Genotypic and environmental variation in grain, flour, dough and bread-making characteristics of western Canadian spring wheat

G. J. Finlay[1], P. R. Bullock[1], H. D. Sapirstein[2], H. A. Naeem[2], A. Hussain[2], S. V. Angadi[3], and R. M. DePauw[4]

[1]*Department of Soil Science,* [2]*Department of Food Science, University of Manitoba, 362 Ellis Building, Winnipeg, Manitoba, Canada R3T 2N2 (email: Paul_Bullock@umanitoba.ca);* [3]*Agricultural Science Center, New Mexico State University, 2346 State Road 288, Clovis, New Mexico, USA, 88101-9998; and* [4]*Agriculture and Agri-Food Canada, Semiarid Prairie Agricultural Research Centre, Box 1030, Swift Current, Saskatchewan, Canada S9H 3X2.* *Received 2 August 2006, accepted 20 April 2007.*

Finlay, G. J., Bullock, P. R., Sapirstein, H. D., Naeem, H. A., Hussain, A., Angadi, S. V. and DePauw, R. M. 2007. **Genotypic and environmental variation in grain, flour, dough and bread-making characteristics of western Canadian spring wheat**. Can. J. Plant Sci. **87**: 679–690. Wheat (*Triticum aestivum* L.) grain, flour, dough and bread quality characteristics are strongly influenced by growing-season weather conditions. Understanding the impact of genotype, environment, and their interactions on Canadian wheat quality is important for Canada to maintain its high standard for delivery of consistent quality wheat to domestic and international customers. The effects of genotype, environment and genotype by environment (G × E) interaction on numerous grain, flour, dough and bread-making characteristics were assessed. The Canadian Western Red Spring (CWRS) cultivars were AC Barrie, Superb, AC Elsa, and Neepawa; the Canadian Prairie Spring (CPS-white) cultivar was AC Vista; and the Canadian Western Hard White Spring (CWHWS) cultivar was Snowbird. These genotypes were grown at five locations across the Canadian prairies in 2 yr to provide a total of 7 site-years of milling quality wheat for analysis. Genotype, environment and their interactions had significant effects on most parameters tested. The relative magnitude of the environmental contribution to wheat quality variance, depending on the trait, was considerably larger (14 to 89%) than the variance contribution of either genotype (0 to 33%) or G × E interaction (0 to 17%). The greatest environmental contribution to total variance (83%) was, on average, for grain traits including yield. Genotypic contribution to variation was greatest (~15%) for flour characteristics. The G × E interaction contributed relatively little to total variance and was comparable for flour, dough and bread properties (~6.5% on average). This large difference in variance between environmental and genotypic influences clearly demonstrates the importance of growing-season weather impacts on yield and quality for adapted bread wheat genotypes and strategies to mitigate these effects are discussed.

Key words: Wheat, bread-making quality, Canadian prairies, environment, genotype, genotype by environment

Finlay, G. J., Bullock, P. R., Sapirstein, H. D., Naeem, H. A., Hussain, A., Angadi, S. V. et DePauw, R. M. 2007. **Variations génotypiques et environnementales du grain, de la farine, de la pâte et de la panification du blé de printemps de l'Ouest canadien**. Can. J. Plant Sci. **87**: 679–690. Les conditions météorologiques durant la période végétative exercent une profonde influence sur le grain du blé (*Triticum aestivum* L.), sa farine, la pâte et la panification. Pour que le blé canadien garde sa réputation de qualité auprès de la clientèle canadienne et étrangère, il importe de comprendre l'incidence du génotype et de l'environnement ainsi que de leurs interactions. Les auteurs ont évalué l'effet du génotype, de l'environnement et de l'interaction génotype × environnement (G ×E) sur de nombreuses caractéristiques du grain, de la farine, de la pâte et de la panification. Les essais ont porté sur les cultivars de blé roux de printemps de l'Ouest canadien AC Barrie, Superb, AC Elsa et Neepawa, sur le cultivar de blé de printemps blanc des Prairies canadiennes AC Vista et sur le cultivar de blé dur blanc de printemps des Prairies canadiennes Snowbird. Les variétés ont été cultivées à cinq endroits dans les Prairies canadiennes pendant deux ans, ce qui a donné sept années-sites pour l'analyse de la qualité meunière. Le génotype, l'environnement et leur interaction ont d'importantes répercussions sur la majorité des paramètres examinés. Selon le paramètre, l'environnement a une influence relative considérablement plus importante sur la variation de la qualité (de 14 à 89 %) que celle du génotype (de 0 à 33 %) ou de l'interaction G ×E (de 0 à 17 %). Dans l'ensemble, la plus forte contribution de l'environnement à la fluctuation globale de la qualité (83 %) concerne les paramètres du grain, y compris le rendement. Le génotype concourt le plus à la variation des propriétés de la farine (~15 %) L'interaction G × E apporte relativement peu à la variance globale, et son incidence est comparable pour les propriétés de la farine, de la pâte et du

Abbreviations: **CGC**, Canadian Grain Commission; **CNA**, combustion nitrogen analysis; **CPS-white**, Canadian Prairie Spring White; **CWRS**, Canadian Western Red Spring; **CWHWS**, Canadian Western Hard White Spring; **E**, environment; **FAB**, farinograph absorption; **FarDDT**, farinograph dough development time; **FarSTAB**, farinograph stability; **G**, genotype; **GPC**, grain protein concentration; **G x E**, genotype by environment; **HMW-Glutenin**, high molecular weight glutenin; **mb**, moisture basis; **MTI**, mixing tolerance index; **MTP**, mixing time to peak; **PBW**, peak bandwidth; **PDR**, peak dough resistance; **TKW**, thousand kernel weight; **WIP**, work input to peak

pain (~6,5 % en moyenne). Cet important écart de variance entre les influences de l'environnement et du génotype démontre clairement l'incidence des conditions météorologiques sur le rendement et la qualité des génotypes de blé panifiables durant la période végétative. Suit une discussion sur les stratégies permettant d'atténuer ces effets.

Mots clés: Blé, propriétés de panification, Prairies canadiennes., environnement, génotype, variation

Wheat kernel development and biomolecule accumulation are strongly influenced by genotype and environmental parameters (Baenziger et al. 1985; Peterson et al. 1992). Environmental parameters such as useful-heat accumulation, higher than optimal temperature, and water stress are predominant factors influencing grain development. Wheat classes grown in Canada vary significantly in quality and yield. Although the response of different classes and genotypes of wheat to the growing environment are expected to vary significantly, very little research, especially under field conditions, has been conducted. The vast size of the wheat-growing region in western Canada creates a very large range of temperature and precipitation conditions each year, leading to a wide range in wheat quality outcomes across the Prairie region. However, millers and bakers need consistent quality of wheat from shipment to shipment and from year to year to manufacture food products of consistent quality in line with standard processing conditions.

Several studies have examined the effects of genotype and environmental conditions during grain development (Baker et al. 1971; Fowler and De La Roche 1975; Baker and Kosmolak 1977; Lukow and McVetty 1991; Peterson et al. 1992, 1998; Graybosch et al. 1995; Ames et al. 1999; Mikhaylenko et al. 2000; Panozzo and Eagles 2000; Preston et al. 2001; Zhang et al. 2004). The results of these studies have generally shown that environment, genotype and genotype by environment (G × E) interactions are all significant factors contributing to variation in quality. However, most of these studies have indicated that environment is the main contributing factor to variation in quality while G × E interaction contributes a relatively small portion to that variation.

Of particular interest to Canadian agriculture are the studies that examine Canadian genotypes and environments. One of the earliest Canadian studies to evaluate the contributions made by genotype and environment to bread-making quality (Fowler and de la Roche 1975), examined winter and spring wheats from 15 environments spanning Manitoba to Prince Edward Island; no western Canadian genotypes or western Prairie locations were used. An extensive list of quality parameters was analyzed, covering grain properties, flour yield, dough mixing properties and loaf volume. A large environmental effect was observed for yield, test weight, protein and protein related parameters. Flour pigment, mixograph development time, and kernel hardness were found to have the smallest response to environment. It was also found that genotype-location and genotype-year interactions were relatively insignificant for most quality parameters.

Baker and Kosmolak (1977) examined eight hard red spring wheat quality characteristics from wheat grown at several Manitoba and Saskatchewan sites. Genotypes were pooled into only two environments, thus masking the true environmental impact. G × E interaction was found to be important in determining mixograph development time, Falling Number, and remix loaf volume, while flour yield, flour protein, farinograph absorption, and grinding time (a measure of wheat hardness) were relatively insensitive to G × E interaction.

Lukow and McVetty (1991) studied the effect of genotype, environment, and G × E interactions on eight diverse semi-dwarf genotypes grown at three sites within central Manitoba over 2 yr. Sixteen quality parameters were analyzed, including grain, flour, dough, and bread loaf characteristics. Genotype, environment, and G × E interactions were significant for all quality parameters, except for environment effects on flour yield and farinograph dough development time. Variation due to environment was pronounced for all quality parameters but the variance component for genotype was greater in all cases, contributing 52 to 93% of total variation. The G × E contribution to variation was considerably smaller in comparison with either environment or genotype, contributing 3.8 to 30% to the total variance and was considered relatively unimportant in most cases.

In a quality study of durum wheat (*T. durum* L.)(Ames et al. 1999), 10 diverse genotypes from the USA and Canada were grown in eight environments in western Canada. Environment was found to be the main source of variation for grain protein concentration and mixograph dough development time, while genotype played a more important role in gluten index and strength variation. The G × E interaction was significant for all quality parameters tested but contributed only a small portion to variation in quality.

Preston et al. (2001) studied farinograph and Canadian Short Process (CSP) baking properties of Canada Western Red Spring (CWRS) wheat from six locations in Saskatchewan in 1 yr. This study was conducted during the 1995 growing season and thus the genotypes analyzed are no longer current. The variation due to environment was found to be greater than that of genotype for farinograph absorption, CSP baking absorption and flour protein. However, genotype effects were greater than environment effects for kernel hardness, farinograph dough development time and stability, CSP dough mixing time, and mixing energy. No significant environmental effect was found for farinograph stability. The G × E interaction was also found to be significant for all quality parameters except kernel hardness, farinograph stability, and flour protein concentration. However, the overall contribution of G × E interaction was relatively small in comparison to the main effects.

Although several researchers (Fowler and De La Roche 1975; Baker and Kosmolak 1977; Lukow and McVetty 1991; Ames et al. 1999; Preston et al. 2001) have studied the effect of genotype, environment and their interaction on various Canadian spring wheat quality parameters over the past

30 yr, the effect of these impacts have not been studied recently using current Canadian genotypes, nor has any recent study completed a comprehensive review of grain, flour, dough, and bread quality characteristics. In addition, none of these studies involving common wheat spanned representative growing areas in the Prairie provinces.

In this study, six adapted spring wheat genotypes were grown under field conditions at widely scattered locations across western Canada, and grain was subjected to a comprehensive analysis of wheat compositional traits and technological quality. The main objective was to assess the effects of genotype, environment and G × E interaction on the analytical outcomes. In addition, the technological quality response of the genotypes to the environment was evaluated in comparison to other studies conducted in different locations and under different testing conditions.

MATERIALS AND METHODS

Field Setup

Six spring wheat genotypes from three commercial classes were grown in nine environments in the Canadian prairies during the 2003 and 2004 growing seasons, providing a very diverse range of growing environments. The wheat genotypes included CWRS cultivars AC Barrie (McCaig et al. 1996), AC Elsa (Clarke et al. 1997), Neepawa (Campbell 1970) and Superb (Townley-Smith and Humphreys 2000), CWHWS cultivar Snowbird (Humphreys et al. 2007), CPS-white cultivar AC Vista (DePauw et al. 1998). Cultivars were selected to encompass a wide range in milling and baking quality characteristics for spring wheat adapted to Prairie growing conditions.

Field sites were established at Agriculture and Agri-Food Canada research stations at Regina, Melfort and Swift Current, Saskatchewan and as well as the University of Manitoba in Winnipeg, Manitoba, in 2003 and 2004. In 2004, a fifth site at the University of Manitoba field facility at Carman, Manitoba, was added. The experimental layout in each environment was a randomized complete block design with three replicates. In 2003, Regina, Swift Current and Melfort plots consisted of 16 rows spaced at 23 cm, while that at Winnipeg consisted of 20 rows spaced at 20 cm. Plot lengths at Regina and Swift Current were 5 m long, at Melfort were 6 m and at Winnipeg were 9 m. Final harvested lengths were 3 m at Regina and Swift Current, 4.2 m at Melfort and 8.4 m at Winnipeg. The numbers of rows in 2004 were increased to 24 at Swift Current and to 20 at Regina and Melfort. Plot size at Carman was the same as at Winnipeg, and harvested length was 7 m. All Saskatchewan sites were seeded at a rate of 200 seeds m^{-2} and the Manitoba sites were seeded at a rate of 220 seeds m^{-2}. A low disturbance plot seeder was used at each location. Plots and replicates in Saskatchewan were separated by spring-seeded winter triticale (*X Triticosecale* Wittmack) and plots in Manitoba were seeded side by side with late-seeded spring wheat separating replicates.

Soil tests were conducted prior to seeding at all locations except Melfort where a soil sample was taken the previous fall. Nutrients were then applied as per soil test recommendations at the time of seeding to bring soil N to 160 kg ha^{-1}, P to 80 kg ha^{-1} and S to 35 kg ha^{-1} in Melfort, Regina, Winnipeg and Carman. Due to dryer conditions in Swift Current, soil N was brought to 112 kg ha^{-1}, P to 75 kg ha^{-1}, and S to 35 kg ha^{-1}. Broad leaf and grassy weeds were controlled using recommended post-emergence herbicides. At the Winnipeg location, Tilt (propiconazole) was applied at recommended rates at the flag leaf stage in 2003 to control leaf disease while in 2004, Folicur (tebuconazole) was applied at the recommended rate at anthesis for control of fusarium head blight.

Field and Analytical Techniques

Phenological Development

At each location, phenological observations were recorded every 10 to 15 days for each plot using the Zadoks decimal code (Zadoks et al 1974; Tottman 1987). Observations from emergence to heading were taken from a 1-m row, three or four rows from the edge of the plot, while observations from heading to maturity were taken from 15 randomly selected heads. Dates of emergence, dates of anthesis, and dates of maturity were recorded at each site. Date of emergence was defined as the date when 50% of the germinated plants emerged from the soil. Date of anthesis was defined as the date when 50% of the spikes reached anthesis. Date of maturity was defined as the date of maximum dry matter accumulation and the time when kernels reached their maximum weight, usually about 35% moisture on a wet weight basis (Clarke 1983).

Agrometeorlogical Data

Automated weather stations (Campbell Scientific, Logan, UT; Spectrum, Plainfield, IL) were installed at each location at seeding to collect on an hourly and daily basis air temperature, rainfall, wind speed, relative humidity, solar radiation, soil temperature and soil moisture. Hourly and daily average, maximum and minimum values were recorded for each measured weather variable. Soil moisture was monitored every 10 to 15 d at each location using a neutron probe (Troxler, Research Triangle Park, NC). Soil water content at the 0- to 15-cm depth was determined gravimetrically. Soil moisture data were averaged from the six plots for each date at each location.

Grain Properties

A plot combine was used to harvest the center eight rows of the plots, avoiding edge effects. The grain yield was expressed at 13.5% moisture basis (mb). Moisture was assessed using Labtronics Grain Moisture Meter (Model No. 919) (Labtronics, Canadian Aviation Electronics Ltd., Winnipeg, MB).

Grain samples from each plot were inspected and officially graded by the Canadian Grain Commission (CGC 2004). Wheat grain protein concentration (GPC) was determined by Approved Method 39-10 using near-infrared reflectance spectroscopy (AACC International 2000). CGC grading also included determination of test weight, fusarium damaged kernels, and level of sprout damage assessment

(CGC 2004). A minimum of two replications of 250 clean seeds were counted using a seed counter to assess thousand kernel weight (TKW), expressed at 13.5% mb. Kernel number per meter square was derived using harvest yield (g m^{-1}) and TKW (g $kernel^{-1}$) data and the following equation:

$$\frac{\text{No. of Kernels}}{m^2} = \frac{\text{Yield (g m}^{-2}\text{)}}{\text{Kernel Weight (g kernel}^{-1}\text{)}}$$

The remaining analytical results below are reported on a 14% mb.

Wheat Quality Analysis

Grain samples from each plot at each location were collected and their identity preserved. Each field plot was assayed individually. The grain was then used for an extensive array of wheat quality analysis. Wheat quality characteristics examined included those pertinent to grain, flour, dough and bread as described below.

Wheat Milling

Grain samples were tempered to 16.5% mb for 24 h prior to milling. A Buhler Pneumatic Laboratory mill (MLU-202) (Buhler Bros., Ltd., Uzwil, Switzerland) was used to mill approximately 3 kg of wheat to straight grade flour of approximately 14% mb. Flour was stored in polyethylene bags and allowed to mature at room temperature for at least one month before further testing.

Flour Properties

Flour protein concentration (%N × 5.7) was determined by combustion nitrogen analysis (CNA) according to Approved Method 46-30 (AACC International 2000) with a LECO instrument (Model FP-428 CNA Analyzer, St. Joseph, MI) calibrated against ethylenediaminetetraacetic acid (EDTA).

Flour protein composition was determined according to the method of Sapirstein and Johnson (2000). This procedure quantifies three fractions, i.e., protein soluble in 50% 1-propanol (mainly gliadins), propanol insoluble glutenin (mainly high molecular weight polymeric glutenin) and residue protein that contains mainly non-gluten protein (Fu et al. 1996).

Flour ash was determined according to Approved Method 08-01 (AACC International 2000). Total flour pentosan content was determined as described by Douglas (1981). Flour colour (reflectance at 546 nm) was analyzed with a computerized Minolta spectrophotometer (Model CM-3500d, Minolta Co. Ltd., Osaka, Japan) using a flour-water slurry procedure similar to that used in Agtron Colour measurement according to approved Method 14-30 (AACC International 2000). Details of our modified procedure have been described in Machet (2005). Starch damage, a measure of kernel hardness, was analyzed according to approved Method 76-31 (AACC International 2000). Falling Number was determined using Approved Method 56-81B (AACC International 2000).

Dough Properties

The farinograph is one of the most widely accepted methods of measuring flour water absorption and dough strength. Optimum flour water absorption (FAB) was determined with a Brabender Farinograph (C.W Brabender Instruments Inc., South Hackensack, NJ) using Approved Method 54-21 (AACC International 2000). The farinograph was also used to determine dough development time (FarDDT), farinograph stability (FarSTAB), and mixing tolerance index (MTI).

A complementary method of measuring dough mixing properties of flour was applied using a mixograph. Mixograph curves (National Manufacturing Division, TMCO, Lincoln, NE) were obtained at 62% absorption (14% mb) with a 10 g computerized moving bowl mixograph equipped with a water-jacketed bowl maintained at 25°C and 88 rpm. A spring setting of 12 was used. Data were analyzed using Power-to-Mixing Software (Roller 2004) generating results for mixograph parameters essentially as described by Khatkar et al. (1996). Parameters recorded were mixing time to peak dough development (MTP, min), peak dough resistance (PDR, % torque), peak bandwidth (PBW, % torque), and work input to peak (WIP) dough resistance.

Bread Properties

The final quality parameters measured were the bread properties of full formula mix time and loaf volume, which are considered the most important quality characteristics for bread making. Flour samples were prepared and baked using a modified version of Approved Method 10-10B (AACC International 2000). Fleishman's Quick-Rise™ dry yeast was substituted in place of compressed yeast, and ascorbic acid (20 ppm) replaced potassium bromate. The formula used was 100 g flour, 6 g sugar, 1.5 g of salt, 0.75 g of yeast, 4 g of whey, 3 g of shortening, and optimal water absorption as determined by the farinograph.

Statistical Analysis

To determine replicate effects within sites data for each quality parameter at each location were analyzed by PROC GLM (SAS Institute, Inc. 2001) as a randomized complete block design. PROC UNIVARIATE was used to check normality and determine outliers using residuals. Homogeneity of variance was tested using Levene's test prior to and after removal of outliers. Residuals were plotted and visually examined for outliers. The Proc Univariate procedure provided output of extreme residual observations for each quality parameter. Outliers were then excluded based on residual values that were obviously higher or lower than the other extreme residual values found. The number of outliers removed ranged from 0 to 4, depending on the quality property. Each analysis was completed with the outliers removed.

Error variances across site years were not homogeneous according to Levene's test for GPC, test weight, soluble protein, total flour protein, residue protein, starch damage, falling number, FarDDT, FarSTAB, MTI, mixograph PBW, and loaf volume. Data were subjected to analysis of variance (ANOVA) using the PROC MIXED procedure, with environment (year by location) and environment by genotype as random effects and genotype as a fixed effect. The statement

REPEATED/GROUP=SITEYEAR was added to account for heterogeneous error variances across years. Variance components were estimated using restricted maximum likelihood (REML) and the degrees of freedom method was set to "Satterthwaite".

Error variances were found to be homogenous across site years for yield, TKW, kernel number, flour ash, high molecular weight glutenin (HMW-Glutenin), pentosans, FAB, mixograph MTP, mixograph PDR, mixograph WIP, and full formula mix time. The PROC MIXED procedure was again used to analyze the data with the estimation method used being REML and the degrees of freedom method set to "Containment". The LSMEANS statement was added to determine the least significant difference (LSD) among genotypes at the 5% significance level.

RESULTS AND DISCUSSION

The 2003 and 2004 growing seasons provided a wide range of growing conditions across the study sites, leading to a very diverse set of wheat quality characteristics. Some basic weather data are summarized in Table 1. The 2003 season provided warmer, drier conditions for crop growth, with an average growing season temperature range across the sites from 16.5 to 19.2°C and growing season precipitation range from 81 to 200 mm. The 2004 season was much cooler and wetter, with an average growing season temperature range across the sites of 12.9 to 16°C and growing season precipitation from 225 to 370 mm. As would be expected, precipitation and wind speed were quite variable across the locations as reflected in their coefficients of variation (CV) (Table 1). Wind speed is an important factor driving evapotranspiration and its variability combined with that of precipitation suggest that the crop water supply/demand ratio was also quite variable across the study sites.

Due to a severe frost event in parts of Saskatchewan during the grain-filling stage in 2004, wheat from Regina 2004 and Melfort 2004 were graded as feed, and accordingly, quality data were excluded. The purpose of this study was to examine growing-season weather impacts on milling wheat quality, and the effects of a severe frost early in kernel development would adversely affect wheat quality (Preston et al. 1991) and confound results.

The average wheat grade of all remaining samples was 1.75. Accordingly, most genotypes samples achieved either No. 1 or No. 2 grade and were of excellent milling quality. AC Vista was somewhat different in this regard, as its average grade over all locations was 2.5, which is indicative of its lower tolerance to disease and adverse weather generally found in CPS genotypes.

Genotype Effects

Genotypes varied moderately to widely in quality depending on the trait (Table 2). AC Vista had the highest yield and kernel weight and the lowest protein concentration among the six genotypes. The oldest CWRS genotype, Neepawa (registered in 1969, Campbell 1970), had the lowest yield and kernel weight with a grain protein concentration similar to more recently registered genotypes. This was also expected as crop breeding has consistently improved CWRS wheat yields while maintaining grain protein concentration. It was also apparent in the dough properties (Table 2), that Neepawa had a tendency towards weaker dough with significantly lower FarDDT, MTP, PDR, PBW and WIP than most or all of the other genotypes. The mean grain protein concentration was closely related to flour protein for each genotype as would be expected. AC Vista, with the lowest flour protein concentration, had the lowest loaf volume averaged across growing locations, another relationship that would be expected. The link between flour protein and loaf volume was not entirely consistent. For example, Neepawa had a significantly lower loaf volume than AC Barrie and AC Elsa, despite having comparable flour protein concentration. This is a classical indication of a relative deficiency in the gluten protein quality of Neepawa, as both protein concentration and quality are the key factors in wheat bread-making performance (Bushuk et al. 1969). Evidence of a lower protein quality of Neepawa is clearly indicated by its relatively low content of insoluble protein, i.e. HMW-Glutenin (Table 2), compared with all other genotypes in this study. Neepawa's relatively weak dough properties are likely also a reflection of its lower content of HMW-Glutenin.

Highly significant genotypic effects ($P < 0.0001$) were found for yield, GPC, TKW, test weight, starch damage, soluble protein, total flour protein, pentosans, flour colour, FAB, PDR, WIP, and loaf volume both within and across all growing locations. A significant genotypic effect ($P < 0.01$) was found for HMW-Glutenin, Falling Number, and FarDDT. For kernel number and flour ash, a significant genotypic effect at the $P < 0.05$ level was found. There was no significant genotypic effect for FarSTAB, MTI, and residue protein (Table 3). The overall extent of genotypic variation observed in this study is comparable with previous reports (Fowler and De La Roche 1975; Lukow and McVetty 1991; Ames et al. 1999; Preston et al. 2001). The lack of difference between genotypes in our study for a few traits may be due to large experimental error terms precluding detection of small genotypic differences. Smaller environmental differences found in the Preston et al. (2001) study might make the detection of smaller genotypic differences possible. LSD mean separations for all quality parameters are summarized in Table 2.

The CVs for all traits were determined for each genotype across growing locations in order to evaluate the relative environmental stability of yield, grain and bread-making quality characteristics (Table 4). Some differences among the genotypes were apparent, with Superb being the most distinct overall. Superb clearly had higher CVs than other cultivars for yield and yield related traits such as TKW and kernel number. Superb was also more variable compared with other CWRS and CWHWS wheats for GPC, flour protein, HMW-Glutenin, and FAB (Table 4). The higher CVs suggest that Superb tended towards being less stable or more variable across growing locations for these traits. At the same time, Superb was the most uniform cultivar for starch damage (i.e. kernel hardness), all mixograph dough parameters and bread properties including the important trait of loaf volume. These results suggest that Superb is a

Table 1. Growing season weather conditions at the western Canada study site locations

Location	Year	Coordinates		Growing season mean[z]				
				Temp [y]	RH[x]	Rad[w]	Wind[v]	Prec[u]
Carman	2004	49.50°N	98.03°W	15.5	72.9	209.3	2.6	224.7
Melfort	2003	52.82°N	104.61°W	16.5	62.8	240.0	2.3	136.3
Regina	2003	50.41°N	104.57°W	19.2	58.3	262.4	2.4	87.7
Swift Current	2003	50.27°N	107.73°W	17.6	56.1	267.7	4.3	82.6
Swift Current	2004	50.27°N	107.73°W	13.3	76.5	232.7	5.1	233.6
Winnipeg	2003	49.81°N	97.12°W	18.5	69.3	201.7	1.7	199.6
Winnipeg	2004	49.81°N	97.12°W	16.0	72.8	160.7	2.0	328.9
CV				12.0	11.8	16.7	43.7	48.0

[z] Mean daily value between planting and maturity.
[y] Air temperature (°C) at 1.8 m.
[x] Relative humidity (%) at 1.8 m.
[w] Incoming solar radiation (Watts m^{-2} d^{-1}) at 2.3 m.
[v] Wind speed (m s^{-1}) at 2.5 m.
[u] Total precipitation (mm) from planting through maturity.

Table 2. Mean[z] grain, flour, dough and bread quality variables of six wheat genotypes grown in 2003 and 2004

Trait	Genotype							
	AC Barrie	AC Elsa	Neepawa	Snowbird	Superb	AC Vista	Mean[y]	SD[x]
				Grain property				
Yield (kg ha^{-1})	3849.5*bc*	3966.0*b*	3592.9*c*	4059.7*b*	4113.8*b*	4712.5*a*	4065.1	1440.5
1000-kernel weight (g)	32.00*c*	30.44*cd*	29.59*d*	30.64*cd*	34.30*b*	37.61*a*	32.44	6.42
Kernel number m^{-2}	11610*b*	12556*a*	11528*b*	12761*a*	11409*b*	12317*ab*	12030	3245.9
Test weight (kg hL^{-1})	81.57*a*	80.90*ab*	80.44*b*	81.14*ab*	81.08*ab*	78.99*c*	80.66	3.27
Grain protein concentration (%)	14.73*a*	14.81*a*	14.67*a*	14.24*b*	14.16*b*	13.08*c*	14.26	1.91
				Flour property				
Flour yield[v] (%)	74.80*a*	73.65*b*	71.57*d*	73.09*bc*	73.92*ab*	72.57*c*	73.29	2.27
Flour ash (%)	0.380*bc*	0.395*ab*	0.383*abc*	0.363*c*	0.407*a*	0.399*ab*	0.388	0.04
Flour protein (%)	13.96*a*	13.92*a*	13.78*a*	13.64*ab*	13.31*b*	12.05*c*	13.44	1.98
Soluble protein (%)	9.57*a*	9.48*a*	9.59*a*	9.13*b*	8.97*b*	7.71*c*	9.07	1.33
HMW-glutenin (%)	3.62*a*	3.62*a*	3.34*c*	3.53*ab*	3.64*a*	3.41*bc*	3.53	0.51
Residue protein (%)	0.78*ab*	0.78*ab*	0.83*ab*	0.92*ab*	0.71*b*	0.99*a*	0.84	0.43
Pentosans (%)	1.65*c*	2.04*a*	1.99*ab*	1.97*ab*	1.90*b*	2.08*a*	1.94	0.28
Starch damage (%)	5.49*cd*	5.55*cd*	5.66*bc*	5.36*d*	5.90*b*	6.77*a*	5.79	0.79
Flour colour[w] (%)	85.09*c*	86.48*a*	85.05*c*	85.67*b*	85.30*bc*	86.19*a*	85.67	1.05
Falling number (s)	554.68*a*	546.33*a*	509.21*b*	559.53*a*	494.92*b*	518.29*b*	529.98	83.33
				Dough property				
Farinograph absorption (%)	61.50*d*	63.45*ab*	62.96*bc*	62.46*c*	63.13*bc*	64.15*a*	62.94	2.12
Dough dev. time (min)	5.85*ab*	6.36*a*	5.14*c*	5.85*ab*	6.33*a*	5.50*bc*	5.75	2.46
Farinograph stability[v] (min)	11.68*bc*	13.01*abc*	11.08*c*	12.22*abc*	13.97*ab*	14.65*a*	12.34	7.51
Mixing tolerance index (BU)	38.83*a*	38.33*a*	36.32*a*	36.69*a*	33.22*a*	36.16*a*	36.79	19.04
Mixing time to peak (min)	2.88*a*	2.50*bc*	2.36*c*	2.81*ab*	2.82*a*	3.00*a*	2.72	0.77
Peak dough resistance (% torque)	58.14*b*	62.00*a*	53.43*d*	55.85*c*	57.97*bc*	58.89*b*	58.01	8.91
Peak bandwidth (% torque)	25.00*a*	23.94*a*	21.55*b*	24.16*a*	24.77*a*	24.82*a*	24.03	5.79
Work input to peak (% torque × min)	111.18*ab*	104.58*b*	88.63*c*	108.29*ab*	109.82*ab*	117.31*a*	106.64	20.97
				Bread property				
Full formula mix time (min)	4.36*a*	3.44*b*	3.58*b*	4.46*a*	4.31*a*	4.51*a*	4.11	0.93
Loaf volume (cc)	969.95*b*	1023.00*a*	928.35*c*	937.50*c*	996.93*ab*	866.02*d*	952.12	116.09

[z] Means of three reps and seven environments.
[y] Mean of six genotypes and seven environments.
[x] Standard deviation.
[w] Agtron equivalent % reflectance at 546 nm.
[v] Non-normal data.
a–c Within rows, means followed by the same letter are not significantly different according to LSD ($P < 0.05$).

less predictable cultivar for western Canadian producers because of variability across growing locations for grain yield and grain protein concentration, but is more predictable for millers and bakers due to its more consistent bread-making characteristics compared with other comparable genotypes in this study. Averaging over all bread-making quality traits, i.e., flour, dough and bread, distinctions among the genotypes become rather small with CVs ranging between 18.7% for Superb and 21.3% for AC Elsa and Neepawa (Table 4).

Table 3. Variance components contribution to variation (percent of total estimate) for environment (E), genotype (G), and G × E interaction effects for grain, flour, dough and bread quality variables of six wheat genotypes grown at seven locations

	Variance component				
Trait	E	G	G ×E	Rep(E)	Error
			Grain property		
Yield	88.32*	5.23****	3.24***	1.96**	1.25****
1000-kernel weight	74.71*	18.54****	4.70***	0.01	2.03****
Kernel number m^{-2}	86.15*	2.01*	4.59***	3.49**	3.76****
Test weight	88.78*	6.26****	2.73***	0.51*	1.72
Grain protein concentration	78.60*	8.16****	2.44**	6.82*	2.97
Grain property average	83.51	8.04	3.54	2.56	2.35
			Flour property		
Flour ash	13.91NS	9.81*	4.60NS	5.27NS	66.40****
Flour protein	78.13*	9.03****	3.07*	5.42NS	4.34
Soluble protein	64.65*	22.06****	4.18*	3.98NS	5.14
HMW-glutenin	80.80*	4.51**	5.45**	2.83*	6.41****
Residue protein	39.25NS	1.60NS	10.52NS	2.22NS	46.41
Pentosans	31.08NS	26.97****	0.00NS	0.88NS	41.06****
Starch damage	45.37NS	32.80****	9.98*	5.39**	6.46
Flour colour	51.76NS	25.53****	8.83*	7.88*	6.00
Falling number	61.12*	10.22***	11.84NS	6.15NS	10.66
Flour property average	51.79	15.84	6.50	4.45	21.43
			Dough property		
Farinograph absorption	63.40*	14.46****	7.51**	2.03NS	12.59****
Dough development time	87.13*	3.00**	2.71**	1.70NS	5.48
Farinograph stability[z]	84.18*	1.72NS	8.79**	1.05NS	4.26
Mixing tolerance index	68.55*	0.00NS	9.74*	10.94NS	10.77
Mixing time to peak	68.89NS	6.98**	10.17***	7.76*	6.19****
Peak dough resistance	81.85*	8.07****	2.72**	4.00*	3.36****
Peak bandwidth	73.75*	4.82****	0.61NS	1.92NS	18.90
Work Input to peak	44.76NS	17.13****	10.65**	6.53*	20.93****
Dough property average	71.56	7.02	6.61	4.49	10.31
			Bread property		
Full formula mix time	48.90NS	20.50****	16.88***	7.11*	6.61****
Loaf volume	62.79*	22.87****	1.94*	4.14NS	8.25
Bread property average	55.85	21.69	9.41	5.63	7.43
Total average[y]	65.68	13.15	6.51		

[z] Non-normal data.

[y] Mean % contribution to variation for all quality parameters.

*, **, ***, **** Significance at the 0.05, 0.01, 0.001, and 0.0001 probability levels, respectively; NS is non-significant at 0.05 probability level.

Environment Effect

Very wide ranges in yield and quality parameter means were observed across growing environments (Table 5) as evidenced by large environmental CV values (Table 4). Significant environmental effects ($P < 0.05$) were found for all traits except starch damage, flour ash, residue protein, pentosan content, flour colour, MTP, WIP, and full formula mix time (Table 3). The large difference in grain or flour protein concentration between some growing locations, such as Winnipeg 2003 (GPC 10.7%) and Swift Current 2003 (GPC 15.4%) is both striking and noteworthy. It is important to point out in this regard, that soil fertility (i.e., nitrogen) was not a factor, as all sites were optimally fertilized and well-managed agronomically. This indicates that weather was the main factor driving protein concentration and related quality variation. Determining which components of weather are more or less influential in this regard is very complex. The basic growing season weather at our growing locations (Table 1) suggest that future studies focus on factors such as wind speed and precipitation, which were highly variable across our research sites. Only total growing season indices of weather are summarized in Table 1. Our early analysis indicates that both the timing and duration of a wide range of both basic and derived weather factors during crop development significantly affect wheat quality outcomes (Jarvis 2006).

In some previous work (Fowler and De La Roche 1975; Lukow and McVetty 1991), the environmental effect was significant for all the grain, flour, dough, and loaf properties tested. Mikhaylenko et al. (2000) reported that the environment significantly influenced protein and ash contents, mixograph absorption and mixing time for soft and hard wheat flours. Preston et al. (2001) also found a significant environmental effect for farinograph and bake test parameters except for farinograph stability. The reasons why starch damage, flour ash, residue protein, pentosans, flour colour, MTP, WIP, and full formula mix time did not have a significant response to environmental variation in our study were

Table 4. Coefficients of variation (CV) due to environment effects for grain, flour, dough and bread quality parameters of six spring wheat genotypes grown in 2003 and 2004[z]

Trait	Genotype						Environment C[y]
	AC Barrie	AC Elsa	Neepawa	Snowbird	Superb	AC Vista	
				Grain property			
Yield	37.9	36.3	36.9	36.8	42.1	33.6	37.3
1000-kernel weight	17.9	16.0	17.7	18.7	21.7	19.4	18.6
Kernel number m^{-2}	27.2	27.9	26.0	24.9	33.1	27.6	27.8
Test weight	4.1	4.1	4.5	3.8	4.3	4.1	4.2
Grain protein conc.	13.6	14.1	13.3	10.7	14.2	13.6	13.3
Grain property average	20.1	19.7	19.7	19.0	23.1	19.7	20.2
				Flour property			
Flour yield	2.9	2.1	3.7	2.4	1.6	2.9	2.6
Flour ash	8.0	6.9	8.5	9.4	3.5	5.5	7.0
Flour protein	14.5	15.7	13.9	12.4	15.8	14.3	14.4
Soluble protein	12.9	15.1	12.5	11.2	13.7	12.9	13.0
HMW-glutenin	12.1	13.8	12.1	12.3	17.8	16.5	14.1
Residue protein	54.7	45.8	50.4	30.5	45.9	39.6	44.5
Pentosans	7.1	10.3	9.4	9.5	10.2	11.4	9.7
Starch damage	13.0	10.5	12.8	11.7	9.4	9.9	11.2
Flour colour	1.2	1.3	1.1	1.1	1.1	0.7	1.1
Falling number	13.4	12.2	12.8	11.1	13.7	23.3	14.4
Flour property average	14.0	13.4	13.7	11.2	13.3	13.7	13.2
				Dough property			
Farinograph absorption	2.9	2.7	2.6	3.3	4.2	2.8	3.1
Dough development time	43.1	46.7	40.1	40.3	39.7	50.2	43.3
Farinograph stability	50.8	69.0	73.6	53.0	53.1	71.8	61.9
Mixing tolerance index	40.5	50.6	46.1	59.0	49.2	58.8	50.7
Mixing time to peak	32.8	35.5	32.0	25.9	21.8	15.6	27.3
Peak dough resistance	16.4	16.2	18.7	16.1	14.7	14.3	16.1
Peak bandwidth	22.6	25.7	25.2	22.6	21.5	20.9	23.1
Work input to peak	16.5	17.7	16.5	21.0	15.6	13.1	16.7
Dough property average	28.2	33.0	31.8	30.2	27.5	30.9	30.3
				Bread property			
Full formula mix time	24.7	19.7	23.3	21.9	12.1	16.1	19.6
Loaf volume	11.1	8.4	11.1	12.8	8.9	14.2	11.1
Bread property average	17.9	14.0	17.2	17.4	10.5	15.2	15.4
Average quality[x]	20.1	21.3	21.3	19.4	18.7	20.7	20.2

[z] Mean CV of three reps and seven environments

[y] Mean CV of six genotypes.

[x] Average quality excluding yield and grain properties.

varied. For flour ash and colour, and residue protein, differences due to environment were quantitatively small. On the other hand, for starch damage, MTP, WIP, and full formula mix time, some specific location differences appeared to be significant on a practical basis, e.g. starch damage results for Winnipeg 2003 (6.57%) and Swift Current 2003 (4.67%) or WIP for Winnipeg 2003 (14% torque) compared with Carman 2004 (28.7% torque). Clearly environmental variances were not sufficiently large compared with the error term to pass the statistical threshold of significance. Regardless, the size of environment CVs compared with genotype CVs (Tables 4 and 6) clearly indicated that environment was more influential on these quality traits and others in general.

Genotype by Environment Interaction

The G × E interactions were also significant for all quality parameters except for flour ash, residue protein, falling number and pentosan content (Table 3). Interaction effects for grain yield, TKW, kernel number, test weight, MTP and full formula mix time were significant at $P < 0.001$, while interaction effects for GPC, FAB, FarDDT, FarSTAB, PDR, WIP, and HMW-Glutenin were significant at the $P < 0.01$ level. Interaction effects for soluble proteins, total flour protein, starch damage, flour colour, MTI, and loaf volume were all significant at the $P < 0.05$ level. While G × E interactions were generally significant, the relative G × E contribution to total variance was considerably smaller (2-17% of total variance) than that of genotype or environment (Table 3). Our results are in general agreement with previous studies. Fowler and De La Roche (1975), Baker and Kosmolak (1977), Lukow and McVetty (1991), Ames et al. (1999), Mikhaylenko et al. (2000), Panozzo and Eagles (2000) and Preston (2001) all found significant, yet relatively minor, G × E interactions for most quality parameters tested. Baker and Kosmolak (1977) reported some conflicting results that found the G × E interaction effect was important in determining MTP, falling number, and loaf volume. Their field

Table 5. Mean[z] grain, flour, dough and bread quality variables of spring wheat grown at seven environments in 2003 and 2004

	Environment								
Trait	Carman 2004	Melfort 2003	Regina 2003	Swift Current 2003	Swift Current 2004	Winnipeg 2003	Winnipeg 2004	Mean[y]	SD[x]
					Grain property				
Yield (kg ha^{-1})	4997.7	5857.3	3119.8	1237.3	4196.9	4474.6	4371.3	4036.4	1485.8
1000-kernel weight (g)	34.72	39.93	33.14	20.80	32.92	35.71	30.09	32.47	5.97
Kernel number m^{-2}	14399.7	14762.6	9419.3	5947.5	12713.3	12481.4	14487.6	12030.2	3255.9
Test weight (kg hL^{-1})	81.21	83.91	82.93	74.11	81.25	82.53	78.94	80.69	3.31
Grain protein concentration (%)	14.34	14.49	14.56	16.75	15.44	10.71	13.71	14.29	1.86
					Flour property				
Flour yield (%)	73.36	74.90	74.06	72.98	74.84	72.93	69.61	73.24	1.80
Flour ash (%)	0.37	0.38	0.40	0.39	0.37	0.42	0.39	0.39	0.02
Flour protein (%)	13.72	13.26	13.29	15.97	14.89	9.86	12.99	13.43	1.90
Soluble protein (%)	9.08	9.22	9.05	10.55	9.91	6.85	8.87	9.08	1.15
HMW-glutenin (%)	3.63	3.41	3.61	4.09	3.93	2.58	3.40	3.52	0.49
Residue protein (%)	1.00	0.63	0.62	1.33	1.02	0.39	0.72	0.82	0.32
Pentosans (%)	1.78	2.25	2.06	1.84	1.82	1.94	1.86	1.94	0.17
Starch damage (%)	5.86	6.09	5.95	4.67	5.48	6.57	5.90	5.79	0.59
Flour colour[v] (%)	85.05	86.31	85.94	84.59	85.43	87.01	84.87	85.60	0.87
Falling number (sec)	509.19	537.61	504.11	607.33	636.08	487.17	428.36	529.98	71.37
					Dough property				
Farinograph absorption (%)	62.31	66.64	63.80	62.58	62.43	61.72	61.11	62.94	1.83
Dough development time (min)	4.29	6.59	8.07	9.09	6.86	1.95	4.15	5.86	2.50
Farinograph stability[w] (min)	6.86	10.81	22.76	24.91	11.65	5.31	8.21	12.93	7.79
Mixing tolerance index (BU)	65.28	28.61	18.61	18.72	32.22	44.82	49.72	36.86	17.26
Mixing time to peak (min)	2.02	2.23	2.98	3.11	2.44	4.03	2.25	2.73	0.70
Peak dough resistance (% torque)	63.17	57.98	56.41	62.81	66.14	39.09	58.53	57.73	8.91
Peak bandwidth (% torque)	28.66	21.71	21.99	26.89	29.24	14.00	25.99	24.07	5.33
Work input to peak (% torque × min)	89.30	87.18	114.27	126.29	110.66	121.66	96.68	106.58	15.62
					Bread property				
Full formula mix time (min)	3.38	3.38	4.23	4.68	4.10	5.34	3.65	4.11	0.72
Loaf volume (cc)	997.78	952.06	919.17	1044.86	1026.53	744.85	968.06	950.47	100.42

[z] Means of three reps and six genotypes.

[y] Mean of seven environments and six genotypes.

[x] Standard deviation.

[w] Non-normal data.

[v] Agtron equivalent % reflectance at 546 nm.

study differed compared with ours in that composite samples from two to four growing environments were used.

Relative Influence of Genotype, Environment and G × E Interactions

The relative importance of the growing environment on wheat quality can be clearly seen by comparing CVs for genotype (Table 6) and environment (Table 4), e.g., grain protein concentration genotype CV~ 5% versus environment CV~13%. For all quality parameters except flour pentosan content, flour ash, and starch damage, environmental variation was 1.3 to 3.5 times greater than the corresponding variation due to genotype (Table 4 compared with Table 6). In contrast, the environmental variation for pentosan content, flour ash, and starch damage was only 1.04, 1.1, and 1.17 times greater than that of the respective genotypic variations. Environment and genotype were equally important in determining the outcomes for these flour quality traits. For the remaining quality parameters, environment played a more important role. These results agree with numerous other studies showing that environment was the major source of variation for wheat end-use quality (Baker et al. 1971; Fowler and De La Roche 1975; Baker and Kosmolak 1977; Lukow and McVetty 1991; Peterson et al. 1992; Gaines et al. 1996; Graybosch et al. 1996; Ames et al. 1999; Mikhaylenko et al. 2000; Panozzo and Eagles 2000; Preston et al. 2001). To specifically quantify this aspect, each variance component estimate (genotype, environment, and G × E interaction) was compared with the total variance (Table 3). The relative magnitude of the environmental contribution to wheat quality variance was considerably larger (14 to 89%) than the variance contribution of either genotype (0 to 33%) or G × E interaction (0 to 17%). Fowler and De La Roche (1975) found grain yield, GPC and test weight to have a large variation response due to environment, while kernel hardness, flour pigment, and MTP were less affected by environmental effects. Variance component results (Table 3) similarly indicated that environment was not significant for starch damage (related to kernel hardness), flour colour and MTP. Ames et al. (1999) also found that envi-

Table 6. Coefficient of variation (CV) due to genotype effects for grain, flour, dough, and bread quality parameters of wheat grown at seven locations[z]

	Environment							
Trait	Carman 2004	Melfort 2003	Regina 2003	Swift Current 2003	Swift Current 2004	Winnipeg 2003	Winnipeg 2004	Genotype CV[y]
				Grain Property				
Yield	11.9	5.2	14.1	15.0	13.8	8.1	12.9	11.6
1000-kernel weight	10.5	11.5	13.3	9.1	7.4	10.0	5.5	9.6
Kernel number m^{-2}	6.7	7.1	12.4	11.3	8.3	4.4	8.0	8.3
Test weight	1.9	0.7	1.0	1.1	1.7	1.5	1.1	1.3
Grain protein conc.	5.8	4.5	4.9	3.5	4.9	3.0	7.1	4.8
Grain property average	7.3	5.8	9.2	8.0	7.2	5.4	6.9	7.1
				Flour property				
Flour yield	2.6	1.3	2.0	1.3	1.8	2.0	3.0	2.0
Flour ash	9.7	4.2	4.8	3.4	7.5	5.8	8.4	6.3
Flour protein	6.8	5.6	5.8	3.6	5.7	3.7	7.9	5.6
Soluble protein	8.4	8.8	7.9	6.6	8.3	6.1	10.3	8.1
HMW-glutenin	5.2	5.0	5.7	4.4	5.0	5.3	5.5	5.2
Residue protein	29.0	32.8	26.1	13.7	20.2	32.9	28.1	26.1
Pentosans	8.3	8.5	11.3	7.8	8.9	11.6	8.4	9.3
Starch damage	10.5	10.1	11.3	7.9	10.9	5.9	10.4	9.6
Flour colour	0.8	0.7	0.9	1.0	0.8	0.7	0.7	0.8
Falling number	8.7	4.8	5.4	6.1	5.9	5.6	19.6	8.0
Flour property average	9.0	8.2	8.1	5.6	7.5	8.0	10.2	8.1
				Dough property				
Farinograph absorption	1.4	1.5	2.1	1.9	1.8	1.8	2.1	1.8
Dough development time	13.0	9.4	14.1	7.3	10.5	13.1	19.8	12.5
Farinograph stability	19.9	9.5	19.9	21.3	21.2	22.2	9.9	17.7
Mixing tolerance index	15.4	21.3	15.4	9.5	32.0	28.2	11.5	19.0
Mixing time to peak	16.5	7.4	14.1	15.7	15.3	9.4	15.2	13.4
Peak dough resistance	6.8	5.4	4.7	5.4	4.6	9.7	6.7	6.2
Peak bandwidth	6.9	13.2	7.3	10.9	6.3	8.1	7.2	8.6
Work input to peak	15.2	12.4	12.2	13.3	13.4	9.1	11.7	12.5
Dough property average	11.9	10.0	11.2	10.7	13.1	12.7	10.5	11.5
				Bread property				
Full formula mix time	11.9	10.4	14.9	17.7	15.0	14.0	17.1	14.4
Loaf volume	6.1	4.9	8.1	5.5	5.4	12.9	6.3	7.0
Bread property average	9.0	7.7	11.5	11.6	10.2	13.4	11.7	10.7

[z] Mean CV of three reps and six genotypes.
[y] Mean CV of seven environments.

ronment was important in determining GPC and had greater influence for gluten strength properties. Ames et al. (1999) studied 10 diverse American and Canadian durum genotypes that likely contributed to the greater genotypic effects in certain cases. Preston et al. (2001) found the effects of environment to be greater than that of genotype for flour protein, farinograph absorption and CSP water absorption, which is in agreement with our results. However, for kernel hardness, FarDDT and stability, they found genotypic effects were greater than those of environment. Preston et al. (2001) used 14 CWRS genotypes and six Saskatchewan growing locations in one crop year thus potentially yielding results reflecting greater genetic effects compared with environment. Lukow and McVetty (1991) reported that the environmental effect was pronounced for all quality parameters, but the genotypic variance component was greater in all cases. This was likely due to the relatively limited environmental effect arising from the use of only three Manitoba growing sites over 2 yr. As well, eight genetically diverse genotypes were used in the Lukow and McVetty (1991) study, thus promoting the genotype effects. Several other genotype × environment studies on wheat quality have shown similar results to ours with the relative magnitude of the genotype × environment interaction effect being considerably smaller than either genotype or environment (Busch et al. 1969; McGuire and McNeal 1974; Fowler and De La Roche 1975; Baker and Kosmolak 1977; Baenziger et al. 1985; Lukow and McVetty 1991; Peterson et al. 1992; Ames et al. 1999; Mikhaylenko et al. 2000; Preston et al. 2001).

Wheat traits that appeared to be the most sensitive to environment (based on E variance >75%, Table 3) included yield and all other grain properties, flour protein, HMW-Glutenin, FarDDT, and FarSTAB. On the other hand, wheat quality traits with the highest genetic variance contribution (>20%, Table 3) were soluble protein, pentosans, starch damage, flour colour, full formula mix time, and loaf volume.

The variance result for flour pentosan content in particular may warrant special attention by wheat breeders as it indicates that this flour trait is relatively amenable to genetic manipulation. The heritability of wheat flour pentosans is not well studied, but relatively high genotypic variability for durum wheat arabinoxylans (i.e., pentosans) has been previously reported (Lempereur et al. 1997). This outcome is of practical significance as pentosans are well known to be related to dough physical properties especially flour water absorption as well as farinograph absorption (Michniewicz et al 1991). The latter is one of the most important technological properties of CWRS wheat for bread making from both a processing perspective as well as for purposes of marketing. Hard wheats possessing high farinograph absorption are preferred by millers and bakers. In that respect, the popular CWRS genotype AC Barrie is a noteworthy exception. AC Barrie has long been known to possess relatively low farinograph absorption compared with other contemporary CWRS wheat cultivars. Among the six genotypes in this study, AC Barrie possessed both the lowest pentosan content and farinograph absorption (Table 2). It seems clear that AC Barrie's low farinograph absorption is due at least in part to a deficiency in total pentosans. The variance data indicate that there is potential to cull candidate bread wheat genotypes with low farinograph absorption early in cultivar development activities by screening for low pentosan content.

CONCLUSIONS

For all of the wheat quality parameters tested, environment-related variation was generally much larger than genotype related variation. This clearly demonstrates the importance of growing-season weather impact on wheat yield and technological quality characteristics. There were significant environmental effects for all quality parameters except starch damage, flour ash, residue protein, pentosans, flour colour, MTP, WIP, and full formula mix time. This was generally in agreement with earlier work; however, others have found significant environmental effects on flour ash and mixing time. Significant genotype effects were noted for all quality parameters except farinograph stability, MTI, and residue protein. Significant genotype by environment interactions were also found for all quality parameters except flour ash, residue protein, falling number and total flour pentosans. The contribution of the G × E interaction to total variation was considerably less than either genotype or environment.

This study has provided a comprehensive assessment of genotype and environment variation in bread-making characteristics for milling quality wheat grown in the Prairie region. Our results point clearly to the challenge for the grain industry to satisfactorily manage the effects of weather and the growing environment on wheat quality in order to deliver product of uniform and expected quality to customers of western Canadian wheat. Our results underscore the need to maintain or enhance regional blending of wheat to reduce the impact of environment on end-use quality, which can be significant even for wheat of similar grade and protein concentration.

It is worth emphasizing that soil fertility was not a factor in the protein concentration and related quality variation we observed in this study, as the wheat was grown at very well-managed sites that were optimally fertilized. Accordingly, there is a pressing need to develop a better understanding of the nature of the environmental effects on wheat quality and normal weather variation in particular, apart from acute weather-related events causing frost damage or pre-harvest sprouting for which the science is generally well established. Knowledge of growing-season weather impacts on wheat quality would go far towards the development of science-based wheat sourcing that would also facilitate the delivery of uniform quality wheat to market and enhance market development activities. In that regard, work is underway on the quantification of weather on wheat quality using the comprehensive base of hourly weather data collected for all the growing locations in this study. Those results and results related to the feasibility of developing predictive models for wheat quality prior to harvest will be discussed in future reports.

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