Genetic Improvement in Milling and Baking Quality of Hard Red Winter Wheat Cultivars, 1919 to 1988

T. S. Cox,* M. D. Shogren, R. G. Sears, T. J. Martin, and L. C. Bolte

ABSTRACT

Concern has been expressed that recently released hard red winter wheat (*Triticum aestivum* L.) cultivars have inferior milling and baking quality when compared with older cultivars. This concern results from recent experiences in some commercial bakeries, as well as from negative correlations between grain yield and protein concentration commonly reported for cereal crops. We evaluated milling and baking quality traits of 40 hard red winter wheat genotypes, representing the past 70 yr of cultivar release, using grain harvested from replicated experiments at three Kansas locations in 1986 and 1987. Our objective was to determine the direction and magnitude of changes in milling and baking quality traits of hard red winter wheat resulting since breeding efforts were initiated. No significant change over time was detected for flour yield. Mean flour protein was 2 g kg^{-1} lower for 20 cultivars released between 1976 and 1988 (recent group) than for the 20 released previously (early group); however, regression analysis showed a significant increase since 1976. Absorption, mixing time, loaf volume, crumb grain score,and an overall baking quality index increased 0.1 to 4.6% annually, compared to the mean of 'Turkey'. Regression coefficients were homogeneous over environments for all traits except flour yield. There were few significant correlations between quality traits and grain yield or volume weight. Any deterioration in quality of hard red winter wheat perceived by the baking industry must be caused by nongenetic factors, such as changes in the environment, milling practices, commercial baking methods and formulations, or some combination of these factors.

HARD RED WINTER WHEAT is used primarily to produce yeast-leavened bread products. Though "quality . . . of wheat cannot be expressed in terms of a single property" (Finney et al., 1987), traits used as indicators of milling quality include test weight, 1000-kernel weight, and flour yield. Indicators of baking quality include wheat or flour protein concentration, mixing time, mixing tolerance, water absorption, loaf volume, and crumb grain and color (Finney et al., 1987). Several of these traits have moderate to high heritability in wheat (Braaten et al., 1962; Davis et al., 1961; Halloran, 1975; Haunold et al., 1962b, Löffler and Busch, 1982; Lofgren et al., 1968; Schlehuber et al., 1967); however, the end-use quality of any wheat genotype can vary tremendously depending on the production environment (Mangels, 1925; Haunold et al., 1962a).

The dramatic genetic improvement in grain yield achieved in hard red winter wheat in the past 70 yr (Cox et al., 1988) has generated concern in the baking industry that a decline in end-use quality may have resulted from these improvements (Anonymous, 1986; Pates, 1988). It is known that grain yield and protein concentration often are negatively correlated in cereal crops, especially when soil N is limiting (Frey, 1977; Haunold et al., 1962a). However, end-use quality traits are important selection criteria in all hard red winter wheat breeding programs. The generally negative correlations between protein concentration and grain yield computed from segregating populations may not be valid for cultivars selected for yield and quality traits, and released over time.

We evaluated milling and baking traits of 40 hard red winter wheat genotypes introduced or released from 1874 to 1988. Our objective was to determine the changes in quality that may have occurred due to breeding over the past 70 yr, since the first survey of wheat cultivar acreages in the USA was published.

MATERIALS AND METHODS

Entries evaluated (Table 1) included two cultivars, Turkey and 'Kharkof', introduced from Russia in the 1870s and 1900, respectively; 'Cheyenne' and 'Blackhull', selection from 'Crimean' and Turkey, respectively; 35 other cultivars released from 1932 to 1988; and one germplasm release, KS831957 (originally to be released as a cultivar but withdrawn because of susceptibility to stem rust, caused by *Puccinia graminis* f. sp. *tritici*). Blackhull, 'Tenmarq', 'Eagle', and 'Karl' were evaluated only in the second year.

Experiments were conducted in 1985–1986 and 1986–1987 at the Ashland Research Farm near Manhattan, KS; the South Central Experiment Field near Hutchinson, KS; and the Fort Hays Branch Experiment Station near Hays, KS. The Manhattan experiments were located in an area mapped as Reading silt loam, 0 to 1% slope (fine, mixed, mesic, Typic Argiudolls); the Hutchinson experiments in an area mapped as a Clark-Ost complex, 0 to 1% slope (fine-loamy, mixed, thermic Typic Calciustolls and fine-loamy, mixed, thermic Typic Arguistolls, respectively); and the Hays experiments in an area mapped as part Harney silt loam, 0 to 1% slope (fine, montmorillonitic, mesic Typic Argiustolls) and part Armo loam (fine-loamy, mixed, mesic Typic Haplustolls). These sites were chosen to represent northeastern, south central, and western Kansas, respectively. All sowings were in early to mid-October and all harvests in mid- to late June. One hundred kilograms per hectare N and 30 kg ha^{-1} P were added to the soil before sowing at Manhattan; 80 kg ha^{-1}N and 30 kg ha^{-1} P were added at Hutchinson; and 45 kg ha^{-1} N were added at Hays. Sowing rates were 1.2×10^6; 7.8×10^5, and 5.8×10^5 seeds ha^{-1} at Manhattan, Hutchinson, and Hays, respectively.

Each experiment was in a randomized complete block design with three replicates. An experimental unit consisted of the center two rows of a four-row plot; at Manhattan and Hutchinson, rows were 5.9 m long, with 25 cm between rows, whereas at Hays, rows were 2.4 m long, with 30 cm between rows.

All plots in each experiment were harvested on the same day, after all had reached full harvest maturity, but before any shattering was detected in early cultivars. The center two rows of each plot were harvested with a cutter-binder near the soil surface and threshed with a stationary thresher. Grain was weighed to obtain grain yield of each plot in kil-

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ograms per hectare. Volume weight in kilograms per cubic meter was determined on a Dickey-John Grain Analysis Computer II (Dickey-John Corp., Auburn, IL)[1]. Grain of each entry from each location-year was then bulked, providing one replicate per entry per environment for quality analyses.

Wheat samples were cleaned and tempered to a 150 g kg^{-1} moisture concentration, except for those cultivars known to be harder than normal, such as 'Redchief', and those softer than normal, such as 'Triumph 64', which were tempered to 160 and 145 g kg^{-1}, respectively. After the tempered wheat weight was recorded, each wheat sample was milled on an Allis experimental mill. Weights of bran, shorts, red dog, and the combined flour streams were recorded for flour yield calculations (Finney et al., 1987). Flour yield was calculated as the weight of the combined flour streams divided by the tempered wheat weight. Flour was rebolted over a 9XX flour cloth, blended for 5 min, and subsampled for determination of protein concentration, as Kjeldahl N × 5.7, on a 140 g kg^{-1} moisture basis.

An optimized straight-dough baking method was used to determine the bake absorption, mixing time, loaf volume, and crumb grain score of each sample (Finney, 1984). Mixing time of samples with < 120 g kg^{-1} flour protein was adjusted to a 120 g kg^{-1} level, and all loaf volumes were adjusted to a 115 g kg^{-1} protein basis, using regression formulas (Finney, 1984). All loaves were cut in half, and a crumb grain score, from 1 to 9 inclusive, was assigned using the following benchmark values: 4 = unsatisfactory, 6 = questionable, 8 = satisfactory, and 9 = flawless. Scores 1 to 3 would be assigned to extremely defective loaves.

A quality index was computed to represent the overall baking quality of an entry-environment combination. Entries in each environment were ranked for flour protein, adjusted mixing time, adjusted loaf volume, and crumb grain score. The ranks were averaged over the four traits for each entry to obtain its quality index for that environment. The quality index was considered to be a composite score for total flour protein concentration; physical dough strength (mixing time) and gas retention (loaf volume), both adjusted for protein concentration; and texture (crumb grain score). These are primary baking quality components for hard red winter wheat (Finney et al., 1987). The possible range for the quality index was 1 to 40, with higher values indicating high baking quality.

Entries were divided into two groups of 20: those released in or before 1970 (the early group) and those released in or after 1976 (the recent group). Although we attempted to sample important cultivars from throughout this century, the point at which we made this division marked a transition in plant type and genetic diversity of hard red winter wheat. Only one of the entries 'Sturdy', in the older group is a semidwarf cultivar, while in the recent group, all are semidwarfs except 'Larned', 'Centurk 78', and 'Siouxland'. Furthermore, cultivars released after 1975 began to account for a significant proportion of hard red winter wheat production in the early 1980s, at a time when a decline in quality was being perceived by the baking industry (Anonymous, 1986; Pates, 1988).

A two-way analysis of variance for flour yield, flour protein concentration, bake absorption, baking mixing time, loaf volume, crumb grain score, and quality index was performed for the 36 entries evaluated in all six environments. The entry × environment mean square was used as the error term in the *F* test for significance of variation among entries. There was no error term for testing the significance of the entry × environment interaction mean square. In a separate regression analysis, significance of mean squares for year of release, year of release × location, year of release × year of evaluation, and the three-way interaction was tested using the deviations-within-environments mean square as the error term (Snedecor and Cochran, 1980). Where interaction mean squares were significant, regression coefficients were computed within appropriate environments.

Because of the many years that elapsed between the introduction of Turkey and Kharkof and the first releases of hard red winter wheat cultivars arising from breeding programs, we used the year 1919 (the year of the first USDA wheat cultivar-acreage survey, in which 99.5% of the hard red winter area was sown to Turkey) as the value of the independent variable for Turkey, Kharkof, and Blackhull in regression analyses.

Product-moment correlations between quality traits on the one hand, and grain yield and volume weight on the other were computed on the basis of entry means over environments. Both simple correlations and partial correlations holding year-of-release constant (Snedecor and Cochran, 1980) were computed.

RESULTS

In the two-way analyses of variance (not shown), there was a highly significant difference between the two groups of cultivars (released 1919–1970 and 1976–1988) for all traits except flour yield, and there was highly significant variation among entries within groups for all traits. Means over the six environments for the 40 entries (Table 1) indicate the wide range in quality characteristics. All seven entries with quality indices higher than 25 (indicating higher baking quality) were released in 1982 or later. All five entries with quality indices lower than 15 were released in 1943 or before. There also was significant variation among environments for all traits (except quality index, which was computed from ranks within environments). Environment means are shown in Table 1.

In the analysis of variance for regression on year-of-release, interactions between year-of-release and locations, (evaluation) years, and locations × years were all nonsignificant for flour protein, absorption, mixing time, loaf volume, crumb grain score, and quality index. All significant regression coefficients were positive, indicating improvement. Flour protein was slightly (2 g kg^{-1}) lower for the recent group than for the early group, but exhibited a positive slope within the recent group (Table 2). Absorption was higher in recent entries and had a positive slope in both groups. Mean mixing time was nearly a full minute longer for recent entries and has increased significantly in both groups. Mean loaf volume and crumb grain score were higher for recent entries, having increased up to and remained stable since the 1970s. All entries released in the 1960s had mean crumb grain scores of 8.0 (satisfactory), whereas entries released since then have varied from 7.0 to 8.0 (Table 1). However, no modern entries were in the questionable to unsatisfactory range (below 7.0). The quality index has improved consistently from 1919 to the present (Table 2). All interactions involving year-of-release, locations, and year-of-evaluation were highly significant for flour yield.

[1] Mention of a proprietary name does not constitute endorsement by the USDA and does not imply approval to the exclusion of other suitable products.

Mean flour yields were similar for the two groups. For the early group in the six environments, one slope was positive, one was negative, and four were nonsignificant (Table 2). The negative slope occurred under an epidemic of tan spot (caused by *Helminthosporium tritici-repentis*) at Hutchinson in 1987, where no grain yield improvement could be demonstrated and volume weight declined (Cox et al., 1988). We detected no significant change in flour yield for any 1987 environments.

Visual impressions of the different patterns of change for flour protein and quality index are provided by the scatter plots in Fig. 1 and 2. Though mean flour protein has not changed significantly during the century (Table 2), the range was larger for recent entries than for older ones (Fig. 1). Overall baking quality, as indicated by the quality index, has improved slowly, but steadily, through the decades and shows no signs of deteriorating (Fig. 2). Scatter plots for individual traits (not shown), including absorption, mixing time, and loaf volume, exhibited patterns of gradual improvement similar to that of the quality index.

Simple product-moment correlations (Table 3) between quality and productivity traits indicated whether the two types of traits were associated for this set of cultivars, ignoring the generally positive slopes for all traits over time; partial correlations showed whether cultivars with higher-than-average values for the time at which they were released had higher- or lower-than-average values for another trait. There were no significant simple or partial correlation coefficients between flour protein or loaf volume on the one hand, the grain yield or volume weight on the other. The same was true of absorption, except for a simple cor-

Table 1. Means for six milling and baking quality traits, as well as a baking quality index for 40 entries over all environments and for six environments over all entries.

Entry or environment		Flour yield	Flour protein	Absorption	Mixing time	Loaf volume	Crumb grain score	Quality index‡
Year†	Name		g kg^{-1}		min	mL		
1874	Turkey	715	115	555	2.4	935	6.3	14.7
1900	Kharkof	717	117	541	3.4	893	6.3	16.6
1917	Blackhull§	745	115	526	1.7	869	4.8	7.7
1932	Tenmarq§	746	120	565	2.7	943	8.0	18.6
1933	Cheyenne	728	111	547	3.4	893	6.5	14.2
1940	Redchief	736	110	566	2.0	834	4.3	5.7
1942	Comanche	736	120	581	3.1	917	7.0	18.5
1943	Pawnee	734	114	546	2.0	928	6.8	13.8
1944	Wichita	761	112	540	2.2	946	7.2	15.3
1949	Triumph 64	757	115	548	2.5	917	8.0	17.4
1951	Ponca	719	118	558	2.7	942	6.8	17.5
1956	Bison	739	117	559	2.9	985	7.7	24.0
1959	Tascosa	741	116	564	4.3	944	7.3	23.6
1960	Warrior	737	110	538	2.8	958	7.3	18.1
1961	Kaw 61	747	110	532	3.8	895	6.8	15.9
1963	Lancer	736	111	542	2.5	987	8.0	21.4
1966	Scout 66	743	115	558	3.0	959	8.0	22.0
1967	Sturdy	742	126	555	3.4	928	7.3	23.5
1967	Shawnee	725	116	590	3.7	979	8.0	27.1
1970	Eagle§	747	123	585	4.6	922	8.0	23.9
1976	Larned	743	109	556	2.8	984	7.8	20.1
1976	Vona	725	105	563	3.2	976	7.5	18.4
1977	Newton	717	109	554	3.3	980	7.7	21.7
1978	Centurk 78	722	113	589	4.4	936	7.5	22.8
1982	Arkan	746	120	555	3.4	966	7.7	25.1
1982	Brule	731	105	539	3.7	978	7.5	20.5
1982	Hawk	730	111	559	4.3	939	7.8	23.6
1983	Chisholm	746	104	569	4.8	1006	7.8	25.5
1984	Mustang	755	107	578	3.6	968	7.8	21.8
1984	Siouxland	751	114	578	3.6	915	7.0	17.8
1985	Stallion	726	116	557	3.8	927	7.8	23.4
1985	TAM 107	734	109	624	4.0	997	7.2	23.6
1985	TAM 108	725	109	550	2.7	951	7.7	17.2
1985	Victory	735	111	558	3.1	917	7.3	15.8
1986	KS831957	732	128	588	5.0	941	8.0	30.5
1986	Norkan	722	121	588	4.7	928	7.5	25.9
1986	Dodge	726	123	558	4.1	906	8.0	25.6
1986	Century	706	112	594	4.1	950	7.3	23.4
1987	TAM 200	725	108	626	5.1	1034	8.0	29.6
1988	Karl§	748	119	583	5.1	1003	8.0	28.1
	LSD (0.05)	24	07	15	0.5	42	0.8	4.6
1986	Manhattan	702	107	552	3.7	875	6.8	20.5
1987	Manhattan	726	129	575	3.5	953	7.7	20.5
1986	Hutchinson	741	108	566	4.0	889	7.3	20.5
1987	Hutchinson	741	113	567	3.7	978	7.4	20.5
1986	Hays	739	118	572	4.4	940	7.3	20.5
1987	Hays	761	116	556	3.3	970	7.7	20.5

† Year = year of release for entries, year of evaluation for environments; name = name of entry or location.
‡ Mean rankings for flour protein, mixing time, loaf volume, and crumb grain score. Higher values indicate better index of quality.
§ Estimated 2-yr mean.

relation of 0.49* (significant at the 0.05 probability level) with volume weight for recent entries.

For the early group, flour yield was positively correlated with both grain yield and volume weight, either with or without removing the effect of year-of-release (Table 3; partial and simple correlations, respectively). However, there were no significant correlations between flour yield and volume weight for the recent group. Mixing time showed negative simple and partial correlations with volume weight in the early group. In the recent group, there were highly significant negative simple and partial correlations between crumb grain score and grain yield. Quality index was not associated with grain yield. It had a negative correlation

Table 2. Means and coefficients of regression on year-of-release for six milling and baking quality traits, and a baking quality index, within two groups of cultivars released in different eras. Means in different columns of the same row differ significantly at the 1% level for all traits except flour yield.

			Mean		Regression coefficient	
Trait	Year	Location	1919–1970	1976–1988	1919–1970	1976–1988
Flour protein†	Both	All	115	113	0.01	0.73**
Absorption†	Both	All	555	574	0.37**	2.60**
Mixing time‡	Both	All	3.0	3.9	0.02**	0.11**
Loaf volume§	Both	All	929	960	1.35**	1.41
Crumb grain score	Both	All	7.0	7.6	0.04**	0.01
Quality index	Both	All	18	23	0.22**	0.48**
Flour yield†	1986	Manhattan	697	706	0.89	−0.66
		Hutchinson	737	746	0.33	0.38
		Hays	744	733	−0.24	−0.79
	1987	Manhattan	729	724	0.20	2.51
		Hutchinson	757	756	−0.43*	−0.29
		Hays	764	757	0.64*	0.04

*,** Significantly different from zero at the 5 and 1% probability levels.
† Means and regression coefficients in g kg^{-1} and g kg^{-1} yr^{-1}, respectively.
‡ Means and regression coefficients in min and min yr^{-1}, respectively.
§ Means and regression coefficients in mL and mL yr^{-1}, respectively.

Table 3. Simple correlation coefficients and partial correlation coefficients, holding year-of-release constant, for flour yield, mixing time, crumb grain score, and quality index vs. grain yield and volume weight within two groups of cultivars released in different eras.

	Grain yield				Volume weight			
	1919–1970		1976–1988		1919–1970		1976–1988	
Trait	Simple	Partial	Simple	Partial	Simple	Partial	Simple	Partial
Flour yield	0.69**	0.61**	0.07	0.05	0.74**	0.70**	0.19	0.18
Mixing time	0.07	−0.23*	0.20	−0.10	−0.11	−0.31	0.57**	0.50*
Crumb grain score	0.32	−0.04	−0.49*	−0.63**	0.02	−0.30	0.21	0.18
Quality index	0.22	−0.20	−0.06	−0.21*	−0.11	−0.46*	0.52*	0.45*

*,** Significantly different from zero at the 5 and 1% probability levels.

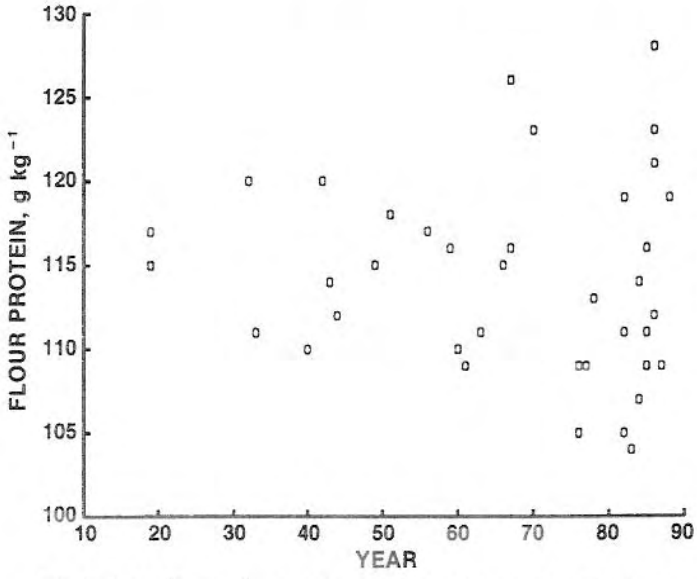

Fig. 1. Plot of mean flour protein concentration vs. year-of-release for 40 hard red winter wheat cultivars evaluated at three Kansas locations in 2 yr. (Cultivars released before 1919 are plotted at the year 1919.)

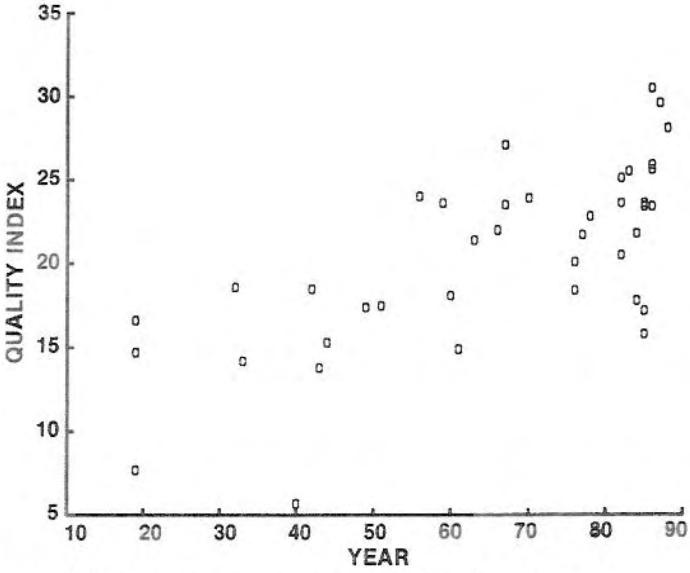

Fig. 2. Plot of mean quality index (mean of rankings for flour protein, mixing time, loaf volume, and crumb grain score) vs. year-of-release for 40 hard red winter wheat cultivars evaluated at three Kansas locations in 2 yr. (Cultivars released before 1919 are plotted at the year 1919.)

with volume weight for early entries, but was positively correlated with volume weight in recent entries.

DISCUSSION

For different groups and individual traits, excluding flour yield, all significant regression coefficients on year-of-release were positive and ranged from 0.1 to 4.6% of the mean of Turkey. The annual increases in quality index within the early and recent groups were 1.5 and 3.3%, respectively. These gains compare with an annual grain yield increase of 1.0% of Turkey's mean between 1919 and 1987 (Cox et al., 1988).

This parallel improvement is not a contradiction of the general crop breeding axiom that yield and quality, especially as indicated by protein concentration, are negatively related. If hard red winter wheat breeders had selected only for grain yield or only for end-use quality, it is likely that either trait could have been improved more rapidly. But the fact is that breeders selected for both, and they improved both. Furthermore, much selection pressure has been applied for some traits, for example, disease resistances, that positively affect both grain yield and quality. It is interesting that among these released cultivars, which represent the most elite material from breeding programs, there were few significant correlations between yield and quality traits.

The trend in milling quality, as indicated by flour yield, was highly dependent on the evaluation environment. There was no evidence of a general decline over years, and increasing selection pressure for improved disease and insect resistance should help reduce the occurrence of shriveled grain in future cultivars, thus improving milling quality. Although recent cultivars showed no significant correlation between volume weight and flour yield, the former is often used commercially as a predictor of the latter. This practice may still have validity in commerce, where environmental variation in volume weight and flour yield could play a larger role than phenotypic variation among cultivars.

For the baking quality traits, including flour protein, absorption, mixing time, and loaf volume, we have regarded higher values as superior. It is conceivable that excessively high values for some of these traits, especially mixing time, could be undesirable. However, none of the entries we evaluated had means above the acceptable range. Pure flours from strong cultivars usually are undesirable for bakers' pan bread flour because of their excessive mixing requirement. In addition the "bucky" or tough doughs from these flours lack the extensibility required for high speed mechanical molding. However, these strong wheat genotypes are needed for blending with weaker genotypes to improve mixing tolerance and overall baking performance, especially when weather and diseases reduce the overall quality of the wheat crop. The environment has adverse effects on quality in large areas of the Great Plains every year. Therefore, the increase over time in mixing time and other traits indicates an increase in desirability for the range within which we are working.

The quality index should be considered to be a composite indicator of trends in overall baking quality. It does not reflect the processes of selection in breeding programs or cultivar release decisions. In those processes, breeding lines or cultivars seriously deficient in one or more quality traits are rejected, regardless of their desirability in other respects.

It is important that there was no significant heterogeneity of the regression slopes in the six environments for any of the six baking quality traits. Our conclusions concerning baking quality improvement are independent of evaluation environment, at least for these typical Kansas locations. This is true even though the environments varied considerably in level of productivity and disease occurrence, causing estimates of genetic improvement for grain yield and other agronomic traits to vary significantly (Cox et al., 1988).

The release of a cultivar does not guarantee that it will be grown widely enough to have an influence on quality of the overall crop in a given year. Of the entries we studied, none of the six released since 1985 has yet entered commercial production on a significant scale. Even if we omit these recent cultivars, which have a relatively high mean quality index of 27.2, we detect no decrease in overall quality. For example, the mean quality indices of cultivars that were in commercial production in 1974, 1979, and 1984 are 20.8, 21.3, and 20.9, respectively, when indices of cultivars we studied are weighted by their proportional share of the hard red winter wheat acreage in those years (Siegenthaler et al., 1986; Briggle et al., 1982).

These results lead us to conclude that any perceived decline in quality of wheat for milling and baking purposes over the past decade (Anonymous, 1986; Pates, 1988) is a result of (i) an increased occurrence of negative environmental conditions (e.g., late rainfall, inadequate soil N, disease), (ii) wheat procurement changes, (iii) increased milling extraction, (iv) changes in commercial baking methods and formulations, or some combination of these factors. There is no evidence of a decline in genetic potential for end-use quality in released hard red winter wheat cultivars. Adoption of recently released, high-quality cultivars by growers will depend at this point only on their agronomic desirability and adaptation, since there is no economic incentive for growers to select cultivars on the basis of end-use quality.

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Tiller Phenology and Yield of Spring Wheat in a Semiarid Environment

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ABSTRACT

Cereal grain yields are, in part, determined by tillers formed during the plant's vegetative phase. This study was conducted to determine the extent of genotypic differences in tiller phenology and yield characteristics of individual tillers of spring wheat (*Triticum aestivum* L.) grown in a semiarid environment. Time to emergence, percent emergence, and survival of individual tillers were determined for 10 genetically diverse genotypes seeded into a Typic Haploborall clay loam at Saskatoon, SK on two dates (4 and 28 May) in 1983. Genotypes differed significantly for percent tiller emergence and survival. Tiller emergence was more rapid (11–12 d) for the later seeding date. Genotype differences in time of tiller emergence (2–6 d) were significant for specific tillers. Main stem Haun stage at the time of tiller emergence (MSHE) was not influenced by seeding date but varied significantly among genotypes (0.40–1.07 Haun units). At maturity, the main stem and tillers T0, T1, T2, and T3 contributed an average of 26.0, 4.4, 21.8, 18.8, and 12.2 % to plant grain yield, respectively, at a seeding rate somewhat below that used commercially. Tillers T1, T2, and T3 did not differ from the main stem in culm length, spikelets spike^{-1}, or harvest index; but produced fewer, lighter kernels. Tiller grain yields, spikelets spike^{-1}, and culm length were negatively correlated with MSHE. Days to tiller emergence was not related to mature plant traits. The ability of MSHE to detect small differences in tillering pattern among genotypes and its relationship to yield should prove useful in the study of genotype-environmental interaction.

THE TILLERING PROCESS is an important determinant of spring wheat grain yields. The relationship between tillering pattern and yield is of importance in establishing whether genotypes with a particular pattern are better adapted to particular environments. Tillering in cereals has been quantified by determining maximum tiller and final spike numbers on either a single plant or crop basis. Tiller mortality or its converse, tiller survival, has also been used to describe differences in tillering patterns (Rawson, 1971; Shanahan et al., 1985). More detailed studies have reported the proportion of plants that exhibit specific tillers as well as the time taken for these tillers to emerge (Rawson, 1971; Kirby and Faris, 1972; Fraser et al., 1982; Simmons et al., 1982).

Early tillers emerge in a sequence that appears to be relatively unaffected by genotype and environment. Tillers arising at the coleoptilar node and from the axil of the first leaf emerge at about the same time, followed by tillers developing from buds on the axils of the second leaf, first tiller prophyll third leaf and second tiller prophyll (Rawson, 1971). According to Rawson (1971), tillering ceases at about the time of terminal spikelet differentiation and is followed by a period of tiller senescence, which ends at the time of spike emergence.

Delayed seeding results in more rapid tiller emergence (Cannell, 1969; Stern and Kirby, 1979). However, the emergence of fewer higher-order tillers, and their lower grain yield coupled with an increase in their mortality following emergence have been shown to drastically reduce yields in barley (*Hordeum vulgare* L.) (Cannell, 1969). Significant reductions in spike number due to delayed planting have been reported for spring wheat (Black and Siddoway, 1977).

Virtually all of the currently available information on tillering in wheat has been obtained from the study of genotypes with a winter habit or from environments in which spring wheats have an extended (> 70 d) preanthesis period. Furthermore, studies carried out on a crop population basis have failed to clarify the relationship between tillering pattern and grain yield in spring cereals (Hucl and Baker, 1988). The

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