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Characterization of the end-use quality of soft wheat cultivars from the eastern and western US germplasm 'pools'

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Abstract

Soft wheat (*Triticum aestivum* L.) improvement could be enhanced by the identification of germplasm with superior end-use quality traits. Due to the geographic and historical separation of eastern and western US soft wheat germplasm 'pools', genetic differences in end-use quality may exist among cultivars arising from these two pools. To identify such differences, 30 US soft wheat cultivars were evaluated in 'head-to-head' trials over 3 years in Washington state. Cultivars were classified as: eastern soft red winter (SRW), eastern soft white winter (ESWW), western soft white (WSWW) and western Club. These four soft wheat cultivar classifications clearly differed systematically for some of the quality traits examined. The Club wheat cultivar group had the highest flour yield and flour ash. The Club group also had the lowest mixograph dough water absorption. Milling score (which incorporates break flour yield) was highest for Club and ESWW. Eastern soft red and white wheat cultivar groups had lower flour ash and alkaline water retention capacity (AWRC) compared to the western Club and soft white wheats; ESWW had the lowest AWRC of any classification. Cookie diameter was greatest for the ESWW group, followed by the SRW and Club groups (which were not significantly different), and then by the WSWW group. Individual cultivars with exceptional quality traits were also identified. These results indicate that the four US soft wheat germplasm pools differ, and they may be valuable genetic resources for 'inter-pool' wheat improvement.

Keywords: alkaline water retention capacity; ash; cookie; end-use quality; flour yield; milling; mixograph; soft wheat

Introduction

A vital aspect of efficient utilization of plant genetic resources is the characterization of traits or genes that different germplasms may contribute to the development of superior cultivars. In wheat (*Triticum aestivum* L.), milling and baking quality traits, or in other words specific end-use qualities, are critical considerations in the development of new cultivars.

In the USA, soft wheat has been produced traditionally in two divergent regions: the eastern US with production mostly east of the Mississippi River, or about 92°W longitude, and the Pacific Northwest (comprising the states of Washington, Oregon and Idaho). Because each of these regions has a long history of wheat cultivation and each

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is environmentally and geographically distinct, new cultivars have generally arisen from crosses made within each of the respective germplasm 'pools'. For example, Bacon (2001) indicated that in eastern US breeding programmes less than 10% of the germplasm used in crossing was derived from lines with 'specific traits, other US wheat classes and foreign germ plasm'. For these reasons, it is reasonable to assume that eastern and western US soft wheat cultivars might differ in their end-use quality due to differences in some unknown number of quantitative genetic factor(s). Further, individual cultivars or subclasses within a region may differ also. The extent to which commercial US soft wheat cultivars vary across or within regions is largely unknown.

Genetic comparisons of the end-use quality of different wheat germplasms is often hindered because grain samples are derived from different locations and/or crop years, i.e. quality is confounded with the effects of the environment. Consequently, direct comparison of germplasm requires that samples originate from plots grown under a uniform environment at the same site; and preferably multiple environments (including several geographic locations and crop years). Germplasms with specific qualities can thus be identified and used for improvement of wheat quality in crosses with elite breeding lines.

Some prior research on the end-use quality of US soft wheat germplasm has been conducted. Baenziger *et al.* (1985) compared the quality of 22 US soft wheat cultivars across 12 south-east US locations; cultivars represented 'much of the current elite and historic germplasm grown in the Southeast'. Cultivars with exceptional flour yield, Particle Size Index and alkaline water retention capacity (AWRC) were identified. Gains *et al.* (1996b) analysed nine eastern and six western US soft wheat cultivars grown together in a Washington state and a Michigan state environment. Their results indicated few consistent differences in kernel texture (grain hardness), whereas cookie diameter of eastern wheats was greater than western. Individual cultivars, however, were not compared. Yamamoto *et al.* (1996) compared 17 soft wheat cultivars representing four US market classes or sub-classes. Although individual cultivars were compared, samples came from two different crop years and four different US states. Consequently, cultivar responses were confounded with growing environment. Lin and Czuchajowska (1997) compared the quality of four Club and seven western soft white winter wheat cultivars grown at eight Washington state locations over three crop years. Cultivars were prominent in terms of commercial Pacific Northwest production. The Club group had harder kernels and higher Bühler flour yield and milling score compared to the soft white group. The two groups did not differ for Bühler break flour yield. Hazen *et al.* (1997) examined two soft white and three soft red eastern wheat cultivars. Some differences in flour yield and cookie diameter were found. Guttieri *et al.* (2001, 2002) examined the quality of Pacific Northwest soft white wheat cultivars in relationship to solvent retention capacities.

With this background, we formulated the following hypothesis: US soft wheat cultivars may differ in end-use quality due to genetic factor(s), and these factor(s) may vary among US soft wheat regions and/or subclasses due to the limited 'gene flow' between these germplasm 'pools'. To provide direct comparisons of the genetic component of eastern and western US soft wheat end-use quality, 30 cultivars representing four distinct classifications were grown 'side-by-side' in two replicate plots at two locations in each of three crop years in Washington state. A companion report will document differences in kernel texture among these samples (Campbell *et al.*, data not shown).

Materials and methods

Cultivars and grain production

Thirty cultivars were selected from the USDA Western Wheat Quality Laboratory's (WWQL) Hall-of-Fame nursery and were included in this research. Their release dates ranged from 1926 to 1998 (Table 1), and were fairly evenly distributed over time with eight cultivars released before 1970, five during the 1970s, eight during the 1980s and nine during the 1990s. Although not the primary purpose of this study, this distribution over time should provide broader interpretation of findings as well as some historical perspective. (NB. Quality data drawn from historical databases suffer the same confounding with environment as noted above.) The cultivars were all prominent and commercially grown on a significant area, and represented white Club, eastern soft red winter (SRW), eastern soft white winter (ESWW) and western soft white winter (WSWW) wheat classification groups. One cultivar, 'Pomerelle', is a western soft white spring wheat but it generally survives the winter in south-eastern Washington state so it was included in this research, and was included with the western soft white winter wheat classification group as a spring-type representative (note that the *Official United States Standards for Grain* (USDA, 1996) does not differentiate soft white spring and winter types in commerce). Although eastern and western soft white wheat are not separate market classes in the US grain marketing system, they were separated for the purposes of this analysis due to their historical and regional separation.

Table 1. Cultivars used to assess the end-use quality of eastern and western US soft wheat germplasm 'pools'

Cultivar	Classification[a]	Year of release	Identifier[b]	Developer[c]
Albit	Club	1926	CItr8275	WA
Elgin	Club	1942	CItr11755	OR
Elmar	Club	1949	CItr12392	WA
Hiller	Club	1998	PI587026	WA
Hymar	Club	1935	CItr11605	WA
Moro	Club	1965	CItr13740	OR
Omar	Club	1955	CItr13072	WA
Paha	Club	1970	CItr14485	WA
Rely	Club	1991	PI542401	WA
Tres	Club	1984	CItr17917	WA
Becker	SRW	1985	PI494524	OH
Coker 762	SRW	1980	CItr17924	–
Coker 9907	SRW	1991	PI548847	–
Dynasty	SRW	1987	PI506409	OH
FFR555W	SRW	1988	–	VA
Glacier	SRW	1991	PI555586	WI
Madison	SRW	1990	PI547041	VA
McNair1003	SRW	1977	PI552975	–
Pioneer 2568	SRW	1995	PI590943	–
Pioneer 2684	SRW	1993	PI566923	–
Roy	SRW	1979	CItr17763	NC
Geneva	ESWW	1983	PI505819	NY
Houser	ESWW	1977	CItr17736	NY
Yorkstar	ESWW	1968	CItr14026	NY
Brevor	WSWW	1949	CItr12385	WA
Hill 81	WSWW	1983	CItr17954	OR
Kmor	WSWW	1990	PI536995	WA
Lewjain	WSWW	1982	CItr17909	WA
Pomerelle	WSWS[d]	1996	PI592983	ID
Stephens	WSWW	1977	CItr17596	OR

[a]Classification: SRW, soft red winter; ESWW, eastern soft white winter; WSWW, western soft white winter; WSWS, western soft white spring.
[b]CItr and PI numbers refer to accession identifiers in the USDA-ARS National Plant Germplasm System, Germplasm Resources Information Network (GRIN).
[c]Developer identifies the state in which the state university Agricultural Experiment Station, frequently in conjunction with the USDA-ARS, released the public variety. Coker and McNair, and Pioneer are branded names of the Northrup King and Pioneer Hi-Bred International Inc. seed companies, respectively.
[d]For purposes of cultivar classification, Pomerelle soft white spring was grouped with the western soft white winter cultivars.

Seed was obtained from Dr Harold Bockelman at the USDA National Small Grains Collection in Aberdeen, ID, USA, the original source, or a state foundation seed programme. Original seed was grown in small field plots and rogued for purity for 1 year prior to inclusion in the Hall-of-Fame (HofF) nursery. HofF nurseries were planted at Pullman and Walla Walla, WA in 1997, 1998 and 1999, in a two-replicate randomized complete block design. Heading date, plant height, lodging, spring stand and stripe rust measurements were recorded. Harvested grain from each plot was cleaned using an 'air-screen' cleaner and a 600-g sample of the grain was used for the following end-use quality analyses.

Grain and flour analyses

Flour protein was determined by the Dumas combustion nitrogen method (Method 46-30) (American Association of Cereal Chemists (AACC), 2000) (model FP-428, Leco Corp., St. Joseph, MI) using ~0.25 g of sample, and multiplying N × 5.7. Wheat moisture was determined following Method 44-16 (AACC, 2000). Approximately 500-g samples were tempered to 13% moisture content and milled on a modified Quadrumat (C. W. Brabender Instruments, Inc., Hackensack, NJ) milling system following the method of Jeffers and Rubenthaler (1977). Break and straight-grade flour yields were calculated based on recovered products divided by total products, times 100. Milling score was calculated as: ({100 − (0.5 × [16 − temper level]) + (80 − flour yield) + (50 × [flour ash − 0.30])} × 1.274) − 21.602.

Flour ash was determined using Method 08-01 (AACC, 2000). AWRC was determined using Method 56-10 (AACC, 2000). Dough water absorption was measured using the 10 g mixograph (Method 54-40A) (AACC, 2000). Sugar-snap cookies were prepared using a modification of Method 10-52 (AACC, 2000). Modifications included increased $NaHCO_3$ (1.06% w/v in 'Solution A'), increased NH_4Cl (0.677% w/v in 'Solution B') and decreased NaCl (0.261% w/v in 'Solution B'). Top grain of cookies was scored using reference photographs and a scale of 0–10, with 10 indicating the greatest amount of 'islanding'.

Statistical analysis

The Levene test for variance heteroscedasticity (Schabenberger and Pierce, 2001) indicated that environments had significantly different error variances for most traits. Therefore the combined analysis of variance over environments was conducted using weighted least squares analysis of variance. The weighting factor was the reciprocal of the within-environment error variance. Least square means and standard errors were obtained for all traits and cultivars both within and over environments. The probability of a difference between two means was calculated. Within each classification, the number of cultivars that were examined was limited so all effects were fixed in the analyses of variance. Pearson product-moment correlations were determined on trait means both within and over environments. Biplot analysis of trait means within environments and over environments was conducted in order to better visualize patterns in end-use quality for the cultivars (Yan, 2001).

Results

Description of cultivars and classifications

The 30 cultivars included in this study (Table 1) were selected to represent those that have been typically grown in the eastern and western US soft wheat regions. They were also selected from the different US soft wheat market classes, sub-classes and geographical groupings. Soft white winter cultivars are grown in the eastern and western USA, SRW only in the east and Club only in the west. Cultivars were selected from four time periods relating to the last three decades and those released prior to 1970. The *Official United States Standards for Grain* (USDA, 1996) continues to use the botanical names *T. aestivum* L. and *T. compactum* Host. for common and Club wheats, respectively. The *Standards* further define two classes of soft wheat: soft red winter wheat and soft white wheat. There are no sub-classes in soft red winter wheat; soft white wheat has the sub-classes: soft white wheat, white Club wheat and western white wheat. The last of these three is simply a mixture of the other two. The standards do not differentiate eastern from western soft white wheat, nor western soft white winter from western soft white spring. In commerce, western soft white winter and spring wheat grain are routinely mixed; whereas eastern and western soft white wheat grain are rarely mixed due to their geographic separation. Western white wheat either results from farmers producing the two types together (usually by over-planting soft white spring into fields of winter-injured winter Club fields) or exporter blending to meet customer specifications. To avoid confusion, 'classification' is used here to designate the cultivar groupings, as opposed to 'class' which has a specific meaning in the *Standards*. It should be noted that the *Standards* provide no indication of milling or end-use quality *per se*, only that which has been traditionally associated with classes, sub-classes and grades (USDA, 1996).

Analysis of variance

Classification, which grouped cultivars according to their market class, sub-class or geographical location (eastern or western USA), was the most significant (greatest *F*-value) source of variation for milling quality (Table 2). Cultivar-within-classification was also highly significant and was the second most important source of variation. These results indicate that there were indeed meaningful genetic differences among classification groupings, as well as differences among cultivars bred for the same market class, sub-class or region. Although modest in magnitude, there were significant interactions with the environment for all the milling quality traits. Coefficients of variation (CV) were small, except that for flour ash; model R^2 values ranged from 0.86 to 0.93.

Flour protein, unlike milling, was highly influenced by the environment and to a markedly greater extent than the other sources of variation (Table 3). As observed in the previous traits, classification and cultivar-within-classification were also significant, as were the interactions with environment. For AWRC and mixograph water absorption, classification was the most significant source of variation, followed by cultivar-within-classification. For cookie diameter, environment, classification and cultivar-within-classification were all highly significant. Of particular interest to plant breeders, the

Table 2. *F*-values from combined analysis of variance for milling quality of eastern and western US soft wheat cultivars

Source	df	Flour ash	Flour yield	Milling score
Environment	5	6.56*	3.29	6.89*
Replicate (environment)	6	2.23*	11.09****	4.24***
Classification	3	90.12****	250.14****	15.02****
Cultivar (classification)	26	10.61****	41.38****	11.53****
Environment × Class	15	4.44****	16.89****	8.17****
Environment × Cultivar (classification)	130	1.96****	2.90****	1.82****
Error mean square	175	0.97	0.84	0.99
CV	–	271.09	1.34	1.17
R^2	–	0.86	0.93	0.88

*, **, ***, **** indicate the probability of a greater *F*-value at $P = 0.05$, 0.01, 0.001 and 0.0001, respectively.

Table 3. *F*-values from combined analysis of variance for flour protein, alkaline water retention capacity, mixograph water absorption and cookie quality of eastern and western US soft wheat cultivars

Source	Flour protein	AWRC	Mixograph water absorption	Cookie diameter	Cookie top grain score
Environment	142.51****	1.00	0.09	36.95***	13.74*
Replicate (environment)	1.51	3.91*	3.20*	1.25	0.70
Classification	23.01****	37.66****	23.29****	27.77****	3.49*
Cultivar (classification)	13.97****	5.95****	2.17**	9.60****	3.02****
Environment × Classification	4.87****	2.14	0.11	1.58	1.99*
Environment × Cultivar (classification)	2.19****	0.73	0.89	1.33*	1.19
Error mean square	0.83	1.17	0.99	1.03	0.94
CV	9.47	1.90	1.96	10.79	13.34
R^2	0.94	0.89	0.87	0.89	0.72

*, **, ***, **** indicate the probability of a greater *F*-value at $P = 0.05$, 0.01, 0.001 and 0.0001, respectively. Degrees of freedom for model components are the same as listed in Table 2.

interactions with the environment were of little relative importance to variation in cookie diameter. Variation in cookie top grain score was most highly significant for cultivar-within-classification, although variation among the six environments produced the greatest *F*-value. CVs ranged from 1.9 to 13.34; model R^2 values from 0.72 to 0.94.

Comparisons among cultivar classifications

In terms of milling quality, the Club classification group produced significantly the highest flour yield but also produced the highest flour ash content (Table 4). Milling score, which rationalizes yield and ash and incorporates break flour yield, was highest for the Club and ESWW groups. The SRW classification group of cultivars produced the lowest flour yield, but its lower ash content resulted in a higher milling score over that of the WSWW group.

Flour protein differed significantly but relatively little among the four classifications, varying from 0.2% to 0.7%. The two eastern soft wheat cultivar classifications had lower AWRC compared to those from the western USA, and the ESWW group was significantly lower than the SRW group. Between the two western soft wheat classifications, the Club group was 1.5% lower that the WSWW group. Mixograph dough water absorption ranged from 49.6% to 51.5% and was lowest for the Club classification group.

Cookie diameter was greatest for the ESWW group, followed by the SRW and Club groups (which were not significantly different), and then by the WSWW cultivar group (Table 5). ESWW cultivars also had the best top grain score (7.7, scale 0–10 with 10 highest), followed by the Club group, which was not statistically different.

Table 4. Mean separation of US eastern and western soft wheat cultivar classifications for milling quality

Classification	Flour ash (%)	Flour yield (%)	Milling score
Club	0.38 a	70.0 a	85.8 a
Soft red winter	0.35 c	67.4 c	84.9 b
Eastern soft white winter	0.35 c	68.1 b	85.7 a
Western soft white winter	0.36 b	67.8 b	84.3 c

Means followed by the same letter are not significantly different at the $P = 0.05$ level.

Table 5. Mean separation of US eastern and western soft wheat cultivar classifications for flour protein, alkaline water retention capacity, mixograph water absorption and cookie quality

Classification	Flour protein (%)	AWRC (%)	Mixograph water absorption (%)	Cookie diameter (cm)	Cookie top grain score
Club	9.6 a	57.4 b	49.6 c	9.41 b	7.3 ab
Soft red winter	9.4 b	56.2 c	51.3 b	9.42 b	7.0 b
Eastern soft white winter	8.9 d	55.1 d	50.7 ab	9.51 a	7.7 a
Western soft white winter	9.2 c	58.9 a	51.5 a	9.30 c	7.1 b

Means followed by the same letter are not significantly different at the $P = 0.05$ level.

Identification of exceptional cultivars

One of our primary interests was to compare the individual wheat cultivars as representatives of elite germplasm and identify cultivars with exceptional quality traits. Consequently, an ANOVA was conducted without the nested hierarchy of cultivar-within-classification. The lowest ash flour was produced from Dynasty (0.31%), followed by McNair 1003 (0.32%) and Roy (0.33%); these three cultivars were all SRW and comprised the lowest Duncan's multiple range test (DMRT) group. The first seven lowest ranked cultivars for flour ash were of eastern US origin. At the other extreme was Elmar (0.40%) and four other older Club cultivars (Elgin, Hymar, Paha and Omar, 0.40–0.39%). Those particular Club cultivars also tended to produce some of the highest flour yields: Paha, 71.0%; Elgin, 70.9%; Hiller, 70.8%; Omar, 70.6%; Hill 81, 70.4%; and Tres, 70.3% (members of the highest DMRT group). Notably Hiller, a recently released Club cultivar, and Hill 81, a WSWW, were present in the top DMRT group for flour yield. The lowest flour yield (64.0%) was obtained from McNair 1003, which was in a DMRT group by itself. The next lowest ranked cultivars were SRW Pioneer 2568 (65.7%) and WSWW Brevor (65.8%). Milling score was highest for Roy (89.0) followed by Geneva (87.7), and those two Eastern cultivars comprised the highest DMRT group. Hiller (87.0) and Paha (86.9) Clubs held the third and fourth ranks, respectively, for milling score. The bottom rankings were held by Brevor (82.3), McNair 1003 (82.3), Pioneer 2568 (82.4) and Stephens (82.5).

AWRC was lowest for Coker 9907 SRW (53.7%). Other members, in rank order, of that lowest DMRT group were Madison, Glacier, Yorkstar, Houser, Hiller, Dynasty and Geneva (range 54.0–55.8%). Other than the Club cultivar Hiller, all were from the eastern USA. The next lowest AWRC cultivar of western origin was Moro (56.5%). Stephens, an historically prominent WSWW, was alone in the highest DMRT group at 62.8%.

Mixograph dough water absorption was lowest for the Club cultivar Tres (48.4%) followed by the Club cultivars (in rank order) Paha, Rely, Moro, Hiller, Omar and Elgin. The next-ranked cultivar (and lowest among the eastern US wheats) was Houser (50.2%), followed by the older Club cultivars Elmar and Albit. Stephens had the highest mixograph dough water absorption at 52.4%.

The largest cookies were produced by Glacier (9.63 cm), Hiller (9.59 cm), Houser (9.55 cm) and Geneva (9.54 cm); those cultivars comprised the top DMRT group. Alone in the poorest cookie diameter DMRT group was Stephens at 9.02 cm. Notable were the next two lowest ranked cultivars, Hymar and McNair 1003 (9.22 and 9.23 cm, respectively). Cookie top grain score ranged from 8.25 for Paha down to 5.88 for Stephens. Cultivar mean top grain scores were poorly separated by DMRT and the model R^2 for this trait was only 0.67 in the non-nested design, compared to most other traits which were in the range of ~0.85–0.95.

Correlations among traits

Correlation coefficients among selected traits are presented in Table 6. Flour ash was highly correlated with flour yield ($r = 0.67$), but a plot of these variables (Fig. 1) indicated that individual cultivars deviated considerably from the least squares regression line, such that selection and genetic improvement could be realized (i.e. higher flour yield at lower ash levels). Club and WSWW cultivars were generally at or above the flour yield–ash least squares regression line, whereas those cultivars from the eastern USA were generally at or below this line. Overall, the regression relationship indicated an increase in 0.0087% ash per 1% increase in flour yield. Both flour yield and milling score were significantly correlated with break flour yield (data not shown). Indeed, variation in break flour yield among these soft wheat cultivars accounted for two-thirds ($r = 0.81$) of the variation in milling score.

AWRC was not correlated to milling performance nor flour protein. Mixograph dough water absorption was moderately and negatively correlated with milling performance parameters, primarily due to the influence of the Club cultivars. Club cultivars had low water absorption and very weak gluten characteristics. Mixograph water absorption was not correlated with AWRC or flour protein.

Table 6. Correlation coefficients (*r*) among end-use quality traits of eastern and western US soft wheat cultivars

	Flour ash	Flour yield	Milling score	Flour protein	AWRC	Mixograph water absorption
Flour yield	0.67 <0.0001					
Milling score	0.019 0.92	0.75 <0.0001				
Flour protein	0.12 0.51	−0.087 0.65	−0.19 0.31			
AWRC	0.12 0.53	−0.16 0.40	−0.33 0.078	0.17 0.38		
Mixograph absorption	−0.36 0.0503	−0.55 0.0016	−0.43 0.019	0.22 0.25	0.16 0.40	
Cookie diameter	−0.014 0.94	0.41 0.03	0.55 0.0016	−0.48 0.0074	−0.70 <0.0001	−0.31 0.095

The upper number is the coefficient (*r*), the lower number is the *P*-value (level of significance).

Cookie quality is of particular importance due to the emphasis it receives in soft wheat breeding and improvement. Flour ash was not correlated and flour yield was moderately correlated ($r = 0.41$) with cookie diameter, whereas milling score was highly correlated, explaining 30% of the variation. Upon further analysis, this relationship was seen to result from differences in break flour yield (data not shown), which provided an even better correlation with cookie diameter, explaining about 40% of the variation in cookie diameter. All but one of the cultivars that were above the grand mean for break flour yield (48.5%) were also above the grand mean for cookie diameter. This relationship between break flour yield and cookie diameter was essentially independent of market class, sub-class or geographic origin.

Flour protein was negatively correlated with cookie diameter (Table 6). Least squares regression calculated a decrease of 0.11 cm in cookie diameter with each 1% increase in flour protein. AWRC was the single most highly correlated parameter with cookie diameter and explained nearly 50% of the variation. A 0.043-cm increase in cookie diameter per 1% reduction in AWRC was observed (Fig. 2). Lastly, cookie top grain score was correlated with cookie diameter ($r = 0.61$). Top grain score correlations with other traits tended to follow those of cookie diameter.

Biplot analysis

A summary of the results is presented graphically in a biplot analysis (Fig. 3). To provide as complete an analysis as possible, kernel texture data (data not shown) were also included. Biplot analysis has the

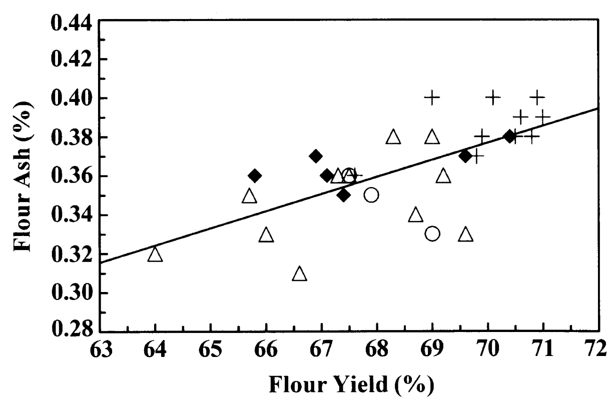

Fig. 1. Flour yield versus flour ash for 30 eastern and western US soft wheat cultivars representing four germplasm 'pool' classifications, and grown at two locations in each of 3 years in eastern Washington state. Data points are the mean of 12 observations; (+) soft white Club, (Δ) soft red winter, (O) eastern soft white winter, (◆) western soft white wheat cultivars. The least squares regression line is: ash = (0.00877 × flour yield) − 0.237.

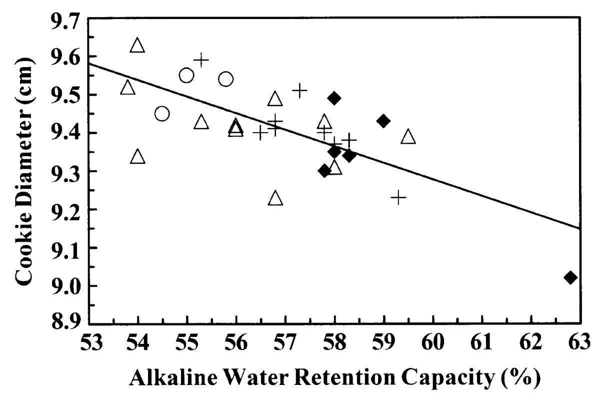

Fig. 2. AWRC versus cookie diameter for 30 eastern and western US soft wheat cultivars representing four germplasm 'pool' classifications, and grown at two locations in each of 3 years in eastern Washington state. Data points are the mean of 12 observations; (+) soft white Club, (Δ) soft red winter, (O) eastern soft white winter, (◆) western soft white wheat cultivars. The least squares regression line is: cookie diameter = (− 0.043 × AWRC) + 11.88.

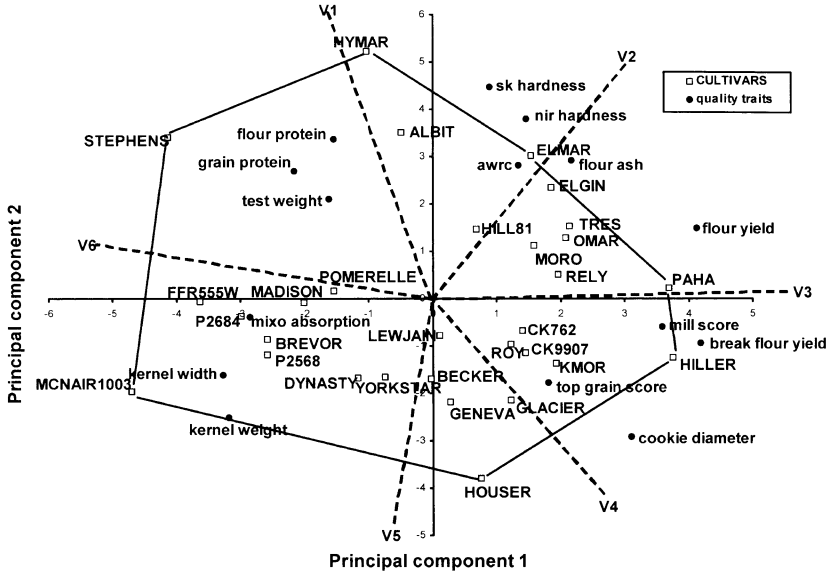

Fig. 3. Biplot of end-use quality for 30 eastern and western US soft wheat cultivars representing four germplasm 'pool' classifications. The results of principal components analysis of the matrix of quality trait means for each cultivar are graphed so that the eigenvalues of principal component 1 (*x*-axis) are plotted against those for principal component 2 (*y*-axis) (Yan, 2001). The correlation coefficient between any two traits is approximated by the cosine of the angle between their vectors. Cultivars can be compared by determining their position relative to each other and to a trait name (Yan and Rajcan, 2002). 'P2568', Pioneer 2568; 'P2684', Pioneer 2684; 'CK762', Coker 762; 'CK9907', Coker 9907.

advantage of describing multivariate relationships. The results of principal component (PC) analysis of the data were graphed so that the eigenvalues of PC1 were plotted against those for PC2 (Yan, 2001) for both the cultivars and for the quality traits. For the cultivars, PC1 and PC2 explained 32% and 28% of the variation, respectively, for a total of 60%. This value is moderate and reflects the complexity of the variation among traits. In the biplot, the correlation coefficient between any two traits is approximated by the cosine of the angle between vectors drawn from the origin to the trait. An angle of 180° is completely negatively correlated and an angle of 90° represents a correlation coefficient of 0. The biplot will differ from correlation analysis among pairs of traits because it is explaining interrelationships among all traits simultaneously (Yan and Rajcan, 2002).

The angle between break flour yield and flour yield is acute and the correlation between those two traits is $r = 0.72$. Cookie diameter and flour protein have an obtuse angle between their vectors and their correlation coefficient is $r = -0.48$. The angle of the vectors between single kernel characterization (SKCS) and near-infrared reflectance (NIR) kernel hardness indicates high correlation. In contrast, the *ca* 90° angle between SKCS and NIR kernel hardness vectors and the vector for break flour yield indicates a lack of correlation.

The distance from a cultivar to a trait name is an indication of the rank of that trait for that cultivar. Cultivars can be compared by determining their position relative to each other and to a trait name. For example, the Club wheat cultivars Paha and Hiller had high break flour yields and high milling scores. Omar also had high break flour yield but higher ash and lower cookie diameter than Hiller and Paha. Pioneer 2568 ('P2568') had high kernel weight as well as low kernel hardness values. The older club wheat cultivars Hymar and Albit as well as Stephens had high protein and all three produced the lowest cookie diameters in this set of cultivars.

A polygon is drawn around the biplot from the most extreme cultivar vectors. Vectors drawn from the origin and intersecting the polygon sides perpendicularly separate the data into groups based on their composite trait values. In the group with Hiller are the cultivars Kmor, Roy and the two Coker-derived soft red winter cultivars. This group had higher break flour yield and milling score, larger cookie diameter and greater cookie top grain score than other groups. In the group with Houser are the eastern soft white wheats plus the soft red winter cultivar Becker. This group had low kernel hardness and lower protein than other groups. Several soft red winter cultivars grouped with McNair 1003, all possessing high kernel weight and width (diameter), and low flour ash. The older club wheats grouped closer to Stephens and had high protein and test weight as well as low break flour and cookie diameter.

Agronomic traits

Major agronomic traits (heading date, plant height, lodging, spring stand and stripe rust reaction) were rated in order to determine if adaptation or lack thereof was biasing the results in this study. With the exception of heading date, which varied systematically among the four cultivar classifications, agronomic traits were not correlated with the quality traits within or over environments. Also, agronomic traits were not correlated among themselves (data not shown).

Discussion

Successful soft wheat cultivars must combine a large number of desirable traits which include yield (and its underlying components), resistance to multiple pests, adaptation to various abiotic stresses and weather conditions, agronomic production considerations and end-use quality. Due to the complexity of this situation and the very low probability of recovering superior genetic recombination in progeny, wheat breeders are often 'conservative' in the crosses (parent selection) that they make (Bacon, 2001). In other words, parents are usually recently released, successful cultivars or elite breeding lines from their own or closely related breeding programmes. Use of non-adapted germplasm generally carries with it the burden of many less desirable genes/alleles, which then must be selected against among progeny. Clearly the results presented here indicate that in terms of end-use quality traits, the four discrete US soft wheat germplasm 'pools' carry different genetic factors.

Soft wheat cultivars of eastern origin differed from those of western origin, particularly the Club wheat group. Club wheat cultivars had higher flour yield but higher flour ash, higher break flour yield, harder kernel texture, smaller kernels and lower dough water absorption (Tables 4 and 5; Fig. 1; data not shown). It seems that the endosperm properties and therefore the texture and milling performance of this germplasm 'pool' differs. Club cultivars have also been purposefully selected for low dough water absorption (Table 5) in combination with very weak gluten mixing properties. On a longer-flow mill (Bühler), Lin and Czuchajowska (1997) found that break flour yield of Club cultivars was similar to WSWW.

Cultivars from the two eastern US soft wheat germplasm 'pools' (SRW and ESWW) had significantly softer kernel texture than the western cultivar classifications (data not shown), and produced lower ash flours (Table 4). Overall milling performance of eastern US cultivars was not particularly noteworthy and individual cultivars tended to perform at or below the flour yield–flour ash regression (Fig. 1). Eastern cultivars had significantly lower AWRC, considered a key quality trait for soft wheat where many foods are slightly alkaline due to chemical leavening agents and where low hydration characteristics are desirable. The ESWW group was notably the lowest of all classifications for AWRC. Optimum water absorption in developed doughs is different from the capacity of flours to retain alkaline solution. The 10-g mixograph was employed to measure dough water absorption in the present study. As noted above, mixograms showed that Club cultivars have very weak gluten properties and the lowest water absorption of the various classifications. The low dough water absorption of the Club group contrasted the WSWW which had the highest absorption. This difference may justify the continued separation of these two sub-classes in the *Standards* (USDA, 1996) as they are both white winter wheats grown in the same region. Club wheat cultivars also appear to be more uniform in their quality attributes, and considering their early history of being developed via backcrossing for pathogenic fungi resistance, and their more rigorous selection for quality, this result is not surprising.

Cookie diameter has long been the primary 'bake test' criterion for end-use quality in the two US soft wheat regions. Germplasm and cultivars with larger cookie diameters are considered to be superior in a wide range of soft wheat uses. ESWW performed the best, whereas WSWW performed the poorest. This difference highlights one of the consistent differences among the eastern and western germplasm 'pools'. SRW and Club performed equally for cookie diameter, although they would rarely, if ever, be interchanged in US domestic end-uses; essentially 100% of all US Club production is exported. The best predictor of cookie diameter among this set of cultivars was AWRC (Table 6; Fig. 2). Again, cultivars of the ESWW classification exhibited lowest AWRC and largest cookie diameter.

Beyond the fact that the four cultivar classifications clearly differed genetically, differences were also resolved among cultivars within each of the classifications. For straight-grade flour yield, individual Club wheat cultivars held the first eight of nine rank positions, and only the two oldest Club cultivars, Albit and Hymar, were not present in this top group. Noteworthy was the lowest flour yield cultivar, McNair 1003, which was significantly worse than all other cultivars and in a DMRT group by itself, but which possesses a unique kernel texture which is softer than all 29 other cultivars (data not shown). Among the 22 eastern soft winter wheat cultivars examined by Baenziger *et al*. (1985), McNair 1003 exhibited the softest kernel texture based on Particle Size Index, but also the lowest flour yield. Coker 9907 SRW had the lowest AWRC; nine of the lowest 10 ranked cultivars for AWRC were from the eastern region. Hiller, a recently released Club cultivar, was lowest of all western soft wheats. The lowest AWRC WSWW was the spring cultivar Pomerelle. Guttieri *et al.* (2001, 2002) conducted extensive studies of western soft white spring wheat cultivars, including Pomerelle. In the present study, all of the western soft white winter cultivars clustered near the high-end of the AWRC range. AWRC, then, appears to be a notable difference between eastern and western soft winter wheat germplasm 'pools'. Bassett *et al.* (1989) found that Stephens had the lowest AWRC of the four cultivars examined in their study. In contrast, our study indicated that Stephens was genetically distinct and inferior for AWRC. The top four cultivars and members of the top DMRT group for cookie diameter were, in rank order, Glacier SRW, Hiller Club, Houser ESWW and Geneva ESWW. The best performing WSWW was Kmor at rank position eight. Noteworthy were the three poorest cookie 'performers', Stephens, Hymar and McNair 1003. Bassett *et al.* (1989) reported that Lewjain produced the largest cookie diameter among a few WSWW, but it did not distinguish itself here where there were many more cultivars of high quality. In Hazen *et al.* (1997) the cultivars Augusta and Chelsea baked the largest cookies. We plan to include these two cultivars in future WWQL HofF nurseries.

Several correlations observed in this study are worthy of discussion. Break flour yield was found to be a relatively good predictor of cookie diameter (Table 6). The break flour yield–cookie diameter relationship appears to hold true over a range of cultivars within each of the four classifications. Whether higher break flour yield itself confers larger cookie diameters, say, through reduced starch damage or slightly different particle size distribution is unknown. It is plausible that higher break flour yield and larger cookie diameter are both manifestations of the same underlying macromolecular differences; for example, differences in pentosan content or composition (Bettge and Morris, 2000). As noted above, AWRC had the highest correlation with cookie diameter (Table 6), but surprisingly was not significantly correlated with break flour yield. There was no significant correlation between AWRC and mixograph absorption (Table 6). One test assesses retention of alkaline solution and the other the optimum absorption of a developed dough. Consequently, the relevance that each has to predict flour performance in specific end-uses is open to more research or empirical association. It may be desirable to enhance the very low dough water absorption of Club wheat cultivars with lower AWRC or other solvent retention capacities (Guttieri *et al.*, 2001, 2002).

In conclusion, four distinct germplasm 'pools' of soft wheat cultivars exist in the USA and each differs somewhat in specific soft wheat quality traits. Additionally, individual cultivars were shown to differ within a classification. Some of these cultivars will prove useful as sources of exceptional quality traits and research material, and may 'enrich' the germplasm 'pools' of other regions, classes or sub-classes.

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