Assessing Environmental Influences on Solvent Retention Capacities of Two Soft White Spring Wheat Cultivars

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ABSTRACT

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The solvent retention capacity test (SRC) (AACC Approved Method 56-11) of flour is used to evaluate multiple aspects of wheat (*Triticum aestivum* L.) quality including pentosan content, starch damage, gluten strength, and general water retention based on the ability of flour to retain a range of solvents. The objectives of this study were to evaluate the effects of grain production environment in general and crop irrigation and fertility management in particular on SRC of soft wheat flour, and to evaluate the ability of SRC to predict end-use quality across diverse environments. Two soft white spring wheat cultivars ‘Pomerelle’ and ‘Centennial’ were produced in a range of irrigated and rain-fed production environments. SRC profiles and milling and baking quality parameters were measured. In a two-year study at Aberdeen, ID, with two late-season irrigation management regimes and two crop nitrogen fertility treatments, only wheat genotype significantly affected flour SRC. In two-year studies at Tetonia, ID, one conducted under rain-fed conditions and the other under irrigation, additional fertilizer applied at anthesis did not affect SRC. Correlations among quality parameters were determined using the Aberdeen and Tetonia flour samples, as well as samples of the same genotypes grown in fertility trials under rain-fed conditions at Havre and Bozeman, MT, and under irrigation at Bozeman. Patterns of correlations among SRC values were similar for both genotypes. Grain test weight was negatively correlated with sodium carbonate and sucrose SRC of both genotypes. Flour protein was strongly positively correlated with sucrose and lactic acid SRC of both genotypes. The optimal regression models for predicting sugar snap cookie diameter (AACC Approved Method 10-52) as a function of protein, SRC, flour extraction, and kernel hardness were different for the two cultivars. SRC evaluations of flours from these trials were consistent with large genotype and environment effects, yet minimal genotype × environment interaction. This suggests that selection among genotypes within an environment will produce a gain-from-selection observable in multiple and diverse environments.

The solvent retention capacity (SRC) test is a relatively new (Approved Method 56-11, AACC 2000) method for evaluating soft wheat quality (Slade and Levine 1994; Gaines 2000). The test measures the ability of flour to retain a set of four solvents (water, 50% sucrose, 5% sodium carbonate, and 5% lactic acid) after centrifugation. Retention of these solvents produces a practical flour quality functionality profile for predicting commercial bakery performance. Generally, lactic acid SRC is associated with gluten strength, sodium carbonate SRC is associated with levels of damaged starch, sucrose SRC is associated with pentosan and gliadin content, and water SRC is influenced by all of these flour constituents (Gaines 2000).

Desirable cookie and cracker flours hold water poorly (Faridi et al 1994). When flour holds water poorly, more water is available to the sugar to form syrup. Thus, dough viscosity decreases during baking and the dough spreads farther, producing larger diameter cookies (Slade and Levine 1994). Flours with high water retention require increased baking times in cookie and cracker manufacturing, which produces a less tender product and increases energy costs in bakeries.

Damaged starch absorbs much more water than undamaged starch. Increased damaged starch increased sugar snap cookie dough stiffness and decreased cookie diameter (Gaines et al 1988). Pentosans are highly hydrophyllic, absorbing as much as 10× their weight in water (Kulp 1968; Jelaca and Hlynka 1971). Water soluble and total pentosan content have been correlated with smaller cookie diameter and cake volume across a range of production environments (Kaldy et al 1991). Therefore, low sodium carbonate SRC and low sucrose SRC flours are desirable for confectionary products.

Within irrigated production environments in Idaho, SRC effectively differentiated 26 soft white spring wheat genotypes into groups of similar end-use quality with very limited genotype × environment interaction (Guttieri et al 2001). Taken together, flour protein content and sucrose SRC effectively predicted sugar snap cookie diameter (AACC Approved Method 10-52). Flour extraction and sodium carbonate SRC were negatively correlated, and whole grain hardness measurements were correlated with sucrose and sodium carbonate SRC. Multivariate analysis clustered the 26 genotypes into groups of similar quality.

Studies of soft winter wheats have demonstrated that physical and chemical properties of wheat flours are influenced both by grain production environment and by genotype (Lin and Czuchajowska 1997). Gaines et al (1996) noted that climatic conditions during grain production had a greater impact on soft wheat flour quality than the genotype of the winter wheat. Similarly, sugar snap cookie diameter of soft spring wheats grown under semi-arid or high precipitation conditions was affected predominately by grain production environment, although significant cultivar and cultivar × environment interaction effects were observed (Mikhaylenko et al 2000). Soft spring wheat produced in the semi-arid environment had higher flour protein content, stronger gluten, and greater mixograph water absorption, and produced smaller diameter cookies than soft spring wheat produced in the high-precipitation environment.

The objective of this study was to further assess environmental influence on SRC and its relationship to soft spring wheat functionality by expanding the set of observations from irrigated locations used for our previous study of SRC of soft spring wheats (Guttieri et al 2001) to include rain-fed and irrigated trials in contrasting environments within Idaho and Montana. The growing environments were further modified by including late season nitrogen fertilization and moisture regime treatments.

MATERIALS AND METHODS

Grain Production

Two soft white spring wheat cultivars, Centennial and Pomerelle, were grown in replicated yield trials at Aberdeen and Tetonia, ID, in 1999 and 2000, and in Bozeman and Havre, MT, in 2000. Pomerelle and Centennial were included in previous SRC research (Guttieri et al 2001). Based on multivariate analysis, the two lines had acceptable yet distinctive soft wheat quality. Centennial had harder grain and greater gluten strength than Pomerelle.

Trials at Aberdeen were uniformly fertilized before planting to provide 0.03 kg of N/ha (residual + applied) per kg/ha target yield, based on Kephart et al (1991). The trial was arranged as a randomized arrangement of a split-split plot design. Main plots were irri-

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gation treatments: full-season sprinkler irrigation to replace 100% of estimated evapotranspiration, and irrigation to replace 100% of estimated evapotranspiration until the crop reached one week post-anthesis, at which point irrigation was terminated. Within these main plots of irrigation treatment, subplots of top-dress fertilizer application were applied at anthesis (0, 44 kg/ha). Within these subplots of top-dress fertilizer application were sub-subplots of each cultivar (Centennial, Pomerelle).

Two trials were conducted at Tetonia and Bozeman. In each location, one trial was conducted with sprinkler irrigation to replace 100% of estimated evapotranspiration, and the other trial was conducted without supplemental irrigation using overhead sprinklers. The trial at Havre was rain-fed. Within moisture regimes in each environment, two levels of fertilization were applied, 100 and 70% of recommended N (0.04 and 0.03 kg of N/ha [residual + applied] per kg/ha target yield) based on historical grain yields. Preplant fertilizer was uniformly applied according to soil test recommendations. The high fertility treatments received an additional top-dress application of fertilizer when the wheat was at the jointing stage.

Grain was harvested using a small-plot combine and cleaned. Test weight was recorded and single kernel characteristics were determined (SKCS, 4100, Perten Instruments, Springfield, IL).

Milling and Baking Analyses

Grain from two replicates of the Aberdeen, Tetonia, and Bozeman trials and three replicates of the Havre trial was evaluated. Samples were tempered (Approved Method 26-10, AACC 2000) and milled (Approved Method 26-21A). Flour protein concentration was determined with a near-infrared analyzer (Approved Method 39-10A), calibrated by automated combustion analysis of total nitrogen content (model NFP-428, Leco, St. Joseph, MO), and corrected to 12% moisture. Sugar snap cookies were prepared and evaluated (Approved Method 10-52).

SRC Evaluation

Solvent retention capacity evaluations were conducted on each flour sample as described in Approved Method 56-11, with minor modifications as described in Guttieri et al (2001).

Statistical Analysis

The Aberdeen trials were analyzed by a mixed effects analysis of variance (Steele and Torrie 1980) using PROC MIXED in SAS (v. 8.01, SAS Institute, Cary, NC). Year interactions, where they were observed, were limited, therefore the analysis was combined over years with year and replicate as random effects and irrigation, fertility, and cultivar as fixed effects. Irrigated and rain-fed Tetonia trials were analyzed independently by mixed effects analysis of variance using PROC MIXED in SAS. Year interactions in the Tetonia trials, where they were observed, were nonsevere (did not alter treatment rankings), therefore analysis was combined over years with year and replicate as random effects, fertility and cultivar as fixed effects.

To assess general production environment effects on SRC and genotype × environment interaction, the nine trials (Aberdeen 1999, Tetonia irrigated 1999, Tetonia rain-fed 1999, Aberdeen 2000, Tetonia irrigated 2000, Tetonia rain-fed 2000, Bozeman irrigated 2000, Bozeman rain-fed 2000, and Havre rain-fed 2000) were analyzed by a mixed effects analysis of variance. Trial environment and cultivar were treated as fixed effects, and rep, the rep(× env) interaction, and the rep × cult (× env) interaction as random effects. Fertility treatments were not specified in the model, as they did not have significant effects on quality parameters, therefore there were two observations per replicate. The rep(× env) error was used to test the significance of environmental effects, and the rep × cult (× env) error was used to test the significance of cultivar and cultivar × environment interaction effects.

Pearson's linear correlation coefficients among quality parameters were calculated using PROC CORR in SAS. Regression analyses were conducted using PROC REG in SAS. Heterogeneity of slope was evaluated using PROC GLM in SAS, by testing for the interaction of the class variable, cultivar, with the dependent variable.

Multiple regression was conducted with cookie diameter as the dependent variable. Independent variables were selected on the basis of their ability to optimize the R^2 value of the model. Regression models were selected using the Mallows $C(P)$ statistic, identifying models for which $C(P)$ approximated $(p+1)$, where p is the number of independent variables in the model. Optimum regression models

TABLE I
***F* Values for Partial Analysis of Variance of Quality Parameters for an Irrigation, Fertility, and Cultivar Trial Grown at Aberdeen, ID, in 1999 and 2000[a,b]**

Effect	Test Weight	Flour Yield	Flour Protein	Solvent Retention Capacity: Water	Na_2CO_3	Sucrose	Lactic Acid	SKCS: Hardness	Diameter	Kernel Wt	Cookie Diameter
Irrigation (I)	0.35	0.42	1.73	1.81	0.07	1.09	0.63	0.00	0.28	0.18	2.89
Fertility (F)	0.02	0.00	1.94	0.91	2.12	0.11	0.03	0.37	0.03	0.02	1.72
I × F	0.03	0.52	0.46	2.94	0.13	1.61	3.32	0.20	0.28	0.15	3.95
Cultivar (C)	42.4***	0.28	3.44	6.74*	17.4***	8.90**	0.69	20.96***	30.57***	183.5***	8.86**
C × I	0.01	2.35	0.10	0.14	1.32	0.49	0.10	0.33	0.04	1.20	0.11
C × F	0.92	2.58	1.94	1.49	0.28	2.50	1.24	0.27	2.07	9.29**	2.75
C × I × F	0.00	1.79	0.02	2.02	0.29	0.00	1.01	0.14	0.04	0.12	0.42

[a] *, **, *** = significant at $P = 0.05, 0.01, 0.001$, respectively.
[b] Year and replicate (× year) interaction were treated as random effects. Irrigation, fertility, and cultivar were treated as fixed effects.

TABLE II
***F* Values for Partial Analysis of Variance of Quality Parameters for Rainfed and Irrigated Fertility Experiments at Tetonia, ID, in 1999 and 2000[a,b]**

Effect	Test Weight	Flour Yield	Flour Protein	Solvent Retention Capacity: Water	Na_2CO_3	Sucrose	Lactic Acid	SKCS: Hardness	Diameter	Kernel Wt	Cookie Diameter
Rain-fed trial											
Fertility (F)	0.58	0.26	0.73	1.41	0.17	0.38	0.06	1.13	2.76	2.60	9.81*
Cultivar (C)	0.58	4.63	0.59	5.71*	0.68	0.57	2.26	2.90	1.41	0.29	1.66
C × F	0.58	0.33	0.59	0.18	1.35	0.33	0.30	0.13	0.51	0.01	0.03
Irrigated trial											
F	1.25	0.49	10.09*	1.30	0.92	5.68	2.89	0.29	2.93	0.57	1.28
C	6.97*	3.28	0.24	2.58	5.51	0.00	0.43	11.56**	0.04	4.47	0.51
C × F	0.01	0.51	1.74	0.00	0.45	0.09	0.51	0.07	0.04	0.03	0.13

[a] *, **, *** = significant at $P = 0.05, 0.01, 0.001$, respectively.
[b] Year and replicate (× year) interaction were treated as random effects. Fertility, and cultivar were treated as fixed effects.

were identified as models having p with the greatest difference in $C(P)$ between the optimum and second optimum subset of independent variables (SELECTION = RSQUARE in PROC REG).

RESULTS AND DISCUSSION

Aberdeen Trial

No significant effects of irrigation treatment, top-dress fertilizer application, cultivar or the interactions were observed on flour extraction, flour protein, or lactic acid SRC (Table I). Only cultivar effect was significant for test weight, water SRC, sodium carbonate SRC, sucrose SRC, all SKCS parameters, and sugar snap cookie diameter. No significant interactions of cultivar and fertility were observed, indicating that the cultivars responded similarly to fertility conditions. The lack of response of flour protein concentration to increasing fertilizer may indicate that the low fertility treatment was adequate for optimum yield. Both Centennial and Pomerelle are cultivars released from our breeding program, and the tendency of these genotypes to maintain a relatively low flour protein concentration across a wide range of production environments was a factor in favor of their release as cultivars for commercial production.

Tetonia Rain-Fed and Irrigated Trials

In the rain-fed trial, cultivar effect was significant for water SRC (Centennial 52.0%, Pomerelle 52.8%). Top-dress fertilizer application decreased mean sugar snap cookie diameter from 8.4 cm to 8.2 cm (Table II). However, no effect of fertilizer application on flour protein was observed. In the irrigated trial, cultivar effect was significant for test weight (Centennial 79.1 kg/hl, Pomerelle 77.1 kg/hl) and SKCS kernel hardness (Centennial 19.7, Pomerelle 26.8), and top-dress fertilizer application increased flour protein content from 10.3 to 11.1%. The effect of top-dress fertilizer on flour protein concentration in the irrigated but not in the rain-fed trial may reflect improved incorporation of the fertilizer by the irrigation water. Alternatively, the preplant fertilizer rate may have been inadequate for the crop yield potential in the irrigated trials, but not in the rain-fed trials. As in the Aberdeen trials, interactions between cultivar and top-dress fertilizer application were nonsignificant in both irrigated and rain-fed trials, indicating that the cultivars responded similarly to the fertility treatments.

General Effects of Production Environment

The nine production environments ranged in mean yield from 2,210 kg/ha at Havre in 2000 to 8,110 kg/ha at Aberdeen in 2000 (Table III). The yields of the trials at Bozeman were intermediate between the yields of the Tetonia trials and the yields of the Aberdeen trials. The Havre trial represented the most extreme stress environment. Production environment had highly significant effects on all quality parameters, except flour extraction. Cultivar effects also were significant for test weight, flour extraction, water and

TABLE III
Environment and Genotype Mean Values and Analysis of Variance for Nine Trials[a,b]

	Grain Yield (kg/ha)	Test Wt (kg/hL)	Flour Extraction (%)	Flour Protein (%)	Cookie Diameter (cm)	Solvent Retention Capacity (%) Water	Na_2CO_3	Sucrose	Lactic Acid	SKCS Hardness	Diameter (mm)	Kernel Wt. (mg)
Aberdeen												
1999 I	6,370	74.4	64.1	9.3	8.2	53.0	69.3	97.0	93.5	19.9	2.1	30.4
2000 I	8,110	80.7	67.4	8.7	9.1	49.8	60.5	88.2	79.4	21.2	2.5	38.5
Bozeman												
2000 I	6,950	78.0	66.9	10.0	8.6	50.9	62.9	93.6	94.9	18.4	2.2	32.6
2000 R	4,880	76.7	64.8	10.4	8.5	51.0	64.3	97.9	107.5	17.3	2.1	31.1
Havre												
2000 R	2,210	77.1	63.8	11.0	8.7	48.7	61.6	96.5	111.2	2.7	2.0	30.0
Tetonia												
1999 I	4,260	79.7	68.8	10.3	8.1	53.5	67.3	97.8	102.2	29.4	2.3	33.2
1999 R	2,371	80.9	68.5	11.2	8.0	53.4	66.0	99.2	115.4	30.8	2.3	32.1
2000 I	5,161	76.5	67.6	11.1	8.6	51.4	69.1	97.9	103.5	17.2	2.2	32.0
2000 R	2,718	77.9	67.1	11.2	8.6	51.4	66.7	96.8	109.7	13.8	2.1	30.7
Genotype												
Centennial	5,020	78.9	66.7	10.2	8.5	50.9	64.0	95.8	99.9	16.3	2.2	34.2
Pomerelle	5,150	77.0	66.0	10.1	8.6	51.7	66.1	95.2	99.5	20.7	2.2	31.0
F Value												
E	56.2***	8.9**	2.1	14.5***	9.7**	35.6***	11.2***	4.6*	24.7***	38.7***	5.0**	5.5***
G	2.9	34.0***	7.8**	0.6	4.1	31.9***	23.1***	0.2	0.3	35.6***	8.6***	50.6***
G × E	1.3	2.6	1.1	0.6	0.3	2.2	0.7	1.6	1.0	3.7*	3.9*	3.6*

[a] *, **, *** = significant at $P = 0.05$, 0.01, 0.001, respectively.
[b] I = irrigated; R = rainfed. Replicate, replicate × environment (E), and replicate × cultivar (C) × environment were treated as random effects. Environment and genotype (G) were treated as fixed effects.

TABLE IV
Correlation of Solvent Retention Capacities with Flour Protein, Flour Extraction, and Cookie Diameter from Centennial and Pomerelle[a]

	Solvent Retention Capacity Water	Na_2CO_3	Sucrose	Lactic Acid	Flour Protein	Flour Extraction	Cookie Diameter
Centennial (n = 46)							
Water	· · ·	0.72***	0.51***	ns	ns	0.63***	–0.65***
Sodium carbonate	0.72***	· · ·	0.64***	0.33*	ns	ns	–0.55***
Sucrose	0.51***	0.64***	· · ·	0.78***	0.70***	ns	–0.71***
Lactic acid	ns	0.33*	0.78***	· · ·	0.91***	ns	–0.44**
Pomerelle (n = 45)							
Water	· · ·	0.71***	0.50***	ns	ns	ns	–0.77***
Sodium carbonate	0.71***	· · ·	0.56***	ns	ns	ns	–0.58***
Sucrose	0.50***	0.56***	· · ·	0.78***	0.74***	–0.56***	–0.67***
Lactic acid	ns	ns	0.78***	· · ·	0.83***	–0.37**	–0.48**

[a] *, **, *** = significant at $P = 0.05$, 0.01, 0.001, respectively.

sodium carbonate SRC, and all SKCS parameters. Genotype × environment interactions were significant only for the SKCS parameters and were small relative to the cultivar effects.

The production environments at Aberdeen 1999, Tetonia 1999 irrigated, and Tetonia 1999 rain-fed produced small cookies (8.0–8.2 cm). Flours from these sites characteristically had higher water, sodium carbonate, and sucrose SRC. The Aberdeen 2000 trial, which was the highest yielding trial, produced the heaviest, largest diameter kernels, and had the lowest flour protein, also had the lowest sodium carbonate, sucrose, and lactic acid SRC values (Table III).

Correlation Analyses

The 46 Centennial flour samples and 45 Pomerelle flour samples from the trials at Aberdeen, Tetonia, Bozeman, and Havre represented a wide range values within each quality parameter (Table III). Correlation among parameters was evaluated for all flour samples from all locations, years, fertility, and irrigation treatments. Correlation analyses were conducted separately for each of the two cultivars to assess correlations among parameters within a cultivar. Correlations among SRC were similar for both cultivars (Table IV). Water and sodium carbonate SRC were highly correlated ($r = 0.71$, 0.72). Water and sucrose SRC were less highly correlated ($r = 0.51$, 0.50). Water and lactic acid SRC were uncorrelated. Sucrose and sodium carbonate SRC were correlated, and sucrose and lactic acid SRC were highly correlated ($r = 0.78$). Sodium carbonate and lactic acid SRC were weakly correlated in the Centennial flours but uncorrelated in the Pomerelle flours.

Flour protein content was not particularly well correlated with any of the SRC values in the collaborative testing of the SRC method (Gaines 2000). And in a previous cultivar survey (Guttieri et al 2001), we also found that flour protein among cultivars was not correlated significantly with lactic acid or sucrose SRC. In contrast, flour protein in the present study was correlated significantly with lactic acid SRC and sucrose SRC. Therefore, it appears that among cultivars, gluten strength, as measured by lactic acid SRC and flour protein are not related. Yet within a cultivar, increasing flour protein concentration is associated with greater lactic acid SRC.

In the previous cultivar survey (Guttieri et al 2001), sucrose and sodium carbonate SRC were negatively correlated with flour extraction. However, this relationship was not consistently observed within the cultivars in the present study. Water SRC increased with increasing flour extraction of Centennial and was the only significant correlation of SRC with flour extraction for that cultivar. Only sucrose and lactic acid SRC were significantly correlated with Pomerelle flour extraction, and the correlation was negative. Therefore, the correlation between flour extraction and specific SRC within a cultivar across environments may be unique to each cultivar.

Increasing test weight of both Centennial and Pomerelle was significantly correlated with lower sodium carbonate and sucrose SRC (Table V). Test weight correlations with lactic acid SRC and water SRC varied for the two cultivars. SKCS kernel hardness of both Centennial and Pomerelle was positively correlated with water SRC. Lactic acid SRC was negatively correlated with kernel hardness of Pomerelle but not of Centennial.

In our previous cultivar survey (Guttieri et al 2001), we observed a negative correlation of sucrose and sodium carbonate SRC with SKCS hardness. This suggests that SKCS hardness and sucrose and sodium carbonate SRC may be negatively correlated among cultivars,

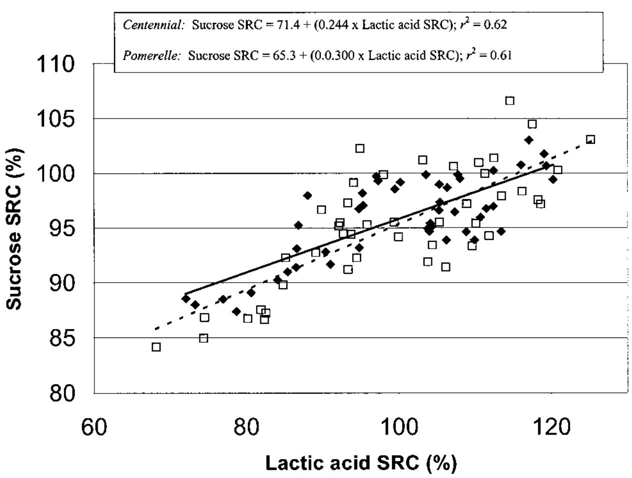

Fig. 1. Relationship between sucrose solvent retention capacity (SRC) and lactic acid SRC of Centennial (◆, —) and Pomerelle (□,– – –) flours.

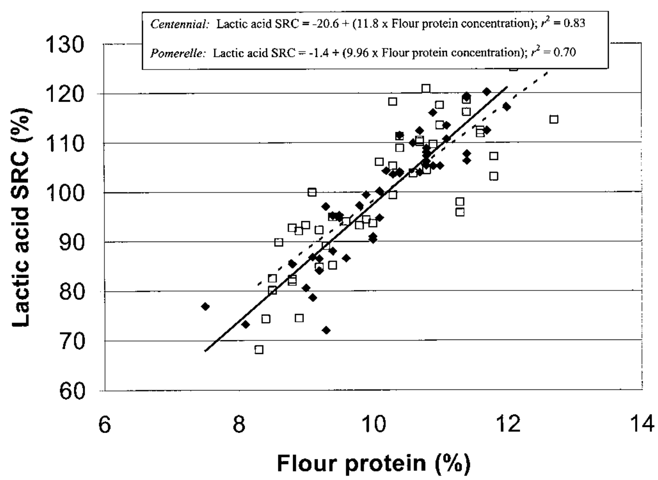

Fig. 2. Relationship between lactic acid solvent retention capacity and flour protein of Centennial (◆, —) and Pomerelle (□,– – –) flours.

TABLE V
Correlations of Whole Grain Quality Measures with Solvent Retention Capacities of Centennial and Pomerelle Flours[a]

		SKCS		
Solvent Retention Capacity	**Grain Test Weight**	**Hardness**	**Diameter**	**Weight**
Centennial ($n = 46$)				
Water	ns	0.63***	ns	ns
Sodium carbonate	–0.52***	ns	–0.40**	–0.47***
Sucrose	–0.57***	ns	–0.66***	–0.75***
Lactic acid	–0.36**	ns	–0.68***	–0.77***
Pomerelle ($n = 45$)				
Water	–0.31*	0.58***	–0.31*	–0.45***
Sodium carbonate	–0.60***	ns	–0.36**	–0.48***
Sucrose	–0.55***	ns	–0.67***	–0.75***
Lactic acid	ns	–0.37**	–0.48***	–0.51***

[a] *, **, *** = significant at $P = 0.05$, 0.01, 0.001, respectively.

but within a cultivar, the response of SRC to kernel hardness may be unique to each cultivar.

SKCS kernel diameter was negatively correlated with sodium carbonate, sucrose, and lactic acid SRC (Table V) for both Centennial and Pomerelle. Greater diameter kernels produced flours with lower sodium carbonate and sucrose SRC, which are desirable. Solvent retention capacities of both cultivars also were negatively correlated with SKCS kernel weight. Sodium carbonate, sucrose, and lactic acid SRC of both Centennial and Pomerelle flours were similarly negatively correlated with kernel weight (heavier kernels produced flours better suited for end-uses). Correlation of water SRC with kernel weight was significant for Pomerelle but not for Centennial.

Sugar snap cookie diameter was negatively correlated with all four SRC of both Centennial and Pomerelle flours (Table IV). The magnitudes of the correlation coefficients are similar for the two cultivars, suggesting that the SRC may have similar relationships to sugar snap cookie diameter.

Regression Analyses

Flours with greater lactic acid SRC and lower sucrose SRC are desirable in confectionary manufacturing processes that require a combination of moderate gluten strength and low water absorption due to pentosans. However, sucrose SRC and lactic acid SRC were highly correlated in flours from both cultivars (Table IV, Fig. 1). The test for heterogeneity of slope of the two cultivars was not significant, ($F = 1.41$, $P > 0.05$), indicating that the relationship between sucrose SRC and lactic acid SRC of the two cultivars was not different. Therefore, environments that produce flours with greater gluten strength also appear to produce flours with greater pentosan content.

Similar analysis was applied to the relationship between lactic acid SRC and flour protein (Table IV, Fig. 2). The test for heterogeneity of slope between cultivars was not significant ($F = 1.9$, $P > 0.05$), indicating that the relationship between lactic acid SRC and flour protein of the two cultivars was not different. Therefore protein concentration may be a useful indicator of lactic acid SRC, and by extension, of gluten strength of flour.

In the cultivar survey (Guttieri et al 2001), sugar snap cookie diameter was effectively predicted by a multiple regression model that included flour protein concentration and sucrose SRC. In the present study, significant regression models were built for both Centennial and Pomerelle cookie diameter involving flour protein and sucrose SRC (Centennial $r^2 = 0.58$, $C(P) = 5.59$; Pomerelle $r^2 = 0.45$, $C(P) = 42.0$). Both regression models had relatively high Mallows $C(P)$ statistics, indicating autocorrelation of the independent variables. The optimal two-parameter regression model for cookie diameter of Centennial flour was based on water SRC and sucrose SRC ($r^2 = 0.62$, $C(P) = 1.03$), while the optimal two-parameter regression model for cookie diameter of Pomerelle flour was based on water SRC and lactic acid SRC ($r^2 = 0.72$, $C(P) = 2.36$).

Cookie diameter can be viewed as a measure of the degree to which the outward flow of the dough is constrained by flour characteristics during the baking process (Slade and Levine 1994). The fundamentally different prediction models for cookie diameter in Centennial and Pomerelle flours suggest that different factors constrain the spread of dough between genotypes. Although the individual components of Centennial and Pomerelle respond similarly to environment, the cultivars differ for individual flour components that are the primary factors constraining outward flow of the cookie dough. This is consistent with multivariate analysis of SRC of 26 spring wheats, including Centennial and Pomerelle, that assigned these two genotypes to separate clusters based on SRC profile (Guttieri et al 2001).

CONCLUSIONS

Clear associations of flour SRC with crop irrigation and fertility management were not observed in this study. Genotype differences were more important than specific crop management treatments, and genotype × environment interactions were not observed with individual components of quality. This is consistent with our earlier observation (Guttieri et al 2001) of limited genotype × environment interaction for SRC. This suggests that selection among genotypes within an environment will produce a gain-from-selection observable in multiple and diverse environments. The large effects of environment upon the SRC value suggest that the selection of environment and management of that environment through irrigation may be as important (if not more important) a determinant of end-use quality as cultivar selection, when the choice of cultivars is restricted to adapted genotypes with acceptable quality. Correlations among SRC parameters were similar for the two cultivars, and regression models for lactic acid SRC as a function of flour protein concentration were similar for the two cultivars. This suggests consistent and intrinsic relationships among SRC parameters and between lactic acid SRC and flour protein content. However, the optimum regression models for cookie diameter were different for the two cultivars. Therefore it may be difficult to generate predictive models for cookie diameter that will be equally effective for all cultivars.

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