GROWING SEASON WEATHER IMPACTS ON BREADMAKING QUALITY OF CANADA WESTERN RED SPRING WHEAT GROWN IN PRODUCER FIELDS ACROSS WESTERN CANADA

BY

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Abstract

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A study was conducted to quantify the relationships between growing season weather conditions and end-use quality of Canada Western Red Spring (CWRS) wheat (*Triticum aestivum*) grown in producer fields across western Canada (Alberta, Saskatchewan and Manitoba). Samples of CWRS wheat, cultivars AC Barrie and Superb, were received from producer fields where growing season weather conditions had been monitored. Samples were collected from 2003, a hot dry season, and 2004, a cool wet growing season with late season problems of frost and excessive moisture. As a result, there was a wide range in quality in the samples collected. Grain samples received an official grade at the Canadian Grain Commission and were milled into flour using a Buhler flour mill at the University of Manitoba. Flour samples underwent an extensive analysis of flour, dough, and breadmaking quality. Those samples that received grades #1CWRS and #2CWRS were analyzed with the environmental data to search for relationships between growing season weather conditions and wheat quality. Single basic temperature-derived or precipitation variables accumulated over the entire growing season were simple to calculate from weather data but generally explained a low level of variance in the quality variables. The R^2 values ranged from 0.02 to 0.50. When the same weather variables were accumulated over the first half of planting to anthesis, the second half of planting to anthesis, the first half of anthesis to maturity, the second half of anthesis to maturity, planting to anthesis and anthesis to maturity, the amount of variance

explained in quality variables increased. The R^2 values ranged from 0.06 to 0.53. If the sophistication of the environmental variables was increased to include derived crop water demand and crop water use accumulated over the same periods above, the amount of variance explained in quality variables was increased further. The R^2 values ranged from 0.06 to 0.53. Multiple regression equations using up to three environmental variables from any of the time periods explained the greatest amount of the variance in quality variables. The R^2 values ranged from 0.20 to 0.75. For protein content and the protein fractions, typically, the most sensitive period to an environmental stress was the first half of anthesis to maturity. During this period, either heat or water stress had a negative effect on the synthesis of protein. However, useful heat or water use during the same period was beneficial to the synthesis of protein. Conversely, heat or water stress during the second half of the filling period or any time prior to anthesis caused an increase in final protein content. AC Barrie responded predominantly to useful heat and water use variables while Superb responded predominantly to heat and water stress variables. Superb had a higher heat stress threshold than AC Barrie. In some instances there was a significant relationship found for only one of the two cultivars for a quality parameter

In this study we also investigated the effectiveness of the Canadian grain grading system's ability to segregate wheat samples into levels of increasing quality performance and uniformity. We found that for several flour and dough quality analysis, this was often achieved for either quality performance or uniformity, but there was not an improvement in both with an improvement in grade. However, bread quality did improve in both performance quality and uniformity with an increase in grade.

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Foreword

This thesis contains the results from one component of a larger multi-partner research project investigating growing season weather effects on wheat quality. The goals of this particular component of the project were, first, to identify relationships between quantitative weather parameters and the breadmaking quality characteristics of producer-grown Canada Western Red Spring (CWRS) and, second, to test the ability of the current CWRS grading system to segregate those quality characteristics into categories which accurately reflect breadmaking properties.

Chapter 2, the main section, details statistical relationships between growing season weather conditions and grain, flour, dough, and bread quality of producer-grown CWRS in western Canada. Chapter 3 contains an evaluation of the Canadian grain grading system ability to differentiate CWRS with varying quality characteristics.

The appendices contain the details of several important methods utilized in the study including estimation of soil moisture, air temperature and nitrogen availability as well as the impact of mixing speed of the 10-gram mixograph on dough quality parameters.

Each section represents an important piece of the collective knowledge required to understand growing season weather effects on CWRS quality and how we can use that knowledge to improve our ability to source and segregate CWRS of varying quality.

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1. Introduction

Wheat is Canada's most important crop. Over the past five years, 2000-2004, Canada has averaged a yearly production of 22.6 million tonnes of wheat (FAOSTAT, 2005). Wheat and its value-added processing have an important impact on the Canadian economy. In 2002 and 2003, wheat crops marketed by the Canadian Wheat Board grossed revenues of $2.1 Billion and $2.8 Billion, respectively (CWB, 2005c). Canada exports nearly 75% of its wheat production, selling to nearly 70 different countries and has about 20% of the world market share in wheat (CWB, 2005a). It is the high processing quality of Canadian wheat that provides Canada with a strong marketing advantage over other larger competing wheat exporters like the United States and Australia.

Wheat is a very diverse agricultural commodity. Wheat as a raw material can be made into a large number of different end products including noodles, bread, and pastries. Each of these end products has its own unique range in quality properties. As a result, wheat classes have been used in western Canada to segregate wheat cultivars into similar groupings with the same final end-use product. In this study we investigated Canada's most important wheat class, Canada Western Red Spring (CWRS).

CWRS wheat is primarily used for bread production. CWRS accounts for nearly 70% of total wheat production in Canada (FAOSTAT, 2005). Canada has become a major global grain exporter through maintaining a reputation of growing high quality wheat. However, the variability in wheat quality can vary significantly due to the wide range of growing conditions that occur annually over the vast Canadian wheat growing region. The Canadian Wheat Board (CWB), as the sole marketer of prairie wheat, has become very efficient at predicting the yield of wheat crops grown in western Canada. This information provides the CWB with an advantage in the grain market by having early information on the amount of grain they will soon have in the grain system ready to market. However, the ability to predict wheat quality is not yet well understood. The ability to know the quality of wheat to be expected in the grain system prior to the fall harvest would provide another significant advantage to the CWB's marketing plan of CWRS wheat over competing exporting counties.

Wheat quality assurance is an issue of increasing importance in the global wheat market. The ability for the Canadian grading system to provide assurance to its customers on the performance of the wheat they purchase is a much desired ability by many other competing nations. However, for Canada to remain in the elite group in this regard they must constantly review their grading standards and regulations to be able to consistently and confidently ensure their customers of the uniformity and performance level of Canadian wheat.

This study was conducted to investigate the impacts of growing season weather conditions on CWRS wheat quality from wheat samples collected from producer fields. What makes this project unique from previous work is that we determined the variation in quality by growing location and investigated how the growing season weather affects the quality.

1.1 Objectives

The specific objectives of this study include:

1) to determine the impacts of growing season weather on grain, flour, dough, and bread quality parameters of CWRS wheat from western Canadian producers
2) to determine the effectiveness of the Canadian grain system's ability to segregate wheat samples into classes of improving quality and uniformity using grade.

2. Growing Season Weather Impacts on Breadmaking Quality of Canada Western Red Spring Wheat Grown in Producer Fields across Western Canada

2.1. Abstract

A study was conducted to determine the growing season weather impacts on end-use quality of CWRS wheat grown on producer fields in western Canada during 2003 and 2004 cropping years. The two growing seasons were very different with 2003 being a hot, dry season and 2004 being a much cooler, wet season. Ninety-six grain samples grading either #1 CWRS or #2 CWRS were collected from producer cooperators spatially distributed across the Canadian Prairies. Samples were analyzed by the Canadian Grain Commission for grain properties and assessed an official grade before being milled into flour. An extensive set of analysis was conducted to determine flour and dough quality properties. The flour was baked and analyzed for final breadmaking quality. All quality variables were analyzed using stepwise regression to find the independent environmental variable with the highest regression coefficient. Several different modeling techniques were used with the conclusion that as the model sophistication increased, there was an improvement to quality predictability. There was also a difference in cultivar responses to environmental stresses and useful heat variables with AC Barrie more highly correlated to useful heat variables and Superb more highly correlated to stress variables. Flour protein content and protein quality were the most important quality parameters because they were the main driving force for a large majority of the dough and bread quality properties.

2.2. Introduction

Canada has a crop growing region of 40 million hectares. Ten million hectares of this crop growing region is typically planted to wheat (average for past five years, 2000 – 2004) (FAOSTAT, 2005). The Prairie Provinces, Alberta, Saskatchewan, and Manitoba, account for over 95% of the wheat sown hectares. An area of this size experiences a wide range of precipitation and temperature variation. This enormous spatial and temporal range of growing season conditions can create very wide variability on the quality and quantity of wheat produced. Fluctuation in quality can be a major issue for Canada's wheat export market, whose customers demand a reliable source of consistent, uniform wheat quality they have come to expect. Changes in the quantity of acceptable harvested wheat for end-use is also impacted by growing season weather. Changes in the environment can impact production through increased stresses on the wheat plant such as drought or disease pressure. Therefore, an unfavorable season of environmental conditions can greatly impact the Canadian wheat market directly on the farm level and indirectly through decreased exports of raw wheat material and value-added products.

There has been extensive work performed on the impacts of genotype and environment interaction on wheat quality. Many of these studies have a similar conclusion: genotype and environment both have significant effects on wheat quality. Furthermore, depending on the season and the quality constituents being studied, environmental impacts can actually exceed those of genotype (Panozzo and Eagles, 2000; Peterson et al., 1986; Stone and Nicolas, 1996).

Wheat is a very diverse raw product that can be transformed into a range of breads, bakery goods, and noodles. Each of these end-products has different requirements of wheat quality to create a satisfactory end product. This study focuses on those wheat quality characteristics best suited for breadmaking.

The demand for uniform, high breadmaking quality wheat is always high (Lukow and Preston, 1998). Therefore, for Canada to remain a prominent player in the wheat export market, it must be prepared to meet their customers' demands. The first step of achieving this is to gain more understanding of the impacts that environmental variation can have on wheat quality. This study examined how growing season weather conditions impact protein content, protein quality, starch, and non-starch polysaccharides, specifically pentosans, and how these constituents of wheat quality impact dough and bread properties. Our investigation also assessed the level of variability in dough and bread properties that can be accounted for by growing season variability.

2.2.1. Protein

Protein is the second most abundant substance in a wheat kernel next to starch. Wheat protein has been traditionally classified as albumins, globumins, gliadins, and glutenin based on their solubility (Osborne, 1907). Albumins and globumins make up the non-storage metabolic proteins in wheat while gliadins and glutenin make up the wheat N-storage proteins or gluten protein.

Wheat protein is measured as a percentage of the weight of a wheat kernel. Wheat protein content can range from 6% to 20%. This variation depends on factors such as genotype and environment (Triboi and Triboi-Blondel, 2001). The ability of wheat to synthesize protein is controlled by both genetics and environment. In addition, any environmental factor, such as temperature or moisture stress, that restricts grain yield can increase protein content. This is because of the inverse relationship between protein content and yield. However, a temperature or moisture stress can also directly decrease protein content if the period of stress occurs during a period where protein synthesis is most sensitive.

2.2.1.1. Gluten Protein

Gluten proteins make up 85% of endosperm proteins (Carceller and Aussenac, 1999). Gluten protein is made up of two different types of proteins, monomeric gliadins and glutenin polymers. Glutenin polymers are composed of two different types of subunits, high molecular weight subunits (~90 kDa) and low molecular subunits (~60 kDa), held together by di-sulphide bonds (Altenbach et al., 2002). The gluten protein fraction is the major component influencing the viscoelastic properties of dough and ultimately baking quality (Panozzo et al., 2001). Gliadins make up 40-50% of the endosperm proteins (Altenbach et al., 2002). Gliadins give wheat its extensibility characteristics while glutenin gives wheat its strength and elasticity (Altenbach et al., 2002). It is the balance of gliadin:glutenin that gives wheat its desired viscoelastic properties for breadmaking.

2.2.1.2. Gluten Synthesis during Wheat Development

Movement of photosynthates from the plant to wheat kernel occurs almost immediately after anthesis. The period of highest nitrogen content in the wheat kernel as a source for wheat protein synthesis occurs during the first two – three weeks after flowering (Bushuk and Wrigley, 1971). This N is eventually moved into storage proteins as the filling period progresses.

Synthesis of albumins and globumins occurs only initially after anthesis (up to 19 days after anthesis) and then remains constant (Gupta et al., 1996). During this period, storage proteins are also being synthesized, however, they continue to be synthesized much later into the grain filling period.

Gliadin synthesis occurs early after anthesis, from 7 days after anthesis (DAA) until 35 DAA. By 12 – 14 DAA all types of gliadin proteins are being synthesized. The most rapid phase of gliadin synthesis occurs between 7 – 21 DAA

HMW-glutenin subunits have been found in the kernel almost immediately after anthesis. LMW-glutenin subunits are found in the kernel shortly after the HMW-glutenin subunits (Huebner et al., 1990; Panozzo et al., 2001). By 7 DAA both HMW- and LMW-glutenin subunits can be found in the wheat kernel (Gupta et al., 1996).

2.2.1.3. Effect of Temperature on Wheat Protein

Several studies have shown that the impacts of environmental variability have exceeded those of genotypic variation on wheat quality traits, including protein (Lukow and McVetty, 1991; Peterson et al., 1992). In fact it has been found that temperature specifically has a greater impact on protein content than either soil moisture or nitrogen fertilization (Campbell and Davidson, 1979; Selles and Zentner, 1998). There also can be differences in protein response to increasing temperatures between wheat cultivars (Blumenthal et al., 1993).

A common observation in many experiments investigating temperature impacts on wheat protein, was a direct relationship between temperature during the filling period and wheat protein content (Correll et al., 1994; Fido et al., 1997). As temperature increases up to a threshold value of 30-32°C, there is an increase in the synthesis of protein and starch. However, the increased rate of protein synthesis is greater than that of starch, and thus, the end result is an increase in the relative proportion of protein to starch. However, when temperatures increase above this threshold value of 30-32°C there is a decrease in protein and starch synthesis. The decrease in rate of protein synthesis is greater than the decrease in rate of starch synthesis, and thus, we see a decrease in the relative proportion of protein to starch. The rate of decline in protein synthesis increases as the time spent at a temperature exceeding 30-32°C increases (Graybosch et al., 1995). An increase in temperature can also contribute to higher protein levels because of its ability to shorten wheat's growing season. As temperature increases and quickens development, there is a decreased period of filling and the wheat reaches senescence prematurely. This causes a decrease in starch accumulation, creating a higher percentage of protein in the kernel (Campbell and Davidson, 1979).

However, a change in protein concentration due to increasing temperatures doesn't necessarily mean an improvement to gluten protein (Mangels, 1925). Wheat grown at different locations with variability in temperature can cause variability in wheat protein composition in crops having very similar total protein levels (Randall and Moss, 1990). In general, as temperature increases there is an increase in the ratio of gliadin to glutenin polymers (Blumenthal et al., 1993; Ciaffi et al., 1996; Johansson et al., 2004; Panozzo and Eagles, 2000; Zhu, 2001). These studies attribute the change in protein quality composition to an increase in the synthesis of gliadin at the expense of glutenin polymer synthesis with increasing temperature. While gliadin has been found to be responsive to environment, glutenin has been found to be relatively unresponsive to environmental variability and is more influenced by genetic variability (Panozzo and Eagles, 2000).

2.2.1.4. Effect of Moisture Stress on Protein

Moisture stress has been found to have similar impacts to temperature on wheat protein. Moisture stress plays a less significant role in determining protein levels than temperature but a more significant role than nitrogen (Campbell and Davidson, 1979). As with temperature impacts on protein content, there are also differences in responses to moisture stress between cultivars (Bunker et al., 1989).

Generally, an increase in moisture stress creates a higher protein content (Entz and Fowler, 1988; Hutcheon and Paul, 1966; Selles and Zentner, 1998). Selles and Zentner (1998) attributed the impacts of moisture stress on protein content to moisture stress impacts on yield. Generally, an increase in moisture stress causes a decrease in yield and, due to the inverse relationship between yield and protein (Campbell and Davidson, 1979; Terman, 1978; Triboi and Triboi-Blondel, 2001), there is an increase in protein content. Timing of the moisture stress can have a significant impact on how protein content responds. An early study discovered that moisture stress on a wheat crop at early shot blade would result in a bigger increase in protein content than if the moisture stress occurred during tillering. Campbell and Davidson (1979) supported this finding in that moisture stress occurring between flag leaf and anthesis causes a decrease in yield (recall the inverse relationship between yield and protein) while moisture stress between tillering and flag leaf actually caused minimal impact on yield.

Moisture stress is also capable of influencing wheat protein quality. When a wheat crop experiences a period of drought or moisture stress the stage of rapid protein polymerization begins earlier than normal in the kernel (Daniel and Triboi, 2002). Despite drought conditions causing a shortened growing season, moisture stress on a wheat crop causes an increase in the amount of total polymeric proteins (glutenin) formed, thus decreasing the gliadin to glutenin ratio (Hussain and Lukow, 1994).

2.2.2. Starch

Starch is important in breadmaking as it has a great influence on the physico-chemical properties of flour dough products (Matsuki et al., 2003). Starch composes approximately 60-75% of the total dry weight of a wheat kernel (Morrell et al., 1995; Triboi and Triboi-Blondel, 2001). Just as in protein, the assimilation of polysaccharides, including starch, is a function of genotype and environmental conditions and does vary between cultivars (Matsuki et al., 2003; Panozzo and Eagles, 1998).

Starch is composed of glucose and two carbohydrate polymers, amylose and amylopectin. Starch occurs in the endosperm of a wheat kernel in two types of granular form. The two types of granules can be separated by size, a larger A-type and a smaller B-type. The relative proportion of these types of starch granules is believed to influence starch gelatinizing and pasting properties (Panozzo and Eagles, 1998).

2.2.2.1. Starch Accumulation during Wheat Development

Grain filling in wheat generally follows a sigmoidal pattern from anthesis to maturity. The filling process consists of three distinct phases. The first period occurs shortly after anthesis and is often referred to as the initial lag phase. During this period, there is rapid cell division in the endosperm with the formation of starch and protein bodies, resulting in an increase in endosperm volume. The number of cells created in this time determines the potential grain size. During the second phase there is a constant rate of grain filling. This rate is determined by cultivar and environmental conditions. The final phase begins when the pigment strands are closed and the flow of assimilates to the grain ceases. This phase is also known as physiological maturity (Panozzo and Eagles, 1998).

A-type granules are created early in the filling period and B-type granules are initiated later within A-type amyloplasts (Parker, 1985). Amylose is also created earlier than amylopectin during grain filling. Therefore, since starch has different phases of synthesis during the grain filling stage, the timing of an environmental stress can impact the effectiveness of starch accumulation and the accumulation of different starch components in the grain.

2.2.2.2. Effect of Environment on Starch

In general, an increase in temperature above 30°C will cause an overall decrease in starch content of a kernel. This results in decreased thousand kernel weight and yield (Randall and Moss, 1990). Randall and Moss (1990) also found that high temperatures, especially after a period of exposure to a low temperature environment, caused wheat plants to reach maturity more quickly. The earlier maturity of plants resulted in a 33% decrease of kernel weight when compared to the control.

The make up of wheat starch also changes with environmental stress. A high temperature stress (>30˚C) occurring during the first 2 weeks after anthesis can cause an increase in the proportion of A-type granules to B-type granules and proportion of amylose to amylopectin (Panozzo and Eagles, 1998). The increase in amylose to amylopectin ratio is due to the higher temperature sensitivity associated with soluble starch synthase, which is involved in forming of amylopectin, more so than GBSS, an enzyme involved with amylose synthesis (Jenner, 1994). This would agree with Panozzo and Eagles (1998) findings of a high correlation between A-type granules and amylose content.

Amylopectin in wheat kernels grown at lower temperatures have a higher proportion of shorter chain lengths in their branch makeup. Also, due to its correlation with amylopectin chain length, there is a direct relationship between starch gelatinization temperature and the temperature experienced by the wheat crop during its filling period (Matsuki et al., 2003).

2.2.3. Effect of Environment on Wheat End-use Quality

Several studies have looked at the impact of the environment on wheat breadmaking quality (Blumenthal et al., 1991; Bunker et al., 1989; Corbellini et al., 1997; Peterson et al., 1998; Preston et al., 2001). A general trend found in these studies was an increase in temperature above 30-32˚C and increase in duration above this temperature threshold results in dough weakening due to an increase in gliadin content compared to glutenin content (Blumenthal et al., 1991; Corbellini et al., 1997). This increase in the gliadin to glutenin ratio is the major reason for the decrease in breadmaking quality (Bushuk et al., 1978). Thus as temperatures exceed 30-32°C, there is a decline in several quality parameters such as loaf volume and loaf weight. Past research by Peterson et al. (1998) found an original increase in loaf volume with increasing temperature. However, as duration spent above 32°C exceeded 90 hours, there was a rapid decrease in loaf volume. Several researchers have come to the conclusion that the impacts of environment on end-use quality are directly related and can be explained by the effect of environmental variation of protein content and, specifically, protein quality (Blumenthal et al., 1991; Bunker et al., 1989; Peterson et al., 1998). As a result, several studies investigating the impact of the environment on end-use quality demonstrated that it would be beneficial to investigate the possibility of growing specific wheat classes/cultivars in separate regions, with each combination suited for a specific end-use quality (Mikhaylenko et al., 2000; Zhang et al., 2004)

2.2.4. Effect of Protein on End-use Quality

The impacts of protein content and protein quality (gluten protein composition) on wheat end-use quality have been extensively studied. A common finding of these studies was the direct relationship between protein content with dough strength and loaf volume (Bushuk et al., 1969; Hamada et al., 1982; Lukow and Preston, 1998; Mikhaylenko et al., 2000; Uthayakumaran and Lukow, 2003). This relationship helps explain the correlation between environmental conditions and breadmaking quality. As mentioned earlier, an environmental condition that results in an increase in protein content also results in an increase in dough strength and loaf volume. Specific findings from these studies showed a direct relationship between protein content and peak mixing resistance on the mixograph, mixing tolerance on the Farinograph, and maximum resistance to extension on the Extensigraph.

Additional studies found protein quality to also have significant impact on wheat end-use quality (Sapirstein and Fu, 1998; Uthayakumaran and Lukow, 2005; Weegels et al., 1996). A general trend from these studies found as the glutenin to gliadin ratio increased there was an increase in dough strength and loaf volume (Blumenthal et al., 1993; Fido et al., 1997; MacRitchie, 1987; Uthayakumaran et al., 1999; Uthayakumaran et al., 2000b). Several of these studies were performed by adding extracted proteins to wheat flours to change the protein composition. Fido et al. (1997) discovered that not only does the addition of gliadins decrease dough strength but the type of gliadin added to wheat flour affected the magnitude of dough weakening. This finding has also been confirmed by other researchers (Uthayakumaran et al., 2001).

Further investigation into protein quality impacts on results with improved protein fractionation techniques discovered that HMW-glutenin was the main driving force for the relationship between protein quality and breadmaking quality (Lemelin et al., 2005; Uthayakumaran et al., 2000a; Weegels et al., 1996). Thus, the ratio referred to earlier as glutenin to gliadin could be more accurately considered a ratio between HMW-glutenin to LMW-glutenin and gliadin since it appears that the HMW-glutenin content is the protein fraction primarily responsible for the variability in breadmaking quality.

There is a well studied relationship between protein content and protein quality with breadmaking quality. Thus, due to the relationships between protein content and protein quality on breadmaking quality, by following the impacts of environmental conditions on protein content and quality it is possible to make accurate predictions on the resulting breadmaking quality.

2.3. Materials and Methods

In this study, environmental conditions were quantified by two means. The first was by using simple variables derived from daily maximum and minimum temperatures and daily rainfall recordings and the second by modeling daily potential and actual evapotranspiration values. These environmental variables were then used to look for relationships with wheat quality. This study took a stepwise approach to investigate the different capabilities to predict wheat quality between simple environmental variables and more sophisticated modeled environmental variables.

2.3.1. Selection of Growers

In order to fulfill the objectives for this study, samples were collected from across the entire wheat growing region of western Canada. Two Canada Western Red Spring (CWRS) wheat cultivars were chosen for this experiment, AC Barrie and Superb. These cultivars were chosen on the basis of their large share of the CWRS acreage and the prospect of increasing acreage, respectively. Approximately 120 producers were solicited for cooperation on this project, 60 of these growing Superb and 60 growing AC Barrie. The producers were spatially distributed across the Canadian Prairies, with approximately 10 in Manitoba, 30 in Saskatchewan, and 20 in Alberta for each cultivar. Each grower needed to satisfy specific criteria to be selected for participation in this project. The grower had to be growing certified seed or 1 year removed from certified seed of either AC Barrie or Superb. The grower provided a soil nutrient test and records of crop management practices for the experiment field. Finally, the grower had to be willing to record daily rainfall measurements taken in the experiment field.

2.3.2. Environmental Data Collection

Spring moisture measurements were performed using a simple soil moisture probe constructed with a T-handle on one end of a ½" rod 5'long with a $^{5}/_{8}$" ball bearing on the other end (Brown et al., 1985). Soil moisture probe depth readings were taken at seeding by pushing the probe into the soil until it would no longer penetrate. This depth was assumed to represent the depth of soil in the field at field capacity. Sampling took place at seeding to represent initial soil moisture conditions for the wheat's development. Soil texture was determined by performing particle size analysis using the hydrometer method (Carter, 1993; McKeague, 1978) on soil samples from each field. Soil texture data was then used to convert seeding soil moisture probe depths to estimated soil moisture content at seeding as according to the methods by Haluschak et al. (2004).

A rain gauge was provided to each producer and was situated on-site for daily rainfall recordings. The rain gauge had an inner cylinder, with 0.1mm increments, capable of collecting and measuring a maximum of 25.4mm of rainfall. The inner cylinder was situated inside a larger, outer cylinder capable of catching excess rainfall exceeding 25.4mm during high volume rainfall events. Rainfalls greater than 25.4 mm could then be measured by transferring the excess rainfall into the incremented inner cylinder. The outer cylinder was also capable of collecting other types of precipitation, such as hail, sleet, or snow once the inner cylinder was removed. Once melted, the solid precipitation's rainfall equivalent could be measured using the inner incremented cylinder.

Daily maximum (max) and minimum (min) temperatures were interpolated to each field site from neighbouring Environment Canada weather stations by use of an inverse distance weighted method (Equation 2.1 and Equation 2.2) (Barnes, 1964). Interpolations were performed using a Geographical Information System (GIS) software program called ArcView 3.3. Weather stations and field sites were plotted in ArcView using latitude and longitude coordinates. Distances between field sites and neighbouring weather stations were then measured using a measurement tool provided by ArcView 3.3. Past examination of Barnes (1964) method has confirmed its usefulness for interpolations of daily temperature while possessing downfalls for daily precipitation interpolations (Raddatz and Kern, 1984).

$$e_{t,i} = \sum_{\substack{j=1 \\ j \neq i}}^{k} W_{ij} f_{t,i} \Big/ \sum_{\substack{j=1 \\ j \neq i}}^{k} W_{ij} \qquad (2.1)$$

where

$$W_{ij} = \exp\left(-4d^2_{ij}/R^2\right) \qquad (2.2)$$

Where:

$e_{t,i}$ = Estimated field values of maximum and minimum temperatures at location i at time t.

Wij = Weighted value to multiply the j^{th} point of measured temperatures for estimation of temperatures at location i.

$f_{t,i}$ = temperature observations measured at the i^{th} point at time t

d_{ij} = distance between points i and j, for $j = 1,\ldots,$ k and $j \neq i$.

R = limited range of influence of the distance weighted-average k data points.

Verification of this method of interpolation was performed by interpolating daily maximum (max) and minimum (min) temperatures to an Environment Canada weather station. The interpolated values were then compared to the actual temperatures measured at the Environment Canada weather station. This was repeated five times at weather stations across the three Prairie Provinces. The results indicated that estimated max temperature was very closely related to the actual max temperature (R^2 range of 0.70 to 0.97) and estimated min temperature was very closely related to the actual min temperature (R^2 range of 0.84 to 0.94) (Appendix C). Estimated max and min temperatures were not significantly different from the actual max and min temperatures.

Producers were asked to provide information pertaining to important development stages of the wheat crop. Each producer was provided with a scouting guide to estimate a date of 50% anthesis and date of maturity (20% grain moisture content). Date of 50% anthesis was scouted by taking samples of plant main stems in several areas of the field. The grower then recorded the percentage of the heads having reached anthesis. Date of maturity was defined as the staging of wheat development when the kernels reached 20% moisture content, a typical stage for windrowing of wheat in the northern Great Plains (Bauer and Black, 1989). Growers were equipped with a scouting guide for the determination of this date, complete with photographs provided by Bauer and Black (1989). The use of these scouted dates will be discussed further in this section.

2.3.3. Environmental Parameters

Several environmental parameters were investigated as possible variables to explain variation in wheat quality. The simplest parameter investigated was seasonal rainfall measured at the site by the grower. Several other parameters were derived relatively simply from daily maximum and minimum interpolated temperatures. This included growing degree days (GDD) with base temperatures ranging from 3 through 10˚C (Equation 2.3).

$$GDD_{3-10} = \sum_{Seeding}^{Harvest} \frac{T_{\max} + T_{\min}}{2} - T_{base} \qquad (2.3)$$

A second environmental parameter derived from daily temperature information was crop stress degrees, where each degree above 30°C per day was accumulated as a stress degree. Thus, a day reaching a high of 34°C would accumulate four stress degrees that day. A similar stress parameter measured was crop stress days, where a day with a max temperature above a threshold value accumulated one crop stress day. Thus, using the same scenario as above, a day reaching a high of 34°C would accumulate one crop stress day. The threshold values investigated for crop stress days ranged from 15˚C to 30˚C.

The fourth environmental parameter investigated using temperature values was physiological days (Pdays) (Sands et al., 1979). Pdays are developed on the basis of a minimum temperature, optimal temperature, and maximum temperature describing the development of a crop (Equation 2.4). A total of 450 different combinations of min, optimal, and max temperatures were used to calculated Pdays in this experiment.

$$Pdays = \frac{1}{24}(5 \times P(T_1) + 8 \times P(T_2) + 8 \times P(T_3) + 3 \times P(T_4)) \quad (2.4)$$

where:

$$T_1 = T_{min}$$

$$T_2 = \frac{(2 \times T_{min}) + T_{max}}{3}$$

$$T_3 = \frac{T_{min} + (2 \times T_{max})}{3}$$

$$T_4 = T_{max}$$

The final temperature parameter measured was average daily temperature range. This was derived by computing the daily temperature range from daily max and min temperatures. Two temperature range variables were then created, one daily average range and the other a sum of the daily temperature ranges.

A moisture balance method was used to estimate crop water use. The soil moisture in the surface 1.2 m at seeding was used as the initial condition. The root zone was assumed to be 5 cm deep at seeding and increased in depth using a temperature root function to a maximum of 1.2 m. Water could exit the root zone only via evapotranspiration or by overflowing if the soil moisture capacity was full. Physiological daily development of the wheat was modeled using the biometeorological time scale (BMT) (Robertson, 1968). Water use was calculated using a crop coefficient to estimate daily water demand as a percentage of total potential evapotranspiration. The crop coefficient started at 0.3 at seeding and increased to a value of 1.0 at anthesis, then declined to a value of 0 at physiological maturity. Water use was estimated daily as the lesser of crop water demand or crop water supply remaining in the root zone.

The soil moisture balance was run twice for each producer field in the study. The first run used the same method as the First Generation Model developed at Environment Canada (Raddatz, 1989). This model uses a three parameter model for estimating potential evapotranspiration. The three daily input parameters used are extraterrestrial solar radiation, maximum temperature, and temperature range (Baier and Robertson, 1965). The second method is used a model developed for the Senegal River basin and used three daily input parameters of extraterrestrial solar radiation, maximum temperature, and average temperature (Hargreaves et al., 1985). The maximum temperature and temperature range for each field was obtained using the interpolation method described earlier. Extraterrestrial solar radiation was computed using the latitude obtained from each field with a handheld Global Positioning System (GPS) unit. Both methods of modeling also required daily precipitation as input.

Several environmental parameters were generated from the two potential evapotranspiration estimation equations. These included crop water demand, crop water use, crop water use deficit, and water use ratio.

Each of the environmental parameters discussed above were accumulated for different stages of the growing season including the total growing season, planting to anthesis, anthesis to maturity, and soft dough to maturity. Dates of anthesis and maturity were obtained through farmer scouting and validated with the BMT output from the First Generation Model. Date of soft dough was estimated by the BMT scale. The BMT staging equivalents for 50% anthesis, soft dough, and maturity are 3.3, 4.0, and 5.0, respectively. The growing season was further divided for the periods of planting to anthesis and anthesis to maturity. These two stages were divided in half based solely on calendar days. The accumulation of environmental parameters during the first or second half of these periods was then correlated to wheat quality parameters. A list explaining how the environmental symbols were abbreviated can be seen in Table 2.1.

Table 2.1: Explanation of Environmental Parameter symbols used in analysis.

Environmental Variable	Explanation
Rain_All	Accumulated precipitation during entire growing season.
Days_All	Length of growing season measured in calendar days.
GDD_4Plant-Anth	Accumulated Growing Degree Days base 4˚C during planting to anthesis.
StressDeg_Anth-Mat	Accumulated stress degrees above 30˚C during anthesis to maturity
S_t28_Anth-Mat_Grp1	Accumulated days with max temperature raising above 28˚C during the first half (Grp1) of anthesis to maturity.
Pdays $_{3\text{-}17\text{-}27}$Plant-Anth _Grp2	Accumulated Pdays with temperature min, optimal, and max thresholds of 3, 17, and 27˚C, respectively, during the first half (Grp2) of the planting to anthesis stage.
Trange_avg_All	Average daily temperature range for the entire growing season.
Trange_sum_Plant-Anth_Grp1	Accumulated daily temperature range during the first half of the planting to anthesis stage.
BR3ETp_Anth-SD	Accumulated daily potential evapotranspiration based on Baier & Robertson method during anthesis to soft dough.
BR3WU_Anth-Mat	Accumulated daily water used based on Baier & Robertson method during anthesis to maturity.
HarWUDef_SD-Mat	Accumulated daily water use deficit based on Hargreaves method during soft dough to maturity.
HarWU/ETp_Plant-Anth	Ratio of water use to evapotranspiration potential based on Hargreaves method from planting to anthesis.

2.3.4 Nitrogen Stratification of Fields

It was imperative to address the nutrient, specifically nitrogen, status of each field in order to isolate the growing season weather impacts on wheat quality. This was achieved by obtaining a nutrient soil test analysis and applied fertilizer records from each field. However, since this study was performed in cooperation with growers across western Canada, there was a wide range of soil test analyses and soil sampling techniques used. Therefore, measures had to be taken to quantify the nitrogen status of each field into a value comparable between fields.

The first step was to make the soil test analysis comparable between fields. This was done by extrapolating all soil test extractable nitrogen levels to a 24” equivalent. These extrapolated levels were calculated using either Enivro-Test Laboratories or Norwest Laboratories 24” equivalent estimation technique for the respective soil lab results (M. Gaultier, Norwest Labs, personal communication; P. Rutledge, EnviroTest Labs, personal communication). In the cases where other labs were used for soil test analysis the 24” equivalent values were estimated using conversion factors for estimation of soil available nitrogen from Westco Advances in Agronomy Handbook (2004).

Estimation for mineralization and immobilization during the growing season was also calculated for each field. This was done based on each field site’s soil zone and amount of rainfall received during the growing season (Westco, 2004). Typically, this tool is used by agronomists and farmers to estimate the amount of nitrogen that would be available to the crop during the upcoming growing season to help determine how much fertilizer should be applied. However, since the amount of rainfall during the growing season was known, an appropriate selection of the probability of precipitation received by the crop to improve the estimation of mineralization of nitrogen through the growing season would be made. For fields where soils were analyzed by Western Ag Labs, ion exchange probe measurements were used to estimate net mineralization. Therefore, no further mineralization estimations were needed for these fields (K.Greer, Western Ag Innovations, personal communication ; Qian and Schoenau, 1995) (Appendix B).

2.3.5. Analysis of Wheat Quality

Part of the uniqueness of this project was the detailed quality analysis performed on the wheat samples while maintaining each sample's spatial integrity. Quality analyses included grain properties, flour properties, dough properties, and bread properties for all samples.

2.3.5.1. Analysis of Grain Properties

Grain property analysis began at the Canadian Grain Commission where each sample was given a full analysis and official grade according to the Canadian Grain Commission's (2004) grading system. Grain protein content was determined by Near Infrared Reflectance Spectroscopy (NIR). Levels of sprouting, fusarium, and test weight were all determined as discussed in the Official Grain Grading Guide (Canadian Grain Commission, 2004).

Thousand kernel weights were determined by weighing 250 to 350 wheat kernels and then calculating the equivalent weight for one-thousand kernels. Cracked kernels were removed from the kernel counter to prevent being counted and weighed. Moisture measurements were then taken for each sample using a Model 919 moisture tester. For some site samples, there was not enough grain (200 g) to use the Model 919 moisture tester. In these instances, a sample of grain was weighed before being placed in an oven at 90°C for 12 hours. After drying, samples were then re-weighed to calculate the moisture content of the grain. A comparison between the oven-dry method and Model 919 tester found that conversion needed to be performed on the oven-dry method to generate a Model 919 equivalent moisture value (Appendix E). Thousand kernel weights are reported at 13.5% moisture content.

2.3.5.2. Analysis of Flour Properties

Several methods of analysis were used for the determination of flour quality. Several quality parameters were determined using the following methods of flour quality analysis.

Milling of Wheat Grain samples were milled using a Buhler Experimental Mill. Prior to milling, grain samples were tempered for 24 hours to a moisture content of 16.5%. Three kg grain samples were then milled to straight grade flour at moisture basis of 14%. Exceptions occurred when grain samples weighing less than three kg were milled completely. Milling was performed with constant settings to obtain different extraction rates for samples (Equation 2.5).

$$FlourYield = \frac{Weight\,of\ Flour}{Weight\,of\ Grain} \times 100\% \qquad (2.5)$$

Flour from each grain sample was divided into several smaller bags weighing approximately 500g. The flour was then stored at room temperature and allowed to rest for one month before the beginning of flour quality analysis. The remaining 500g flour samples not being used for immediate analysis were stored for future use at -20ºC to inhibit enzyme activity after milling.

Flour Protein Flour protein content was determined by the Grain Research Laboratory in Winnipeg, MB. Total flour protein content was determined by combustion nitrogen analysis (CNA) using a LECO instrument Model FP-428 (LECO Corp., St. Joseph, MI). In this test flour samples are incinerated at extremely high temperature to convert all the nitrogen from its natural form in the flour to elemental nitrogen, which is subsequently measured by a thermal conductivity cell. Protein content was then determined by multiplying the measured level of nitrogen by 5.7 (Williams et al., 1998) Flour protein content was expressed on a basis of flour at 14% moisture basis.

Flour protein composition was determined by selective fractionation in different solutions of 50% 1-propanol (Sapirstein and Johnson, 2001). The first extraction using 50% 1-propanol obtained monomeric proteins (specifically albumins, globulins, gliadins and low molecular soluble glutenin). Then using the 0.1% DTT additive it was possible to obtain the insoluble HMW-glutenin fraction. The remaining insoluble portion of protein is referred to as residue protein, consisting of large, non-nitrogen-storage proteins. Each protein fraction was expressed as a percentage of total flour protein content at 14% moisture content.

Pentosans Total pentosan content in wheat was determined according to procedures outlined by Douglas (1980). This method was chosen because of its nature as a rapid determination of wheat pentosans relative to the traditional Tollens method of pentosans analysis (Fraser et al., 1956) while obtaining consistent, reliable results.

Flour Ash Flour ash is a measurement of mineral content in the flour. To determine flour ash content, 3 g of flour was heated for 4 hours at 590ºC. The remaining ash was weighed and expressed as a percentage of the original 3 g weight of flour (Equation 2.6).

$$\% Ash = \frac{Weight\ of\ Ash}{Weight\ of\ Flour} \times 100\% \tag{2.6}$$

Rapid Visco Analyzer

Measurement of flour pasting properties was conducted using a Rapid Visco^{TM} Analyser (RVA) produced by Newport Scientific Pty. Ltd. The procedure was conducted according to profile Standard 1 (STD1) as outlined in the Applications Manual for the Rapid Visco^{TM} Analyser (Newport Scientific Pty. Ltd., 1998). The STD1 procedure requires 3.5 g of flour to be mixed with a 25 mL solution of distilled water. For this procedure the distilled water was mixed with silver nitrate ($AgNO_3$) to eliminate α-amylase activity in the flour (Crosbie et al., 1999). An exception to the Crosbie et al. (1999) method was the use of 0.4 mM $AgNO_3$ instead of the recommended 0.1 mM to ensure no enzyme activity. Enzyme activity was eliminated from the procedure in order to have results that reflect the true starch characteristics of the flour.

RVA parameters measured included peak viscosity (RVA_Peak), trough viscosity (RVA_Trough), breakdown between peak viscosity and trough viscosity (RVA Breakdown), final viscosity (RVA_Final). A sample pasting curve and STD1 profile for the RVA can be seen in Appendix A.

2.3.5.3. Analysis of Dough Properties

10-gram Mixograph

A 10-gram mixograph with computerized analysis software recording torque/mixing resistance was used to evaluate the dough-mixing properties of the flour samples at constant absorption. The 10-gram mixograph was designed and produced by National Manufacturing in Lincoln, NE. A software package called Power to Mixing (P2M) was used to record the resistance to mixing (Roller, 2004). Dough mixing was performed on a constant dough basis using 10 grams of flour (corrected to 14% moisture) and 62% absorption of distilled water at 25°C for 8 minutes. Temperature was regulated during mixing using a water-jacketed mixing bowl kept at 25°C. Flours were mixed under the following settings: Mixograph speed 113 rpm; spring setting 12; sampling at 20 points sec^{-1}; top and middle curve smoothing values set at 499.

Data acquisition by the P2M software program creates a computer-generated dough mixing curve. The curve is generated based on the measure of torque (%) required to mix the dough in the mixing bowl. A sample mixogram is presented in Appendix A. Dough mixing time to peak (MTP) is the time (min) required to achieve peak dough resistance (PDR), or height of the mixogram (%torque). Work input to Peak (WIP) is the area under the dough development curve from time 0 to time of peak development (expressed as %torque*min). Peak Bandwidth (PBW) is the width of the mixing curve at peak development and is expressed as (%torque).

Farinograph

The farinograph is one of the most commonly used methods for flour quality analysis. In this experiment the Brabender farinograph was utilized according to the AACC approved methods Method 54-21 (AACC, 2000). Variables resulting from this analysis include dough development time (DDT), optimal water absorption (FarAbs), farinograph stability (FarStab), and mixing tolerance index (MTI). A sample farinogram can be seen in Appendix A.

Micro-Extension Test

A TA.XT2*i* texture analyzer with fitted Kieffer rig (Texture Technologies, Inc., Scarsdale, NY; Stable Microsystems, SMS, Surry, UK) was used to measure dough extensibility as described by Smewing (1995) with small modifications. Dough was prepared with the 10-gram mixograph as described previously except for some modifications. Salt was added to the dough before the addition of distilled water at a rate of 2% of the flour weight. Mixing speed was changed to 113 rpm from 91 rpm by changing the pulley with a diameter of 50 mm to a pulley with a diameter of 70mm. These new settings were chosen because of the enhanced reproducibility of extension curves that resulted (see Appendix G).

A preliminary run on the mixograph was performed to determine time for peak dough resistance. The mixing process was then repeated with mixing halted at 10% past MTP. The dough was removed from the mixograph pins and mixing bowl using a wooden spatula lubricated with paraffin oil. Two drops of paraffin oil was added to the palm of each hand before rolling the dough into a cylinder with 4 gentle rotations. The cylinder of dough was then placed onto a sheet of Teflon paper. The dough was rolled out using a customized roller, lubricated with paraffin oil. The flattened dough was then formed into strips using a Teflon block apparatus lubricated with Crisco™ oil. Each Teflon block yielded 6 dough strips. The dough was then allowed to rest for 60 minutes in a controlled environment of 30˚C and 85% relative humidity.

The extension analysis was carried out by removing a dough strip from the Teflon block and loading it onto the Kiefer rig apparatus. Once a strip was removed, the remaining strips on the Teflon block were placed into an oven at 30˚C to maintain consistency among dough strips. The dough strip was then pulled by a hook located on the texture analyzer at a rate of 3 mm sec^{-1} until the dough piece was torn. During the extension process, a computerized extensigram was generated using Texture Expert for Windows Version 1.0 software (Stable Microsystems Inc. ,1995) with the following settings; pre-test speed 3 mm sec^{-1}, trigger force 5 g; test speed 3 mm sec^{-1}, post-test speed 10 mm sec^{-1}, data acquisition rate 200 pps. A sample extensigram is presented in Appendix A. Maximum resistance to mixing (Rmax, expressed in g) is a measure of dough resistance to extension. Dough extension (E, expressed in mm) is a measure of dough extensibility at dough rupture. Extensigraph area (EA) is measured as an integral of resistance to mixing over time.

2.3.5.4. Analysis of Bread Properties

Wheat quality analysis concluded by baking the wheat flour into bread. Flour was baked using the American Association of Cereal Chemists long bake method as outlined in AACC Method 10-10B (AACC, 2000) with the exception of using Fleishhman's quick rise dry yeast instead of compressed yeast. The formulation included 100 g of flour, 6 g of sugar, 1.5 g of salt, 0.75 g of yeast, 4 g of whey, 3 g of shortening, and water to optimal water absorption level as determined by the farinograph. All ingredients measurements were performed at a 14% moisture basis. Full formula mix times were recorded. Loaf volume was measured appropriate cooling by rapeseed displacement.

2.3.6. Statistical Analysis

Statistical analysis was performed on the dataset according to procedures outlined in the SAS Institute Inc User Guide (2001). Determination of the best suited explanatory variable for each dependent variable was done by performing a regression using the MaxR option to select the explanatory variable providing the highest R^2 value. Once a relationship model was found the variables were tested for normality. Normally distributed variables were reported in the original form while non-normally distributed variables were transformed. The box-cox method was used to find the most appropriate exponent for data transformation into a normal distribution. Once a non-normal variable had been transformed, the transformed variable was sent through the regression process using MaxR analysis again to determine if the transformed variable still yielded the strongest R^2 value. The MaxR analysis was run again to determine which three environmental variables in a multiple regression provided the highest R^2 value.

2.4. Results and Discussion

2.4.1. Grading of Grain Samples

The 2003 and 2004 growing seasons were very dissimilar. In 2003, conditions were generally hot and dry across the Canadian Prairies and 82.1% of the grain samples graded #1 and #2 CWRS by the Canadian Grain Commission (CGC). In 2004, the weather was unusually cool, and in some locations, very wet and only 17.5% of the grain samples graded #1 and #2 CWRS.

In 2003, 95 of the collected grain samples received official grades from the CGC. A breakdown of the growing location of samples in the project can be seen in Table 2.2. Some additional samples were collected from growers but were removed from the project due to problems with data collection either during the growing season or at time of harvest.

Chad, the numbers in this paragraph do not match those shown in Figure 2.1. Please correct either this paragraph or Figure 2.1

For the 2003 crop year, 46 of the samples collected were AC Barrie and 49 were Superb. Thirty-eight of the 46 AC Barrie samples graded #1 and 4 graded #2 (Figure 2.1). In other words, 82.6% of the AC Barrie samples grown in 2003 were graded to #1 CWRS and 8.7% graded to #2 CWRS. The remaining samples were graded #3 or poorer. Thirty-six of the 49 (73.5%) Superb samples graded #1 CWRS and 6 (12.2%) graded #2 CWRS.

In 2004, 103 grain samples (42 AC Barrie, 61 Superb) received an official grade by the CGC (Table 2.2). There was a trend towards more Superb growers in the project in 2004 reflecting the growing popularity for Superb. This was especially true in Alberta due to the lack of fusarium pressure in the area, a disease to which Superb is more susceptible than AC Barrie.

Table 2.2: Growing location distribution by province of all samples collected for study.

	AC Barrie		Superb	
Province	2003	2004	2003	2004
Alberta	14	13	14	24
Saskatchewan	23	21	27	27
Manitoba	9	8	8	10
Total	46	42	49	61

For 2004, 4 of the 42 (9.5%) AC Barrie grain samples received a grade of #1 CWRS and 6 (14.3%) received a grade of #2 CWRS. Four of the 61 (6.6%) Superb grain samples received a grade of #1 CWRS and 6 (9.8%) received a grade of #2 CWRS. The remaining samples received grades of #3 CWRS or poorer.

It should be noted that some of the wheat crops in this study were grown under irrigation. Further analysis of these samples revealed a weakening of the dough during the mixograph (specifically increased breakdown) that was consistently observed only for samples grown under irrigation. Therefore, these samples were removed from the analysis because of the confounding factors resulting from this observation. A list of samples removed under this premise included three AC Barrie samples (two #1's from 2003 and one #1 from 2004) and five Superb samples (three #1's from 2003, one #2 from 2003, and one #1 from 2004).

The spatial distribution of samples used for analysis in this chapter can be seen in Figure 2.2. The samples included on this map are those receiving a grade of either #1 or #2 CWRS and not grown under irrigation.

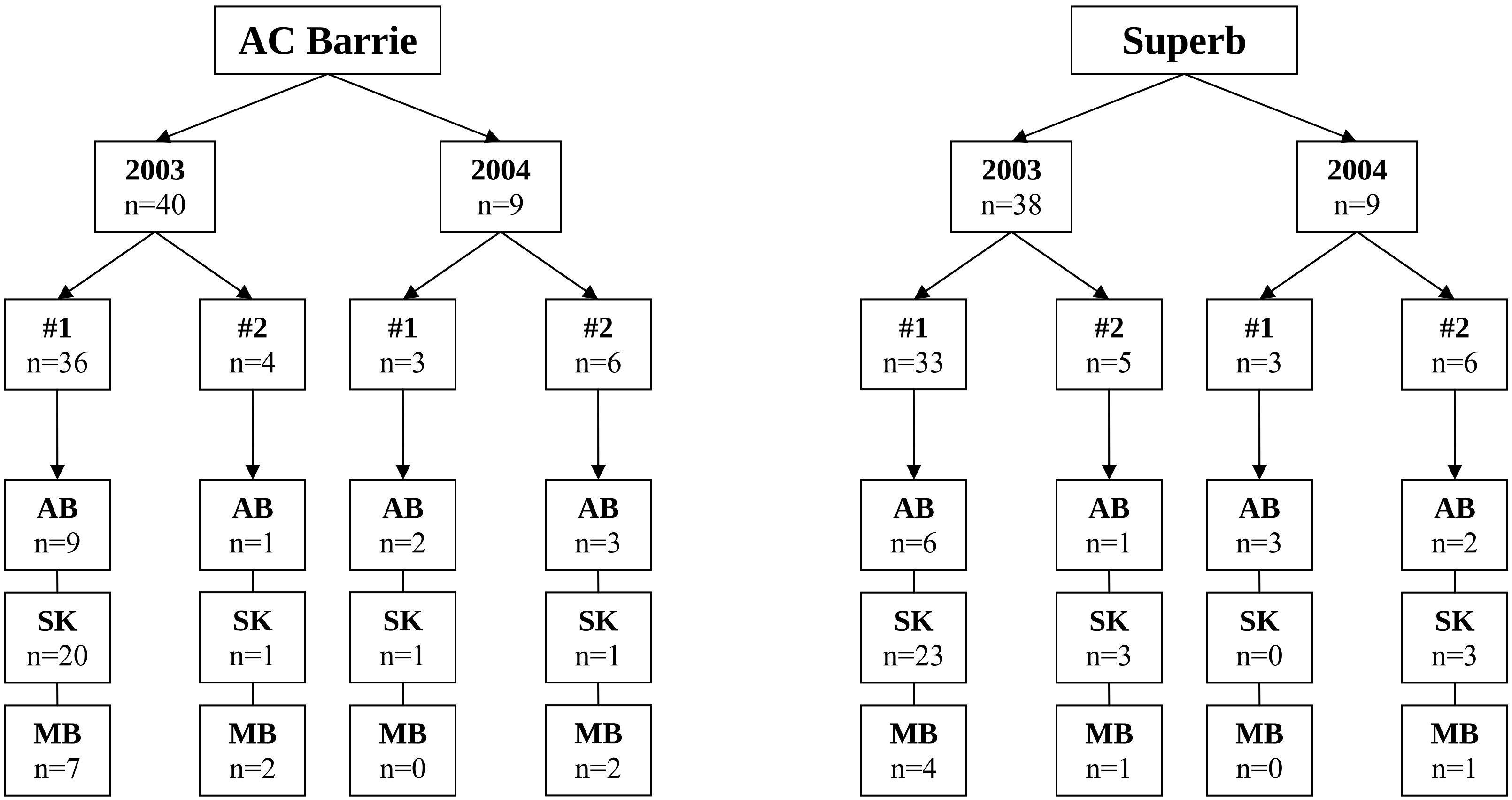

Figure 2.1: Flow chart displaying breakdown of samples graded and used in this analysis by cultivar (AC Barrie, Superb), growing season (2003, 2004), official CWRS grade (#1, #2), and growing location (AB=Alberta, SK=Saskatchewan, MB=Manitoba).

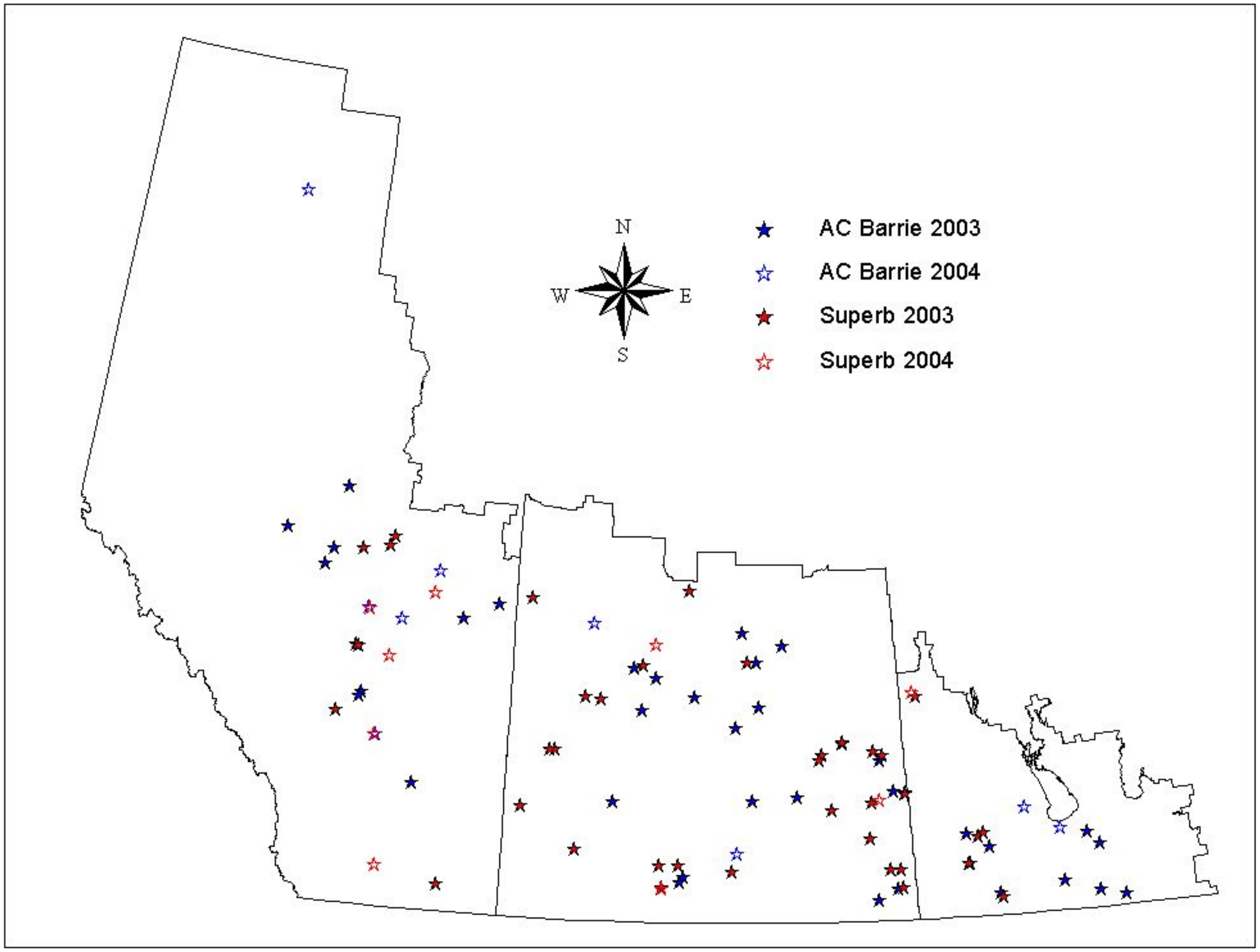

Figure 2.2: Field site locations for AC Barrie and Superb wheat samples receiving grades of either #1 or #2 CWRS and not grown under irrigation conditions in 2003 and 2004.

2.4.2. Growing Season Conditions

The nature of the two growing seasons created a huge variation in growing conditions experienced by the wheat crops in the study.

Virtually none of the 2003 wheat grain samples experienced post-mature weather stress. Thus, the 2003 crop harvest was generally high quality. Unfortunately, a large majority of the wheat grain samples collected in 2004 were downgraded due to several post-mature weather conditions (mainly frost and immature/green). These samples downgraded due to post-mature weather stress had to be removed from the main analysis of the project since the purpose of this study was to investigate growing season weather impacts on wheat quality.

In general, 2003 was a hot, dry growing season that began with ample spring soil moisture conditions due to a wet fall in 2002 on most of the prairies. The growing season became especially hot and dry near the end of June and continued through the months of July and August. Some fields in south-western Saskatchewan received no precipitation after the last week of June. The average precipitation during the total growing season (anthesis to maturity) was 140.0 mm ± 70.3 for AC Barrie fields and 139.2 mm ± 56.8 for Superb fields in 2003. The average precipitation during the filling period (anthesis to maturity) was 27.7 mm ± 20.7 for AC Barrie fields and 24.2 mm ± 18.6 for Superb fields in 2003 (Table 2.3).

Heat units were calculated using growing degree days with a base of 5^{o}C to characterize the temperature differences between 2003 and 2004. In 2003, there was a total accumulation of 1639 growing degree days for AC Barrie and 1623 growing degree days for Superb during the entire growing season. During the filling period in 2003, there was an accumulation of 516 growing degree days for AC Barrie and 508 growing degree days for Superb (Table 2.4).

Farmer cooperators reported dates of 50% anthesis occurred in the first two weeks of July for nearly all fields in 2003. In 2003, the average length of the growing season (planting to maturity), for AC Barrie was 95.0 days and 93.5 days for Superb. The average filling period (anthesis to maturity) in 2003 for AC Barrie was 33.4 days and 32.5 days for Superb in 2003 (Table 2.5).

The 2004 growing season was cool and wet but began with deficient spring soil moisture conditions. Seeding was delayed in most parts of the prairies by wet, rainy weather and cool, unfavorable spring temperatures for soil drying and warming. The conditions of rainy weather and cool temperatures continued throughout most of the growing season for a vast majority of fields in this project. The average precipitation during the total growing season of 2004 was 291.5mm ± 92.6 for AC Barrie fields and 305.8mm ± 50.8 for Superb fields. The average precipitation during the filling period of 2004 was 103.8mm ± 38.0 for AC Barrie fields and 98.1mm ± 27.8 for Superb fields (Table 2.3).

In 2004 the growing season was much cooler than 2003. The average accumulated growing degree days for the entire growing season was 1283 for AC Barrie and 1257 for Superb. For the filling period there was an average accumulation of 516 growing degree days for AC Barrie and 438 growing degree days for Superb (Table 2.4). The average accumulated growing degree days for AC Barrie was the same between the filling periods for 2003 and 2004. However, it should also be considered that the filling period was 20 days longer in 2004 for these AC Barrie fields. Thus, the amount of time taken to accumulate 516 growing degree days during the filling period was nearly 3 weeks longer in 2004 than 2003. This is a good indicator of the temperature differences between 2003 and 2004.

In 2004, farmer cooperators reported dates of 50% anthesis to occur between the second and fourth week of July. The average total growing season length of 2004 for AC Barrie was 124.5 days and 124.7 days for Superb. The average filling period for AC Barrie was 53 days and 47.7 days for Superb (Table 2.5). To emphasize the length of this growing season, in 1992 the average temperature in Winnipeg was 15.73°C for June, July and August (the coldest on record up to 2004). In 1992, the wheat cultivar Katepwa required 106.5 days to mature (C. Shaykewich, Univ of Manitoba, personal communication). Katepwa is rated to mature 2 days earlier than AC Barrie according to the Manitoba Seed Guide (2004). This should help to illustrate the abnormal length and , cool temperatures of the 2004 growing season in western Canada.

There was not a significant difference between AC Barrie and Superb for mean precipitation, accumulated GDD, and length of the growing season for either the full season or filling period accumulation in 2003 or 2004. However, there were significant differences between years for these three growing season characterization variables. The total growing season precipitation for 2004 was 214% of the total growing season precipitation of 2003 and the filling period precipitation of 2004 was 390% of the filling period precipitation of 2003.

It should be noted, that these comparisons are based solely on the growing conditions reported for samples receiving a grade of #1 or #2 CWRS. Many of the samples graded poorer than #1 or #2 CWRS in northern Alberta in 2004 and experienced ever higher amounts of rainfall during the late stages of the filling period.

Table 2.3: Mean and standard deviation precipitation (mm) measurements accumulated during different growth stages for 2003 and 2004 growing seasons.

	AC Barrie				Superb			
	2003		2004		2003		2004	
Staging	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total Season	139.4	70.3	291.5	92.6	139.2	56.8	305.8	50.8
Filling Period	27.7	20.7	103.8	38.0	24.2	18.6	98.1	27.8

Table 2.4: Mean and standard deviation heat units (GDD_5All) accumulated during different growth stages for 2003 and 2004 growing seasons.

	AC Barrie				Superb			
	2003		2004		2003		2004	
Staging	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total Season	1639.4	157.1	1282.5	155.0	1623.5	172.5	1256.8	219.7
Filling Period	516.0	99.4	515.9	132.3	507.8	108.6	438.4	153.2

Table 2.5: Mean and standard deviation length of growing season and filling period (days) for 2003 and 2004.

	AC Barrie				Superb			
	2003		2004		2003		2004	
Staging	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total Season	95.0	8.8	124.5	15.6	93.5	15.5	124.7	15.5
Filling Period	33.4	6.2	53.0	10.0	32.5	5.9	47.7	12.5

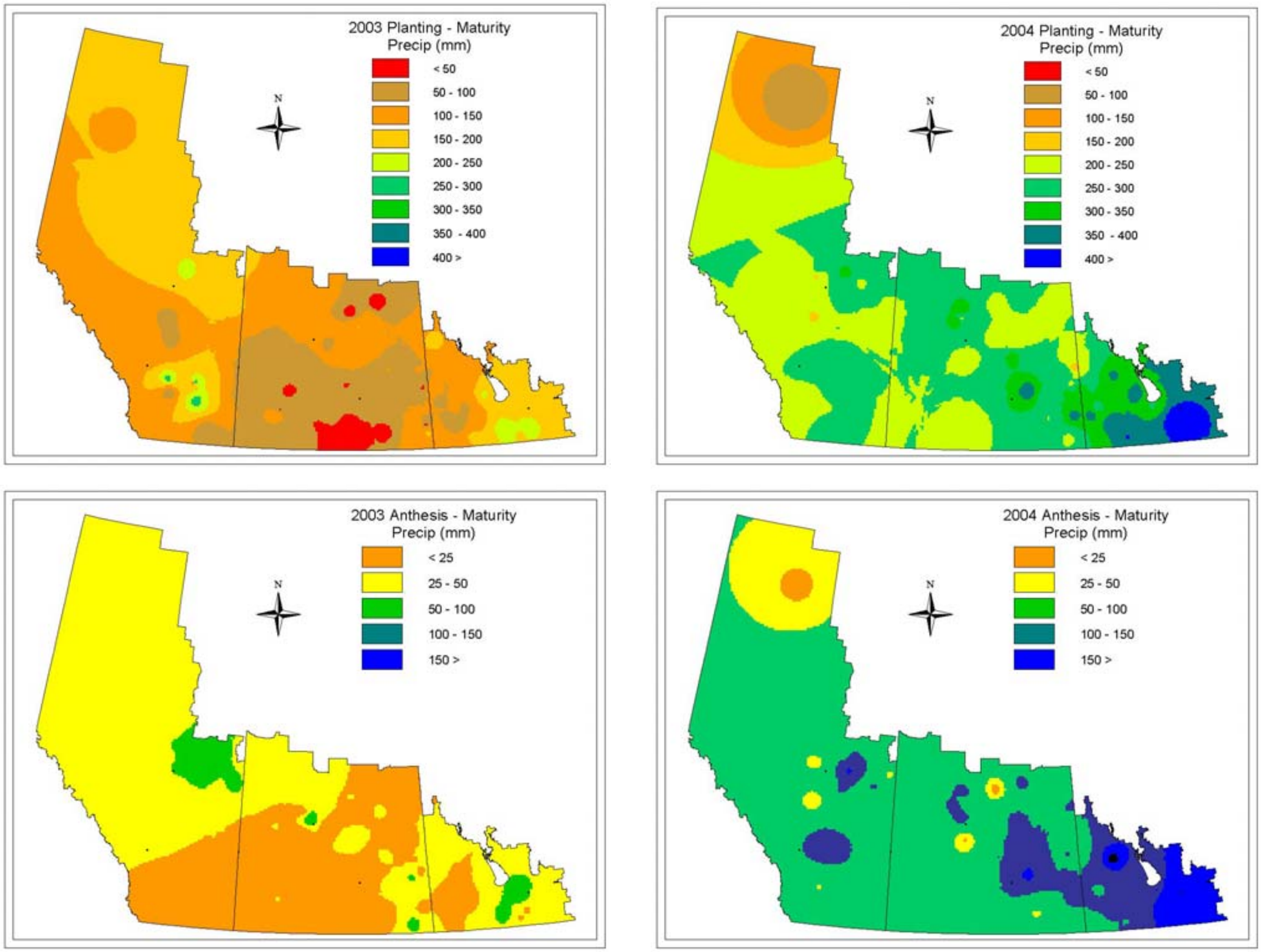

Figure 2.3: Thematic maps displaying precipitation spatial distribution across Canadian Prairies during periods of planting to maturity and anthesis to maturity for 2003 and 2004 growing seasons.
Note: Using data from fields in Figure 2.2.

2.4.3. Analysis of Quality Parameters

Many measurements of grain, flour, dough, and bread quality were taken to establish a good understanding of the impacts of growing season environmental variation on end-use quality. Analysis of these parameters demonstrated significant differences of means between cultivars and between years for several of the parameters.

Grain property analysis included grain protein content, test weight, thousand kernel weight (TKW), and grain yield (Table 2.6). AC Barrie had a significantly lower average TKW than Superb. This was clearly evident visually with Superb samples received from growers as they had very large kernel size and could have been mistaken as a Canada Western Extra Strong cultivar. The 2004 growing season produced significantly higher TKWs and yields than 2003.

Flour property analyses included investigation of flour protein content, flour fractionation, total pentosan content, analysis of starch data through a rapid viscous analyzer (RVA), flour ash content, and flour yield. AC Barrie had significantly higher soluble protein content and total pentosan content than Superb while having a significantly lower RVA breakdown. In, 2004 there were significantly higher average levels of soluble protein and HMW-glutenin than for 2003 while 2003 produced significantly higher total pentosan content than 2004. The RVA peak, trough, and final viscosities were significantly higher for 2003 than for 2004 (Table 2.6).

In 2004, Superb had a flour yield that was 3% lower than the extraction rate for both Barrie and Superb in 2003 and Barrie in 2004. The CV was also higher than normal (6.4) (Table 2.6). There appeared to be no reason for this odd flour yield and, thus, further investigation of Superb flour yields over additional years should be conducted to determine the nature of this irregularity.

Dough property analysis was investigated on the farinograph, 10-gram mixograph, and extensigraph. From the 10-gram mixograph , Superb had significantly higher peak dough resistance (PDR) and significantly more breakdown than AC Barrie. However, there was not a significant difference in the non-weighted breakdown variable (PDR_BR3) between cultivars. It is likely that the weighted breakdown was significant because of the nature of its calculation which includes PDR_BR3 * PDR. The bandwidth at peak for the 2004 samples was significantly higher than that for the 2003 samples (Table 2.6).

Superb had significantly higher farinograph absorption levels (FarAbs), longer dough development time (DDT), and longer farinograph stability (FarStab) than AC Barrie. In 2003, the samples had significantly higher FarAbs, longer DDT, longer FarStab, and better farinograph mixing tolerance time (FarMTI) (lower number is better) than 2004 (Table 2.6).

A third measure of dough strength was measured with the extensigraph. AC Barrie had significantly higher resistance to extension (Rmax) and longer extension (E) than Superb. There was also a year effect with 2003 having a significantly higher Rmax and a significantly higher EA than 2004 (Table 2.6).

Bread quality was assessed by measuring bread loaf volume and full formula mix time. Superb produced a higher average loaf volume than AC Barrie in both years. However, the full formula mix times between AC Barrie and Superb were very similar in 2003 and in 2004. Thus, if we look at some of the key characteristics of AC Barrie and

Superb that a miller or baker are interested in when purchasing wheat, we see that Superb has a similar full formula mix time to AC Barrie but does have a higher absorption rate and eventual loaf volume. This is very important observation since, typically, grain buyers are advised to purchase higher protein wheat to achieve increased absorption rates and loaf volumes. However, despite having a similar average protein content, Superb outperformed AC Barrie in terms of absorption rates and loaf volume. Therefore, there must be variables other than protein content contributing to Superb's superior absorption rates and loaf volume.

Table 2.6: Mean and distribution statistics for grain, flour, dough and bread properties.

A: Grain property means and distribution statistics.

	Mean				Coefficient of Variation			
	Barrie		Superb		Barrie		Superb	
	2003	2004	2003	2004	2003	2004	2003	2004
Protein (%)	14.4	13.9	13.9	13.7	9.0	9.6	8.4	9.8
Test Weight (kg hL^{-1})	82.2	81.7	82.2	81.6	2.8	1.2	2.3	2.9
TKW (g) [V Y]	32.4	35.9	36.7	40.7	11.0	10.0	11.1	11.2
Yield (bu ac^{-1}) [Y]	40.9	51.3	44.9	55.4	35.6	26.7	30.0	22.6

B: Flour property means and distribution statistics.

	Mean				Coefficient of Variation			
	Barrie		Superb		Barrie		Superb	
	2003	2004	2003	2004	2003	2004	2003	2004
Flour Protein (%)	13.3	13.3	13.0	13.0	9.6	11.0	9.2	10.9
Soluble Protein (%) [V Y]	8.8	9.6	8.4	9.1	9.1	10.2	10.3	9.5
HMW-glutenin (%) [Y]	3.4	3.6	3.4	3.6	9.1	11.1	11.4	9.7
Pentosans (%) [V Y]	1.8	1.6	2.0	1.7	12.8	11.7	15.6	7.0
RVA Peak Visc (cP) [Y]	2706	2602	2642	2609	4.3	4.3	4.3	4.0
RVA Trough Visc (cP) [Y]	1717	1607	1732	1675	3.2	6.4	3.8	5.4
RVA Breakdown (cP) [V]	990	995	910	935	10.2	11.6	10.7	15.6
RVA Final Visc (cP) [Y]	3103	2844	3085	2936	2.4	5.5	2.7	4.9
Ash (%)	0.42	0.38	0.41	0.46	10.3	9.5	7.3	11.7
Flour Yield (%)	71.6	71.3	71.3	68.3	2.6	3.5	3.2	6.4

C: Dough property means and distribution statistics.

	Mean				Coefficient of Variation			
	Barrie		Superb		Barrie		Superb	
	2003	2004	2003	2004	2003	2004	2003	2004
Mixograph								
MTP (min)	2.8	2.9	2.6	2.4	16.6	26.0	18.4	20.6
PDR (% torque) [V]	52.6	55.0	55.0	59.0	10.5	15.1	9.6	10.5
PBW (% torque) [Y]	20.4	23.3	20.4	24.5	20.7	20.2	17.5	16.8
PDR_BR3 (% torque)	71.2	70.4	70.2	68.6	4.9	7.7	3.5	4.6
PDR_BR3weighted (% torque) [V]	3732	3837	3850	4037	7.3	9.7	7.7	6.9
WIP (min * % torque)	98.7	108.6	97.9	97.9	13.4	15.1	15.0	22.3
Farinograph								
FarAbs (%) [V Y]	62.4	59.8	65.1	62.3	2.5	1.5	2.4	2.3
DDT (min) [V Y]	6.5	4.4	8.1	5.5	27.1	31.8	37.3	34.6
FarStab (%) [V Y]	16.5	8.7	22.1	9.2	44.5	37.9	40.2	60.2
FarMTI (% * min) [Y]	29.8	54.4	24.0	51.1	30.7	50.0	44.8	34.9
Extensigraph								
Rmax (g) [V Y]	32.2	27.0	30.0	23.6	15.3	15.1	20.9	15.8
Extensibility (E) (cm) [V]	117.1	108.6	122.3	118.5	7.5	14.3	9.0	11.9
EA (g * cm) [Y]	2065	1622	2100	1610	16.5	17.9	19.5	13.5

Table 2.6 cont'd								
D: Bread property means and distribution statistics.								
	Mean				Coefficient of Variation			
	Barrie		Superb		Barrie		Superb	
	2003	2004	2003	2004	2003	2004	2003	2004
Loaf Volume (cc) [V]	976	925	1024	988	6.78	13.0	7.49	9.2
Full Formula Mix Time (min)	4.1	4.2	4.1	3.9	11.48	21.7	14.34	20.4

[V] = Significant varietal difference of means over both years ($Pr < 0.05$).
[Y] = Significant year difference of means over both cultivars ($Pr < 0.05$).

2.4.4. Nitrogen Impacts on Wheat Quality

The impacts of nitrogen on wheat yield and quality was investigated so that fields with lower than optimum nitrogen status growing conditions could be removed from the analysis. However, an investigation into the relationships between field nitrogen status and wheat yield and protein content found no significant relationships (Appendix B). The fields may have been sufficiently fertilized to a non-limiting nitrogen status. The growers involved in the study were progressive farmers and very aware of the consequences for an under-fertilized field. In any case, the fields could not be stratified into separate nitrogen regimes for the environmental impacts on wheat quality.

2.4.5. Prediction of Quality Parameters using Basic Environmental Variables Measured Over Entire Growing Season

This analysis was conducted to determine how much of the variation for each of the quality parameters could be explained using only basic environmental parameters measured daily but aggregated for the entire growing season. The environmental parameters used in this analysis (called basic environmental parameters) are those calculated from daily maximum and minimum temperatures and daily rainfall measurements. In other words, no derived water-use parameters were used in this analysis.

In this analysis, and in those to follow later in this chapter, AC Barrie and Superb were examined separately despite possessing the statistical characteristics to be analyzed together according to homogeneity of variance and homogeneity of slope. This was done because there were differences between AC Barrie and Superb, in terms of their relationship to related independent variables as discussed in the following sections.

Several quality variables showed significant relationships for one cultivar but not the other when analyzed with basic environmental parameters accumulated over the entire growing season (Table 2.7). Those quality variables with non-significant relationships for AC Barrie while having a significant relationship with Superb included RVA peak viscosity, flour yield, mixograph MTP, baking full formula DDT. Those quality variables with non-significant relationships with Superb while having a significant relationship with AC Barrie included grain and flour protein content, RVA trough viscosity, extensigraph maximum extension, and loaf volume. The strongest protein variable relationship with a basic environmental parameter was AC Barrie flour protein content with an R^2 of 0.28. Superb flour protein content was not significantly related with any of the basic environmental parameters used in this analysis (Figure 2.4). This is important because, as shown in the upcoming section, protein content and protein compositional variables were the main driving force for predicting the technological properties of dough and bread.

The strongest relationship between dough properties and the basic environmental parameters accumulated over the entire season was for extensigraph parameter EA and

Days_All for Barrie (R^2 = 0.44) (Table 2.7). For dough variables, only mixograph MTP for AC Barrie and WIP for both cultivars didn't exhibit a significant relationship with any of the basic environmental parameters.

Another important difference between the two cultivars was the nature of the environmental parameters that were significantly related with quality parameters. The dependent variables for AC Barrie were explained by useful heat independent variables (Pdays and GDD) 16 times. This compares to only five dependent quality variables explained by useful heat for Superb. However, Superb had 14 dependent variables explained by temperature stress variables (stress days and stress degrees) while AC Barrie had only six. A second difference noted between the two cultivars was that Superb appeared to have a higher temperature threshold than AC Barrie with temperature stress variables. The average temperature stress threshold for Superb was 22.4˚C while the average temperature stress threshold for Barrie was 20.3˚C.

Several of the Pday combinations shared similar threshold values between closely related quality parameters. For example, all the RVA parameters with a Pday explanatory variable have the lowest possible maximum temperature threshold (27˚C). This threshold was also present with other quality variables traditionally associated with wheat starch, including TKW, test weight, and yield. As expected, grain protein content and flour protein content share similar Pday variables as explanatory variables. These two Pdays ($Pdays_{5\text{-}21\text{-}32}$All for grain protein and $Pdays_{5\text{-}25\text{-}35}$All for flour protein) both had 5˚C as their minimum threshold and 32˚C as their maximum threshold. However, there was a difference between the two protein fractions. While both soluble protein and HMW-glutenin fractions both had minimum and optimum thresholds of 7˚C and 25˚C, respectively, soluble protein had a higher maximum threshold of 35˚C compared to HMW-glutenin maximum threshold of 30˚C. Another important observation was that over half (9 of the 17 total) of different Pday combinations found in Table 2.7 had a minimum temperature threshold of 7˚C. This means that temperatures below 7˚C did not have a significant effect on the majority of wheat quality parameters.

Useful heat variables $Pdays_{5\text{-}21\text{-}32}$All and $Pdays_{5\text{-}25\text{-}35}$All showed negative coefficients with grain protein and flour protein, respectively, for AC Barrie. This was as expected since more useful heat is beneficial to starch synthesis, which results in a lower percentage of protein content measured as a percentage of total wheat/flour weight. However, knowledge about the timing of this useful heat effect was needed to properly understand the impact of useful heat on AC Barrie protein. The growing season is divided and analyzed later in this section.

Heat stress was expected to be detrimental to starch synthesis. This would decrease the amount of starch present in flour and, thus, increase the relative amount of protein in the flour. Therefore, a positive relationship between heat stress parameters and protein content was expected. Again, the timing of the heat stress variable was the most important factor determining if this relationship had a positive or negative coefficient. A better understanding is possible only by dividing the growing season to determine the sensitive growing stage of the crop. Other quality parameters with similar responses to the level of starch included pentosans and protein compositional factors.

In general, only weak to moderate relationships existed between basic environmental parameters aggregated for the entire growing season and quality parameters. These variables reveal little about the timing of specific environmental conditions during the growing season (an example is “When in the growing season did the period of heat stress above 27°C impact flour protein levels in a inverse manner?”). Therefore, the growing season was divided into four stages of development in an attempt to improve the strength of relationships and to determine periods of sensitivity for each quality parameter and the environment.

Table 2.7: The single basic environmental parameter accumulated over the entire growing season that explained the highest level of variance for each grain (A), flour (B), dough (C), and bread (D) quality variable.

A

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Protein	AC Barrie	$Pdays_{5-21-32}$All	0.25**	Protein = -0.009* $Pdays_{5-21-32}$All + 21.71
	Superb	StressDeg_All	0.02^{ns}	
TKW	AC Barrie	$Pdays_{7-17-27}$All	0.45***	TKW = 0.0323* $Pdays_{7-17-27}$All + 11.52
	Superb	$Pdays_{3-20-27}$All	0.30**	TKW = 0.029* $Pdays_{3-20-27}$All + 16.78
Test_Weight	AC Barrie	$Pdays_{7-22-27}$All	0.23**	Test_Weight = 0.012* $Pdays_{7-22-27}$All + 74.45
	Superb (non normal)	Rain_all	0.11*	Test_Weight = -0.008*Rain_All + 83.42
Yield	AC Barrie	$Pdays_{7-22-27}$All	0.47***	Yield = 0.17* $Pdays_{7-22-27}$All - 65.96
	Superb	S_t30_all	0.29**	Yield = -0.703*S_t30_All + 58.75

B

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Flour Protein	AC Barrie	$Pdays_{5-25-32}$All	0.28**	Flour Protein = -0.01* $Pdays_{5-25-32}$All + 20.45
	Superb	S_t16_All	0.07^{ns}	
Soluble Protein	AC Barrie	$Pdays_{7-25-35}$All	0.17**	Soluble Protein = -0.006* $Pdays_{7-25-35}$All + 12.66
	Superb	Trange_avg_All	0.11*	Soluble Protein = -0.25*Trange_avg_All + 11.96
HMW-glutenin	AC Barrie	$Pdays_{7-25-30}$All	0.16*	HMW-glutenin = -0.002 $Pdays_{7-25-30}$All + 4.84
	Superb	S_t17_All	0.10*	HMW-glutenin = -0.09*S_t17_All + 4.52
Pentosans	AC Barrie	S_t22_All	0.17**	$(Pentosans)^2$ = 0.024*S_t22_All
	Superb	Days_All	0.24**	$(Pentosans)^2$ =-0.04*Days_All + 7.63
RVA_Peak	AC Barrie	$Pdays_{7-25-27}$All	0.05^{ns}	
	Superb	StressDeg_All	0.17**	RVA_Peak = -2.04* StressDeg_All + 2675.40
RVA_Trough	AC Barrie	Days_All	0.21**	RVA_Trough = -2.38*Days_All + 1930.52
	Superb	S_t17_All	0.08^{ns}	
RVA Breakdown	AC Barrie	$Pdays_{7-20-27}$All	0.25**	RVA Breakdown = 0.703* $Pdays_{7-20-27}$All + 528.90
	Superb	Trange_avg_All	0.16*	RVA Breakdown = -31.34*Trange_avg_All + 1336.90

Table 2.7 cont'd

RVA_Final	AC Barrie	$Pdays_{3-16-27}All$	0.50***	RVA_Final = -0.89* $Pdays_{3-16-27}All$ + 3706.17
	Superb	S_t18_All	0.29**	RVA_Final = 3.70*S_t18_All + 2639.40
Flour Yield	AC Barrie	Days_All	0.06^{ns}	
	Superb (non normal)	S_t18_All	0.21**	$(Flour\ Yield)^{0.5}$ = 0.005*S_t18_All + 7.89
Ash	AC Barrie	Days_All	0.20**	Ash = -0.0013*Days_All + 0.54
	Superb	$Pdays_{3-16-27}All$	0.30**	Ash = -0.0002* $Pdays_{3-16-27}All$ + 0.54

C

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Mixograph				
Mixing Time to Peak	AC Barrie	Days_All	0.07^{ns}	
	Superb	S_t27_all	0.17**	MTP = 0.004*S_t27_All + 0.77
Peak dough resistance	AC Barrie	$Pdays_{7-25-31}All$	0.24**	PDR = --0.05* $Pdays_{7-25-31}All$ + 84.86
	Superb	S_t26_All	0.29**	PDR = -0.143*S_t26_All + 62.93
Bandwidth at Peak	AC Barrie	S_t17_All	0.15*	PBW = -0.156*S_t17_All + 39.91
	Superb	S_t27_All	0.31**	PBW = -0.105*S_t27_All + 25.52
	Superb	S_t16_All	0.27**	PDR_BR2weighted = -13.60*S_t16_All + 5888.77
Breakdown at MTP+3min	AC Barrie	$Pdays_{7-25-28}All$	0.21**	PDR_BR3 = 0.03* $Pdays_{7-25-28}All$ + 52.58
	Superb	S_t23_All	0.23**	PDR_BR3 = 0.057*S_t23_All + 65.63
Weighted Breakdown 3	AC Barrie	$Pdays_{7-25-32}All$	0.19**	PDR_BR3weighted = -2.15* $Pdays_{7-25-32}All$ + 5123.30
	Superb	S_t27_All	0.22**	PDR_BR3weighted = -7.21*S_t27_All + 4184.17
Workinput to peak	AC Barrie	S_t19_All	0.05^{ns}	
	Superb	S_t15_All	0.04^{ns}	

Table 2.7 cont'd

Farinograph				
Farinograph Absorption	AC Barrie	S_t20_All	0.18**	FarAbs = 0.058*S_t20_All + 56.22
	Superb	Rain_All	0.17**	FarAbs = -0.009*Rain_All + 66.17
Dough Development Time	AC Barrie	$Pdays_{3-19-29}$All	0.32***	FarDDT = -0.01* $Pdays_{3-19-29}$All + 14.08
	Superb	Days_All	0.16**	Log(FarDDT) = -0.011*Days_All + 3.02
Farinograph Stability	AC Barrie	StressDeg_All	0.36***	FarStab = 0.204* StressDeg_All + 10.45
	Superb	$Pdays_{3-16-27}$All	0.29**	FarStab = -0.05* $Pdays_{3-16-27}$All + 56.04
Farinograph Mixing Tolerance	AC Barrie	S_t22_All	0.17**	$(FarMIT)^{-0.5}$ = 0.0009*S_t22_All + 0.112
	Superb	GDD_{10}All	0.41***	FarMIT = -0.05*GDD_{10}All + 72.79
Extensigraph				
Maximum Resistance	AC Barrie	Rain_All	0.27**	Rmax = -0.029*Rain_All + 35.88
	Superb	Days_All	0.24**	Rmax = -0.19*Days_All + 48.18
Maximum Extension	AC Barrie	$Pdays_{3-24-35}$All	0.41***	E^3 = -3399*Pdays_All_CB441 + 4140957
	Superb	$Pdays_{6-23-27}$All	0.10^{ns}	
Area under Ext. Curve	AC Barrie	Days_All	0.44***	EA = -16.13*Days_All + 3596.46
	Superb	Days_All	0.18*	EA = -11.52*Days_All + 3154.25

D

Loaf Volume	AC Barrie	$Pdays_{7-17-27}$All	0.29**	LV = -0.51* $Pdays_{7-20-27}$All + 1312.67
	Superb	StressDeg_All	0.06^{ns}	
Full Formula Mix Time	AC Barrie	StressDeg_All	0.02^{ns}	
	Superb	$Pdays_{3-17-27}$All	0.23**	Log(Baking_DDT) = -0.0007* $Pdays_{3-17-27}$All + 1.92

* = significant at p=0.05 level.
** = significant at p=0.01 level.
*** = significant at p<.0001 level.
ns = not significant at p=0.05 level.

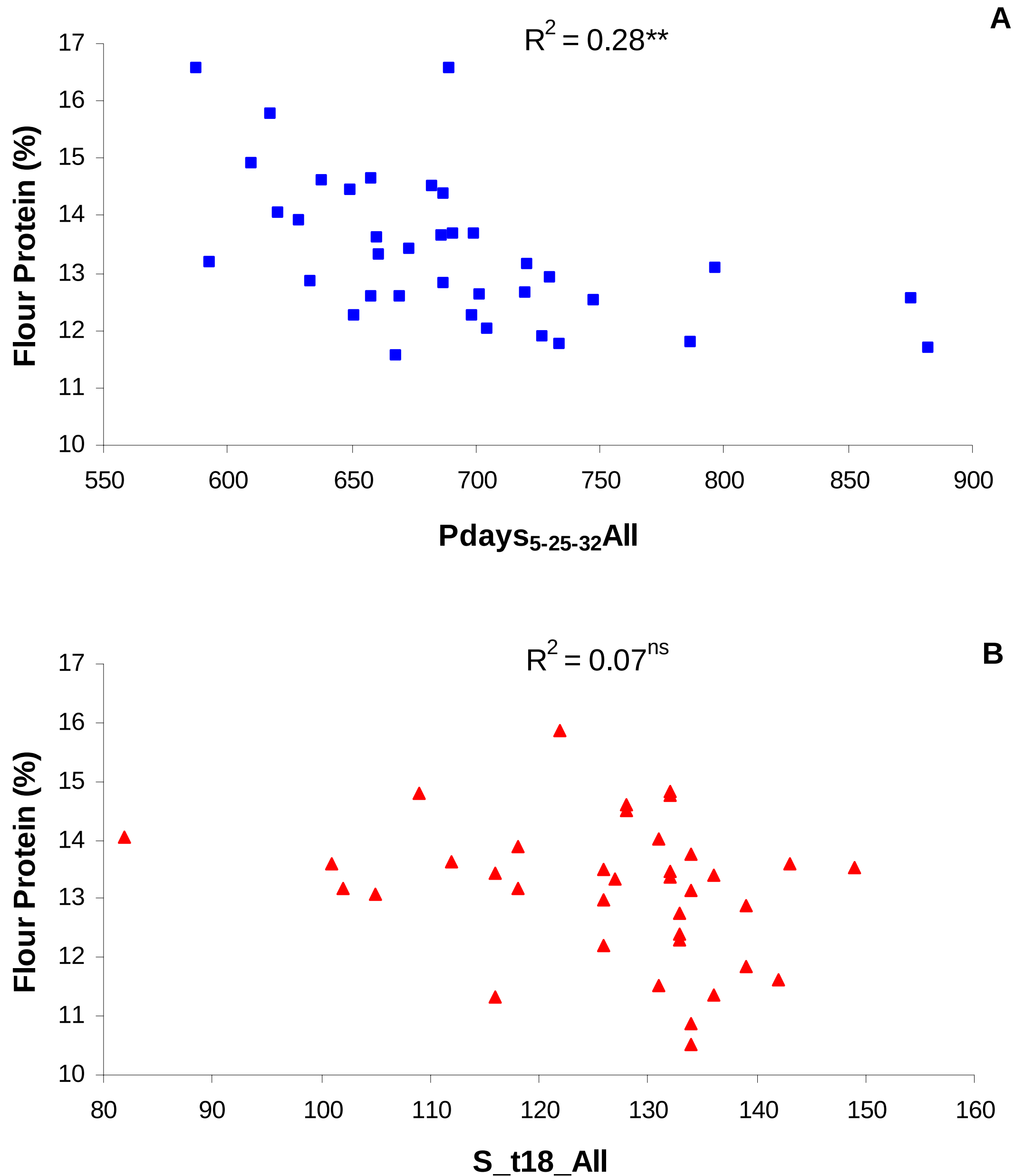

Figure 2.4: Effect of growing season weather variable $Pdays_{5\text{-}25\text{-}32}$All on flour protein content for AC Barrie (A). Effect of growing season weather variable S_t16_All on flour protein for Superb (B).

2.4.6. Prediction of Quality Parameters using Basic Environmental Variables Accumulated during Different Stages of the Growing Season

Dividing the growing season into four periods was successful in improving the strength of relationships between basic environmental variables and many quality parameters. This process improved our ability to recognize possible sensitive periods in grain development for most of the quality variables.

Prediction of AC Barrie grain and flour protein content by basic environmental parameters did not improve by dividing up the growing season. However, the relationship between Superb grain and flour protein content and basic environmental parameters was improved and was significant (Table 2.8). Other notable improvements in protein variable prediction by dividing up the growing season included Superb soluble protein fraction and Superb HMW-glutenin.

It is important to note the direct versus inverse relationship between each of the environmental parameters and the protein variables. Any useful heat measurements, including growing degree days and Pdays, had an inverse effect on protein variables. The exception occurred when the specified growing season staging was Anth_Mat_Grp1 (first half of stage from anthesis to maturity). This period coincided with the period of most rapid protein synthesis that occurred during the first three weeks after anthesis (Panozzo et al., 2001). The earliest stage after anthesis is the period when most of the plant nitrogen assimilates would be present in the grain kernel and awaiting to be assimilated into proteins (Bushuk and Wrigley, 1971). Thus, stress at this period would actually affect the "source" of nitrogen available to be made into storage proteins (the sink). There was also an inverse effect of stress days during Anth-Mat_Grp1 on Superb HMW-glutenin. Thus, the stress at this period was detrimental to protein synthesis and caused a decrease in HMW-glutenin content. This most likely impacted those HMW subunits usually found in wheat kernels almost immediately after anthesis.

The protein variables' response to average temperature range was similar to their response to useful heat variables. The level of protein components increased with increasing temperature range during the period of Anth-Mat_Grp1. However, during the phase of Anth-Mat_Grp2, increasing average temperature range had a negative effect on Superb soluble protein. This may be because average temperature range was having a direct effect on starch accumulation in the kernel later in the filling period and, thus, the relative amount of protein to starch was actually decreasing. This effect was different from that during Anth-Mat_Grp1 where useful heat variables and stress heat variables had a direct and inverse impact, respectively, on protein synthesis.

An interesting difference between cultivars was observed for combinations of Pday and protein variables. Two protein variables, flour protein content and soluble protein had Pday useful heat variables as their strongest explanatory variables. AC Barrie had Pday combinations of 5-25-32 for flour protein content and 7-25-35 for soluble protein. Superb had Pday combinations of 3-25-32 for flour protein content and 7-16-30 for soluble protein. For both flour protein content and soluble protein, Superb had lower Pday threshold levels, a lower minimum threshold for flour protein content and a lower maximum temperature threshold for soluble protein. This suggests that Superb synthesized protein, total protein and protein fractions, more rapidly and/or efficiently at lower temperatures than AC Barrie.

Pentosans responded similarly to protein in the timing of stress heat variable impacts. For AC Barrie and Superb, stress heat variables provided the best prediction of pentosan levels in the flour. There was a direct relationship for both cultivars. The sensitive stage for AC Barrie was Anth-Mat_Grp2 and for Superb was Plant-Anth. During these stages pentosans are not at their most rapid rate of synthesis. The most rapid stage of pentosans synthesis is the first 20 days after anthesis (Cerning and Guilbot, 1973) and thus the stress heat variables were likely restricting starch development and creating a large relative amount of pentosans in the kernel.

All RVA variable relationships improved with division of the growing season. Final viscosity still had the highest R^2 values (0.55 and 0.41 for AC Barrie and Superb respectively). Peak viscosity (RVA Peak) responded more to useful heat and rainfall early in the growing season while the RVA trough viscosity increased with increasing heat stress early in the growing season (Table 2.8). These two RVA variables are closely related to amylose content in the starch. Several other researchers have found strong inverse relationships between RVA_Peak and amylose content (Loney et al., 1975; Oda et al., 1980; Zeng et al., 1997). Zeng et al. (1997) also found a very strong relationship (r=0.99) between trough viscosity and peak viscosity on the RVA. RVA final viscosity for AC Barrie decreased with increasing useful heat during Anth-Mat_Grp2, while for Superb, RVA final viscosity increased with increasing heat stress during planting to anthesis. Thus, useful heat and heat stress had opposing effects on RVA final viscosity.

Mixograph relationships also improved from dividing up the growing season. The strongest relationships with basic environmental parameters still belonged to peak dough resistance and peak dough bandwidth (Table 2.8). Peak dough resistance decreased with increasing heat stress or decreasing average temperature during the Anth-Mat_Grp1 stage, similar to the protein variable response. This suggested the existence of a relationship between protein variables and mixograph peak dough resistance.

After dividing up the growing season, mixograph work input to peak on the mixograph was significantly correlated with environmental variables. However, AC Barrie mixing time to peak still did not have a significant relationship, while Superb mixing time to peak improved from $R^2 = 0.17$ to $R^2 = 0.26$ (Table 2.8).

Relationships for the farinograph variables also improved by dividing up the growing season. Precipitation was the most highly correlated variable for three of the possible four Superb farinograph parameters (FarAbs, FarStab, and FarMTI). There were no useful heat variables that significantly impacted Farinograph variables for either cultivar (Table 2.8).

Relationships with extensigraph variables also improved after dividing up the growing season. Similar to the farinograph relationships, useful heat variables did not play a large role in predicting extensigraph parameters. The exception occurred with AC Barrie Rmax being most highly correlated to $Pdays_{3\text{-}24\text{-}35}$All with a negative coefficient.

Table 2.8: The single basic environmental parameter accumulated over different periods within the growing season that explained the highest level of variance for each grain (A), flour (B), dough (C), and bread (D) quality variable.

A

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Protein	Barrie	$Pdays_{5-21-32}All$	0.25**	Protein = -0.009* $Pdays_{5-21-32}All$ + 21.71
	Superb	S_t30_Anth-Mat_Grp1	0.16**	Protein = -0.17*S_t30_Anth-Mat_Grp1 + 14.51
TKW	AC Barrie	S_t27_Plant-Anth_Grp1	0.45***	TKW = -1.13*S_t27_Plant-Anth_Grp1 + 35.67
	Superb	S_t27_Plant-Anth_Grp1	0.39***	TKW = -1.10*S_t27_Plant-Anth_Grp1 + 40.47
Test_Weight	AC Barrie	Trange_avg_Anth-Mat_Grp1	0.35***	Test_Weight = -0.606*Trange_avg_Anth-Mat_Grp1 + 90.71
	Superb (non normal)	Rain_all	0.11*	Test_Weight = -0.008*Rain_All + 83.42
Yield	AC Barrie	$Pdays_{7-22-27}All$	0.47***	Yield = 0.17* $Pdays_{7-22-27}All$ - 65.96
	Superb	S_t29_Anth-Mat_Grp2	0.30**	Yield = -1.70*S_t29_Anth-Mat_Grp2 + 57.55

B

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Flour Protein	AC Barrie	$Pdays_{5-25-32}All$	0.28**	Flour Protein = -0.01* $Pdays_{5-25-32}All$ + 20.45
	Superb	$Pdays_{3-25-32}Plant-Anth$	0.12*	Flour Protein = -0.037* $Pdays_{3-25-32}Plant-Anth$ + 26.79
Soluble Protein	AC Barrie	$Pdays_{7-25-35}All$	0.17**	Soluble Protein = -0.006* $Pdays_{7-25-35}All$ + 12.66
	Superb	$Pdays_{7-16-30}Plant-Anth\_Grp1$	0.21**	Soluble Protein = -0.028* $Pdays_{7-16-30}Plant-Anth\_Grp1$+ 14.03
HMW-glutenin	AC Barrie	Rain_Plant-Anth_Grp2	0.19**	HMW-glutenin = -0.005*Rain_Plant-Anth_Grp2 + 3.67
	Superb (non-normal)	S_t25_Anth-Mat_Grp1	0.23**	HMW-glutenin = -0.042*S_t25_Anth-Mat_Grp1 + 3.98
Pentosans	AC Barrie	S_t22_Anth-Mat_Grp2	0.26**	$(Pentosans)^{2.75}$ = 0.194*S_t22_Anth_Mat+Grp2 + 2.10
	Superb	S_t19_Plant-Anth	0.33***	$(Pentosans)^{2.75}$ = 0.2768*S_t19_Plant-Anth - 5.95
RVA_Peak	AC Barrie	Rain_Plant-Anth_Grp2	0.18**	RVA_Peak = 1.42*Rain_Plant-Anth_Grp2 + 2590.00
	Superb	S_t24_Plant-Anth_Grp2	0.21**	RVA_Peak = -12.90*S_t24_Plant-Anth_Grp2 + 2817.26
RVA_Trough	AC Barrie	S_t15_Plant-Anth_Grp1	0.34**	RVA_Trough = 14.11*S_t15_Plant-Anth_Grp1 + 1329.07
	Superb	S_t16_Plant-Anth	0.20**	RVA_Trough = 9.82*S_t16_Plant-Anth + 1185.91
RVA Breakdown	AC Barrie	Trange_c_avg_Anth-Mat	0.33**	RVA Breakdown = -36.43*Trange_c_avg_Anth-Mat + 1509.31
	Superb	$Pdays_{3-16-27}Anth-Mat$	0.18**	RVA Breakdown = 0.53* $Pdays_{3-16-27}Anth-Mat$ + 772.00
RVA_Final	AC Barrie	$Pdays_{3-16-27}Anth-Mat\_Grp2$	0.53***	RVA_Final = -2.39* $Pdays_{3-16-27}Anth-Mat\_Grp2$+ 3343.98
	Superb	S_t17_Plant-Anth	0.41***	$(RVA\_Final)^{0.75}$ = 1.76*S_t17_Plant-Anth + 319.87

Table 2.8 cont'd

Flour Yield	AC Barrie	Days_All	0.06^{ns}	
	Superb (non normal)	S_t18_All	0.21**	$(\text{Flour Yield})^{0.5}$ = 0.005*S_t18_All + 7.89
Ash	AC Barrie	Trange_sum_Plant-Anth	0.28**	$(\text{Ash})^{-0.25}$ = -0.0002*Trange_sum_Plant-Anth + 1.065
	Superb	StressDeg_SD-Mat	0.36***	Ash = 0.0015*StressDeg_SD-Mat + 0.38

C

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Mixograph				
Mixing Time to Peak	AC Barrie	$\text{Pdays}_{7\text{-}21\text{-}29}$Plant-Anth_Grp2	0.10^{ns}	
	Superb	S_t26_Plant-Anth_Grp1	0.26**	Log(MTP) = 0.034*S_t26_Plant-Anth_Grp1 + 0.80
Peak dough resistance	AC Barrie	$\text{Pdays}_{7\text{-}25\text{-}31}$All	0.24**	PDR = --0.05* $\text{Pdays}_{7\text{-}25\text{-}31}$All + 84.86
	Superb	S_t26_Anth-Mat_Grp1	0.32**	PDR = -0.70*S_t26_Anth-Mat_Grp1 + 63.14
Bandwidth at Peak	AC Barrie	S_t17_All	0.15*	PBW = -0.156*S_t17_All + 39.91
	Superb	S_t17_Plant-Anth	0.34***	PBW = -0.524*S_t17_Plant-Anth + 48.49
Breakdown at MTP+3min	AC Barrie	Trange_avg_Plant-Anth_Grp2	0.23**	PDR_BR3 = -1.403*Trange_avg_Plant-Anth_Grp2 + 89.92
	Superb	S_t17_Plant-Anth	0.26**	PDR_BR3 = 0.307*S_t17_Plant-Anth + 53.70
Weighted Breakdown 3	AC Barrie	$\text{Pdays}_{7\text{-}25\text{-}32}$All	0.19**	PDR_BR3weighted = -2.15* $\text{Pdays}_{7\text{-}25\text{-}32}$All + 5123.30
	Superb	S_t25_Anth-Mat_Grp1	0.30**	PDR_BR3weighted = -37.29*S_t25_Anth-Mat_Grp1 + 4323.01
Work input to peak	AC Barrie	Trange_avg_Anth-Mat_Grp2	0.12*	WIP = -2.49*Trange_avg_Anth-Mat_Grp2 + 135.05
	Superb	S_t15_Plant-Anth	0.14*	WIP = 1.71*S_t15_Plant-Anth + 0.37
Farinograph				
Farinograph Absorption	AC Barrie	Days_Anth-Mat_Grp1	0.26**	FarAbs = -0.18*Days_Anth-Mat_Grp1 + 65.26
	Superb	Rain_Plant-Anth	0.22**	FarAbs = -0.017*Rain_Plant-Anth + 66.34
Dough Development Time	AC Barrie	Trange_c_avg_Anth-Mat	0.39***	FarDDT = 0.74*Trange_c_avg_Anth-Mat - 4.66
	Superb	Days_Anth-Mat	0.22**	Log(DDT) = -0.02*Days_Anth-Mat + 2.68
Farinograph Stability	AC Barrie	S_t29_Anth-Mat_Grp2	0.38***	FarStab = 1.01*Pdays_Anth-Mat_Grp2 + 9.27
	Superb (non normal)	Rain_Anth-Mat	0.37***	FarStab = -0.17*Rain_Anth-Mat + 26.07
Farinograph Mixing Tolerance	AC Barrie	S_t15_Plant-Anth_Grp1	0.36***	FarMTI = -3.17*S_t15_Plant-Anth_Grp1 + 114.83
	Superb	Rain_Anth-Mat	0.49***	FarMIT = 0.334*Rain_Anth-Mat + 17.32

Table 2.8 cont'd

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Extensigraph				
Maximum Resistance	AC Barrie	S_t24Plant-Anth_Grp1	0.33***	Rmax = 0.982*S_t24_Plant-Anth_Grp1 + 24.92
	Superb	Days_Anth-Mat	0.27**	Rmax = -0.341*Days_Anth-Mat + 40.90
Maximum Extension	AC Barrie	$Pdays_{3\text{-}24\text{-}35}All$	0.41***	E^3 = -3399* $Pdays_{3\text{-}24\text{-}35}All$ + 4140957
	Superb	S_t15_Plant-Anth	0.20**	E = -1.51*S_t15_Plant-Anth + 207.33
Area under Ext. Curve	AC Barrie	S_t15_Anth-Mat_Grp1	0.46***	EA = -52.44*S_t15_Anth-Mat_Grp1 + 2929.62
	Superb	Rain_Plant-Anth_Grp1	0.23**	EA = -6.13*Rain_Plant-Anth_Grp1 + 2282.74

D

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Loaf Volume	AC Barrie	S_t22_Plant-Anth	0.30**	LV = 7.65*S_t22_Plant-Anth + 739.48
	Superb	S_30_Anth-Mat_Grp1	0.12*	LV = -9.66*S_t30_Anth-Mat_Grp1 + 1054.88
Full Formula Mix Time	AC Barrie	$Pdays_{3\text{-}16\text{-}27}Plant\text{-}Anth\_Grp1$	0.11*	$(Baking\_DDT)^{-1}$ = 0.0006* $Pdays_{3\text{-}16\text{-}27}Plant\text{-}Anth\_Grp1$+ 0.12
	Superb	S_t27_Plant-Anth_Grp1	0.33***	Baking_DDT = 0.15*S_t27_Plant-Anth_Grp1 + 3.67

* = significant at p=0.05 level.
** = significant at p=0.01 level.
*** = significant at p<.0001 level.
ns = not significant at p=0.05 level.

2.4.7. Prediction of Quality Parameters using Derived Water Use Variables Accumulated during Different Stages of the Growing Season

The next step taken in analyzing the environmental impacts on wheat quality variables was to introduce derived water use variables including crop water demand, crop water use, crop water use deficit, and crop water use ratio. These four variables were derived using the Baier and Robertson (1965) method and Hargreaves et al. (1985) method. These water use variables were added after the first two steps of analysis because more environmental information and additional manipulation of the data is required to derive the variables.

Protein relationships improved dramatically upon the addition of water use variables to the analysis (Table 2.9). Interestingly, the Baier and Robertson (1965) method provided the greatest relationship improvements in protein relationships for AC Barrie, while the Hargreaves (1985) method did the same for Superb. For the protein compositional fractions, the addition of the water use variables improved the relationships for Superb but not for AC Barrie.

The response pattern of protein variables to environmental factors remained similar after adding the water use variables. For example, when a stress such as water use deficit was imposed late in the filling period (Anth-Mat_Grp2), there was an increase in protein content because of the detrimental impact of water stress on starch accumulation late in the filling stage. Water use had an inverse effect on protein content and protein composition if the staging period was not the period of most rapid protein synthesis (ie. Anth-Mat_Grp1) (Table 2.9).

Most of the improvements on the dough quality parameters with addition of water analysis occurred on those parameters closely related to protein variables. This was apparent on the peak dough resistance and peak dough bandwidth parameters. In the mixograph, AC Barrie mixograph variables were highly related to crop water use deficit parameters while Superb mixograph variables were highly related to crop water use parameters. This is in contrast to the temperature-based variables where AC Barrie seemed to be more sensitive to useful heat and Superb was more sensitive to heat stress.

Table 2.9: The single basic environmental or modeled crop water use parameter accumulated over different periods of the growing season that explained the highest level of variance for each grain (A), flour (B), dough (C), and bread (D) quality variable.

A

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Protein	AC Barrie	BR3WU_SD-Mat	0.36***	Protein = -0.99*BR3WU_SD-Mat + 16.17
	Superb	HarWU_Plant-Anth_Grp2	0.33***	$(\text{Protein})^2$ = -0.840*HarWU_Plant-Anth_Grp2 + 292.91
TKW	AC Barrie	S_t27_Plant-Anth_Grp1	0.45***	TKW = -1.13*S_t27_Plant-Anth_Grp1 + 35.67
	Superb	S_t27_Plant-Anth_Grp1	0.39***	TKW = -1.10*S_t27_Plant-Anth_Grp1 + 40.47
Test_Weight	AC Barrie	Trange_avg_Anth-Mat_Grp1	0.35***	Test_Weight = -0.606*Trange_avg_Anth-Mat_Grp1 + 90.71
	Superb (non normal)	Rain_all	0.11*	Test_Weight = -0.008*Rain_All + 83.42
Yield	AC Barrie	$\text{Pdays}_{7\text{-}22\text{-}27}$All	0.47***	Yield = 0.17* $\text{Pdays}_{7\text{-}22\text{-}27}$All - 65.96
	Superb	S_t29_Anth-Mat_Grp2	0.30**	Yield = -1.70*S_t29_Anth-Mat_Grp2 + 57.55

B

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Flour Protein	AC Barrie	BR3WUDef_Anth-Mat_Grp2	0.42***	Flour Protein = 0.088*BR3WUDef_Anth-Mat_Grp2 + 12.13
	Superb	HarWU_Plant-Anth_Grp2	0.34***	Flour Protein = -0.031*HarWU_Plant-Anth_Grp2 + 16.75
Soluble Protein	AC Barrie	$\text{Pdays}_{7\text{-}25\text{-}35}$All	0.17**	Soluble Protein = -0.006* $\text{Pdays}_{7\text{-}25\text{-}35}$All + 12.66
	Superb	HarWU_Plant-Anth_Grp2	0.42***	$(\text{Soluble Protein})^3$ = -6.09*HarWU_Plant-Anth_Grp2 + 1348.89
HMW-glutenin	AC Barrie	Rain_Plant-Anth_Grp2	0.19**	HMW-glutenin = -0.005*Rain_Plant-Anth_Grp2 + 3.67
	Superb	HarWU_Plant-Anth_Grp2	0.29**	$(\text{HMW-glutenin})^2$ = -0.069*HarWU_Plant-Anth_Grp2 + 20.36
Pentosans	AC Barrie	S_t22_Anth-Mat_Grp2	0.26**	$(\text{Pentosans})^{2.75}$ = 0.194*S_t22_Anth_Mat+Grp2 + 2.10
	Superb	S_t19_Plant-Anth	0.33***	$(\text{Pentosans})^{2.75}$ = 0.2768*S_t19_Plant-Anth - 5.95
RVA_Peak	AC Barrie	Rain_Plant-Anth_Grp2	0.18**	RVA_Peak = 1.42*Rain_Plant-Anth_Grp2 + 2590.00
	Superb	S_t24_Plant-Anth_Grp2	0.21**	RVA_Peak = -12.90*S_t24_Plant-Anth_Grp2 + 2817.26
RVA_Trough	AC Barrie	S_t15_Plant-Anth_Grp1	0.34**	RVA_Trough = 14.11*S_t15_Plant-Anth_Grp1 + 1329.07
	Superb	S_t16_Plant-Anth	0.20**	RVA_Trough = 9.82*S_t16_Plant-Anth + 1185.91
RVA Breakdown	AC Barrie	Trange_ avg_Anth-Mat	0.33**	RVA Breakdown = -36.43*Trange_c_avg_Anth-Mat + 1509.31
	Superb	BR3WUDef_Anth-Mat_Grp2	0.27**	RVA Breakdown = -6.723*BR3WUDef_Anth-Mat_Grp2 + 999.79

Table 2.9 cont'd

RVA_Final	AC Barrie	$Pdays_{3\text{-}16\text{-}27}$Anth-Mat_Grp2	0.53***	RVA_Final = -2.39* $Pdays_{3\text{-}16\text{-}27}$Anth-Mat_Grp2+ 3343.98
	Superb	S_t17_Plant-Anth	0.41***	$(RVA\_Final)^{0.75}$ = 1.76*S_t17_Plant-Anth + 319.87
Flour Yield	AC Barrie	Days_All	0.06^{ns}	
	Superb (non normal)	S_t18_All	0.21**	$(Flour\ Yield)^{0.5}$ = 0.005*S_t18_All + 7.89
Ash	AC Barrie	Trange_sum_Plant-Anth	0.28**	$(Ash)^{-0.25}$ = -0.0002*Trange_sum_Plant-Anth + 1.065
	Superb	StressDeg_SD-Mat	0.36***	Ash = 0.0015*StressDeg_SD-Mat + 0.38

C

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Mixograph				
Mixing Time to Peak	AC Barrie	BR3WUDef_Plant_Anth_Grp2	0.12*	$(MTP)^{-.5}$ = 0.0007*BR3WUDef_Plant-Anth_Grp2 + 0.59
	Superb	S_t26_Plant-Anth_Grp1	0.26**	Log(MTP) = 0.034*S_t26_Plant-Anth_Grp1 + 0.80
Peak dough resistance	AC Barrie	BR3WUDef_Anth-Mat_Grp2	0.33**	PDR = 0.374*BR3WUDef_Anth-Mat_Grp2 + 48.00
	Superb	BR3WU_Plant-Anth_Grp2	0.32**	PDR = -0.167*BR3WU_Plant-Anth_Grp2 + 74.54
Bandwidth at Peak	AC Barrie	BR3WUDef_Plant-Anth	0.34**	PBW = 0.09*BR3WUDef_Plant-Anth + 17.81
	Superb	S_t17_Plant-Anth	0.34***	PBW = -0.524*S_t17_Plant-Anth + 48.49
Breakdown at MTP+3min	AC Barrie	Trange_avg_Plant-Anth_Grp2	0.23**	PDR_BR3 = -1.403*Trange_avg_Plant-Anth_Grp2 + 89.92
	Superb	S_t17_Plant-Anth	0.26**	PDR_BR3 = 0.307*S_t17_Plant-Anth + 53.70
Weighted Breakdown 3	AC Barrie	BR3WUDef_Anth-Mat_Grp2	0.30**	PDR_BR3weighted = 17.56*BR3WUDef_Anth-Mat_Grp2 + 3520.29
	Superb	HarWU_Plant-Anth_Grp2	0.32**	$(PDR\_BR3weighted)^3$ = -356076638*Har_WU_Plant-Anth_Grp2 + $1.01*10^{11}$
Work input to peak	AC Barrie	Trange_avg_Anth-Mat_Grp2	0.12*	WIP = -2.49*Trange_avg_Anth-Mat_Grp2 + 135.05
	Superb	S_t15_Plant-Anth	0.14*	WIP = 1.71*S_t15_Plant-Anth + 0.37

Table 2.9 cont'd

Farinograph				
Farinograph Absorption	AC Barrie	Days_Anth-Mat_Grp1	0.26**	FarAbs = -0.18*Days_Anth-Mat_Grp1 + 65.26
	Superb	Rain_Plant-Anth	0.22**	FarAbs = -0.017*Rain_Plant-Anth + 66.34
Dough Development Time	AC Barrie	HarWU_SD-Mat	0.43***	FarDDT = -0.132*HarWU_SD-Mat + 8.75
	Superb	Days_Anth-Mat	0.22**	Log(DDT) = -0.02*Days_Anth-Mat + 2.68
Farinograph Stability	AC Barrie	S_t29_Anth-Mat_Grp2	0.38***	FarStab = 1.01*Pdays_Anth-Mat_Grp2 + 9.27
	Superb	BR3WUDef_Anth-Mat_Grp2	0.48***	FarStab = 0.905*BR3WUDef_Anth-Mat_Grp2 + 6.97
Farinograph Mixing Tolerance	AC Barrie	S_t15_Plant-Anth_Grp1	0.36***	FarMTI = -3.17*S_t15_Plant-Anth_Grp1 + 114.83
	Superb	Rain_Anth-Mat	0.49***	FarMIT = 0.334*Rain_Anth-Mat + 17.32
Extensigraph				
Maximum Resistance	AC Barrie	S_t24Plant-Anth_Grp1	0.33***	Rmax = 0.982*S_t24_Plant-Anth_Grp1 + 24.92
	Superb	Days_Anth-Mat	0.27**	Rmax = -0.341*Days_Anth-Mat + 40.90
Maximum Extension	AC Barrie	$\text{Pdays}_{3\text{-}24\text{-}35}$All	0.41***	E^3 = -3399* $\text{Pdays}_{3\text{-}24\text{-}35}$All + 4140957
	Superb	HarWU_Anth-Mat_Grp1	0.26**	$(E)^3$ = 14281*HarWU_Anth-Mat_Grp1 + 1220400
Area under Ext. Curve	AC Barrie	S_t15_Anth-Mat_Grp1	0.46***	EA = -52.44*S_t15_Anth-Mat_Grp1 + 2929.62
	Superb	Rain_Plant-Anth_Grp1	0.23**	EA = -6.13*Rain_Plant-Anth_Grp1 + 2282.74

D

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Loaf Volume	AC Barrie	S_t22_Plant-Anth	0.30**	LV = 7.65*S_t22_Plant-Anth + 739.48
	Superb	S_30_Anth-Mat_Grp1	0.12*	LV = -9.66*S_t30_Anth-Mat_Grp1 + 1054.88
Full Formula Mix Time	AC Barrie	$\text{Pdays}_{3\text{-}16\text{-}27}$Plant-Anth_Grp1	0.11*	$(\text{Baking\_DDT})^{-1}$ = 0.0006* $\text{Pdays}_{3\text{-}16\text{-}27}$Plant-Anth_Grp1+ 0.12
	Superb	S_t27_Plant-Anth_Grp1	0.33***	Baking_DDT = 0.15*S_t27_Plant-Anth_Grp1 + 3.67

* = significant at p=0.05 level.
** = significant at p=0.01 level.
*** = significant at p<.0001 level.
ns = not significant at p=0.05 level.

2.4.8. Prediction of Quality Parameters with Mutliple Regression Analysis using All Available Environmental Variables

As expected, increasing the number of environmental variables allowed to enter the regression from one to three created improved the R^2 values for regressions. The stepwise regression created a problem if the three variables that provided the best relationship were too strongly correlated because they occurred in the same crop stage. For example, AC Barrie farinograph absorption analysis provided three Pday combinations, all for the stage Anth-Mat_Grp1. Pday combinations all in the same stage have very high correlations to one another. Thus, the additional regression variables in this statement did not add any new or valuable information for prediction of farinograph absorption. If the three variable model was not appropriate, the best two environmental variable model was considered and used in the analysis. If the two variable model also had two highly correlated independent variables, it was also not included in the analysis.

Stepwise regression was successful in improving the relationships between protein variables and the environmental parameters. The strongest relationship was an R^2 of 0.53 for AC Barrie grain protein content. The lowest was an $R^2 = 0.33$ for Superb soluble protein (Table 2.10).

The trend of protein variable response to useful heat or water use variables and stress heat/water use variables was less consistent in the stepwise regression analysis. To reiterate, stress variables occurring during any period other than Anth-Mat_Grp1 generally had a direct effect on protein variables, while useful heat/water use variables generally had an inverse effect.

The filling period stage (Anth-Mat) was an important component in nearly all protein variable regression equations. However, there were a large number of other variables that were significant at different stages. That would imply that the protein content and protein composition variability was explained not only in relative terms to starch accumulation variation but also in actual variability in the protein synthesis during early grain filling.

In the earlier analysis using only one environmental variable, AC Barrie possessed stronger relationships for protein content (both grain and flour protein content) than Superb. This, again was true for the multiple regression analysis on protein content (Table 2.10). Thus, more of the variation in AC Barrie than Superb protein levels was explained using our environmental parameters. This is important because there has been a trend of increasing Superb acres across western Canada over the past two to three years and our ability to predict incoming crop protein levels may actually decrease unless we utilize cultivar specific regression models.

While protein content of AC Barrie was better predicted than that of Superb, the opposite was true for protein quality. Through the previous two methods of analysis (Table 2.8 and Table 2.9), Superb soluble protein and HMW-glutenin had higher R^2 values than AC Barrie. However, after the multiple regression analysis, soluble protein was best predicted for AC Barrie, not Superb. The ability to predict HMW-glutenin was still strongest with Superb. This is important because, as shown later, protein quality, as well as protein content, is key to predicting the end-use quality of wheat.

AC Barrie pentosans improved significantly to an R^2 of 0.47 with the multiple regression. However, the pentosans relationships did not contain the early period after anthesis as an input variable to the regression equation. This would lead us to suspect that the changes in pentosans were controlled mainly during periods outside their rapid accumulation stage. Therefore, pentosan concentration in the kernel was controlled mainly by the amount of starch accumulation in the filling period.

A large majority of the environmental parameters entered in the regression equations for the RVA variables were accumulated over the full growing season or from planting to anthesis. This is not what would be expected since the majority of starch accumulation in the kernel occurs during the later stages of grain filling (Parker, 1985; Panozzo and Eagles, 1998).

The mixograph results also improved significantly with multiple regression. The biggest improvement was for AC Barrie WIP, which increased from R^2 of 0.12 to R^2 of 0.51. The weakest relationship was an R^2 of 0.20 for AC Barrie MTP. Superb had stronger relationships with environmental parameters for all mixograph variables except WIP (Table 2.10).

Farinograph relationships improved with multiple regression to $R^2 \geq 0.41$. As mentioned earlier, AC Barrie Farinograph absorption could not produce a multiple regression equation with non-correlated environmental variables.

Extensigraph variables had a range of R^2 values from 0.43 to 0.61 resulting from the multiple regression analysis. Four of the six environmental variables explaining Rmax for both AC Barrie and Superb were measured for either the entire season or from planting to anthesis. Some of the explanatory variables were common between Rmax and flour protein content for AC Barrie and HMW-glutenin for Superb (the major driving force for Rmax for AC Barrie and Superb, respectively). These common explanatory variables included stress days at 27°C, stress days at 25°C, and the sum of daily temperature ranges. For E and EA, most of the environmental variables here were measured from anthesis to maturity. This would lead us to believe that these two extensigraph variables were also closely related to protein because of the timing of the impacts of environmental factors.

Table 2.10: The three basic environmental and modeled crop water use parameters accumulated over different periods of the growing season that explained the highest level of variance for each grain (A), flour (B), dough (C), and bread (D) quality variable.

A

Dependent Variable	Cultivar	R^2	Equation
Protein	AC Barrie	0.53***	Protein = -0.12*S_t17_Anth-Mat - 0.26*S_t27_Plant-Anth_Grp2 + 0.24*S_t27_Anth-Mat_Grp1 + 18.61
	Superb	0.36**	$Protein^2$ = -1.08*S_t17_Plant-Anth - 0.85*HarWU_Plant-Anth_Grp2 + 349.76
TKW	AC Barrie	0.66***	TKW = -0.53*S_t24_Plant-Anth_Grp1 + 0.03*Rain_Plant-Anth_Grp2 - 0.92*Trange_avg_Anth-Mat_Grp1 + 47.96
	Superb	0.37***	TKW = 0.13*HarWU_SD-Mat - 0.86*S_t26_Plant-Anth_Grp1 + 36.53
Test_Weight	AC Barrie	0.41***	Test Weight = 0.02*BR3Etp_Plant-Anth - 0.61*Trange_avg_Anth-Mat_Grp1 + 85.17
	Superb	0.33**	Test Weight = -0.24*Rain_All + 0.05*Rain_Anth-Mat + 84.36
Yield	AC Barrie	0.50***	$Yield^{1.5}$ = -2.63*S_t26_Plant-Anth_Grp1 - 0.63*BR3WUDef_Anth-Mat_Grp2 + 62.31
	Superb	0.56***	Yield = -2.46*S_t28_Anth-Mat_Grp2 + 0.43*$Pdays_{6-25-27}$Plant-Anth_Grp2 + 5.50*Trange_avg_Anth-Mat_Grp2 - 101.80

Table 2.10 cont'd

B

Dependent Variable	Cultivar	R^2	Equation
Flour Protein	AC Barrie	0.49***	Flour Protein = -0.05*S_t15_All - 0.03*HarWU_Anth-Mat - 0.03*S_t27_Plant-Anth_Grp1 + 21.81
	Superb	0.40**	Flour Protein = -0.09*S_t17_Plant-Anth + 0.48*S_t30_Plant-Anth_Grp1 + 0.03*BR3WUDef_Plant-Anth_Grp2 + 16.73
Soluble Protein	AC Barrie	0.44***	Soluble Protein = -0.17*S_t27_Plant-Anth_Grp2 - 0.63*S_t20_Anth-Mat_Grp2 + 0.38*Trange_avg_Plant-Anth_Grp2 + 5.96
	Superb	0.33**	Soluble Protein = -0.12*S_t25_Anth-Mat_Grp1 - 0.04*$Pdays_{3-16-30}$Plant-Anth_Grp1 + 18.38
HMW-glutenin	AC Barrie	0.40***	HMW-glutenin = -0.030*S_t23_Anth-Mat + S_t30_Anth-Mat_Grp1 + 3.96
	Superb	0.46***	HMW-glutenin = -0.03*S_t17_Plant-Anth - 0.001*Trange_sum_Anth-Mat - 0.009*HarWU_Plant-Anth_Grp2 + 6.79
Pentosans	AC Barrie	0.47***	$Pentosans^2$ = 0.059*HarWU_SD-Mat - 0.013*GDD_{10}Plant-Anth_Grp2 + 5.00
	Superb	0.47***	Pentosans = 0.05*S_t18_Plant-Anth + 0.03*BR3WUDef_Plant-Anth_Grp1 - 0.02*BR3WUDef_Anth-Mat_Grp2 - 0.62
RVA_Peak	AC Barrie	0.33**	RVA_Peak = -4.88*BR3WUDef_Anth-Mat - 319.12*BR3WURatio_SD-Mat + 3054.17
	Superb	0.45**	RVA_Peak = -16.43*S_t24_Plant-Anth_Grp2 + 3.92*$Pdays_{7-22-27}$Plant-Anth_Grp1 + 1.47*$Pdays_{6-16-27}$Anth-Mat_Grp2 + 2083.34
RVA_Trough	AC Barrie	0.52***	RVA_Trough = -0.81*GDD_4Plant-Anth_Grp1 + 22.48*S_t15_Plant-Anth_Grp1 + 1676.90
	Superb	0.53***	RVA_Trough = 14.21*S_t17_Plant-Anth - 26.84*S_t29_Plant-Anth_Grp1 - 2.35*GDD_8Plant-Anth_Grp2 + 1640.97

Table 2.10 cont'd

RVA Breakdown	AC Barrie	0.38**	RVA Breakdown = -7.37*S_t30_Anth-Mat-Grp2 - 5.59*HarWUDef_Anth-Mat_Grp2 + 1102.64
	Superb	0.46***	RVA Breakdown = -7.16*S_t16_All + 2.30* GDD_6Plant-Anth + 2.58*$Pdays_{7\text{-}16\text{-}27}$Anth-Mat_Grp2 + 228.48
RVA_Final	AC Barrie	0.75***	RVA_Final = 95.60*S_t19_Anth-Mat_Grp1 - 9.67*$Pday_{3\text{-}17\text{-}35}$Anth-Mat_Grp1 + 2952.99
	Superb	0.58***	RVA_Final = 20.54*S_t17_Plant-Anth - 2.48*GDD_6Plant-Anth_Grp2 + 2821.87
Flour Yield	AC Barrie	0.26**	Flour Yield = -0.28*Days_All + 0.04*$Pdays_{3\text{-}16\text{-}27}$Anth-Mat + 0.44*S_t17_Plant-Anth_Grp2 + 79.95
	Superb	0.26**	Flour Yield = 0.10*S_t19_All + 0.05*$Pdays_{6\text{-}16\text{-}35}$Plant-Anth + 37.82
Ash	AC Barrie	0.44**	Ash = -0.008*S_t18_Plant_Anth + 0.015*S_t17_Plant-Anth_Grp1 - 0.01*Trange_avg_Plant-Anth_Grp1 + 0.66
	Superb	0.58***	Ash = 0.0005*$Pdays_{4\text{-}24\text{-}27}$All + 0.002*StressDeg_SD-Mat - 0.01*S_t16_Anth-Mat_Grp1 + 0.24

C

Dependent Variable	Cultivar	R^2	Equation
Mixograph			
Mixing Time to Peak	AC Barrie	0.20*	Log(MTP) = -0.003*HarWUDef_All - 0.47*HarWURatio_Anth-Mat + 1.50
	Superb	0.51***	Log(MTP) = 0.01*$Pdays_{7\text{-}25\text{-}33}$Plant-Anth - 0.04*S_t21_Plant-Anth_Grp2 + 0.03*S_t30_Anth-Mat_Grp1 - 2.11

Table 2.10 cont'd

Peak dough resistance	AC Barrie	0.41***	PDR = -0.01*$Pdays_{4-16-27}$All + 0.07*HarWUDef_All + 56.78
	Superb	0.60***	PDR = -1.199*S_t17_Plant-Anth + 0.278*BR3WUDef_Plant-Anth_Grp2 - 0.146*BR3WUDef_Anth-Mat_Grp1 + 117.53
Bandwidth at Peak	AC Barrie	0.47***	PBW = -0.303*S_t15_All + 0.76*S_t30_Plant-Anth + 0.072*HarWUDef_Plant-Anth_Grp2 + 56.35
	Superb	0.51***	PBW = 0.14*S_t21_All - 0.67*S_t17_Plant-Anth - 0.63*S_t26_Anth-Mat_Grp1 + 49.83
Breakdown at MTP+3min	AC Barrie	0.39**	PDR_BR3 = 0.027*BR3Etp_All + 0.066*BR3WU_Anth-Mat_Grp1 - 1.431*Trange_avg_Anth-Mat_Grp2 + 72.24
	Superb	0.40**	PDR_BR3 = 0.074*$Pdays_{35-25-35}$Plant-Anth - 0.027*Rain_Plant-Anth_Grp2 + 0.051*BR3WU_Plant-Anth_Grp2 + 35.69
Weighted Breakdown 3	AC Barrie	0.45***	PDR_BR3weighted = 3.23*HarWUDef_Plant-Anth_Grp2 + 16.13*BR3WUDef_Anth-Mat_Grp2 + 3441.34
	Superb	0.59***	Log(PDR_BR3weighted) = -0.019*S_t17_Plant-Anth_Grp2 + 0.002*HarWUDef_Plant-Anth_Grp2 - 0.011*S_t25_Anth-Mat_Grp1 + 8.86
Work input to peak	AC Barrie	0.51***	WIP = 142.37*Har_WURatio_All + 0.93*Har_WUDef_Anth-Mat - 4.49*Trange_avg_Anth-Mat_Grp2 + 15.33
	Superb	0.34**	Log(WIP) 0.006*$Pdays_{5-24-32}$Plant-Anth - 0.004*BR3Etp_Plant-Anth_Grp2 + 0.010*BR3WUDef_Anth-Mat_Grp2 + 2.62
Farinograph			
Farinograph Absorption	AC Barrie		All variables were correlated for Pdays_Plant-Anth_Grp1
	Superb	0.52***	FarAbs = -0.056*Days_All - 0.025*Rain_Plant-Anth - 0.420*S_t25_Plant-Anth_Grp1 + 73.17

Table 2.10 cont'd

Dough Development Time	AC Barrie	0.52**	FarDDT = -0.11*HarWU_SD-Mat + 0.56*S_t29_Plant-Anth_Grp1 + 7.84
	Superb	0.41**	FarDDT = 0.64*S_t26_Plant-Anth_Grp1 - 0.53*S_t28_Plant-Anth_Grp2 - 0.09*BR3WU_Anth-Mat_Grp1 + 12.36
Farinograph Stability	AC Barrie	0.48***	FarStab = 0.18* StressDeg_All - 0.98*S_t16_Plant-Anth_Grp2 + 38.14
	Superb	0.59***	FarStab = -0.82*S_t17_Plant-Anth + 0.47*$Pday_{7-24-29}$Plant-Anth + 1.02*BR3WUDef_Anth-Mat_Grp2 - 125.66
Farinograph Mixing Tolerance	AC Barrie	0.47***	FarMTI = 0.21*$Pdays_{3-25-35}$Plant-Anth - 3.50*S_t15_Plant-Anth_Grp1 + 29.56
	Superb	0.41***	FarMTI = 0.30*BR3WUDef_All - 0.83*BR3WUDef_Anth-Mat + 41.91
Extensigraph			
Maximum Resistance	AC Barrie	0.51***	Rmax = -0.56*S_t27_Plant-Anth + 1.14*S_t24_Plant-Anth_Grp1 - 0.05*$Pdays_{3-16-27}$Anth-Mat_Grp1 + 37.16
	Superb	0.51***	Rmax = -0.03*Trange_sum_Plant-Anth - 0.78*S_t25_Plant-Anth_Grp2 + 0.72*BR3WUDef_Anth-Mat_Grp2 + 53.26
Maximum Extension	AC Barrie	0.43**	E^3 = -16081*BR3WU_Plant-Anth_Grp1 - 5205*GDD_7Anth-Mat_Grp1 + 21970*S_t28_Anth_Mat_Grp2 + 3475181
	Superb	0.53***	E = -0.36*GDD_{10}Plant-Anth_Grp1 - 5.27*S_t15_Plant-Anth_Grp2 + 321.34
Area under Ext. Curve	AC Barrie	0.61***	EA = -29.64*S_t27_Plant-Anth + 66.99*S_t24_Plant-Anth_Grp1 - 45.25*S_t15_Anth-Mat_Grp1 + 2689.63
	Superb	0.49***	EA = -3.97*Trange_sum_Anth-Mat - 5.58*Rain_Plant-Anth_Grp1 + 9.14*$Pdays_{3-24-35}$Anth-Mat_Grp2 + 3038.55

Table 2.10 cont'd

D

Dependent Variable	Cultivar	R^2	Equation
Loaf Volume	AC Barrie	0.42***	LV = -0.52*HarWU_All - 1.18*$Pdays_{7\text{-}17\text{-}27}$Anth-Mat_Grp2 + 1228.17
	Superb	0.39**	LV = -1.33*Rain_Plant-Anth_Grp1 - 11.62*S_t26_Anth-Mat_Grp1 - 2.02*$Pdays_{3\text{-}16\text{-}27}$Plant-Anth_Grp1 + 1662.93
Full Formula Mix Time	AC Barrie	0.29**	$(Baking\_DDT)^{-1}$ = 0.0001*Rain_All - 0.005*S_t25_Anth-Mat_Grp1 + 0.013*Trange_avg_Anth-Mat_Grp2 + 0.102
	Superb	0.34**	$(Baking\_DDT)^{-1}$ = 0.053*HarWURatio_SD-Mat - 0.001*$Pdays_{3\text{-}25\text{-}35}$Plant-Anth_Grp1 + 0.47

* = significant at p=0.05 level.
** = significant at p=0.01 level.
*** = significant at p<.0001 level.
ns = not significant at p=0.05 level.

2.4.9. Comparison between AC Barrie and Superb Flour Protein Responses to Environmental Variables

Flour protein content was the main driving force for 47% of the end-use quality parameters. Thus, the ability to predict flour protein content was the most valuable of the many biochemical flour constituents investigated in this study. It was stated earlier that R^2 values increased as the complexity of the analysis of growing season weather conditions increased. There was also a difference in the ability to predict flour protein content levels between cultivars. For AC Barrie the relationship was significant with an of R^2 = 0.28** for flour protein content with a Pdays variable measured over the entire season. Superb did not have a significant relationship with any of the environmental variables measured over the entire growing season (Figure 2.4).

Dividing the growing season into several different stages did not improve the R^2 of AC Barrie flour protein and the environmental parameters. However, for Superb the R^2 for flour protein content increased slightly. This analysis showed that Superb was most sensitive to a useful heat Pday variable during the planting to anthesis stage. However, Superb (R^2 = 0.12*) still did not have as strong of a relationship with the environment as AC Barrie (R^2 = 0.28**). Both AC Barrie and Superb had inverse relationships with a Pday environmental parameters (Figure 2.5 and Figure 2.6).

The addition of water use variables improved the R^2 for AC Barrie up to 0.42*** while Superb had an increase in R^2 up to 0.34***. Two different types of evapotranspiration schemes were used for crop water use modeling (Baier and Robertson, 1965 and Hargreaves, 1985). Each of the cultivars responded best to a different model. AC Barrie and Superb were responding not only to different types of environmental parameters at different stages of the growing season, but also to different, though closely related, water use parameters (r = 0.98 (data not shown)). For the protein compositional variables, only Hargreaves (1985) water use variables were significantly correlated with Superb. However, AC Barrie protein composition variables did not have increased R^2 values with the addition of the crop water use variables. As a result, the R^2 values for the protein composition variables were higher for Superb than for AC Barrie with one environmental parameter (Table 2.7, Table 2.8, and Table 2.9).

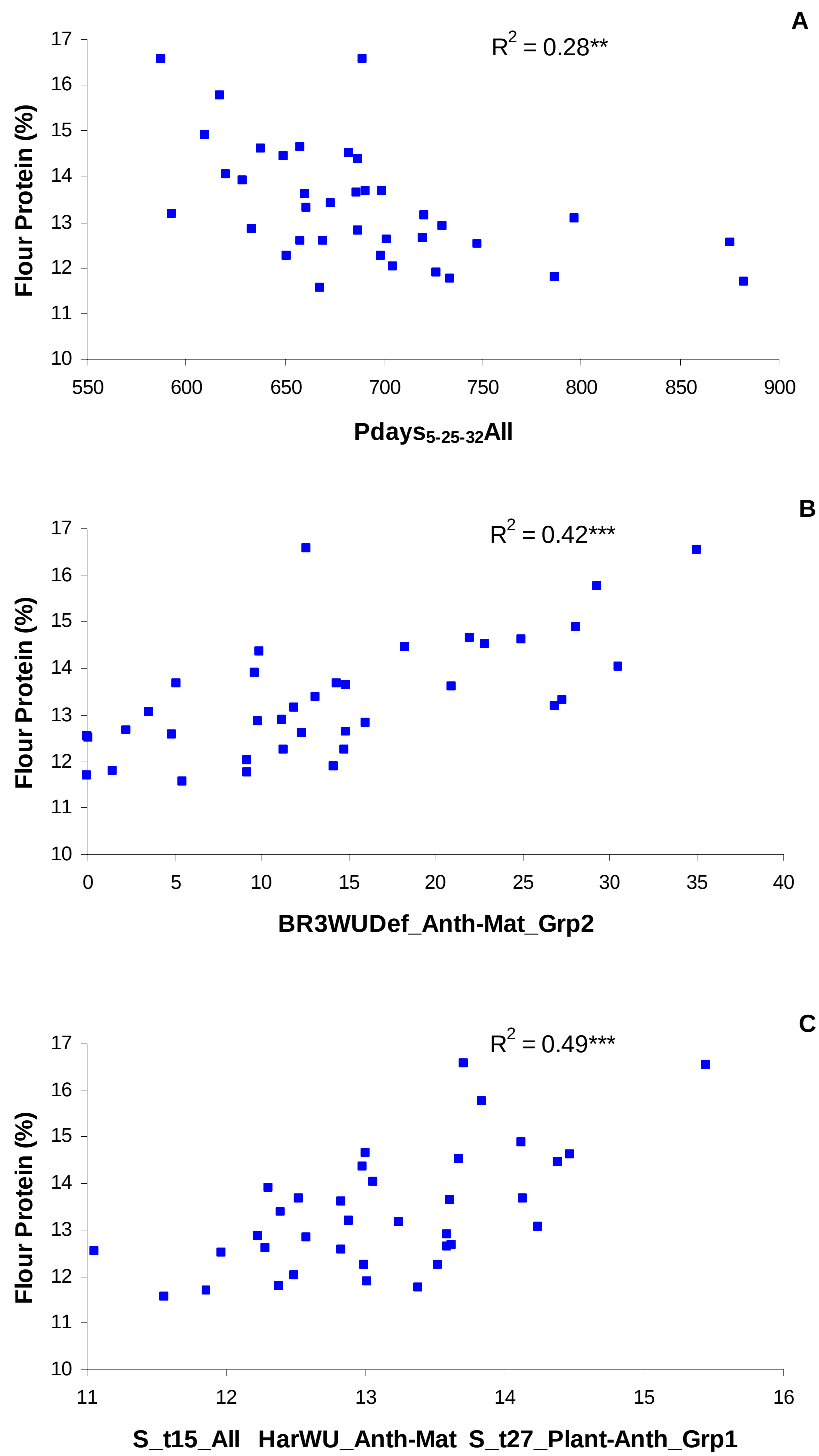

Figure 2.5: Improvement of R^2 values between AC Barrie flour protein and environmental parameters as analysis becomes more complex from (**A**) basic environmental parameters measured over entire season (**B**) to modeled crop water use variables accumulated during different growth stages (**C**) to finally using multiple regression analysis.

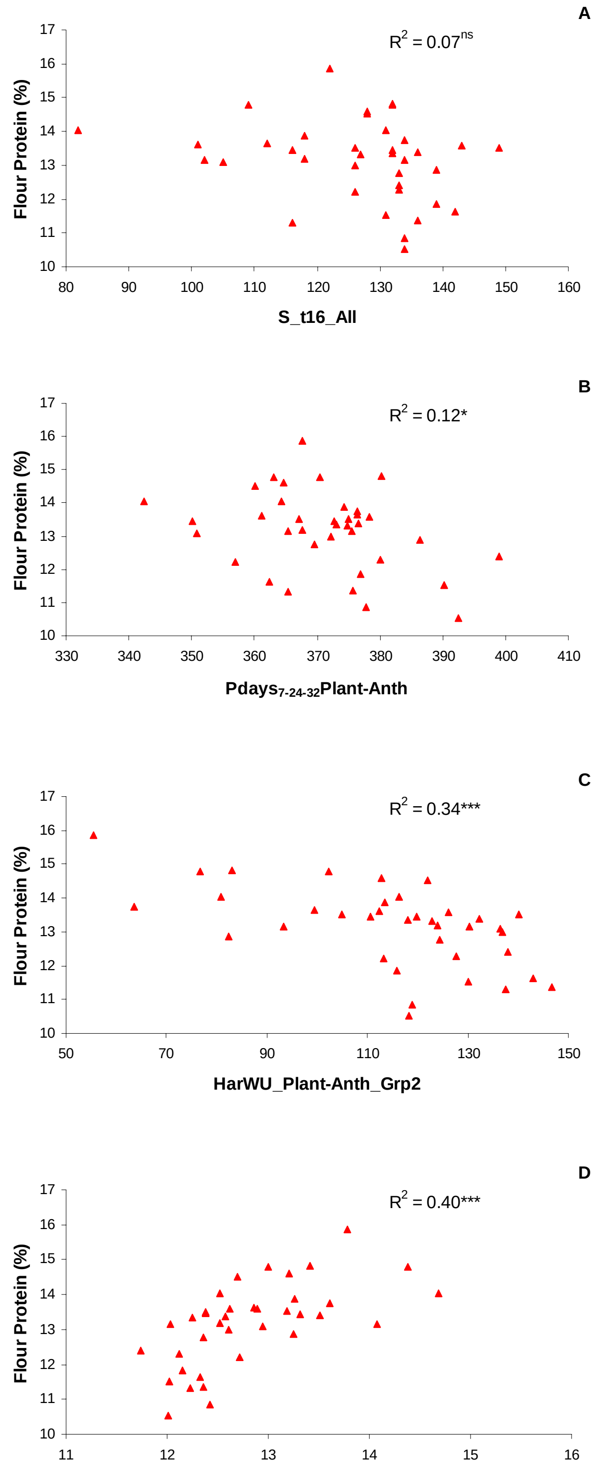

Figure 2.6: Improvement of R^2 values between Superb flour protein and environmental parameters as analysis becomes more complex from (**A**) basic environmental parameters measured over entire season (**B**) to basic environmental parameters accumulated over a different growth stages (**C**) to using modeled crop water use variables accumulated during different growth stages (**D**) to finally using multiple regression analysis.

2.4.10. Predicting Dough and Bread Quality with Grain and Flour Biochemical Characteristics

The ability to predict end-use quality prior to harvest would be very desirable for the Canadian grain industry. It would provide the advantage of assuring our customers (millers and bakers) of the quality of product they will be receiving before the final product is baked. The ability to predict end-use quality of bread wheat grown in western Canada using growing season weather conditions has been investigated. However, the relationship between wheat biochemical constituents and end-use quality variables could provide a means to predict bread quality indirectly. This analysis was performed using many of the dependent variables as independent variables to predict wheat end-use properties.

Flour protein content was the best predictor for 7 of the possible 12 mixograph parameters. The strongest relationship existed between flour protein and peak dough resistance for both AC Barrie and Superb (R^2 = 0.79 and 0.75, respectively) (Table 2.11). HMW-glutenin showed a strong relationship with bandwidth at peak for both AC Barrie (R^2 = 0.30 (Appendix F)) and Superb (R^2 = 0.45). However, flour protein content had a stronger relationship with AC Barrie PBW (R^2 = 0.41) (Table 2.11).

Typically, as protein content increases, there is an increase in the ratio of soluble protein to HMW-glutenin (Figure 2.7). Protein ratios were included in this analysis because they can vary across a range of protein contents. This is because the rate of increase of soluble protein synthesis is greater than the increase in rate of HMW-glutenin synthesis with an increase in flour protein content. The ratio of HMW-glutenin to flour protein was (HMW/Flour Protein) was the strongest predictor for AC Barrie WIP (R^2 =

0.26) and for AC Barrie Baking DDT ($R^2 = 0.28$). Superb Baking DDT had a strong relationship ($R^2 = 0.40$) with another protein ratio, HMW-glutenin divided by soluble protein (HMW/Soluble Protein). Thus, not only protein content but also protein quality had an impact on the mixograph parameters measuring end-use quality.

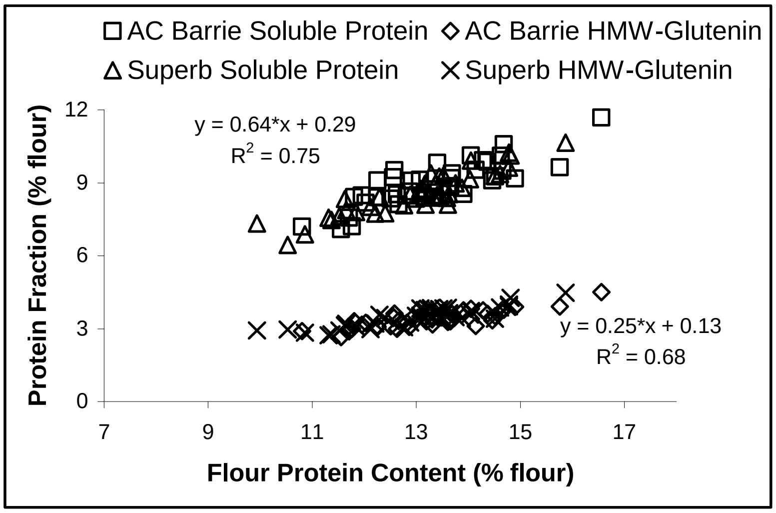

Figure 2.7: Soluble protein and HMW-glutenin protein versus flour protein content to display changing protein fraction ratios with increasing flour protein content.

Work input is defined as the integral of the mixogram curve from time 0 to MTP. This parameter is often used to make conclusions on end-use properties of new CWRS wheat cultivars under examination for registration in western Canada. However, we found in our analysis that WIP was not a reliable predictor for eventual bread quality. WIP was significantly correlated to AC Barrie loaf volume with an $R^2 = 0.20$ but had a non-significant relationship with Superb loaf volume with an $R^2 < 0.01$. WIP was strongly correlated to MTP (AC Barrie $R^2 = 0.67$, Superb $R^2 = 0.71$) but not as strongly correlated to PDR (AC Barrie $R^2 = 0.49$, Superb $R^2 = 0.34$); suggesting that it was more related to the x–axis of a mixogram (MTP) and not the y-axis (PDR). From our findings in this experiment, and several other past researchers, PDR has much stronger relationships with protein variables than MTP. While WIP was significantly correlated to loaf volume of AC Barrie only, PDR had a strong significant relationship to loaf volume for both AC Barrie (R^2 = 0.40) and Superb (R^2 = 0.41) (Appendix F). Another benefit for using PDR over WIP for prediction of loaf volume was that the relationship strength between AC Barrie and Superb was very similar and there was less need for a cultivar specific prediction model. WIP does have stronger relationships with full formula mix time, but the relationship of full formula mix time with MTP is stronger than those with WIP. Thus, from our findings WIP is not a reliable variable to use in analysis of wheat end-use quality when MTP and PDR are readily available.

AC Barrie FarAbs was best predicted by pentosans with an R^2 of 0.26. As discussed earlier, pentosans, despite having a relatively low concentration in CWRS wheat flour, have an extremely high affinity for water and, thus, are critical in flour's ability to absorb water. For Superb, flour protein was the highest contributor to the variation in FarAbs. This was an odd outcome from our dataset since not protein but starch, specifically damaged starch, is much more important in determining wheat flour's ability to absorb water. In this study we did not perform tests of kernel hardness or starch damage on the wheat or flour samples, so we were not able test the relationship between flour protein levels and starch damage. Flour protein and TKW were the main contributors to variation in FarDDT and FarStab, respectively (Table 2.11). Unsurprisingly, the independent variables for AC Barrie (flour protein) and Superb

(TKW) chosen by MaxR analysis for FarDDT were the same, with similar relationship trends, for Mixograph MTP.

FarMTI was strongly correlated to RVA final viscosity for both AC Barrie and Superb. While RVA final viscosity is a function of starch content in wheat flour and starch was the most influential part of wheat flour determining farinograph mixing tolerance.

A possible explanation of how TKW influences Far DDT is the commonly known relationship between heavier kernels and longer filling periods, thus, increased starch accumulation in the kernel. A longer period of starch accumulation in the kernel translates to more amylopectin being formed and accumulated in the starch fraction of the kernel. An increased amount of amylopectin generally leads to increased starch damage.

Flour protein content was the most strongly correlated variable for AC Barrie Rmax, AC Barrie EA, and Superb EA (Table 2.11). Flour protein compositional variables were important determinants for Superb Rmax with an R^2 of 0.32.

Table 2.11: The wheat biochemical constituents that explained the highest level of variance for AC Barrie and Superb end-use quality variables.

Dependent Variable	Cultivar	Explanatory Variable	R^2	Equation
Mixograph				
Mixing time to Peak	AC Barrie	Flour Protein	0.27**	Log(MTP) = -0.072*Flour Protein + 1.96
	Superb	TKW	0.25**	Log(MTP) = -0.019*TKW + 1.66
Peak Dough Resistance	AC Barrie	Flour Protein	0.79***	PDR = 4.19*Flour Protein - 2.83
	Superb	Flour Protein	0.75***	PDR = 3.97*Flour Protein + 4.19
Bandwidth at Peak	AC Barrie	Flour Protein	0.41***	PBW = 2.16*Flour Protein - 7.87
	Superb	HMW-glutenin	0.45***	PBW = 6.82*HMW-glutenin - 2.51
Breakdown @ 3min past peak	AC Barrie	Flour Protein	0.53***	$(PDR\_BR3)^{-1}$ = 0.00042*Flour Protein + 0.009
	Superb	Flour Protein	0.39***	PDR_BR3 = -1.33*Flour Protein + 87.13
Weighted Breakdown @3min	AC Barrie	Flour Protein	0.68***	PDR_BR3weighted = 185.43*Flour Protein + 1280.28
	Superb	Soluble Protein	0.75***	PDR_BR3weighted = 296.34*Soluble Protein + 1353.78
Work input to Peak	AC Barrie	HMW/Flour Protein	0.26**	WIP = 479.97*HMW/Flour Protein - 21.72
	Superb	TKW	0.24**	Log(WIP) = -0.017*TKW + 5.20
Farinograph				
Farinograph Absorption	AC Barrie	Pentosans	0.26**	FarAbs = 3.17*Pentosans + 56.33
	Superb	Flour Protein	0.17**	FarAbs = 0.649*Flour Protein + 56.08
Dough Development Time	AC Barrie	Flour Protein	0.55***	FarDDT = 1.16*Flour Protein - 9.34
	Superb	TKW	0.29***	$(FarDDT)^{-.25}$ = 0.007*TKW + 0.356
Farinograph Stability	AC Barrie	TKW	0.30***	$(FarStab)^{.25}$ = -0.035*TKW + 3.07
	Superb	TKW	0.39***	FarStab = -1.38*TKW + 71.32
Farinograph Mixing Tolerance	AC Barrie	Final Visc	0.30**	Log(FarMIT) = -0.0015*RVA_Final + 8.16
	Superb	Final Visc	0.37***	Log(FarMIT) = -0.0030*RVA_Final + 12.49

Table 2.11 cont'd

Extensigraph				
Maximum Resistance	AC Barrie	Flour Protein	0.24**	Rmax = 1.92*Flour Protein + 5.12
	Superb	HMW-glutenin	0.32***	Rmax = 8.75*HMW-glutenin - 1.92
Maximum Extension	AC Barrie	RVA Breakdown	0.26**	E = -0.06*RVA_Breakdown + 168.96
	Superb	TKW	0.16*	$(E)^3$ = 43559*TKW + 208484
Area under Ext. Curve	AC Barrie	Flour Protein	0.36***	EA = 169.71*Flour Protein - 332.36
	Superb	Flour Protein	0.29**	EA = 179.27*Flour Protein - 344.23
Bread Properties				
Loaf Volume	AC Barrie	Flour Protein	0.45***	$(LV)^3$ = 118144455*Flour Protein - 669590428
	Superb	Flour Protein	0.69***	LV = 46.22*Flour Protein + 417.48
Full Formula Mix Time	AC Barrie	HMW/Flour Protein	0.28**	Full Formula DDT = 20.26*HMW/Flour Protein - 0.96
	Superb	HMW/Soluble Protein	0.40***	Full Formula DDT = 16.48*HMW/Soluble Protein - 2.63

* = significant at p=0.05 level.
** = significant at p=0.01 level.
*** = significant at p<.0001 level.
ns = not significant at p=0.05 level.

2.5. Conclusions

This chapter examined the impacts of growing season weather variability on the end-use quality of CWRS wheat. As mentioned earlier, one of the features about this study is that grain samples were not blended into composites from different regions as is normally done for quality analysis of new varieties in western Canada. All quality data from this study could be linked back to the original growing season weather conditions. Thus, it was possible to analyze how the environment impacted the breadmaking quality of each sample grown across western Canada.

The effects of protein content and protein quality were also tested as factors affecting dough and bread end-use quality. Either protein content or one of the protein fractions was the best explanatory variable for 62% of the dough quality variables and for 100% of the bread quality variables. While this is not a new finding, it is the first time that an experiment was conducted using these methods. These findings support similar conclusions of many earlier researchers (Bushuk et al., 1969; Uthayakumaran and Lukow, 2003; Sapirstein and Fu, 1998).

Peterson et al. (1998) had previously reported that two measures of bread wheat quality, loaf volume and SDS sedimentation, improved with the number of hours with air temperature greater than 32^{o}C during the filling period up to 90 hours, but declined for longer time periods above this temperature. Selles and Zentner (1998) in a review reported that under conditions of increased water deficit starting at flowering, there is an increase in grain protein content. This finding of increasing protein with increasing temperature/drought stress during the filling period has also been reported by other researchers (Campbell and Davidson, 1979; Correll et al., 1994; Fido et al., 1997). Our results have gone a step further and demonstrated that the timing of heat and water stress or accumulation of useful environmental variables within the filling period was very important to the impact on end-use quality. For protein content and the protein fractions, typically, the most sensitive period to an environmental stress was the first half of the filling period. During this period, either heat or water stress had a negative effect on the synthesis of protein. However, useful heat or water use during the same period was beneficial to the synthesis of protein. Conversely, heat or water stress during the second half of the filling period or any time prior to anthesis caused an increase in final protein content. This increase was likely due to a decrease in starch synthesis (or potential synthesis, depending on the timing of the stress) and resulted in a higher proportion of protein relative to starch. Thus, from this experiment we can also conclude that the timing of environmental stress or accumulation of useful environmental variables within the filling period plays an important role on the final proportion of both wheat protein to starch and wheat protein fractions to total protein.

The literature has stated that of the two major protein fractions, gliadin and glutenin, gliadin is responsive to the environment while glutenin is more controlled genetically (Panozzo and Eagles, 2000). In this experiment, both glutenin and gliadin did respond to environmental variability (Table 2.8, Table 2.9, and Table 2.10.). In fact, a single basic environmental variable explained more of the variance in HMW-glutenin than in gliadin. Therefore, our findings agree with others (Panozzo and Eagles, 2000) that gliadin (soluble protein) responds to environmental variability but disagree that variability in glutenin (HMW-glutenin) is controlled more by genetics than the environment.

This study found some new information on impact of environmental stress on starch accumulation. Our finding of a decrease in starch with an increase in temperature late in the filling period agrees with the past research by Randall and Moss (1990). In our experiment we also found moisture stress during the later half of the filling period impacted starch accumulation negatively. This finding was not stated in the current literature and, thus, is considered new information.

In this experiment we also investigated how the type of environmental model affected the ability to predict wheat quality. We began by testing the ability of the most basic environmental models with only daily temperature derived variables and daily precipitation measurements accumulated over the growing season to predict wheat quality. Dividing the growing season, adding more sophisticated variables, and finally including multiple regressions, progressively improved the ability of the environmental variables to explain the variance of end-use quality of CWRS wheat. Basic environmental parameters accumulated over the growing season did make wheat quality prediction possible but did not provide very significant results. The level of significance and amount of variance explained generally improved when the basic environmental variables were accumulated for early planting to anthesis, late planting to anthesis, early anthesis to maturity and late anthesis to maturity. Adding more sophisticated water use variables improved the ability to predict some quality variables, mainly protein content and the protein fractions. This was an important improvement since protein content and the protein fractions were key factors affecting a large majority of dough and bread quality variables. The highest level of wheat quality predictability was achieved using multiple regression analysis with up to three of any of the basic and sophisticated environmental variables accumulated over the various periods of the growing season mentioned above. Therefore, as the sophistication of our quality prediction models increased there was increasing improvement in the prediction models.

Another important finding in this study was the cultivar difference in quality responses to the environment by AC Barrie and Superb. Some of the main differences between the two cultivars include: (i) AC Barrie responded predominantly to useful heat and water use variables while Superb responded predominantly to heat and water stress variables, especially when not using multiple variables, (ii) Superb had a higher heat stress threshold than AC Barrie, and, finally, (iii) in some instances there was a significant relationship found for only one of the two cultivars for a quality parameter (example flour protein in Table 2.7). Thus, we concluded that, despite these two cultivars having statistical support for pooling, there were several differences in the responses of AC Barrie and Superb to environmental conditions. The ability to predict quality properties by an environmental model varied significantly between these cultivars.

3. Investigation into the Effectiveness of the Canadian Grain Grading System's Ability to Segregate Wheat into Levels of Similar End-Use Quality

3.1. Abstract

This study was conducted to investigate the ability of the Canadian grading system to distinguish variation in end-use quality among producer CWRS wheat samples. Samples of two Canada Western Red Spring (CWRS) cultivars (AC Barrie and Superb) were collected from producer fields across western Canada. Over two growing seasons, 2003 and 2004, 48% of AC Barrie samples and 37% of Superb samples graded No. 1 CWRS. A series of t-tests of means and comparison of distribution statistics was performed on several flour, dough, and bread quality characteristics. There was an increase in flour protein content with an increase in grade. This same trend was seen with soluble protein but not with HMW-glutenin. Uniformity of protein content and protein fractions did not improve with an improvement in grade. The Feed grade had significantly lower flour colour reflectance and L* values and the largest variability of all other grades. There was an improvement in uniformity of dough properties on the 10-gram mixograph with an improvement in grade. Farinograph absorption, dough development time, stability, and mixing tolerance index also improved with an improvement in grade. Loaf volume and uniformity also increased with an improvement in grade. The grading system did not consistently segregate higher quality CWRS wheat for breadmaking for all parameters tested. However, the system performed well for some key characteristics, namely farinograph properties and loaf volume.

3.2. Introduction

Production of Canada Western Red Spring (CWRS) wheat has averaged 16 million tonnes per year over the last three decades (Preston et al., 1988). This is 68% of the annual total wheat production in Canada of 23.6 million tonnes for the same period (FAOSTAT, 2005). The vast majority of this wheat production occurs in the three prairie provinces of Manitoba, Saskatchewan, and Alberta, making up a 40 million hectare crop growing region (FAOSTAT, 2005). This large area experiences significant variability in growing season weather. There is significant variability in the quality of CWRS wheat produced at the farm level every year and entering the Canadian grain system.

The Canadian grading system is reputed as one of the best in the world, ensuring that international customers receive the quality they expect when importing wheat from the Canadian Wheat Board (CWB). By maintaining strict standards of quality assurance, Canada has been able to maintain its position as a major wheat exporter in the world wheat market. During the period of 1997 – 1998, Canada exported 73% of its wheat production and was ranked second in the world wheat export market with an 18.7% share of the global market. In 2004 and 2005, Canada was third in world exports with 15% of the world export market behind USA (26%) and Australia (16%) (CWB, 2005b).

In 1912 the Canadian Parliament passed the Canadian Grain Act that introduced the Canadian Grain Commission (CGC, also known as the Board of Grain Commissioners at its inception) as the institute responsible for regulating grain handling and maintenance of quality standards for Canadian wheat (Preston et al., 1988). The current grading system used for CWRS wheat has been in use since 1971. This system includes the following grades in order of decreasing quality; #1CWRS, #2 CWRS,

#3CWRS, and Feed. Each year the grade standards are compiled from samples across western Canada in accordance with the results of the annual crop survey conducted by the CGC. This helps to improve the consistency with which the grades are applied at delivery points across western Canada, especially after a season of unfavorable growing conditions or harvest weather. Occasionally, an additional grade, #4 CWRS, is created to help segregate better quality CWRS Feed in years when there are large volumes of the Feed grade. This first occurred in 1992 when the growing season had a record low average temperature, resulting in late crop maturity and an eventual crop harvest survey full of frost damaged samples. The #4 CWRS grade was also created in 2004 to help market some of the wheat that was of low quality but still had the ability to be marketed as a grade better than Feed.

One of the strong points of the Canadian grain grading system is that it provides customers with high quality wheat that is uniform within grades and between shipments. Large throughput millers and bakers operate highly mechanized and standardized operations. Thus, they prefer to purchase grain/flour that is very uniform to minimize the changes they need to make in their systems. Unfortunately, this can be difficult to assure to a customer since large variability in growing conditions can shift grade distributions and alter the uniformity of wheat shipments. The ability to assure each customer of consistent quality grain is a major function of the Canadian grading system.

Customers purchase their wheat based on protein levels and/or farinograph information from CGC new crop survey samples immediately after harvest as an early indication of eventual end-use quality. Protein content and quality has been found to be the main diving force of many end-use quality parameters (Bushuk et al., 1969; Lukow and Preston, 1998; Uthayakumaran et al., 1999). Thus, the levels and distribution of protein content and quality between each grade are very useful in predicting the end-use quality of the wheat from each grade.

This study was conducted to investigate the effectiveness and accuracy of the Canadian grading system's ability to segregate wheat from producer fields into different grade levels of distinct end-use quality and uniformity. This was performed by looking at mean values and distribution statistics for several flour, dough, and bread quality parameters determined on wheat samples from individual fields in Alberta, Saskatchewan, and Manitoba. A similar analysis has been conducted on composite CWRS wheat samples in grain cargoes (Preston et al., 1988), however, this is the first study to examine grading efficiency on samples from single producer fields.

3.3. Materials and Methods

Wheat samples of AC Barrie and Superb from the 2003 and 2004 growing seasons were collected from producers located across Alberta, Saskatchewan, and Manitoba. A total of 196 samples were analyzed and graded by the Canadian Grain Commission according to the Official Canadian Grading Guide (CGC, 2004). Eighty-seven of the samples collected were AC Barrie with 46 being grown in 2003 and 41 grown in 2004. One hundred-nine of the samples collected were Superb with 49 being grown in 2003 and 60 being grown in 2004. The samples of AC Barrie and Superb were pooled for analysis to imitate the present grading system that segregates only by wheat class. The spatial distribution for the sample locations is shown in Figure 3.1.

3.3.1. Analysis of Flour Quality

Flour was analyzed for protein content, protein composition, total pentosan content, ash, colour, and flour yield. The methods used were the same as those discussed in Chapter 2 except for flour colour which is explained below.

Flour Colour The colour for flour samples was analyzed using a computerized Minolta spectrophotometer (Model CM-3500d, Minolta Co. Ltd., Osaka, Japan). Data acquisition and analysis of colour measurements was performed using the software package Spectramagic. Instrument settings for data analysis using an optical glass Petri dish were downloaded using the disk provided by the instrument. Samples were prepared by creating flour-water slurries used for the analysis by mixing 4 g of flour (14% moisture basis) with 5 mL of water. The flour slurries were then added to a Petri dish and placed on the instrument for measurement. The colour characteristics measured were L* (brightness), a* (red-green colour axis with positive = red and negative = green), b* (yellow-blue colour axis with positive = yellow and negative = blue), and the reflectance (%) across the visible spectrum (400 to 700 nm in 10 nm interals). Reflectance at 546 nm was specifically analyzed as this wavelength is used in the standard Agtron colour test in accordance with AACC methods (method 14-30). Reflectance values for 546 nm were obtained by interpolating between the 540 and 550 nm values.

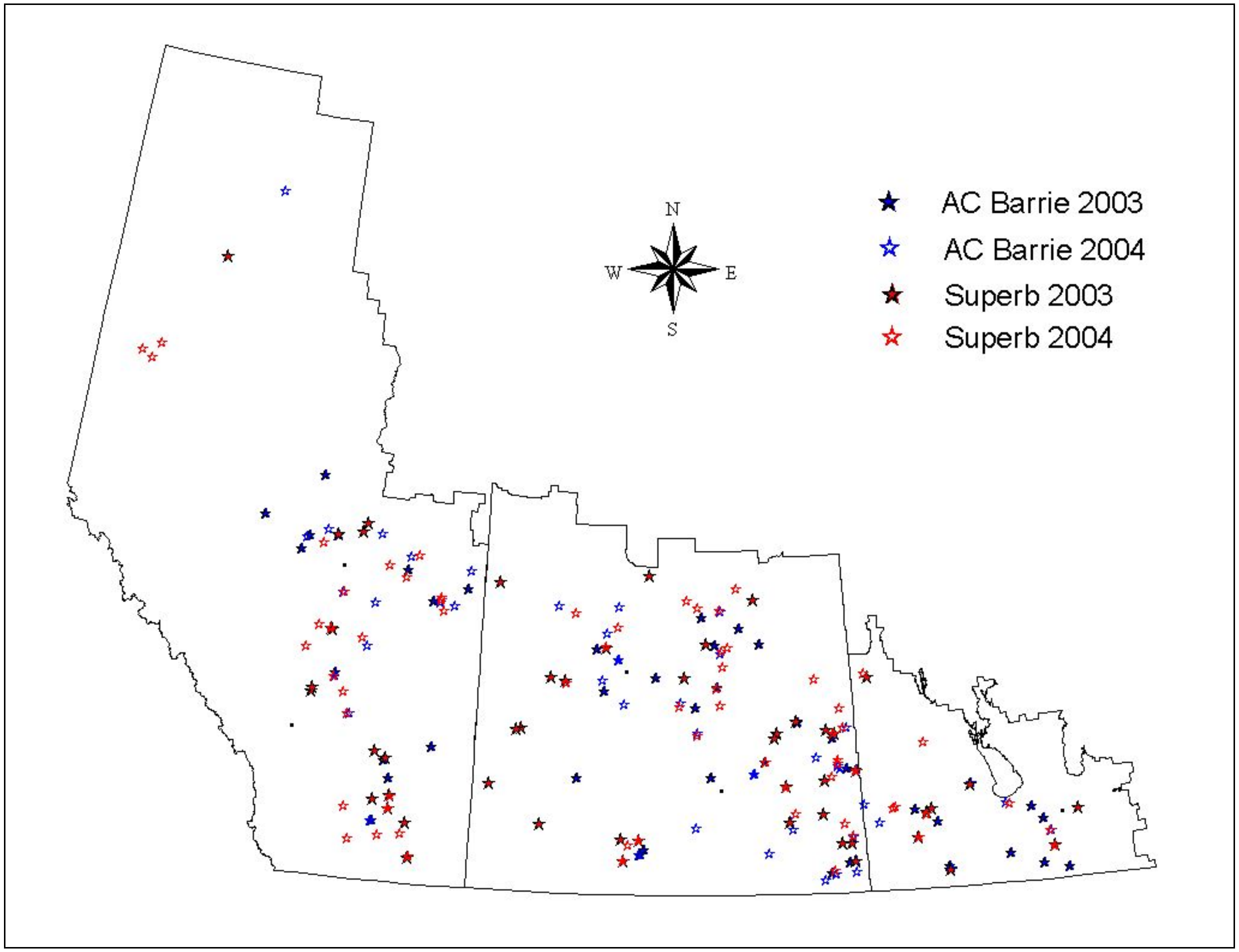

Figure 3.1: Field site locations for AC Barrie and Superb wheat samples collected from 2003 and 2004 growing seasons.

3.3.2. Analysis of Dough and Bread Quality

Analysis of dough quality consisted of measurements using the farinograph and 10-gram mixograph. The methods used for these quality parameters are the same as those discussed in Chapter 2 except that no breakdown parameters from the mixograph were included in the analysis. The methods of baking and loaf volume determination were the same in this study as those discussed earlier in Chapter 2.

3.3.3. Statistical Analysis

Statistical analysis used in this study was conducted according to the procedures outlined by the SAS Institute, Inc (2001). Significant differences of means for each quality parameter between grades were determined by performing a series of t-tests for each grade against all other grades from #1 CWRS to Feed. A mean difference was considered significant at $P < 0.05$.

Coefficients of variation (CV) were used to determine the distribution statistics of each quality parameter for each grade using the structured query language (Proc SQL) of the SAS program. CV's were chosen instead of standard deviations to allow comparison of distribution statistics between quality parameters, despite a difference in magnitude of means.

3.4. Results and Discussion

The growing season conditions between 2003 and 2004 were very different (for a detailed description see Section 2.4.2). The 2003 growing season was very warm and dry, especially late into the grain filling period. The 2003 harvest was quick and occurred without any significant problems due to frost or excessive moisture for nearly all fields in the study. In 2004, the weather was much cooler and wetter with quality problems arising from frost events occurring late August in Manitoba and Saskatchewan and from excessive moisture late in the filling period in many areas of Alberta. As a result, there was a very different distribution of CWRS grades between the 2003 and 2004 samples.

When considering samples from both cultivars, 77.9% of the samples were graded #1 CWRS in 2003 and only 4% were graded as Feed. However, in 2004, only 7.9% of the samples were graded #1 CWRS and 47.5 % were graded as Feed (Table 3.1). It should also be noted that in 2004 there was a #4 CWRS grade added to the grading system as explained in the introduction.

Table 3.1: Distribution of grades for AC Barrie and Superb samples by growing season.

	AC Barrie		Superb	
Grade	2003	2004	2003	2004
#1 CWRS	38	4	36	4
#2 CWRS	4	6	6	6
#3 CWRS	1	8	6	14
#4 CWRS	--	4	--	7
Feed	3	19	1	29
Total	46	41	49	60

There was a difference between the AC Barrie and Superb distributions in the grading system. When combining both years, 48% of the AC Barrie samples and 37% of Superb samples were graded as #1 CWRS (Table 3.2). Within each year, AC Barrie's higher proportion of #1 CWRS grade samples was consistent. Therefore, AC Barrie's quality advantage did not appear to be the result of an increased number of Superb samples collected in 2004 when weather conditions were not favorable for high quality wheat. There was little difference between the AC Barrie and Superb distributions in grades #2 and #4 CWRS. There was an 8% and 3% higher proportion of Superb samples grading #3 CWRS and Feed, respectively, than AC Barrie (Table 3.2).

Table 3.2: Proportion of samples for AC Barrie and Superb for each grade over both 2003 and 2004 growing seasons.

Grade	AC Barrie	Superb
#1 CWRS	48%	37%
#2 CWRS	12%	11%
#3 CWRS	10%	18%
#4 CWRS	5%	6%
Feed	25%	28%

3.4.1. Comparison of Flour Biochemical Constituents between Grades

There were significant differences in the flour biochemical constituents between grades. There was a general trend of decreasing flour protein content as grade decreased (#1 CWRS → Feed) (Figure 3.2). The exception was grade #3 which was slightly, but not significantly, lower than grade #4. Grade #1 had the highest mean value for both flour protein content and soluble protein content. Grades #2 and #4 both had lower mean values than grade #1 but were not significantly lower. The lowest grade, Feed, had the lowest average levels for all three protein parameters, significantly lower than those of grades #1 and #2. Grades #1 and #2 are typically considered milling quality grades of relatively high breadmaking performance.

The variability of the protein parameters was similar between all grades (Figure 3.3). Grades #1, #2, and #3 were very similar with CVs for flour protein content of 9.3, 10.0 and 9.7, respectively. The highest variability was in the #4 grade samples with a CV of 11.6. The CV values between the protein parameters were very similar. Overall, the greatest variability was in soluble protein of the Feed grade with a CV of 17.6.

There was a general trend of decreasing flour yield as grade decreased. Feed grade samples had a significantly lower flour yield than all other grades (68.2%). The highest flour yield occurred with grade #1 (71.5%) (Figure 3.2). The highest variability of flour yield occurred with Feed grade samples (Figure 3.3). This is important since wheat with high extraction rates and with very high uniformity is a strong selling point in a competitive global wheat market. Thus these findings warrant the addition of a premium to the price of #1 CWRS wheat.

Feed grade samples had the highest average total pentosan content. It was significantly higher than any other grade at 2.0%. Grade #1 had the second highest level of pentosans (1.9%) and this was significantly higher than grades #2, #3, and #4 (Figure 3.2). Many of the Feed grade samples (83%) were exposed to premature frosts during the 2004 growing season causing an early termination to the starch accumulation in the filling process. Thus, the high level of pentosans is most likely attributed to a lower than normal level of starch in the kernel, resulting in a higher amount of pentosans relative to starch. The lowest variability in pentosans belonged to grade #4 with a CV of 6.6 followed by grade #1 with CV = 12.6 (Figure 3.3). However, recall that there was no #4 CWRS grade for the 2003 growing season and, thus, the samples belonging to grade #4 are only from the 2004. Therefore, we can expect less variability from the samples of grade #4 CWRS since these samples were taken from only one growing season. This information should be noted when interpreting the results from those samples graded #4 in this study.

There was no significant difference between any of the grade mean values for mineral content (flour ash) (Figure 3.2). Ash content is related to flour yield as higher extraction rates usually mean increased levels of bran in the flour, resulting in an increased flour ash content. However, this dataset showed no significant relationship between flour ash and flour yield.

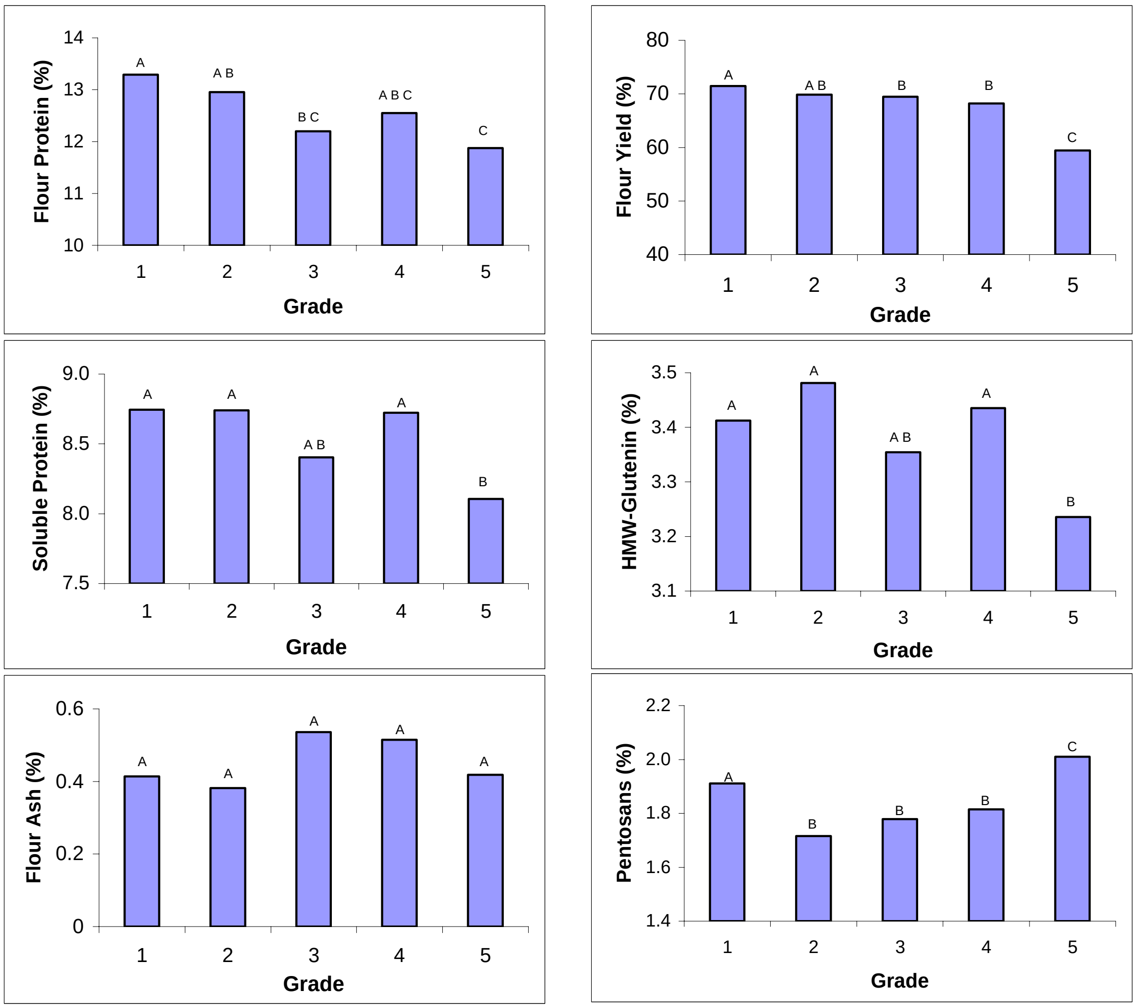

Figure 3.2: Mean values for flour protein content**,** flour yield, flour protein composition, flour ash content and pentosans for grades #1CWRS through Feed (labeled grade 5).

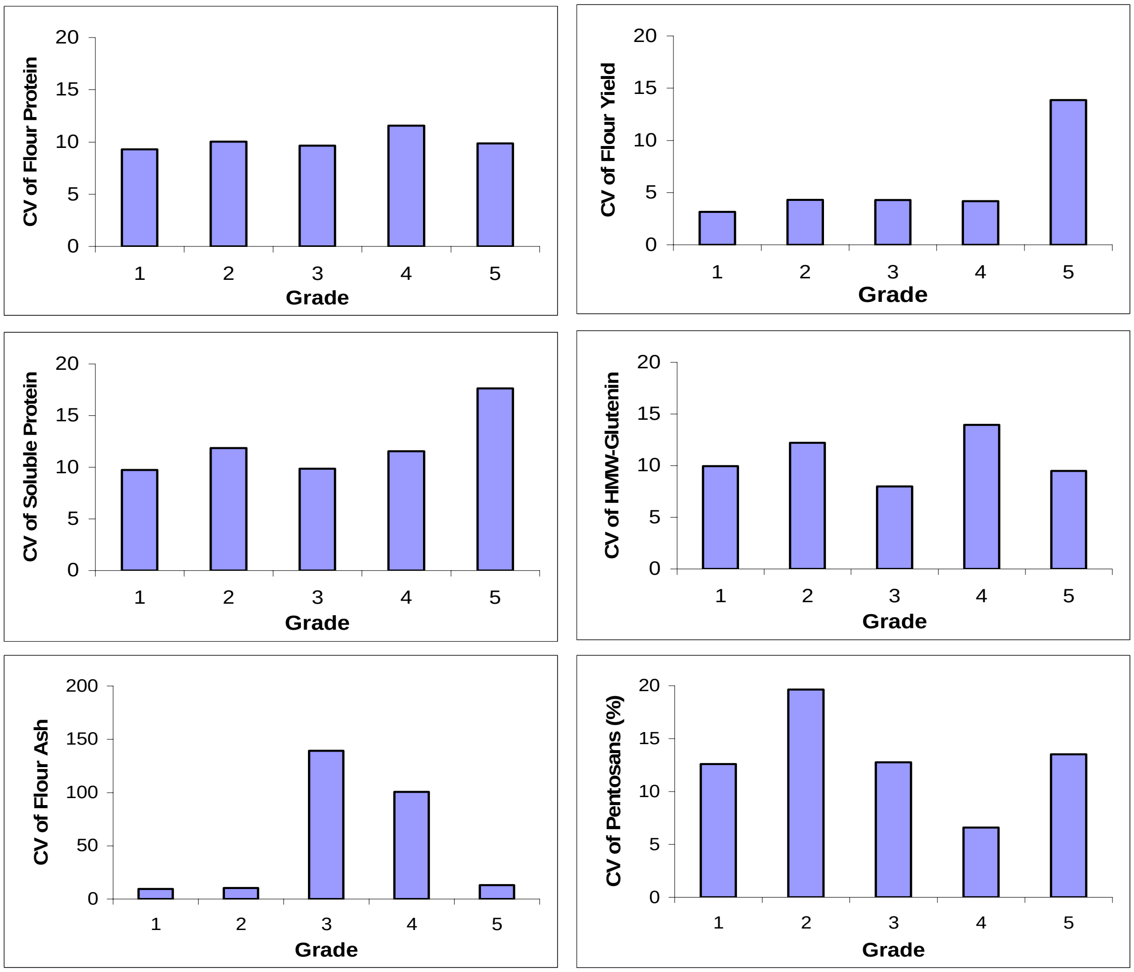

Figure 3.3: Coefficients of variation (CV) for flour protein content, flour yield, protein composition, flour ash content, and pentosans for grades #1CWRS through Feed (labeled grade 5).

3.4.2. Comparison of Farinograph Parameters between Grades

Grade #1 CWRS had the best values for all farinograph parameters. Grade #1 had significantly higher absorption, dough development, and stability measurements than all other grades. Grade #1 also had the lowest (best) mixing tolerance index of all cultivars, significantly lower than grades #3, #4, and Feed (Figure 3.4). Thus, the grading system was effective at discriminating between farinograph parameters for these samples.

Of all the farinograph parameters, absorption had by far the lowest CV's. The CV of farinograph absorption was approximately 10 times lower than for dough development time, stability, and mixing tolerance index. The uniformity between grades for the remaining three farinograph parameters was similar, ranging between 36.6 and 66.7 (Figure 3.5).

Averaged over all grades, CV's were 3.9, 52.3, 65.8, and 59.7 for farinograph absorption, dough development time, stability, and mixing tolerance index, respectively. For all four parameters, #1 CWRS had a lower CV than the CV averaged over all grades. This is an important because it allows us to provide more assurance when a buyer purchases #1 CWRS wheat that they will receive a more uniform product. However, there was not a trend of improved uniformity with improvement in grade. In fact, for farinograph absorption and farinograph mixing tolerance index grades #4 and Feed had lower CV's than grades #1 and #2. However, as mentioned previously, grade #4 contains samples from 2004 only which makes it difficult to compare to other grades.

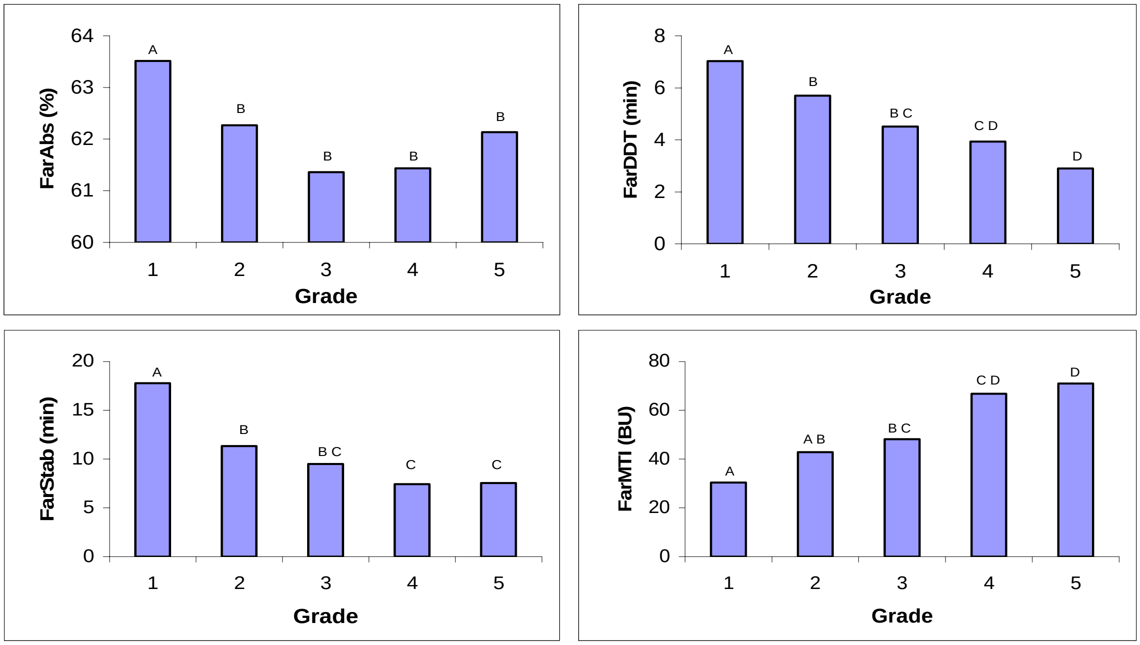

Figure 3.4: Mean values for farinograph absorption (FarAbs), farinograph dough development time (FarDDT), farinograph stability (FarStab), and farinograph mixing tolerance index (FarMTI) for grades #1CWRS through Feed (labeled grade 5).

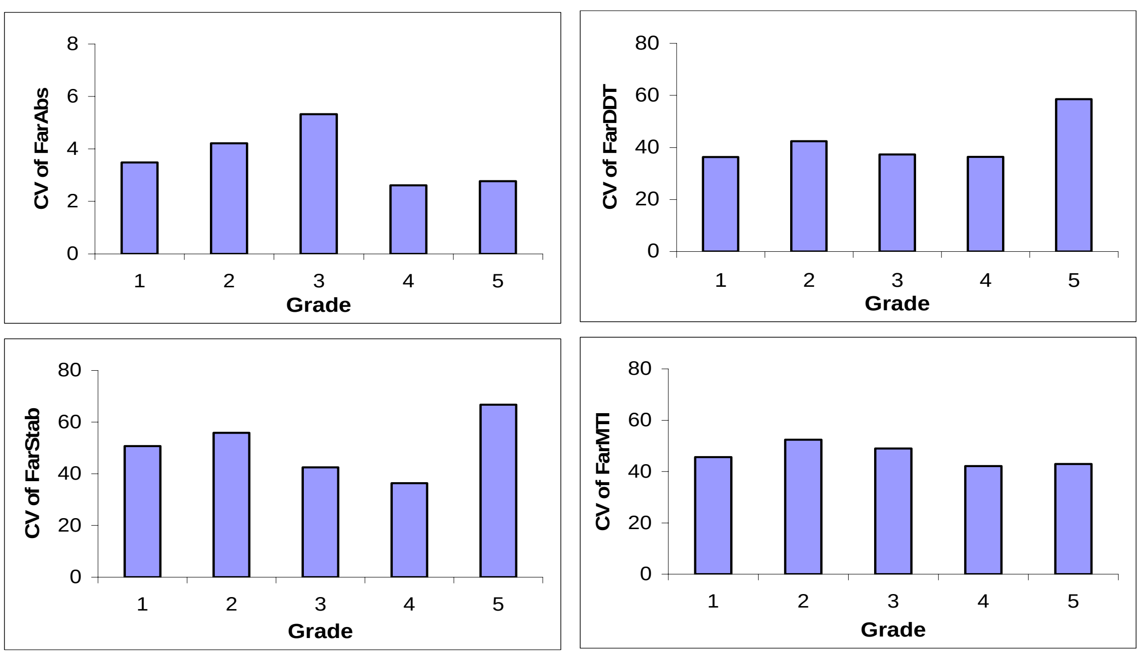

Figure 3.5: Coefficients of variation (CV) for farinograph absorption (FarAbs), farinograph dough development time (FarDDT), farinograph stability (FarStab), and farinograph mixing tolerance index (FarMTI) for grades #1CWRS through Feed (labeled grade 5).

3.4.3. Comparison of Mixograph Parameters between Grades

In Chapter 2 we found that mixograph parameters were driven mainly by protein content and protein quality levels (Table 2.11). Furthermore, earlier in this section we showed that a direct relationship existed between flour protein content and grade. However, this trend was not present in the results of the 10-gram mixograph over the five grades (Figure 3.6). In general, there was little difference in the means between grades for all four mixograph parameters.

For mixing time to peak there were no significant differences among any of the grades. Grade #1 had the lowest variability for mixing time to peak while Feed grade had the highest. The CV for all grades combined was 31.5, lower than the Feed grade CV (41.1) but higher than the CVs for grades #1 through #4.

For peak dough resistance, grades #1 through #4 were all significantly higher than the Feed grade but not significantly different from one another. The CV's for all grades ranged between 10.4 and 14.7 with grade #1 having the lowest variability and Feed grade having the highest (Figure 3.7). Grades #2 and Feed had higher CV's than the combined CV for all combined samples of 13.3.

There were no significant differences of means between any grades for bandwidth at peak (Figure 3.6). Again, grade #1 had the lowest variability while grade #4 had the highest. Grades #2, #4, and Feed all had CV's higher than the CV for all combined samples of 20.1.

For work input to peak, only grades #1 and #4 were significantly different from grade Feed while grades #2 and #3 were not significantly different from any other grades (Figure 3.6). Grade #1 again had the lowest variability in CV while Feed grade had a CV much higher than any other grade at 40.2; more than double that of the second highest CV from grade #2 at 17.5 (Figure 3.7). For work input to peak, only the Feed grade had a higher CV than the combined CV for all samples which was 27.7.

The mixograph did not provide a consistent trend of improving mean values with improving grades unlike the farinograph or protein content. For all mixograph parameters, grade #1 samples did not exhibit the highest values. Grade #4 demonstrated stronger dough characteristics for peak dough resistance and bandwidth at peak than the breadmaking grades (#1 and #2). However the lower uniformity of mixing time to peak and work input to peak for Feed grade is a favorable result. Lower variability in the higher grades for these mixograph parameters is very supportive to the success of the Canadian Grain Grading System as it enforces the argument that customers receive wheat of consistent performing characteristics within and between shipments.

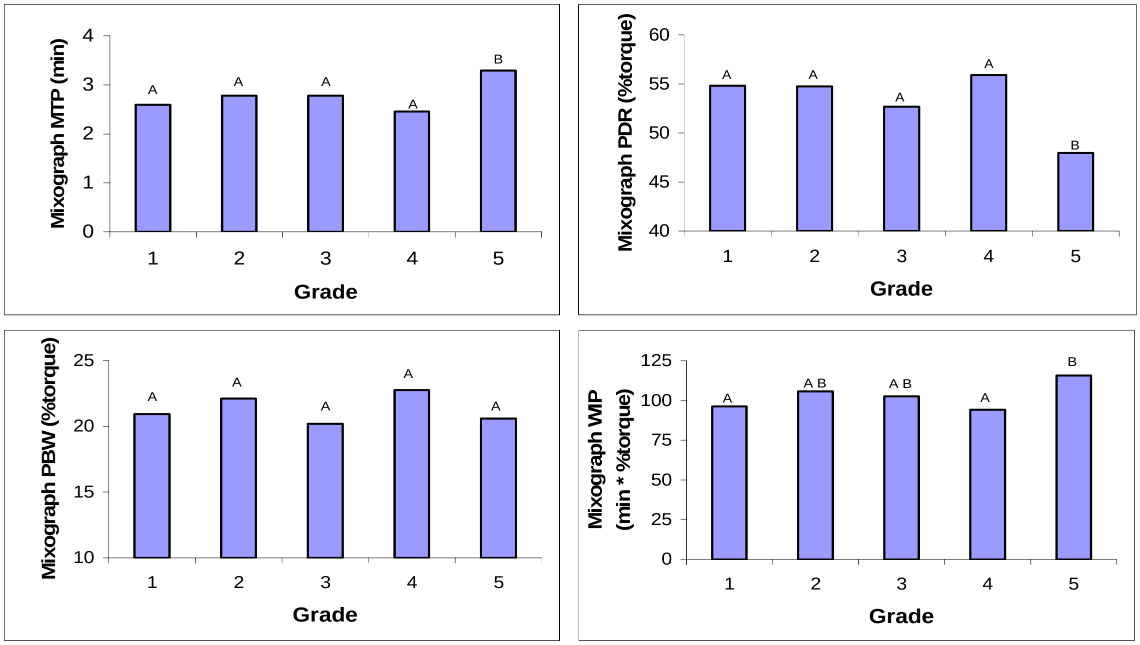

Figure 3.6: Mean values for mixograph peak development time (MTP), mixograph peak dough resistance (PDR), mixograph bandwidth at peak (PBW), and mixograph workinput at peak (WIP) for grades #1CWRS through Feed (labeled grade 5).

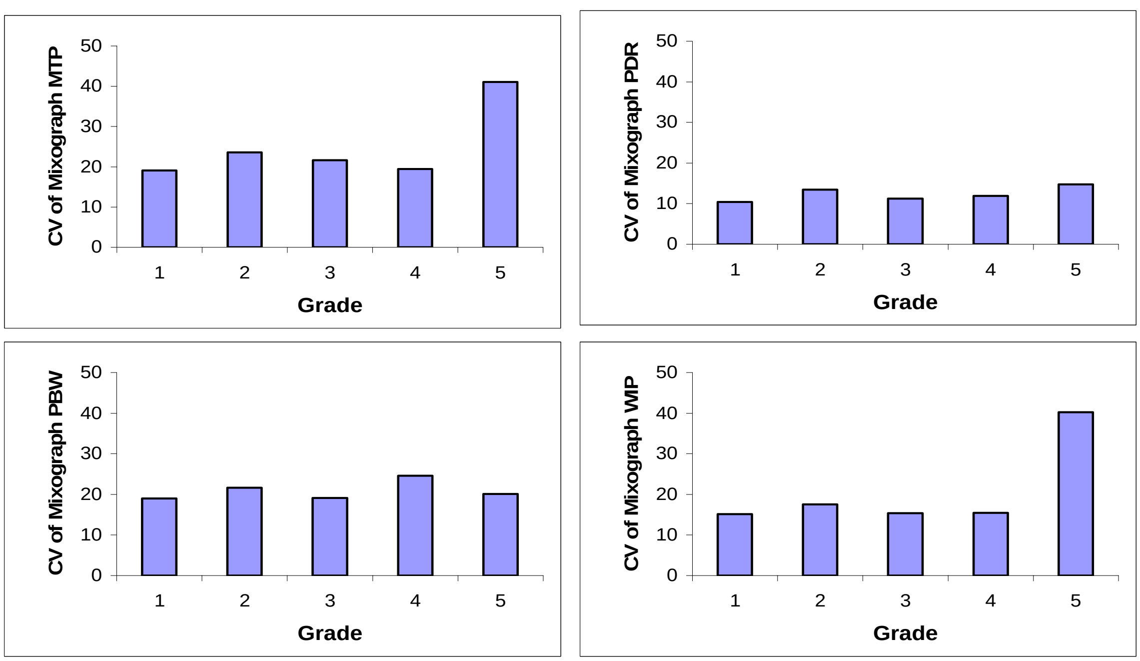

Figure 3.7: Coefficients of variation (CV) for mixograph peak development time (MTP), mixograph peak dough resistance (PDR), mixograph bandwidth at peak (PBW), and mixograph workinput at peak (WIP) for grades #1CWRS through Feed (labeled grade 5).

3.4.4. Comparison of Flour Colour between Grades

Four measurements of light reflectance were used to analyze flour colour. These included reflectance at 540 nm (R546), L* (brightness), a* (measurement along red-green axis) and b* (measurement along yellow-blue axis. The breadmaking quality grades of #1 and #2 both had significantly higher R546 than the Feed grade while grade #1 was also significantly higher than grades #3 and #4 (Figure 3.9). The variability for grades #1 through #4 was very similar with CV values between 1.5 and 1.8. The variability of R546 was much higher for the Feed grade samples with a CV value of 4.7 (Figure 3.10). Thus, there was much more uniformity in the flour colour for samples graded better than Feed.

There was a strong positive relationship found between flour R546 and flour yield with an $R^2 = 0.76$ (Figure 3.8) as would be expected. Higher flour refinement (the degree to which flour is pure starchy endosperm without germ or bran contaminants) should increase flour reflectance at 546 nm level. However, some of these flour yields were very low. All of the samples with flour yields less than 62% were from the Feed grade and all samples less than 63.5% were downgraded because of frost damage. Thus, these low flour yields were from samples that had their filling period prematurely terminated which resulted in shrunken kernels that caused milling difficulties and more bran in the flour. The samples with frost damage were all from the 2004 cropping year. Therefore, if it had not been for that weather event, the relationship in Figure 3.8 would not have such a high R^2 value.

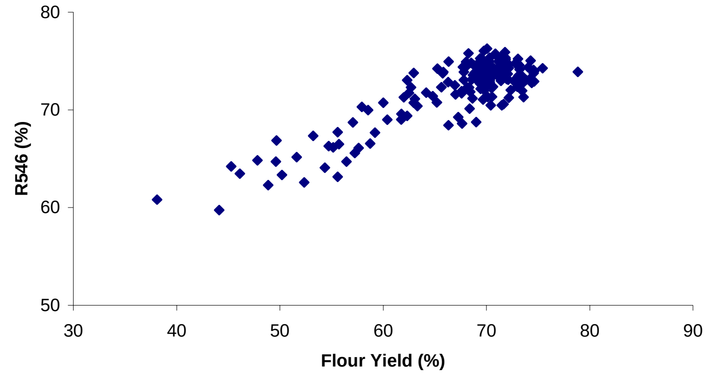

Figure 3.8: Relationship between flour yield and flour light reflectance at 546 nm (R546).

Flour brightness (L*) showed a similar trend to that for R546 values across grades. Generally, as grade decreased, so did the brightness of the flour. Again, the breadmaking grades of #1 and #2 were significantly higher (brighter) than the Feed grade while grade #1 was significantly higher than grades #3 and 4 (Figure 3.9). The variability of L* was very similar to R546 with grades #1 through #4 having similar CV values while the Feed grade had much more variability (Figure 3.10). However, the overall variability for L* was very low.

The measurements a* and b* for flour colour showed very little discrimination between grades. The only significant difference was that the Feed grade had significantly higher a* level (more yellow) than any other grade. The variability for a* showed no trend between grades. The variability for b* was nearly 10 times lower than that for a*. There was also a trend in the variability for b* with an increase in variability with decrease in grade (Figure 3.9 and Figure 3. 10).

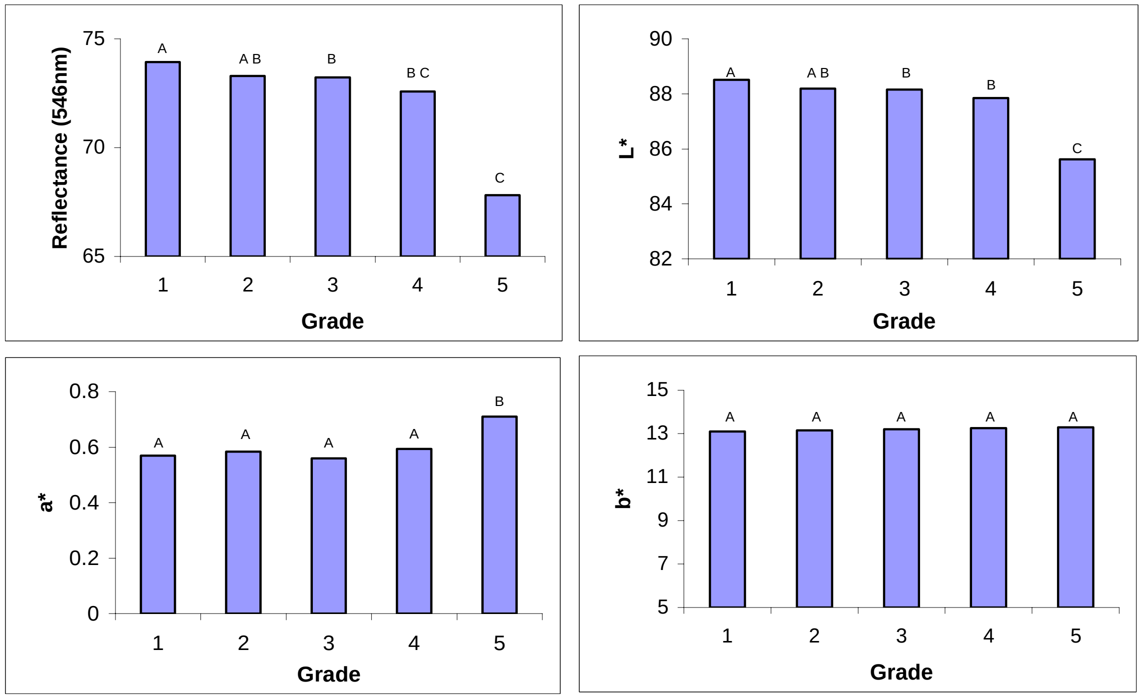

Figure 3.9: Mean values for flour light reflectance at 546nm, L*, a*, and b* for grades #1CWRS through Feed (labeled grade 5).

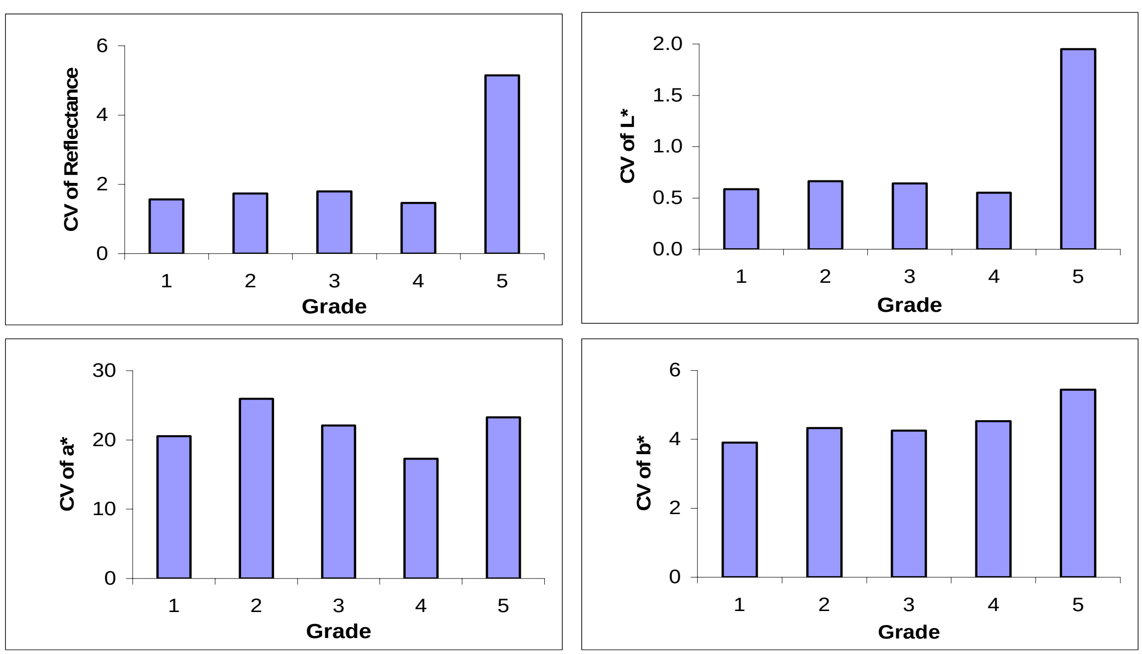

Figure 3.10: Coefficients of variation (CV) for flour light reflectance at 546nm, L*, a*, and b* for grades #1CWRS through Feed (labeled grade 5).

3.4.5. Comparison of Bread Loaf Volume between Grades

There was a positive relationship between increasing loaf volume and increasing grade. Grade #1 CWRS produced loaf volumes that were more uniform and significantly higher than all other grades. Grades #2 through #4 produced average loaf volumes that were not significantly different from each other but were significantly higher than the average loaf volume for Feed grade. The variability for grades #2 through #4 was similar with grade #3 having the lowest CV and grade #4 having the highest CV of the three. Feed grade wheat had the lowest average loaf volume (significantly lower than all other grades) and the highest variability (CV = 22.9) (Figure 3.11).

As previously mentioned, similar to loaf volume, flour protein content increased as grade improved. The uniformity of flour protein and loaf volume was also similar with #1 CWRS having the lowest CV's compared to all other grades. A notable difference between flour protein content and loaf volume was the large increase in loaf volume variability for Feed grade wheat. This was likely due the effect of frost on many of the Feed samples. As discussed earlier, this caused an increase in protein content due to its relation with the premature termination of starch synthesis. Thus, despite having high protein concentrations, there was a detrimental characteristic to either the starch or possibly enzyme content of the flour that resulted in lower than expected loaf volumes. Separating the frost damaged samples from the non-frost damaged samples in the Feed grade created a different picture of loaf volume variability. The CV for the Feed grade samples not affected by frost was 9.6 while the CV for those affected by frost in the Feed grade was 23.4. This was also true about the CV for grade #4 where the CV was 7.0 for non-frost affected samples and 12.1 for frosted samples. Therefore, frost damage on a wheat crop greatly jeopardizes the ability to properly estimate the end-use quality and uniformity of wheat.

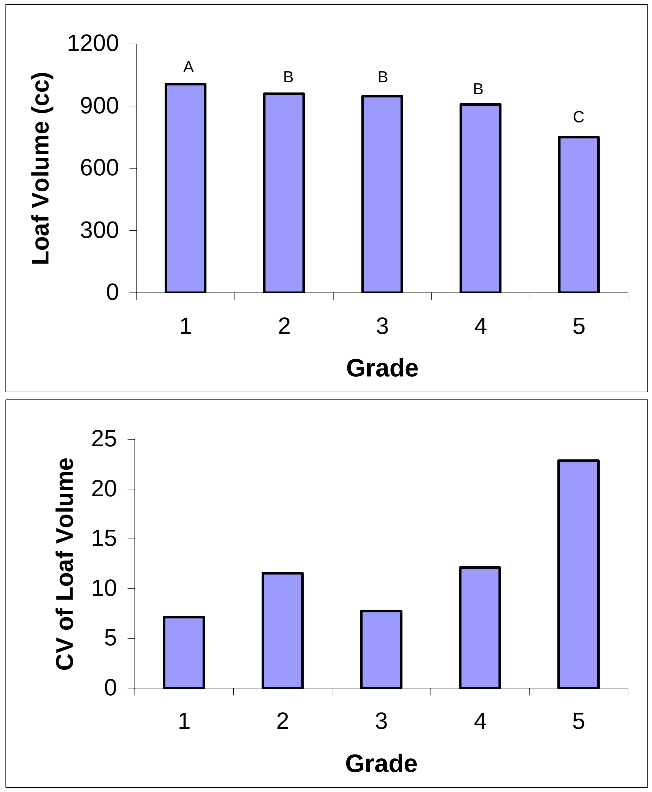

Figure 3.11: Mean and coefficient of variation (CV) values for loaf volume across grades #1 CWRS to Feed (labeled as #5).

3.5. Conclusions

The Canadian grading system was established to ensure that wheat of the same grade from different areas of western Canada will have consistent end-use quality. In our previous study (Chapter 2) we found that not only protein content but also protein quality played a significant role in determining wheat end-use quality. In this experiment we observed that flour protein content and grade were positively related. This observation demonstrates the value of the grading system because of the direct relationship between protein content and several end-use quality parameters. However, we did not see a similar trend with the protein fractions, especially for HMW-glutenin. This may have occurred because as flour protein content increased there was a rapid increase in soluble protein and a much slower increase in HMW-glutenin (Figure 2.7). Thus, a smaller range of HMW-glutenin concentrations existed across a wide range of protein content and there would be a less prominent trend of increasing HMW-glutenin with increasing grade.

The two methods of measuring dough strength, the mixograph and farinograph, provided two very interesting sets of result. The mixograph showed no trend of increasing dough strength with improved grade, but did show lower uniformity in mixing time to peak and work input to peak for the Feed grade. In contrast, the farinograph showed no trend of improved uniformity with improved grade but did show a trend of improved mean absorption, dough development time, stability, and mixing tolerance index as grade improved. Farinograph analysis is widely used by the milling and baking industry as an early indicator of breadmaking quality. Therefore, there is some justification for paying a premium for higher grades of CWRS wheat because of the grading system's ability to segregate farinograph parameters.

Through the flour properties analysis we saw improved flour protein content with an increase in grade but did not see an improvement in uniformity. Flour colour showed no significant trends except that Feed grade samples had significantly lower R546 reflectance and L* values. For dough properties, depending on which measurement of dough strength was used, there was an improvement of either mean dough mixing properties (farinograph) or uniformity (mixograph), but not both. There appears to be a trade off between uniformity and quality performance across grades of CWRS wheat. However, for the final product, bread, there was a definite trend of increasing loaf volume and improved uniformity with increasing grade. This is an important result since loaf volume is considered to be the most critical and all inclusive property of a sample of wheat.

A similar study by the Canadian Grain Commission (Preston et al.,1988) examined the quality and uniformity of CWRS cargo shipments from the Pacific and Atlantic terminals. This experiment examined composite samples gathered over a period of 3 months from shipping vessels of grades #1 CWRS, #2 CWRS, and #3 CWRS during the years1973 to 1986. Our experiment varied from this because it worked with grain samples collected from specific growing locations.

Preston et al. (1988) found an increase in flour protein content and uniformity with improving grade. Our experiment also found an increase in flour protein content with increase in grade from #3 CWRS to #1 CWRS but did not see a notable improvement in quality. Preston et al. (1988) also found decreasing ash content and improved uniformity with improving grade. Our experiment found no significant change in ash content between the top three grades but did see improved uniformity of ash content with increasing grades.

Preston et al. (1988) found increasing quality and uniformity of farinograph parameters with higher grade. Our experiment found an improvement only to farinograph parameters but no consistent improvement in uniformity. However, loaf volume showed improved quality and uniformity from #3 to #1 CWRS in both the study by Preston et al. (1988) and this experiment. While these two studies were aimed at examining the effectiveness of the Canadian grading system there were subtle differences between the results. This is most likely due to the different methods utilized to gather samples. Preston et al. (1988) examined composite samples that had blended out much of the environmental variability present in growing conditions on the Canadian prairies. There was no blending of samples in this study.

It could be argued that there were apparent issues with the Canadian grading system's ability to distinguish between wheat quality levels based on flour and dough properties in this study. However, when bread loaf volume was considered, the grading system was very successful in achieving its goal of segregating wheat samples into grades of appropriate quality and uniformity. Thus, if the Canadian Grain Commission can continue to uphold its performance in regulating and maintaining the standards in place to achieve desirable quality assurance for its customers, then Canada should remain a prominent player in the global quality wheat market for many years to come.

4. General Discussion and Conclusions

This study has investigated the predictability of CWRS wheat quality from growing season weather using wheat samples grown in producer fields from all regions of western Canada. The ability to predict wheat quality would be a valuable asset for Canadian wheat marketing by the CWB. Through its Department of Weather and Crop Surveillance, the CWB has become very effective in predicting wheat yields from western Canada months before the grain enters the grain system. Unfortunately, the ability to predict the quality of this grain is not yet as advanced. If it was possible to know in late July to early August the quantity and quality of grain that could be marketed, the CWB would acquire an additional advantage over the stiff competition of the global wheat market.

This study was unique because it analyzed the impacts of growing season weather conditions from specific fields on CWRS wheat quality from the same fields. Statistical relationships were developed between environmental parameters and wheat quality from the producer fields. This approach was chosen over the use of blended samples from regions for two reasons; one because blended samples hide the impact of environment on wheat quality and, two, because there can be great variability in environmental conditions, especially summer precipitation, even in localized regions.

There were several important results from this study. The main results are contained in an extensive set of regression equations that could be utilized as models to estimate wheat quality with growing season weather data and derived variables. However, in order to achieve improved relationships between environmental conditions and wheat quality parameters there needed to be a model for estimating crop water use from air temperature and precipitation. The simplest weather-quality relationships utilized only daily temperatures and precipitation values. However, as we accumulated the weather variables over specific time periods from the growing season, added modeled water use values, and eventually included multiple regression analysis, both the level of significance and the amount of variance explained for CWRS quality variables increased. This was especially true for protein content and protein quality, which had significantly improved relationships to weather conditions with the introduction of water use variables. Protein content and protein quality are very important properties to predict because they are main variables driving the majority of wheat end-use properties, including bread loaf volume.

The derivation of water demand and use requires agrometeorological models, therefore, a trained and knowledgeable person and a system to derive the variables is needed in order to utilize the weather data for this purpose. Thus, the financial benefit to using the water demand and use variables to achieve higher levels of predictability for CWRS quality would have to be more than the cost of the system needed to generate and utilize the more sophisticated variables for prediction. It should also be considered that a sophisticated model that is predicting wheat quality based on growing season weather conditions is not very useful in a year like 2004 where a widespread severe frost on August 20th suddenly downgraded a large majority of the CWRS wheat samples in western Canada. However, in 2004 a grain marketer could, using the quality prediction model, assure his customers that certain areas in western Canada not affected by the frost were going to have a specific quality. This early information could provide additional notice to the buyer of the potential volume of high quality wheat available from western Canada before they go shopping elsewhere. In order to service those buyers purchasing high quality CWRS in this type of situation, the CWB would have to carefully source wheat from specific regions not affected by frost and predicted to have CWRS of a specified quality.

From our study we also concluded that the differences between cultivar responses to environmental conditions should also be considered in the development of a quality predicting model. Our study focused on the two CWRS cultivars most commonly grown in western Canada, AC Barrie and Superb. Despite these two cultivars being from the same wheat class (CWRS) there were many differences between the responses of each cultivar to the environment. Thus, when creating a quality prediction model, the cultivar or cultivars chosen to develop the model should be carefully considered. In our project, we chose AC Barrie and Superb because of their high level of acceptance by farmers in western Canada. The CWRS class has had a history of a single cultivar having strong dominance for a period of years, then being replaced. For example, in 1982, Neepawa accounted for 65% of the CWRS planted; in 1990, 47% was sown as Katepwa, and in 2002, nearly 50% of the CWRS grown was AC Barrie (Watson, 1993). Through the course of this project (2003-2005) Superb has started to become the new CWRS cultivar of choice in western Canada, especially in Saskatchewan and Alberta. Thus, it would be ill-advised to develop a quality model based on the environmental responses of AC Barrie; instead it should be based on Superb. Possibly a quality model should be designed to be more specific for different regions on the prairies by being based on Superb for fields in Alberta and Saskatchewan and based on AC Barrie in Manitoba where Superb's higher susceptibility to fusarium has discouraged Manitoban farmers from adopting the new cultivar.

If a quality prediction model is based on Superb, we need to consider what happens if a new cultivar eligible for registration comes through the registration process with slightly better agronomic features and breadmaking properties but very different response to the environment than Superb. The introduction of this new cultivar to western Canada would jeopardize the ability of the quality prediction model to provide reliable results. Should this new cultivar be approved for registration even if it would cause a detrimental effect on the marketability of Canada's wheat? If the new cultivar had much superior agronomic and breadmaking characteristics than Superb, it would be foolish to not introduce it but field research would be needed to create modifications to the current quality prediction model.

It might also be possible to consider a series of "multi-cultivar" regression equations, where results from many cultivars are pooled and the predictability of overall quality response for several major CWRS varieties are assessed. If a quality prediction model could be established in this fashion, then it would be less affected by the adoption of a new cultivar and the quality prediction models could be continuously updated with ongoing field data collection.

This project investigated the current Canadian grain grading system's effectiveness to segregate wheat according to breadmaking quality. Typically, customers of Canadian wheat continually purchase our product because they appreciate the high quality and high level of uniformity. In fact, they have come to appreciate it so much that it has now become a demand. In our study, several flour and dough quality measurements were not well separated by the Canadian grading system. Some showed improving quality with higher grade but no trend in uniformity (eg. farinograph). Some dough quality parameters showed the exact opposite with improving uniformity with higher grade but no trend in the quality across grades (eg. mixograph). However, the Canadian grading system was very effective in segregating wheat samples appropriately for bread quality. For loaf volume, there was a definite trend of increasing quality and uniformity with improving grade. Essentially, this is the ultimate test of quality since it is the final product, bread, that matters the most to the final consumers. However, in the grain industry, issues do arise between sellers and buyers about wheat shipments that do not provide the expected flour or dough characteristics based on the grade purchased. When customers purchase #1 CWRS from the CWB, they expect to pay a premium price because of their expectation for the highest quality wheat. Our study indicates that despite any inconsistencies that might exist between CWRS grade and flour or dough properties, that bread quality is well-represented by the grading system. When difficulties arise, a full bake test from a shipment in question may provide some pleasant surprises for both the buyer and seller.

There are numerous opportunities for future research as a result of this project. One of the most important issues would be to gain an understanding of the physical basis for the statistical relationships discovered between growing season weather conditions and CWRS quality. There were some CWRS quality parameters that were most highly correlated to specific weather conditions and growth stages for reasons which were not immediately apparent. For example, it is not clear why Mixograph bandwidth at peak for AC Barrie is positively correlated to the water deficit from planting to anthesis (r^2 =

0.34**) nor why farinograph absorption for Superb is negatively correlated to total rainfall from planting to anthesis (R^2 = 0.22**). There are complex effects of weather on wheat growth and development that collectively affect the starch and protein components in the grain. A physical understanding of these interactions could help with breeding wheat cultivars to be more robust during sensitive periods and provide improved grain uniformity in spatially variable growing seasons. This information would be most useful to wheat breeders.

During our study, fields grown under irrigation were observed to have abnormal mixing curves with weaker mixing tolerance than expected based on grain and flour properties. It would be very useful to understand the reasons why this characteristic was observed.

From the 2004 season there were samples downgraded to the Feed grade category due to frost damage that were later shown to have quality characteristics comparable to a #1 CWRS. It would be very useful and financially beneficial to producers if a better measure of frost damage could be found to differentiate between samples capable of performing optimally and those deserving a feed grade.

The most useful outcome from this study would be the implementation of an operational system to forecast CWRS quality from growing season weather. There will be a number of issues to be addressed in order to make this feasible. Access is needed to a spatially dense network of weather stations. Fortunately these networks exist and the CWB Weather and Crop Surveillance department has real-time access to these data. Another issue would be determining how to handle the variation in quality response between genotypes, as discussed earlier in this section. One of the requirements for quantifying the weather in this study was having each producer obtain a spring soil moisture estimate using a simple probe. Spring soil moisture is not normally measured in a systematic way other than in the fall. However, spring soil moisture could be estimated using fall measurements and weather information gathered at Environment Canada weather stations spatially distributed across western Canada. Therefore, a method of estimating of spring soil moisture levels would need to be implemented. In addition, our study did not show a significant impact of fertility on the quality parameters. We assume that the fields sampled in this study are biased towards producers who tend to use adequate fertilizer in their management. This is not always the case, and there would need to be some mechanism to take account of the effects of fertility, especially soil nitrogen, on CWRS quality.

Issues of wheat quality assurance and traceability are becoming more common in the Canadian grain industry. In the past Canada has been known as a global leader in both of these fields. However, as the wheat market becomes increasingly competitive, Canada must remain proactive in its efforts to discover and implement improved methods and technologies to maintain its hard-fought reputation for growing and delivering wheat with high levels of quality, consistency and performance.

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6. Appendices

6.1. Appendix A – Sample Farinogram, Mixogram, Extensigraph, and RVA Pasting Curve from Quality Analysis.

A.1. Farinograph

Farinograph analysis was conducted on a Brabender farinograph according to the AACC approved methods, Method 54-21. Optimal water absorption (FarAbs) of a flour sample is defined as the amount of water needed to make a dough with a farinogram curve that peaks at 500 BU (Brabender units) and is measured in % water absorption. The time taken to reach peak development is called dough development time (FarDDT). FarDDT is measured in minutes. Farinograph stability (FarStab) is the time from when the farinogram curve first reaches 500 BU till the time the curve drops below 500 BU. The drop in height of the farinogram curve 5 minutes after peak is known as the mixing tolerance index (FarMTI). FarMTI is measured in Brabender Units. (Figure A.1).

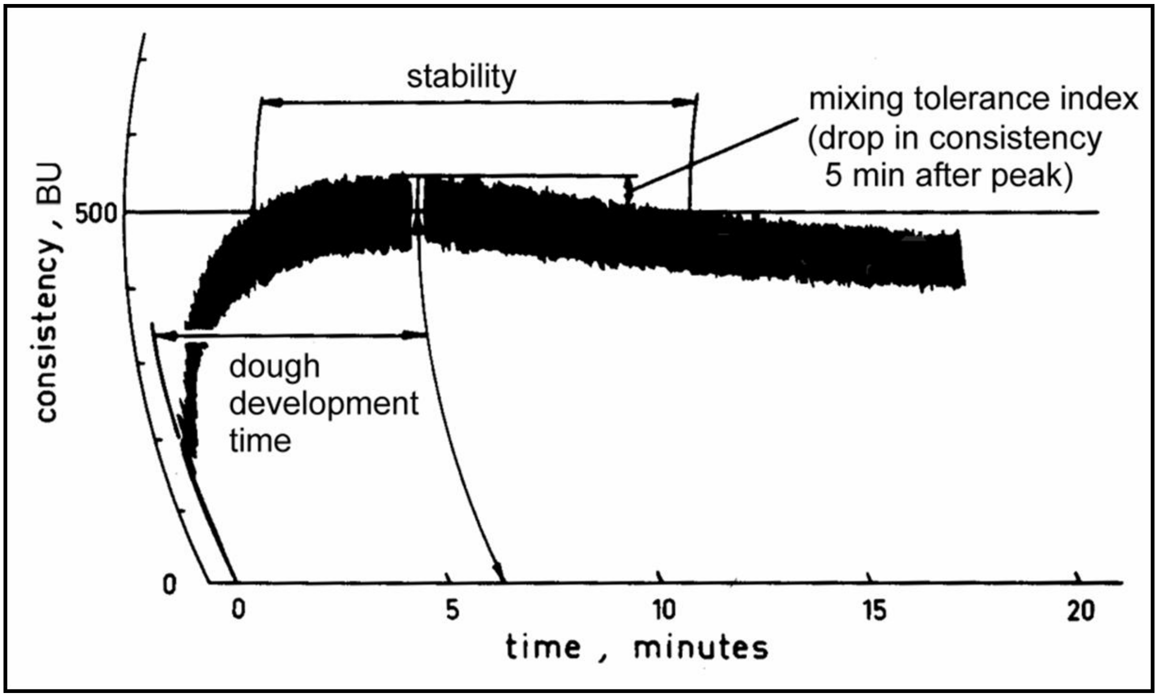

Figure A.1: Typical farinogram generated with Brabender farinograph.

A.2. Mixograph

A 10-gram mixograph from National Manufacturing Ltd. (Lincoln, NE) with computerized software from Power to Mixing Software (P2M) (Roller, 2004) was used in this experiment to analyze dough-mixing properties of the flour. Dough mixing was performed on a constant water basis using 10 grams of flour (corrected to 14% moisture) and 62% absorption with distilled water at 25˚C. Mixing time was 8 minutes and temperature was regulated using a water jacketed mixing bowl kept at 25˚C.

Acquisition of the data was achieved by the torque reading software P2M. There were several parameters generated from each mixogram. Mixing time to peak (MTP) is the time required to reach peak dough resistance. Peak dough resistance (PDR) is the maximum height achieved by the mixogram curve. It is measured in %torque. Bandwidth at peak (PBW) is the width of the mixing curve at PDR. It is also measured in %torque. Work input to peak (WIP) is the area under the dough development curve from time 0 to MTP. It is expressed as min*%torque. A breakdown parameter (PDR_BR3) was generated by comparing the curve height 3 minutes after peak to the height of the curve at peak height. For some weak flour samples there was minimal breakdown because there simply was not good peak development in the mixogram. Thus, when looking at the breakdown variable for these weak samples, they appear to be uncharacteristically strong. So a second breakdown parameter was added to help distinguish between weak and strong samples when looking at the breakdown values. This was done by multiplying the breakdown value at 3 minutes past peak by the PDR (PDR_BR3weighted). Both PDR_BR3 and PDR_BR3weighted are measured as % torque.

Data analysis by the P2M software provided two curves in a mixogram. These are referred to as TopLine and MidLine. Analysis in Chapter 4 found that the TopLine mixing parameters had higher relationships with wheat biochemical constituents. Thus, analysis was conducted using only the TopLine curve mixing parameters. A sample mixogram can be seen in Figure A.2.

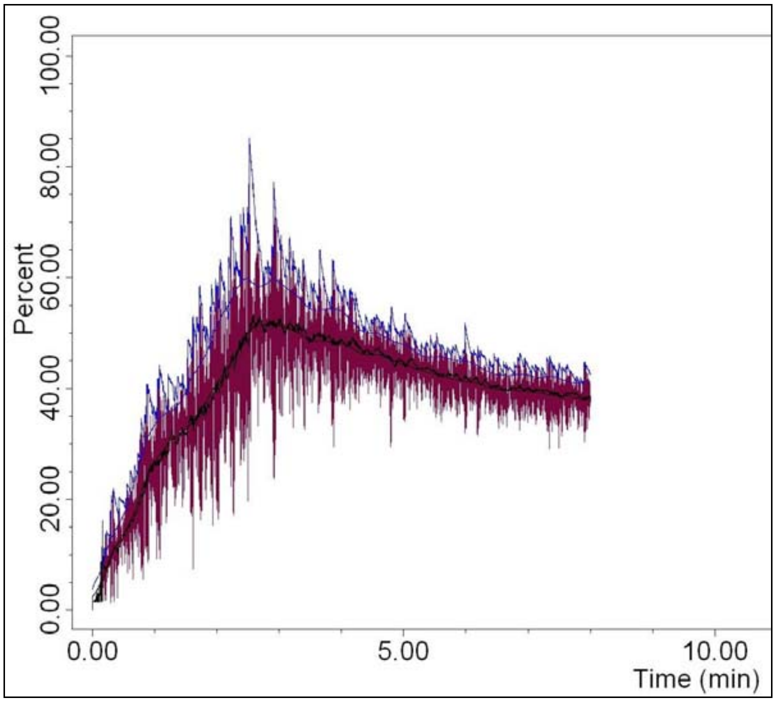

Figure A.2: Typical mixogram from 10-gram mixograph.

A.3. Micro-Extension Test (Extensigraph)

A TA.XT2*i* texture analyzer fitted with a Kieffer rig from Texture Technologies Inc. (Scarscale, NY) was used to measure dough extensibility. The method used in this experiment followed those outlined by Smewing (1995) with some modifications. These modifications included rolling the dough with a customized roller after mixing on the mixograph and before placement onto a Teflon block apparatus. The Teflon block apparatus produced 6 equal dough strips. The dough was allowed to rest for 60 minutes in a controlled environment of 30°C and 85% relative humidity. The extension analysis was then carried out by loading each of the strips on the Kiefer rig apparatus. The dough strip was then pulled by a hook at a rate of 3 mm sec-1 until the dough piece was torn. Extension data was collected by Texture Expert software for Windows Version 1.0. Extensigraph parameters generated included maximum resistance to extension (Rmax, expressed in grams), maximum dough extension (E, expressed in mm), and the area under the extension curve (EA, expressed as g*mm). A typical extensigram can be seen in Figure A.3.

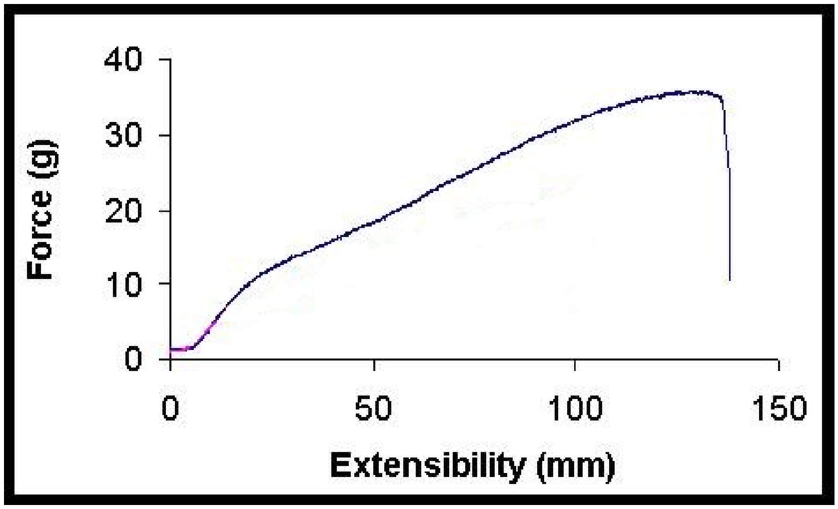

Figure A.3: Typical extensigram from TA.XT2*i* analyzer with Kieffer rig apparatus.

A.4. Rapid Visco Analyser

Measurement of flour pasting properties was conducted using a Rapid Visco™ Analyser (RVA) produced by Newport Scientific Pty. Ltd. The procedure was conducted according to profile Standard 1 (STD1) as outlined in the Applications Manual for the Rapid Visco™ Analyser (1998). Settings for STD1 profile can be seen in Table A.1. For this procedure 0.4mM of AgNO3 was added to eliminate any enzyme activity in the flour in order to observe the pasting properties of the starch without confound enzyme factors. Variables resulting from the RVA include peak viscosity (RVA_Peak), trough viscosity (RVA_Trough), breakdown between peak viscosity and trough viscosity (RVA Breakdown), final viscosity (RVA_Final). A sample pasting curve can be seen in Figure A.4.

Table A.1: Settings for RVA profile STD1.

Time	Type	Value
00:00:00	Temp	50˚C
00:00:00	Speed	960 rpm
00:00:10	Speed	160 rpm
00:01:00	Temp	50˚C
00:04:42	Temp	95˚C
00:07:12	Temp	95˚C
00:11:00	Temp	50˚C
Idle temperature: 50˚ ± 1˚C		
End of test: 13 min.		
Time between readings: 4 sec.		

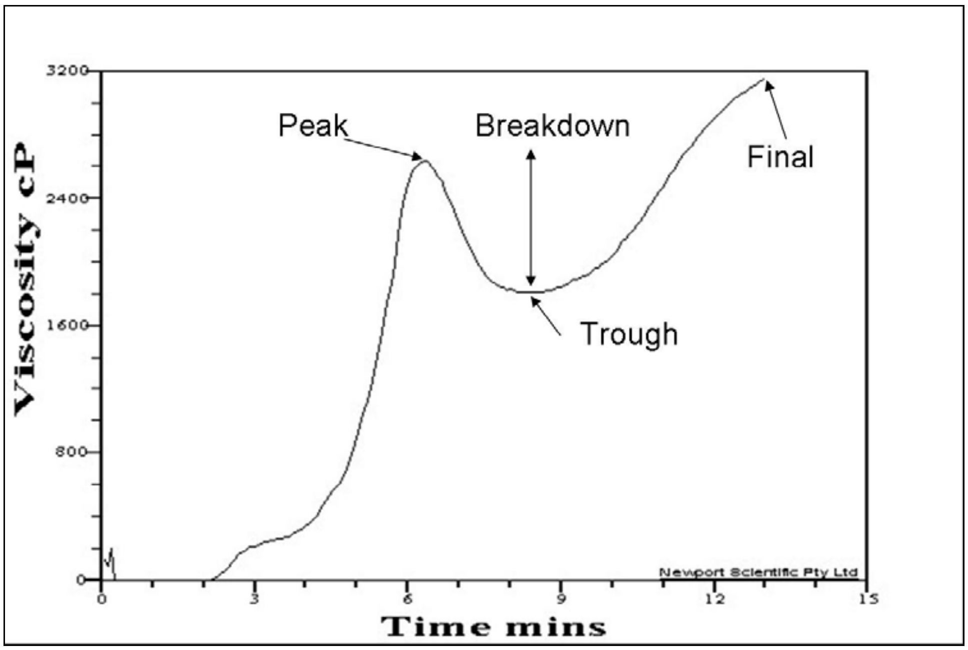

Figure A.4: Typical pasting curve of Rapid Visco Analyser.

6.2. Appendix B – Nitrogen Impacts on Wheat Yield and Protein Content

B.1. Nitrogen Impacts on Wheat Yield

Soil and crop nitrogen status has been shown to have significant effects on wheat yield and protein concentration. However, the majority of studies conducted on this issue have been performed on single plots or regions where the amount of environmental variability is minimal. In our study, producers were encouraged to manage the nutrient status of their fields by the methods usually conducted on his/her farm. This was to achieve our goal of sampling fields that are representative of typical grain farmers in western Canada. However, this may not have been possible since growers who volunteer their services for research projects with limited amounts of compensation, other than shared knowledge, are from a group of more progressive farmers. Typically, farmers from this group of progressive growers are aware of the nutrient status of their wheat fields and manage the nitrogen levels in an optimal fashion.

Farmers provided soil test information and applied fertilizer rates for each research field. However, since soil tests collected from growers were conducted by different soil testing techniques and with a different soil test laboratories, a means had to be taken to quantify the nitrogen status for each field into a value that can be comparable between fields. This was conducted by extrapolating all soil tests analysis to 24" (0.61 m) samples. Some soil tests were done with 24" soil samples and did not require extrapolation of nutrient levels. A mineralization rate for the growing season was also performed on each field. This was performed based on the amount of rainfall that experienced by each field over the growing season according to the methods in the

Westco Advances in Agronomy Handbook (2004). It should be noted that these mineralization rates are a net mineralization rate (gross mineralization – immobilization). Mineralization rates did not need to be performed on soil tests from Western Ag Labs. This is because their Plant Root Simulator (PRS Probe™) method of soil test analysis already includes an estimate mineralization rate in the soil test analysis.

Several indices were created to characterize field nitrogen status. The first was an estimated plant available nitrogen level that was derived by adding up the soil test nitrogen 24" level, fertilizer rate, and mineralization rate. The second was a nitrogen utilization level. This was calculated by adding the nitrogen level in the grain samples protein (protein concentration divided by 5.7), and multiplying this nitrogen level by total yield (test weight (lbs/bu) * yield (bu/ac)). Finally a nitrogen ratio was calculated by dividing the estimated plant available nitrogen level by nitrogen utilized. Examples of these calculations for fields with different nitrogen information can be seen in Figure B.1, Figure B.2, and Figure B.3

AVAILABLE NITROGEN FOR CROP

SOIL TEST	Lab:	EnviroTest	
Soil test depth	N (lbs/ac)		
0-6"	41		
Nitrogen Zone =	Parkland		
24" equivalent*	112.75		
FERTILIZER			
	N (lbs/ac)		
Applied	37		
MINERALIZATION			
	Soil Climatic Zone =	Dark Brown	
	Prob of Precip =	25	%
	Mineralized N** =	53	lbs/ac
	TOTAL NITROGEN =	**203**	lbs/ac

NITROGEN UTILIZED BY CROP

Yield =	66	bu/ac
CGC Test Weight =	64.48	lbs/bu
Total Yield =	4255.68	lbs/ac
Grain Protein =	15.9%	
%N = Protein ÷ 5.7 =	2.79%	N
Total N Removed by Grain=	118.71	lbsN/ac

Nitrogen ratio = $\frac{\text{lbs Estimted Plant Available N/ac}}{\text{lbs N Utilized by Grain}}$

N ratio = 1.708

* 24" equivalent values estimated using Enviro-Test Laboratories extrapolation technique.

**Growing season mineralization rates are estimated based on Westco Advances in Agronomy Handbook (2004)

Figure B.1: Estimation of plant available nitrogen and nitrogen utilized for a field with a 6" soil test.

AVAILABLE NITROGEN FOR CROP			
SOIL TEST	Lab: Norwest		
Soil test depth	N (lbs/ac)		
0-12"	19		
Nitrogen Zone =	Moist Parkland		
24" equivalent*	28.5		
FERTILIZER			
	N (lbs/ac)		
Applied	80		
MINERALIZATION			
	Soil Climatic Zone =	Thick Black	
	Prob of Precip =	50	%
	Mineralized N** =	62	lbs/ac
	TOTAL NITROGEN =	**171**	lbs/ac
NITROGEN UTILIZED BY CROP			
	Yield =	37	bu/ac
	CGC Test Weight =	62.54	lbs/bu
	Total Yield =	2313.98	lbs/ac
	Grain Protein =	15.9%	
	%N = Protein ÷ 5.7 =	2.79%	N
	Total N Removed by Grain=	64.55	lbsN/ac

$$\text{Nitrogen ratio} = \frac{\text{lbs Estimted Plant Available N/ac}}{\text{lbs N Utilized by Grain}}$$

N ratio = 2.649

* 24" equivalent values estimated using Norwest laboratories technique

**Growing season mineralization rates are estimated based on Westco Advances in Agronomy Handbook (2004)

Figure B.2: Estimation of plant available nitrogen and nitrogen utilized for a field with a 12" soil test.

AVAILABLE NITROGEN FOR CROP			
SOIL TEST	Lab:	EnviroTest	
Soil test depth	N (lbs/ac)		
0-6"	112		
0-24"	173		
24" equivalent*	173		
FERTILIZER			
	N (lbs/ac)		
Applied	35		
MINERALIZATION			
	Soil Climatic Zone =	Thick Black	
	Prob of Precip =	25	%
	Mineralized N* =	74	lbs/ac
	TOTAL NITROGEN =	**282**	lbs/ac
NITROGEN UTILIZED BY CROP			
	Yield =	37	bu/ac
	CGC Test Weight =	62.54	lbs/bu
	Total Yield =	2313.98	lbs/ac
	Grain Protein =	15.9%	
	%N = Protein ÷ 5.7 =	2.79%	N
	Total N Removed by Grain=	64.55	lbsN/ac

Nitrogen ratio = $\frac{\text{lbs Estimted Plant Available N/ac}}{\text{lbs N Utilized by Grain}}$

N ratio = 4.369

*Growing season mineralization rates are estimated based on Westco Advances in Agronomy Handbook (2004)

Figure B.3: Estimation of plant available nitrogen and nitrogen utilized for a field with a 12" soil test.

The three nitrogen indices were then compared to protein levels and wheat yields for all fields. Yield was not compared to nitrogen utilized and the nitrogen ratio since yield is one of the components making up the nitrogen utilized variable. There were no significant relationships between any of the nitrogen indices and wheat protein or wheat yield (Figure B.4). From this we concluded that all fields in the project were sufficiently fertilized to a level that nitrogen status was not a limiting factor.

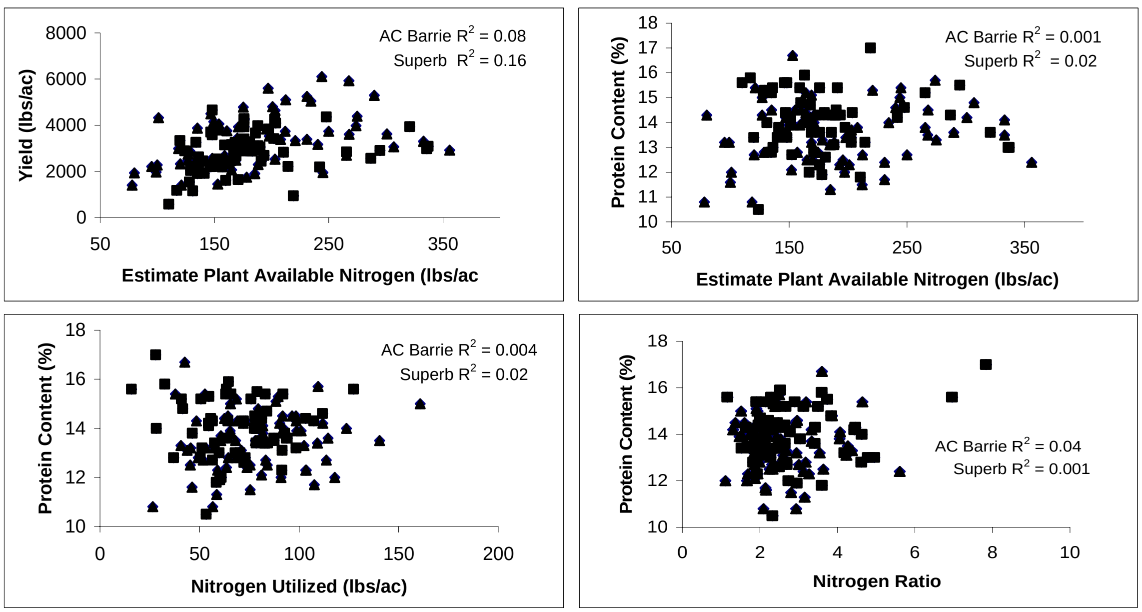

Figure B.4: Relationships between estimated plant available nitrogen, nitrogen utilized, and nitrogen ratio against wheat yield and wheat grain protein content for cultivars AC Barrie (■) and Superb (▲).

6.3. Appendix C – Interpolation of Daily Maximum and Daily Minimum Temperatures based on Barnes (1964)

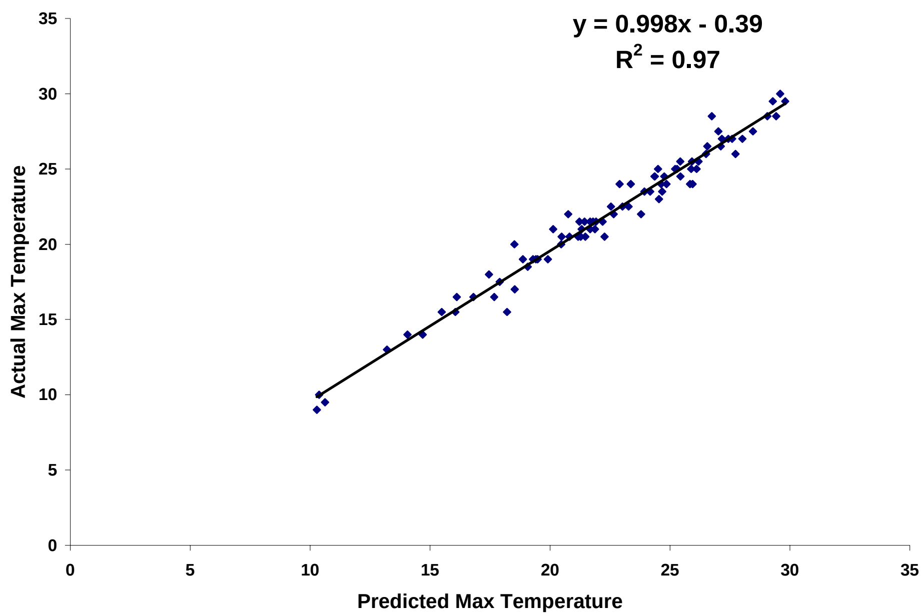

Figure C.1: Comparison of measured daily maximum temperatures vs predicted maximum temperatures using the Barnes (1964) technique for Environment Canada weather station XOD.

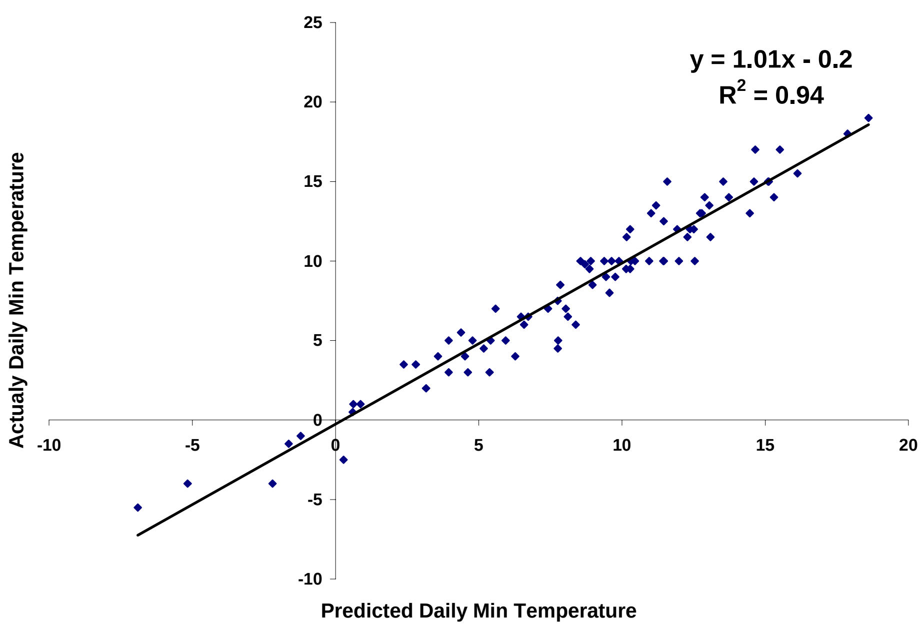

Figure C.2: Comparison of measured daily minimum temperatures vs predicted minimum temperatures using the Barnes (1964) technique for Environment Canada weather station XOD.

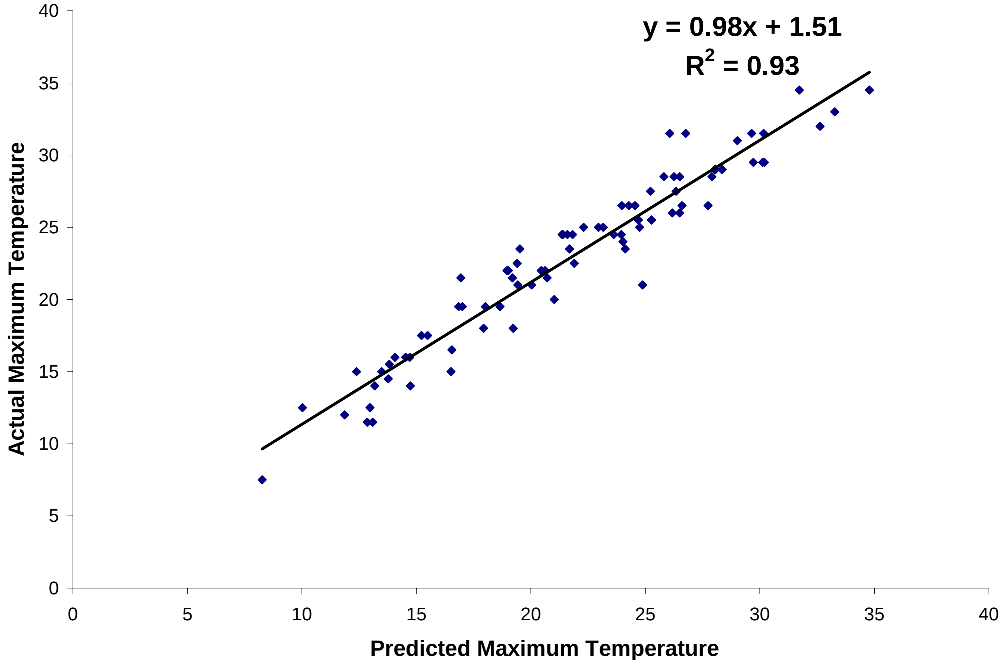

Figure C.3: Comparison of measured daily maximum temperatures vs predicted maximum temperatures using the Barnes (1964) technique for Environment Canada weather station XBG.

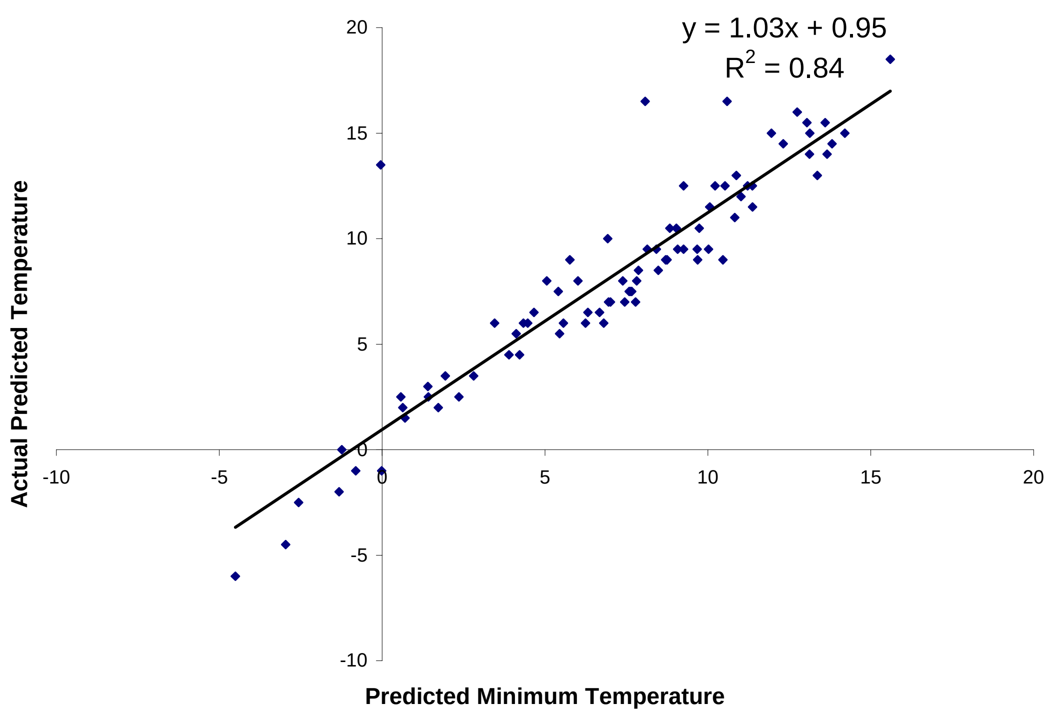

Figure C.4: Comparison of measured daily minimum temperatures vs predicted minimum temperatures using the Barnes (1964) technique for Environment Canada weather station XBG.

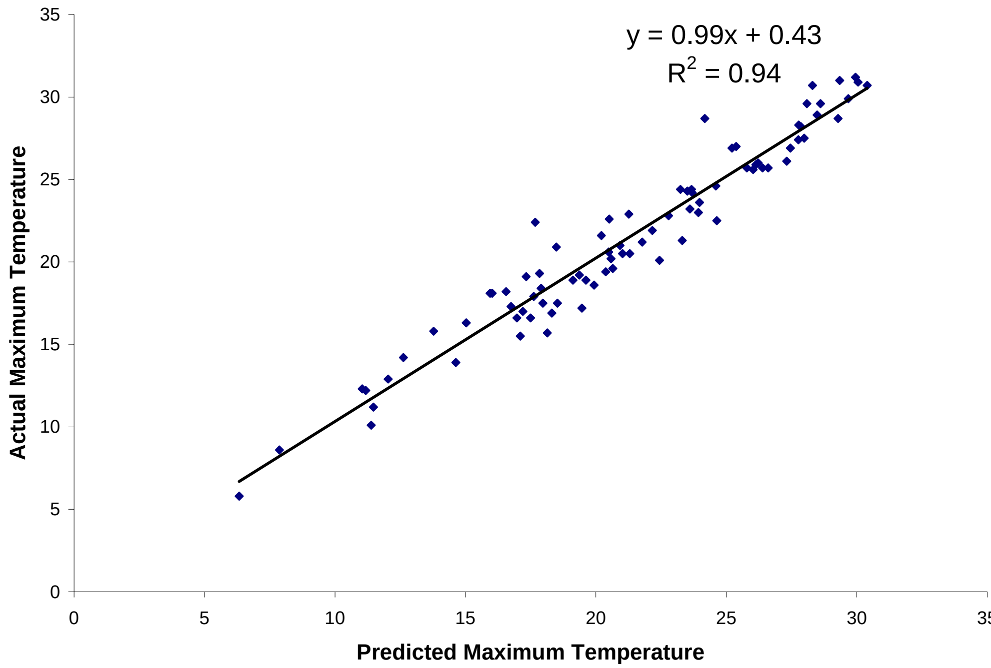

Figure C.5: Comparison of measured daily maximum temperatures vs predicted maximum temperatures using the Barnes (1964) technique for Environment Canada weather station WIK.

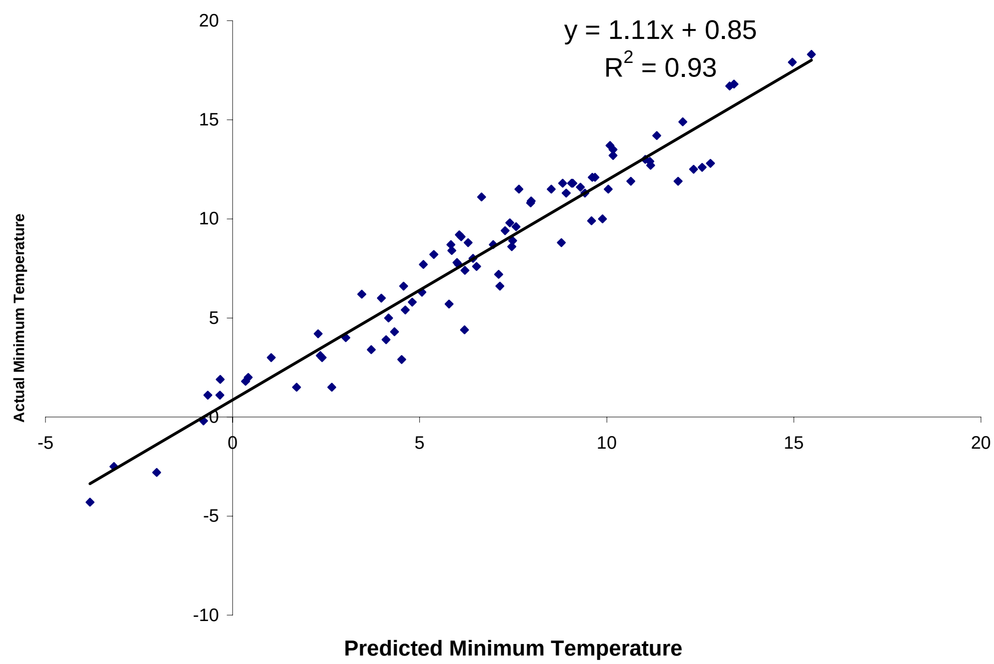

Figure C.6: Comparison of measured daily minimum temperatures vs predicted minimum temperatures using the Barnes (1964) technique for Environment Canada weather station WIK.

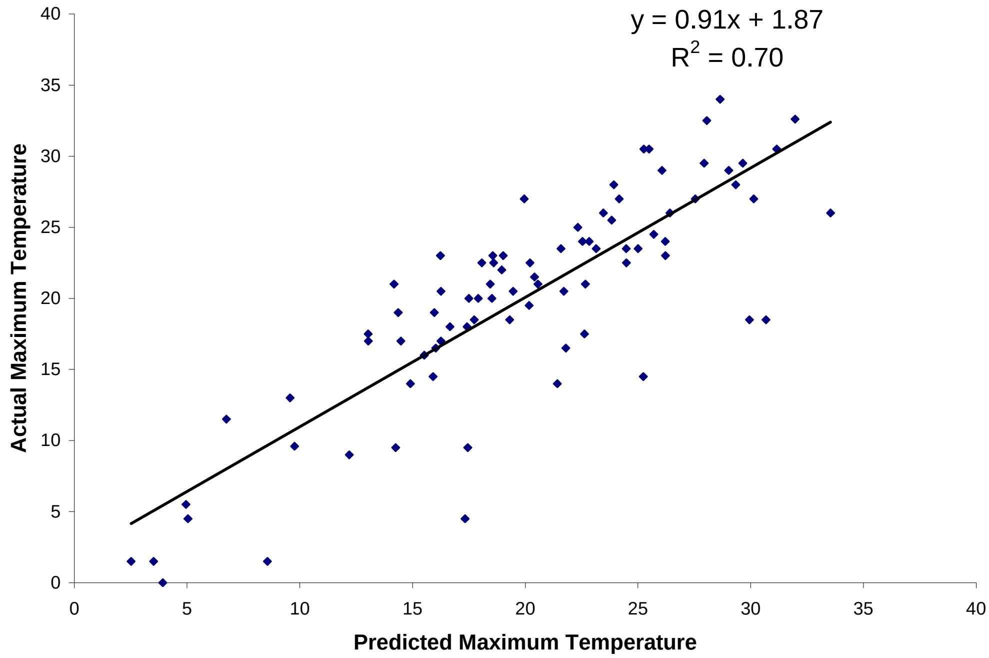

Figure C.7: Comparison of measured daily maximum temperatures vs predicted maximum temperatures using the Barnes (1964) technique for Environment Canada weather station QUE.

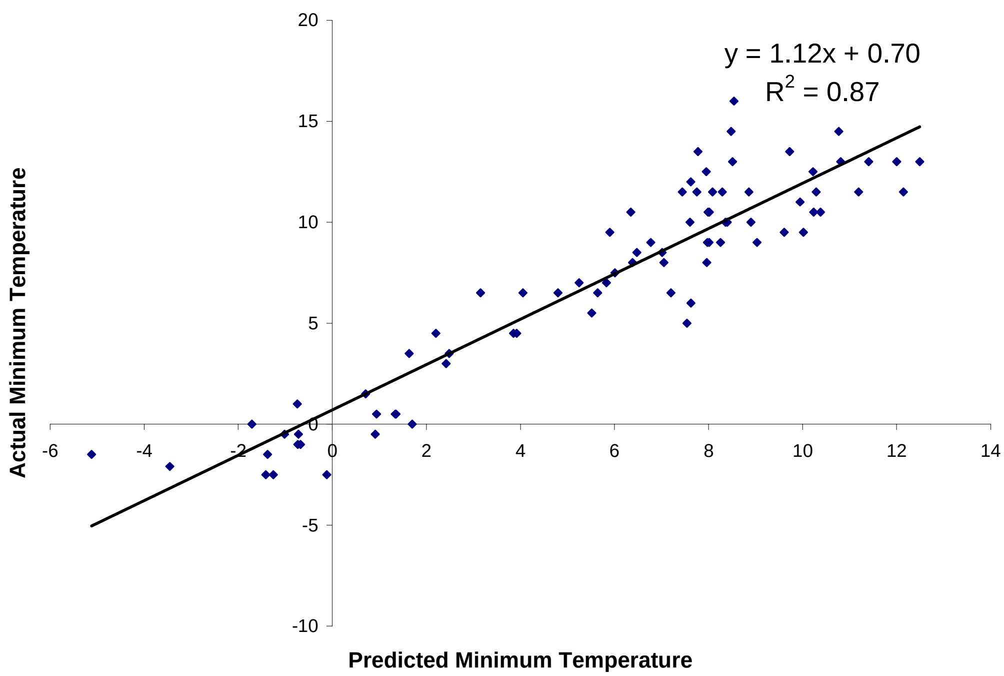

Figure C.8: Comparison of measured daily minimum temperatures vs predicted minimum temperatures using the Barnes (1964) technique for Environment Canada weather station QUE.

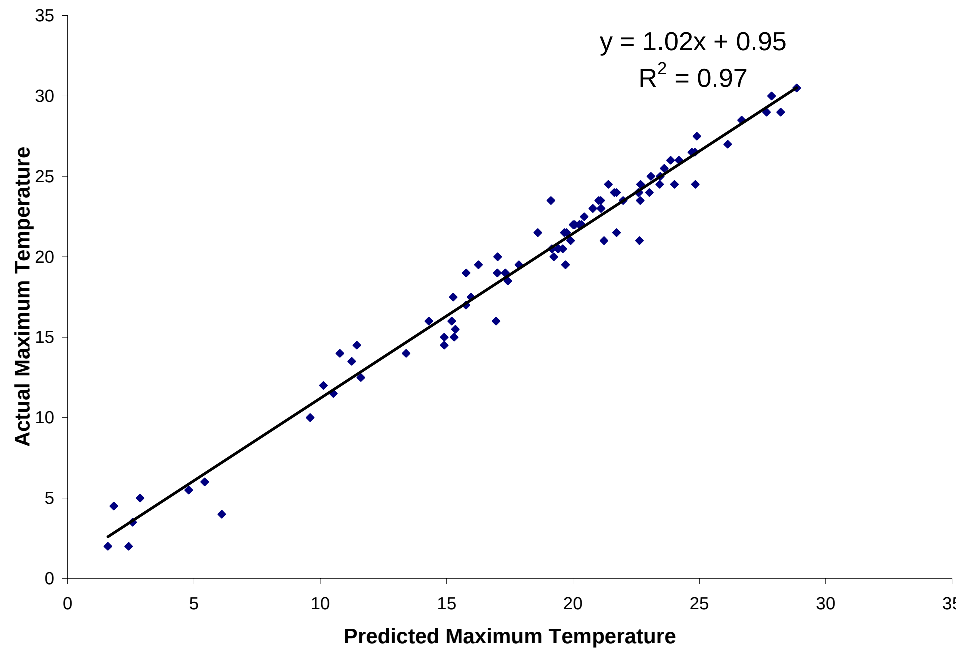

Figure C.9: Comparison of measured daily maximum temperatures vs predicted maximum temperatures using the Barnes (1964) technique for Environment Canada weather station CAM.

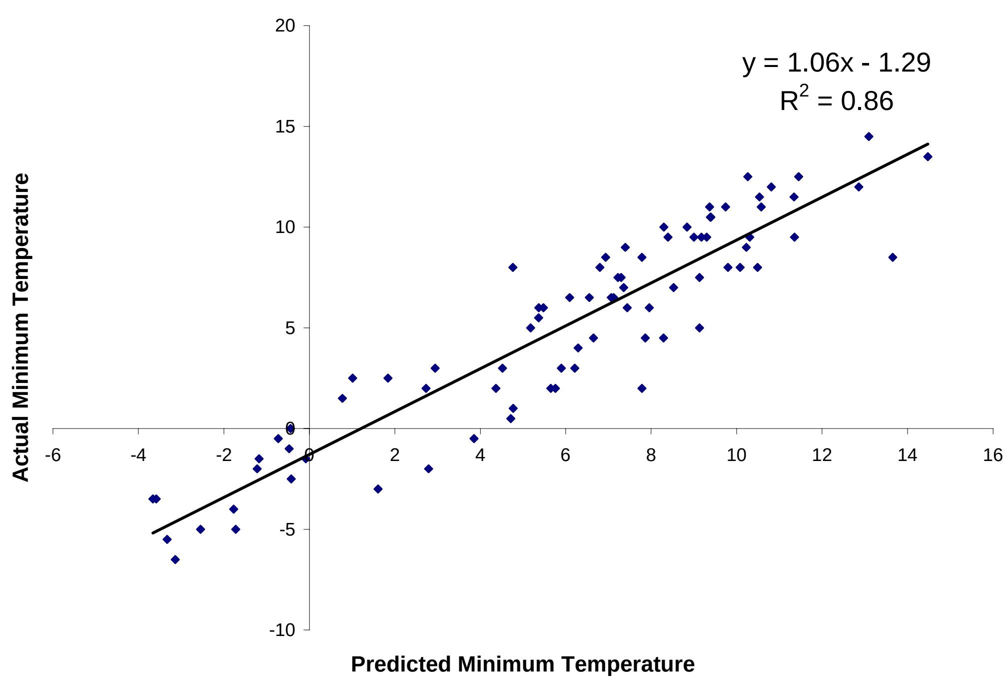

Figure C.10: Comparison of measured daily minimum temperatures vs predicted minimum temperatures using the Barnes (1964) technique for Environment Canada weather station CAM.

6.4. Appendix D – Investigation into accuracy of Brown (1985) soil moisture probe for estimation of spring soil moisture conditions.

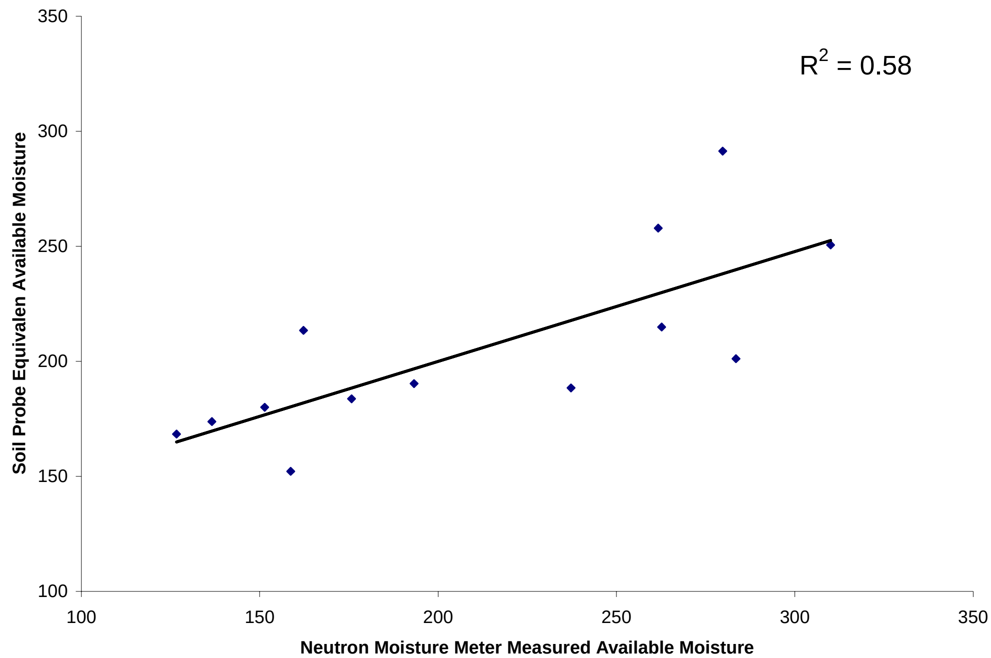

Figure D.1: Comparison between Neutron Moisture Meter measurements of available moisture against Brown's (1985) soil moisture probe equivalent available moisture equivalent from sites in Winnipeg, MB, Carmen, MB, Melfort, SK, Regina, SK, and Swift Current SK in the spring of 2005.

6.5. Appendix E – Correction Curve for Thousand Kernel Weight Moisture

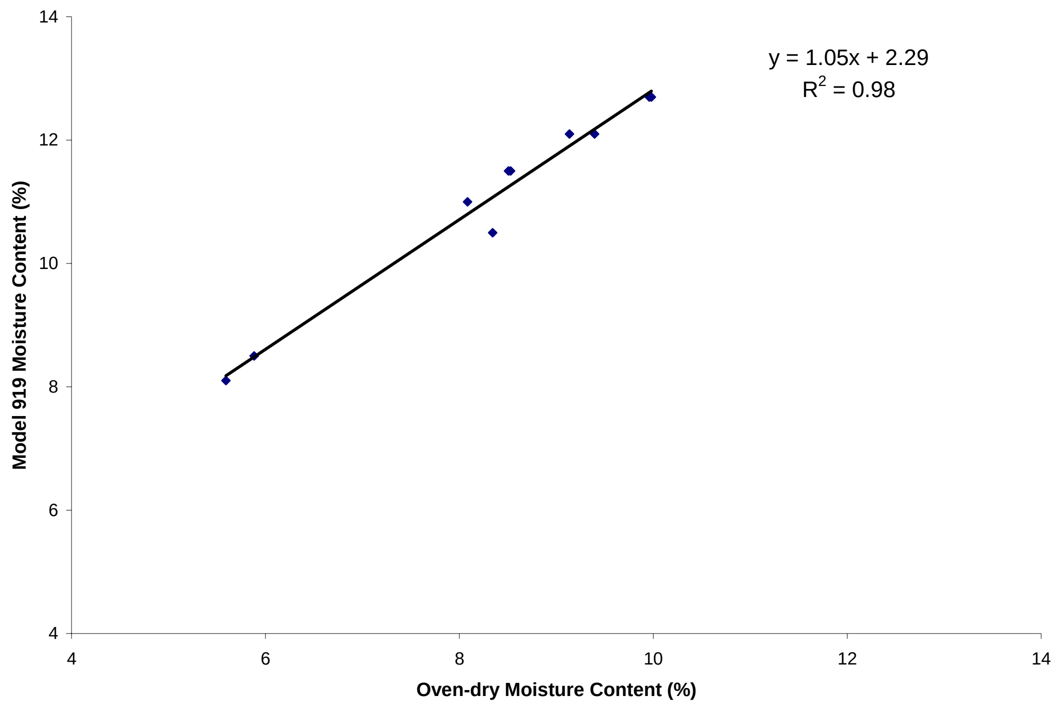

Figure E.1: Correction for grain moisture measurements for thousand kernel weight using Model 919 moisture tester and oven-dry method.

6.6. Appendix F – Correlation Matrices

Table F.1: Coefficients of correlation (r) among grain, flour, dough, and bread quality parameters for AC Barrie (1of2).

AC Barrie	*Protein*	*Test Weight*	*TKW*	*Yield*	*Ash*	*Flour Protein*	*Soluble Protein*	*HMW-Glutenin*	*HMW-Glu/Sol.Pr.*	*HMW-Glu/Flour PC*	*Sol. Pr ./Flour PC.*	*Pentosans*	*RVA Peak*	*RVA Trough*	*RVA Breakdown*	*RVA Final Visc*
Protein	1															
Test Weight	-0.36	1														
TKW	-0.40	0.56	1													
Yield	-0.42	0.57	0.71	1												
Ash	0.32	-0.22	-0.43	-0.24	1											
Flour Protein	0.98	-0.41	-0.34	-0.43	0.30	1										
Soluble Protein	0.73	-0.27	-0.14	-0.28	0.01	0.83	1									
HMW-Glutenin	0.76	-0.48	-0.41	-0.48	0.11	0.82	0.82	1								
HMW-Glu/Sol.Pr	0.05	-0.37	-0.45	-0.29	0.13	-0.01	-0.29	0.30	1							
HMW-Glu/Flour PC	-0.11	-0.19	-0.20	-0.15	-0.21	-0.10	0.19	0.48	0.53	1						
Sol. Pr./Flour PC	-0.15	0.20	0.29	0.12	-0.38	-0.09	0.48	0.20	-0.46	0.50	1					
Pentosans	-0.03	0.26	-0.05	-0.16	0.26	-0.12	-0.31	-0.36	-0.09	-0.38	-0.26	1				
RVA Peak	-0.39	0.37	0.20	0.33	-0.11	-0.40	-0.54	-0.49	0.08	-0.11	-0.22	0.32	1			
RVA Trough	-0.01	0.18	-0.06	0.01	0.12	0.01	-0.18	-0.30	-0.22	-0.49	-0.28	0.38	0.55	1		
RVA Breakdown	-0.45	0.29	0.29	0.33	-0.22	-0.48	-0.50	-0.35	0.27	0.25	-0.04	0.08	0.75	-0.14	1	
RVA Final Visc	0.08	-0.10	-0.46	-0.31	0.18	0.06	-0.21	-0.19	0.02	-0.40	-0.44	0.41	0.41	0.85	-0.18	1
MTP	-0.49	-0.02	0.03	0.04	-0.40	-0.53	-0.36	-0.28	0.16	0.31	0.15	-0.08	0.28	-0.11	0.43	0.00
PDR	0.83	-0.31	-0.26	-0.35	0.29	0.89	0.76	0.78	0.04	0.02	-0.02	-0.19	-0.39	-0.02	-0.44	-0.06
PBW	0.59	-0.12	-0.09	-0.21	0.18	0.64	0.48	0.55	0.12	0.09	-0.03	-0.22	-0.17	-0.12	-0.12	-0.19
PDR_BR3	-0.64	0.17	0.21	0.25	-0.18	-0.71	-0.64	-0.52	0.21	0.14	-0.07	0.16	0.39	-0.15	0.58	-0.08
PDR_BR3 weighted	0.79	-0.34	-0.27	-0.36	0.31	0.82	0.66	0.77	0.18	0.10	-0.08	-0.15	-0.32	-0.10	-0.30	-0.11
WIP	-0.16	-0.18	-0.12	-0.11	-0.31	-0.16	0.03	0.14	0.21	0.51	0.31	-0.24	0.18	-0.12	0.30	-0.03
Flour Yield	0.30	-0.04	0.00	0.28	0.11	0.27	0.14	0.14	0.03	-0.24	-0.23	0.07	-0.24	-0.05	-0.24	-0.08
Far Abs	0.50	0.14	0.04	0.11	0.35	0.43	0.17	0.01	-0.24	-0.57	-0.38	0.51	0.09	0.27	-0.11	0.18
Far DDT	0.72	-0.27	-0.45	-0.49	0.20	0.74	0.44	0.43	0.01	-0.31	-0.31	0.15	-0.20	0.23	-0.42	0.41
Far Stab	0.30	-0.34	-0.52	-0.58	0.16	0.33	0.11	0.19	0.13	-0.19	-0.31	0.17	-0.12	0.22	-0.31	0.50
Far MTI	-0.31	0.14	0.34	0.33	-0.19	-0.30	-0.15	-0.10	0.08	0.37	0.33	-0.37	-0.06	-0.51	0.33	-0.61
Ext. Rmax	0.52	-0.24	-0.43	-0.54	0.18	0.49	0.19	0.37	0.32	-0.02	-0.31	0.23	0.03	0.03	0.01	0.29
Ext. Distance (E)	0.44	-0.09	-0.32	-0.27	0.21	0.44	0.33	0.30	-0.05	-0.24	-0.14	0.17	-0.28	0.21	-0.51	0.26
Ext. Area (EA)	0.62	-0.22	-0.45	-0.55	0.21	0.60	0.29	0.40	0.20	-0.17	-0.32	0.28	-0.09	0.11	-0.19	0.36
Loaf Volume	0.62	-0.25	-0.44	-0.31	0.14	0.65	0.43	0.49	0.12	-0.13	-0.27	-0.12	-0.29	0.13	-0.44	0.26
Baking DDT	-0.17	-0.02	-0.06	-0.14	-0.10	-0.23	-0.19	-0.03	0.28	0.34	0.09	0.02	0.29	-0.09	0.41	0.02

Table F.2: Coefficients of correlation (r) among grain, flour, dough, and bread quality parameters for AC Barrie (2of2).

AC Barrie	*MTP*	*PDR*	*PBW*	*PDR_BR3*	*PDR_BR3 weighted*	*WIP*	*Flour Yield*	*Far Abs*	*Far DDT*	*Far Stab*	*Far MTI*	*Ext. Rmax*	*Ext. Distance (E)*	*Ext. Area (EA)*	*Loaf Volume*	*Baking DDT*
MTP	1															
PDR	-0.70	1														
PBW	-0.53	0.79	1													
PDR_BR3	0.68	-0.82	-0.59	1												
PDR_BR3 weighted	-0.62	0.93	0.75	-0.57	1											
WIP	0.82	-0.27	-0.24	0.38	-0.19	1										
Flour Yield	-0.47	0.39	0.27	-0.42	0.32	-0.41	1									
Far Abs	-0.40	0.27	0.11	-0.10	0.31	-0.43	0.32	1								
Far DDT	-0.36	0.63	0.41	-0.65	0.51	-0.16	0.22	0.24	1							
Far Stab	-0.06	0.23	0.10	-0.35	0.13	-0.01	-0.07	-0.10	0.63	1						
Far MTI	0.37	-0.28	-0.04	0.37	-0.22	0.25	-0.12	-0.24	-0.52	-0.51	1					
Ext. Rmax	-0.01	0.31	0.27	-0.11	0.38	0.18	-0.09	0.25	0.56	0.52	-0.37	1				
Ext. Distance (E)	-0.62	0.55	0.29	-0.58	0.48	-0.49	0.49	0.36	0.44	0.10	-0.37	0.11	1			
Ext. Area (EA)	-0.28	0.49	0.36	-0.35	0.50	-0.07	0.15	0.37	0.68	0.52	-0.48	0.92	0.46	1		
Loaf Volume	-0.59	0.63	0.36	-0.63	0.55	-0.45	0.25	0.36	0.56	0.34	-0.38	0.36	0.62	0.54	1	
Baking DDT	0.77	-0.37	-0.14	0.54	-0.25	0.76	-0.42	-0.35	-0.07	0.10	0.22	0.25	-0.55	-0.05	-0.52	1

Table F.3: Coefficients of correlation (r) among grain, flour, dough, and bread quality parameters for Superb (1of2).

Superb	*Protein*	*Test Weight*	*TKW*	*Yield*	*Ash*	*Flour Protein*	*Soluble Protein*	*HMW-Glutenin*	*HMW-Glu/Sol.Pr.*	*HMW-Glu/Flour PC*	*Sol. Pr ./Flour PC*	*Pentosans*	*RVA Peak*	*RVA Trough*	*RVA Breakdown*	*RVA Final Visc*
Protein	1															
Test Weight	-0.41	1														
TKW	-0.11	0.54	1													
Yield	-0.09	0.09	0.33	1												
Ash	0.22	-0.03	-0.36	-0.30	1											
Flour Protein	0.99	-0.48	-0.11	-0.29	0.20	1										
Soluble Protein	0.88	-0.44	0.06	-0.09	-0.06	0.90	1									
HMW-Glutenin	0.85	-0.58	-0.26	-0.19	0.05	0.86	0.86	1								
HMW-Glu/Sol.Pr.	0.02	-0.32	-0.61	-0.20	0.18	0.09	-0.17	0.35	1							
HMW-Glu/Flour PC	0.01	-0.40	-0.39	-0.17	-0.24	0.02	0.18	0.52	0.69	1						
Sol. Pr./Flour PC	-0.16	-0.08	0.31	0.00	-0.53	-0.10	0.34	0.09	-0.43	0.36	1					
Pentosans	-0.17	0.19	-0.06	-0.03	0.24	-0.28	-0.36	-0.46	-0.25	-0.53	-0.38	1				
RVA Peak	-0.30	0.23	0.31	0.15	-0.37	-0.29	-0.22	-0.36	-0.30	-0.22	0.13	0.38	1			
RVA Trough	-0.11	0.08	0.13	0.10	-0.26	-0.12	-0.16	-0.22	-0.14	-0.25	-0.13	0.24	0.37	1		
RVA Breakdown	-0.23	0.18	0.23	0.07	-0.20	-0.22	-0.12	-0.22	-0.21	-0.05	0.21	0.22	0.77	-0.31	1	
RVA Final Visc	-0.06	-0.09	-0.20	-0.07	-0.02	-0.08	-0.20	-0.17	0.02	-0.23	-0.31	0.44	0.29	0.86	-0.28	1
MTP	-0.38	-0.10	-0.50	-0.08	-0.15	-0.41	-0.44	-0.17	0.46	0.34	-0.17	0.05	-0.02	0.31	-0.23	0.47
PDR	0.83	-0.41	0.13	-0.12	0.03	0.87	0.88	0.80	-0.01	0.12	0.14	-0.36	-0.23	-0.26	-0.05	-0.33
PBW	0.59	-0.41	0.05	-0.10	-0.18	0.64	0.69	0.70	0.14	0.31	0.19	-0.39	-0.27	-0.23	-0.12	-0.31
PDR_BR3	-0.58	0.20	-0.35	-0.08	-0.07	-0.62	-0.62	-0.39	0.32	0.28	-0.06	0.09	0.08	0.31	-0.13	0.34
PDR_BR3 weighted	0.83	-0.45	0.00	-0.18	0.01	0.85	0.86	0.86	0.14	0.27	0.14	-0.42	-0.27	-0.19	-0.14	-0.26
WIP	-0.01	-0.30	-0.51	-0.08	-0.15	-0.04	-0.05	0.20	0.47	0.43	-0.07	-0.17	-0.17	0.21	-0.31	0.35
Flour Yield	0.01	0.29	0.01	-0.03	0.39	0.01	-0.12	-0.15	-0.07	-0.32	-0.24	0.20	0.02	0.22	-0.13	0.28
Far Abs	0.45	0.20	0.18	-0.09	0.47	0.41	0.21	0.14	-0.14	-0.49	-0.48	0.25	0.01	0.21	-0.13	0.16
Far DDT	0.33	-0.35	-0.54	-0.02	0.20	0.23	0.16	0.42	0.51	0.36	-0.34	-0.09	-0.23	0.26	-0.41	0.38
Far Stab	0.19	-0.22	-0.61	-0.21	0.26	0.09	-0.01	0.17	0.35	0.12	-0.39	0.15	-0.26	0.27	-0.45	0.44
Far MTI	0.02	0.03	0.43	0.21	-0.12	0.13	0.21	0.12	-0.13	0.09	0.33	-0.36	0.01	-0.50	0.35	-0.65
Ext. Rmax	0.50	-0.29	-0.56	-0.27	0.24	0.47	0.25	0.56	0.61	0.31	-0.50	-0.04	-0.29	0.17	-0.41	0.31
Ext. Distance (E)	0.34	0.17	0.37	0.13	0.19	0.23	0.31	0.01	-0.55	-0.60	-0.06	0.34	0.21	-0.06	0.25	-0.05
Ext. Area (EA)	0.61	-0.18	-0.40	-0.25	0.31	0.54	0.34	0.54	0.42	0.11	-0.53	0.05	-0.22	0.23	-0.38	0.31
Loaf Volume	0.86	-0.38	-0.18	-0.02	0.31	0.83	0.71	0.68	0.00	-0.11	-0.29	0.00	-0.24	-0.03	-0.22	0.07
Baking DDT	-0.13	-0.34	-0.66	-0.38	-0.09	0.00	-0.20	0.12	0.63	0.51	-0.17	-0.10	-0.17	0.14	-0.27	0.35

Table F.4: Coefficients of correlation (r) among grain, flour, dough, and bread quality parameters for Superb (2of2).

Superb	*MTP*	*PDR*	*PBW*	*PDR_BR3*	*PDR_BR3 weighted*	*WIP*	*Flour Yield*	*Far Abs*	*Far DDT*	*Far Stab*	*Far MTI*	*Ext. Rmax*	*Ext. Distance (E)*	*Ext. Area (EA)*	*Loaf Volume*	*Baking DDT*
MTP	1															
PDR	-0.58	1														
PBW	-0.37	0.82	1													
PDR_BR3	0.65	-0.76	-0.48	1												
PDR_BR3 weighted	-0.45	0.95	0.85	-0.52	1											
WIP	0.84	-0.14	-0.03	0.32	-0.03	1										
Flour Yield	-0.14	-0.19	-0.31	0.10	-0.19	-0.32	1									
Far Abs	-0.44	0.26	0.03	-0.28	0.22	-0.40	0.33	1								
Far DDT	0.50	0.03	0.04	0.31	0.18	0.52	0.03	0.08	1							
Far Stab	0.49	-0.19	-0.21	0.43	-0.04	0.45	0.23	0.09	0.67	1						
Far MTI	-0.50	0.40	0.35	-0.50	0.28	-0.40	-0.13	-0.20	-0.52	-0.70	1					
Ext. Rmax	0.31	0.18	0.25	0.22	0.35	0.42	0.12	0.27	0.71	0.71	-0.49	1				
Ext. Distance (E)	-0.63	0.33	0.14	-0.64	0.15	-0.51	0.09	0.48	-0.35	-0.26	0.18	-0.20	1			
Ext. Area (EA)	0.11	0.27	0.26	0.06	0.39	0.25	0.16	0.45	0.63	0.66	-0.47	0.94	0.06	1		
Loaf Volume	-0.26	0.64	0.41	-0.45	0.64	0.03	0.02	0.43	0.38	0.27	-0.04	0.49	0.37	0.60	1	
Baking DDT	0.75	-0.16	0.10	0.52	0.04	0.74	-0.06	-0.37	0.48	0.45	-0.43	0.48	-0.69	0.24	-0.15	1

6.7. Appendix G – Effect of Mixing Speed in the 10-gram Mixograph on Development of Mixogram Peaks for a Canada Western Red Spring Wheat

G.1. Abstract

An experiment was conducted on the 10-gram mixograph to investigate the affect of mixing speed on the development of peak for weak, low protein flour samples of AC Barrie and Superb of the wheat class Canada Western Red Spring (CWRS). Three mixing speeds of 129 rpm, 113 rpm, and 91 rpm were used to mix each of the flour samples. Coefficients of variation between reps ($C.V._r$) and between samples ($C.V._s$) were analyzed to search for the optimal mixing speed for peak development of weak, low protein samples. It was found that the mixing speed of 113 rpm provided the best results with low $C.V._r$'s and high $C.V._s$'s. A mixing speed of 91 rpm was not able to clearly produce a developed peak of the mixograph. A mixing speed of 129 rpm created too much mixing intensity and resulted in increased shear of the dough, resulting in high breakdown. The mixing speed of 113 rpm also had the best relationships between mixograph parameters and protein variables. The mixing speed of 113 rpm proved to be the best suited for mixing of CWRS flour samples with a range of weak to strong dough strengths.

G.2. Introduction

In 1939, the 35-gram mixograph was designed and developed as a means for studying the action of high speed commercial mixers in the USA by National Manufacturing Company in Lincoln, Nebraska. In 1972, the 35-gram mixograph was modified to develop a mixograph capable of using 10-gram flour samples for the evaluation of dough properties from early generation progenies of bread wheat (Finney and Shogren, 1972). The mixograph has been used so extensively that it became approved as an official flour physical test in the American Association of Cereal Chemists (AACC) methods (Method 54-40A) in 1961, with revisions made in 1988 (AACC, 2000).

Digitization of mixograph data has further advanced the analysis ability to generate several mixing parameters formerly difficult to measure manually (Stearns and Barta, 1990). Originally, mixing time to peak was the most commonly used parameter because it was the easiest to measure. Now with the digitization of parameters, several parameters can be easily investigated.

The 10-gram mixograph was originally developed for the analysis of American Dark Northern Spring cultivars, well known to be of high protein and strong dough strength. However, when analyzing Canada Western Red Spring (CWRS) flour samples with low protein it can be difficult to determine the location of peak development in the mixogram. Due to the wide acceptance of the 10-gram mixograph, it is warranted to investigate new measures to improve CWRS dough development with the 10-gram mixograph. Much research has been performed comparing the results from different mixograph machines (2-gram vs 10-gram vs 35-gram) (Khatkar et al., 1996; Rath et al., 1990) and alternative recording mechanisms (mobile vs fixed-bowl) (Wooding and Walker, 1992). However, no further research has been performed to determine how altering the mechanics of the mixograph would affect mixing results. Specifically, we were interested in how increasing the mixing intensity of the mixograph would influence mixing parameters of a sample of CWRS flour samples possessing a wide range of protein content and protein quality characteristics.

In this experiment, we investigated the impacts of increasing the intensity of mixing on the mixograph parameters mixing time to peak (MTP), peak dough resistance (PDR), bandwidth at peak (PBW), and work input to peak (WIP). WIP can be defined as the area under the curve from time 0 to MTP. The hypothesis was that increased mixing intensity would assist in peak development of low protein flour samples of Canada Western Red Spring wheat.

G.3. Materials and Methods

In this study we used the National 10-gram mixograph with 3 different pulley sizes on 13 samples of CWRS wheat flour of different protein content and composition. The thirteen flour samples were of two CWRS cultivars widely grown in western Canada (AC Barrie – 7 samples and Superb – 6 samples). The difference in dough handling properties did not vary significantly between these cultivars, thus, the results from the two cultivars were combined in the analysis.

Flour protein content and protein composition was considered in the choice of flour samples for this study. Flour samples were obtained from grain samples graded #1 CWRS by the Canadian Grain Commission. The samples were grown under various growing season weather conditions across western Canada, and thus, possess important differences in protein content and protein composition. Flour protein content was determined by the Kjeldahl method according to AACC procedures Method 46-16 (AACC, 2000). Protein composition was determined using an extraction method of 50%

1-propanol and 50% 1-propanol + 0.1% dithiothreitol (DTT) at 55ºC to obtain 3 fractions as outlined by (Sapirstein and Johnson, 2001). The first extraction using 50% 1-propanol extracted the monomeric proteins (specifically albumins, globulins, gliadins and low molecular soluble glutenin), referred to as soluble protein. The 0.1% DTT additive extracted the insoluble high molecular weight glutenins, referred to as HMW-glutenin fraction. The remaining insoluble portion of protein is referred to as residue protein, consisting of large, non-nitrogen-storage proteins. The protein content, soluble protein content, and HMW-glutenin content for each of the samples is outlined in Table G.1.

Table G.1: Flour protein content (14% moisture basis) and protein composition (% of flour) for 13 CWRS samples used in pulley experiment.

Sample	Protein Content	Soluble Protein	HMW-Glutenin
1	10.6	6.9	3.0
2	10.8	7.3	2.7
3	11.0	7.4	2.7
4	12.0	8.1	3.3
5	12.4	8.8	2.9
6	12.5	8.4	3.3
7	13.3	8.7	3.6
8	13.4	9.3	3.2
9	14.0	10.1	3.5
10	14.2	9.3	4.1
11	15.0	10.3	3.9
12	15.2	11.0	4.1
13	16.7	11.4	4.1

G.3.1. Mixograph Procedure

A 10-gram mixograph with computerized analysis software recording torque/mixing resistance was used to evaluate the dough-mixing properties of the flour samples. The 10-gram mixograph was designed and produced by National Manufacturing in Lincoln, NE. Power to Mixing software (P2M) was used to record the resistance to mixing (Roller, 2004). Dough mixing was performed on a constant dough basis using 10 grams of flour (corrected to 14% moisture) and 62% absorption of distilled water at 25°C for 8 minutes. Temperature was regulated during mixing using a water-jacketed mixing bowl kept at 25°C.

Three pulleys with different diameters were used in this experiment to alter the intensity of mixing. The pulleys had diameters 40mm, 50mm, and 70mm and will be referred to as Pulley40, Pulley50, and Pulley70 respectively. Pulley70 is the standard pulley that comes with National's 10-gram mixograph. Pulley40 and Pulley50 were also provided by National Manufacturing. Pulley40, Pulley50, and Pulley70 mixed at speeds of 129 rpm, 113 rpm, and 91 rpm respectively. This is an increase of 24% in mixing speed from Pulley70 to Pulley50 and an additional increase of 14% in mixing speed from Pulley50 to Pulley40. Flour samples were mixed by all pulley treatments in triplicate.

Data acquisition by the P2M software program created two computer-generated dough mixing curves. Each curve was generated based on the measure of torque (%) required to mix the dough in the mixing bowl. The two mixing curves will be refereed to as TopLine and MidLine based on their location on the resulting Mixogram respectively. A sample mixogram is presented in Figure G.1.

Several dough mixing parameters were obtained from the two mixing curves. Dough mixing time to peak (MTP) was the time (min) required to achieve peak dough resistance (PDR), or height of the mixogram (%torque). Work input to Peak (WIP) was the area under the dough development curve from time 0 to time of peak development (expressed as %torque*min). Peak Bandwidth (PBW) was the width of the mixing curve at peak development and is expressed as %torque. To identify these parameters associated with the TopLine curve a "TL-" will be placed in front of each of the parameter acronyms (TL-MTP, TL-PDR, TL-PBW, and TL-WIP). To identify these parameters associated with the MidLine curve a "ML-" will be placed in front of each of the parameter acronyms (ML-MTP, ML-PDR, ML-PBW, and ML-WIP).

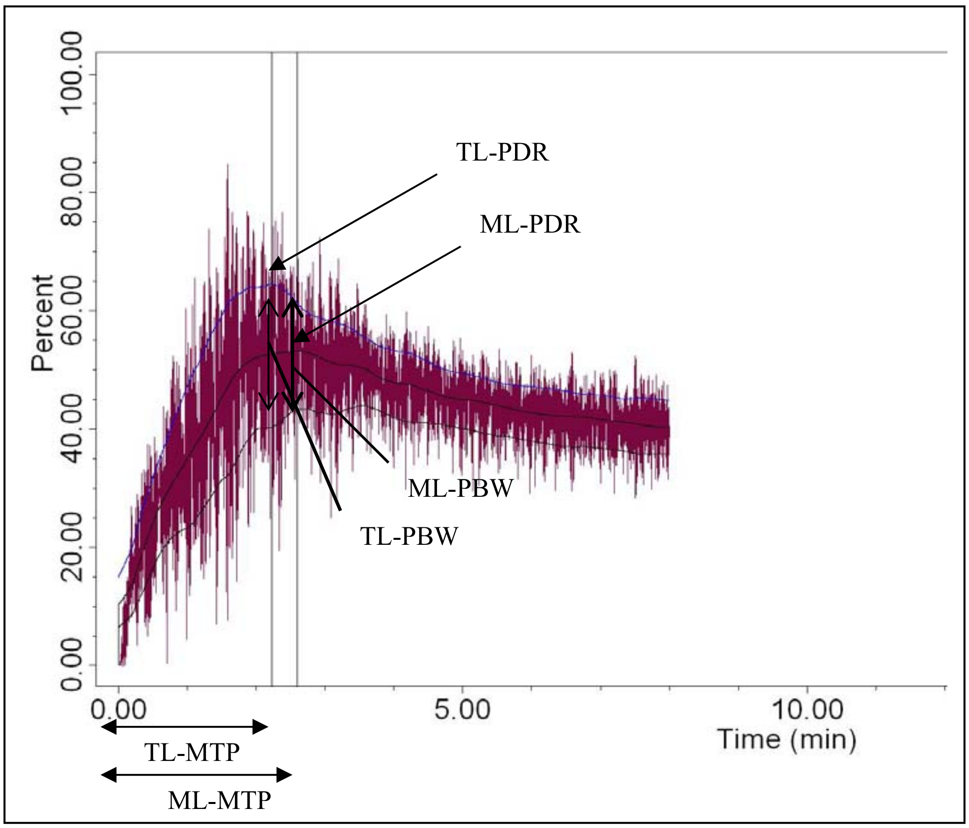

Figure G.1: Sample mixogram generated with 10 gram mixograph.

G.3.2. Statistical Analysis

Results were analyzed using Microsoft Excel (Windows XP Version) and SAS version 8.1(SAS, 2001). SAS was used for the determination of regression coefficients of flour protein content and flour protein composition to each of the earlier described mixing parameters. Coefficients of variation within reps of a sample ($C.V._r$) and between samples ($C.V._s$) were calculated using Excel (Equation G.1). SAS was then used to test for significance between each Pulley's $C.V._r$'s.

$$C.V. = \frac{\text{Standard Deviation}}{\text{Mean}} x100\% \qquad \text{(G.1)}$$

A ratio of the coefficient of variation (C.V. Ratio) was derived by dividing $C.V._s$ by $C.V._r$ (Equation G.2).

$$C.V.Ratio = \frac{C.V._s}{C.V._r} \qquad \text{(G.2)}$$

A Pulley possessing a high C.V. Ratio would be desired since the components of this ratio would favor a large variation between samples but a high level of reproducibility due to a smaller variation between reps.

A test of significance could not be performed on $C.V._s$' or C.V. Ratio since no means could be calculated from the single values representing each Pulley mixing parameter used in the analysis.

G.4. Results and Discussion

G.4.1. Improvement of Peak Development

Changing the mixing intensity of the mixograph caused several changes to the resulting mixograms. The most noticeable difference was a decrease in MTP with an increase in mixing intensity (Pulley70→Pulley50→Pulley40). For PDR and PBW there were no trends found between pulleys. There was a trend of decreasing WIP with an increase in mixing speed. However, recall that WIP is a function of MTP and PDR, and since peak dough resistance shows no change with mixing intensity, we can attribute the decrease in work input to be as a result of the decrease in mixing time to peak.

Recall that the objective of this experiment was to investigate if an increase in mixing speed would improve the mixogram peak formation of weak CWRS flour. By viewing mixograms from three of the studied samples, two with low protein content and one with high protein content, we determined that increasing the mixing speed did improve the peak formation of the mixogram of weaker CWRS flour (Figure G.2). In Figure G.2 both Pulley50 and Pulley40 were able to improve mixogram peak formation. However, for the strong flour (Figure G.2) there was a change in the overall shape of the mixogram compared to the original Pulley70 as mixing intensity increased. It should be noted that Pulley40 changed the shape of the mixogram noticeably more than Pulley50. Therefore, there appeared to be a trade off between the ability to improve peak development between weak, low protein flours and maintaining other mixing parameters for strong, high protein flours. Thus, it is important to view how each of the mixing parameters were influenced by increasing the mixing intensity of the mixograph before any conclusions could be made regarding a preferred pulley treatment.

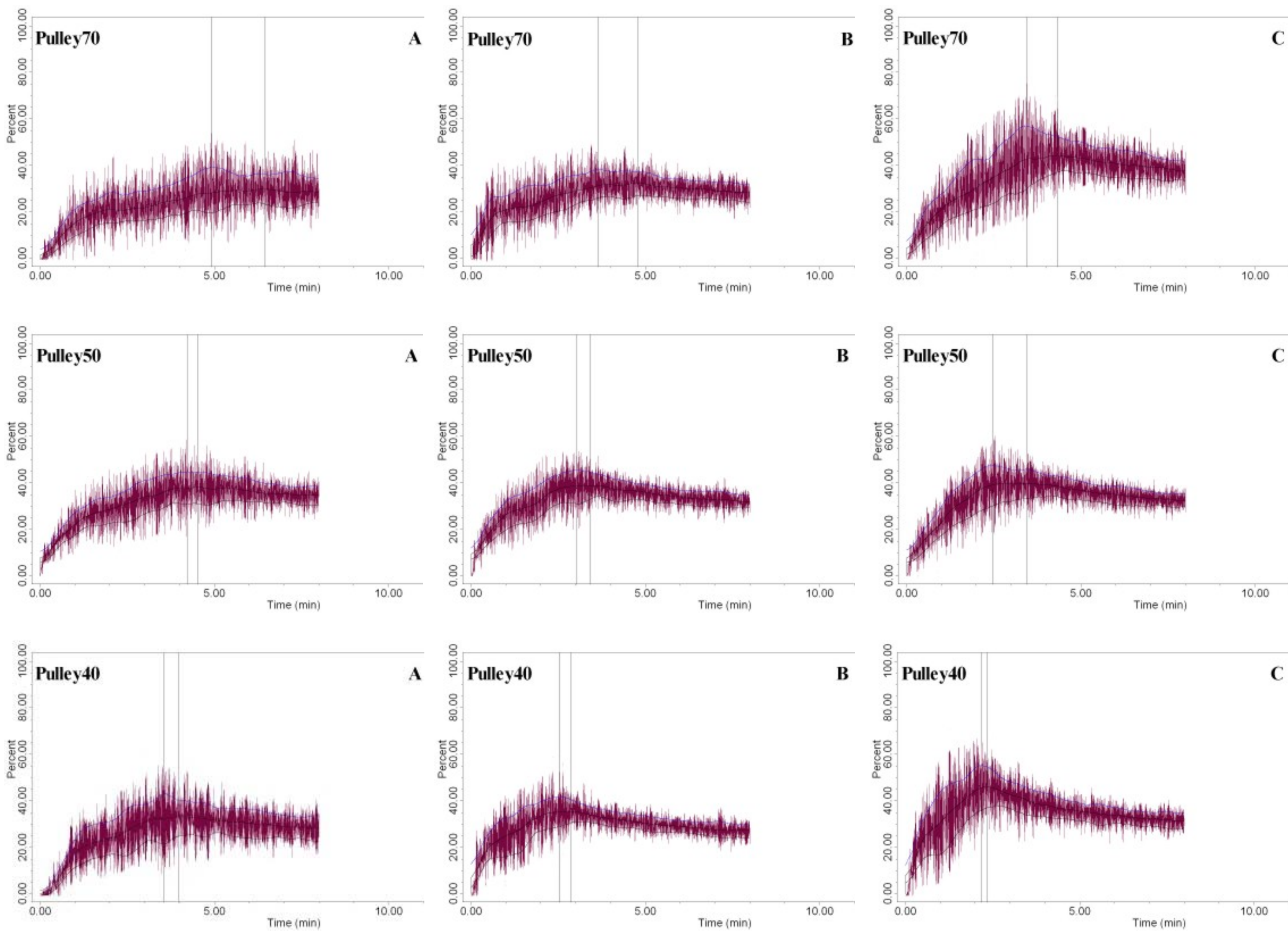

Figure G.2: Comparison of Mixograms from Pulley70, Pulley50, and Pulley40 for the lowest flour protein sample (**A**), the second lowest flour protein sample (**B**), and the highest flour protein sample (**C**)

Table G.2: Mean and distribution statistics for mixograph parameters mixing time to peak (MTP), peak dough resistance (PDR), peak bandwidth (PBW), and work input to peak (WIP) for top-line (TL) and mid-line (ML) curves across 3 pulley systems P40, P50, and P70.

	Mean			Standard Deviation		
	P40	P50	P70	P40	P50	P70
TL-MTP (min)	2.3	2.8	3.9	0.7	0.8	1.3
TL-PDR (% torque)	51.9	53.4	48.8	7.0	8.2	8.6
TL-PBW (% torque)	20.8	19.9	22.0	3.6	4.7	5.3
TL-WIP (integral)	77.3	100.9	127.2	17.2	22.1	29.1
ML-MTP (min)	2.7	3.3	4.5	0.7	0.8	1.2
ML-PDR (% torque)	43.1	44.6	38.1	6.2	6.3	6.5
ML-PBW (% torque)	14.8	15.4	15.1	3.2	3.8	3.2
ML-WIP (integral)	76.8	101.0	118.7	13.1	15.5	21.3

G.4.2. Coefficient of Variation between Reps

The values for coefficient of variation between reps ($C.V._r$) are more desirable if they are lower. A decrease in $C.V._r$ by a pulley treatment implies a pulley treatment possessing a higher level of reproducibility of results. This would be very desirable for obtaining consistent results when mixing CWRS wheat.

There was small, but significant, variation between the average mixing time to peak $C.V._r$'s. For the TopLine curve, Pulley50, with a $C.V._r$ of 6%, had the lowest $C.V._r$. It was significantly lower than Pulley70 ($C.V._r$ of 11%) but not significantly lower than Pulley40 ($C.V._r$ of 10%) at the p=.05 level (Figure G.3). Pulley40 and Pulley70 were not significantly different from each other. However, for the MidLine curve, none of the pulleys had a significantly different mixing time to peak than the others. Qualitatively though, Pulley40, with a C.V.r of 6%, had a lower average $C.V._r$ than both Pulley50 and Pulley70. In this case, Pulley50 had a $C.V._r$ of 8% while Pulley70 had a $C.V._r$ of 9%.

A significantly lower $C.V._{r}$, indicated that Pulley50 was able to reduce the amount of variability within reps of a sample for mixing time to peak for the TopLine curve. For the MidLine curve there were minimal differences between the $C.V._{r}$'s between pulleys.

Overall, $C.V._{r}$'s for peak dough resistance were lower than those of mixing time to peak. There was, however, important differences in the average $C.V._{r}$'s attributed to each pulley. The TopLine curve for Pulley50 had a significantly lower $C.V._{r}$ (with a value of 2%) than both Pulley40 and Pulley70 (Figure G.3). Pulley40 and Pulley70 again were not significantly different from one another since they both had $C.V._{r}$ values of 6%. For peak dough resistance on the MidLine curve, Pulley50 again had a significantly lower $C.V._{r}$ (3%) than Pulley40 and Pulley70. Pulley40 and Pulley70 were not significantly different with $C.V._{r}$ values of 8% and 6%, respectively.

For peak dough resistance, Pulley50 produced the lowest $C.V._{r}$'s for both the TopLine and MidLine curves. These were significantly lower at the p=0.05 level compared to both Pulley40 and Pulley70 (Figure G.3). This means that Pulley50 produced the most reproducible results when examining peak dough resistance for both curves.

The highest $C.V._{r}$'s obtained in this experiment occurred in the analysis of bandwidth at peak. There were no significant differences in $C.V._{r}$ values for bandwidth at peak with either the Topline or Midline curves (Figure G.3). However, some qualitative observations can still be made. Pulley50 again had the lowest $C.V._{r}$ when looking at TL-PBW with a value of 10%. The $C.V._{r}$'s for Pulley40 and Pulley70 were 13% and 14% respectively. When looking at the MidLine curve for bandwidth at peak, Pulley50 had the lowest C.V.$_r$ at 12%. Pulley40 and Pulley70 had C.V.$_r$'s of 17% and 15%, respectively.

Although there were no significant differences at the p=0.05 level in bandwidth at peak between pulley treatments, qualitatively there was a consistent trend. For bandwidth at peak, Pulley50 possessed the lowest C.V.$_r$ values between all pulleys.

The trend of low C.V.$_r$'s by Pulley50 carried through to the TL-WIP and ML-WIP. Pulley50 had a significantly lower C.V.$_r$ for TL-WIP when compared to Pulley70 but was not significantly different from Pulley40 (Figure G.3). Pulley40 and Pulley70 were also not significantly different. Pulley50 had a C.V.$_r$ of 8% while Pulley40 and Pulley70 had C.V.$_r$ values of 10% and 13%, respectively. For ML-WIP, there were no significant differences between C.V.$_r$ values of each pulley. Qualitative observations revealed that Pulley50 again had the lowerst C.V.$_r$ with 9% while Pulley40 had a C.V.$_r$ of 13% and Pulley70 had a C.V.$_r$ of 14%.

The observations made on work input to peak followed the trends set by mixing time to peak, peak dough resistance, and bandwidth at peak. Pulley50 provided the most reproducible results when compared to Pulley40 and Pulley70 for work input to peak from both the TopLine and MidLine curves. The ability to improve reproducibility of results is very desirable in science as it allows for greater success when other researchers attempt to reproduce a past experiment. Therefore, up to this point Pulley50 proved to be the most desirable pulley out of these 3 pulley treatments.

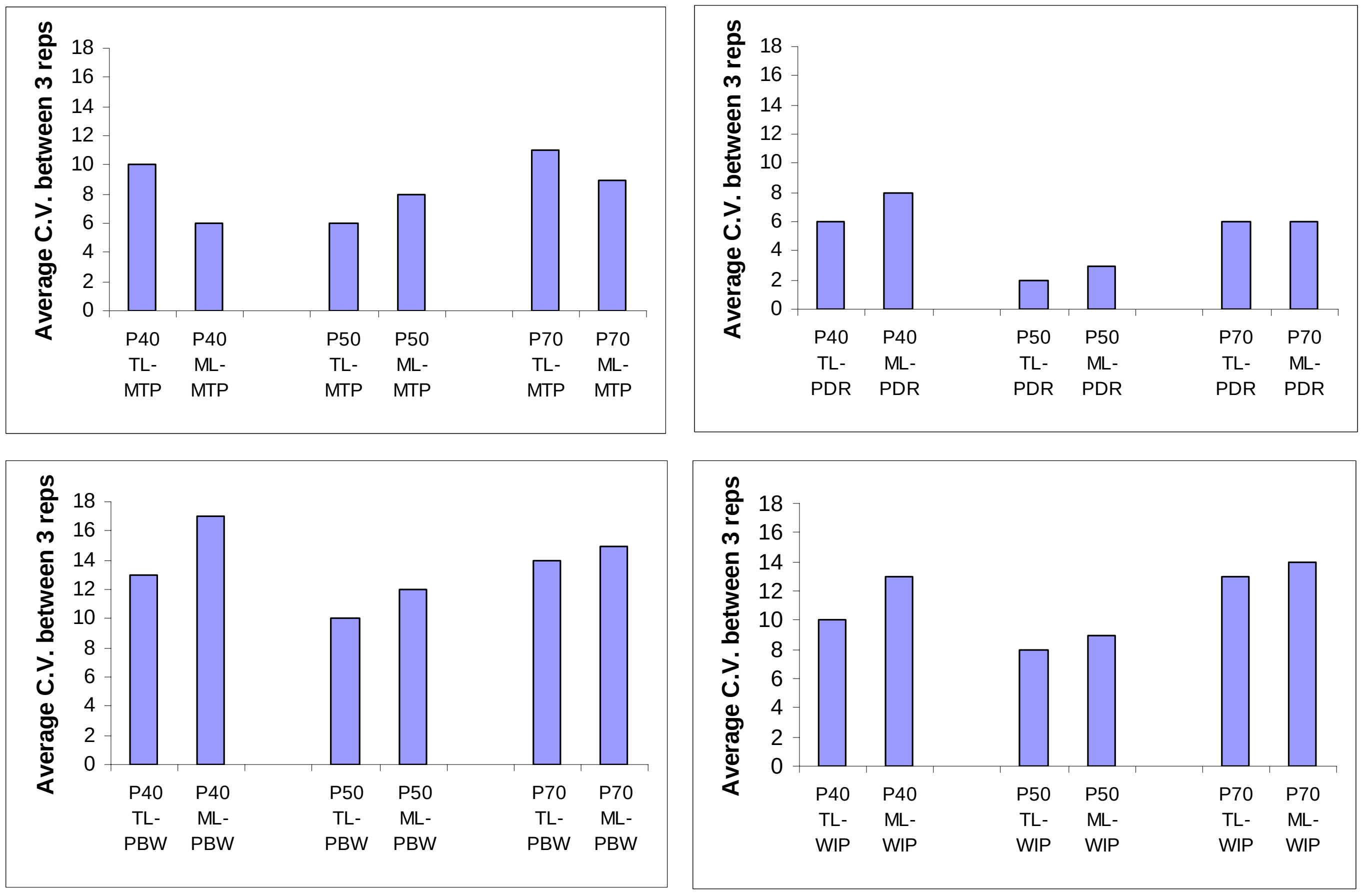

Figure G.3: Average Coefficients of Variation (C.V.) for TopLine and MidLine mixing time to peak (TL-MTP, ML-MTP), peak dough resistance (TL-PDR, ML-PDR), bandwidth at peak (TL-PBW, ML-PBW), and work input (TL-WIP, and ML-WIP) between 3 reps for Pulley40 (P40), Pulley50 (P50), and Pulley70 (P70).

G.4.3. Coefficient of Variation between Samples

There is an important difference between a desirable coefficient of variation between samples ($C.V._s$) and a desirable coefficient of variation between reps ($C.V._r$). As mentioned earlier, a lower $C.V._r$ is preferred because it translates into more reproducible results. In the case of $C.V._s$, a higher value is more desirable because this translates into a wider spread of values between wheat flour of different qualities. A wider spread of points for the dependent mixing parameters creates a better opportunity to find important differences in dough quality between flour samples.

An analysis for significant differences between $C.V._s$' could not be performed since each pulley treatment parameter (ex: Pulley40 TL-MTP) had only a single value. For example, the $C.V._s$ for Pulley40 TL-MTP is the coefficient of variation of each flour sample's individual $C.V._r$. Since tests of significance could not be performed, qualitative observations were made between the $C.V._s$' of each pulley.

The differences between $C.V._s$' were very small for mixing time to peak. For the TopLine curve Pulley70 had the largest $C.V._s$ at 34% while Pulley40 and Pulley50 had slightly smaller $C.V._s$' with values of 31% and 30%, respectively (Figure G.4). When assessing the MidLine curve, Pulley70 again had the largest $C.V._s$ at 28%. In this case, Pulley40 and Pulley50 had $C.V._s$ values of 27% and 25%, respectively.

The coefficients of variation for peak dough resistance were noticeably less than those of mixing time to peak. There again was less variability of $C.V._s$' between pulley systems than for $C.V._r$'s. For the TopLine mixing curve, Pulley70 had the highest $C.V._s$ at 18%. Pulley40 and Pulley50 had lower $C.V._s$' with values of 13% and 15%, respectively Figure G.4). Pulley70 again had the highest C.V.$_s$ for MidLine curve with a value of 17%. The C.V.$_s$' values of Pulley40 and Pulley50 for ML-PDR were both 14%.

The highest C.V.$_s$ for TopLine bandwidth at peak belonged to Pulley70, with a C.V.$_s$ of 24%. Pulley50 had a very similar C.V.$_s$ of 23%, while Pulley40 had a noticeably smaller C.V.$_s$ of 17% (Figure G.4). However, when looking at the MidLine curve, Pulley50 had the highest C.V.$_s$ at 25%. Pulley40 had the second highest with 22% and Pulley70 had a C.V.$_s$ of 21%.

There was little variation in the work input C.V.$_s$ between pulley settings. For the TL-WIP, Pulley70 had the highest C.V.$_s$ with a value of 23%, but Pulley40 and Pulley50 had very similar values, both with C.V.$_s$' of 22% (Figure G.4). Pulley70 again had the highest C.V.$_s$ when looking at the MidLine curve with a value of 18%. Pulley40 had the second highest C.V.$_s$ with 17%. Pulley50 had the lowest C.V.$_s$ with 15%.

Overall, pulley treatment did not have a large effect on the coefficient of variation between samples. There was no visible trend of a single treatment continually providing higher C.V.$_s$. Thus, since no difference could be seen in the C.V.$_s$ between treatments, a good basis does not exist for making a decision on a preferred pulley for use in the mixograph for CWRS wheat based on C.V.$_s$ levels alone.

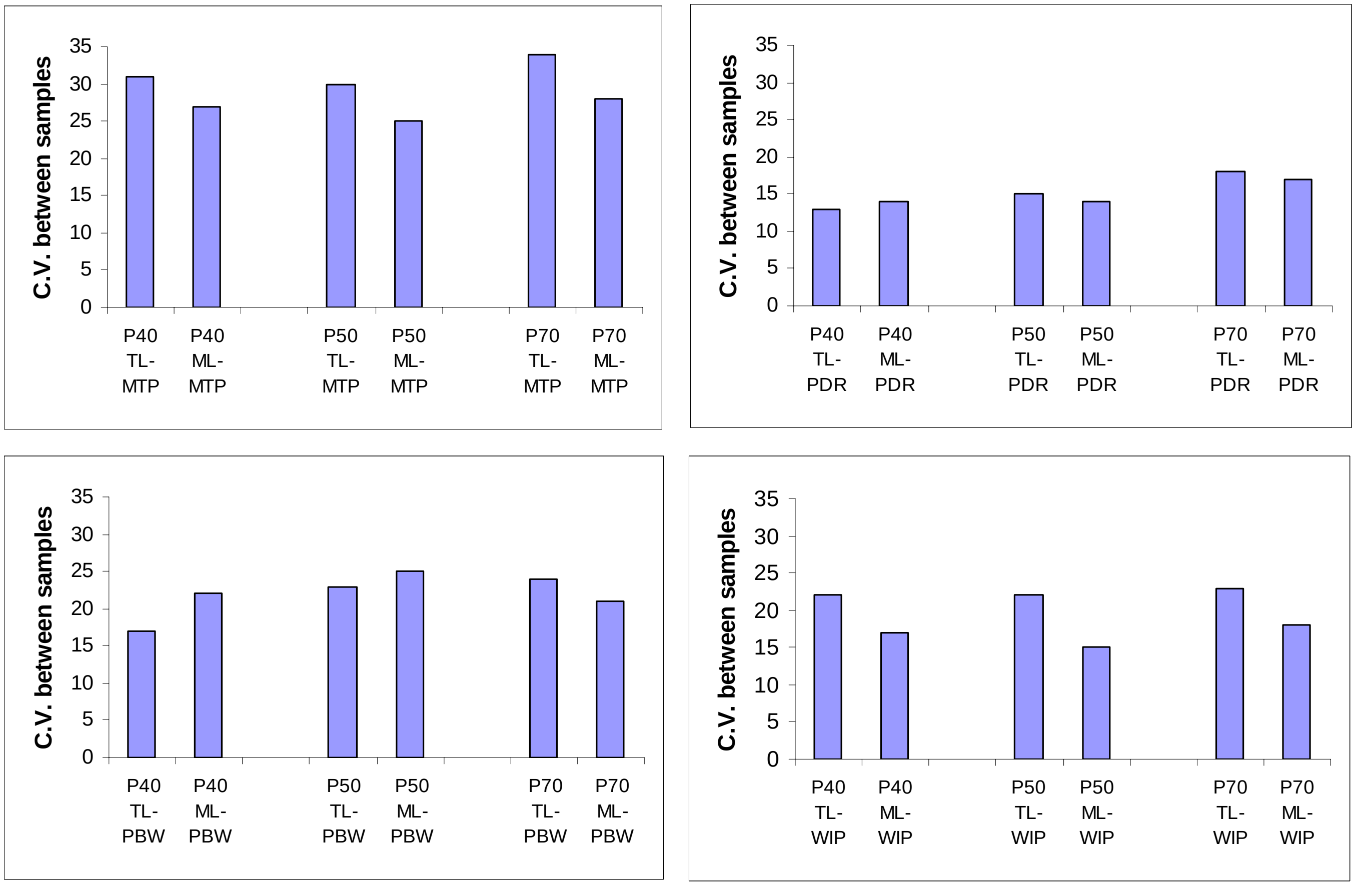

Figure G.4: Coefficients of Variation (C.V.) between samples for TopLine and MidLine mixing time to peak (TL-MTP, ML-MTP), peak dough resistance (TL-PDR, ML-PDR), bandwidth at peak (TL-PBW, ML-PBW), and work input (TL-WIP, and ML-WIP) for Pulley40 (P40), Pulley50 (P50), and Pulley70 (P70).

G.4.4. Coefficient of Variation Ratios

The purpose of the coefficient of variation ratio is to help decide which pulley treatment performed the best when there was not a clear decision after investigating the $C.V._r$'s and $C.V._s$'. For the $C.V._r$, Pulley50 was a clear choice for the best pulley treatment. However, with the $C.V._s$, no single pulley treatment stood out above the others as a possible desired pulley.

A test of significance could not be performed on the C.V. Ratios since there was only one value generated for each mixing parameter for each pulley. Again, qualitative observations help illustrate the results.

There was a large difference in the C.V. Ratio's for TL-MTP. Pulley50 had the largest C.V. Ratio with 4.68. Pulley40 and Pulley70 had C.V. Ratio values of 3.17 and 3.02, respectively (Figure G.5). For ML-MTP, Pulley40 had the largest C.V. Ratio with 4.30. Pulley50 and Pulley70 had similar C.V. Ratio values of 2.95 and 2.99, respectively.

The largest differences in C.V. Ratio's, for both mixing curves, were found when observing peak dough resistance. Pulley50 had the largest C.V. Ratio for TL-PDR with a value of 6.71. Pully40 and Pulley70 had much smaller C.V. Ratios with values of 2.10 and 3.17, respectively (Figure G.5). For ML-PDR, Pulley50 again had the largest C.V. Ratio (5.07) while Pulley40 and Pulley70 were much smaller with C.V. Ratios of 1.72 and 2.88, respectively.

C.V. Ratio's for bandwidth at peak were generally smaller than those for mixing time to peak and peak dough resistance. For TL-PBW, Pulley50 had the largest C.V. Ratio at 2.26. Pulley40 and Pulley70 had C.V. Ratio's of 1.30 and 1.78, respectively

(Figure G.5). For ML-PBW, Pulley50 again had the largest C.V. Ratio with a value of 1.97. Pulley40 and Pulley70 had similar C.V. Ratios with 1.29 and 1.39, respectively.

The parameter work input to peak also had smaller C.V. Ratios compared to mixing time to peak and peak dough resistance. For TL-WIP, Pulley50 had the largest C.V. Ratio with 2.81. Pulley40 had the next highest at 2.20, followed by Pulley70 with 1.74 (Figure G.5). When looking at ML-WIP, Pulley50 again had the largest C.V. Ratio with a value of 1.69. Pulley40 and Pulley70 had similar C.V. Ratios with 1.35 and 1.31, respectively.

When examining the C.V. Ratios, the most desirable value is the highest value. This is because of the nature of how the ratio is generated with a desirable high value as the numerator and a desired low value as the denominator (Equation G.2). After examining the C.V. Ratios, Pulley50 seems to be a clear choice as the most desirable pulley treatment. In fact, Pulley50 had the largest C.V. Ratio for all mixing parameters except ML-MTP, where Pulley40 had a larger C.V. Ratio. This trend in the C.V. Ratio can be accounted for by the trend of Pulley50 having the lowest $C.V._{\cdot r}$ values. Therefore, by looking at these three different coefficients of variation ($C.V._{\cdot r}$, $C.V._{\cdot s}$, and C.V. Ratio) it can be stated that Pulley50 shows the most promise in the becoming the most desirable pulley treatment.

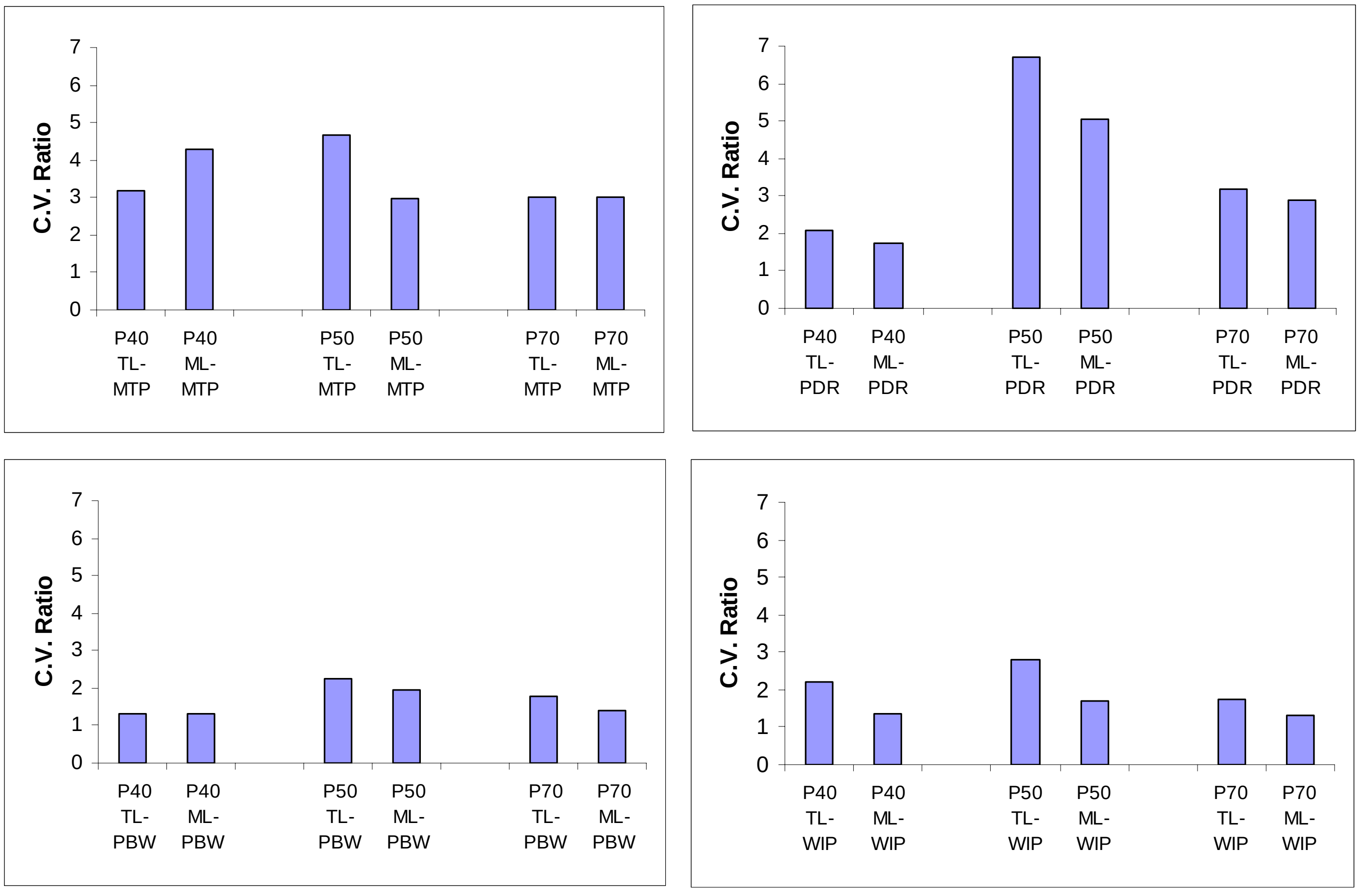

Figure G.5: Coefficient of Variation (C.V.) Ratios for TopLine and MidLine mixing time to peak (TL-MTP, ML-MTP), peak dough resistance (TL-PDR, ML-PDR), bandwidth at peak (TL-PBW, ML-PBW), and work input (TL-WIP, ML-WIP) for Pulley40 (P40), Pulley50 (P50), and Pulley70 (P70).

G.4.5. Mixograph Parameter Relationships with Protein

Before any conclusions can be made on the decision of the most appropriate pulley for mixing CWRS wheat on the mixograph, some comparative analysis should be performed with a sample set of explanatory variables. Earlier work has shown that protein content and protein quality have a good relationship to several of the discussed mixing parameters in this paper (Hamada et al., 1982; Martinant et al., 1996; Sapirstein and Fu, 1998). As mentioned earlier, these 13 flour samples were chosen because of their wide variation in flour protein content and flour protein composition. Therefore, a regression analysis for each pulley system was performed to ensure that altering the pulley system from Pulley70 to Pulley50 or Pulley40 did not jeopardize these relationships but actually improved them or helped discover new ones.

Weak relationships were found between each of the protein independent variables and the mixing time parameters for both TopLine and MidLine curves. Regressions between flour protein content (PC), soluble protein (SP), and HMW-glutenin (HMW) were very similar between Pulley40, Pulley50, and Pulley70. For the TopLine curve, the highest R^2 of 0.39 with soluble protein was obtained with Pulley40 (Figure G.6). For the MidLine curve, the highest R^2 of 0.47 with soluble protein content was obtained with Pulley50.

The strongest relationships were found between peak dough resistance and the protein independent variables. The lowest R^2 for peak dough resistance of the TopLine curve was found between Pulley40 and soluble protein content with $R^2 = 0.75$ (Figure G.6). The highest R^2 was found between Pulley50 TL-PDR and flour protein content and HMW-glutenin content, both with an $R^2 = 0.83$. Relationships were not as strong as the

TopLine curve when observing the relationships between the MidLine curve and protein variables. The weakest relationship was found with Pulley70 between HMW-glutenin and ML-PDR with $R^2 = 0.68$. Pulley50 had the strongest relationship with an $R^2 = 0.81$ between soluble protein and ML-PDR.

There was considerably more variability in the strength of relationships between the protein variables and the bandwidth at peak. The variability was greater between pulley systems, between TopLine and MidLine curves, and between protein variables. Overall, Pulley50 produced the strongest relationships between bandwidth at peak and the protein variables. The strongest relationships were both protein content and HMW-glutenin content with TL-PBW from Pulley50 ($R^2 = 0.84$) (Figure G.6). The weakest relationship existed between soluble protein content and both the TopLine and MidLine bandwidths at peak from Pulley40 ($R^2 = 0.35$). Pulley40 had the lowest R^2 values in all instances for bandwidth at peak. It is possible that the mixing speed of Pulley40 was too intense and the shear of the mixing caused a dough weakening affect. Overall, the TopLine curve produced higher R^2 values then the MidLine curve. This was especially true for Pulley50 and Pulley70. Pulley40 showed the smallest improvement in relationship from the MidLine to the TopLne curve. Pulley50 produced the strongest relationship between bandwidth at peak height and each protein variable in every situation except for ML-PBW vs soluble protein when Pulley70 had an $R^2 = 0.61$ and Pulley50 had an $R^2 = 0.46$.

The weakest relationships between protein variables and mixing parameters were found with work input. The lowest R^2 was 0.001, found between flour protein content and both TL-WIP and ML-WIP for Pulley70. The highest R^2 was 0.34, found between soluble protein content and Pulley50 ML-WIP (Figure G.6).

The relationships between dough and protein variables for the different pulley treatments also indicated that Pulley50 was a superior pulley. In most cases, especially in the more important parameters peak dough resistance and bandwidth at peak, Pulley50 increased the R^2 from the original Pulley70 level. For 11 out of 12 parameters for peak dough resistance and bandwidth at peak Pulley50's R^2 was larger than the R^2 of Pulley70 from as little as 0.004% (Flour Protein vs ML-PBW) to as much as 32% (HMW-glutenin vs ML-PBW). When looking at the weaker relationships of mixing time to peak and work input, there was little variation in R^2 levels between pulley treatments. The mixing parameters for Pulley40, Pulley50 and Pulley70 could be considered to have equally weak relationships between the protein variables and mixing time to peak as well as work input to peak.

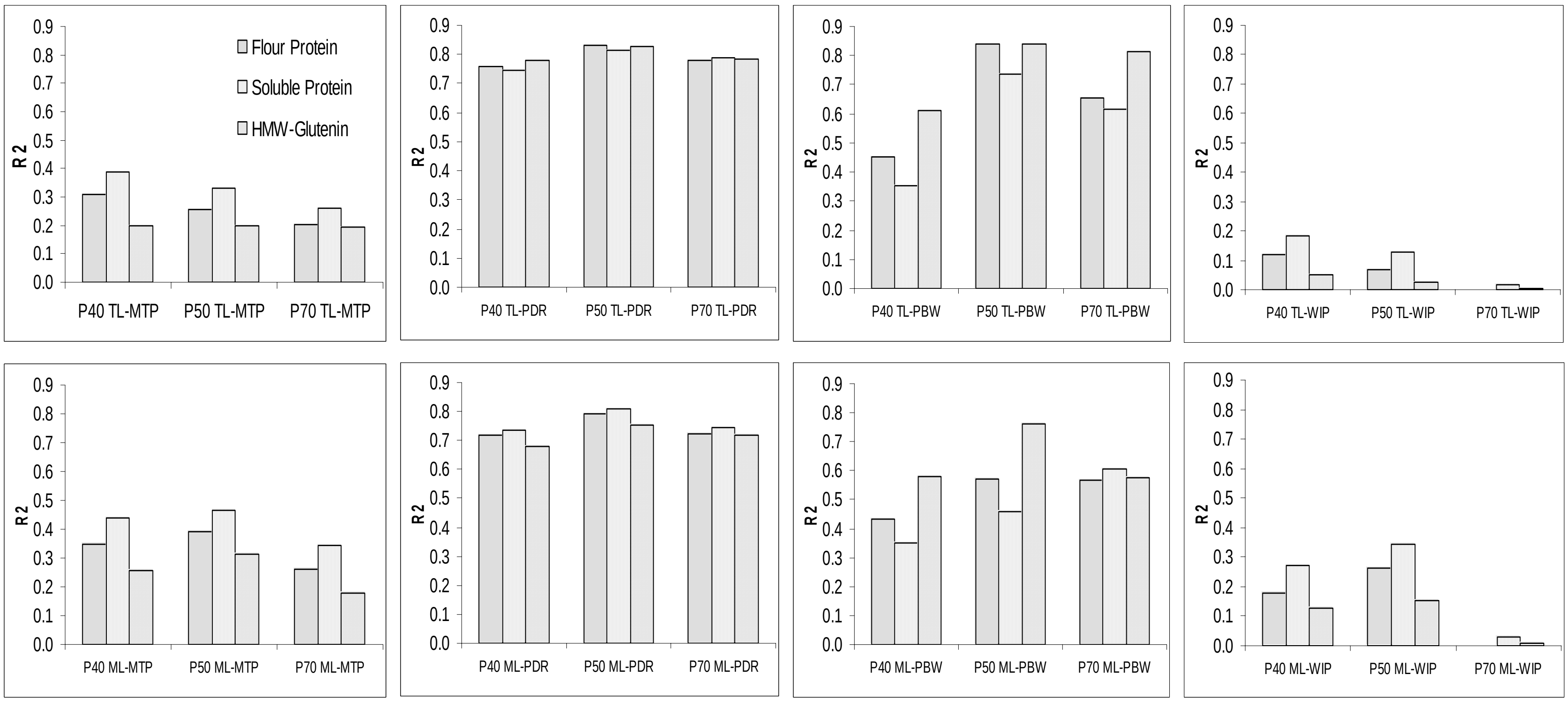

Figure G.6: Regression coefficients for TopLine and MidLine mixing time to peak (TL-MTP, ML-MTP), peak dough resistance (TL-PDR, ML-PDR), bandwidth at peak (TL-PBW, ML-PBW), and work input (TL-WIP, ML-WIP) for Pulley40 (P40), Pulley50 (P50), and Pulley70 (P70) against total flour protein content, soluble protein content, and HMW-glutenin content.

G.5. Conclusions

The purpose of this experiment was to investigate how mixing intensity of the 10-gram mixograph influenced peak development of low protein CWRS flour samples. From our findings, we can conclude that increasing the mixing intensity was successful in improving dough development for low protein CWRS flour samples (Figure G.2). It was also noted that a side effect from increasing the mixing intensity was a change in the mixogram shape for high protein CWRS flour samples. We found that a moderate increase in the mixing intensity (by Pulley50 vs Pulley40) was able to improve the peak development of low protein mixograms while maintaining the shape of the high protein mixograms.

Pulley50 was also chosen as the preferred pulley treatment because it produced the lowest $C.V._r$ values (Figure G.3). In other words, Pulley50 produced the most reproducible results of the three pulley treatments. Pulley50 also had the most desirable (highest) C.V. Ratio levels (Figure G.5). This is because of the low $C.V._r$ values since there was not a noticeable difference between $C.V._s$ levels between the three pulley treatments (Figure G.4).

The Pulley50 mixograph data was also found to have the best relationships between dough and protein variables (Figure G.6). This is very important since these relationships that existed with the original Pulley70 system have actually improved with Pulley50.

Therefore, it can be concluded that Pulley50 was a superior pulley to be used with the 10-gram mixograph for mixing CWRS flour because of its ability to improve peak development of low protein CWRS flour samples, improve reproducibility of mixogram results, and improved relationships between dough and protein variables.