COMPARISON OF RHEOLOGICAL PROPERTIES OF U.S. WINTER WHEAT CULTIVARS AND ADVANCED BREEDER LINES USING PRINCIPAL COMPONENT ANALYSIS

By

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CHAPTER I

INTRODUCTION

Fundamental understanding of dough properties is important in predicting the machinability and baking potential of wheat flour. Dough is viscoelastic material having complex rheological properties that are key parameters in many mechanical processing steps (kneading, rolling, laminating and forming) during fermentation and oven-rise (Launay and Michon, 2006). Numerous studies have been devoted to understand the rheological behavior of dough. Rheology is the study of the deformation and flow of matters (Dobraszczyk and Morgenstern, 2003). Wheat breeders, flour millers and bakers have related rheological test assessments to product functionality, predicting the final product quality, baking performance, mixing behavior and texture. Rheological measurements are increasingly used as rapid, sensitive indicators of polymer structure, machinability and predictors of end-use performance. Baking test is the ultimate test for determining the baking performance of a wheat cultivar before being released for commercial production. However, baking test is impractical at the early stages of breeding programs due to the constraints of large sample size, specialized training and labor needed for their determinations. As a result, a number of simpler and rapid small-scaled tests have long been devised and widely adopted in the breeding programs to predict the end-use quality and baking potential of wheat lines.

Farinograph and mixograph are the two most common dough mixers employed in the baking industry and breeding program to monitor flour mixing quality. The mixograph test provides information about the mixing requirement of flour. It is a rather useful instrument in the breeders' screening program as the test is simple, requires small sample size (2-10g flour) and has a high through-put (50-100 samples/day). Mixograph data has also been found to be highly correlated with sensory data in durum wheats (Kovacs et al., 1997). The farinograph is widely known as a useful industrial quality control tool which provides reliable and reproducible results. This may due to the fact that farinograph is temperature-controlled. However, the results from both instruments remain empirical and are difficult to interpret in terms of material properties (Tronsmo et al., 2003). There is a need to develop more sensitive and reliable tests which reflect the extensibility, strength and viscoelastic properties in the wheat lines. Today, these rheological assessments can be done using rheometer, texture analyzer and glutomatic system. These methods are not routinely used due to either the cost of the equipment, time of analysis, sample size or operator expertise.

The task of determining the extensibility properties from a mixing curve is intricate as it involves more complex manipulations for extracting this information from the graph (Anderssen et al., 2004). The micro-extension test currently used can actually reflect the processing and proofing of a dough that occurs in an industrial context (Anderssen et al., 2004). Anderssen and fellow associates came up with a way of differentiating between weak, intermediate and strong flour by observing the behavior of the extensibility curves or detecting the number of viscoelastic responses in the extensibility curves. They also proposed that the relevant parameters for measuring how bubble expansion controls the loaf volume and thereby, baking performance, were the dough maximum resistance of extension (Rmax), extensibility at maximum resistance (Emax) and extensibility difference between maximum resistance and rupture point (Emr), and not the traditional Rmax and extensibility at rupture point (Erup) parameters. In this study, we measured both the suggested and traditional parameters to evaluate their usefulness in differentiating among the wide range of winter wheat cultivars. Farinograph, mixograph and micro-extension are all large-deformation rheological tests used to monitor flour quality. Small-deformation measurements such as creep-recovery tests are used to provide information about the elasticity and viscosity properties without destroying the inherent structure. Glutens with high elasticity are needed for the dough to retain its shape during proofing and baking. Lastly, the glutomatic test is used to measure the gluten quantity and quality.

In this study, we analyzed the routinely used traditional assessments (TRAD), which were the mixing properties, SDS sedimentation and bake test, and compared the findings with parameters obtained from Creep-Recovery (viscoelastic properties), micro-Extensibility, and Glutomatic (CREG) of two sets of winter wheat cultivars and advance breeder lines grown in 2006 and 2007 crop years with differing annual growing conditions. The objectives of this study were to predict the usefulness of introducing new analytical tools, which are the CREG methods, to the breeding program as well as to compare the potential of breeder lines in terms of viscoelastic and extensibility properties.

CHAPTER II

REVIEW OF LITERATURE

Wheat quality

Wheat has the ability to produce such a widely diverse range of end-use products because each class of wheat had distinct characteristics that lead to a unique end-use functionality. Each end-use requires a specific ‘quality’ in the wheat protein (Bushuk 1998). Durum wheats which have the hardest texture, high protein content and yellow pigmentation, are used for manufacture of pasta and couscous. Extensibility property is not important in either process, but strong gluten strength is highly desired for good pasta cooking quality (Bushuk 1998). Common wheats with the hardest texture and highest protein content are used for pan bread (Bushuk 1998). Those with medium hardness, lower protein content and weaker gluten strength, on the hand, are used for noodles and other types of bread, such as French bread and steam bread (Bushuk 1998). However, wheats of softest grain texture have lowest protein content and weakest dough strength. These wheats are most suitable for manufacture of cakes and cookies (Bushuk 1998). Besides baking performance, machinability is another major factor for wheat flour quality. Over the past decades, there has been an extensive transfer of bread making from home to the commercial bakery (Call et al. 1925). The home use includes mixing bread by hand or household mixers with a much gentle force compared to the mechanical mixers used in the industry. Commercial bakers want flour that will make large and light loaves from each batch, as well as flour dough that is strong enough to withstand the harshness of the mechanical mixing machines (Call et al., 1925). Hence, the adequate protein content (10%-13%) of wheat is in high demand for pan bread as that is the quality parameter of wheat which is easily measured at the present time and is associated with desirable mixing characteristics (Call et al., 1925).

According to Dobraszczyk (2003), growth and stability of gas cells in terms of their size, distribution, growth and failure during the baking process, are also the major determinants for the baking performance of bread, essentially the appearance (texture) and loaf volume. Gas production can be controlled and adjusted with amount of yeast used in formulation, fermentable sugars maltose and glucose added or present, as well as fermentation time and temperature (Weiper, 2006). Wheat with good protein quality shows thin cell walls, great tendency to retain the gas, numerous small gas cells in large loaf volume, and smooth texture (Dobraszczyk, 2003). Wheat with poor protein quality, on the other hand, found to have weak cell walls, fail to retain escaping gas, and hence producing small loaf with large bubbles, giving a harsh, undesirable texture (Dobraszczyk, 2003).

Rheological assessments

Farinograph and mixograph were constructed in early century to assess the baking properties of wheat varieties. Dough mixing involves the blending and hydration of the flour components, as well as initiating bubble structure and the development of the gluten proteins (Millar, 2003). Strong flour doughs generally require longer times to reach peak resistance. Dough mixed below optimum time produces inferior quality (Zounis and Quail, 1997). Long mixing doughs, however, may affect the production schedules, have higher costs and it is troublesome to maintain the conventional final dough temperature (Zounis and Quail, 1997). Mixograph is especially useful at the early stages of breeders' screening program as the test is rapid, simple, requires small sample size (2-10g flour) and could easily be automated (Dobraszczyk and Salmanowicz, 2008). The data has also found to be highly correlated with sensory data in durum wheats (Kovacs et al., 1997). However, the disadvantages of farinograph and mixograph are that they use relatively strong deformation forces, and only able to describe the dough properties in the cold phase of the bread-making process, during mixing and after fermentation. Also, the results from these two mixers remain empirical to this day and are difficult to interpret in terms of material properties (Tronsmo et al., 2003).

Sedimentation test has been used in the wheat breeding program to predict the resting time of the dough, its gas retention capacity and the volume yield of the baked products by measuring the gluten strength using the principles of swelling power and solubility (Carter, 1999). It involves the dispersion of flour in lactic acid and observing the amount of sediment after a fixed period of time. Hard wheats with high sedimentation volumes have been associated with strong gluten and superior bread-making quality and vice-versa (Carter, 1999).

Creep-recovery test measures the viscoelastic properties using extremely small deformation forces to prevent the inherent structure of the dough from damage. This allows us to monitor the changes in the dough properties as a function of time and temperature, as in baker's oven (Weiper, 2006). Doughs with high elasticity are short and bucky; while doughs with low elasticity are weak and soft (Weiper, 2006).

The micro-extension test is another large deformation assessment developed by Kieffer et al. (1998) to measure the extensibility and strength of dough and gluten. Anderssen et al. (2004) reported an inverse relationship between dough strength (resistance to extension) and extensibility in the extension curve. They also highlighted the occurrence of double peak response in weak flours and double response but not double peaks in intermediate flours. Strong flours however, only show single peak response in the extension curve (Anderssen et al., 2004). Strong flour produces doughs which incorporate less air during mixing than doughs from weak flour and give larger loaf volumes, finer crumb structures or both (Campbell et al. 2001).

Glutomatic has high reproducibility, allowing a reliable prediction of gluten quantity and quality (Freund and Kim, 2006). However, these results can only be achieved if the test is carried out by very experienced persons (Freund and Kim, 2006).

Environmental factors

Wheat protein is generally considered the prime factor that determines the quality of wheat flour. Protein quantity is influenced largely by environmental conditions and crop management practices, while the quality of the protein is genetically determined (Cornish et al., 1991). Environment factors which are the largest source of variation among the quality parameters tested include climate (moisture and temperature during growing seasons), soil type and use of nitrogen fertilizer (Call et al., 1925). Generally, growing season with frequent rainfall affects grain yield and quality due to water-logging

(Wrigley and Batey, 2003). This would wash out great amount of nitrates from the soil, causing production of low-protein wheats. Dry growing season also tend to reduce grain yield while increases protein content (Wrigley and Batey, 2003). There may have a great variation in the protein quantity and quality of wheat in different seasons on the same farm as in different farms in one particular growing season. Hence, we cannot assume that high-protein wheat grown on a given farm this year will produce the same quality of wheat next year. Sandy loam soils have greater tendency to absorb and give up water to plants and are also more deficient in nitrogen than the soil of heavier texture, such as clay slit loam (Call et al., 1925).

Principal Component Analysis (PCA)

Principal Component Analysis **(**PCA) is used for dimensionality (variable) reduction while still retaining those characteristics of the data set that contribute most to its variance. This bi-plot of samples and variables graphically discloses the similarities and dissimilarities among the wheat varieties as well as the relationships among the parameters tested. Parameters that are closer to each other correspond to the variables that are positively related, while the variables lying on the opposite axes are negatively related (Dobraszczyk and Salmanowicz, 2008). Parameter that has the longest vector explains the most of the variances and the one with the shortest vector explains the least variability among the wheat varieties (Dobraszczyk and Salmanowicz, 2008). PCA also evaluates which rheological parameters are useful in predicting the baking performance when compared to loaf volume. Besides, it can be a useful tool for wheat breeders to screen the lines with superior baking qualities while eliminating those with inferior qualities.

Machinability and baking performance factors are largely attributed to the functionality of wheat proteins. Protein content has been found highly correlated with the bread-making quality within a cultivar. However, for a given protein content, bread-making quality differences among wheat cultivars are largely a function of the qualitative nature of the gluten proteins, which affects their rheological properties (Khatkar et al., 1995). Partial PCA is performed with adjustment for protein content variation to evaluate the wheat flour quality per protein unit. Non-adjusted PCA graphs show the performance and quality of the wheat cultivars at the specific level of protein quantity and quality. Data from multiple years would be needed to predict the performance of wheats for crop years with differing climate and environment growing conditions. Wheat cultivars which produced a high amount of protein content this year might not be able to produce the same amount next year. This is because protein quantity is influenced largely by environmental conditions and crop management practices, while the quality of the protein is genetically determined (Cornish et al. 1991). Partial PCA has been used by wheat breeders in the selection of potential parents for specific targeted traits. Also, we can observe what other factors become important in explaining the variability among the wheat cultivars besides protein quantity and protein quality. Partial PCAs may show similar behavior in most wheat samples (samples clumping together or concentrate at the center), making it less useful in differentiating between the samples. Yet, it is able to separate out the samples which properties in a protein unit are distinctively different from the other samples. Thus, we can eliminate the outliers which show distinctive inferior baking quality and select the ones with distinctive superior baking quality for crossbreeding.

CHAPTER III

MATERIALS AND METHODS

Wheat samples

Two sets of hard winter wheat cultivars representing commercial cultivars and elite breeding lines grown in 2006 and 2007 were analyzed. The samples were cultivated at different nurseries across Oklahoma with differing environmental growing conditions. The samples from 2006, varying in protein content from 9.7 to 13.1%, were composites of four plots and reported as four groups designated 90, 91, 92 and 93. The samples included red (78.6%) and white (21.4%) winter wheats. The wheat cultivars from 2007, varying in protein content from 9.6 to 13.0%, consisted of 81.6% red and 18.4% white winter wheats, were composites of three plots and were reported as groups 89, 91 and 92.

Rheological assessments

Creep-recovery test

Gluten viscoelasticity properties were characterized by a constant stress rheometer (TA Instruments AR1000-N) using creep-recovery tests as described by Zhao et al. (2007) measured with relatively small deformation. The gluten obtained from the glutomatic was clamped between two plates and rested for an hour. The top plate was 2.5

kg and the gap between the plates was 2.5 mm. The dough was transferred onto the rheometer plate and clamped between two parallel plates (25 mm diameter), which were serrated to prevent the gluten from slipping. The gap between the plates was set to 2.5 mm. The extra edges were then cut with a scalpel to obtain a piece of gluten with exactly 25 mm diameter. The gluten flows in the direction of the force (creep compliance) and when the force is removed, the gluten recovers from the deformation (recovery compliance). The creep and recovery steps were done for 100 and 1000 seconds, respectively, at a constant temperature of 25 °C. A shear stress of 40 Pa was applied during the creep step. Three variables were measured: delta compliance, rubbery plateau departure time and percent recovery. Delta compliance (DCp) is the difference between the creep and recovery compliance measured at 100 seconds. Rubbery Plateau Departure (RPD) time is the time at which the two compliance curves (creep and recovery) separate (depart from being superimposed) and measured at a defined value ($0.1e^{-3}$ Pa^{-1}). Percent recovery (%Rec) is the ratio of recovery compliance to the creep compliance and expressed as percentage. The values were reported as an average of three replicates, with coefficient of variation less than 10%.

Micro-extension test

Large deformation micro-extension test measures the ability of dough to extend when a constant force is applied. The parameters obtained are related to the properties of dough extension during fermentation and subsequent baking. The micro-extension test was performed on dough using Kieffer dough extensibility test (Kieffer et al., 1998) with some modifications. Doughs were prepared in a 10 g-sample Farinograph bowl by mixing the flour until it reached a peak at consistency of 500 BU (Brabender Unit). Dough samples were then rolled out and compressed into a Teflon mould, and allowed to stand for 40 minutes in a zip lock bag to prevent drying. Doughs were tested using the Kieffer Dough Extensibility Rig with a Texture Analyzer TA-XT2 at test speed of 4.0mm/sec with trigger force of 5 g for 2006 samples according to Kieffer at al. (1998). The trigger force was changed to 1 g for 2007 samples to catch the initial viscoelastic responses in the extension curves (Anderssen et al. 2004). Rmax measures the dough resistance to extension at its maximum peak. Emax measures the extensibility at the maximum peak of resistance to extension, while Erup measures the extensibility at the dough rupture point. Emr is the difference in extensibility between peak and the rupture point, which tells us about the extent of dough to be able to retain its structure from start of rupture point until complete rupture is reached. Area represents the total work required to extend the dough to Rmax. Rvr measures the resistance at the initial viscoelastic response (first peak response), while Evr measures the extensibility at Rvr. This test was done in duplicates, each with ten measurements and coefficient of variations less than 10%.

Glutomatic

Glutomatic model 2200 (Perten Instruments, Huddinge, Sweden) is used to measure the amount of swollen gluten obtained from washing out a paste of flour according to AACC Approved Methods 38-12A (AACC 2000). It can be related to gluten quantity and quality. The viscoelastic gluten is obtained from 10 grams of wheat flour dough by washing out the water-soluble albumin proteins, the salt-soluble globulin proteins and starch (Liang et al., 2006) with 2% NaCl solution from the chamber equipped with 88 microns polyester sieves (Perten Instruments). The gluten is the result of glutenin and gliadin proteins forming an elastic network in the presence of water and some mechanical energy input (Liang et al., 2006). The gluten was then transferred to a metal sieve cassette and centrifuged one minute at 6000 ± 5 rpm in Centrifuge 2015 to remove the adhered water (Perten Instruments). The cassette holes are 0.5 mm in diameter and are distributed in an array of center spacing of 1.4 mm. The total weight of this gluten ball was reported as the wet gluten (WG), which is generally positively related to protein quantity which is also an estimate of the gluten strength. The ratio of gluten that is retained vs what passes through the metal sieve from the cassette to the total wet gluten was reported as the gluten index. If all materials pass through, it shows the gluten is weak (GI=0); when nothing passes through, it shows that the gluten is strong (GI=100). The values were reported as an average of four replicates.

Mixing properties

The mixing characteristics of the flour samples were evaluated using a 50 g-sample Farinograph (C.W. Brabender Instruments, South Hackensack, NJ) and a 10 g-sample Mixograph (National Manufacturing Co., Lincoln, NE) according to AACC Approved Methods 54-21 and 54-40A, respectively. Farinograph peak time (FPT) and mixograph corrected mixing time (CMT) represent the dough development time, measuring the time required to reach peak dough resistance. Farinograph and mixograph stability (FST and MST) were recorded as the time (min) the dough maintains maximum consistency. Mixograph tail width (MTW) measured the tendency of the dough to hold its structure before degrading. Farinograph and mixograph water absorption (FWA and MWA) determine the amount of water necessary for the flour to reach a desired consistency. Farinograph profiles were only obtained for samples from 2006 because of limited 2007 samples.

Baking test

Baking tests were run in duplicates. Bread loaves were evaluated objectively and subjectively for the volume, weight, height, symmetry, interior and exterior characteristics, such as crumb structure in terms of cell size and uniformity, crumb texture and color. The loaf volume (LV) was measured using rapeseed displacement. The crumb interior and exterior characteristics were evaluated on a designated scale and the scores were summed up to give visual score (ViSc). Baking water absorption (BWA) was also recorded as the amount of water added to achieve the properly hydrated dough.

Sodium dodecyl sulfate (SDS) Sedimentation

Small-scale SDS sedimentation test has been used in wheat breeding programs with the aim to predict the gluten strength, by measuring its swelling power and solubility (Carter, 1999). It involves the dispersion of flour in 48 parts of 2% (w/v) SDS and 1 part of 85% lactic acid solutions and observing the amount of sediment after a fixed period of time (AACC Approved Method 56-61A, 2000). Wheat protein comprises of different protein components, mainly the gliadin and glutenin. The sediment in the SDS solution consists of swollen glutenin strands (Ram and Singh, 2004). Hard wheats have high SDS sedimentation volumes (SED) which have been associated with strong gluten and superior bread-making quality, while low SED are due to weak gluten, which is associated with the soft wheats. SED values were obtained only from 2006 samples because of limited 2007 samples.

Statistical analysis

Correlations

Pearson correlation and partial correlation coefficient adjusted for protein variation were applied using SPSS 15.0 for Windows (Lead Technologies, Inc.) to find the linear relationships between two rheological parameters. Only correlations with significant levels at $P<0.001$, $P<0.01$ and $P<0.05$ were reported. Pearson correlation was employed to show the effect of flour protein on the wheat performance grown in a particular year. Partial correlation adjusted for protein variation was carried out to normalize the differences affected by flour protein.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was performed using Canoco software (Biometris, Plant Research International, Wageningen, the Netherlands). For each set of samples of 2006 and 2007, non-adjusted PCA and partial PCA were performed separately for each of the three different testing methods: TRAD, CREG and ALL (included both TRAD and CREG testing methods). Variables were centered and normalized (mean subtracted). The data were compressed into two new independent variables, also known as principal components (axis 1 and 2), which were orthogonal to each other.

CHAPTER IV

RESULTS AND DISCUSSION

Creep-recovery test

Creep-recovery test measures the power to recover after an extension is exerted on the gluten. Lower modulus, strain and delta compliance (DCp) (i.e., lower curves) represent stronger gluten wheats, while the higher values (i.e., upper curves) represent weaker gluten wheats (Fig. 1).

Creep and recovery moduli superimpose up to the Rubbery Plateau Departure (RPD) time (Fig. 1). After this time, the recovery is slower, most likely representing the maximum recoverable structure in terms of bond reformation after the strain is removed. The gluten takes longer to recover and springs back to a specific recovered structure and is a function of the rate of formation/reformation of bonds depending on its intrinsic properties. Longer RPD time is observed in the strong wheat glutens compared to the weaker glutens (Fig. 1).

The three creep-recovery test parameters (DCp, RPD and %Rec) were strongly correlated with each other, especially DCp and RPD (Table 2-5). The three parameters showed Pearson and partial correlations with at least r=0.60 (P<0.001) among themselves in both set of samples (Table 2-5). The strong correlations may suggest redundancy among the three parameters in reference to reflect viscoelastic properties.

DCp and RPD showed greater correlations with all the other parameters tested than %Rec did, suggesting that %Rec may be less useful than the other two parameters or either DCp or RPD are good candidate to be used as a single viscoelasticity parameter. In both sets of samples, DCp and RPD showed high partial and Pearson correlations with GI, but %Rec showed weak or no correlation with GI (Table 2-5). However, only %Rec was correlated with extensibility properties (Emax and Erup) in partial correlation in 2007 samples (Table 5). In the same set of sample, DCp and %Rec showed weak but significant correlations with extensibility properties in Pearson correlation (Table 4) but not RPD. This suggests that even though %Rec showed weaker correlations with all of the other parameters tested compared to DCp and RPD, it was able to show some degree of Pearson and partial correlations with extensibility properties, which DCp and RPD were not able to (Table 4 and 5).

The range values of viscoelastic properties for 2006 samples were % creep-recovery compliance mean 80.3% (range 74.4-83.3%), RPD time 11.7 s (3.8-20.8 s) and DCp 1.1 Pa^{-1} (0.5-2.3 Pa^{-1}) (Table 9). The range values of viscoelastic properties for 2007 samples were % creep-recovery compliance mean 79.4% (range 74.1-83.9%), RPD time 14.7 s (5.0-27.8 s) and DCp 1.0 Pa^{-1} (0.4-2.6 Pa^{-1}) (Table 11).

Micro-extension test

Anderssen et al. (2004) highlighted the occurrence of double peak response in weak flours and double response but not double peaks in intermediate flours. Strong flours however, only show single peak response. The set of 2007 samples studied were all intermediate flours, except Guymon Nursery (N) 91 (Fig. 2), which appeared to be a weak flour. In the same set of samples, the dough strength (Rmax) of intermediate flours ranged from 0.10 N to 0.24 N, while the weak flour had less 0.10 N. Samples of the same variety grown in different environments, such as Bullet, Custer and Duster were expected to show similar strength and extension behavior (Fig. 2). However, Guymon N91 showed larger extensibility and low dough strength compared to Guymon N92, which showed lower extensibiliy but higher dough strength (Fig. 2). This might be explained in part by the inherent larger variability to different environment of Guymon compared to the other samples. Bullet and Overley showed similar strength and extension, the same for BigMax and Centerfield (Fig. 2). Custer, Endurance, Duster and Tam111 had similar dough strength but showed a wide range of extensibility (Fig. 2). Guymon N91 showed the greatest extensibility but lowest dough strength among the set of 2007 samples (Fig. 2). Line 5711W showed greatest dough strength, while Custer and Custer-related samples showed lowest extensibility (Fig. 2).

It has been widely known that flour protein (FP) content contributes significantly to the bread-making quality. FP was significantly correlated with LV at $P<0.001$ (r=0.62 and 0.51 for 2006 and 2007 set samples respectively) (Table 2 and 4). A higher dough strength, dough resistance to extension (Rmax), is also demanded as good bread-making dough should have the ability to retain gas during baking (Stojceska et al., 2007). Dough strength has been reported to influence the loaf volume (Nash et al., 2006). Only Pearson correlation for 2006 samples showed significant relationship between Rmax and LV with a positive correlation of r=0.40, $P<0.01$ (Table 2). Area, total work required to extend the dough to the maximum resistance to extension, was correlated with Rmax (Pearson correlation of r=0.93 and partial correlation of r=0.94, $P<0.001$) and not Emax (only showed in 2007 samples) (Table 4 and 5). This suggests that the amount of work required to extend the dough to Emax is highly dependable on the resistance of the dough to overcome the extension and that the extensibility of this sample set was more variable. The difference between Emax and Erup, Emr, revealed the ability of dough to retain its structure from the maximum resistance to extension until the point where it ruptures completely. Rmax and Emr had an average negative Pearson and partial correlation of r=-0.47 (*P*<0.01) (Table 2-5) between both sets of sample. This suggests that weaker dough is able to retain the structure longer before breaking than the stronger dough after the maximum dough strength is reached. This probably is due to the selection of winter wheat varieties with stronger gluten and generally, stronger gluten is less extensible.

Emax and Erup were highly correlated to each other in both Pearson and partial correlation with r=0.99 (*P*<0.001 for both Pearson and partial correlation) (Table 4 and 5). The strong correlation between Emax and Erup indicated the redundancy among the two variables, suggesting the possibility of using only one of them. Erup might be a better variable than Emax as it showed slightly higher correlations with all the other parameters. Emr did not contribute much to the explanation for the percent variances in the PCA graphs as it only showed fairly weak correlations with few parameters (Table 2-5). Therefore, Emax and Emr can be discarded from the analyses. Pearson correlation for 2007 samples (Table 4) showed significant but weak correlations of Emax and Erup with many other parameters tested, such as LV, WG, Emr, Rvr, DCp, %Rec and MST. When the responses were corrected flour protein content in partial correlation, Emax and Erup only showed significant correlations with Rvr and %Rec (Table 5). Overall, extensibility properties showed weak or no correlations with other parameters tested.

This suggests that extensibility properties are independent quality parameters not related to protein quantity or other parameters tested in these sets of samples.

Nash et al. (2006) reported a negative correlation (r=-0.74) between strength and extensibility in spring wheats, which was undesirable as both strength and extensibility properties were highly demanded in many end-uses. Our study on winter wheats showed relatively negative weak but insignificant correlation between dough strength and extensibility (insignificant correlations not shown). This is due to the overall lower gluten strength compared to spring wheats. The results suggest that candidates with higher extensibility need to be identified in different genetic pools for potential breeding material to improve the extensibility of winter wheats.

Rvr and Evr, are related to the dough strength and extensibility at the initial viscoelastic response (only shown in 2007 set samples) (Table 4 and 5). Rvr and Evr were highly correlated with each other (Pearson correlation r=0.77, *P*<0.001; partial correlation r=0.71, *P*<0.001) (Table 4 and 5). Both Rvr and Evr were highly correlated with Rmax, but only Rvr was correlated with Emax and Erup (Table 4 and 5). These two parameters showed significant relationships with many other parameters tested, comparable to Rmax and Emax or Erup. However, the two parameters may not be very useful in showing differences among the samples as the ranges for both were not very large in our datasets. The second viscoelastic response is more desirable since it might be able to characterize the dynamics of expansion up to the point where the bulk of gas bubbles are able to retain its structure (Anderssen et al., 2004).

The range values of micro-extensibility properties for 2006 samples were Rmax mean 0.15 N (range 0.09-0.23 N) and Emr 8.7 mm (6.0-12.6 mm) (Table 9). The range values of micro-extensibility properties for 2007 samples were Rmax mean 0.17 N (range 0.09-0.24 N), Emax 107.1 mm (86.7-146 mm), Area to Rmax 11.3 N.mm (7.8-17.3 N.mm), Rvr 0.05 N (0.03-0.07 N), Evr 9.93 mm (8.0-12.8 mm), Erup 115.6 mm (93.4-157.2 mm) and Emr 8.5 mm (4.9-12.2 mm) (Table 11). In 2006 set of samples, line 5905C had the greatest Rmax and line 4904C showed the lowest Rmax (Table 9). Meanwhile, in 2007 set samples, Guymon N91 showed the lowest Rmax but highest Emax and Erup (Table 11). Line 5711W showed the greatest Rmax, while Custer had the lowest Emax and Erup (Table 11).

Glutomatic

Gluten Index (GI) and Wet Gluten (WG) from 2007 set samples showed a relatively good Pearson and partial correlation, with r=-0.51 ($P<0.001$) and r=-0.60 ($P<0.001$), respectively (Table 4 and 5). However, these two variables showed weak partial correlation (r=-0.32, $P<0.05$) and no Pearson correlation in 2006 set samples (Table 2 and 3). The differences in the correlations might be largely due to the environment effect on the protein quantity and quality of wheat varieties and breeder lines.

Mixograph and Farinograph

Dough mixing is a critical step in bread-making as it is at this stage where blending and hydration of the flour components occur, initiating bubble structure and the development of the gluten proteins (Millar, 2003). Strong flour doughs generally require longer times to reach peak resistance. Dough mixed below optimum time produces inferior quality (Zounis and Quail, 1997). Long mixing doughs, however, may affect the production schedules, have higher costs and it is troublesome to maintain the conventional final dough temperature (Zounis and Quail, 1997). Wheat lines with a mixograph mixing time of >3 min are considered as having an acceptable baking quality (Fufa et al., 2005). In 2006 samples, there were three lines: AP N90, 4525 and 4904C, which showed mixing time (CMT) lower than 3 minutes (Table 8). 4525 appeared to be the wheat with most inferior qualities (Table 8 and 9). It showed the lowest dough strength, elasticity, loaf volume and visual score and had the greatest tendency to hold the dough structure longer from the start of breaking point until it ruptured completely (Table 8 and 9). Mixograph stability (MST) showed positive correlations with protein content, water absorption, baking performance and extensibility variables, but negative correlations with protein quality, which were reflected by dough and gluten strength, viscoelasticity and mixing properties (Fig. 3 and 9). This suggests a limited use of MST.

Farinograph water absorption (FWA) had a relatively low Pearson correlation with flour protein (r=0.33, $P<0.05$) and the other parameters compared to water absorption values obtained from mixograph (MWA) and baking (BWA), suggesting the latter two variables may be more useful and reliable than FWA (Table 2). This may due to a few factors: 1) the mixing in farinograph was much gentle than mixograph (Hwang and Gunasekaran, 2001), 2) the dough from baking test was mixed in a mixograph instead of farinograph, 3) the values for MWA and BWA were obtained at the room temperature while FWA values were temperature-controlled. MWA and BWA from 2006 set samples showed comparable Pearson correlations to a number of parameters tested, including FP, WG, LV and ViSc (Table 2). However, MWA and BWA from

2007 set samples did not show much Pearson correlations with all the other parameters tested (Table 4). This distinctive behavior of the water absorption ability in flour protein from 2007 crop year may be due to the water-stress caused by the rainy season. The water stress may have caused the expression of gluten proteins in a different ratio compared to non-water-stress situations.

Baking test

Baking tests are the final test of wheat quality after the screening process is done. This is because baking requires large amount of sample. It is laborious, time-consuming and demands technical expertise. Bread loaf volume (LV) is the most important predictor for baking potential of the wheat cultivars. Pearson correlation showed that LV was correlated with FP, ViSc, WG, Rmax, Emax, Erup, FPT, MST, MWA and BWA (Table 2 and 4). LV was best predictable by FP or WG as these two variables showed a fairly consistent Pearson correlation from both set of samples regardless of the environmental growing conditions (Table 2 and 4). Visual Score (ViSc) was found to be highly correlated with LV in 2006 samples (with a Pearson correlation of $r=0.71$, $P<0.001$) (Table 2) and lower correlated in 2007 samples (with a Pearson correlation of $r=0.32$, $P<0.05$) (Table 4). This could be explained in part due to excessive rain at the key development stages of the plant during the 2007 crop year.

SDS Sedimentation

Pearson correlation for 2006 samples (Table 2) showed that SDS sedimentation volumes (SED) had relatively weak but significant negative correlations with FP, WG, MWA and BWA, while it was positively correlated with FST. When flour protein content was adjusted (Table 3), SED did not show any significant relationship with any of the parameters tested. The Pearson and partial correlations matched with the results observed from the non-adjusted and partial PCAs adjusted for FP variation (Fig. 3 and 4). This suggests that in these set of samples protein quantity is the major factor influencing SDS sedimentation volumes but when tested on a protein unit, SDS sedimentation was independent.

Principal Component Analysis (PCA)

2006 Samples

In the non-adjusted PCA for TRAD and ALL methods (Fig. 3 and 7), the first principal component (PC1) or axis 1, which explained the most variance, reflected protein quantity, in addition to water absorption and baking performance. The second PC (PC2) reflected protein quality, which measured dough and gluten strength, viscoelasticity, and mixing properties (Table 16). The PC1 for CREG methods reflected protein quality and PC2 reflected protein quantity (Fig. 5) (Table 16). Parameters from TRAD methods highly reflected protein quantity, except mixing parameters which mainly reflected protein quality and partially reflected protein quantity (Fig. 3). Parameters from CREG methods highly reflected protein quality, except WG and GI, which mainly measured protein quantity and partially measured protein quality (Fig. 5).

In partial PCA adjusted for flour protein (FP) variation for ALL methods, PC1 reflected protein quality, while PC2 reflected mainly baking performance and a small part of water absorption (Fig. 8). In partial PCA for CREG methods, PC1 reflected dough strength and gluten viscoelasticity while PC2 reflected the gluten quality and agglomeration of the gluten (Fig. 6). Meanwhile, in partial PCA for TRAD methods, PC1 reflected the mixing properties and PC2 mainly reflected water absorption (particularly FWA) and partly reflected baking performance and gluten quality (Fig. 4).

Both non-adjusted and partial PCAs for CREG methods explained 70% and 69% of the variance, respectively, in the loading plot (Fig. 5 and 6). The non-adjusted PCAs for TRAD and ALL methods explained 62 and 60% of the variance, respectively (Fig. 3 and 7), and the values decreased to 49% in partial PCAs for both testings (Fig. 4 and 8). The drastic decrease was because FP was highly correlated with more parameters in the TRAD methods than in CREG methods. When FP was standardized, the parameters are now reflecting protein quality dominated by dough mixing properties, specifically by FWA, MTW and FST.

TRAD methods for 2006 samples

Non-adjusted PCA for TRAD methods (Fig. 3) was very similar to ALL methods (Fig. 7). It explained 62% variance (2% more than ALL), with PC1 explaining 43% and PC2 explaining 19% (Fig. 3). FP, MWA, BWA, LV, ViSc and FWA had high loadings on positive PC1, along with SED on the opposite side, suggesting negative correlation. PC1 reflected protein quantity, gluten quality, baking performance and water absorption, while PC2 reflected mostly the mixing properties (Table 16).

Partial PCA for TRAD methods explained much lower percent variance (49%), with PC1 and PC2 explaining 20% and 11%, respectively (Fig. 4). FPT and FST had strong positive loadings along PC1, with little or no amplitude along PC2. Meanwhile, MST had fairly strong negative loading on the opposite side. CMT and MTW were both mainly associated with positive PC1 but also partly influenced by positive PC2 and negative PC2, respectively. In contrast with non-adjusted PCA (Fig. 3), the PC1 of partial PCA for TRAD methods (Fig. 4) reflected the mixing properties and PC2 mainly reflected water absorption (particularly from farinograph) while partly reflected baking performance and gluten quality (Table 16). An average of 11% of the variability in each of LV, ViSc and SED was explained (Table 18). SED was negatively related to flour protein, baking performance and water absorption in the non-adjusted PCA (Fig. 3), but had an opposite relationship when FP was adjusted (Fig. 4). This confirms that the test (SED) is highly dependent on protein quantity. Parameters that were highly correlated with FP, such as LV, ViSc, BWA and MWA become less significant in explaining the loading plot in partial PCA (Fig. 4). Conversely, FWA, which was less correlated with FP (Fig. 3), become more important in explaining the variances in the partial PCA adjusted for FP variation (Fig. 4). Non-adjusted PCA for TRAD methods only explained about 11% of the variability in FWA (Table 17), while partial PCA for TRAD explained 63% (Table 18). This suggests that FWA is highly influenced by flour protein quality and less by protein quantity.

The partial PCA for TRAD methods (Fig. 4) showed that the varieties and breeder lines behaved very similarly except StFe, 2405 and 4108. Line 4108 showed distinctively high MTW per protein unit (Table 12). Even though the AP varieties were found to have high FWA by a unit of protein (Fig. 4), they showed overall low water absorption and inferior baking performance due to their lower protein content (Fig. 3). TRAD methods were able to separate out 2405, which showed distinctively high CMT and FST (Fig. 3 and 4) (Table 8 and 12). CREG methods showed that 2405 was closely related to GI and RPD as well as few other samples (i.e. 4505 and 3522) (Fig. 5 and 6).

CREG methods for 2006 samples

Non-adjusted PCA for CREG methods explained 70% variance, with PC1 and PC2 explaining 42% and 28%, respectively (Fig. 5). Rmax, %Rec and RPD had high negative loadings along negative PC1. DCp and Emr had fairly high loadings on the opposite quadrant. GI was mainly influenced by negative PC2 and partially influenced by negative PC1. FP was closely related to LV and WG and the parameters had fairly high loadings along positive PC2. Thus, PC1 reflected dough strength and gluten viscoelasticity while PC2 reflected protein quantity and baking performance (Table 16).

Partial PCA with adjusted FP for CREG methods (Fig. 6) explained about the same percent variance (69%) as the non-adjusted PCA (70%) (Fig. 5). Both PCAs for CREG methods explained the highest percent variance among all three different testing methods. As expected, the distribution of samples and variables in both loading plots (non-adjusted and partial PCA) were quite different. When FP was adjusted, LV and WG became highly insignificant in explaining the loading plot (Fig. 6). Both parameters only had less than 2.5% of their variability explained in the plot (Table 6). All the other parameters explained more than 60% of the variability (Table 6). Emr which was highly related to DCp before adjusted for FP variation was now separated far away from each other (Fig. 5 and 6). Emr had 55% of its variability explained by negative PC2 and 26% by positive PC1 (Table 18). Thus, it can be considered that PC1 reflected the dough strength and gluten viscoelasticity, while PC2 reflected the gluten quality and agglomeration of gluten when flour protein was adjusted (Table 16). Lines 4111, 2125, 5830 and 4315 appeared to be outliers showing relatively lower GI and Emr per protein unit compared to the rest of the samples (Fig. 6) (Table 13).

Partial PCA for comparison of CREG methods showed differences in per protein unit basis within the two samples of AP and Cfield from N90 and N92 (Fig. 6), which was not seen in any other graphs. It revealed that both AP and Cfield samples from N90 (yellow) were negatively related to Emr while the ones from N92 (green) were positively related to Emr. The difference in Emr within the same varieties suggests a significant influence of environmental conditions on the protein quality of the wheat flour. Nursery 92 may tend to produce wheats with higher Emr, which is the ability to retain the dough structure after its maximum peak and before its total rupture.

ALL methods for 2006 samples

The non-adjusted PCA for ALL methods (with both TRAD and CREG methods) explained 60% variance, with PC1 and PC2 explaining 34% and 26%, respectively (Fig. 7). FP, LV, ViSc, WG, BWA, MWA and FWA were closely related to each other. MST was partially related to PC1 and PC2. On the other hand, GI had fairly strong negative loading on PC2, along with FST, MTW, RPD, %Rec, CMT, Rmax, FPT, FST and MTW, which were all partially related to PC1 as well. DCp and Emr had fairly high positive loadings along PC2. Thus, PC1 reflects protein quantity, baking performance and water absorption, while PC2 reflects the variability in protein quality for both dough and gluten, in terms of strength, viscoelasticity and stability (Table 16). SED was mainly negatively associated with protein quantity, but also partly influenced by protein quality (Fig. 7). The negative relationship between SED and FP in this set of samples suggests that high protein quantity does not necessary give high sedimentation of swollen proteins, which indicates good bread-making quality.

Partial PCA for ALL methods (Fig. 8) showed similar type of relationships, except that most parameters that were related to FP, such as WG, FWA, MWA, BWA and SED, now explained lower variability (<6%) (Table 18). This loading plot explained 49% variance, with PC 1 and 2 explaining 26% and 7.7%, respectively. LV and ViSc had negative loadings along PC2, and were closely related to each other as expected. PC1 reflects the variability in dough and gluten strength, viscoelasticity and stability, while PC2 reflects the baking performance of the wheat cultivars on a protein basis (Table 16).

Lines 0611W and 2522W were closely related to each other and to LV when their protein content was taken into account (Fig. 7). However, line 2522W showed greater LV per protein unit than 0611W, which made 2522W a better candidate line than 0611W (Fig. 8). Even though BulletR showed the smallest increase in LV per protein unit (Fig. 8), it appeared to have a good yield of flour protein, which led to favorably high bread loaf volume (Fig. 7). Guymon N93 appeared to be well-isolated from the other cultivars. This was because Guymon N93 showed highest values in LV, ViSc, BWA, MWA, MST and lowest value in MTW within the set of samples. There is no logical explanation for the peculiar properties of Guymon and such properties have been observed in multiple years and environments (Carver, personal communication, 2008). Cultivars from N93 were generally closely related to LV. All samples from N90 showed good LV per protein unit (Fig. 8) but had low protein content, resulting in reduced LV as seen in the non-adjusted PCA (Fig. 7). All these results may be due to favorable growing condition of nursery 93 compared to nursery 90. Given a favorable growing environment, samples from N90 might show similar baking performance as the samples from N93. In partial PCA for ALL methods (Fig. 8), the samples were closely related to each other except 2405, 4525 and Duster, thus singling them out their different protein performance. Duster showed low MST and FPT per protein unit (Table 12). Line 4525 appeared to have the weakest dough, which showed lowest Rmax, RPD, LV and highest in DCp and Emr per protein unit in this set of samples (Table 12). Even though line 2405 had the lowest DCp and highest RPD and CMT per protein unit, which suggested a strong and elastic dough, it had low LV per protein (Table 12). This suggests that the quality of the gluten matrix might be associated with a strong dough with a high ratio of elastic vs viscous components, i.e., higher elastic behavior. Thus, this limits the expansion properties during fermentation and oven spring. Line 2405 may be a good candidate for strength and viscoelasticity properties that could be used for blending purposes.

2007 samples

In the non-adjusted PCA for CREG and ALL methods (Fig. 11 and 13), the first principal component (PC1), reflected the protein quality, measuring dough and gluten strength, stability as well as the viscoelasticity properties (Table 16). The second principal component (PC2) reflected protein quantity, in addition to water absorption, baking performance and extensibility (Table 16). Mixing properties were partially reflected on both PCs as well. However, the PC1 in non-adjusted PCA for TRAD methods (Fig. 9) reflected protein quantity and water absorption, while PC2 reflected mixing properties and little contribution from baking performance (Table 16).

As mentioned earlier, when we performed partial PCA with adjusted FP (Fig. 10, 12 and 14), the variables which were highly correlated to FP, such as LV, WG, BWA and MWA, become insignificant in explaining the percent variance in the PCA plot (vectors shortened). The principal components in partial PCA for CREG and ALL methods explained the same factors (Fig. 12 and 14). PC1 reflected protein quality while PC2 reflected baking performance and dough extensibility. In partial PCA for TRAD methods (Fig. 10), the PC1 reflected mixing properties and baking performance, while PC2 reflected water absorption (Table 16).

The non-adjusted PCAs for TRAD and ALL methods (Fig. 9 and 13) explained 52% variance each and CREG methods (Fig. 11) explained 64% of the variance. The partial PCAs for TRAD and ALL methods (Fig. 10 and 14) explained 53% and 54% of the variance, respectively, and 68% variance for CREG methods (Fig. 12). PCA for CREG methods were very similar to PCA for ALL methods and it typically explained higher percent variance than TRAD or ALL methods, suggesting that parameters from CREG methods showed better discrimination in the sample variances than parameters from TRAD methods.

TRAD methods for 2007 samples

The non-adjusted PCA for TRAD methods (Fig. 9) explained 52% of the variance, with PC1 and PC2 explaining 30% and 23% variance respectively. FP, LV, BWA, MWA and MST had fairly high positive loadings along PC1, while MTW, CMT and ViSc had moderate positive loadings along PC2. MST was mainly correlated with PC1 and partially negatively correlated with PC2. PC1 seemed to reflect protein quantity and baking performance, while PC2 reflected mixing properties and part of baking performance (i.e., visual score of loaf bread) (Table 16).

Partial PCA for TRAD methods (Fig. 10) explained 54% of the variance, with PC1 explaining 23% variance and PC2 19%. MTW, CMT and ViSc had negative loadings along PC1, while BWA and MWA had high loadings along positive PC2. MST was mainly associated with PC1 and slightly associated with PC2. LV only had a cumulative value of 0.73% of its variability explained in the loading plot (Table 20). Thus, this is not a good model to predict the baking performance.

Water absorption is usually closely associated with loaf volume. Even though Overley had good mixograph and baking water absorption ability per protein unit, it showed distinctively low loaf volume or low loaf volume per protein unit. Overley had the lowest loaf volume (683 cc) while the rest of the samples ranged from 750 cc to 980 cc (Table 10). This suggests that Overley has limited protein quality due to water absorption difficulty. PC2 of partial PCA (Fig. 10) showed that samples from nursery 89 had distinctively low water absorption ability per protein unit. Also, TRAD methods were able to separate the two Guymon samples into two different quadrants and this was not revealed with CREG and ALL methods. Guymon N91showed close relation with MST, while Guymon N92 was more closely related to BWA and MWA. Guymon N92 had slightly higher BWA and MWA than Guymon N91 but Guymon N91 had higher MST than Guymon N92. These observations might be explained in part by the environmental effects.

CREG methods for 2007 samples

The non-adjusted PCA for CREG methods (Fig. 11) explained 64% variance, with PC1 explaining 43% and PC2 explaining 21%. Partial PCA for CREG methods (Fig. 12) explained 68% variance, with PC1 explaining 41% and PC2 explaining 16%. Both partial and non-adjusted PCAs for CREG methods (Fig. 11 and 12) were very similar to the ones for ALL methods (Fig. 13 and 14), except that CREG PCAs did not include traditional testing parameters. The observations for PCA graph for CREG methods will be explained in the discussion for PCA graph for ALL methods.

ALL methods for 2007 samples

The non-adjusted PCA and partial PCA for ALL methods (Fig. 13 and 14), which explained 52% and 53% variance, respectively, were very similar to each other with some slight differences in the distribution of the variables and the varieties. In the non-adjusted PCA for ALL methods (Fig. 13), PC1 explained 35% variance and PC2 explained 17% variance. Rvr, Evr, %Rec, RPD, GI and MTW had high loadings along negative PC1, while Emr and DCp located positively along PC1. Rmax, CMT, Area and ViSc had dependence on negative PC1 and positive PC2. BWA and MWA were highly correlated with positive PC2, along with FP, LV, Emax and Erup. WG seemed to be influenced by both positive PC1 and PC2. MST was mainly associated with positive PC2 and partly influenced by positive PC1. Thus, PC1 reflected the overall protein quality, which included dough and gluten strength, stability and viscoelasticity (Table 16). PC2 reflected water absorption, in addition to protein quantity, baking performance and extensibility (Table 16). TRAD parameters had the lowest explanation of percent variability (less than 20%) except CMT and MST (Table 19). Besides Emr and %Rec, the percent variability of all the other CREG parameters was explained by more than 52% (Table 19). This shows that CREG variables contribute more than TRAD variables in explaining the percent variances in the loading plot.

In partial PCA for ALL methods, PC1 and PC2 explained 33% and 12% variance, respectively (Fig. 14). The percent variability of BWA and MWA were least explained (<3%) (Table 20). Like PC1 in non-adjusted PCA (Fig. 13), PC1 in partial PCA (Fig. 14) reflected the same factor, which was the overall protein quality, involving dough and gluten strength, stability and the viscoelastic properties, in addition to gluten quantity (Table 16). Since BWA and MWA become insignificant after protein quantity was standardized, PC2 in partial PCA reflected the baking performance in addition to dough extensibility (Table 16).

Custer and Custer-related breeder lines (3825-) (Table 7) showed distinctively low Emax and Erup per protein unit (Fig. 14). Partial PCA was able to separate BigMax and CO16 from the group of samples (Fig. 14). BigMax had low Emax, Erup, Evr, Area, GI, CMT and ViSc per protein unit (Table 14 and 15). Even though BigMax had the highest WG among all the samples, it showed considerably inferior dough and gluten properties. CO16 and 5711W had similar baking performance but different protein quality (Fig. 13 and 14). Partial PCA for ALL methods revealed that CO16 was closely related to LV, Emax and Erup while 5711W to Rmax (Fig. 14). 5711W showed slightly greater Rmax per protein unit than CO16 but CO16 was able to produce higher LV, Emax and Erup per protein unit than 5711W (Table 15). Even though CO16 does not produce as much protein as 5711W, it still shows superior baking performance and strength as 5711W, plus it has better extensibility properties than 5711W. An important question to ask is whether CO16 might be able to produce higher protein content in different growing environments and show better performance than 5711W. There were a lot of samples concentrating at the center of both axes in the non-adjusted and adjusted PCAs (Fig. 13 and 14). These varieties were not related to any of the parameters.

TRAD vs CREG methods for 2006 and 2007 set samples

This study gave an overview of the relationships between the variables from TRAD and CREG testing methods. The Principal Component Analysis (PCA) graphs for TRAD, CREG and ALL methods without standardizing for flour protein (FP) variation showed the independency between protein quantity and quality as reflected by both principal components (PCs). This is in agreement with the findings of Tronsmo et al. (2003).

TRAD and CREG variables measure different properties of wheat flour. TRAD variables measure baking performance, optimal water absorption and mixing properties. CREG variables measure dough and gluten strength, dough extensibility, gluten elasticity and wet gluten content. Protein quantity is highly related to wet gluten content, baking performance, optimal water absorption and extensibility properties (only shown in 2007 samples). On the other hand, protein quality is mainly reflected by viscoelasticity properties, gluten strength and micro-extension properties at the initial viscoelastic response. Mixing properties, dough strength (resistance to extension) and area (work required for extension to maximum peak resistance) at the maximum peak resistance (or second viscoelastic response) are partially correlated with both protein quantity and quality. Mixograph corrected mixing time (CMT) and dough strength (Rmax) were two parameters which were partially positively related to protein quality and protein quantity, in addition to water absorption and extensibility properties. Varieties which were closely related to these variables were highly desirable as they showed a good balance of machinability and baking performance.

Machinability and baking performance are two important desirable characteristics in wheat flour quality. Since flour protein is highly correlated with loaf volume, which is the primary indicator of baking performance, we can predict the baking performance of certain wheat cultivars by measuring the flour protein content without doing any other rheological test assessments. However, there is a need to develop a useful methodology which can accurately predict the machinability of a wheat cultivar. This is when CREG methods become important.

CREG methods have most parameters highly reflecting both protein quality and few parameters reflect protein quantity, which is also closely associated with baking performance and extensibility. TRAD methods have most parameters reflecting protein quantity and few parameters partially reflecting a combination of protein quantity and protein quality. Also, CREG variables had always explained higher percent variance than the TRAD or ALL (when both TRAD and CREG methods were analyzed together) variables. The samples had much higher loadings (more spread out) when tested with CREG than TRAD or ALL methods. This shows that CREG variables are able to discriminate the quality of wheat cultivars better than TRAD variables or when all TRAD and CREG variables are analyzed together. The PCA graphs for ALL methods enable us to see the relationships between the TRAD and CREG parameters, and show which parameters are more dominant (longer vectors) in explaining the variability of the loading plot. This is useful in selecting the parameters which could show better differentiation or discrimination among the varieties and lines.

Besides flour protein content, extensibility parameters followed by wet gluten content are found to be the more useful variables in predicting the bread loaf volume (LV) using CREG methods while the mixograph and baking water absorption variables are more useful for TRAD testing methods. However, when we test the wheat cultivars which are subjected to water-stress, the water absorption parameters may not be as useful because the parameters do not show high correlations with all the other parameters tested, as seen in Table 3 and 4. Also, the water absorption parameters did not contribute much to the explanation of percent variances in the PCA graphs of 2007 samples which were subjected to water-stress (Fig. 13). TRAD variables generally did not contribute much to the explanation of percent variances in the PCA graphs, except mixograph corrected mixing time (CMT). Even though mixograph and SDS sedimentation testing methods are rapid and do not require much sample, the parameters are not highly correlated with all the other parameters tested.

2006 vs 2007 crop year

In 2006, warm temperatures and drought dominated the wheat growing season in Oklahoma, while the following year the samples were subjected to water stress (heavy rainfall/precipitation) (Edwards et al., 2007). Generally, growing season with frequent rainfall and low temperatures often favors the development of soft and starchy grains with low protein content, low water absorption level, prolonged mixing times, and significantly low bread loaf volumes (Mikhaylenko et al., 2000). Heavy rainfall tends to wash out great amount of nitrates from the soil, causing production of low-protein wheats. On the other hand, wheats grown in dry weather and in soil with ample amount of nitrogen will often lead to favorable processing and product quality (Mikhaylenko et al., 2000). These statements are in overall agreement with our findings. Samples grown in 2007, which had heavy rainfall and low temperatures throughout the growing season, showed lower protein content, lower baking water absorption level and longer mixing times than the samples grown in 2006. The protein content in 2007 wheat samples averaged 10.9% (Table 10), which was 0.5% lower than the average protein content in 2006 samples (11.4%) (Table 8). However, on average, 2007 set samples did not show overall lower bread loaf volume than 2006 set samples as expected. The bread loaf volume of 2006 samples averaged 816.2cc (Table 8) and the ones from 2007 were 46.5cc higher (Table 10) than 2006 average.

The samples from two different years with differing growing conditions allowed us to compare the effect of environment on production of wheat protein and its quality. Pearson correlations of both 2006 and 2007 samples showed different correlations between the parameters tested. The differences in the behavior or expression of the wheat proteins are largely due to the effect of environmental stress on the wheat cultivars from both crop years with opposing climates. Hence, we cannot assume that high-protein wheat grown on a given farm this year will produce the same quality of wheat next year. Key flour proteins from 2007 samples (most likely high molecular weight glutenin subunits) might have been produced in lower amounts or their ratio to low molecular weight glutenin subunits produced lower quality than the flour proteins from 2006 samples. Flour protein from 2006 samples was correlated with LV, ViSc, WG, Rmax, CMT, MST, MTW, MWA and BWA (Table 2). However, flour protein from 2007 samples only correlated with LV, WG, MST and MWA (Table 4). This suggests a substantial difference of the protein performance.

Flour protein from 2006 samples was highly correlated with the optimal water absorption, MWA and BWA (r=0.94 and 0.79, $P<0.001$) (Table 2), but flour protein from 2007 samples only showed weak correlation with MWA (r=0.28, $P<0.05$) (Table 4). This may due to the effect of water stress on 2007 wheat cultivars. As seen from PCA graphs of 2006 samples for TRAD methods, the percentage variance explained was significantly reduced from 62% in non-adjusted PCA (Fig. 3) to 49% in partial PCA adjusted for flour protein content (Fig. 4). This behavior was not observed in PCA graphs for CREG testing methods (Fig. 5 and 6) or any of the PCA graphs for 2007 samples (Fig. 9-14). This can be in part explained by the large number of variables from TRAD testing methods which were highly correlated with flour protein from 2006 wheat samples. These variables became less significant in explaining the percent variances in the loading plot when the flour protein was adjusted.

New Variables with ALL methods for 2007 set samples

The new variables PCA graph for 2007 set of samples (Fig. 15) explained 55% variance, with PC1 explained 42% and PC2 explained 14%. DRc, DCp, MaxCp and DCp2 closely resembled the poor viscoelastic properties. DCp and MaxCp were highly correlated to each other and had high loadings along axis 1. It is suggested that MaxCp would be a better parameter to use compared to DCp, DCp2 or DRc as the values for MaxCp are easily obtained. MaxCp (the maximum creep compliance) and %Rec (percent recovery of gluten from deformation), have been used in a number of studies, all the other parameters are new. There was a slight difference between the %Rec and %Rec2. Variable %Rec2 was partially correlated with both principal components, and its variability was less explained in the loading plot compared to %Rec, which had fairly high loading on PC1. The ratios of dough resistance and extensibility at both initial viscoelastic response and maximum peak point, R/Evr and R/Emax, were highly related to PC1, which reflected protein quality. Thus, we can use these variables to measure protein quality when samples are analyzed with micro-extension test.

CHAPTER V

CONCLUSIONS

Principal Component Analysis (PCA) showed the independency between protein quantity and protein quality. It graphically depicted the wheat varieties and elite lines that are more closely or distantly related based on tested variables and can assist in the wheat screening process. PCA graphs also showed the redundancy among the parameters and will allow us to choose the most representative parameter for the desired characteristics. This helps in predicting the usefulness of introducing new analytical tools to the breeding program.

The TRAD methods presently used are not able to measure the dough strength, dough extensibility and gluten viscoelasticity, which are revealed by CREG methods. CREG methods showed overall better discrimination among the wheat varieties judging from the highest percent variance explained in the loading plot, compared to TRAD methods or when all the variables from both types of method were analyzed together. In this study, CREG methods improved the explanation of percent variance by an average of 10% among the two set of samples. Furthermore, CREG methods have variables which are highly correlated with protein quantity, protein quality as well as partially reflecting both factors together. This shows the usefulness of CREG methods in predicting wheat cultivars with good baking performance, machinability and a balance of both factors.

Among the different rheological tests, the micro-extension test would be recommended as the best assessment which can reflect higher number of wheat properties. Even though micro-extension is highly time-consuming, laborious and requires high operation expertise, most importantly it does not require large sample size and it is able to predict three important factors. R/Emax and R/Evr closely measure protein quality or machinability, Emax and Erup are closely related to baking performance, while Rmax and Area are closely associated with both machinability and baking performance. Although mixograph and SDS sedimentation tests are rapid and require small amount of sample size, the variables from these two tests do not contribute much in explaining the percent variance in the PCA graph. These two tests are rather useful especially for breeders' screening program.

TRAD methods alone are not enough in interpreting the rheological properties of wheat as these methods are only able to tell us about the mixing properties of wheat flour and give estimation about the gluten strength. We should look into CREG testing methods which provide us more information about the protein quality of the wheat cultivars, on the basis of strength, extensibility and viscoelasticity. There is not a single test which can be expected to describe the wheat dough system comprehensively. Several tests can give good indicators of the baking and machinability potential. This study was mainly conducted to evaluate the predictive power of each parameter (variable) on the desired properties of wheat. Thus, serious consideration should be given to introducing the Creep-Recovery, micro-Extension, and Glutomatic (CREG) analyses into the wheat breeding program or baking industry even though most of the tests are highly time-consuming, laborious and require expensive equipments. Until better methods are commercially available, CREG analysis represent an improved alternative for predicting gluten and dough quality.

CHAPTER VI

FUTURE RESEARCH

- More data sets from different crop years of differing climates are needed in order to improve comparison and accurately predict the rheological properties of the wheat cultivars. In this study, we can only analyzed and compared the data set from 2006 and 2007 crop years, which is a good start but has limitations in predicting quality properties of wheat in different environments.

- From the data analyzed so far, it appears that the parameters from creep-recovery test are good tools to evaluate the viscoelastic properties and protein quality but they have limited relationship in predicting baking performance. We might find one variable in the creep-recovery curve which can closely relate to baking potential of the wheat cultivars. It is also possible that the data set analyzed has a reduced baking performance spread (relatively similar). Therefore, the inclusion of different wheat varieties and lines with wider baking performance could answer the question of whether viscoelastic properties of dough are more related to machinability than baking performance.

- As seen in Figure 15, R/Emax and R/Evr can highly predict the protein quality of wheat cultivars. We should look into these two new variables, by taking the ratio of dough strength and extensibility instead of using the variables individually and evaluate its potential.

- The presence and absence of specific high-molecular-weight and low-molecular-weight of glutenin subunit compositions have also found to be correlated with the rheological properties of wheat (Payne et al., 1987). Although the correlation has a large number of expectations, more studies on the allelic glutenin subunit composition are needed to elucidate the variation in the protein expression of the wheat cultivars.

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TABLE 1

List of abbreviations for parameters used

Tests	Abbr.	Units	Parameters
	FP	%	Flour Protein
Baking	LV	cc	Loaf Volume
	ViSc	score	Visual Score
	BWA	ml	Baking Water Absorption
Mixograph	MWA	ml	Mixograph Water Absorption
	CMT	sec	Corrected Mixing Time
	MST	min	Mixograph Stability
	MTW	mm	Mixograph Tail Width
Farinograph	FWA	ml	Farinograph Water Absorption
	FPT	sec	Farinograph Peak Time
	FST	min	Farinograph Stability
SDS Sedimentation	SED	ml	Sodium Dodecyl Sulfate (SDS) sedimentation volume
Creep-recovery	DCp	Pa^{-1}	Delta Compliance
	%Rec	%	% Recovery
	RPD	sec	Rubbery Plateau Departure
Micro-extension	Rmax	N	Maximum resistance to extension
	Emax	mm	Extensibility at maximum resistance
	Erup	mm	Extensibility at rupture point
	Emr	mm	Extensibility difference between Emax and Erup
	Rvr	N	Maximum resistance to end of initial viscoelastic response
	Evr	mm	Extension to end of initial viscoelastic response
	Area	N/mm	Total work required to extend the dough to Rmax
Glutomatic	GI	%	Gluten Index
	WG	%	Wet Gluten

TABLE 2

Pearson correlations for 2006 wheat varieties and breeder lines

	FP	LV	ViSc	BWA	MWA	CMT	MST	MTW	FWA	FPT	FST	SED	GI	WG	Rmax	Emr	DCp	%Rec	RPD
FP		0.62	0.58	0.79	0.94	0.44	0.65	-0.31	0.33	0.44		-0.48		0.93	0.48				
LV	0.62		0.71	0.67	0.69		0.50			0.31				0.58	0.40				
ViSc	0.58	0.71		0.67	0.61		0.44							0.58	0.33				
BWA	0.79	0.67	0.67		0.75		0.53		0.31	0.30		-0.41		0.74	0.40				
MWA	0.94	0.69	0.61	0.75		0.41	0.69	-0.39		0.38		-0.38		0.89	0.44				
CMT	0.44				0.41					0.66	0.41				0.77		-0.55	0.54	0.66
MST	0.65	0.50	0.44	0.53	0.69			-0.70			-0.45			0.63			0.33		
MTW	-0.31				-0.39		-0.70				0.60		0.38	-0.31			-0.34		0.37
FWA	0.33			0.31										0.39					
FPT	0.44	0.31		0.30	0.38	0.66									0.74	-0.37	-0.47	0.48	0.55
FST						0.41	-0.45	0.60				0.32	0.35			-0.33	-0.41	0.34	0.50
SED	-0.48			-0.41	-0.38						0.32			-0.37					
GI								0.38			0.35				0.37		-0.46		0.44
WG	0.93	0.58	0.58	0.74	0.89		0.63	-0.31	0.39			-0.37			0.31				
Rmax	0.48	0.40	0.33	0.40	0.44	0.77				0.74			0.37	0.31		-0.42	-0.65	0.63	0.69
Emr										-0.37	-0.33				-0.42		0.31	-0.37	
DCp						-0.55	0.33	-0.34		-0.47	-0.41		-0.46		-0.65	0.31		-0.68	-0.88
%Rec						0.54				0.48	0.34				0.63	-0.37	-0.68		0.79
RPD						0.66		0.37		0.55	0.50		0.44		0.69		-0.88	0.79	

Abbreviations defined in Table 1.

🟥	Correlation is significant at the 0.001 level (2-tailed).
🟨	Correlation is significant at the 0.01 level (2-tailed).
🟦	Correlation is significant at the 0.05 level (2-tailed).
⬜	Not significant.

TABLE 3

Partial correlations for 2006 wheat varieties and breeder lines

	LV	ViSc	BWA	MWA	CMT	MST	MTW	FWA	FPT	FST	SED	GI	WG	Rmax	Emr	DCp	%Rec	RPD
LV		0.54	0.36	0.40														
ViSc	0.54		0.43															
BWA	0.36	0.43																
MWA	0.40						-0.32											
CMT						-0.60	0.38	-0.37	0.58	0.58		0.34	-0.40	0.69		-0.61	0.48	0.65
MST					-0.60		-0.69			-0.40						0.42	-0.33	-0.49
MTW				-0.32	0.38	-0.69		0.31		0.57		0.36				-0.36		0.46
FWA					-0.37		0.31											
FPT					0.58					0.42		0.38	-0.36	0.66	-0.44	-0.52	0.43	0.53
FST					0.58	-0.40	0.57		0.42			0.33		0.43	-0.33	-0.42	0.42	0.57
SED																		
GI					0.34		0.36		0.38	0.33			-0.32	0.50		-0.47		0.48
WG					-0.40				-0.36			-0.32		-0.43		0.34		-0.38
Rmax					0.69				0.66	0.43		0.50	-0.43		-0.54	-0.76	0.61	0.70
Emr									-0.44	-0.33				-0.54		0.31	-0.40	
DCp					-0.61	0.42	-0.36		-0.52	-0.42		-0.47	0.34	-0.76	0.31		-0.71	-0.90
%Rec					0.48	-0.33			0.43	0.42				0.61	-0.40	-0.71		0.78
RPD					0.65	-0.49	0.46		0.53	0.57		0.48	-0.38	0.70		-0.90	0.78	

Abbreviations defined in Table 1.

🟥 Correlation is significant at the 0.001 level (2-tailed).
🟨 Correlation is significant at the 0.01 level (2-tailed).
🟦 Correlation is significant at the 0.05 level (2-tailed).
⬜ Not significant.

TABLE 4

Pearson correlations for 2007 wheat varieties and breeder lines

	FP	LV	ViSc	BWA	MWA	CMT	MST	MTW	GI	WG	Rmax	Emax	Erup	Emr	Rvr	Evr	Area	DCp	%Rec	RPD
FP		0.51			0.28		0.50			0.81						-0.32				
LV	0.51		0.32				0.35			0.56		0.33	0.34							
ViSc		0.32					-0.30		0.36									-0.36		
BWA					0.59															
MWA	0.28			0.59			0.38													
CMT							-0.43		0.51		0.73			-0.29	0.47		0.73	-0.58	0.33	0.60
MST	0.50	0.35	-0.30		0.38	-0.43		-0.42	-0.56	0.66	-0.42	0.31	0.35	0.32	-0.53	-0.40		0.59		-0.37
MTW							-0.42				0.32						0.32			
GI			0.36			0.51	-0.56			-0.51	0.70				0.61	0.52	0.63	-0.83	0.28	0.69
WG	0.81	0.56					0.66		-0.51			0.30	0.32		-0.42	-0.54		0.53		-0.43
Rmax						0.73	-0.42	0.32	0.70					-0.45	0.72	0.50	0.93	-0.78	0.42	0.73
Emax		0.33					0.31			0.30			0.99		-0.45		0.29	0.28	-0.37	
Erup		0.34					0.35			0.32		0.99		0.30	-0.48			0.33	-0.42	
Emr						-0.29	0.32				-0.45		0.30		-0.35		-0.34	0.43	-0.40	-0.33
Rvr						0.47	-0.53		0.61	-0.42	0.72	-0.45	-0.48	-0.35		0.77	0.54	-0.71	0.46	0.68
Evr	-0.32						-0.40		0.52	-0.54	0.50				0.77		0.38	-0.61	0.36	0.59
Area						0.73		0.32	0.63		0.93	0.29		-0.34	0.54	0.38		-0.64		0.62
DCp			-0.36			-0.58	0.59		-0.83	0.53	-0.78	0.28	0.33	0.43	-0.71	-0.61	-0.64		-0.61	-0.87
%Rec						0.33			0.28		0.42	-0.37	-0.42	-0.40	0.46	0.36		-0.61		0.74
RPD						0.60	-0.37		0.69	-0.43	0.73			-0.33	0.68	0.59	0.62	-0.87	0.74	

Abbreviations defined in Table 1.

🟥 Correlation is significant at the 0.001 level (2-tailed).
🟨 Correlation is significant at the 0.01 level (2-tailed).
🟦 Correlation is significant at the 0.05 level (2-tailed).
⬜ Not significant.

TABLE 5

Partial correlations for 2007 wheat varieties and breeder lines

	LV	ViSc	BWA	MWA	CMT	MST	MTW	GI	WG	Rmax	Emax	Erup	Emr	Area	Rvr	Evr	DCp	%Rec	RPD
LV		0.51							0.29										
ViSc	0.51				0.34			0.33						0.33			-0.33		
BWA				0.57															
MWA			0.57			0.28													
CMT		0.34				-0.65		0.58	-0.52	0.70			-0.32	0.71	0.51		-0.68	0.35	0.64
MST				0.28	-0.65		-0.43	-0.54	0.51	-0.54			0.31	-0.47	-0.50	-0.29	0.55		-0.37
MTW						-0.43				0.32				0.35					
GI		0.33			0.58	-0.54			-0.60	0.74				0.71	0.58	0.49	-0.82		0.69
WG	0.29				-0.52	0.51		-0.60		-0.43				-0.36	-0.41	-0.50	0.59	-0.29	-0.60
Rmax					0.70	-0.54	0.32	0.74	-0.43				-0.47	0.94	0.73	0.60	-0.84	0.43	0.76
Emax												0.99			-0.40			-0.37	
Erup											0.99				-0.43			-0.42	
Emr					-0.32	0.31				-0.47				-0.38	-0.34		0.42	-0.40	-0.33
Area		0.33			0.71	-0.47	0.35	0.71	-0.36	0.94			-0.38		0.60	0.50	-0.73		0.66
Rvr					0.51	-0.50		0.58	-0.41	0.73	-0.40	-0.43	-0.34	0.60		0.71	-0.67	0.39	0.59
Evr						-0.29		0.49	-0.50	0.60				0.50	0.71		-0.58	0.36	0.59
DCp		-0.33			-0.68	0.55		-0.82	0.59	-0.84			0.42	-0.73	-0.67	-0.58		-0.62	-0.87
%Rec					0.35				-0.29	0.43	-0.37	-0.42	-0.40		0.39	0.36	-0.62		0.74
RPD					0.64	-0.37		0.69	-0.60	0.76			-0.33	0.66	0.59	0.59	-0.87	0.74	

Abbreviations defined in Table 1.

🟥	Correlation is significant at the 0.001 level (2-tailed).
🟨	Correlation is significant at the 0.01 level (2-tailed).
🟦	Correlation is significant at the 0.05 level (2-tailed).
⬜	Not significant.

TABLE 6

Pedigree of 2006 wheat varieties and breeder lines

	Abbr.	Name	Nursery	Pedigree
1	5903C	OK05903C	90	
2	5905C	OK05905C	90	
3	Cfield	Centerfield	90	
4	AP	AP502CL	90	
5	End	Endurance	90	
6	End	Endurance	91	
7	Bullet	Bullet	91	
8	Jagln	Jagalene	91	
9	StFe	Santa Fe	91	
10	Guymon	Guymon	91	
11	4733W	OK04733W	91	
12	4726W	OK04726W	91	
13	4505	OK04505	91	OK91724/2*Jagger
14	4525	OK04525	91	FFR525W/Hickok//Coronado
15	4108	OK04108	91	
16	4111	OK04111	91	2174*2/Jagger
17	4315	OK04315	91	N563/OK94P597
18	514-4	OK00514-05804	91	KS93U206//KS82W418/Stephens
19	514-6	OK00514-05806	91	KS93U206//KS82W418/Stephens
20	5830	OK05830	91	OK93617/Jagger
21	Bullet	Bullet	92	
22	Deliver	Deliver	92	
23	End	Endurance	92	
24	Jagln	Jagalene	92	
25	AP	AP502CL	92	
26	Duster	Duster	92	
27	1420	OK01420	92	
28	1307	OK01307	92	
29	2405	OK02405	92	Tonkawa/GK50
30	2125	OK02125	92	
31	Cfield	Centerfield	92	
32	4904C	OK04904C	92	
33	3522	OK03522	92	N566/OK94P597
34	3305	OK03305	92	N40/OK94P455
35	3311	OK03311	92	
36	Bullet	Bullet	93	
37	Guymon	Guymon	93	
38	Danby	Danby	93	
39	3716W	OK03716W	93	OK92403/Oro Blanco
40	2522W	OK02522W	93	
41	0611W	OK00611W	93	
42	BulletR	Bullet R	93	

TABLE 7

Pedigree of 2007 wheat varieties and breeder lines

	Abbr.	Name	Nursery	Pedigree
1	3825-5	OK03825-5403-5	89	Custer*3/S. African BC1F2 seln
2	3825-6	OK03825-5403-6	89	Custer*3/S. African BC1F2 seln
3	Custer	Custer	89	Custer
4	Bullet	OK Bullet	89	KS96WGRC39/Jagger (=PI642415)
5	Duster	Duster	89	W0405D/NE78448//W7469/TX81V6187
6	Tam111	TAM 111	89	TAM 111
7	CO16	CO00016	89	CO00016
8	Hatcher	Hatcher	89	Hatcher
9	BigMax	Big Max	91	Big Max
10	Bullet	OK Bullet	91	OK Bullet
11	Guymon	Guymon	91	Guymon
12	5711W	OK05711W	91	G1878/OK98G508W
13	5723W	OK05723W	91	SWM866442/Betty
14	5742W	OK05742W	91	KS93U206//KS82W418/Stephens
15	6029	OK06029	91	TXGH12588-120*4/FS4//2*2174
16	5108	OK05108	91	Lut 13686/2174//Jagger
17	5122	OK05122	91	KS94U337/NE93427
18	5128	OK05128	91	KS94U275/OK94P549
19	5526	OK05526	91	KS94U275/OK94P549
20	5134	OK05134	91	OK97411/TX91D6825
21	5303	OK05303	91	OK95548/TXHBG0358
22	5312	OK05312	91	TX93V5919/WGRC40//OK94P549/WGRC34
23	5511	OK05511	91	TAM 110/2174
24	5204	OK05204	91	SWM866442/OK95548
25	5212	OK05212	91	OK95616-1/Hickok//Betty
26	Duster	Duster	92	
27	End	Endurance	92	
28	Bullet	OK Bullet	92	
29	Overley	Overley	92	
30	Cfield	Centerfield	92	
31	Guymon	Guymon	92	
32	0611W	OK00611W	92	
33	2522W	OK02522W	92	
34	5737W	OK05737W	92	KS93U206//KS82W418/Stephens
35	5741W	OK05741W	92	KS93U206//KS82W418/Stephens
36	2405	OK02405	92	Tonkawa/GK50
37	3305	OK03305	92	N40/OK94P455
38	3522	OK03522	92	N566/OK94P597
39	4304	OK04904C	92	TXGH12588-26*4/FS4//2174
40	5903C	OK05903C	92	TXGH12588-120*4/FS4//2174/3/Jagger
41	5905C	OK05905C	92	TXGH12588-105*4/FS4//2174/3/Jagger
42	4505	OK04505	92	OK91724/2*Jagger
43	514-4	OK00514-05804	92	KS93U206//KS82W418/Stephens
44	514-6	OK00514-05806	92	KS93U206//KS82W418/Stephens
45	5830	OK05830	92	OK93617/Jagger
46	4507	OK04507	92	OK95593/Jagger //2174
47	4111	OK04111	92	2174*2/Jagger
48	4315	OK04315	92	N563/OK94P597
49	4525	OK04525	92	FFR525W/Hickok//Coronado

TABLE 8

Mean values of TRAD methods for 2006 wheat varieties and breeder lines

				Baking			Mixograph				Farinograph			SED
	Flour ID	Sample	FP (%)	LV (cc)	BWA (ml)	ViSc (score)	CMT (sec)	MST (min)	MWA (mm)	MTW (mm)	FPT (sec)	FST (min)	FWA (ml)	SED (ml)
1	9002	5903C	11.3	815	68.0	58.0	4.3	16.1	7.0	9.3	11.0	15.0	61.8	6.0
2	9003	5905C	12.0	800	67.0	58.5	5.6	18.3	7.1	8.5	12.2	14.4	61.8	6.3
3	9010	Cfield	10.9	830	67.5	54.5	3.7	12.6	7.0	11.5	8.6	13.2	61.8	6.5
4	9013	AP	9.7	750	67.0	56.0	2.6	11.0	6.9	11.0	7.2	24.3	61.8	7.1
5	9015	End	10.7	790	67.5	56.0	3.9	12.6	7.0	6.6	7.1	11.2	58.6	5.4
6	9102	End	10.8	825	67.5	58.0	4.0	11.5	7.0	8.8	5.9	12.9	57.6	5.4
7	9103	Bullet	11.7	818	67.5	56.0	4.6	16.7	7.1	9.4	9.0	15.5	60.0	5.2
8	9104	Jagln	11.2	825	68.0	55.5	5.1	13.2	7.0	12.6	10.0	24.2	58.6	5.8
9	9106	StFe	11.2	735	67.0	54.5	4.3	16.4	7.0	6.9	8.2	16.0	57.0	6.0
10	9107	Guymon	11.7	760	67.5	55.5	3.5	23.3	7.1	6.0	5.9	8.9	58.8	6.0
11	9110	4733W	11.6	805	67.5	56.5	3.6	21.0	7.1	6.1	6.2	11.0	59.4	6.0
12	9111	4726W	10.8	760	67.0	54.5	3.7	17.2	7.0	8.9	6.4	18.3	61.0	6.3
13	9112	4505	10.7	773	66.0	54.0	4.8	13.7	7.0	9.6	7.6	25.3	56.6	6.9
14	9115	4525	11.4	713	66.5	53.5	2.9	15.8	7.0	9.7	5.4	11.1	62.0	5.9
15	9118	4108	11.4	810	67.5	56.0	4.5	10.6	7.0	18.8	11.1	23.1	62.0	6.3
16	9119	4111	11.2	763	66.5	55.0	4.4	12.3	7.0	9.9	9.5	15.6	62.0	5.9
17	9122	4315	11.3	750	66.5	56.0	3.7	13.3	7.0	13.0	8.7	16.5	62.0	6.0
18	9124	514-4	10.6	760	66.0	55.5	4.3	11.8	7.0	11.1	8.2	20.5	59.4	5.2
19	9125	514-6	10.4	755	67.0	56.0	4.0	9.3	6.9	10.8	8.4	10.9	60.0	5.2
20	9130	5830	11.6	870	66.0	58.0	5.0	14.2	7.1	6.5	10.0	19.4	59.4	6.0
21	9202	Bullet	12.1	858	68.5	57.0	4.8	17.7	7.1	8.6	8.0	13.9	61.6	4.5
22	9203	Deliver	11.8	875	68.0	56.5	5.4	16.0	7.1	10.3	15.3	13.2	60.9	6.2
23	9204	End	11.2	825	67.0	55.5	4.0	13.6	7.0	8.9	6.5	12.8	59.6	5.4
24	9206	Jagln	11.9	850	68.0	54.5	5.2	13.3	7.1	12.3	10.0	18.5	61.0	6.1
25	9207	AP	9.7	768	65.0	55.5	3.1	6.2	6.9	13.7	5.0	13.9	61.8	7.2
26	9208	Duster	10.9	778	67.0	56.0	4.8	4.6	7.0	17.6	2.4	17.5	59.8	5.6
27	9210	1420	10.9	820	67.0	57.5	3.8	11.3	7.0	16.9	5.8	18.3	61.4	6.9
28	9211	1307	11.7	850	68.0	57.0	5.2	12.7	7.1	8.4	9.1	14.0	59.8	6.7
29	9216	2405	12.0	760	68.0	55.5	6.7	6.8	7.1	16.8	12.4	26.7	59.8	5.6
30	9217	2125	11.3	750	66.5	54.5	4.1	10.8	7.0	5.5	6.8	9.5	60.5	4.5
31	9218	Cfield	10.8	825	66.0	55.0	3.9	11.2	7.0	13.3	7.4	12.6	61.8	5.9
32	9219	4904C	10.7	820	66.5	54.0	2.4	16.0	7.0	8.9	5.0	8.7	62.0	6.1
33	9223	3522	11.3	833	67.5	55.0	3.9	11.2	7.0	14.3	7.8	21.3	61.4	6.1
34	9228	3305	10.7	855	66.5	58.0	3.6	16.3	7.0	7.1	6.7	14.4	57.6	6.1
35	9229	3311	11.6	880	67.5	57.0	4.2	17.9	7.1	8.1	8.6	12.5	62.2	5.9
36	9301	Bullet	12.2	885	69.0	58.5	4.5	19.2	7.1	8.6	9.2	12.8	61.4	4.6
37	9303	Guymon	12.8	943	70.0	60.5	3.4	24.3	7.2	5.6	6.1	10.3	61.4	5.9
38	9304	Danby	12.0	915	69.0	59.5	4.1	18.2	7.1	6.7	9.1	10.3	61.2	6.3
39	9305	3716W	12.0	790	69.0	59.0	3.9	12.9	7.1	10.3	5.3	11.8	62.4	4.9
40	9307	2522W	12.7	920	70.0	60.5	4.5	19.1	7.2	7.0	10.1	12.1	63.4	5.3
41	9309	0611W	13.1	890	69.0	58.5	4.3	23.2	7.2	8.7	11.8	13.3	63.4	5.2
42	9310	BulletR	12.7	885	69.0	58.0	4.9	19.3	7.2	7.5	9.6	14.2	61.6	4.6
		Mean	11.4	816.2	67.5	56.4	4.2	14.6	7.0	10.0	8.2	15.2	60.7	5.8
		Std. dev.	0.8	55.3	1.1	1.8	0.8	4.4	0.1	3.3	2.4	4.6	1.6	0.7
		Min.	9.7	713.0	65.0	53.5	2.4	4.6	6.9	5.5	2.4	8.7	56.6	4.5
		Max.	13.1	943.0	70.0	60.5	6.7	24.3	7.2	18.8	15.3	26.7	63.4	7.2

Abbreviations defined in Table 1 and Table 6. Maximum value in blue; minimum value in yellow.

TABLE 9

Mean values of CREG methods for 2006 wheat varieties and breeder lines

				Creep-Recovery			micro-Extensibility		Glutomatic	
	Flour ID	Sample	FP (%)	DCp (Pa^{-1})	%Rec (%)	RPD (sec)	Rmax (N)	Emr (mm)	GI (%)	WG (%)
1	9002	5903C	11.3	0.90	82.0	12.4	0.18	7.5	92.4	32.0
2	9003	5905C	12.0	0.69	81.2	14.5	0.23	9.4	94.4	33.0
3	9010	Cfield	10.9	0.72	83.3	13.5	0.17	7.1	89.0	30.6
4	9013	AP	9.7	0.88	80.9	12.4	0.11	7.7	88.9	28.3
5	9015	End	10.7	0.84	80.7	12.4	0.15	9.8	86.6	30.0
6	9102	End	10.8	1.05	82.1	11.4	0.15	8.8	76.5	29.7
7	9103	Bullet	11.7	1.06	82.3	13.5	0.16	8.1	93.3	33.2
8	9104	JagIn	11.2	0.64	82.8	18.8	0.20	7.0	95.3	31.1
9	9106	StFe	11.2	1.44	79.4	9.4	0.13	9.3	91.7	32.0
10	9107	Guymon	11.7	1.59	79.2	7.2	0.13	9.7	91.0	33.4
11	9110	4733W	11.6	1.40	80.0	8.3	0.13	10.6	80.3	33.8
12	9111	4726W	10.8	1.46	77.4	7.7	0.13	7.6	81.0	29.1
13	9112	4505	10.7	0.77	81.0	16.7	0.17	9.5	94.2	28.1
14	9115	4525	11.4	2.26	76.3	3.8	0.09	12.6	71.6	32.4
15	9118	4108	11.4	0.92	82.1	13.5	0.17	6.1	97.2	30.7
16	9119	4111	11.2	1.00	81.7	12.4	0.19	6.0	85.1	31.2
17	9122	4315	11.3	1.72	79.8	6.7	0.13	8.0	71.7	32.5
18	9124	514-4	10.6	1.14	79.6	9.4	0.15	6.8	91.3	29.0
19	9125	514-6	10.4	1.24	78.4	9.4	0.14	9.1	97.3	27.7
20	9130	5830	11.6	1.45	80.0	7.7	0.15	6.7	80.0	34.2
21	9202	Bullet	12.1	1.20	78.3	9.4	0.16	8.6	82.0	34.6
22	9203	Deliver	11.8	0.71	81.8	18.8	0.18	9.5	91.3	32.4
23	9204	End	11.2	0.74	82.4	13.5	0.15	9.9	89.9	30.7
24	9206	JagIn	11.9	0.72	81.9	15.5	0.19	8.3	87.4	34.1
25	9207	AP	9.7	1.06	74.4	7.7	0.11	9.5	93.7	27.9
26	9208	Duster	10.9	0.87	81.7	15.5	0.14	9.5	88.0	30.6
27	9210	1420	10.9	0.88	80.5	13.5	0.15	9.8	89.0	32.6
28	9211	1307	11.7	0.97	82.3	15.5	0.16	9.5	83.3	33.2
29	9216	2405	12.0	0.50	82.8	20.8	0.17	10.2	94.3	32.5
30	9217	2125	11.3	0.81	82.2	12.4	0.13	7.4	69.1	31.2
31	9218	Cfield	10.8	0.94	77.8	10.4	0.14	9.1	91.7	29.8
32	9219	4904C	10.7	1.56	76.2	5.2	0.09	11.3	91.2	30.5
33	9223	3522	11.3	0.65	81.8	18.8	0.15	9.3	92.9	31.4
34	9228	3305	10.7	1.84	78.6	6.2	0.13	7.9	85.7	28.5
35	9229	3311	11.6	1.12	81.1	10.4	0.16	6.7	91.4	32.8
36	9301	Bullet	12.2	1.07	76.4	8.3	0.17	8.7	87.1	33.9
37	9303	Guymon	12.8	1.80	79.2	6.7	0.13	12.0	83.2	36.7
38	9304	Danby	12.0	1.31	80.2	9.4	0.15	9.7	72.0	34.7
39	9305	3716W	12.0	2.02	77.0	5.7	0.13	8.6	85.8	35.5
40	9307	2522W	12.7	0.79	82.2	16.7	0.20	7.3	95.5	34.6
41	9309	0611W	13.1	0.79	82.6	18.8	0.19	7.4	88.5	37.0
42	9310	BulletR	12.7	0.88	81.6	12.4	0.18	9.3	83.9	35.9
		Mean	11.4	1.11	80.3	11.7	0.15	8.7	87.3	32.0
		Std. dev.	0.8	0.41	2.2	4.3	0.03	1.5	7.2	2.4
		Min.	9.7	0.50	74.4	3.8	0.09	6.0	69.1	27.7
		Max.	13.1	2.3	83.3	20.8	0.23	12.6	97.3	37.0

Abbreviations defined in Table 1 and Table 6. Maximum value in blue; minimum value in yellow.

TABLE 10

Mean values of TRAD methods for 2007 wheat varieties and breeder lines

				Baking			Mixograph			
	Flour ID	Sample	FP (%)	LV (cc)	ViSc (score)	BWA (ml)	MWA (ml)	CMT (sec)	MTW (mm)	MST (min)
1	8904	3825-5	11.4	875	52.0	64.0	6.9	4.6	6.1	8.5
2	8905	3825-6	10.9	835	52.0	64.0	6.9	4.7	6.2	8.8
3	8909	Custer	11.0	858	51.5	64.0	6.9	4.7	5.2	8.0
4	8910	Bullet	11.0	865	53.5	64.0	6.9	6.3	14.4	4.7
5	8911	Duster	10.4	880	53.0	62.0	6.8	5.3	14.8	5.1
6	8913	Tam111	11.0	850	52.0	63.5	6.9	4.9	12.3	9.6
7	8914	CO16	11.8	980	54.0	65.0	7.0	6.2	14.1	8.9
8	8915	Hatcher	10.7	828	52.0	64.0	6.9	7.1	13.2	2.6
9	9101	BigMax	12.7	878	44.5	66.0	7.1	3.3	7.5	18.9
10	9103	Bullet	12.5	950	51.5	65.5	7.1	5.9	10.0	11.3
11	9104	Guymon	12.4	975	50.0	67.0	7.2	3.6	7.3	19.6
12	9105	5711W	12.4	950	50.0	66.0	7.1	8.8	11.3	9.5
13	9107	5723W	11.4	900	51.0	65.0	7.0	6.5	15.6	11.6
14	9108	5742W	11.8	973	52.0	66.0	7.1	4.7	6.5	15.7
15	9114	6029	10.9	940	51.0	65.0	7.0	5.0	10.1	9.2
16	9115	5108	11.3	875	48.0	65.0	7.0	3.6	7.4	14.2
17	9116	5122	11.3	875	50.5	65.0	7.0	3.4	8.3	12.0
18	9117	5128	10.5	925	52.0	66.0	7.1	5.7	14.4	6.6
19	9118	5526	11.2	875	53.0	67.0	7.2	8.0	14.5	6.1
20	9120	5134	11.1	855	52.0	67.0	7.2	3.8	8.9	13.0
21	9121	5303	9.7	800	51.0	65.0	7.0	5.0	13.4	5.5
22	9122	5312	9.8	760	50.5	65.0	7.0	3.1	8.9	10.1
23	9125	5511	10.2	820	51.5	65.0	7.0	6.1	11.2	5.6
24	9128	5204	9.7	750	51.0	64.0	7.0	4.5	14.9	5.7
25	9129	5212	11.4	825	51.0	66.0	7.1	4.4	15.9	8.8
26	9202	Duster	10.4	910	57.0	68.0	6.8	5.3	15.0	4.0
27	9203	End	9.7	820	52.0	70.0	7.0	5.6	8.2	5.1
28	9205	Bullet	10.7	900	53.5	69.0	7.0	6.8	13.5	5.4
29	9206	Overley	10.5	683	46.0	70.0	7.3	4.8	14.7	10.0
30	9207	Cfield	10.6	918	54.5	69.0	7.4	3.3	14.6	14.9
31	9208	Guymon	10.9	935	55.5	68.0	7.4	6.2	7.7	9.8
32	9210	0611W	11.4	850	55.0	66.5	7.3	5.9	8.7	12.7
33	9211	2522W	11.0	885	55.0	65.5	7.3	7.5	8.7	10.9
34	9213	5737W	10.7	860	53.5	66.0	7.2	7.7	9.9	6.5
35	9214	5741W	11.2	890	54.5	66.0	7.2	6.2	8.8	10.6
36	9217	2405	11.3	810	51.5	67.0	7.3	11.7	11.3	5.0
37	9218	3305	9.6	858	54.5	63.5	7.1	5.5	7.0	7.3
38	9221	3522	9.6	885	51.0	64.0	7.0	5.2	8.9	4.6
39	9222	4304	10.2	850	52.5	64.0	7.0	3.6	9.3	10.3
40	9223	5903C	9.6	808	51.5	63.5	7.0	4.8	11.1	5.7
41	9224	5905C	10.6	833	53.0	63.5	7.0	7.7	10.7	11.7
42	9225	4505	10.3	838	51.5	63.5	7.0	6.7	7.8	8.1
43	9227	514-4	11.2	870	52.5	64.0	7.0	7.3	13.7	8.7
44	9228	514-6	13.0	825	51.5	66.0	7.2	9.4	12.6	5.4
45	9229	5830	10.5	855	53.0	63.5	7.0	5.5	9.6	10.0
46	9230	4507	10.3	808	52.0	63.5	7.0	3.9	8.9	11.8
47	9231	4111	10.3	825	51.0	64.0	7.0	5.3	12.5	6.6
48	9232	4315	11.1	888	51.5	65.0	7.1	4.6	11.3	8.7
49	9233	4525	10.2	775	50.0	64.0	7.0	4.0	12.3	6.0
		Mean	10.9	862.8	51.9	65.4	7.1	5.6	10.8	9.0
		Std. dev.	0.8	59.2	2.2	1.8	0.1	1.7	3.0	3.7
		Min.	9.6	683.0	44.5	62.0	6.8	3.1	5.2	2.6
		Max.	13.0	980.0	57.0	70.0	7.4	11.7	15.9	19.6

Abbreviations defined in Table 1 and Table 7. Maximum value in blue; minimum value in yellow.

TABLE 11

Mean values of CREG methods for 2007 wheat varieties and breeder lines

				Creep-Recovery			micro-Extensibility							Glutomatic	
	Flour ID	Sample	FP (%)	DCp (Pa^{-1})	% Rec (%)	RPD (sec)	Rmax (N)	Emax (mm)	Erup (mm)	Emr (mm)	Area (N/mm)	Rvr (N)	Evr (mm)	GI (%)	WG (%)
1	8904	3825-5	11.4	0.81	81.8	14.9	0.16	91.2	99.7	8.6	9.8	0.050	9.4	84.7	30.7
2	8905	3825-6	10.9	0.70	81.8	17.6	0.17	89.5	99.1	9.6	9.9	0.051	10.0	89.1	28.3
3	8909	Custer	11.0	0.87	80.5	13.3	0.16	86.7	93.4	6.7	9.3	0.060	10.6	88.7	28.0
4	8910	Bullet	11.0	0.87	78.3	14.9	0.17	105.7	113.2	7.5	11.5	0.046	9.6	94.2	29.5
5	8911	Duster	10.4	0.95	76.8	13.5	0.16	103.9	113.1	9.2	10.6	0.043	8.7	95.7	28.1
6	8913	Tam111	11.0	1.24	77.3	11.6	0.16	118.0	127.2	9.2	11.8	0.045	10.0	91.2	30.1
7	8914	CO16	11.8	0.96	74.4	11.4	0.23	129.9	137.3	7.4	17.3	0.056	11.0	98.6	31.7
8	8915	Hatcher	10.7	0.64	79.9	17.6	0.21	120.3	125.8	5.6	14.6	0.052	10.4	99.1	27.6
9	9101	BigMax	12.7	2.29	79.2	7.1	0.13	93.7	100.4	6.7	8.2	0.044	8.9	61.8	35.3
10	9103	Bullet	12.5	1.08	79.1	14.1	0.18	110.4	119.4	9.0	12.7	0.044	9.3	87.3	35.3
11	9104	Guymon	12.4	2.35	78.3	8.3	0.09	146.0	157.1	11.2	8.7	0.032	8.9	58.4	34.9
12	9105	5711W	12.4	0.70	82.3	18.4	0.24	112.1	119.1	7.0	16.4	0.048	9.1	95.6	33.9
13	9107	5723W	11.4	2.07	77.6	6.9	0.11	122.2	134.0	11.9	8.9	0.032	8.4	61.4	32.1
14	9108	5742W	11.8	0.96	80.5	14.3	0.18	115.1	123.4	8.3	13.0	0.041	9.3	91.2	32.7
15	9114	6029	10.9	0.88	79.5	13.9	0.19	96.2	105.7	9.5	12.0	0.065	11.7	91.3	29.9
16	9115	5108	11.3	1.74	76.4	8.3	0.10	120.7	129.6	8.9	8.3	0.033	8.0	85.9	31.3
17	9116	5122	11.3	2.57	74.1	5.0	0.12	112.4	124.6	12.2	9.0	0.039	8.8	86.5	31.0
18	9117	5128	10.5	0.39	83.9	27.8	0.19	93.1	101.8	8.8	11.7	0.069	12.8	98.7	26.2
19	9118	5526	11.2	0.66	78.1	16.7	0.21	117.1	126.8	9.7	15.7	0.056	9.8	99.2	27.9
20	9120	5134	11.1	1.81	78.0	8.7	0.11	105.3	112.2	6.9	7.8	0.037	8.4	73.2	32.3
21	9121	5303	9.7	0.84	80.4	14.1	0.16	98.3	105.7	7.4	10.3	0.053	10.8	86.7	25.7
22	9122	5312	9.8	2.03	75.7	5.5	0.12	105.3	114.6	9.3	8.0	0.038	9.4	62.1	28.2
23	9125	5511	10.2	0.75	81.3	15.3	0.18	103.7	108.5	4.9	12.3	0.056	10.0	95.7	26.9
24	9128	5204	9.7	1.32	79.4	10.6	0.15	98.1	104.9	6.9	9.6	0.048	10.3	81.4	26.8
25	9129	5212	11.4	1.36	77.8	10.2	0.14	97.3	108.8	11.5	9.3	0.046	9.4	85.5	32.2
26	9202	Duster	10.4	0.98	78.1	12.2	0.17	110.9	119.2	8.3	11.8	0.048	9.8	90.8	29.0
27	9203	End	9.7	0.59	83.7	21.6	0.16	95.4	102.9	7.5	9.7	0.058	11.1	94.5	24.7
28	9205	Bullet	10.7	0.80	79.9	15.7	0.19	100.6	107.8	7.2	12.3	0.053	9.8	96.9	28.5
29	9206	Overley	10.5	0.45	80.7	24.1	0.20	105.2	113.3	8.1	13.0	0.053	10.1	99.8	25.4
30	9207	Cfield	10.6	0.85	79.3	13.9	0.14	93.0	102.4	9.4	8.7	0.048	10.2	96.2	28.8
31	9208	Guymon	10.9	1.19	79.3	11.8	0.13	123.6	133.0	9.3	10.6	0.036	8.9	89.6	29.0
32	9210	0611W	11.4	0.78	80.8	19.6	0.19	115.1	122.9	7.8	13.2	0.046	10.0	94.0	32.1
33	9211	2522W	11.0	0.72	79.1	16.3	0.20	105.7	115.2	9.6	14.0	0.056	10.7	98.5	29.0
34	9213	5737W	10.7	0.70	82.2	20.0	0.18	104.9	113.6	8.8	12.5	0.053	9.7	97.3	29.7
35	9214	5741W	11.2	0.82	79.0	18.4	0.18	101.3	112.3	11.0	12.0	0.050	10.0	96.8	30.7
36	9217	2405	11.3	0.48	79.8	21.6	0.22	102.0	109.1	7.1	14.5	0.070	9.6	98.5	29.1
37	9218	3305	9.6	1.01	79.1	12.8	0.13	106.6	115.4	8.9	9.3	0.039	9.2	84.0	25.6
38	9221	3522	9.6	0.83	77.6	12.8	0.14	98.1	106.1	7.9	9.5	0.050	10.0	97.4	24.1
39	9222	4304	10.2	1.33	76.2	8.9	0.13	109.1	118.2	9.1	9.5	0.045	10.1	94.5	28.2
40	9223	5903C	9.6	0.66	77.2	17.1	0.17	112.4	121.4	9.0	11.7	0.054	12.4	98.6	24.5
41	9224	5905C	10.6	0.44	81.6	25.3	0.21	121.7	129.0	7.3	15.2	0.054	11.2	99.2	26.4
42	9225	4505	10.3	0.58	81.3	20.4	0.17	112.3	120.0	7.7	11.4	0.043	9.8	98.9	26.0
43	9227	514-4	11.2	0.61	81.5	21.2	0.22	111.9	118.0	6.1	14.9	0.051	10.6	98.0	29.0
44	9228	514-6	13.0	0.69	79.6	18.4	0.18	102.6	110.9	8.4	12.1	0.055	10.7	98.1	28.6
45	9229	5830	10.5	1.10	79.8	12.4	0.17	105.4	113.6	8.2	11.1	0.046	10.2	87.3	30.3
46	9230	4507	10.3	1.35	79.2	11.2	0.12	106.8	116.5	9.7	8.5	0.037	9.2	77.6	30.0
47	9231	4111	10.3	0.65	82.0	20.8	0.20	103.9	113.3	9.4	13.7	0.065	10.7	96.0	27.0
48	9232	4315	11.1	1.20	80.3	11.6	0.16	102.3	109.7	7.4	10.9	0.049	9.9	77.9	32.6
49	9233	4525	10.2	1.31	79.6	10.8	0.12	103.1	112.6	9.5	8.5	0.044	9.8	96.2	26.8
		Mean	10.9	1.04	79.4	14.7	0.17	107.1	115.6	8.50	11.34	0.05	9.9	89.8	29.2
		Std. dev.	0.8	0.52	2.1	5.2	0.04	11.2	11.5	1.54	2.38	0.01	1.0	10.8	2.8
		Min.	9.6	0.39	74.1	5.0	0.09	86.7	93.4	4.87	7.79	0.03	8.0	58.4	24.1
		Max.	13.0	2.57	83.9	27.8	0.24	146.0	157.1	12.23	17.34	0.07	12.8	99.8	35.3

Abbreviations defined in Table 1 and Table 7. Maximum value in blue; minimum value in yellow.

TABLE 12

Adjusted mean values of TRAD methods for 2006 wheat varieties and breeder lines

			Baking			**Mixograph**				**Farinograph**			**SED**
	Flour ID	**Sample**	**LV (cc)**	**BWA (ml)**	**ViSc (score)**	**CMT (sec)**	**MST (min)**	**MWA (mm)**	**MTW (mm)**	**FPT (sec)**	**FST (min)**	**FWA (ml)**	**SED (ml)**
1	9002	5903C	72.0	6.01	5.12	0.38	1.42	0.62	0.83	0.97	1.33	5.46	0.53
2	9003	5905C	66.8	5.59	4.88	0.46	1.53	0.59	0.71	1.02	1.20	5.16	0.52
3	9010	Cfield	76.2	6.20	5.01	0.34	1.16	0.64	1.06	0.79	1.21	5.68	0.60
4	9013	AP	77.3	6.91	5.77	0.26	1.13	0.71	1.14	0.74	2.50	6.37	0.73
5	9015	End	73.8	6.31	5.23	0.36	1.18	0.65	0.61	0.66	1.05	5.48	0.51
6	9102	End	76.3	6.24	5.36	0.37	1.06	0.65	0.82	0.55	1.19	5.33	0.50
7	9103	Bullet	69.8	5.76	4.78	0.40	1.42	0.61	0.80	0.77	1.32	5.12	0.44
8	9104	JagIn	73.6	6.07	4.95	0.46	1.18	0.62	1.13	0.89	2.16	5.23	0.52
9	9106	StFe	65.8	5.99	4.88	0.39	1.47	0.63	0.62	0.73	1.43	5.10	0.53
10	9107	Guymon	65.0	5.77	4.75	0.30	1.99	0.61	0.51	0.50	0.76	5.03	0.52
11	9110	4733W	69.4	5.82	4.87	0.31	1.81	0.61	0.53	0.53	0.95	5.12	0.52
12	9111	4726W	70.6	6.23	5.06	0.35	1.60	0.65	0.82	0.59	1.70	5.67	0.59
13	9112	4505	72.2	6.17	5.05	0.45	1.28	0.65	0.90	0.71	2.36	5.29	0.65
14	9115	4525	62.5	5.83	4.69	0.25	1.39	0.61	0.85	0.47	0.97	5.44	0.52
15	9118	4108	71.1	5.92	4.92	0.39	0.93	0.61	1.65	0.97	2.03	5.44	0.56
16	9119	4111	68.2	5.94	4.91	0.39	1.10	0.63	0.89	0.85	1.39	5.54	0.53
17	9122	4315	66.3	5.88	4.95	0.33	1.18	0.62	1.15	0.77	1.46	5.48	0.53
18	9124	514-4	71.7	6.23	5.24	0.40	1.11	0.66	1.04	0.77	1.93	5.60	0.49
19	9125	514-6	72.7	6.45	5.39	0.39	0.90	0.66	1.04	0.81	1.05	5.78	0.50
20	9130	5830	74.7	5.67	4.98	0.43	1.22	0.61	0.56	0.86	1.67	5.10	0.52
21	9202	Bullet	70.8	5.66	4.71	0.39	1.46	0.59	0.71	0.66	1.15	5.09	0.37
22	9203	Deliver	74.3	5.77	4.80	0.45	1.36	0.60	0.87	1.30	1.12	5.17	0.53
23	9204	End	73.8	5.99	4.97	0.36	1.22	0.63	0.80	0.58	1.15	5.33	0.48
24	9206	JagIn	71.6	5.73	4.59	0.44	1.12	0.60	1.04	0.84	1.56	5.14	0.52
25	9207	AP	79.2	6.70	5.72	0.32	0.64	0.71	1.41	0.52	1.43	6.37	0.74
26	9208	Duster	71.4	6.15	5.14	0.44	0.42	0.64	1.62	0.22	1.61	5.49	0.51
27	9210	1420	75.2	6.15	5.27	0.35	1.04	0.64	1.55	0.53	1.68	5.63	0.63
28	9211	1307	72.8	5.82	4.88	0.44	1.09	0.61	0.72	0.78	1.20	5.12	0.57
29	9216	2405	63.4	5.67	4.63	0.56	0.57	0.59	1.40	1.03	2.23	4.99	0.47
30	9217	2125	66.3	5.88	4.82	0.36	0.96	0.62	0.48	0.60	0.84	5.35	0.40
31	9218	Cfield	76.5	6.12	5.10	0.36	1.04	0.65	1.23	0.69	1.17	5.73	0.55
32	9219	4904C	76.7	6.22	5.05	0.23	1.50	0.66	0.83	0.47	0.81	5.80	0.57
33	9223	3522	73.9	5.99	4.88	0.35	0.99	0.62	1.27	0.69	1.89	5.45	0.54
34	9228	3305	80.0	6.22	5.43	0.34	1.53	0.66	0.67	0.63	1.35	5.39	0.57
35	9229	3311	75.9	5.82	4.92	0.36	1.54	0.61	0.70	0.74	1.08	5.36	0.51
36	9301	Bullet	72.5	5.66	4.80	0.37	1.57	0.58	0.70	0.75	1.05	5.03	0.37
37	9303	Guymon	73.6	5.46	4.72	0.26	1.90	0.56	0.44	0.48	0.80	4.79	0.46
38	9304	Danby	76.3	5.75	4.96	0.35	1.52	0.59	0.55	0.76	0.86	5.10	0.53
39	9305	3716W	65.8	5.75	4.92	0.33	1.08	0.59	0.86	0.44	0.98	5.20	0.41
40	9307	2522W	72.4	5.51	4.76	0.36	1.50	0.57	0.55	0.80	0.95	4.99	0.41
41	9309	0611W	67.7	5.25	4.45	0.33	1.77	0.55	0.66	0.90	1.01	4.83	0.40
42	9310	BulletR	69.6	5.43	4.56	0.39	1.52	0.57	0.59	0.75	1.12	4.84	0.36
		Mean	71.8	5.95	4.97	0.37	1.27	0.62	0.89	0.72	1.35	5.35	0.52
		Std. dev.	4.2	0.33	0.28	0.06	0.34	0.04	0.32	0.20	0.45	0.35	0.08
		Min.	62.5	5.25	4.45	0.23	0.42	0.55	0.44	0.22	0.76	4.79	0.36
		Max.	80.0	6.91	5.77	0.56	1.99	0.71	1.65	1.30	2.50	6.37	0.74

Abbreviations defined in Table 1 and Table 6. Maximum value in blue; minimum value in yellow. Each mean was divided by its protein content.

TABLE 13

Adjusted mean values of CREG methods for 2006 wheat varieties and breeder lines

			Creep-Recovery			micro-Extensibility		Glutomatic	
	Flour ID	**Sample**	**DCp (Pa^{-1})**	**%Rec (%)**	**RPD (sec)**	**Rmax (N)**	**Emr (mm)**	**GI (%)**	**WG (%)**
1	9002	5903C	0.08	7.24	1.10	0.016	0.66	8.17	2.83
2	9003	5905C	0.06	6.78	1.21	0.019	0.78	7.87	2.76
3	9010	Cfield	0.07	7.65	1.24	0.015	0.65	8.17	2.81
4	9013	AP	0.09	8.34	1.28	0.011	0.80	9.17	2.92
5	9015	End	0.08	7.54	1.16	0.014	0.91	8.09	2.81
6	9102	End	0.10	7.59	1.05	0.013	0.81	7.07	2.74
7	9103	Bullet	0.09	7.02	1.15	0.013	0.69	7.96	2.83
8	9104	JagIn	0.06	7.39	1.68	0.018	0.62	8.51	2.77
9	9106	StFe	0.13	7.11	0.84	0.011	0.83	8.20	2.86
10	9107	Guymon	0.14	6.77	0.62	0.011	0.83	7.78	2.86
11	9110	4733W	0.12	6.90	0.72	0.011	0.92	6.92	2.91
12	9111	4726W	0.14	7.19	0.72	0.012	0.70	7.53	2.70
13	9112	4505	0.07	7.57	1.56	0.016	0.89	8.81	2.63
14	9115	4525	0.20	6.69	0.34	0.008	1.11	6.28	2.84
15	9118	4108	0.08	7.21	1.18	0.015	0.54	8.53	2.69
16	9119	4111	0.09	7.30	1.11	0.017	0.53	7.61	2.78
17	9122	4315	0.15	7.06	0.59	0.012	0.70	6.34	2.87
18	9124	514-4	0.11	7.51	0.88	0.014	0.64	8.61	2.73
19	9125	514-6	0.12	7.55	0.90	0.014	0.88	9.37	2.67
20	9130	5830	0.12	6.87	0.66	0.013	0.57	6.87	2.93
21	9202	Bullet	0.10	6.47	0.77	0.013	0.71	6.77	2.85
22	9203	Deliver	0.06	6.95	1.59	0.016	0.80	7.75	2.75
23	9204	End	0.07	7.37	1.20	0.013	0.89	8.04	2.75
24	9206	JagIn	0.06	6.90	1.31	0.016	0.70	7.36	2.88
25	9207	AP	0.11	7.67	0.80	0.011	0.97	9.65	2.88
26	9208	Duster	0.08	7.49	1.42	0.013	0.87	8.07	2.81
27	9210	1420	0.08	7.38	1.24	0.014	0.90	8.17	2.99
28	9211	1307	0.08	7.05	1.33	0.014	0.81	7.13	2.84
29	9216	2405	0.04	6.91	1.74	0.014	0.85	7.87	2.71
30	9217	2125	0.07	7.27	1.10	0.011	0.65	6.12	2.76
31	9218	Cfield	0.09	7.21	0.96	0.013	0.85	8.50	2.77
32	9219	4904C	0.15	7.13	0.48	0.009	1.06	8.54	2.86
33	9223	3522	0.06	7.26	1.67	0.013	0.82	8.25	2.79
34	9228	3305	0.17	7.35	0.58	0.012	0.74	8.02	2.67
35	9229	3311	0.10	6.99	0.90	0.014	0.58	7.88	2.83
36	9301	Bullet	0.09	6.27	0.68	0.014	0.71	7.14	2.78
37	9303	Guymon	0.14	6.18	0.52	0.010	0.94	6.49	2.87
38	9304	Danby	0.11	6.69	0.78	0.013	0.81	6.00	2.89
39	9305	3716W	0.17	6.41	0.47	0.011	0.72	7.15	2.96
40	9307	2522W	0.06	6.47	1.32	0.016	0.57	7.52	2.72
41	9309	0611W	0.06	6.29	1.43	0.014	0.56	6.74	2.82
42	9310	BulletR	0.07	6.42	0.98	0.014	0.73	6.59	2.82
		Mean	0.10	7.08	1.03	0.014	0.77	7.71	2.81
		Std. dev.	0.04	0.45	0.36	0.002	0.14	0.88	0.08
		Min.	0.04	6.18	0.34	0.008	0.53	6.00	2.63
		Max.	0.20	8.34	1.74	0.019	1.11	9.65	2.99

Abbreviations defined in Table 1 and Table 6. Maximum value in blue; minimum value in yellow. Each mean was divided by its protein content.

TABLE 14

Adjusted mean values of TRAD methods for 2007 wheat varieties and breeder lines

			Baking			Mixograph			
	Flour ID	Sample	LV (cc)	ViSc (score)	BWA (ml)	MWA (ml)	CMT (sec)	MTW (mm)	MST (min)
1	8904	3825-5	76.7	4.56	5.61	0.60	0.40	0.54	0.75
2	8905	3825-6	76.6	4.77	5.87	0.63	0.43	0.57	0.81
3	8909	Custer	78.0	4.68	5.82	0.63	0.42	0.47	0.73
4	8910	Bullet	78.3	4.85	5.80	0.62	0.57	1.31	0.43
5	8911	Duster	84.7	5.10	5.97	0.65	0.51	1.43	0.49
6	8913	Tam111	77.4	4.74	5.79	0.63	0.45	1.13	0.87
7	8914	CO16	83.0	4.57	5.50	0.59	0.53	1.19	0.75
8	8915	Hatcher	77.5	4.87	5.99	0.65	0.66	1.24	0.24
9	9101	BigMax	69.0	3.50	5.19	0.56	0.26	0.59	1.49
10	9103	Bullet	76.2	4.13	5.25	0.57	0.47	0.80	0.91
11	9104	Guymon	78.7	4.04	5.41	0.58	0.29	0.59	1.58
12	9105	5711W	76.5	4.03	5.32	0.57	0.71	0.91	0.77
13	9107	5723W	79.2	4.49	5.72	0.62	0.57	1.37	1.02
14	9108	5742W	82.4	4.40	5.59	0.60	0.40	0.55	1.33
15	9114	6029	86.1	4.67	5.96	0.64	0.46	0.93	0.84
16	9115	5108	77.4	4.25	5.75	0.62	0.32	0.65	1.26
17	9116	5122	77.3	4.46	5.74	0.62	0.30	0.73	1.06
18	9117	5128	88.3	4.97	6.30	0.68	0.54	1.38	0.63
19	9118	5526	78.1	4.73	5.98	0.64	0.71	1.30	0.54
20	9120	5134	77.2	4.69	6.05	0.65	0.34	0.80	1.17
21	9121	5303	82.5	5.26	6.70	0.72	0.51	1.38	0.57
22	9122	5312	77.7	5.16	6.65	0.72	0.31	0.91	1.03
23	9125	5511	80.4	5.05	6.38	0.69	0.60	1.10	0.55
24	9128	5204	77.2	5.25	6.59	0.72	0.46	1.54	0.59
25	9129	5212	72.2	4.46	5.77	0.62	0.39	1.39	0.77
26	9202	Duster	87.4	5.48	6.53	0.65	0.50	1.44	0.38
27	9203	End	84.4	5.35	7.21	0.72	0.58	0.85	0.53
28	9205	Bullet	83.8	4.98	6.43	0.65	0.63	1.26	0.50
29	9206	Overley	64.9	4.37	6.65	0.69	0.46	1.40	0.95
30	9207	Cfield	86.4	5.13	6.50	0.70	0.31	1.38	1.40
31	9208	Guymon	85.8	5.09	6.24	0.68	0.57	0.70	0.90
32	9210	0611W	74.8	4.84	5.85	0.64	0.52	0.76	1.12
33	9211	2522W	80.4	5.00	5.95	0.66	0.68	0.79	0.99
34	9213	5737W	80.2	4.99	6.15	0.67	0.72	0.92	0.61
35	9214	5741W	79.3	4.86	5.88	0.64	0.55	0.79	0.94
36	9217	2405	71.9	4.57	5.94	0.65	1.03	1.00	0.44
37	9218	3305	89.0	5.65	6.58	0.74	0.57	0.72	0.76
38	9221	3522	92.2	5.31	6.67	0.73	0.55	0.93	0.48
39	9222	4304	83.2	5.14	6.26	0.69	0.36	0.91	1.01
40	9223	5903C	83.9	5.35	6.59	0.73	0.50	1.15	0.59
41	9224	5905C	78.9	5.02	6.01	0.66	0.73	1.01	1.11
42	9225	4505	81.0	4.98	6.14	0.68	0.65	0.76	0.78
43	9227	514-4	77.5	4.67	5.70	0.62	0.65	1.22	0.77
44	9228	514-6	63.4	3.96	5.07	0.55	0.73	0.97	0.42
45	9229	5830	81.6	5.06	6.06	0.67	0.53	0.92	0.95
46	9230	4507	78.2	5.03	6.15	0.68	0.38	0.86	1.14
47	9231	4111	80.1	4.95	6.22	0.68	0.52	1.21	0.64
48	9232	4315	79.7	4.62	5.83	0.64	0.41	1.01	0.78
49	9233	4525	75.8	4.89	6.26	0.69	0.39	1.20	0.59
		Mean	79.4	4.80	6.03	0.65	0.51	1.00	0.82
		Std. dev.	5.5	0.43	0.44	0.05	0.15	0.29	0.30
		Min.	63.4	3.50	5.07	0.55	0.26	0.47	0.24
		Max.	92.2	5.65	7.21	0.74	1.03	1.54	1.58

Abbreviations defined in Table 1 and Table 7. Maximum value in blue; minimum value in yellow.
Each mean was divided by its protein content.

TABLE 15

Adjusted mean values of CREG methods for 2007 wheat varieties and breeder lines

			Creep-Recovery			micro-Extensibility							Glutomatic	
	Flour ID	Sample	DCp (Pa^{-1})	% Rec (%)	RPD (sec)	Rmax (N)	Emax (mm)	Erup (mm)	Emr (mm)	Area (N/mm)	Rvr (N)	Evr (mm)	GI (%)	WG (%)
1	8904	3825-5	0.07	7.17	1.31	0.014	8.0	8.7	0.75	0.86	0.0043	0.82	7.43	2.69
2	8905	3825-6	0.06	7.51	1.61	0.015	8.2	9.1	0.88	0.91	0.0047	0.92	8.17	2.59
3	8909	Custer	0.08	7.32	1.20	0.014	7.9	8.5	0.61	0.85	0.0055	0.96	8.06	2.54
4	8910	Bullet	0.08	7.09	1.35	0.016	9.6	10.3	0.68	1.04	0.0042	0.87	8.53	2.67
5	8911	Duster	0.09	7.40	1.30	0.015	10.0	10.9	0.88	1.02	0.0041	0.84	9.22	2.71
6	8913	Tam111	0.11	7.05	1.06	0.015	10.8	11.6	0.84	1.07	0.0041	0.91	8.31	2.74
7	8914	CO16	0.08	6.30	0.97	0.019	11.0	11.6	0.62	1.47	0.0048	0.93	8.35	2.69
8	8915	Hatcher	0.06	7.48	1.64	0.019	11.3	11.8	0.52	1.36	0.0049	0.97	9.27	2.58
9	9101	BigMax	0.18	6.23	0.56	0.010	7.4	7.9	0.53	0.65	0.0035	0.70	4.86	2.78
10	9103	Bullet	0.09	6.34	1.13	0.015	8.9	9.6	0.72	1.02	0.0035	0.75	7.00	2.83
11	9104	Guymon	0.19	6.32	0.67	0.007	11.8	12.7	0.90	0.70	0.0026	0.72	4.71	2.81
12	9105	5711W	0.06	6.63	1.48	0.020	9.0	9.6	0.56	1.32	0.0038	0.73	7.70	2.73
13	9107	5723W	0.18	6.82	0.61	0.010	10.8	11.8	1.04	0.78	0.0028	0.74	5.40	2.83
14	9108	5742W	0.08	6.82	1.21	0.015	9.7	10.5	0.70	1.10	0.0035	0.79	7.73	2.77
15	9114	6029	0.08	7.28	1.27	0.018	8.8	9.7	0.87	1.10	0.0059	1.07	8.37	2.74
16	9115	5108	0.15	6.75	0.74	0.009	10.7	11.5	0.79	0.74	0.0029	0.71	7.60	2.77
17	9116	5122	0.23	6.54	0.44	0.011	9.9	11.0	1.08	0.80	0.0035	0.78	7.64	2.74
18	9117	5128	0.04	8.01	2.65	0.018	8.9	9.7	0.84	1.12	0.0066	1.22	9.42	2.50
19	9118	5526	0.06	6.97	1.49	0.019	10.5	11.3	0.87	1.40	0.0050	0.88	8.86	2.49
20	9120	5134	0.16	7.04	0.79	0.010	9.5	10.1	0.62	0.70	0.0034	0.76	6.61	2.92
21	9121	5303	0.09	8.28	1.45	0.017	10.1	10.9	0.76	1.06	0.0055	1.11	8.93	2.65
22	9122	5312	0.21	7.74	0.56	0.012	10.8	11.7	0.96	0.81	0.0039	0.96	6.35	2.88
23	9125	5511	0.07	7.97	1.50	0.018	10.2	10.6	0.48	1.21	0.0055	0.98	9.39	2.64
24	9128	5204	0.14	8.18	1.09	0.016	10.1	10.8	0.71	0.99	0.0050	1.06	8.38	2.76
25	9129	5212	0.12	6.81	0.89	0.013	8.5	9.5	1.00	0.82	0.0041	0.82	7.48	2.82
26	9202	Duster	0.09	7.50	1.17	0.017	10.7	11.5	0.79	1.14	0.0046	0.94	8.72	2.78
27	9203	End	0.06	8.62	2.23	0.016	9.8	10.6	0.77	1.00	0.0060	1.14	9.73	2.54
28	9205	Bullet	0.07	7.44	1.46	0.018	9.4	10.0	0.67	1.15	0.0049	0.91	9.02	2.66
29	9206	Overley	0.04	7.66	2.29	0.019	10.0	10.8	0.77	1.24	0.0050	0.96	9.48	2.42
30	9207	Cfield	0.08	7.47	1.30	0.013	8.7	9.6	0.89	0.82	0.0045	0.96	9.06	2.71
31	9208	Guymon	0.11	7.27	1.08	0.012	11.3	12.2	0.86	0.97	0.0033	0.82	8.22	2.66
32	9210	0611W	0.07	7.12	1.73	0.016	10.1	10.8	0.69	1.17	0.0040	0.88	8.27	2.82
33	9211	2522W	0.07	7.19	1.48	0.018	9.6	10.5	0.87	1.27	0.0051	0.97	8.95	2.63
34	9213	5737W	0.06	7.67	1.87	0.017	9.8	10.6	0.82	1.16	0.0049	0.91	9.08	2.77
35	9214	5741W	0.07	7.04	1.64	0.016	9.0	10.0	0.98	1.07	0.0045	0.89	8.63	2.74
36	9217	2405	0.04	7.08	1.92	0.020	9.0	9.7	0.63	1.29	0.0062	0.85	8.74	2.58
37	9218	3305	0.10	8.20	1.33	0.014	11.0	12.0	0.92	0.97	0.0040	0.95	8.70	2.66
38	9221	3522	0.09	8.09	1.34	0.015	10.2	11.0	0.83	0.99	0.0053	1.04	10.14	2.51
39	9222	4304	0.13	7.46	0.88	0.013	10.7	11.6	0.89	0.93	0.0044	0.99	9.25	2.76
40	9223	5903C	0.07	8.01	1.78	0.017	11.7	12.6	0.93	1.21	0.0056	1.29	10.23	2.54
41	9224	5905C	0.04	7.73	2.40	0.020	11.5	12.2	0.69	1.44	0.0052	1.06	9.40	2.50
42	9225	4505	0.06	7.86	1.97	0.016	10.9	11.6	0.74	1.10	0.0041	0.94	9.56	2.51
43	9227	514-4	0.05	7.26	1.89	0.019	10.0	10.5	0.54	1.33	0.0045	0.94	8.73	2.58
44	9228	514-6	0.05	6.12	1.41	0.014	7.9	8.5	0.64	0.93	0.0042	0.82	7.54	2.20
45	9229	5830	0.10	7.61	1.19	0.016	10.1	10.8	0.78	1.06	0.0044	0.97	8.33	2.89
46	9230	4507	0.13	7.66	1.08	0.012	10.3	11.3	0.94	0.83	0.0036	0.89	7.51	2.90
47	9231	4111	0.06	7.97	2.02	0.019	10.1	11.0	0.91	1.33	0.0063	1.04	9.33	2.62
48	9232	4315	0.11	7.20	1.04	0.015	9.2	9.8	0.67	0.98	0.0044	0.89	6.99	2.92
49	9233	4525	0.13	7.79	1.06	0.012	10.1	11.0	0.93	0.83	0.0043	0.96	9.41	2.62
		Mean	0.10	7.33	1.36	0.015	9.9	10.6	0.78	1.04	0.0045	0.92	8.30	2.68
		Std. dev.	0.05	0.58	0.50	0.003	1.0	1.1	0.14	0.21	0.0009	0.13	1.22	0.14
		Min.	0.04	6.12	0.44	0.007	7.4	7.9	0.48	0.65	0.0026	0.70	4.71	2.20
		Max.	0.23	8.62	2.65	0.020	11.8	12.7	1.08	1.47	0.0066	1.29	10.23	2.92

Abbreviations defined in Table 1 and Table 7. Maximum value in blue; minimum value in yellow. Each mean was divided by its protein content.

TABLE 16

Categories of principal components

Principal components		
Protein quantity		
Protein quantity	FP	Flour Protein
Gluten quantity	WG	Wet Gluten
Gluten quantity	SED	SDS Sedimentation volume
Protein quality		
Gluten strength	GI	Gluten Index
Dough strength	Rmax	Maximum resistance to extension
Dough extensibility	Emax	Extensibility at maximum resistance
Dough extensibility	Erup	Extensibility at rupture point
Dough extensibility	Emr	Extensibility difference between Emax and Erup
Dough strength	Rvr	Maximum resistance to end of initial viscoelastic response
Dough extensibility	Evr	Extension to end of initial viscoelastic response
Dough work of extension	Area	Total work required to extend the dough to Rmax
Gluten viscosity	DCp	Delta Compliance
Gluten elasticity	%Rec	% Recovery
Gluten elasticity	RPD	Rubbery Plateau Departure
Baking performance		
	LV	Loaf Volume
	ViSc	Visual Score
Mixing properties		
	MTW	Mixograph Tail Width
	CMT	Corrected Mixing Time
	FPT	Farinograph Peak Time
	MST	Mixograph Stability
	FST	Farinograph Stability
Water absorption capacity		
	MWA	Mixograph Water Absorption
	FWA	Farinograph Water Absorption
	BWA	Baking Water Absorption

TABLE 17

Explained variances (%) for non-adjusted PCA of 2006 wheat varieties and breeder lines

2006		**TRAD**			**CREG**			**ALL**		
	PC (%)	**1**	**2**	**1+2**	**1**	**2**	**1+2**	**1**	**2**	**1+2**
	AXIS	**43.1**	**18.9**		**42.0**	**27.6**		**33.6**	**25.9**	
	FP	85.2	3.3	88.4	21.9	70.5	92.5	85.7	4.2	89.9
	LV	61.7	0.3	62.0	21.6	38.0	59.6	57.2	2.0	59.2
TRAD	ViSc	56.5	0.0	56.6				46.6	7.5	54.2
	FPT	17.1	44.4	61.5				35.4	24.7	60.2
	FST	15.4	57.1	72.5				2.5	54.9	57.4
	CMT	8.9	68.2	77.1				28.3	38.0	66.4
	MST	56.2	14.2	70.4				36.0	30.6	66.6
	MTW	24.8	36.4	61.1				9.5	36.6	46.1
	FWA	10.8	0.0	10.8				9.4	2.0	11.4
	MWA	85.5	1.4	87.0				82.5	5.5	88.0
	BWA	72.4	1.1	73.4				69.6	2.9	72.5
	SED	22.6	0.5	23.1				17.6	4.7	22.4
CREG	GI				16.7	21.8	38.4	0.0	30.9	30.9
	WG				9.9	81.1	91.1	69.5	11.6	81.0
	Rmax				81.1	0.2	81.3	46.6	35.9	82.4
	Emr				17.0	8.8	25.9	1.3	20.2	21.5
	DCp				65.8	18.8	84.6	5.7	69.6	75.3
	% Rec				68.0	1.4	69.3	19.8	41.4	61.2
	RPD				76.5	7.7	84.2	14.2	69.4	83.6

Abbreviations defined in Table 1.

TABLE 18

Explained variances (%) for partial PCA of 2006 wheat varieties and breeder lines

2006			**TRAD**			**CREG**			**ALL**	
	PC (%)	**1**	**2**	**1+2**	**1**	**2**	**1+2**	**1**	**2**	**1+2**
	AXIS	**20.0**	**10.7**		**38.7**	**10.4**		**26.3**	**7.7**	
	LV	3.3	10.7	14.0	1.9	0.0	1.9	0.2	31.7	31.8
TRAD	ViSc	6.0	9.4	15.3				1.1	28.1	29.2
	FPT	27.4	0.2	27.5				38.2	3.6	41.9
	FST	66.4	0.0	66.4				46.5	8.7	55.2
	CMT	54.0	9.2	63.2				50.9	4.0	54.9
	MST	28.2	0.7	28.8				16.2	13.6	29.8
	MTW	50.6	18.2	68.8				26.3	20.4	46.7
	FWA	0.4	62.5	62.9				0.5	1.5	2.0
	MWA	0.6	0.0	0.6				0.1	1.3	1.4
	BWA	1.1	3.8	4.9				0.1	6.2	6.2
	SED	2.2	14.1	16.3				1.5	0.7	2.2
CREG	GI				32.2	27.7	59.9	30.2	2.6	32.8
	WG				2.4	0.1	2.5	2.3	0.0	2.3
	Rmax				58.7	0.8	59.5	54.6	7.3	61.8
	Emr				25.6	55.1	80.7	22.1	13.9	36.1
	DCp				85.3	1.9	87.2	75.9	2.0	77.8
	% Rec				61.6	4.1	65.7	53.0	1.2	54.2
	RPD				80.6	3.6	84.2	80.1	0.1	80.2

Abbreviations defined in Table 1.

TABLE 19

Explained variances (%) for non-adjusted PCA of 2007 wheat varieties and breeder lines

2007		**TRAD**			**CREG**			**ALL**		
	PC (%)	**1**	**2**	**1+2**	**1**	**2**	**1+2**	**1**	**2**	**1+2**
	AXIS	**29.5**	**22.7**		**43.2**	**20.9**		**35.0**	**17.0**	
	FP	56.5	1.8	58.4	9.4	44.5	53.9	8.6	50.9	59.6
	LV	32.0	3.8	35.8	5.9	39.7	45.7	4.7	38.9	43.6
TRAD	ViSc	2.9	31.6	34.5				9.4	4.7	14.1
	CMT	0.5	62.2	62.8				39.4	26.4	65.8
	MST	68.4	18.4	86.8				48.3	11.3	59.6
	MTW	14.7	24.0	38.7				10.5	0.5	11.0
	MWA	38.8	18.1	56.9				0.0	19.5	19.5
	BWA	22.2	21.5	43.7				0.3	8.8	9.1
CREG	GI				63.6	3.8	67.3	67.2	1.6	68.8
	WG				35.4	27.6	63.0	34.9	33.2	68.1
	Rmax				63.6	26.5	90.2	67.7	18.8	86.6
	Emax				16.2	46.9	63.2	11.3	42.2	53.6
	Erup				21.0	43.8	64.8	15.3	40.6	55.9
	Emr				26.1	0.0	26.1	24.2	0.3	24.5
	Area				37.5	53.6	91.2	44.1	42.4	86.5
	Rvr				67.4	0.1	67.4	66.6	0.0	66.6
	Evr				55.1	0.2	55.3	50.0	1.8	51.8
	DCp				87.8	1.3	89.1	88.8	0.4	89.2
	%Rec				40.7	0.2	40.9	33.9	0.1	33.9
	RPD				75.5	3.8	79.3	72.8	3.2	76.0

Abbreviations defined in Table 1.

TABLE 20

Explained variances (%) for partial PCA of 2007 wheat varieties and breeder lines

2007		**TRAD**			**CREG**			**ALL**		
	PC (%)	**1**	**2**	**1+2**	**1**	**2**	**1+2**	**1**	**2**	**1+2**
	AXIS	**23.0**	**19.4**		**40.7**	**15.5**		**33.1**	**12.3**	
	LV	0.3	0.4	0.7	0.3	8.6	8.9	0.2	12.1	12.2
TRAD	ViSc	30.4	1.5	31.9				8.1	23.7	31.7
	CMT	66.3	0.2	66.5				55.4	6.8	62.2
	MST	44.2	14.8	59.0				30.7	0.1	30.8
	MTW	36.0	1.8	37.8				9.6	6.4	16.0
	MWA	2.1	72.0	74.1				1.2	0.2	1.4
	BWA	5.0	64.1	69.1				1.9	0.5	2.4
CREG	GI				61.2	5.5	66.7	63.9	2.9	66.9
	WG				12.1	0.0	12.1	12.6	0.3	12.8
	Rmax				81.7	5.9	87.6	83.8	2.2	86.0
	Emax				8.1	77.7	85.7	4.8	72.3	77.1
	Erup				11.7	75.8	87.6	7.6	72.9	80.5
	Emr				25.4	1.7	27.1	22.8	5.2	28.0
	Area				57.5	28.1	85.7	63.5	19.6	83.1
	Rvr				64.4	1.6	66.0	63.0	3.0	66.0
	Evr				45.2	0.1	45.4	40.0	0.4	40.3
	DCp				82.9	0.3	83.3	83.1	0.0	83.1
	% Rec				41.1	11.0	52.1	34.3	18.0	52.3
	RPD				78.0	0.5	78.4	75.2	0.3	75.5

Abbreviations defined in Table 1.

FIGURE 1

Examples of creep-recovery compliance for selected gluten from 2006 hard winter wheats (N93). The graph distinguishes between weak, intermediate and strong glutens in terms of elasticity and viscosity properties. Strong glutens have high elasticity (high RPD and %Rec) and low viscosity (low DCp).

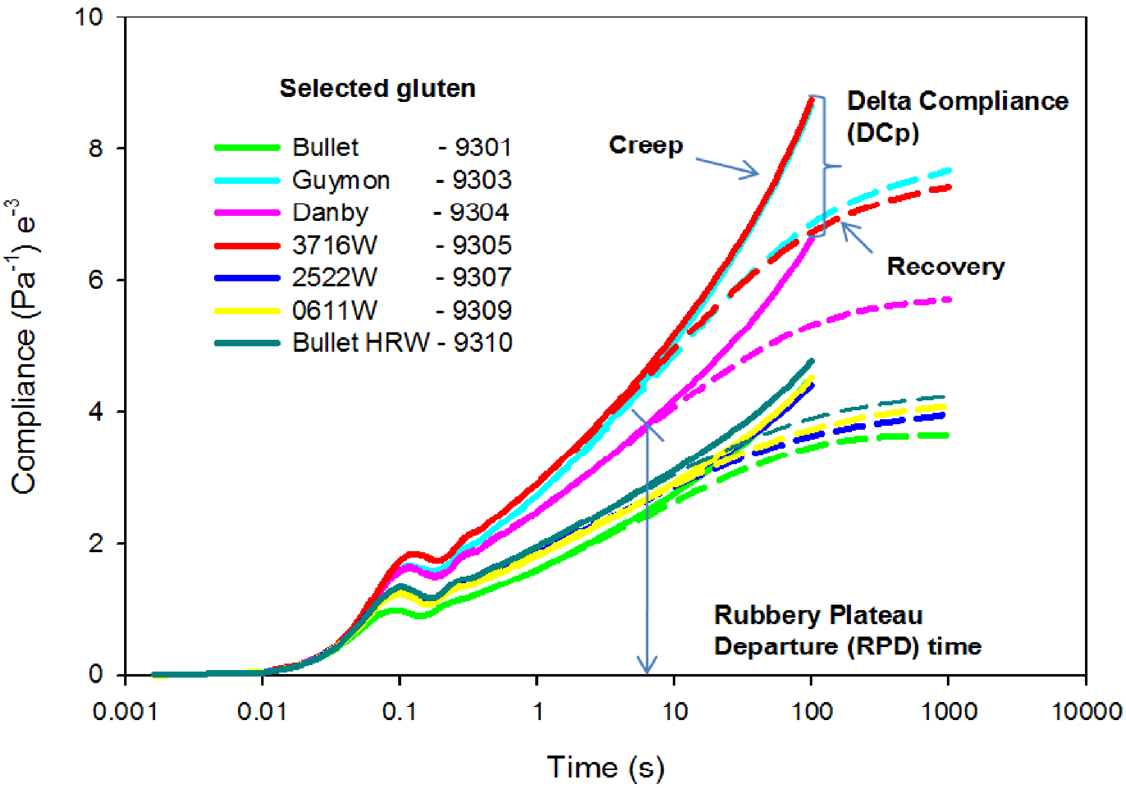


FIGURE 2

Examples of dough micro-extension analysis for selected 2007 hard winter wheat varieties. All the wheat doughs appear to be intermediate flour which show double responses, but not double peaks, except Guymon N91, which appear to be weak flour with double peak responses.

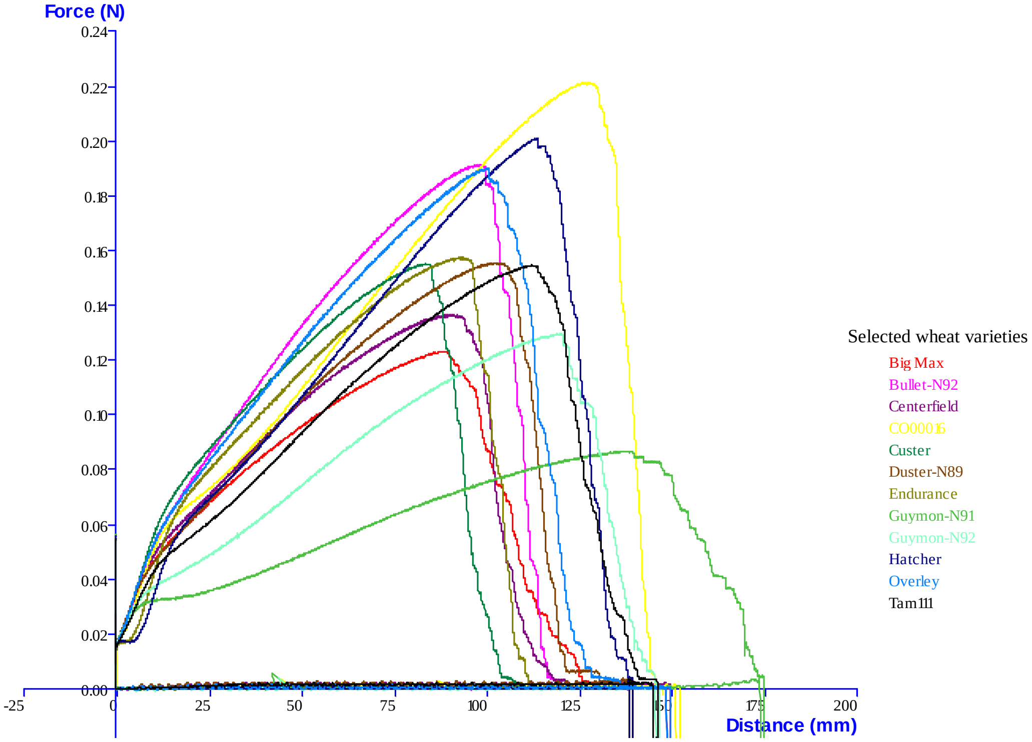
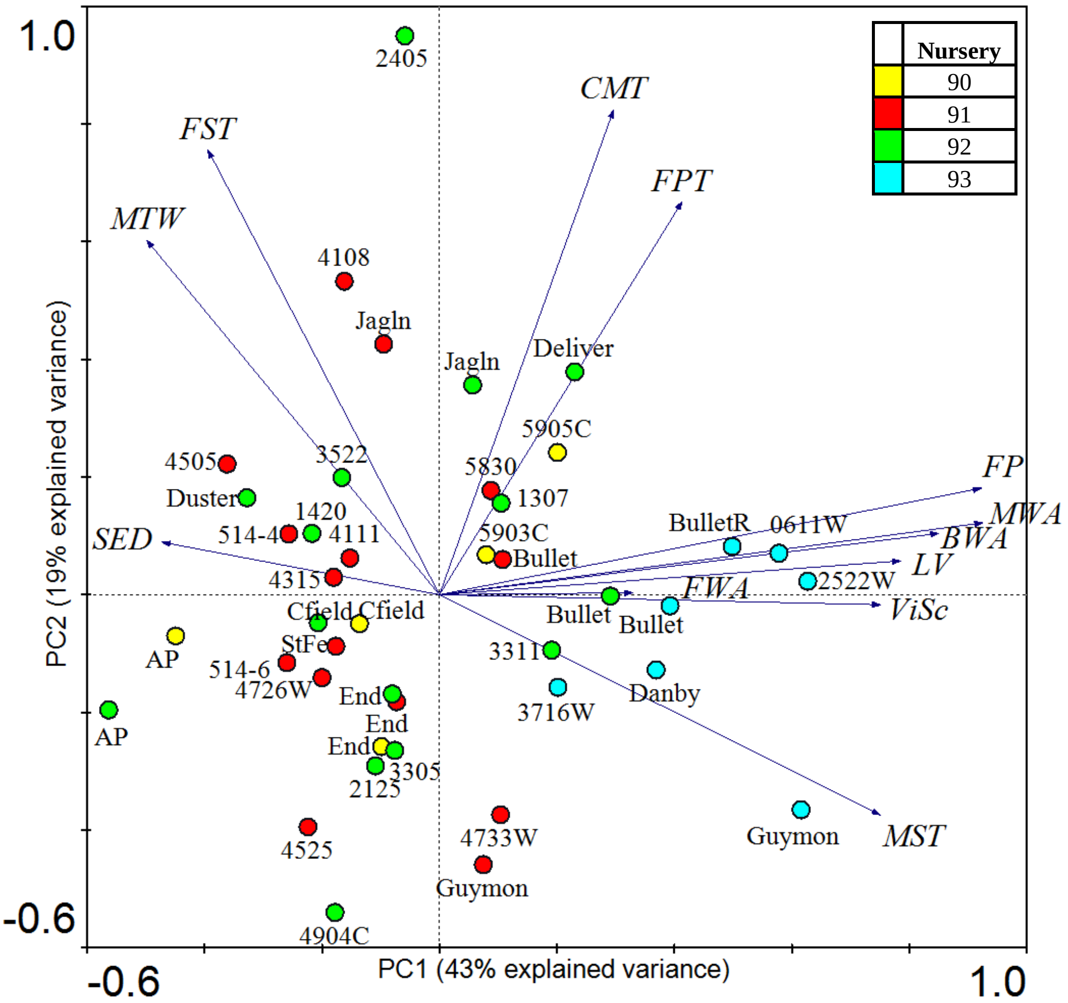


FIGURE 3

Non-adjusted PCA for TRAD methods of 2006 wheat varieties and breeder lines from four Oklahoma nurseries

(62% explained variance)

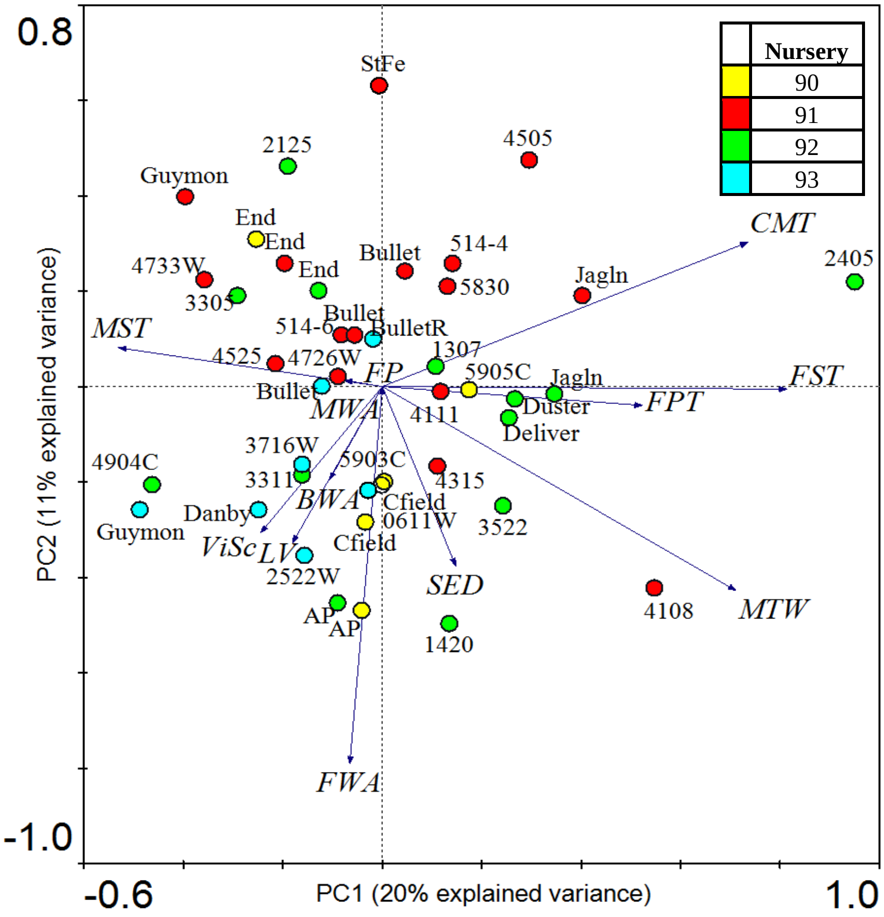


Abbreviations defined in Table 1 and 6.

FIGURE 4

Partial PCA for TRAD methods of 2006 wheat varieties and breeder lines from four Oklahoma nurseries

(49% explained variance)

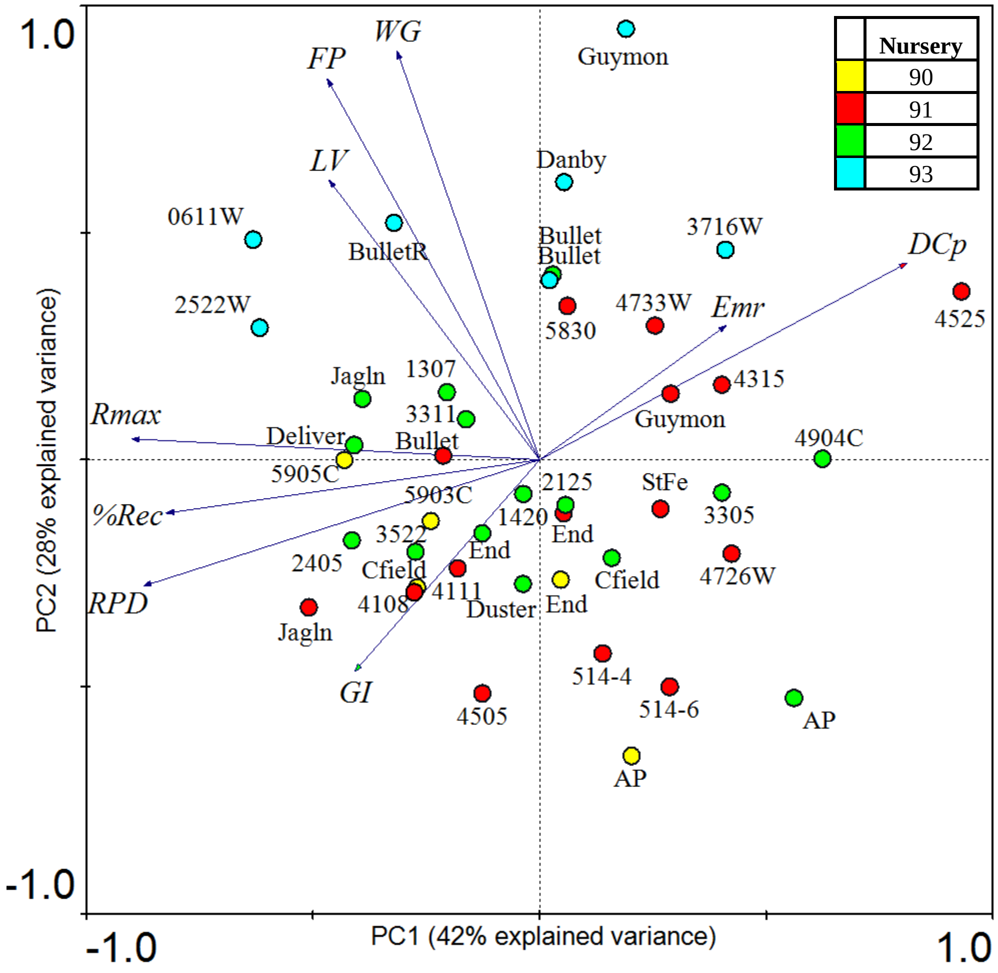


Abbreviations defined in Table 1 and 6.

FIGURE 5

Non-adjusted PCA for CREG methods of 2006 wheat varieties and breeder lines from four Oklahoma nurseries

(70% explained variance)

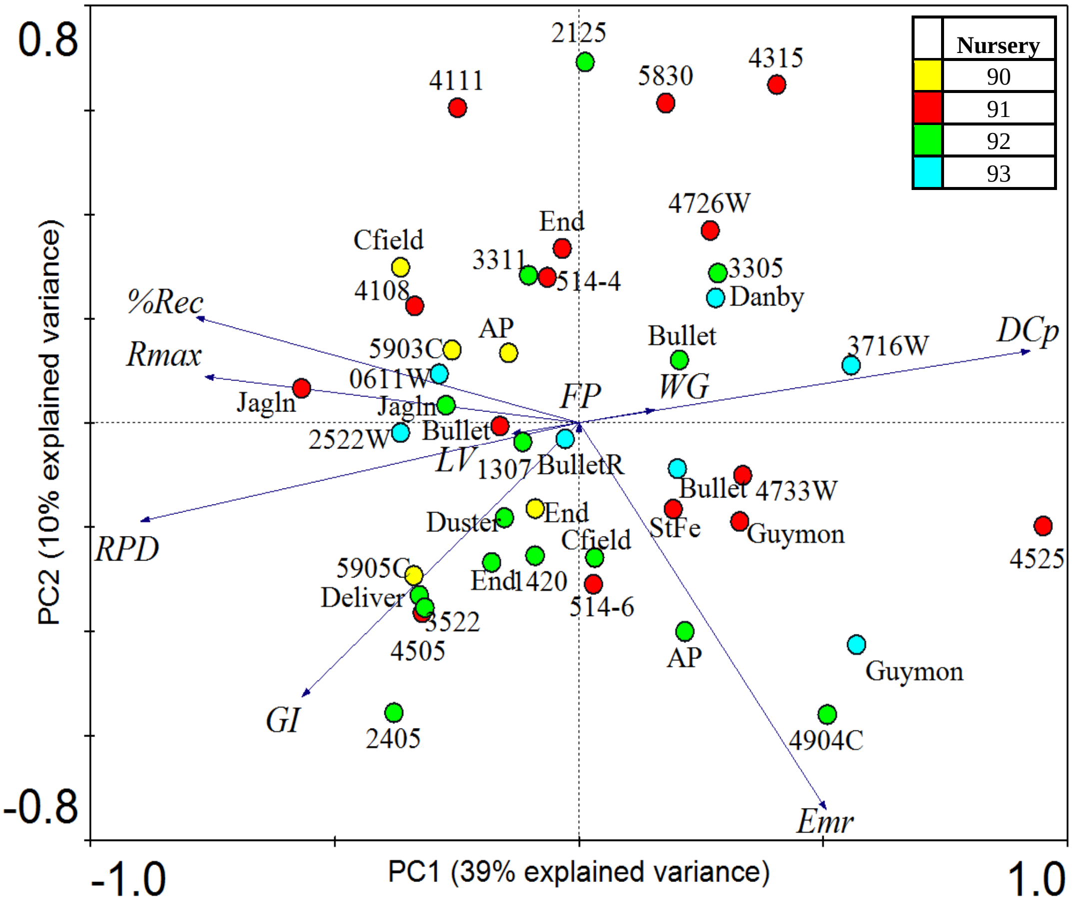


Abbreviations defined in Table 1 and 6.

FIGURE 6

Partial PCA for CREG methods of 2006 wheat varieties and breeder lines from four Oklahoma nurseries

(69% explained variance)

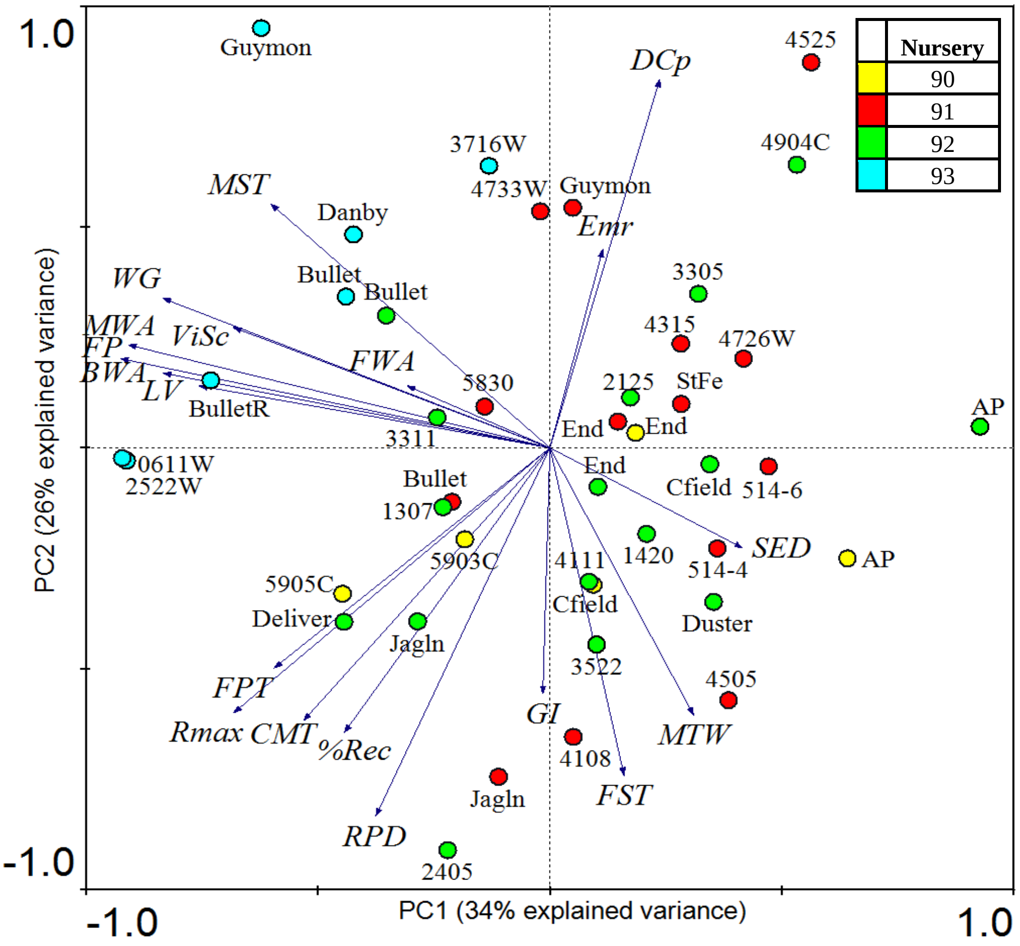


Abbreviations defined in Table 1 and 6.

FIGURE 7

Non-adjusted PCA for ALL methods of 2006 wheat varieties and breeder lines from four Oklahoma nurseries

(60% explained variance)

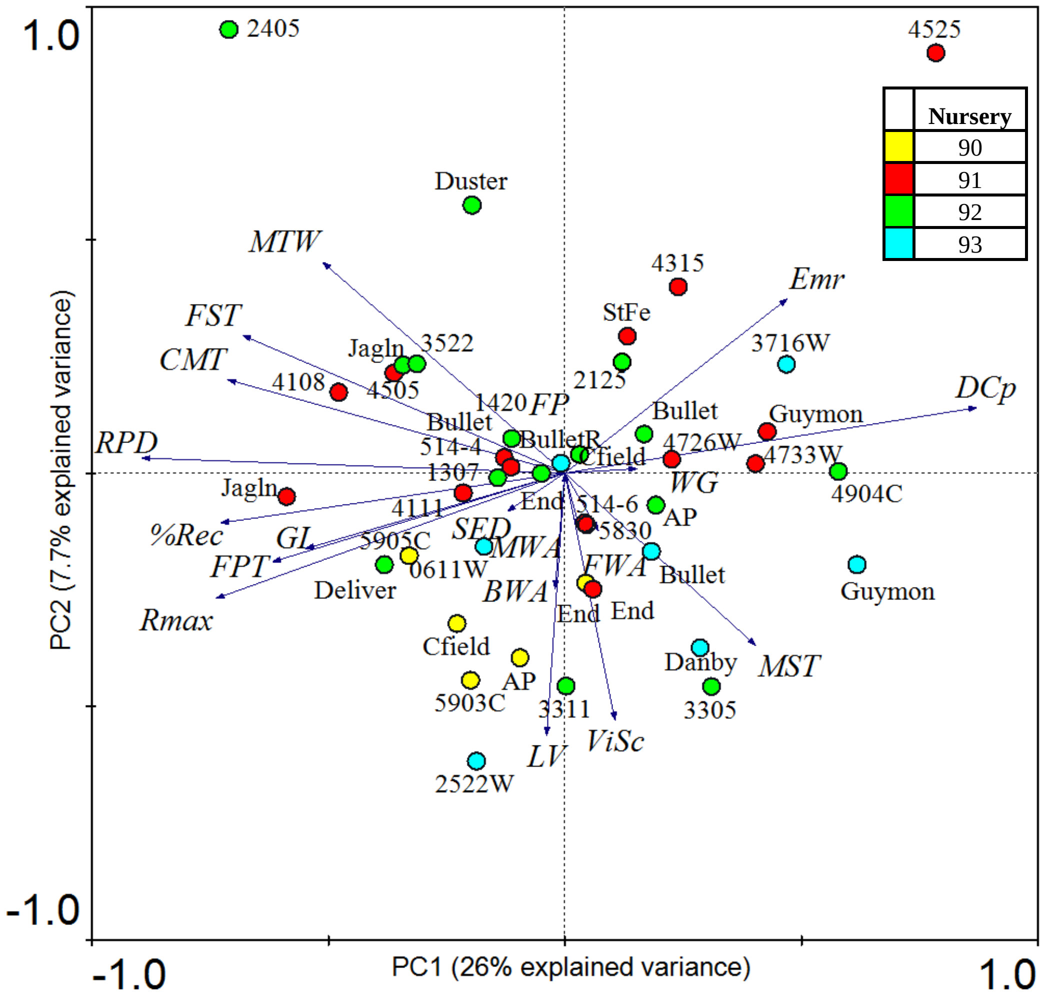


Abbreviations defined in Table 1 and 6.

FIGURE 8

Partial PCA for ALL methods of 2006 wheat varieties and breeder lines from four Oklahoma nurseries

(49% explained variance)

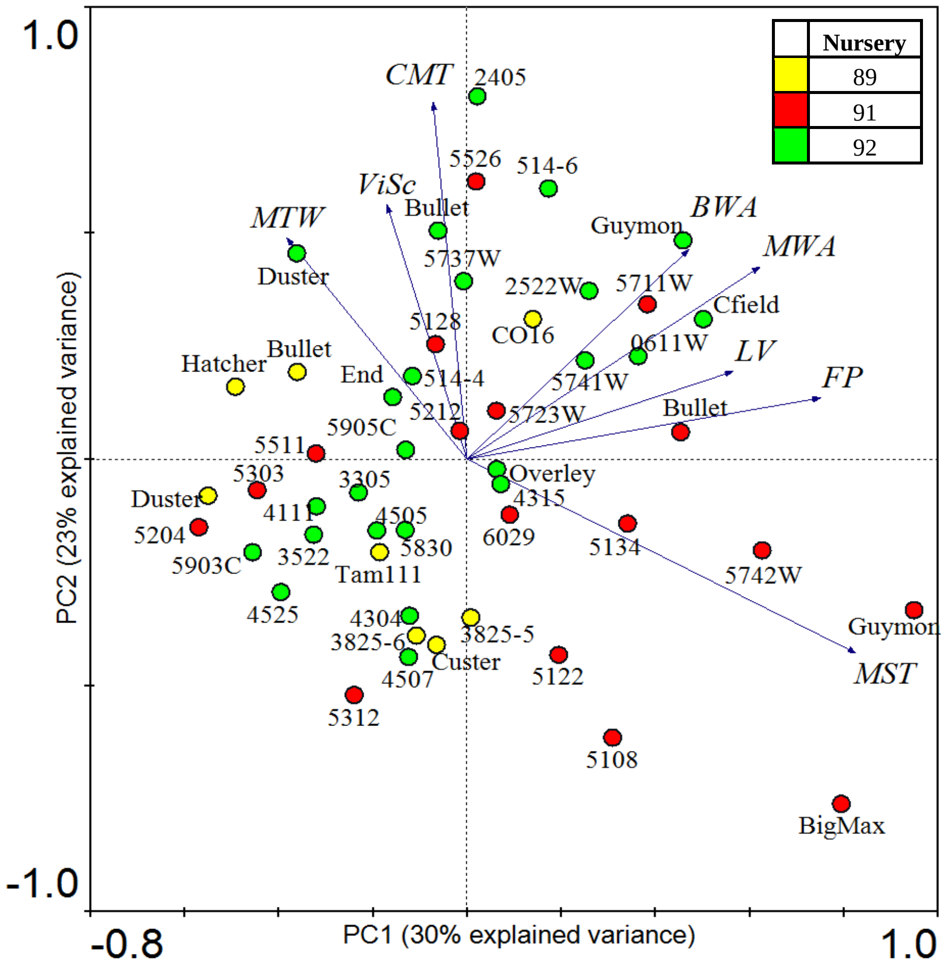


Abbreviations defined in Table 1 and 6.

FIGURE 9

Non-adjusted PCA for TRAD methods of 2007 wheat varieties and breeder lines from three Oklahoma nurseries

(52% explained variance)

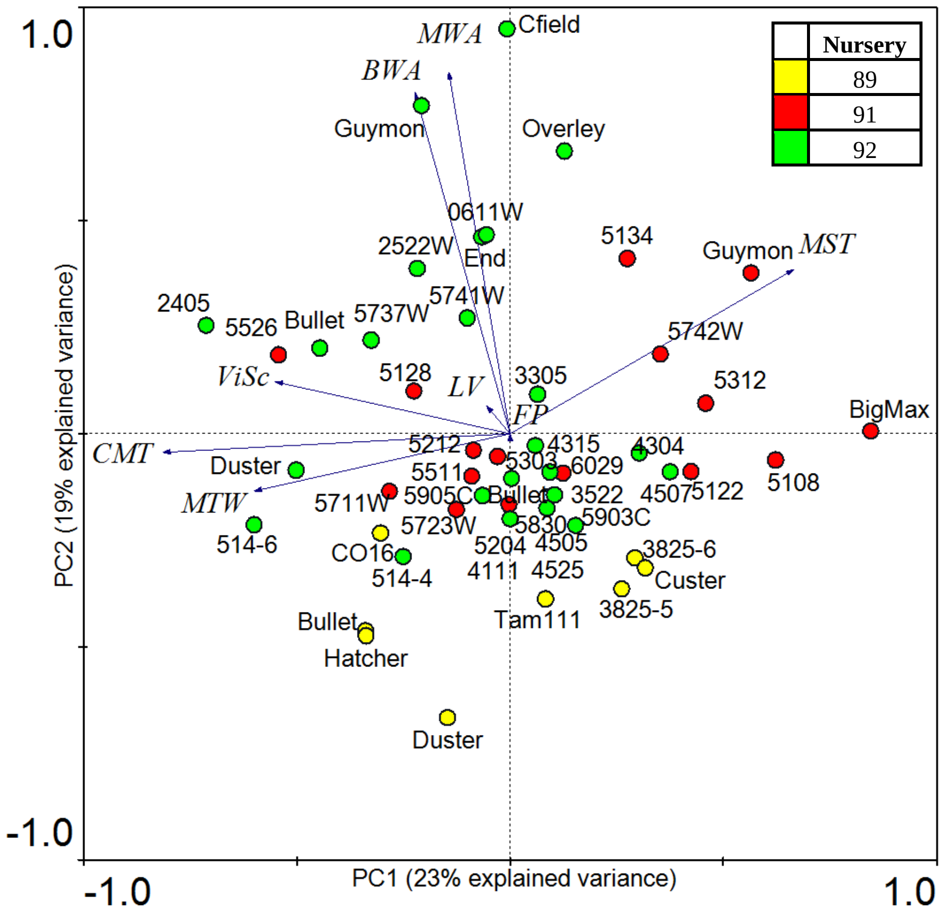


Abbreviations defined in Table 1 and 7.

FIGURE 10

Partial PCA for TRAD methods of 2007 wheat varieties and breeder lines from three Oklahoma nurseries

(54% explained variance)

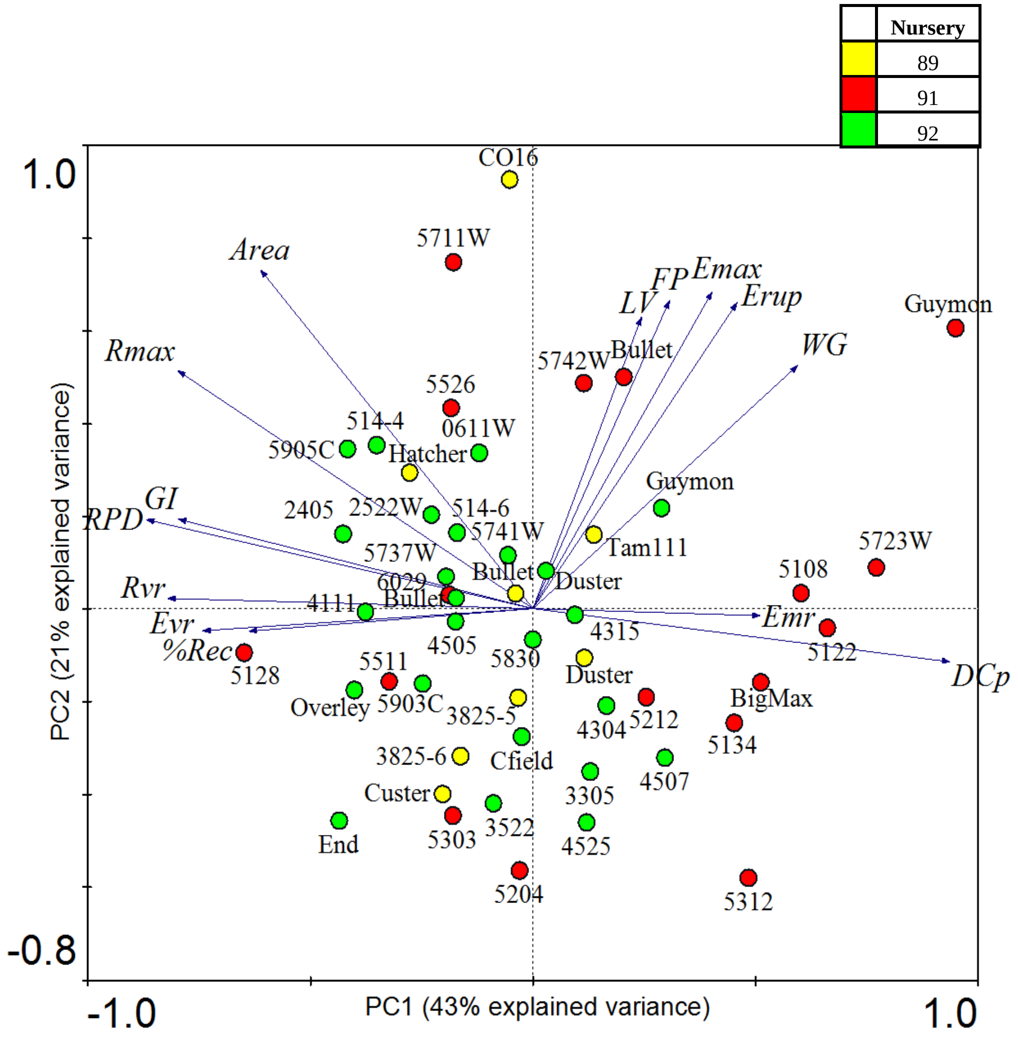


Abbreviations defined in Table 1 and 7.

FIGURE 11

Non-adjusted PCA for CREG methods of 2007 wheat varieties and breeder lines from three Oklahoma nurseries

(64% explained variance)

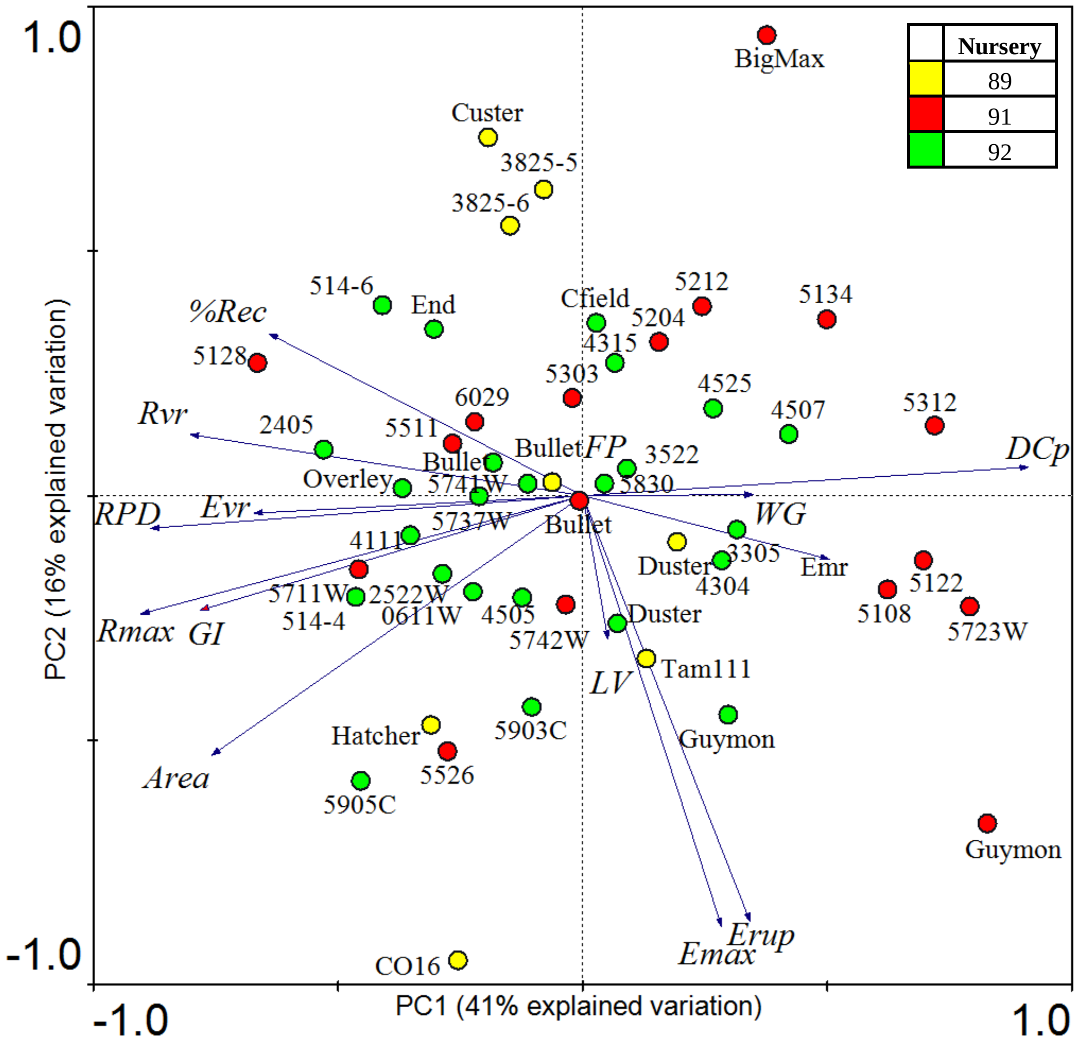


Abbreviations defined in Table 1 and 7.

FIGURE 12

Partial PCA for CREG methods of 2007 wheat varieties and breeder lines from three Oklahoma nurseries

(68% explained variance)

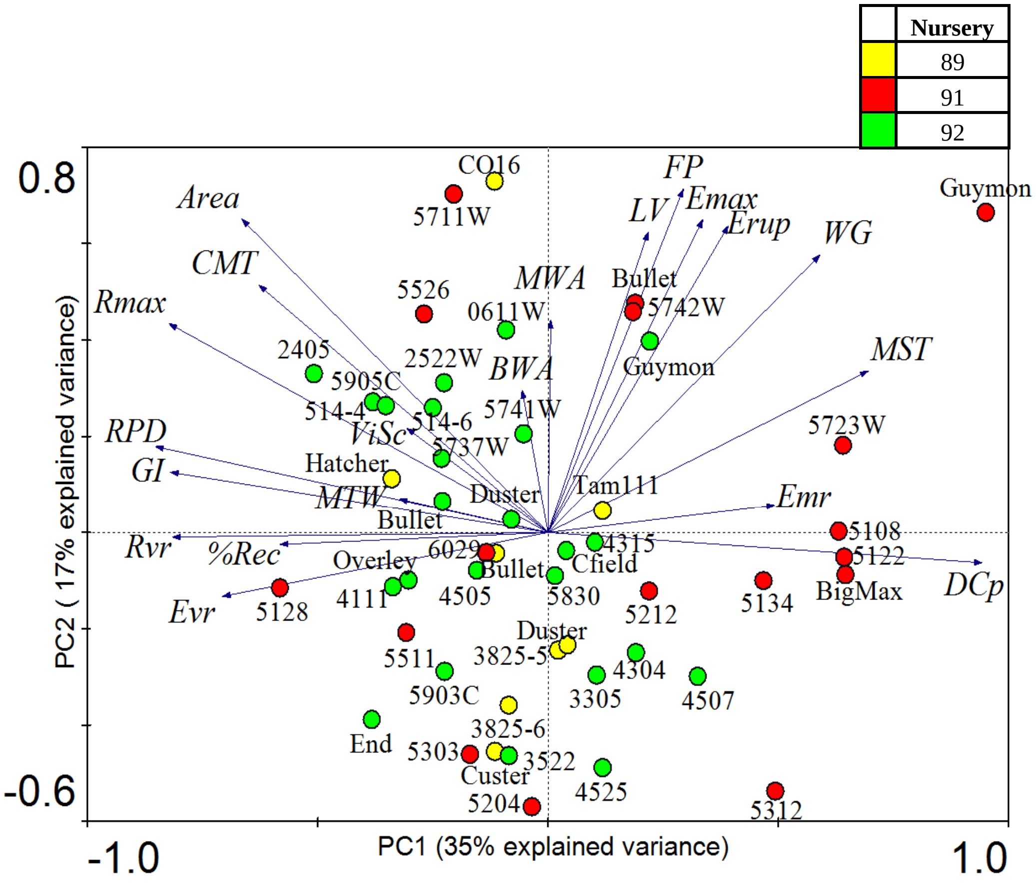


Abbreviations defined in Table 1 and 7.

FIGURE 13

Non-adjusted PCA for ALL methods of 2007 wheat varieties and breeder lines from three Oklahoma nurseries

(52% explained variance)

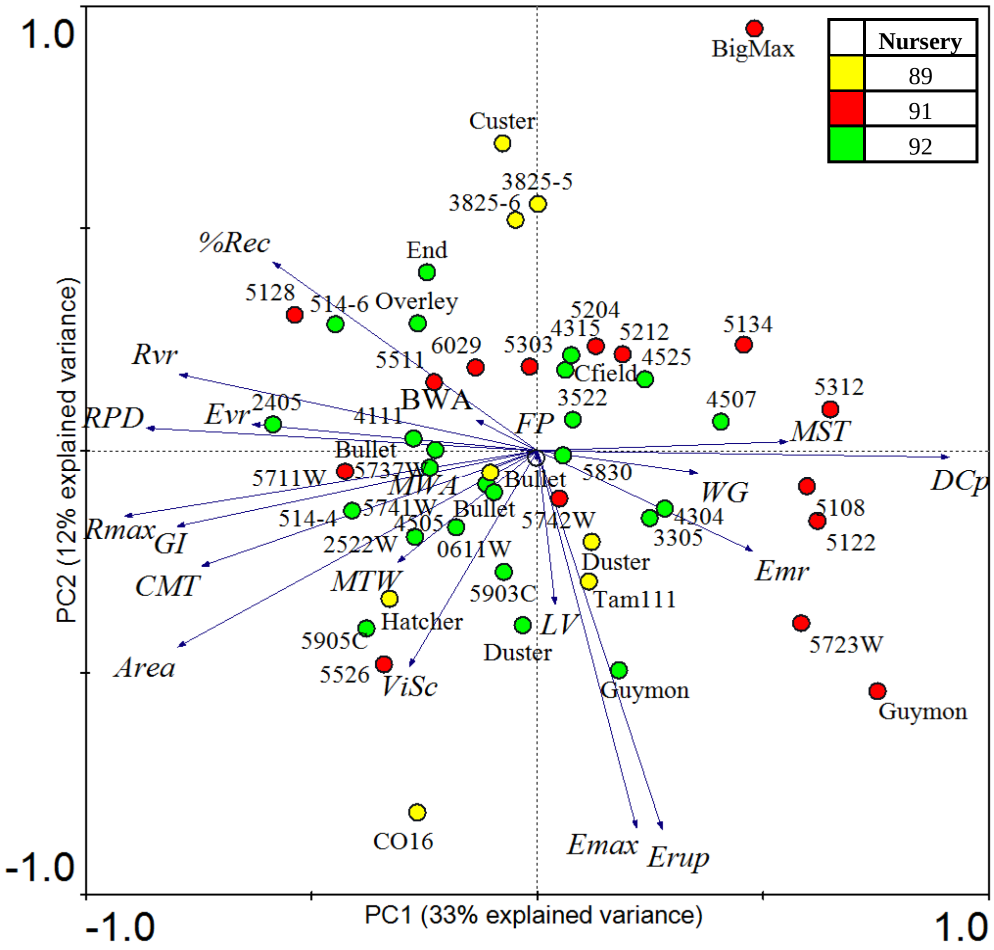


Abbreviations defined in Table 1 and 7.

FIGURE 14

Partial PCA for ALL methods of 2007 wheat varieties and breeder lines from three Oklahoma nurseries

(53% explained variance)

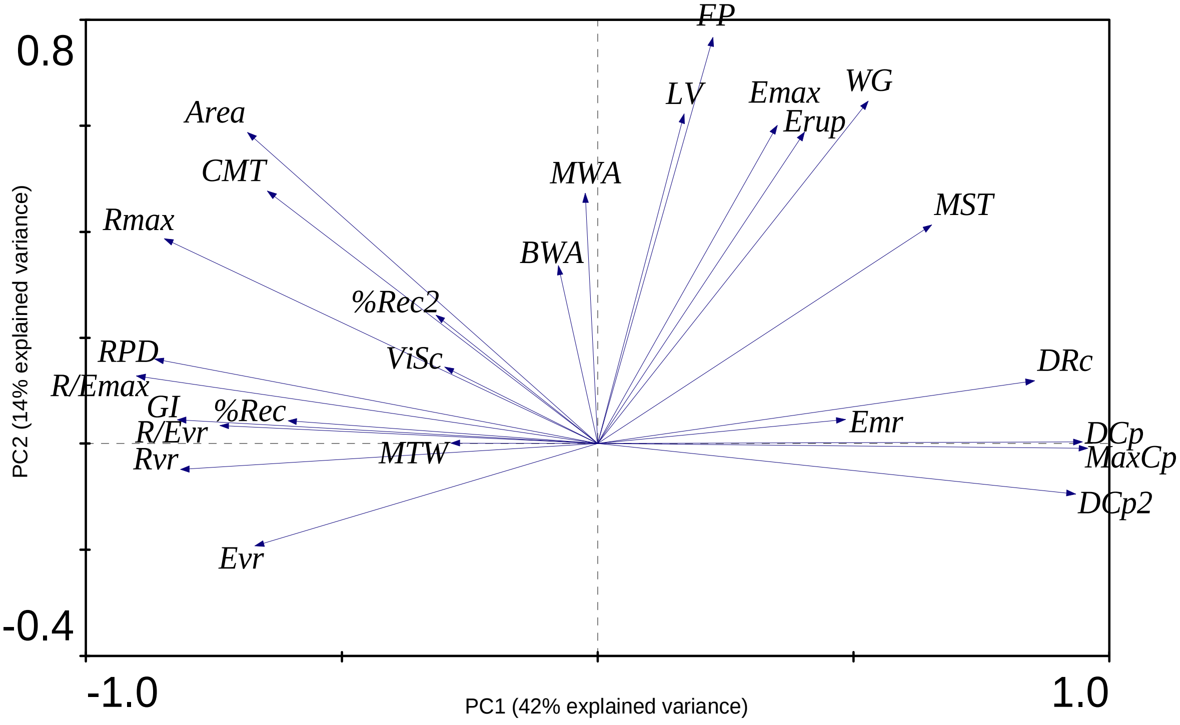


Abbreviations defined in Table 1 and 7.

FIGURE 15

Non-adjusted PCA for New Variables of 2007 wheat varieties and breeder lines from three Oklahoma nurseries

(55% explained variance)



Abbreviations: Evr: extensibility at initial viscoelastic response; Rvr: resistance at initial viscoelastic response; R/Evr: ratio of resistance over extensibility at the initial viscoelastic response; R/Emax: ratio of resistance over extensibility at the peak point; MTW: mixograph tail width; GI: gluten index; RPD: rubbery plateau departure time; %Rec: percent recovery (R100s/C100s); %Rec2: percent recovery (R1000s/C100s); ViSc: visual score; Rmax: dough resistance to extension at the maximum peak; CMT: mixograph mixing time; Area: total work required to extend the dough to Rmax; BWA: optimal baking water absorption; MWA: optimal mixograph water absorption; LV: bread loaf volume; FP: flour protien; Emax: extensibility at the maximum peak of resistance to extension; Erup: extensibility at the dough rupture point; WG: wet gluten; MST: mixograph stability; DRc: recover between R100s-R1000s; MaxCp: maximum creep compliance; DCp: Delta Compliance (C100s-R100s); DCp2: Delta Compliance at recovery steady state (C100s-R1000s); Emr: difference between Emax and Erup.

VITA

PauWei Yeap

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Master of Science

Thesis: COMPARISON OF RHEOLOGICAL PROPERTIES OF U.S. WINTER WHEAT CULTIVARS AND ADVANCED BREEDER LINES USING PRINCIPAL COMPONENT ANALYSIS

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Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: COMPARISON OF RHEOLOGICAL PROPERTIES OF U.S. WINTER WHEAT CULTIVARS AND ADVANCED BREEDER LINES USING PRINCIPAL COMPONENT ANALYSIS

Pages in Study: 84 Candidate for the Degree of Master of Science

Major Field: Food Science

Scope and Method of Study: Principal Component Analysis (PCA)

Findings and Conclusions:

Modern industrial bakeries and specialty baked products demand a balance of dough strength, extensibility and viscoelastic properties, which are accurate indicators of their machinability and baking performance. Two sets of U.S. hard winter wheats which included a total of 91 varieties and breeder elite lines from 2006 and 2007 crop years were subjected to a range of rheological tests. We included the separation of quality properties based on methods used traditionally (TRAD) in the wheat breeding program to estimate wheat protein quality versus three methods: Creep-Recovery, micro-Extension, and Glutomatic (CREG) analyses. The analyses performed were viscoelasticity, extensibility and mixing properties, wet gluten content, gluten index, sodium dodecyl sulfate (SDS) sedimentation and baking. Principal Component Analysis (PCA) which enabled us to see two-dimensional relationships in an otherwise complex, multi-dimensional data set, was used to compare the three CREG methods of quality assessment with the TRAD methods used in wheat breeding programs. Partial PCA with adjustment for protein content variation was performed to evaluate the extent of variation of each property as affected per protein unit. Both non-adjusted and adjusted PCAs for CREG methods give the best discrimination among the wheat cultivars by explaining the highest percentage of the sample variation (with an average of 70% in 2006 samples and 66% in 2007 samples). The non-adjusted and partial PCAs for TRAD and ALL (which included both TRAD and CREG testing methods) explained similar percent variance, with an average of 61% variance in non-adjusted PCA and 49% in partial PCAs for both testings. As for 2007 samples, the non-adjusted and partial PCAs for both TRAD and ALL testing methods explained an average of 53% variance. PCA performed for both traditional and CREG methods improved visualization of the interrelation between distinctive properties (variables) of wheat quality. It graphically depicts the wheat varieties and elite lines that are more closely or distantly related based on certain variables and can assist in predicting the usefulness of introducing new analytical tools to the breeding program.

ADVISER’S APPROVAL: Patricia Rayas Duarte