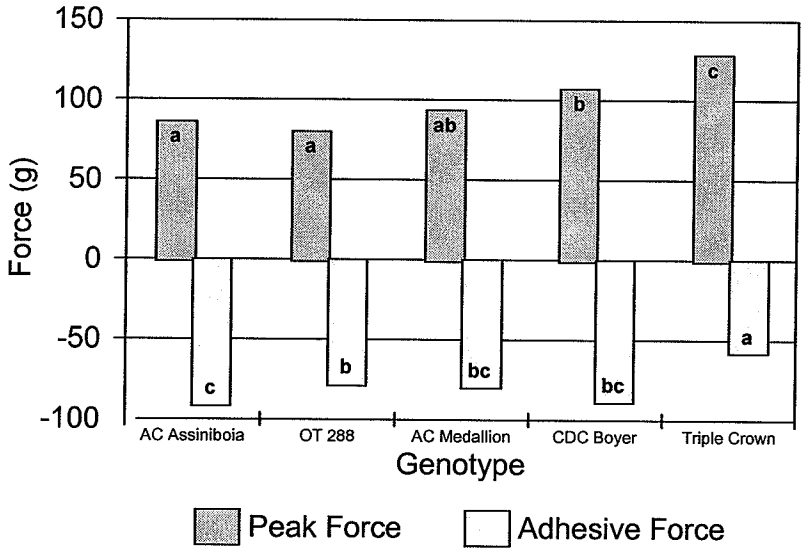
Characteristics other than flake size also seemed to be related to flake hydration. For example, a similar trend was observed between hydration and starch gel texture; AC Assiniboia and AC Medallion had the highest flake water absorption capacity as well as the lowest gel strength ($r = -0.87$; $P = 0.0569$) and the highest gel adhesiveness ($r = -0.83$; $P = 0.0793$), followed by OT 288 in all cases. These similarities could be related to the concurrent trend with lower amylose content ($r = -0.55$; $P = 0.3392$) and higher gelatinization temperature ($r = 0.86$; $P = 0.0641$) of these genotypes or some other property of the starch. For example, a greater ability to swell in the initial stages of the pasting process would support the observed higher flake hydration values as well as the lack of relationship with starch swelling volume ($r = -0.17$; $P = 0.7839$), which one may have expected to occur. The starch swelling volume test entails an incubation period at 92.5 °C, which would have allowed samples with low initial swelling capacities to "equilibrate" or surpass the swelling volumes of the samples that demonstrate high

swelling at the low temperature (23.3 °C) used in the flake hydration test. A similar explanation could be used for the samples with high flake hydration that did not necessarily have corresponding starch with high peak ($r = 0.22$; $P = 0.7220$) or final viscosities ($r = -0.13$; $P = 0.8310$). The conditioning process that the flakes underwent may also have altered their starch properties. For example, pre-gelatinization of starch is thought to alter water absorption properties (Ames and Liu, 2000).

3.3.15 Cooked Oatmeal Texture

Evaluation of cooked oatmeal texture using a TA-XT2*i* Texture Analyser revealed highly significant differences among genotypes. The force required for the probe to descend into the oatmeal was the highest for Triple Crown (Figure 3.27). Genotypes with high peak force values (Triple Crown and CDC Boyer) appeared to be more fluid with two distinct phases: whole flakes and paste. The force of compression also peaked more rapidly. These observations likely corresponded to the relative ease of the probe to travel through the relatively weak paste followed by a rapid increase in force as the probe came into contact with the flakes that had settled to the bottom of the canister. Alternatively, oatmeals which had relatively low peak force values (AC Assiniboia, OT 288, AC Medallion) appeared thicker, with flakes more uniformly dispersed throughout the samples. These texture curves had a more gradual slope approaching the peak.

The amount of oatmeal that adhered to the probe, as shown by the negative force measurements, also differed significantly between genotypes (Figure 3.27). Oatmeal made from Triple Crown stuck to the probe the least and AC Assiniboia tended to stick



Bars within a parameter marked by the same letter are not significantly different ($P \leq 0.01$).

Figure 3.27: Genotypic variation in cooked oatmeal texture.

the most. Starch gels made from Triple Crown and AC Assiniboia were also the least and most adhesive respectively, although the other three genotypes did not rank the same for these two measurements. Environment and genotype-by-environment interactions for oatmeal peak force and adhesiveness were not significant at a 1 % probability level.

Stringiness, which is a measure of the length of time oatmeal is in contact with the ascending probe, varied significantly ($P \leq 0.01$) with genotype and environment. The most stringy oatmeals were made from Triple Crown grown at all environments (Table 3.39). Genotype-by-environment interactions were not significant at a 1 % probability level.

Residual effects contributed to 21.59 to 54.22 % of the total variation in cooked oatmeal texture (Table 3.40). Possible contributors to this extraneous variation could include flake damage to some samples prior to testing and fluctuations in oatmeal temperature despite efforts to time the period between filling the canister with hot sample and testing. Aside from that, the majority of variation was due to genotype, indicating that it would be possible to breed for oat cultivars with specific oatmeal texture.

Some of the trends observed for other characteristics appeared to follow through to oatmeal texture. For example, oatmeals made from Triple Crown and CDC Boyer were texturally distinct from the other genotypes. Triple Crown and CDC Boyer also had flakes with the lowest water absorption capacity and the least proportion of small flakes (between 2.00 and 2.36 mm). It follows logically that oat flakes with these characteristics would be more fluid and stringy. It does not explain some of their other properties that

Table 3.39: Genotype and environment means for cooked oatmeal stringiness.[1]

Environment	Genotype					Std[2]	Mean
	AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	38.22	38.45	37.45	37.60	39.24	0.64	38.19 b
Morden	37.14	38.68	36.79	37.60	38.75	0.80	37.79 ab
Silverton '98	36.88	38.50	36.88	36.25	39.25	1.13	37.55 ab
Carman	37.19	38.09	35.68	38.04	39.23	1.18	37.65 ab
Winnipeg	38.26	39.07	38.05	35.49	39.19	1.34	38.01 ab
Silverton '99	35.95	35.07	34.95	37.14	38.51	1.34	36.32 a
Std[2]	0.80	1.33	1.04	0.88	0.29		
Mean	37.27 ab	37.98 bc	36.63 a	37.02 ab	39.03 c		

[1] Values are expressed in seconds. Values within a row or column followed by the same letter are not significantly different ($P \leq 0.01$).
[2] Std = Standard Deviation

Table 3.40: Relative contributions of factors to total variation in cooked oatmeal texture.

	Variance Component[1]				
Characteristic	Genotype	Environment	GxE[2]	Rep(E)[3]	Residual
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

[1] Values are expressed as a percentage of total variation.
[2] GxE = Genotype-by-environment interaction
[3] Rep(E) = Replicate within environment

would lead one to expect a thicker oatmeal. These properties include firm and gummy starch gels, low gelatinization temperatures, low starch RVA breakdown viscosity, high wholemeal RVA hot paste and final viscosity, and high β-glucan content.

Further investigation may reveal that an underlying property of the starch, such as slower swelling, was brought out by the specific cooking conditions of the oatmeal and not by the other testing methods. It is also possible that despite a starch-based tendency for Triple Crown and CDC Boyer to produce thick pastes, their large proportion of flakes greater than 2.36 mm prevented easy penetration of water and thus resulted in under cooked oatmeal. To test this theory, flakes could be pre-screened to achieve uniform flake distribution.

3.4 SUMMARY

The purpose of the first phase of this thesis was to determine the relative effects of genotype, environment and genotype-by-environment interactions on oat quality characteristics important to the food industry and to determine the nature of the interaction effects. These objectives were achieved by evaluating five genotypes grown at six environments in Manitoba. Summaries of the occurrence of significant effects are presented in Tables 3.41 and 3.42.

Hull content and groat breakage, which are both important physical oat properties desired in low levels, were significantly affected by genotype, environment and genotype-by-environment interactions. In the case of hull content, genotypes did not maintain the same ranking order across the six environments, indicating to breeders the

Table 3.41: Summary of significant genotype, environment and interaction effects for oat quality characteristics.

	Occurrence of Significant Effect ($P \leq 0.01$)		
Quality Parameter	Genotype (G)	Environment (E)	GxE Interaction
Hull Content[1]	YES	YES	YES
Groat Breakage	YES	YES	YES
β-Glucan	YES	NO	NO
Protein	YES	YES	NO
Oil	YES	YES	NO
Total Starch	YES	YES	NO
Iodine Affinity	YES	YES	NO
Starch Swelling Volume	YES	YES	YES
Starch RVA			
Peak	YES	YES	NO
Hot Paste	YES	YES	YES
Final	YES	YES	NO
Breakdown	YES	YES	YES
Final - Peak	YES	YES	NO
Setback	YES	YES	NO
Shear Thinning	YES	YES	YES
Starch Gel Texture			
Gel Strength (1^{st} Compression)	YES	NO	YES
Gel Strength (2^{nd} Compression)	YES	NO	NO
Adhesiveness	YES	NO	NO
Cohesiveness	NO	NO	NO
Springiness	YES	NO	NO
Gumminess	YES	NO	NO
Resilience	YES	YES	NO

[1] Analysis did not include the Winnipeg and Carman environments.

Table 3.41 Continued: Summary of significant genotype, environment and interaction effects for oat quality characteristics.

	Occurrence of Significant Effect ($P \leq 0.01$)		
Quality Parameter	Genotype (G)	Environment (E)	GxE Interaction
Starch DSC[1]			
AP Onset Temp.	YES	YES	NO
AP Max. Temp.	YES	YES	NO
AP ΔH	YES	YES	NO
AM Onset Temp.	YES	YES	NO
AM Max. Temp.	YES	YES	NO
AM ΔH	YES	YES	NO
Wholemeal RVA[2]			
Peak	YES	YES	NO
Hot Paste	YES	YES	NO
Final	YES	YES	NO
Breakdown	YES	YES	YES
Final - Peak	YES	YES	NO
Flake Hydration	YES	YES	YES
Flake Granulation			
> 4 mm	YES	YES	YES
< 4 mm, > 2.36 mm	YES	YES	YES
< 2.36 mm, > 2 mm	YES	YES	NO
< 2 mm	YES	YES	NO
Oatmeal Texture			
Positive Force	YES	NO	NO
Negative Force	YES	NO	NO
Stringiness	YES	YES	NO

[1] AP refers to the enthalpy peak associated with the gelatinization of amylopectin; AM refers to the enthalpy peak associated with the melting of the amylose-lipid complex.
[2] Analysis did not include the Silverton 1998 environment.

Table 3.42: Summary of cross-over interactions for oat characteristics showing significant genotype-by-environment effects.

Quality Characteristic	Significant Cross-Over Interaction (P = ≤0.05)	Number of Cross-Over Interactions (out of 60 comparisons)	Number of Genotype Pairs Involved in Cross-Over
Hull Content[1]	Yes	4	2
Groat Breakage	No		
Starch Swelling	No		
Gel Texture			
Strength (1st Compression)	Yes	3	1
Starch RVA			
Hot Paste	Yes	2	1
Breakdown	Yes	5	2
Shear Thinning	Yes	2	1
Wholemeal RVA[2]			
Breakdown	Yes	3	1
Oat Flake Hydration	Yes	2	1
Flake Granulation			
> 4.00 mm	Yes	2	1
< 4.00, > 2.36 mm	No		

[1] Analysis did not include the Winnipeg and Carman environments.
[2] Analysis did not include the Silverton 1998 environment.

necessity to test at several growing sites. On the other hand, selection of genotypes with low susceptibility to groat breakage would be the same at all locations, suggesting a strong genetic component that would be helpful to breeding programs. The strong environmental impact on breakage that was observed provides to millers who are sourcing high quality oats the knowledge that specific environments could lead to greater economic loss due to groats breaking during the dehulling process.

Oat composition was also significantly affected by the main effects of genotype and environment but genotype response was consistent across environments. The majority of variation in β-glucan content was due to genotype, whereas protein and oil were influenced by environment to a greater extent. Despite weak statistical correlations, relationships observed between parameters suggest that selection for high β-glucan content, which is in great demand by the industry, may also result in high hull content. More favorably, high β-glucan was also associated with low groat breakage and low oil content.

Significant genotypic variation existed for oat total starch, amylose content, starch swelling volume and starch gelatinization properties. Environmental effects were also significant and played a particularly large role in the variation in total starch , starch swelling volume and gelatinization properties. Genotype-by-environment effects were significant for starch swelling volume but the nature of the interaction was quantitative, indicating that ranking of genotypes remained constant across environments. Environmental effects for this trait appeared to be related to differences in amylose. A

strong inverse relationship between total starch and protein was found and was accentuated by the diversity in soil nitrogen levels across environments.

Both starch and wholemeal pasting characteristics were significantly influenced by genotype and environment and some parameters were affected by interactions involving cross-over effects. Starch pasting was predominantly influenced by environment, whereas the greater contributor to variation in wholemeal pasting depended on the parameter. Differences in wholemeal pasting characteristics were not necessarily consistent with starch pasting properties, but were more associated with differences in total starch.

Unlike pasting characteristics, most measurements of starch gel texture were not influenced by environment, but genotypic differences were significant. Weak gels were also the most adhesive. Both of these characteristics were associated with high values for starch paste breakdown viscosity, starch gelatinization temperature, ΔH for the melting of the amylose-lipid complex and low amylose content.

A small scale oat conditioning and flaking method was developed using a bench top flaking machine. This method mimics industrial processing systems but requires less than 100 g of oat groats to produce an end-product. The method was sensitive enough to detect highly significant differences in flake properties and cooked oatmeal texture among genotypes. Environment and genotype-by-environment interactions also influenced flake granulation and water absorption. Significant cross-over effects occurred between the most similar genotypes for hydration capacity but overall, the

genotypic component had the strongest influence on variation. Oat flakes with low hydration capacity and large granulation produced oatmeals that were more fluid and stringy. In addition, genotypes with distinct oatmeal texture also appeared to differ in other characteristics including starch gel texture, starch RVA breakdown, wholemeal RVA hot paste and final viscosities and β-glucan. This method could be used to screen advanced breeding lines for differences in oat end-product quality.

CHAPTER 4

EFFECT OF NITROGEN FERTILIZATION ON OAT QUALITY

4.1 INTRODUCTION

Nitrogen is an essential macronutrient required for the synthesis of plant components such as protein, chlorophyll and enzymes (Raven et al., 1986), making nitrogen fertilization a common agricultural practice. It is estimated that Manitoba farmers collectively spent over $315 million on fertilizer in the year 2000 (Manitoba Agriculture and Food, 2001), the majority of which was for nitrogen. Typical nitrogen fertilizer rates for oat crops range between 62 to 101 kg/ha and are based on target yields (Manitoba Agriculture and Food, 1999). Increasing the application rate increases crop yield (Anderson and McLean, 1989; Brinkman and Rho, 1984; Marshall et al., 1987; Ohm, 1976), however there is a point at which higher rates of nitrogen fail to increase yield (Brinkman and Rho, 1984), decrease test weight (Marshall et al., 1987; Ohm, 1976) and stop being profitable for the producer. These risks, which are largely a result of increased susceptibility to lodging, have prompted Manitoba Agriculture and Food to lower their recommended nitrogen fertilization rates.

Although decisions concerning the application of nitrogen fertilizer are made primarily for improving agronomic traits, it is important to consider potential effects on the food quality of oats. Previous studies have shown that nitrogen influences hull content (Humphreys et al., 1994a), protein (Humphreys et al., 1994b; Ohm, 1976; Potch, 1968; Welch and Yong, 1980; and Zhou et al., 1998b), β-glucan (Brunner and Freed,

1994) and wholemeal pasting characteristics (Zhou et al., 1998b). These reports suggest that there may be potential for oat millers and processors to ensure optimum composition by encouraging the use of specific fertilizer rates. In some cases, the response to nitrogen was dependant on the genotype (Ohm, 1976; Zhou et al., 1998b). Knowing how consistently genotypes perform with varying nitrogen availability is important for breeders to develop cultivars that are suitable for growth in diverse conditions.

The objective of this phase of the study was to determine the relative effects of nitrogen fertilization rate, genotype, environment and interactions amongst these factors on whole and/or milled oat physical attributes, composition and wholemeal pasting characteristics.

4.2 MATERIALS AND METHODS

4.2.1 Sample Set and Experimental Design

Oat test samples were grown in a split-plot design. The main plots were randomly assigned one of five genotypes: AC Assiniboia, CDC Boyer, AC Medallion, Triple Crown and OT 288. These genotypes were chosen because they are suitable for production in the Prairie Provinces of Canada and they exhibit a range in quality characteristics (Table 3.1). A seeding rate of 300 seeds/m^2 was adjusted according to each genotype's germination rate and kernel weight. Fertilizer (11-52-0) was applied to all plots at seeding at a rate of 23.5 kg/ha.

The main plots were divided into four subplots (40 m^2 dimension), which were randomly assigned either 0, 40, 80 or 120 kg/ha of actual nitrogen fertilizer. These treatments were applied at emergence by hand scattering ammonium nitrate.

All treatments were replicated four times at each of six sites in Manitoba, Canada. Plots were grown at Silverton, Glenlea and Morden in 1998 and at Silverton, Carman and Winnipeg in 1999. The growing sites were diverse in their soil type, initial soil nutrients and seeding dates (Table 3.2).

4.2.2 Analytical Methods

The following analytical tests were performed according to the methods described in Chapter 3: hull content, groat breakage, protein, β-glucan, oil and wholemeal pasting properties.

4.2.3 Statistical Analysis

The F-Max test was performed as described in Chapter 3. As a result of heterogeneous error variances (Table 4.1), each environment was analyzed separately for wholemeal RVA parameters. Prior to the analysis of groat breakage, the data was treated with a square root transformation and all environments were pooled.

Analyses were carried out by the same procedures described in Chapter 3 except that nitrogen fertilizer rate was included as a factor. This inclusion required that the ANOVA (PROC MIXED) be performed as a split-plot analysis with separate error terms

Table 4.1: Summary of F-Max test for homogeneity of environment error variances.

Quality Characteristic	Environmental Error Variances			Homogeneous Error Variances (if ≤ 3.6)
	Minimum	Maximum	Ratio Max/Min	
Hull Content	0.778	2.105	2.7	YES
Protein	0.369	0.718	2.0	YES
β-Glucan[1]	0.024	0.076	3.2	YES
Oil	0.008	0.016	2.0	YES
Breakage (Transformed)	0.130	0.210	1.6	YES
Wholemeal RVA				
Peak	39.718	219.326	5.5	NO
Hot Paste	36.755	171.088	4.7	NO
Final	57.938	320.267	5.5	NO
Breakdown	15.183	40.543	2.7	YES
Final - Peak	45.690	117.587	2.6	YES
Setback	14.085	39.304	2.8	YES
Shear Thinning	1.971	8.576	4.4	NO

[1]A square root transformation was performed on breakage data in order to achieve homogeneous error variances prior to analysis.

for genotype (main plot), nitrogen (sub-plot) and environment. Cross-over analysis was performed keeping levels of the nitrogen treatments separate at each environment. This meant that differences between ten possible genotype comparisons were evaluated at each of 24 "environments" (6 locations x 4 nitrogen treatments). For a cross-over to be non-significant, there would have to be no significant change in rank order of the genotypes among the environments and nitrogen treatments.

4.3 RESULTS AND DISCUSSION

ANOVA results are presented in Appendix 3.

4.3.1 Physical Oat Quality

Nitrogen fertilization significantly ($P \leq 0.01$) affected hull content, however its effects were dependent on the location and the genotype. Genotypes did not rank consistently across environments and nitrogen treatments resulting in 49 out of a possible 240 cross-over interactions involving 6 out of 10 genotype pairs. The Winnipeg, Glenlea and Carman sites had low initial soil nitrogen levels before fertilization treatments were applied (20 to 36 kg/ka) (Table 3.2). The hull contents, averaged over genotypes, decreased with increasing fertilizer rate (Table 4.2). The site with the lowest available nitrogen at the 0 kg/ha fertilizer treatment (Winnipeg) showed the largest decrease in hull content (average 3.02 %) at 120 kg/ha. All genotypes showed an incremental decrease in hull content with every increase in fertilizer rate. In contrast, this trend was not true for all genotypes at Carman and Glenlea. For example, CDC Boyer treated with 120 kg/ha of nitrogen had a slightly higher hull content compared to when no fertilizer was added at

Table 4.2: Nitrogen fertilization treatment means for oat hull content.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	30.96	30.35	30.22	32.44	37.52	2.73	32.30
	40	30.68	31.85	29.04	32.86	35.25	2.09	31.94
	80	28.97	31.21	29.52	32.56	37.03	2.88	31.86
	120	28.56	32.47	29.82	31.76	37.16	2.95	31.95
Morden	0	26.87	27.13	28.56	29.46	31.33	1.63	28.97
	40	27.31	28.13	29.72	29.03	29.98	1.00	28.83
	80	27.29	28.11	30.21	27.93	30.82	1.38	28.87
	120	26.26	27.52	30.45	28.09	31.77	2.01	28.82
Silverton '98	0	31.96	30.82	34.66	29.62	33.83	1.86	32.18
	40	32.85	30.57	34.40	28.79	33.42	2.04	32.01
	80	33.28	31.95	33.56	28.67	34.56	2.04	32.40
	120	33.20	31.26	33.48	28.51	33.77	1.97	32.04
Carman	0	30.23	28.32	31.68	32.29	36.01	2.55	31.71
	40	29.00	29.11	31.51	32.07	33.19	1.66	30.98
	80	27.84	28.11	30.50	31.15	32.92	1.91	30.10
	120	27.59	28.90	30.73	30.96	31.97	1.57	30.03
Winnipeg	0	34.12	29.66	33.76	35.44	38.39	2.82	34.27
	40	31.90	30.34	32.13	35.32	35.68	2.08	33.07
	80	29.45	28.68	32.41	34.07	35.32	2.57	31.99
	120	29.54	28.74	31.89	31.61	34.45	2.00	31.25
Silverton '99	0	29.07	25.79	28.78	28.79	31.01	1.67	28.69
	40	27.12	27.08	28.75	28.42	29.83	1.04	28.24
	80	26.47	32.87	28.50	27.87	29.03	2.14	28.95
	120	26.38	31.29	28.70	27.65	28.88	1.62	28.58
	Std[2]	2.38	1.86	1.92	2.34	2.71		
	Mean	29.45	29.59	30.96	30.64	33.46		

[1] Values are expressed in percentage.
[2] Std = Standard Deviation

both of these sites. These differences could be due to genetic factors affecting the plant's nitrogen requirements for or use of nitrogen. The Morden, Silverton 1998 and 1999 sites had much higher levels of initial soil nitrogen (144 to 441 kg/ha). Varying the fertilizer rate at these sites did not cause any change in the mean hull content averaged over genotypes. Individual genotypes responded to higher fertilizer rates with either slight increases (example CDC Boyer) or decreases (example OT 288) in hull content.

Significant genotype-by-nitrogen effects have not been found by other researchers (Humphreys et al., 1994a; Zhou et al, 1998b). However, Humphreys et al. (1994a) also found that the effect of nitrogen is dependent on the environment. They observed a significant ($P \leq 0.05$) decrease in hull content at only one out of four environments studied using 40 kg/ka of nitrogen at seeding in addition to 20 kg/ha at the boot stage. They suggested that high levels of nitrogen delayed maturity therefore increasing grain filling and decreasing the proportion of hull. The observed decrease in hull content due to nitrogen was felt to be of no economic value. Zhou et al. (1998b) found that nitrogen fertilizer rates ranging from 0 to 100 kg/ha did not have a significant effect on the hull content of five Australian genotypes.

The results of this study indicate that the availability of nitrogen is important in helping to reduce the hull content of oats. A concurrent increase in protein and grain filling with increased nitrogen would decrease the proportion of hull. However, at soil nitrogen levels above a certain level, hull content does not change. This level seems to be different depending on the genotype. For example, the semi-dwarf line OT 288 showed

at least some decrease in hull content at all sites including 1998 Silverton (441 kg/ha initial soil nitrogen). It is possible that the increase in the proportion of hull for some tall genotypes such as CDC Boyer and AC Assiniboia could be related to their greater susceptibility to lodging. Response to nitrogen fertilizer did not seem to be related to mean hull content. For example, both AC Assiniboia and Triple Crown exhibited the widest variation in hull content over sites and nitrogen treatments (coefficients of variation > 8 %) but had the lowest and highest overall mean hull contents respectively. AC Medallion was the least affected by growing site and nitrogen fertilization (coefficient of variation = 6.2 %).

The main effect of nitrogen was not significant for groat breakage, however the response to nitrogen did depend on the growing site. Significant cross-over interactions occurred involving one genotype pair (Triple Crown and OT 288). Two of the sites with low initial soil nitrogen (Winnipeg and Glenlea) showed an overall decrease in breakage with an increase in nitrogen fertilization rate (Table 4.3). This trend was not consistent with the other sites. It was observed that the three sites with low initial soil nitrogen had breakage values lower than those with high soil nitrogen. These three sites also tended to have low protein contents, suggesting a possible link between high breakage and high protein, although the site with the highest breakage (1999 Silverton) was not the site with the highest protein (1998 Silverton). It is possible that only very large differences in

Table 4.3: Nitrogen fertilization treatment means for oat groat breakage.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	4.93	4.20	7.50	8.26	2.50	2.13	5.48
	40	4.83	3.39	6.46	4.91	2.19	1.45	4.36
	80	5.02	2.89	6.13	3.94	2.44	1.36	4.08
	120	4.72	3.98	6.39	4.73	2.14	1.38	4.39
Morden	0	8.65	15.32	13.38	8.54	3.39	4.18	9.86
	40	10.23	11.61	15.55	10.03	3.46	3.90	10.18
	80	12.23	11.24	23.58	7.32	3.07	6.86	11.49
	120	11.12	16.16	16.77	9.02	3.90	4.76	11.39
Silverton '98	0	13.36	14.88	16.96	11.75	4.45	4.28	12.28
	40	12.10	10.48	17.64	10.49	4.37	4.24	11.02
	80	17.55	12.31	15.85	11.02	4.49	4.53	12.24
	120	13.20	13.46	16.05	14.23	4.59	3.98	12.31
Carman	0	7.65	12.43	12.22	10.07	2.57	3.65	8.99
	40	9.52	13.13	15.48	7.58	2.77	4.42	9.70
	80	7.80	10.55	10.99	7.85	2.16	3.15	7.87
	120	9.09	12.58	15.34	7.60	3.41	4.11	9.60
Winnipeg	0	6.34	7.07	8.64	6.16	2.35	2.07	6.11
	40	6.16	5.44	7.17	6.82	2.40	1.70	5.60
	80	4.23	3.77	6.23	5.12	1.97	1.42	4.26
	120	3.80	3.46	7.47	3.76	2.38	1.73	4.17
Silverton '99	0	20.54	19.09	20.11	13.22	10.59	4.04	16.71
	40	21.49	18.07	19.87	9.87	11.12	4.71	16.08
	80	22.84	19.92	21.52	10.34	10.54	5.46	17.03
	120	20.52	18.71	21.09	11.96	8.99	4.87	16.25
	Std[2]	5.82	5.43	5.48	2.83	2.84		
	Mean	10.75	11.01	13.68	8.52	4.26		

[1] Values represent untransformed data and are expressed in percentage.
[2] Std = Standard Deviation

nitrogen availability have an effect on breakage; the environments provided this magnitude of difference while the nitrogen treatments did not. Another likely explanation is that there was a specific environmental condition other than soil nutrients, such as excess moisture or lodging, that was prevalent at the sites with high breakage that caused the oats to be susceptible to breakage. Further research is required to determine what that condition is. No other researchers to date have reported on the effects of nitrogen fertilization on groat breakage.

The nitrogen fertilization treatments used in this study contributed practically nothing to total variation in oat physical properties, indicating that controlling nitrogen fertilization rate alone, would not be a successful mechanism for ensuring low hull content and low groat breakage (Table 4.4).

4.3.2 Oat Composition

Nitrogen fertilization rate significantly affected oat composition as did interactions with nitrogen, genotype and environment. Significant cross-over interactions occurred for protein but not for oil or β-glucan content. Protein content was increased by up to 4.41 % with a rate of 120 kg/ha depending on the genotype and the growing site (Table 4.5). AC Assiniboia showed the least variation in protein over the environments and fertilizer rates (coefficient of variation = 9.97 %) whereas CDC Boyer varied the most (coefficient of variation = 13.76 %). CDC Boyer was also involved in two significant cross-over interactions, one with OT 288 and the other with Triple Crown. Other than that, there were no significant changes in ranking of the genotypes over the 24

Table 4.4: Relative contributions of factors to total variation in oat physical properties.

	Variance Component[1]									
Parameter	Genotype	Environment	Nitrogen	GxE[2]	GxN[2]	ExN[2]	GxExN[2]	Rep (E)[3]	Rep*G (E)[3]	Residual
Hull Content	21.63	25.18	0.04	20.29	3.18	1.58	3.33	3.76	4.01	17.01
Groat Breakage	29.32	38.78	0.00	6.93	0.34	0.61	0.04	11.62	1.17	11.19

[1] Values are expressed as a percentage of total variation.
[2] Represent interaction effects between genotype (G), environment (E) and nitrogen (N).
[3] Rep(E) = main plot error; Rep*G(E) = sub plot error.

Table 4.5: Nitrogen fertilization treatment means for oat wholemeal protein.[1]

Location	Nitrogen (kg/ha)	Genotype						
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown	Std[2]	Mean
Glenlea	0	13.47	12.52	12.91	13.52	14.85	0.79	13.45
	40	12.97	12.65	12.95	13.68	13.93	0.48	13.24
	80	13.76	13.99	14.39	14.83	14.40	0.37	14.27
	120	15.24	15.58	14.94	15.96	16.05	0.42	15.55
Morden	0	15.26	15.39	16.51	16.77	16.40	0.62	16.07
	40	15.13	15.60	16.54	15.20	16.80	0.69	15.85
	80	16.11	16.28	16.71	16.45	17.18	0.37	16.55
	120	16.29	17.11	16.46	17.23	17.08	0.38	16.83
Silverton '98	0	17.40	18.35	17.32	17.94	18.14	0.41	17.83
	40	16.92	18.09	17.06	16.98	17.64	0.46	17.34
	80	17.46	18.38	17.13	17.06	17.91	0.50	17.59
	120	17.86	18.91	17.67	17.43	17.96	0.51	17.97
Carman	0	13.14	13.09	12.29	12.89	12.63	0.32	12.81
	40	14.08	13.32	12.98	13.66	13.48	0.36	13.50
	80	15.11	15.13	14.08	14.58	14.71	0.39	14.72
	120	15.55	16.66	15.81	15.51	16.12	0.43	15.93
Winnipeg	0	12.55	12.91	12.25	12.66	13.72	0.50	12.82
	40	12.99	11.86	12.02	12.10	13.05	0.51	12.40
	80	14.03	13.48	13.35	13.74	13.39	0.26	13.60
	120	14.04	14.26	14.79	14.62	14.41	0.26	14.42
Silverton '99	0	14.23	13.62	13.34	15.30	14.49	0.69	14.20
	40	14.94	15.42	13.46	15.32	15.53	0.76	14.93
	80	15.78	17.10	15.00	16.13	15.60	0.69	15.92
	120	16.19	18.03	15.79	16.40	15.99	0.80	16.48
	Std[2]	1.50	2.11	1.79	1.61	1.65		
	Mean	15.02	15.32	14.82	15.25	15.48		

[1] Values are expressed in percentage.
[2] Std = Standard Deviation

growing site and nitrogen rate combinations. Increased fertilizer rates did not have the same magnitude of effect at all growing sites (Figure 4.1). Oats grown at the 1998 Silverton and Morden sites responded very little to fertilizer rates. These two sites also had high initial soil nitrogen, suggesting that due to excess available nitrogen, increases in protein content had reached a plateau. This does not explain, however, the relatively large response to fertilizer observed at the 1999 Silverton site, which also had high residual soil nitrogen levels. It is possible that other environmental factors, such as soil leaching, could have contributed to lower soil nitrogen levels than were determined at the time of soil nutrient testing. Portch et al. (1968) found that in well drained soils, the increase in protein due to nitrogen was less than that in soils with poor drainage. The opposite could be expected in this case where excess residual nitrogen would be lost, thus lowering levels below optimum. This or other environmental conditions independent of nitrogen availability could also explain why this site had overall protein levels that were lower than the Morden and Silverton 1998 sites. Regardless of the cause, it did appear that where protein contents were low, increased nitrogen fertilization was beneficial. Conversely, where conditions allowed for the oats to reach close to their genetic potential for high protein, added nitrogen fertilizer had little effect.

Several researches have also found significant increases in protein up to 3.8 % with increased nitrogen fertilization (Humphreys et al., 1994b; Ohm, 1976; Portch et al., 1968; Welch and Yong, 1980; Zhou et al., 1998b). While not all studies observed

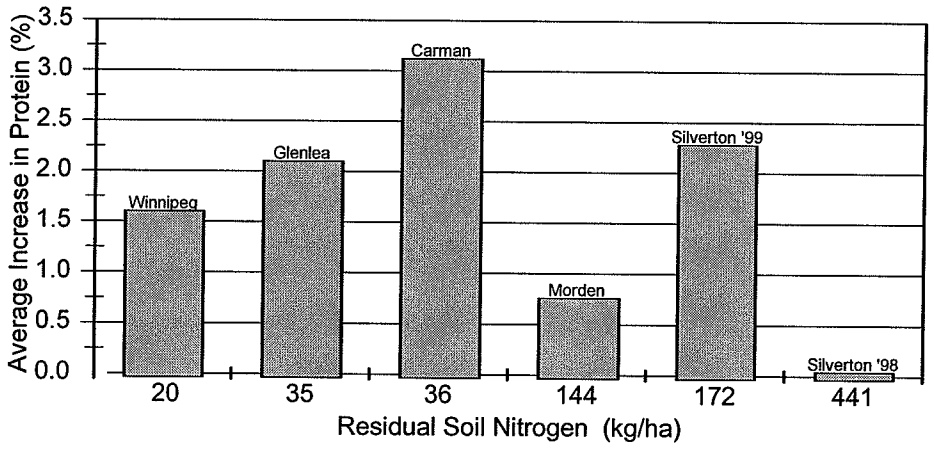


Figure 4.1: Average increase in protein content resulting from nitrogen fertilization (120 vs. 0 kg/ha) at six environments.

significant genotype-by-nitrogen interactions (Humphreys et al., 1994b; Welch and Yong, 1980; Zhou et al., 1998b), Ohm (1976) found that genotypes responded differently to nitrogen. Humphreys et al. (1994b) also found that nitrogen effects were significant at some locations but not others and Portch et al. (1968) observed significant year-by-fertilizer effects.

Nitrogen fertilization also had a significant effect ($P \leq 0.01$) on β-glucan content, where a similar trend to that observed for protein was seen. Oats grown at the three sites with the lowest initial soil nitrogen levels (Winnipeg, Glenlea, and Carman) showed the largest increase in β-glucan content with higher nitrogen fertilizer rates (Table 4.6). For example, Figure 4.2 shows that the oats grown at Winnipeg (20 kg/ha residual soil nitrogen) experienced an increase in β-glucan up to 1 % (AC Medallion) with 120 kg/ha added nitrogen. On the other hand, Figure 4.3 shows that at the Silverton site in 1998, which already contained 441 kg/ha of nitrogen in the soil, nitrogen fertilization had a negligible effect (overall increase 0.01 %) and for OT 288 β-glucan content decreased slightly. Interaction effects were also significant but did not result in a significant change in rank order for the genotypes at the 24 environment and nitrogen rate combinations. Brunner and Freed (1994) also found that nitrogen had an increasing effect on β-glucan but that this response was not significant at all growing environments.

Oil content also significantly ($P \leq 0.01$) decreased, albeit slightly, with an increase in nitrogen fertilization. The most extreme change occurred at the 1999 Silverton site

Table 4.6: Nitrogen fertilization treatment means for oat wholemeal β-glucan.[1]

Location	Nitrogen (kg/ha)	Genotype						
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown	Std[2]	Mean
Glenlea	0	4.26	5.29	4.73	4.22	6.01	0.68	4.90
	40	4.28	5.36	4.88	4.34	5.79	0.58	4.93
	80	4.45	5.44	5.05	4.34	5.88	0.58	5.03
	120	4.73	5.59	5.07	4.55	6.09	0.57	5.21
Morden	0	4.44	4.93	4.82	4.46	5.54	0.40	4.84
	40	4.59	4.95	5.00	4.36	5.62	0.43	4.90
	80	4.58	4.95	4.91	4.51	5.62	0.39	4.91
	120	4.49	5.14	4.84	4.55	5.89	0.51	4.98
Silverton '98	0	4.62	5.12	4.97	4.51	5.97	0.52	5.04
	40	4.49	5.12	4.92	4.35	5.70	0.48	4.92
	80	4.60	5.09	5.04	4.38	5.81	0.49	4.98
	120	4.66	5.23	5.21	4.46	5.70	0.44	5.05
Carman	0	4.34	5.02	4.71	4.27	5.42	0.43	4.75
	40	4.43	5.01	5.03	4.54	5.55	0.40	4.91
	80	4.60	5.42	4.94	4.43	5.75	0.49	5.03
	120	4.78	5.34	5.03	4.61	5.77	0.41	5.11
Winnipeg	0	4.32	5.02	4.46	4.02	5.55	0.55	4.67
	40	4.79	5.08	5.15	4.23	5.92	0.55	5.03
	80	5.02	5.77	5.38	4.57	5.98	0.51	5.34
	120	4.99	5.68	5.46	4.93	5.76	0.34	5.36
Silverton '99	0	4.31	5.24	4.94	4.49	5.65	0.49	4.93
	40	4.59	5.33	5.12	4.83	5.69	0.38	5.11
	80	4.86	5.44	5.02	4.57	5.72	0.41	5.12
	120	4.56	5.21	5.17	4.43	5.65	0.45	5.00
	Std[2]	0.21	0.23	0.31	0.19	0.16		
	Mean	4.57	5.24	4.99	4.46	5.75		

[1] Values are expressed in percentage.
[2] Std = Standard Deviation

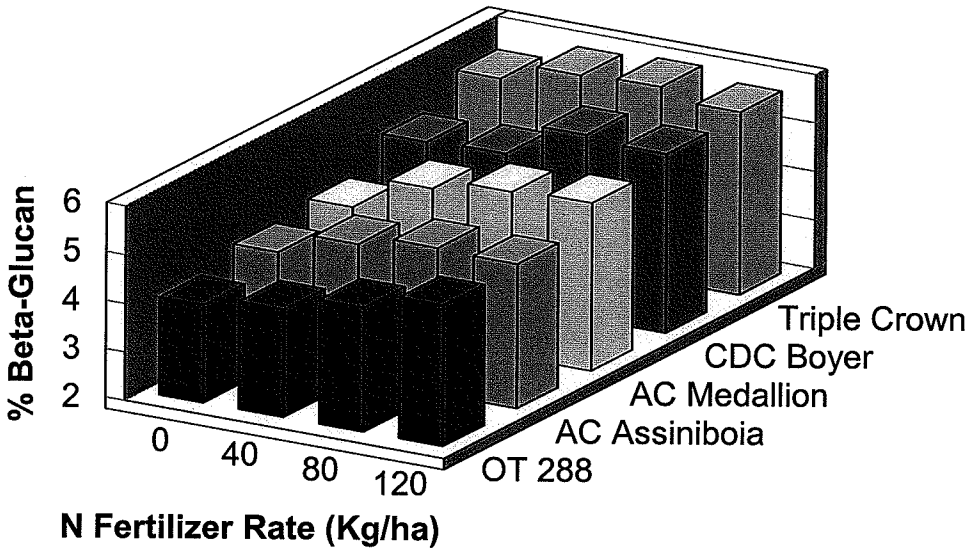


Figure 4.2: Effect of nitrogen fertilization on β-glucan content at Winnipeg (low residual nitrogen).

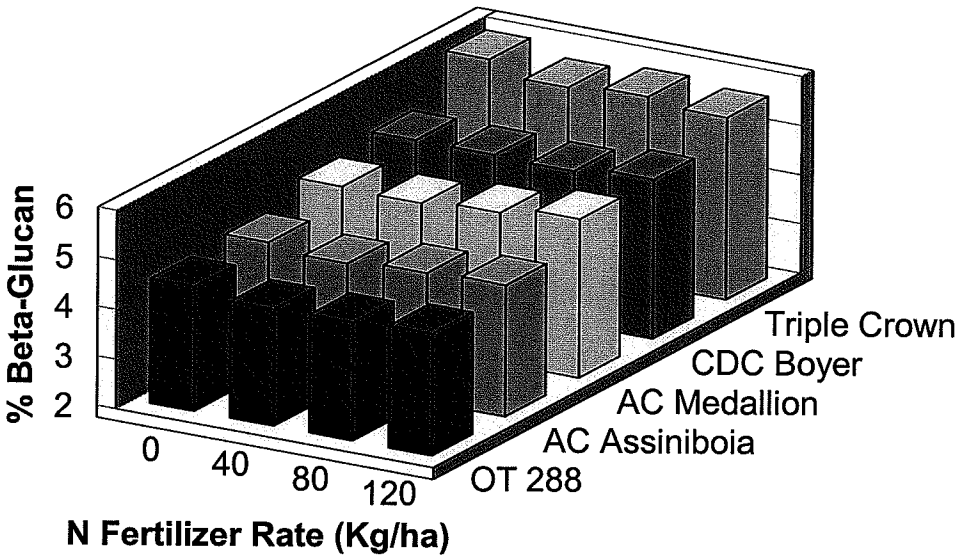


Figure 4.3: Effect of nitrogen fertilization on β-glucan content at Silverton 1998 (high residual nitrogen).

where the 120 kg/ha nitrogen treatment resulted in a decrease in oil content from 4.91 to 4.56 % compared to the 0 kg/ha treatment (Table 4.7). As with protein and β-glucan, nitrogen had the least effect on oil content at the 1998 Silverton site, which had the highest initial soil nitrogen. As with protein, the 1999 Silverton site showed a higher magnitude of response to nitrogen fertilization compared to 1998 Silverton and Morden, despite its hgih soil nitrogen. There was no significant difference in the response of the different genotypes to nitrogen fertilizer. The literature provides conflicting results regarding the effect of nitrogen fertilization on oil content. Zhou et al. (1998b) found that nitrogen fertilization tended to increase oil but that the response was not significant. In a study by Humphreys et al. (1994b), one genotype at one of the environments also showed an increase in oil with an increase in fertilizer. At another site, however, increased nitrogen resulted in decreased oil contents (6.27 verses 6.16 %), which is similar to the response found in this study.

Component of variation analysis (Table 4.8) indicated that nitrogen fertilization contributed more to the variation in protein (13.07 %) than it did for β-glucan and oil (2.93 and 2.99 % respectively). In light of the large differences in soil nitrogen due to environments, these values may underestimate the role of nitrogen in the variation of oat composition. In all three cases, nitrogen fertilization played less of a role in total variation compared to either genotype or environment, as was expected. Zhou et al. (1998b) also found that genotype effects on protein were more important than nitrogen. Genotype selection remains the most important way to ensure high β-glucan content and

Table 4.7: Nitrogen fertilization treatment means for whole oat oil content.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	4.24	4.42	4.56	4.48	4.06	0.18	4.35
	40	4.18	4.41	4.54	4.46	4.08	0.17	4.33
	80	4.14	4.32	4.42	4.32	4.01	0.15	4.24
	120	4.18	4.07	4.45	4.25	4.08	0.14	4.21
Morden	0	4.09	4.35	4.06	4.24	3.98	0.13	4.14
	40	3.96	4.22	4.05	4.27	3.91	0.14	4.08
	80	4.02	4.14	4.07	4.16	3.92	0.09	4.06
	120	4.01	4.09	4.05	4.13	3.94	0.07	4.04
Silverton '98	0	4.29	4.30	4.37	4.49	4.06	0.14	4.30
	40	4.32	4.30	4.41	4.63	4.09	0.17	4.35
	80	4.21	4.27	4.42	4.51	3.96	0.19	4.27
	120	4.28	4.26	4.33	4.57	4.09	0.15	4.31
Carman	0	4.48	4.55	4.80	4.85	4.42	0.17	4.62
	40	4.51	4.54	4.64	4.71	4.44	0.10	4.57
	80	4.53	4.43	4.57	4.69	4.31	0.13	4.51
	120	4.39	4.37	4.58	4.57	4.25	0.13	4.43
Winnipeg	0	4.51	4.68	4.74	4.91	4.35	0.19	4.64
	40	4.51	4.60	4.73	4.95	4.28	0.22	4.61
	80	4.58	4.71	4.66	4.82	4.32	0.17	4.62
	120	4.50	4.61	4.66	4.64	4.29	0.14	4.54
Silverton '99	0	4.58	4.78	4.91	4.99	4.45	0.20	4.74
	40	4.67	4.67	5.01	4.94	4.46	0.20	4.75
	80	4.54	4.46	4.74	4.99	4.48	0.20	4.64
	120	4.55	4.47	4.56	4.87	4.37	0.17	4.56
	Std[2]	0.21	0.19	0.26	0.27	0.19		
	Mean	4.34	4.42	4.51	4.60	4.19		

[1] Values are expressed in percentage.
[2] Std = Standard Deviation

Table 4.8: Relative contributions of factors to total variation in oat composition.

	Variance Component[1]									
Component	Genotype	Environment	Nitrogen	GxE[2]	GxN[2]	ExN[2]	GxExN[2]	Rep (E)[3]	Rep*G (E)[3]	Residual
β-Glucan	74.18	0.00	2.93	1.92	0.08	3.18	0.00	3.18	0.00	14.53
Protein	0.66	52.28	13.07	2.28	0.74	4.88	0.12	11.59	2.04	12.33
Oil	25.12	50.69	2.99	3.08	0.29	0.51	0.68	1.51	2.12	13.01

[1] Values are expressed as a percentage of total variation.
[2] Represent interaction effects between genotype (G), environment (E) and nitrogen (N).
[3] Rep(E) = main plot error; Rep*G(E) = sub plot error.

considering the growing environment is essential for high protein and low oil. Attaining these desirable levels of oat components can however, be further promoted by ensuring adequate nitrogen availability. It must be noted that there is a limit to the potential benefits of nitrogen on oat composition and excessive levels of fertilizer would not likely be economical.

4.3.3 Wholemeal Pasting Properties

Due to heterogeneous error variances, the six sites could not be pooled for analysis. The Morden and two Silverton sites, which had comparatively high soil nitrogen levels, showed high error variances compared to Carman, Winnipeg, and Glenlea.

The effect of nitrogen fertilization was greatly dependent on the growing environment for all RVA parameters (Tables 4.9 to 4.15). Oats grown at the Silverton 1998 and Morden sites, which both had high levels of residual nitrogen, had no significant response to nitrogen fertilization. Oats grown at the Silverton 1999 site however, did respond significantly to nitrogen. Peak, hot paste, final and final minus peak values tended to be lowest at the highest rate of applied nitrogen, whereas breakdown and shear thinning viscosities were highest. There was a significant genotype-by-nitrogen effect at this environment for setback viscosity. The main effect of nitrogen was not significant for any RVA parameter at the Glenlea site, which had relatively low residual nitrogen. Clearly, the lack of response to nitrogen fertilizer observed did not necessarily depend on the presence of excess levels of soil nitrogen. Carman exhibited a significant nitrogen fertilization response, although the relationship between peak viscosity, final viscosity and the fertilizer

Table 4.9: Nitrogen fertilizer treatment means for oat wholemeal RVA peak viscosity.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	303	293	295	292	321	10.40	300
	40	303	285	293	297	322	12.75	300
	80	310	287	287	296	320	12.61	300
	120	307	281	286	295	307	10.63	295
Morden	0	298	287	290	285	302	6.53	292
	40	298	283	295	292	305	7.28	294
	80	299	277	284	288	308	10.71	291
	120	287	279	283	288	301	7.60	289
Silverton '98	0	278	251	251	280	266	12.34	265
	40	277	238	256	291	271	17.92	266
	80	278	241	257	284	256	15.71	263
	120	272	240	252	285	269	15.81	264
Carman	0	324	312	304	318	336	10.54	319
	40	329	322	320	329	342	7.70	328
	80	330	318	317	327	339	8.13	326
	120	322	303	300	322	344	15.85	318
Winnipeg	0	324	312	320	321	342	9.93	324
	40	338	330	333	331	356	9.99	338
	80	354	339	336	348	351	6.95	346
	120	351	333	329	350	363	12.53	345
Silverton '99	0	319	308	312	325	325	6.62	317
	40	324	307	320	326	333	8.60	322
	80	328	282	306	320	335	18.77	314
	120	308	265	302	313	327	20.49	303
	Std[2]	22.34	28.74	24.25	20.89	28.85		
	Mean	311	290	297	308	318		

[1] Values are expressed in RVU.
[2] Std = Standard Deviation

Table 4.10: Nitrogen fertilizer treatment means for oat wholemeal RVA hot paste viscosity.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	169	197	174	161	183	12.37	177
	40	178	192	181	164	195	11.05	182
	80	179	191	173	161	192	11.60	179
	120	173	184	172	159	181	8.70	174
Morden	0	158	178	153	137	176	15.24	160
	40	150	170	158	146	173	10.65	159
	80	152	160	146	138	170	11.07	153
	120	138	156	140	134	161	10.67	146
Silverton '98	0	127	117	107	131	112	9.00	119
	40	127	108	110	138	115	11.32	120
	80	125	110	111	132	105	10.17	117
	120	121	108	109	135	117	9.80	118
Carman	0	178	193	169	166	196	12.21	180
	40	174	193	175	179	199	10.12	184
	80	173	179	167	167	190	8.63	175
	120	160	162	151	167	187	11.98	165
Winnipeg	0	178	189	183	176	189	5.40	183
	40	187	204	193	183	204	8.61	194
	80	196	210	194	185	197	8.01	196
	120	196	195	181	178	199	8.57	190
Silverton '99	0	173	195	177	169	193	10.61	181
	40	173	184	181	171	197	9.26	181
	80	168	156	158	158	195	14.62	167
	120	148	138	152	152	179	13.60	154
	Std[2]	21.64	31.15	26.09	17.10	29.97		
	Mean	163	170	159	158	175		

[1] Values are expressed in RVU.
[2] Std = Standard Deviation

Table 4.11: Nitrogen fertilizer treatment means for oat wholemeal RVA final viscosity.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	353	378	361	337	378	15.60	361
	40	359	374	362	331	382	17.40	362
	80	361	375	361	334	381	16.22	362
	120	364	368	365	336	366	11.97	360
Morden	0	312	343	320	281	340	22.41	319
	40	299	335	332	292	334	18.85	318
	80	304	318	317	279	328	16.82	309
	120	279	317	316	273	316	19.85	300
Silverton '98	0	282	279	265	280	252	11.50	272
	40	284	263	271	282	257	10.48	271
	80	284	265	275	272	243	13.82	268
	120	280	261	275	278	260	8.57	271
Carman	0	325	354	322	310	355	18.10	333
	40	323	361	333	330	360	15.93	341
	80	327	349	333	317	352	13.23	336
	120	315	332	318	324	351	12.88	328
Winnipeg	0	332	353	339	328	358	11.68	342
	40	346	373	355	333	372	15.33	356
	80	367	386	355	339	361	15.36	362
	120	365	368	345	328	372	16.64	356
Silverton '99	0	325	356	335	316	355	15.96	337
	40	330	342	342	321	357	12.21	338
	80	325	323	319	302	355	17.14	325
	120	303	298	322	292	333	15.42	310
	Std[2]	28.68	37.69	29.05	23.50	4.42		
	Mean	323	336	327	309	338		

[1] Values are expressed in RVU.
[2] Std = Standard Deviation

Table 4.12: Nitrogen fertilizer treatment means for oat wholemeal RVA final minus peak viscosity values.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	51	85	66	45	58	13.90	61
	40	55	90	69	35	60	17.97	62
	80	52	88	74	39	62	16.99	63
	120	57	87	80	42	59	16.36	65
Morden	0	14	57	30	-5	38	21.08	27
	40	1	53	37	0	29	20.69	24
	80	5	41	33	-9	21	18.23	18
	120	-9	38	33	-14	15	21.17	13
Silverton '98	0	5	29	14	0	-15	14.62	7
	40	7	24	16	-9	-14	14.44	5
	80	6	24	18	-11	-13	14.91	5
	120	8	21	23	-7	-9	13.45	7
Carman	0	2	42	18	-7	20	16.83	15
	40	-6	38	13	2	18	15.05	13
	80	-3	31	16	-11	14	14.84	9
	120	-7	30	18	1	7	12.98	10
Winnipeg	0	8	41	20	8	16	12.13	19
	40	8	43	22	2	15	14.18	18
	80	14	47	20	-9	10	18.12	16
	120	14	35	17	-2	9	18.51	11
Silverton '99	0	7	48	23	-9	31	19.62	20
	40	6	35	22	-5	24	14.15	16
	80	-3	41	13	-17	20	19.82	11
	120	-5	33	19	-20	7	18.40	7
	Std[2]	19.75	20.49	20.10	19.01	22.22		
	Mean	12	46	30	1	20		

[1] Values are expressed in RVU.
[2] Std = Standard Deviation

Table 4.13: Nitrogen fertilizer treatment means for oat wholemeal RVA breakdown viscosity.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	134	96	121	130	138	15.00	124
	40	125	92	112	133	128	14.74	118
	80	130	96	114	134	128	13.94	120
	120	134	97	114	136	126	14.44	121
Morden	0	140	109	137	149	125	13.83	132
	40	147	112	136	146	132	12.67	135
	80	147	117	138	150	138	11.54	138
	120	149	122	143	154	139	10.97	141
Silverton '98	0	151	133	145	149	155	7.53	147
	40	150	130	146	152	156	9.00	147
	80	154	131	146	151	151	8.21	147
	120	151	133	144	149	152	6.97	146
Carman	0	146	119	135	151	139	10.99	138
	40	154	129	144	149	144	8.37	144
	80	157	139	149	160	148	7.39	151
	120	162	141	149	156	157	7.29	153
Winnipeg	0	146	123	137	145	153	10.24	141
	40	151	125	140	149	154	10.50	144
	80	157	129	142	163	155	12.20	149
	120	156	138	148	172	164	11.89	156
Silverton '99	0	145	113	134	155	131	14.14	136
	40	152	123	139	154	136	11.34	141
	80	160	126	147	162	141	13.20	147
	120	159	127	150	161	147	12.11	149
	Std[2]	9.43	13.95	11.20	9.79	11.11		
	Mean	148	121	138	150	143		

[1] Values are expressed in RVU.
[2] Std = Standard Deviation

Table 4.14: Nitrogen fertilizer treatment means for oat wholemeal RVA setback viscosity.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	184	181	186	175	196	6.89	184
	40	181	182	182	168	188	6.58	180
	80	182	184	187	173	190	5.78	183
	120	191	184	194	178	185	5.61	186
Morden	0	154	165	168	145	164	8.52	159
	40	149	165	173	146	161	10.05	159
	80	152	158	171	141	159	9.79	156
	120	141	161	176	140	155	13.40	155
Silverton '98	0	156	162	158	149	140	7.75	153
	40	157	155	161	144	143	7.21	152
	80	159	155	164	140	138	10.38	151
	120	160	153	167	142	144	9.45	153
Carman	0	148	162	153	145	159	6.41	153
	40	148	167	158	151	162	6.97	157
	80	155	170	165	150	162	7.12	160
	120	155	171	167	157	164	6.01	163
Winnipeg	0	153	164	156	152	169	6.62	159
	40	159	168	162	151	168	6.34	162
	80	171	176	162	154	165	7.55	166
	120	169	172	165	150	173	8.38	166
Silverton '99	0	152	161	157	146	162	5.95	156
	40	157	158	161	150	160	3.87	157
	80	157	166	160	145	160	6.95	158
	120	154	160	169	141	153	9.18	155
	Std[2]	12.55	9.04	10.43	10.91	14.76		
	Mean	160	167	168	151	163		

[1] Values are expressed in RVU.
[2] Std = Standard Deviation

Table 4.15: Nitrogen fertilizer treatment means for oat wholemeal RVA shear thinning viscosity.[1]

Location	Nitrogen (kg/ha)	Genotype					Std[2]	Mean
		AC Assiniboia	CDC Boyer	AC Medallion	OT 288	Triple Crown		
Glenlea	0	44	32	41	45	43	4.69	41
	40	41	32	38	45	40	4.26	39
	80	42	33	39	45	40	3.97	40
	120	44	34	40	46	41	4.10	41
Morden	0	47	38	47	52	42	4.79	45
	40	50	40	46	50	43	3.92	46
	80	49	42	48	52	45	3.43	47
	120	52	44	50	53	47	3.31	49
Silverton '98	0	55	54	59	53	58	2.32	56
	40	54	55	57	52	58	2.14	55
	80	55	55	57	53	59	2.04	56
	120	56	55	57	53	57	1.50	56
Carman	0	45	38	45	48	42	3.38	44
	40	47	40	45	45	42	2.48	44
	80	48	44	47	49	44	2.06	46
	120	51	47	50	48	46	1.85	48
Winnipeg	0	45	39	43	45	45	2.33	43
	40	45	38	42	45	43	2.58	43
	80	44	38	43	47	44	2.93	43
	120	44	41	45	49	45	2.56	45
Silverton '99	0	46	37	43	48	40	3.97	43
	40	47	40	43	47	41	2.94	44
	80	48	45	48	51	42	3.06	47
	120	52	48	50	52	45	2.65	49
	Std[2]	4.22	7.03	5.79	3.03	5.89		
	Mean	48	42	47	49	46		

[1] Values are expressed in RVU.
[2] Std = Standard Deviation

rate did not seem linear. The trends for hot paste, breakdown, and shear-thinning followed those observed for the Silverton 1999 site more closely. The Winnipeg site, which had the lowest residual soil nitrogen (20 kg/ha) was distinct from the other environments in that it showed a tendency for the peak, final and hot paste viscosities to increase with higher nitrogen fertilization rates. This finding also contradicted that of Zhou et al. (1998b) who observed a slight decrease in peak viscosity with higher nitrogen fertilization rates.

In general, the sites showing high RVA viscosities also exhibited low protein and high total starch. This suggests that as protein increases with nitrogen availability, there is a subsequent drop in total starch which results in lower pasting viscosities. Environments showing little change in protein with increasing nitrogen fertilization, such as Silverton 1998 and Morden, also showed little change in wholemeal pasting viscosity. This does not explain however, why the pasting characteristics of oats grown at the Glenlea site showed no change with nitrogen fertilization while those grown at the Winnipeg site showed an opposite trend. Oats grown with no fertilizer at Winnipeg had the highest total starch content and the lowest protein. Protein increased with increasing fertilizer rates, but total starch was not measured. It is possible that the nitrogen rates were sufficiently different to change protein but not different enough to alter total starch to a magnitude that could affect RVA pasting. However, there is no evidence to suggest that the inverse relationship between protein and total starch should behave any differently due to the low nitrogen conditions, based on data from the 0 kg/ha nitrogen fertilization study, which showed decreases in total starch with relatively small increases in residual soil nitrogen between

locations. The unique increase in pasting viscosities observed with higher rates of nitrogen fertilizer at Winnipeg was likely a result of a confounding environmental influence that could not be identified by the parameters measured in this study.

The results of this study suggest that nitrogen does play a minor role in the variation of RVA wholemeal pasting characteristics however, its effects are not consistent across environments. These inconsistencies are likely a result of interactions between nitrogen fertilizer and some other unidentified environmental factor, in addition to initial soil nitrogen levels. Based on these findings, recommending the use of specific nitrogen fertilization rates would not necessarily promote the production of oat wholemeal with desired pasting properties.

4.4 SUMMARY

The second phase of this thesis focused on the potential for nitrogen fertilization, a common agricultural practice, to influence the quality of oats destined for the food industry. Samples included five oat genotypes grown under four nitrogen regimes (0, 40, 80 and 120 kg/ha) at each of six environments in Manitoba. Nitrogen fertilization had a greater impact on oat composition than it did on the physical quality of oats. Groat breakage was not significantly affected by fertilizer rate and its effect on hull content was confused by a number of significant cross-over effects (Table 4.16). On the other hand, increased nitrogen fertilizer rates altered composition in a direction favorable for high quality food oats, but only at locations where initial soil nitrogen was low. This implies that there is a

Table 4.16: Occurrence of cross-over interactions for oat characteristics showing significant genotype-by-environment effects.

Quality Characteristic	Significant Cross-Over Interaction (P = ≤0.05)	Number of Cross-Over Interactions (out of 240 comparisons)	Number of Genotype Pairs Involved in Cross-Over
Hull Content	Yes	49	6
Groat Breakage[1]	Yes	9	1
Protein	Yes	4	2
Oil	No		
β-Glucan	No		

[1] Square root transformation was performed on data prior to analysis.

level above which additional nitrogen is ineffective. This trend was strongest for protein, followed by β-glucan and oil. These results reinforce the importance of soil nutrient testing. If premium markets for oats with high β-glucan are created in the future, this information will help producers make crop management decisions. The response of wholemeal pasting characteristics to nitrogen fertilizer rates were also greatly dependent on environment, but did not necessarily relate to residual soil nitrogen levels at the different locations.

CHAPTER 5

CONCLUSIONS

5.1 OVERALL CONCLUSION

The results of this study indicate that genotype and growing location are the dominant factors controlling oat physical properties (hull content and groat breakage) and altering nitrogen fertilization is not likely to improve these qualities. In the case of hull content, breeding efforts would require multiple test sites to overcome the influence of interactions between genotype and environment. Groat breakage, however, demonstrated consistent genotype rankings across the growing locations studied, indicating a good potential for breeding for low levels of this trait.

Oat composition was affected positively, from a food manufacturing perspective, by increased nitrogen fertilization rates, resulting in slight increases in β-glucan and protein with a concurrent decrease in oil. Genotypic and environmental variation resulted in the greatest differences in oat composition, confirming that breeding efforts and consideration to growing site have the most potential to ensure desired oat composition.

A linear response between oat wholemeal pasting properties and nitrogen fertilization rate was not apparent at all environments. Without further study into the cause of these inconsistent results, it cannot be recommended to use nitrogen fertilization as a tool for controlling this aspect of quality. Genotypic and environmental variation were significant for oat wholemeal pasting properties, and most parameters showed a potential for genetic improvement.

This study found significant genotypic variation for several oat starch characteristics including total starch, amylose, pasting and thermal properties and gel texture. These findings show that there is an opportunity to breed for oats with specific starch characteristics. They also emphasize the need to understand what role starch characteristics play in oat end-product quality so that desired levels of these traits can be defined. The growing environment also had an impact on oat starch characteristics, particularly total starch, which seemed to be lower at environments that had high residual nitrogen levels in the soil. Other characteristics that were influenced by environment include pasting and thermal properties. Breeding for some starch pasting parameters, starch swelling volume and gel strength at the first compression would require multiple testing sites, as genotypes did not rank consistently across environments for these characteristics.

The quality of oat flakes and cooked oatmeal was also assessed, revealing significant differences among genotypes. The potential for genetic improvement in oat end-product quality was particularly strong for cooked oatmeal texture, whereas differences among genotypes for flake hydration capacity were not consistent when the oats were grown in different environments. Flake granulation was also influenced by environment but genotype rankings remained constant over environments.

5.2 IMPACT OF RESEARCH

Overall, the results of this study indicate the potential to improve the food quality of oats through breeding and nitrogen fertilization practices. Development of superior oat cultivars that are suitable for growing in Manitoba will ensure that Canadian produced oats

can continue to compete in the milling and food processing markets. Methodology developed for this study to test oat-end-products provides a basis for future research, as there is currently a lack of laboratory scale testing methods that can process the small quantities of grain available for breeding lines. This could lead to the incorporation of oat end-product quality screening into Canadian breeding programs in the future. There is also potential for the creation of premium markets for oats, similar to those for high protein wheat. Likely the rewarded component in oats would be β-glucan, due to its potential for use in functional foods and nutraceuticals. The fact that increased nitrogen fertilization was found to improve oat composition will be an important consideration in a producer's crop management decisions. Furthermore, the strong environmental influences on oat quality observed in this study will also make millers and processors aware of possible variation in oat sources.

5.3 LIMITATIONS

One of the main benefits of this research study was its replicated experimental design. Many published studies, particularly those investigating starch characteristics, lack the replication needed to statistically analyze for genotypic and environmental effects. The main limitation of the present study, however, was the limited number of genotypes used. Ideally, when more genotypes are tested, the results can be generalized to a larger population.

In addition, the diversity in residual nitrogen levels in the environments used in this study made it difficult to interpret the effects of the nitrogen fertilizer rate treatments.

Recommendations for specific fertilizer rates required to achieve a desired quality were not possible.

Another limitation of this study lies with the correlation analysis. This analysis provided two types of information. First, it measures chemical or physical relationships between compositional and functional factors. Second, it evaluates the result of genetically or environmentally linked traits. Conclusions based on these correlation coefficients are limited in this study by the nature of the analysis (i.e. correlations reflect associations and are not necessarily cause and effect relationships) and the fact that genotype means were used resulting in only five data points supporting the coefficient. Despite these limitations, the correlations in this study are a useful tool to point out relationships that may have fundamental significance and warrant more in depth study.

5.4 FUTURE RESEARCH

The results of this study indicated that environment had an important effect on several quality characteristics. It was not one of the objectives, however, to determine the specific environmental conditions that caused the changes in oat properties. Other researchers have conducted studies designed to test factors such as temperature and rainfall on oat agronomic traits but there are fewer reports on physical properties and composition. It would be very useful for producers, breeders, and millers to have more detailed information regarding what environmental factors influence characteristics such as groat breakage and pasting properties.

Furthermore, although this study identified genotypic variation in oat end-product quality with positive implications for breeding programs, still more work needs to be done to define what good end-product quality means. For example, relating sensory evaluation of oatmeal to instrumental texture data would help ensure that screening criteria are reflective of end-product quality characteristics desired by the industry. In addition, this study generated more questions concerning the relationships between composition, starch and pasting characteristics and end-product quality. Future studies could investigate more detailed aspects of starch chemistry, such as starch structure and swelling properties over time, in an attempt to further understand differences in end-product quality.

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APPENDIX 1

Analysis of Variance Summaries for the Effect of Genotype, Environment and Genotype-by-Environment Interactions on the Quality of Oats Grown in Manitoba

Summary of fixed effects for oat physical properties.

Parameter	Effect	F Value	P Value
Hull Content[1]	Genotype (G)	25.14	<0.0001
	Environment (E)	11.24	0.0008
	GxE	4.49	<0.0001
Groat Breakage	Genotype (G)	35.74	<0.0001
	Environment (E)	9.59	0.0002
	GxE	2.28	0.0065

[1] Analysis does not include the Winnipeg and Carman environments.

Summary of fixed effects for oat hull content (Winnipeg and Carman environments).

Effect	F Value	P Value
Genotype (G)	168.40	<0.0001
Environment (E)	70.12	0.0004
GxE	4.18	0.0133

Summary of fixed effects for oat composition.

Oat Component	Effect	F Value	P Value
β-Glucan	Genotype (G)	105.90	<0.0001
	Environment (E)	3.43	0.0247
	GxE	1.17	0.3078
Protein	Genotype (G)	5.28	0.0009
	Environment (E)	24.05	<0.0001
	GxE	1.76	0.0444
Oil	Genotype (G)	35.31	<0.0001
	Environment (E)	26.29	<0.0001
	GxE	1.33	0.1937

Summary of fixed effects for oat starch characteristics.

Starch Characteristic	Effect	F Value	P Value
Total Starch	Genotype (G)	8.41	<0.0001
	Environment (E)	10.12	0.0001
	GxE	1.75	0.0465
Iodine Affinity	Genotype (G)	45.77	<0.0001
	Environment (E)	12.53	<0.0001
	GxE	1.08	0.3931
Swelling Volume	Genotype (G)	5.28	0.0010
	Environment (E)	6.46	0.0015
	GxE	2.87	0.0007

Summary of fixed effects for oat starch pasting properties.

RVA Parameter	Effect	F Value	P Value
Peak	Genotype (G)	56.05	<0.0001
	Environment (E)	59.64	<0.0001
	GxE	1.53	0.1021
Final	Genotype (G)	17.19	<0.0001
	Environment (E)	28.18	<0.0001
	GxE	1.91	0.0260
Trough	Genotype (G)	10.46	<0.0001
	Environment (E)	55.62	<0.0001
	GxE	2.31	0.0058
Breakdown	Genotype (G)	8.26	<0.0001
	Environment (E)	7.87	0.0005
	GxE	2.55	0.0024
Setback	Genotype (G)	24.77	<0.0001
	Environment (E)	14.95	<0.0001
	GxE	1.79	0.0404
Final-Peak	Genotype (G)	13.72	<0.0001
	Environment (E)	13.73	<0.0001
	GxE	1.82	0.0370
Shear Thinning	Genotype (G)	5.12	0.0012
	Environment (E)	19.00	<0.0001
	GxE	2.94	0.0005

Summary of fixed effects for oat starch gel texture.

Parameter	Effect	F Value	P Value
Strength (1st Compression)	Genotype (G)	76.77	<0.0001
	Environment (E)	2.05	0.1224
	GxE	2.86	0.0007
Strength (2nd Compression)	Genotype (G)	52.81	<0.0001
	Environment (E)	0.48	0.7870
	GxE	1.38	0.1665
Adhesiveness	Genotype (G)	3.89	0.0068
	Environment (E)	2.79	0.0513
	GxE	1.54	0.0972
Springiness	Genotype (G)	6.51	0.0002
	Environment (E)	0.61	0.6901
	GxE	0.98	0.4989
Cohesiveness	Genotype (G)	1.16	0.3375
	Environment (E)	0.83	0.5429
	GxE	2.09	0.0135
Resilience	Genotype (G)	7.92	<0.0001
	Environment (E)	4.96	0.0056
	GxE	1.21	0.2777
Gumminess	Genotype (G)	48.51	<0.0001
	Environment (E)	2.44	0.0771
	GxE	0.93	0.5566

Summary of fixed effects for oat starch thermal properties.

DSC Parameter[1]	Effect	F Value	P Value
AP Onset Temp.	Genotype (G)	59.63	<0.0001
	Environment (E)	28.11	<0.0001
	GxE	1.54	0.0964
AP Max. Temp.	Genotype (G)	65.60	<0.0001
	Environment (E)	27.16	<0.0001
	GxE	1.87	0.0303
AP ΔH	Genotype (G)	10.24	<0.0001
	Environment (E)	9.64	0.0002
	GxE	1.20	0.2838
AM Onset Temp.	Genotype (G)	3.89	0.0063
	Environment (E)	118.95	<0.0001
	GxE	1.46	0.1402
AM Max. Temp.	Genotype (G)	7.01	0.0001
	Environment (E)	78.35	<0.0001
	GxE	1.17	0.3156
AM - ΔH	Genotype (G)	17.39	<0.0001
	Environment (E)	65.72	<0.0001
	GxE	2.07	0.0191

[1] AP refers to the enthalpy peak associated with the gelatinization amylopectin; AM refers to the enthalpy peak associated with the melting of the amylose-lipid complex. AM parameters do not include the Winnipeg environment in the analysis.

Summary of fixed effects for oat wholemeal pasting properties.[1]

RVA Parameter	Effect	F Value	P Value
Peak	Genotype (G)	25.37	<0.0001
	Environment (E)	31.99	<0.0001
	GxE	1.74	0.0668
Final	Genotype (G)	51.81	<0.0001
	Environment (E)	15.86	<0.0001
	GxE	1.01	0.4564
Trough	Genotype (G)	39.08	<0.0001
	Environment (E)	11.83	0.0002
	GxE	1.54	0.1184
Breakdown	Genotype (G)	92.96	<0.0001
	Environment (E)	6.44	0.0038
	GxE	4.37	<0.0001
Final-Peak	Genotype (G)	85.06	<0.0001
	Environment (E)	28.52	<0.0001
	GxE	1.69	0.0767

[1] Analysis does not include the 1998 Silverton environment.

Summary of fixed effects for oat flake granulation.

Size Category	Effect	F Value	P Value
> 4.00 mm	Genotype (G)	50.92	<0.0001
	Environment (E)	10.18	0.0001
	GxE	2.46	0.0033
< 4.00, > 2.36 mm	Genotype (G)	69.34	<0.0001
	Environment (E)	13.42	<0.0001
	GxE	2.56	0.0022
< 2.36, > 2.00 mm	Genotype (G)	41.65	<0.0001
	Environment (E)	8.01	0.0005
	GxE	1.07	0.4029
< 2.00 mm	Genotype (G)	61.77	<0.0001
	Environment (E)	10.70	<0.0001
	GxE	1.73	0.0503

Summary of fixed effects for oat flake water hydration capacity.

Effect	F Value	P Value
Genotype (G)	22.55	<0.0001
Environment (E)	6.54	0.0015
GxE	2.57	0.0022

Summary of fixed effects for cooked oatmeal texture.

Parameter	Effect	F Value	P Value
Peak Force	Genotype (G)	33.22	<0.0001
	Environment (E)	2.23	0.0985
	GxE	0.84	0.6535
Adhesive Force	Genotype (G)	28.63	<0.0001
	Environment (E)	3.44	0.0249
	GxE	1.92	0.0269
Stringiness	Genotype (G)	12.50	<0.0001
	Environment (E)	4.53	0.0083
	GxE	1.81	0.0400

APPENDIX 2

Correlation Matrix for Quality Characteristics of Oats Grown in Manitoba

Correlation matrix for oat quality characteristics.[1]

	Hull %	Groat Breakage	Protein	β-Glucan	Oil	Total Starch	Amylose	SSV	ST RVA Peak	ST RVA Final	ST RVA Hot Paste
Hull %	1.00000 0.0000										
Groat Breakage	-0.84733 0.0699	1.00000 0.0000									
Protein	0.70780 0.1811	-0.90514 0.0346	1.00000 0.0000								
β-Glucan	0.50555 0.3849	-0.57472 0.3108	0.34887 0.5650	1.00000 0.0000							
Oil	-0.57881 0.3065	0.72542 0.1654	-0.38364 0.5238	-0.66365 0.2220	1.00000 0.0000						
Total Starch	-0.83478 0.0786	0.66832 0.2175	-0.70095 0.1873	-0.53345 0.3545	0.17989 0.7722	1.00000 0.0000					
Amylose	-0.30689 0.6155	-0.22037 0.7217	0.27648 0.6525	0.32500 0.5936	-0.25461 0.6794	0.23127 0.7082	1.00000 0.0000				
SSV	0.93425 0.0200	-0.61058 0.2740	0.42584 0.4747	0.44720 0.4502	-0.45380 0.4427	-0.78602 0.1149	-0.57681 0.3086	1.00000 0.0000			
ST RVA Peak	0.57852 0.3069	-0.49289 0.3989	0.54070 0.3468	-0.36746 0.5429	-0.15512 0.8033	-0.29753 0.6268	-0.41061 0.4923	0.47720 0.4163	1.00000 0.0000		
ST RVA Final	0.93320 0.0205	-0.60867 0.2760	0.49324 0.3985	0.29141 0.6343	-0.34203 0.5732	-0.79955 0.1044	-0.62412 0.2605	0.9784 0.0038	0.62065 0.2639	1.00000 0.0000	
ST RVA Hot Paste	0.73304 0.1588	-0.73205 0.1596	0.86895 0.0558	-0.02995 0.9619	-0.14711 0.8134	-0.67536 0.2109	-0.16567 0.7900	0.54627 0.3408	0.84427 0.0720	0.67896 0.2075	1.00000 0.0000
ST RVA Breakdown	-0.01095 0.9861	0.15246 0.8067	-0.25040 0.6845	-0.65780 0.2276	-0.06015 0.9235	0.44405 0.4538	-0.49768 0.3936	0.06288 0.9200	0.63279 0.2519	0.14109 0.8210	0.11980 0.8478

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
SSV = Starch Swelling Volume; ST = Starch ; RVA = Rapid Visco-Analyser

Correlation matrix for oat quality characteristics.[1]

	Hull %	Groat Breakage	Protein	β-Glucan	Oil	Total Starch	Amylose	SSV	ST RVA Peak	ST RVA Final	ST RVA Hot Paste
ST RVA Setback	0.82441 0.0860	-0.41298 0.4895	0.20450 0.7414	0.37163 0.5380	-0.35353 0.5594	-0.68353 0.2033	-0.71476 0.1748	0.97183 0.0057	0.38527 0.5219	0.93755 0.0186	0.38129 0.5266
ST RVA Final - Peak	0.82080 0.0886	-0.46820 0.4264	0.29388 0.6313	0.59626 0.2886	-0.33855 0.5773	-0.82545 0.0852	-0.52730 0.3612	0.93759 0.0185	0.16659 0.7889	0.87650 0.0511	0.33821 0.5777
ST RVA Shear Thinning	-0.21859 0.7239	0.40956 0.4935	-0.58452 0.3006	-0.57413 0.3114	-0.02980 0.9621	0.62144 0.2631	-0.50282 0.3879	-0.04797 0.9389	0.29583 0.6289	-0.03266 0.9584	-0.26027 0.6724
WM RVA Peak	0.86337 0.0594	-0.94813 0.0141	0.75037 0.1440	0.51223 0.3776	-0.84672 0.0704	-0.53041 0.3578	0.06542 0.9168	0.68212 0.2046	0.56865 0.3172	0.66370 0.2219	0.64794 0.2371
WM RVA Final	0.13576 0.8277	-0.28769 0.6388	0.02736 0.9652	0.90721 0.0335	-0.61903 0.2655	-0.13712 0.8260	0.49423 0.3974	0.10506 0.8665	-0.64066 0.2442	-0.08551 0.8913	-0.40795 0.4954
WM RVA Hot Paste	0.03883 0.9506	-0.27116 0.6590	0.05283 0.9328	0.86330 0.0594	-0.57956 0.3058	-0.06457 0.9178	0.62965 0.2550	-0.03336 0.9575	-0.67213 0.2139	-0.21356 0.7302	-0.41896 0.4826
WM RVA Breakdown	0.54513 0.3420	-0.38081 0.5271	0.44920 0.4479	-0.43928 0.4592	-0.02722 0.9653	-0.30830 0.6138	-0.54208 0.3453	0.49510 0.3964	0.98532 0.0021	0.64637 0.2386	0.81293 0.0944
WM RVA Final - Peak	-0.29248 0.6330	0.17836 0.7741	-0.34716 0.5670	0.66107 0.2244	-0.21417 0.7294	0.13346 0.8306	0.46961 0.4248	-0.23444 0.7043	-0.92672 0.0235	-0.41854 0.4831	-0.73658 0.1557
ST Gel Strength 1st Compression	-0.00193 0.9975	-0.38086 0.5271	0.41123 0.4916	0.69055 0.1968	-0.29090 0.6349	-0.22137 0.7205	0.85261 0.0664	-0.21792 0.7247	-0.52126 0.3677	-0.30402 0.6190	-0.07768 0.9012
ST Gel Strength 2nd Compression	-0.01496 0.9810	-0.34981 0.5639	0.38868 0.5179	0.69133 0.1960	-0.25122 0.6835	-0.23551 0.7029	0.83183 0.0807	-0.21767 0.7251	-0.55034 0.3365	-0.30470 0.6181	-0.09561 0.8785
ST Gel Adhesiveness	0.23136 0.7081	-0.20384 0.7423	0.35046 0.5631	0.56024 0.3260	0.19344 0.7552	-0.70137 0.1869	0.16539 0.7904	0.20585 0.7398	-0.38581 0.5212	0.17350 0.7802	0.13457 0.8292
ST Gel Springiness	0.00928 0.9882	-0.04136 0.9473	0.44355 0.4544	-0.521169 0.3673	0.62582 0.2588	-0.28390 0.6434	-0.06804 0.9134	-0.11518 0.8537	0.46548 0.4295	0.07439 0.9054	0.63383 0.2509

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
SSV = Starch Swelling Volume; ST = Starch; WM = Wholemeal; RVA = Rapid Visco-Analyser

Correlation matrix for oat quality characteristics.[1]

	Hull %	Groat Breakage	Protein	β-Glucan	Oil	Total Starch	Amylose	SSV	ST RVA Peak	ST RVA Final	ST RVA Hot Paste
ST Gel Cohesiveness	-0.10555 0.8659	0.57312 0.3125	-0.55065 0.3361	-0.62239 0.2622	0.52764 0.3608	0.13053 0.8343	-0.90924 0.0324	0.18470 0.7662	0.25837 0.6747	0.25251 0.6819	-0.07869 0.8999
ST Gel Resilience	0.66847 0.2174	-0.62004 0.2645	0.58819 0.2968	0.82173 0.0879	-0.30603 0.6165	-0.89151 0.0422	0.08607 0.8906	0.60705 0.2776	-0.11445 0.8546	0.54194 0.3454	0.35476 0.5580
ST Gel Gumminess	0.06781 0.9137	-0.41305 0.4894	0.41114 0.4917	0.76323 0.1333	-0.34085 0.5746	-0.28250 0.6452	0.80129 0.1031	-0.12891 0.8363	-0.52980 0.3585	-0.22867 0.7114	-0.07915 0.8993
DSC AP Onset Temperature	-0.86670 0.0572	0.80508 0.1002	-0.64946 0.2356	-0.84848 0.0692	0.60823 0.2764	0.86513 0.0582	0.00338 0.9957	-0.79351 0.1091	-0.11676 0.8517	-0.71867 0.1714	-0.45545 0.4408
DSC AP Max Temperature	-0.66128 0.2242	0.74592 0.1477	-0.61930 0.2653	-0.94242 0.0164	0.59268 0.2922	0.74224 0.1509	-0.30939 0.6125	-0.53762 0.3501	0.14519 0.8158	-0.43673 0.4622	-0.27856 0.6500
DSC AP ΔH	-0.86750 0.0567	0.81356 0.0939	-0.59572 0.2891	-0.86738 0.0568	0.72266 0.1678	0.78082 0.1190	-0.00000 1.0000	-0.80110 0.1032	-0.12049 0.8470	-0.70861 0.1803	-0.39527 0.5102
DSC AM Onset Temperature	-0.62179 0.2628	0.14702 0.8135	0.08979 0.8858	-0.13946 0.8230	0.24675 0.6890	0.41025 0.4927	0.85817 0.0627	-0.84682 0.0703	-0.36752 0.5428	-0.81514 0.0927	-0.18811 0.7619
DSC AM Max Temperature	-0.73675 0.1556	0.50931 0.3808	-0.30544 0.6172	-0.82927 0.0825	0.45784 0.4381	0.78814 0.1133	0.23420 0.7046	-0.80866 0.0975	0.09698 0.8767	-0.69790 0.1900	-0.17542 0.7778
DSC AM ΔH	0.32202 0.5972	0.04739 0.9397	-0.05172 0.9342	-0.57405 0.3115	0.16224 0.7943	-0.08954 0.8861	-0.86021 0.0614	0.46094 0.4346	0.77021 0.1276	0.57557 0.3099	0.43204 0.4675
Flake Size > 4.00 mm	-0.78309 0.1172	0.63112 0.2535	-0.76779 0.1295	-0.22075 0.7212	0.00662 0.9916	0.93347 0.0204	0.29844 0.6257	-0.69949 0.1886	-0.54760 0.3394	-0.78587 0.1150	-0.86035 0.0613
Flake Size <4.00, > 2.36 mm	0.82758 0.0837	-0.72846 0.1628	0.81951 0.0895	0.40935 0.4937	-0.15055 0.8090	-0.97358 0.0051	-0.16642 0.7891	0.71852 0.1715	0.44329 0.4547	0.77082 0.1271	0.81422 0.0934
Flake Size <2.36, > 2.00 mm	-0.47235 0.4218	0.63109 0.2536	-0.40384 0.5002	-0.98305 0.0026	0.73994 0.1528	0.45010 0.4469	-0.45797 0.4380	-0.36162 0.5498	0.33521 0.5813	-0.20994 0.7347	0.01283 0.9837

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
SSV = Starch Swelling Volume; ST = Starch; RVA = Rapid Visco-Analyser; DSC AP = gelatinization of amylopectin enthalpy curve; DSC AM = melting of amylose-lipid complex enthalpy curve

Correlation matrix for oat quality characteristics.[1]

	Hull %	Groat Breakage	Protein	β-Glucan	Oil	Total Starch	Amylose	SSV	ST RVA Peak	ST RVA Final	ST RVA Hot Paste
Flake Size < 2.00 mm	-0.56083 0.3254	0.65202 0.2331	-0.49393 0.3977	-0.98092 0.0032	0.59886 0.2859	0.64692 0.2381	-0.35241 0.5608	-0.46279 0.4325	0.28994 0.6361	-0.33519 0.5814	-0.11778 0.8504
Flake Water Hydration	-0.37399 0.5353	0.59748 0.2873	-0.68829 0.1989	-0.71437 0.1752	0.22100 0.7209	0.66312 0.2225	-0.54774 0.3392	-0.17058 0.7839	0.22016 0.7220	-0.13312 0.8310	-0.32016 0.5994
Oatmeal Texture (Peak Force)	0.51704 0.3723	-0.62130 0.2633	0.37668 0.5320	0.99369 0.0006	-0.73774 0.1547	-0.49067 0.4013	0.36651 0.5440	0.43597 0.4630	-0.32127 0.5981	0.28050 0.6476	-0.59805 0.2867
Oatmeal Adhesive Force	0.92805 0.0229	-0.82268 0.0872	0.74085 0.1521	0.69124 0.1951	-0.47822 0.4152	-0.94988 0.0134	-0.12910 0.8361	0.84790 0.0696	0.30785 0.6142	0.82283 0.0871	-0.38006 0.5280
Oatmeal Stringiness	0.49597 0.3954	-0.79204 0.1102	0.62808 0.2565	0.86087 0.0610	-0.78866 0.1129	-0.41386 0.4885	0.61996 0.2646	0.27136 0.6588	-0.11603 0.8526	0.16783 0.7873	-0.51611 0.3733

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
SSV = Starch Swelling Volume; ST = Starch; RVA = Rapid Visco-Analyser

Correlation matrix for oat quality characteristics.[1]

	ST RVA Breakdown	ST RVA Setback	ST RVA Final - Peak	ST RVA Shear Thinning	WM RVA Peak	WM RVA Final	WM RVA Hot Paste	WM RVA Breakdown	WM RVA Final - Peak	ST Gel Strength 1st Compr.	ST Gel Strength 2nd Compr.
ST RVA Breakdown	1.00000 0.0000										
ST RVA Setback	0.12770 0.8378	1.00000 0.0000									
ST RVA Final - Peak	-0.21489 0.7285	0.94112 0.0170	1.00000 0.0000								
ST RVA Shear Thinning	0.92013 0.0268	0.08872 0.8872	-0.22772 0.7126	1.00000 0.0000							
WM RVA Peak	0.45960 0.4361	0.52317 0.3657	0.48963 0.4025	-0.11569 0.8530	1.00000 0.0000						
WM RVA Final	-0.61148 0.2731	0.07624 0.9030	0.28925 0.6369	-0.40848 0.4948	0.26500 0.6666	1.00000 0.0000					
WM RVA Hot Paste	-0.64772 0.2373	-0.08006 0.8982	0.14810 0.8121	-0.45865 0.4372	0.22024 0.7219	0.98606 0.0020	1.00000 0.0000				
WM RVA Breakdown	0.64884 0.2362	0.43385 0.4655	0.20694 0.7384	0.33241 0.5847	0.45960 0.4361	-0.72010 0.1701	-0.76483 0.1320	1.00000 0.0000			
WM RVA Final - Peak	-0.66027 0.2252	-0.18475 0.7661	0.04408 0.9439	-0.34557 0.5689	-0.22354 0.7178	088052 0.0487	0.88883 0.0437	-0.95429 0.0117	1.00000 0.0000		
ST Gel Strength 1st Compression	-0.84463 0.0718	-0.35531 0.5573	-0.05633 0.9283	-0.82409 0.0862	0.16430 0.7918	0.72063 0.1696	0.80367 0.1013	-0.62400 0.2606	0.64382 0.2411	1.00000 0.0000	
ST Gel Strength 2nd Compression	-0.87321 0.0532	-0.34751 0.5666	-0.03952 0.9497	-0.84226 0.0734	0.12614 0.8398	0.71962 0.1705	0.80009 0.1040	-0.64498 0.2399	0.66103 0.2245	0.99832 0.0001	1.00000 0.0000
ST Gel Adhesiveness	-0.91648 0.0286	0.15024 0.8094	0.45781 0.4382	-0.90963 0.0322	-0.05654 0.9281	0.37299 0.5364	0.36936 0.5406	-0.35779 0.5544	0.39242 0.5135	0.61219 0.2724	0.64946 0.2356

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
ST = Starch; WM = Wholemeal; RVA = Rapid Visco-Analyser

Correlation matrix for oat quality characteristics.[1]

	ST RVA Breakdown	ST RVA Setback	ST RVA Final - Peak	ST RVA Shear Thinning	WM RVA Peak	WM RVA Final	WM RVA Hot Paste	WM RVA Breakdown	WM RVA Final - Peak	ST Gel Strength 1st Compr.	ST Gel Strength 2nd Compr.
ST Gel Springiness	-0.03342 0.9575	-0.20212 0.7444	-0.19165 0.7575	-0.31942 0.6003	-0.1550 0.8034	-0.7300 0.1614	-0.66652 0.2192	0.50637 0.3840	-0.66874 0.2171	-0.10049 0.8723	-0.09066 0.8847
ST Gel Cohesiveness	0.58020 0.3051	0.36480 0.5460	0.15224 0.8069	0.64201 0.2428	-0.41881 0.4828	-0.64962 0.2354	-0.74211 0.1510	0.40600 0.4976	-0.45049 0.4465	-0.92107 0.0263	-0.89705 0.0390
ST Gel Resilience	-0.74365 0.1497	0.50752 0.3827	0.75565 0.1396	-0.79659 0.1067	0.45186 0.4449	0.54221 0.3451	0.49152 0.4004	-0.13344 0.8306	0.31537 0.6052	0.57288 0.3127	0.58980 0.2952
ST Gel Gumminess	-0.86246 0.0600	-0.26007 0.6726	0.04358 0.9445	-0.82848 0.0830	0.20719 0.7381	0.77522 0.1235	0.84208 0.0735	-0.62894 0.2557	0.67749 0.2089	0.99409 0.0005	0.99402 0.0006
DSC AP Onset	0.46600 0.4289	-0.68207 0.2046	-0.83595 0.0778	0.55471 0.3318	-0.73826 0.1543	-0.55099 0.3358	-0.47387 0.4201	-0.06880 0.9125	-0.18678 0.7636	-0.42096 0.4803	-0.41994 0.4815
DSC AP Max	0.68828 0.1989	-0.40883 0.4943	-0.64343 0.2415	0.72805 0.1631	-0.62056 0.2640	-0.73456 0.1575	-0.70126 0.1870	0.21877 0.7237	-0.43052 0.4693	-0.70361 0.1848	-0.70336 0.1851
DSC AP ΔH	0.37367 0.5355	-0.69763 0.1903	-0.82087 0.0885	0.44042 0.4579	-0.79303 0.1095	-0.60393 0.2808	-0.52053 0.3685	-0.06058 0.9229	-0.21535 0.7279	-0.38514 0.5220	-0.37795 0.5305
DSC AM Onset	-0.37464 0.5344	-0.93997 0.0175	-0.79603 0.1071	-0.39959 0.5051	-0.33732 0.5788	0.06234 0.9207	0.22605 0.7147	-0.44134 0.4569	0.23036 0.7094	0.60898 0.2756	0.60099 0.2837
DSC AM Max	0.46582 0.4291	-0.79025 0.1116	-0.93875 0.0180	0.41980 0.4816	-0.48826 0.4040	-0.58792 0.2971	-0.47212 0.4220	0.09031 0.8852	-0.34681 0.5675	-0.26007 0.6726	-0.27616 0.6529
DSC AM ΔH	0.79188 0.1104	0.52817 0.3602	0.24655 0.6893	0.64504 0.2399	0.12603 0.8400	-0.75088 0.1436	-0.84135 0.0740	0.85239 0.0665	-0.81980 0.0893	-0.92899 0.0225	-0.93329 0.0205
Flake Size >4.0mm	0.23956 0.6979	-0.58130 0.3040	-0.65423 0.2310	0.51599 0.3735	-0.48722 0.4052	0.20352 0.7427	0.25401 0.6801	-0.56685 0.3190	0.45608 0.4401	-0.03934 0.9499	-0.04837 0.9384
Flake Size <4.00, > 2.36 mm	-0.36787 0.5424	0.58207 0.3032	0.70036 0.1878	-0.62060 0.2640	0.57270 0.3129	-0.00387 0.9951	-0.05196 0.9339	0.43936 0.4592	-0.29632 0.6283	0.20970 0.7350	0.21645 0.7266

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
ST = Starch; RVA = Rapid Visco-Analyser; DSC AP = gelatinization of amylopectin enthalpy curve; DSC AM = melting of amylose-lipid complex enthalpy curve

Correlation matrix for oat quality characteristics.[1]

	ST RVA Breakdown	ST RVA Setback	ST RVA Final - Peak	ST RVA Shear Thinning	WM RVA Peak	WM RVA Final	WM RVA Hot Paste	WM RVA Breakdown	WM RVA Final - Peak	ST Gel Strength 1st Compr.	ST Gel Strength 2nd Compr.
Flake Size <2.36, > 2.00 mm	0.61803 0.2665	-0.26028 0.6724	-0.47473 0.4191	0.55910 0.3272	-0.57073 0.3150	-0.91808 0.0278	-0.89594 0.0397	0.43407 0.4652	-0.64485 0.2401	-0.74955 0.1447	-0.74117 0.1518
Flake Size < 2.00 mm	0.72478 0.1660	-0.35677 0.5556	-0.60435 0.2803	0.70180 0.1865	-0.5390 0.3480	-0.83213 0.0805	-0.79982 0.1042	0.36253 0.5487	-0.56990 0.3158	-0.74061 0.1523	-0.74263 0.1505
Flake Water Hydration	0.86997 0.0552	-0.00780 0.9901	-0.30845 0.6136	0.96774 0.0039	-0.34002 0.5756	-0.53228 0.3558	-0.57172 0.3139	0.28856 0.6378	-0.36178 0.5496	-0.86724 0.0569	-0.87428 0.0525
Oatmeal Texture (Peak Force)	-0.59805 0.2867	0.34873 0.5652	0.55446 0.3321	-0.52896 0.3594	0.57531 0.3102	0.91143 0.0312	0.87283 0.0534	-0.40832 0.4949	0.63549 0.2492	0.68041 0.1969	0.68476 0.2021
Oatmeal Adhesive Force	-0.38006 0.5280	0.72641 0.1646	0.84917 0.0687	-0.54438 0.3428	0.73904 0.1536	0.32442 0.5943	0.24605 0.6899	0.27781 0.6509	-0.04400 0.9440	0.28953 0.6366	0.28992 0.6361
Oatmeal Stringiness	-0.51611 0.3733	0.10406 0.8677	0.28855 0.6378	-0.57519 0.3103	0.70825 0.1807	0.77374 0.1247	0.79145 0.1107	-0.25353 0.6807	0.43251 0.4670	0.79066 0.1113	0.76677 0.1304

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
ST = Starch; WM = Wholemeal; RVA = Rapid Visco-Analyser

Correlation matrix for oat quality characteristics.[1]

	ST Gel Adhesive.	ST Gel Spring.	ST Gel Cohesive.	ST Gel Resilience	ST Gel Gumminess	DSC AP Onset Temp.	DSC AP Max Temp.	DSC AP ΔH	DSC AM Onset Temp.	DSC AM Max Temp.	DSC AM ΔH
ST Gel Adhesiveness	1.00000 0.0000										
ST Gel Springiness	0.24917 0.6861	1.00000 0.0000									
ST Gel Cohesiveness	-0.31940 0.6004	0.13363 0.8304	1.00000 0.0000								
ST Gel Resilience	0.84630 0.0706	0.00000 1.0000	-0.42258 0.4784	1.00000 0.0000							
ST Gel Gumminess	0.64434 0.2406	-0.16043 0.7966	-0.90486 0.0347	0.63934 0.2455	1.00000 0.0000						
DSC AP Onset Temp.	-0.56901 0.3168	0.17646 0.7765	0.40385 0.5001	-0.91953 0.0271	-0.50025 0.3907	1.00000 0.0000					
DSC AP Max Temp.	-0.67342 0.2127	0.22391 0.7173	0.65136 0.2338	-0.93274 0.0207	-0.76674 0.1304	0.93866 0.0181	1.00000 0.0000				
DSC AP ΔH	-0.44396 0.4539	0.31107 0.6104	0.40929 0.4938	-0.85127 0.0673	-0.46834 0.4263	0.98589 0.0020	0.91866 0.0275	1.00000 0.0000			
DSC AM Onset Temp.	0.10985 0.8604	0.29396 0.6312	-0.60371 0.2810	-0.20549 0.7402	0.52102 0.3680	0.40867 0.4945	0.10806 0.8627	0.45203 0.4447	1.00000 0.0000		
DSC AM Max Temp.	-0.59291 0.2920	0.34777 0.5663	0.13584 0.8276	-0.87416 0.0526	-0.35988 0.5519	0.91427 0.0297	0.83045 0.0816	0.90514 0.0346	0.59628 0.2886	1.00000 0.0000	
DSC AM ΔH	-0.48226 0.4107	0.27048 0.6599	0.80585 0.0996	-0.33757 0.5785	-0.91538 0.0292	0.15197 0.8073	0.48179 0.4112	0.13742 0.8256	-0.68038 0.2062	0.09579 0.8782	1.00000 0.0000

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
ST = Starch; RVA = Rapid Visco-Analyser; DSC AP = gelatinization of amylopectin enthalpy curve; DSC AM = melting of amylose-lipid complex enthalpy curve

Correlation matrix for oat quality characteristics.[1]

	ST Gel Adhesive.	ST Gel Spring.	ST Gel Cohesive.	ST Gel Resilience	ST Gel Gumminess	DSC AP Onset Temp.	DSC AP Max Temp.	DSC AP ΔH	DSC AM Onset Temp.	DSC AM Max Temp.	DSC AM ΔH
Flake Size > 4.00 mm	-0.55296 0.3337	-0.56958 0.3162	0.00439 0.9944	-0.69242 0.1951	-0.07255 0.9077	0.66981 0.2161	0.50505 0.3854	0.56831 0.3175	0.33844 0.5775	0.53038 0.3579	-0.29878 0.6253
Flake Size < 4.00, > 2.36 mm	0.62975 0.2549	0.44515 0.4525	-0.17303 0.7808	0.81146 0.0954	0.25133 0.6834	-0.79446 0.1083	-0.67068 0.2153	-0.70248 0.1859	-0.29965 0.6243	-0.64012 0.2447	0.13629 0.8270
Flake Size < 2.36, > 2.00 mm	-0.47111 0.4232	0.52651 0.3620	0.73681 0.1555	-0.75300 0.1418	-0.80989 0.0966	0.80619 0.0994	0.92744 0.0232	0.83771 0.0765	0.02505 0.9681	0.72916 0.1622	0.62869 0.2559
Flake Size < 2.00 mm	-0.66312 0.2225	0.34669 0.5676	0.66499 0.2207	-0.89914 0.0379	-0.80603 0.0995	0.89293 0.0414	0.98644 0.0019	0.88457 0.0463	0.07954 0.8988	0.82616 0.0847	0.57153 0.3141
Flake Water Hydration	-0.83382 0.0793	-0.17757 0.7751	0.75562 0.1396	-0.85332 0.0659	-0.88306 0.0472	0.69681 0.1910	0.85605 0.0641	0.61254 0.2721	-0.32505 0.5935	0.51869 0.3705	0.65135 0.2338
Oatmeal Texture (Peak Force)	0.47943 0.4138	-0.55048 0.3363	-0.66487 0.2208	0.77712 0.1220	0.75963 0.1363	-0.83844 0.0760	-0.93294 0.0206	-0.87082 0.0546	-0.12100 0.8463	-0.79018 0.1117	-0.56870 0.3171
Oatmeal Adhesive Force	0.56725 0.3186	0.04763 0.9394	-0.28099 0.6470	0.89536 0.0400	0.36077 0.5508	-0.96715 0.0071	-0.85253 0.0665	-0.92856 0.0227	-0.44944 0.4476	-0.85455 0.0651	0.02681 0.9659
Oatmeal Stringiness	0.35108 0.5623	-0.33471 0.5819	-0.88316 0.0471	0.65825 0.2271	0.82309 0.0869	-0.74739 0.1465	-0.87897 0.0496	-0.77696 0.1221	0.15964 0.7976	-0.52987 0.3584	-0.60598 0.2787

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0
ST = Starch; DSC AP = gelatinization of amylopectin enthalpy curve; DSC AM = melting of amylose-lipid complex enthalpy curve

Correlation matrix for oat quality characteristics.[1]

	Flake Size > 4.00 mm	Flake Size < 4.00, > 2.36 mm	Flake Size < 2.36, > 2.00 mm	Flake Size < 2.00 mm	Flake water Hydration	Oatmeal Texture (Peak Force)	Oatmeal Adhesive Force	Oatmeal Stringiness
Flake Size > 4.00 mm	1.00000 0.0000							
Flake Size < 4.00, > 2.36 mm	-0.97860 0.0037	1.00000 0.0000						
Flake Size < 2.36, > 2.00 mm	0.15568 0.8026	-0.35378 0.5591	1.00000 0.0000					
Flake Size < 2.00 mm	0.37003 0.5399	-0.55007 0.3368	0.96451 0.0080	1.00000 0.0000				
Flake Water Hydration	0.52582 0.3628	-0.66073 0.2248	0.72017 0.1700	0.82693 0.0841	1.00000 0.0000			
Oatmeal Texture (Peak Force)	-0.18654 0.7639	0.37946 0.5287	-0.99479 0.0005	-0.96946 0.0064	-0.68993 0.1973	1.00000 0.0000		
Oatmeal Adhesive Force	-0.83247 0.0802	0.91458 0.0296	-0.63973 0.2451	-0.77063 0.1272	-0.66100 0.2245	0.67594 0.2103	1.00000 0.0000	
Oatmeal Stringiness	-0.21200 0.7321	0.39880 0.5060	-0.93234 0.0209	-0.87968 0.0492	-0.75661 0.1388	0.90032 0.0372	0.61905 0.2655	1.00000 0.0000

[1] Upper value = Pearson correlation coefficients, N = 5. Lower value = Prob > |r| under HO: Rho = 0

APPENDIX 3

Analysis of Variance Summaries for the Effect of Nitrogen Fertilization on Oat Quality Characteristics

Summary of fixed effects for oat physical properties.

Parameter	Effect	F Value	P Value
Hull Content	Genotype (G)	69.35	<0.0001
	Environment (E)	21.71	<0.0001
	Nitrogen (N)	8.70	<0.0001
	GxE	10.64	<0.0001
	GxN	6.14	<0.0001
	ExN	3.57	<0.0001
	GxExN	1.79	0.0010
Groat Breakage[1]	Genotype (G)	171.98	<0.0001
	Environment (E)	13.14	<0.0001
	Nitrogen (N)	1.96	0.1202
	GxE	7.66	<0.0001
	GxN	1.61	0.0879
	ExN	2.15	0.0086
	GxExN	0.99	0.5073

[1] A square root transformation was performed prior to analysis of groat breakage

Summary of fixed effects for oat composition.

Component	Effect	F Value	P Value
β-Glucan	Genotype (G)	446.12	<0.0001
	Environment (E)	1.10	0.3960
	Nitrogen (N)	27.94	<0.0001
	GxE	2.99	<0.0001
	GxN	1.22	0.2695
	ExN	4.97	<0.0001
	GxExN	0.84	0.7970
Protein	Genotype (G)	6.33	0.0002
	Environment (E)	16.84	<0.0001
	Nitrogen (N)	128.59	<0.0001
	GxE	2.69	0.0013
	GxN	2.32	0.0079
	ExN	8.72	<0.0001
	GxExN	1.03	0.4290
Oil	Genotype (G)	96.39	<0.0001
	Environment (E)	68.04	<0.0001
	Nitrogen (N)	24.04	<0.0001
	GxE	3.08	0.0004
	GxN	1.62	0.0856
	ExN	1.88	0.0261
	GxExN	1.14	0.2520

Summary of fixed effects for wholemeal pasting properties of oats grown at Glenlea.

RVA Parameter	Effect	F Value	P Value
Peak	Genotype (G)	55.50	<0.0001
	Nitrogen (N)	0.68	0.5826
	GxN	1.63	0.1146
Hot Paste	Genotype	55.09	<0.0001
	Nitrogen	1.27	0.3283
	GxN	1.39	0.2020
Final	Genotype	45.70	<0.0001
	Nitrogen	0.09	0.9627
	GxN	1.03	0.4395
Breakdown	Genotype	158.33	<0.0001
	Nitrogen	1.29	0.3218
	GxN	1.56	0.1351
Final-Peak	Genotype	72.11	<0.0001
	Nitrogen	0.73	0.5555
	GxN	0.75	0.6942
Set Back	Genotype	12.68	<0.0001
	Nitrogen	1.09	0.3897
	GxN	1.02	0.4499
Shear Thinning	Genotype	138.94	<0.0001
	Nitrogen	1.71	0.2183
	GxN	1.19	0.3153

Summary of fixed effects for wholemeal pasting properties of oats grown at Morden.

RVA Parameter	Effect	F Value	P Value
Peak	Genotype (G)	14.43	<0.0001
	Nitrogen (N)	0.57	0.6462
	GxN	0.66	0.7814
Hot Paste	Genotype	22.11	<0.0001
	Nitrogen	1.74	0.2129
	GxN	0.57	0.8557
Final	Genotype	28.67	<0.0001
	Nitrogen	1.63	0.2339
	GxN	0.74	0.7100
Breakdown	Genotype	63.73	<0.0001
	Nitrogen	1.95	0.1764
	GxN	0.59	0.8358
Final-Peak	Genotype	53.08	<0.0001
	Nitrogen	2.25	0.1386
	GxN	0.81	0.6423
Setback	Genotype	41.40	<0.0001
	Nitrogen	0.62	0.6145
	GxN	1.25	0.2785
Shear Thinning	Genotype	40.14	<0.0001
	Nitrogen	2.18	0.1444
	GxN	0.59	0.8426

Summary of fixed effects for wholemeal pasting properties of oats grown at Silverton 1998.

RVA Parameter	Effect	F Value	P Value
Peak	Genotype (G)	14.54	<0.0001
	Nitrogen (N)	0.11	0.9502
	GxN	0.32	0.9817
Hot Paste	Genotype	8.02	<0.0001
	Nitrogen	0.10	0.9593
	GxN	0.25	0.9935
Final	Genotype	4.96	0.0020
	Nitrogen	0.08	0.9686
	GxN	0.36	0.9698
Breakdown	Genotype	52.57	<0.0001
	Nitrogen	0.10	0.9573
	GxN	0.54	0.8757
Final-Peak	Genotype	70.78	<0.0001
	Nitrogen	0.24	0.8649
	GxN	0.92	0.5326
Set Back	Genotype	30.90	<0.0001
	Nitrogen	0.16	0.9214
	GxN	1.09	0.3917
Shear Thinning	Genotype	7.01	0.0002
	Nitrogen	0.10	0.9587
	GxN	0.24	0.9951

Summary of fixed effects for wholemeal pasting properties of oats grown at Carman.

RVA Parameter	Effect	F Value	P Value
Peak	Genotype (G)	30.93	<0.0001
	Nitrogen (N)	6.28	0.0089
	GxN	1.19	0.3193
Hot Paste	Genotype	26.54	<0.0001
	Nitrogen	15.90	0.0002
	GxN	1.65	0.1096
Final	Genotype	31.29	<0.0001
	Nitrogen	4.89	0.0042
	GxN	1.33	0.2259
Breakdown	Genotype	48.78	<0.0001
	Nitrogen	21.48	<0.0001
	GxN	1.72	0.0923
Final-Peak	Genotype	89.40	<0.0001
	Nitrogen	1.72	0.2148
	GxN	1.99	0.0470
Set Back	Genotype	36.46	<0.0001
	Nitrogen	15.45	<0.0001
	GxN	0.87	0.5773
Shear Thinning	Genotype	34.82	<0.0001
	Nitrogen	26.36	<0.0001
	GxN	2.24	0.0242

Summary of fixed effects for wholemeal pasting properties of oats grown at Silverton 1999.

RVA Parameter	Effect	F Value	P Value
Peak	Genotype (G)	18.95	<0.0001
	Nitrogen (N)	7.11	0.0004
	GxN	1.58	0.1211
Hot Paste	Genotype	11.70	<0.0001
	Nitrogen	18.78	<0.0001
	GxN	1.60	0.1238
Final	Genotype	15.87	<0.0001
	Nitrogen	14.58	0.0003
	GxN	1.23	0.2936
Breakdown	Genotype	79.34	<0.0001
	Nitrogen	6.25	0.0085
	GxN	0.51	0.8970
Final-Peak	Genotype	95.04	<0.0001
	Nitrogen	5.19	0.0158
	GxN	1.26	0.2710
Set Back	Genotype	38.76	<0.0001
	Nitrogen	0.92	0.4615
	GxN	3.71	0.0006
Shear Thinning	Genotype	29.68	<0.0001
	Nitrogen	16.09	0.0002
	GxN	1.28	0.2605

Summary of fixed effects for wholemeal pasting properties of oats grown at Winnipeg.

RVA Parameter	Effect	F Value	P Value
Peak	Genotype (G)	21.04	<0.0001
	Nitrogen (N)	19.96	0.0005
	GxN	1.68	0.1208
Hot Paste	Genotype	10.38	<0.0001
	Nitrogen	1.79	0.2268
	GxN	0.99	0.4788
Final	Genotype	26.59	<0.0001
	Nitrogen	2.02	0.1899
	GxN	1.86	0.0818
Breakdown	Genotype	45.92	<0.0001
	Nitrogen	5.53	0.0246
	GxN	1.27	0.2843
Final-Peak	Genotype	51.75	<0.0001
	Nitrogen	0.69	0.5824
	GxN	1.73	0.1089
Set Back	Genotype	33.21	<0.0001
	Nitrogen	3.38	0.0736
	GxN	2.65	0.0146
Shear Thinning	Genotype	27.71	<0.0001
	Nitrogen	1.09	0.4078
	GxN	0.73	0.7111