GENETIC IMPROVEMENT FOR WINTER WHEAT YIELD AND QUALITY UNDER DUAL-PURPOSE AND GRAIN-ONLY MANAGEMENT SYSTEMS

By

IFTIKHAR HUSSAIN KHALIL

Bachelor of Science (Hons.) Agric.
NWFP Agricultural University
Peshawar, Pakistan
1986

Master of Science
Oklahoma State University
Stillwater, Oklahoma
1993

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Graduate College of the
Oklahoma State University
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Thesis Approved:

Brett F Carver

Thesis Advisor

Eugene G. Krenzer Jr.

Charles M Taliaferro

Gerald W. Horn

Alfred Carlozzi

Dean of the Graduate College

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THESIS FORMAT

Each chapter in this thesis conforms to the Publications Handbook and Style Manual of the American Society of Agronomy. Chapter I gives a broad view of the problems investigated. Chapter II, III, and IV are separate and complete manuscripts to be submitted for publication in Crop Science, a Crop Science Society of America publication.

An appendix has also been provided at the end of the thesis. The appendix provides additional data from the experiments but not incorporated in the manuscripts.

CHAPTER I

HARD WINTER WHEAT MANAGEMENT SYSTEMS IN THE SOUTHERN GREAT PLAINS

INTRODUCTION

Management of hard red winter (HRW) wheat (*Triticum aestivum* L.) in the southern Great Plains is unique to most of the world, as both forage and grain is harvested from the same crop. About two-thirds of the 2.8 million hectares of Oklahoma winter wheat may be used for this dual purpose in a given year. Dual-purpose wheat provides high quality forage for the multi-billion dollar cattle industry during the fall and winter, when other forage sources are still low in quantity and quality.

Wheat producers continue to show a preference toward cultivars that perform well in a dual-purpose management system. However, wheat breeding programs in the Great Plains, including Oklahoma, have traditionally emphasized cultivar selection in a grain-only production environment, probably because this system is easily manageable and more economical. Consequently, the released cultivars are not adapted to abiotic and biotic stresses usually encountered in a dual-purpose system due to early planting and cattle grazing. The negative association of statewide wheat grain yield in the last 30 years vs. frequency of acreage planted for dual-purpose production forced us to investigate whether genetic progress for grain yield and other traits improved by breeding is reduced in a dual-purpose system. No research has yet been conducted to suggest that wheat breeders should specifically use dual-purpose production environment during cultivar development. There are also concerns that wheat grain from a dual-purpose crop may have inferior quality compared to that produced from a grain-only crop.

This study is designed to address these questions. The objectives were: (i) to measure the impact of dual-purpose system on grain yield and quality traits of HRW wheat cultivars representing different breeding eras, (ii) to quantify the rates of genetic progress for agronomic and grain quality traits under each system, and (iii) to suggest an optimum selection strategy for simultaneous genetic improvement of grain yield in the two management systems.

CHAPTER II

GENETIC TRENDS IN WINTER WHEAT GRAIN YIELD AND TEST WEIGHT UNDER DUAL-PURPOSE AND GRAIN-ONLY MANAGEMENT SYSTEMS

Genetic Trends in Winter Wheat Grain Yield and Test Weight Under Dual-purpose and Grain-only Management Systems

Iftikhar H. Khalil, Brett F. Carver*, Eugene G. Krenzer, Charles T. MacKown, and Gerald W. Horn

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I.H. Khalil, B.F. Carver, and E.G. Krenzer, Dep. of Plant and Soil Sciences, Oklahoma State Univ., Stillwater, OK 74078; C.T. MacKown, USDA-ARS, Grazinglands Res. Lab., El Reno, OK 73036; and G.W. Horn, Dep. of Animal Sci., Oklahoma State Univ., Stillwater, OK 74078. Work supported by USDA-CSREES agreement no. 97-34198-3970 and 99-34198-7481. Published with approval of the Director, Oklahoma Agric. Exp. Stn. Part of a dissertation submitted by I.H. Khalil in partial fulfillment of the Ph.D. degree requirements at Oklahoma State University. Received ________________

*Corresponding author (bfc@mail.pss.okstate.edu)

ABSTRACT

Wheat (*Triticum aestivum* L.) cultivars of the southern Great Plains are traditionally bred in environments managed for grain production only, but are commonly grown for the dual-purpose of producing winter forage and grain from the same crop. To what extent grain yield and test weight are consistently expressed in those environments requires further investigation relative to long-term attempts to genetically improve them. A historical set of hard red winter (HRW) cultivars was evaluated under grain-only and dual-purpose management systems to compare their agronomic performance and derived estimates of genetic progress. Separate experiments were established for each system featuring whole-plot treatments of a foliar fungicide and split-plot treatments of 12 cultivars spanning from Turkey to 2174 (released in 1997). The study was conducted for 3 yr at the Wheat Pasture Research Center near Marshall, OK. Dual-purpose experiments were generally grazed from November through February, with the intent to maximize animal performance and grain yield. Though the correlation between systems was high (r=0.89, P<0.01), estimates of yield progress differed markedly between systems. Yield in the grain-only system improved 18.8 kg ha^{-1} yr^{-1}, equivalent to 1.3% of the mean yield for Turkey or 0.7% of the mean of all cultivars in that system. The rate of progress in the dual-purpose system was significantly lower at 11.3 kg ha^{-1} yr^{-1}, equivalent to 0.9% of the mean for Turkey or 0.6% of the mean of all cultivars. Management for grazing had a more profound influence on estimates of yield improvement than did management for fungal disease protection. Linear trends in test weight were not evident under either system when averaged across years, nor were cultivar differences influenced by

management system in a consistent fashion across years. Breeding practices should emphasize selection for grain yield in both environments if future progress is to be maximized in both.

INTRODUCTION

Winter wheat in the southern Great Plains provides a forage pasture resource and a source of grain, often from the same crop. More than 3.2 million hectares of hard winter wheat are managed annually for forage and grain (Pinchak et al., 1996). When used for this dual purpose, winter wheat is planted from August to September, grazed by cattle (*Bos taurus* L.) from November until early March, and harvested for grain in June. Dual-purpose wheat provides high quality forage for stocker cattle during the winter, when other forage sources are low in quantity and quality (Krenzer, 2000).

Wheat cultivars used for dual purpose in the Great Plains are traditionally bred for a grain-only production environment, and hence, may not satisfy expectations for quality and yield of grain produced strictly for that purpose. Grazing, in conjunction with earlier planting, intensifies or prolongs exposure to abiotic and biotic stress conditions that may not be encountered to the same extent in a grain-only environment. For example, earlier planting allows earlier infestations of the wheat curl mite (*Aceria tosichella*) and aphids (*Schizaphis graminum*, *Rhopalosiphum padi*), leading to greater pressure from wheat streak mosaic and barley yellow dwarf viruses for which they vector (Wiese, 1991). Root rot diseases are also more prevalent with earlier planting (Cook and Baker, 1983).

Grain yields often decline in an early-planted, forage-plus-grain system compared to a later-planted grain-only system. Yield reductions of 30% in clipped plots (Ud-Din et al., 1993), or 20 to 50% in grazed plots (Winter and Thompson, 1990; Winter and Musick, 1991), may occur depending on the genotype, severity and termination date of forage removal, and the environment. Some semidwarf cultivars may suffer from a reduced leaf area index at anthesis compared to non-semidwarfs following grazing (Winter et al., 1990). Reduction in leaf area may reduce delivery of photosynthate and redistribution of accumulated N to the grain (MacKown and Rao, 1998). However, grazing early-planted winter wheat may have minimal effects on grain yield if soil moisture and fertility are adequate, if grazing is terminated prior to the first-hollow-stem stage, and if leaf regeneration potential is good following cattle removal (Redmon et al., 1995).

Breeders tend to evaluate their materials under a grain-only system, apparently because it is less difficult to manage and less expensive than a forage-plus-grain system, especially one that involves actual grazing. Genetic modification under a grain-only system may differ from that under a dual-purpose system if the two systems invoke different adaptive mechanisms. Historical genetic gains for winter wheat in the southern Great Plains are typically estimated in grain-only production environments (Cox et al., 1988, Schmidt, 1984; Khalil et al., 1995), similar to the environments in which the tested cultivars were selected. These estimates often differ across evaluation environments, and are usually lower under a less productive environment compared to a more productive one (Cox et al., 1988; Feyerherm et al., 1984; Schmidt, 1984). We hypothesized that genetic progress for grain yield and other agronomic traits of HRW wheat may be compromised in a dual-purpose management system. Our objectives were to: (i) measure the effect of an early-planted, grazing system on grain yield, yield components, and test weight of a set of cultivars representing several HRW wheat breeding eras, and (ii) estimate and compare genetic progress for grain yield and test weight of HRW wheat cultivars under the two management systems. A fungicide treatment was included to allow cultivar comparisons with or without the added benefit of foliar disease resistance provided in contemporary cultivars.

MATERIALS AND METHODS

Twelve HRW wheat cultivars were evaluated during the 1996-1997, 1997-1998, and 1998-1999 crop years (hereafter referred to as 1997, 1998, and 1999, respectively) at the Wheat Pasture Research Center near Marshall, OK. With their year of release, they were Turkey (1919, according to Cox et al., 1988), Triumph 64 (1964), Scout 66 (1966), TAM W-101 (1971), Vona (1976), TAM 105 (1979), Chisholm (1983), 2157 (1987), 2163 (1989), Karl 92 (1992), Custer (1994), and 2174 (1997). This sample represents some of the most widely grown wheat cultivars throughout the southern Great Plains after the introduction of Turkey. In addition to their direct contribution to wheat production, these cultivars have contributed profusely as parents to wheat breeding programs in the Great Plains.

Two experiments were established each year in a 7-to-10 ha pasture to accommodate independent, but proximate, positioning of dual-purpose and grain-only management systems. The wheat pastures were grazed by stocker cattle as a part of stocking rate or supplementation studies at stocking rates of 2.30, 2.06, and 1.65 steers ha^{-1} during each of the three years, respectively. Additional information relative to dates of grazing initiation, termination, forage mass and forage allowance, growth performance of cattle, and beef production per hectare are shown in Table 1. The plot area representing the grain-only system was protected from grazing by an electrical fence. As recommended by Krenzer (2000), plots representing the dual-purpose system were planted 3 Sept. 1996 and 1997, and 28 Sept. 1998, with a seeding rate of 77 kg ha^{-1}, while those in the grain-only system were planted 15 Oct. 1996, 7 Oct. 1997, and 16 Oct. 1998, using a seeding rate of 58 kg ha^{-1}. Grazing termination was determined by the appearance of hollow stem in ungrazed plants of an early-maturing cultivar planted on the same day as the dual-purpose experiment (Redmon et al., 1996).

The soil was a fine, mixed, thermic Udertic Paleustoll (Kirkland silt loam). Nitrogen was applied as anhydrous ammonia across the entire experimental area in amounts considered to meet a target grain yield of 3000 kg ha^{-1} and a dry forage yield of 3500 kg ha^{-1} (total N supply of 220 kg ha^{-1}). Actual applied N was adjusted for residual mineral nitrogen in the top 60 cm of soil each year. Fertilizer applications for both systems were dictated by requirements of the dual-purpose system, thus providing more N in the grain-only system than the yield goal, since forage was not removed. However, this amount was believed to exceed N requirements for grain yield historically measured at this site (<3500 kg ha^{-1}). Soil phosphorus and potassium were adequate for the target grain and forage yields during all years. Soil pH was 5.5 during the first two years, and 4.7 in 1998. The plot area was limed with 2500 kg ha^{-1} ECCE in July 1998.

The experimental design for each system was a split-plot with five replicates of the two whole plots (foliar fungicide vs. no fungicide) and 12 cultivars as sub-plots. The foliar fungicide propiconazole, 1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1H-1,2,4-triazole, was applied 292 mL a.i. ha^{-1} at wheat growth stage 8, or approximately at flag leaf emergence (Large, 1954). This fungicide controlled the two predominant foliar diseases, leaf rust caused by *Puccinia triticina* and Septoria leaf blotch caused by *Septoria tritici*. Each sub-plot was 3 m long with five rows spaced 23 cm apart. All five rows per sub-plot were combine-harvested on the same day. We measured grain yield as weight of threshed, cleaned grain; test weight; spike density as number of spikes per meter squared counted from a 0.5-m section in one of the three middle rows; kernels per spike as average number of kernels from 15 randomly selected spikes; and 1000-kernel weight calculated from the average kernel weight of the 15 random spikes. Grain yield, 1000-kernel weight, and kernels per spike were measured in all replicates, while test weight and spike density were measured in three to four of the five replicates.

Data were analyzed across years and systems using a mixed model. Systems, fungicide treatments, and cultivars were considered as fixed effects, while replications and years were considered random. The respective error term for each *F*-test was estimated with the random statement in PROC GLM from SAS. The sum of squares associated with cultivars in the combined analysis of variance, or in the analysis within systems, fungicide treatments, or years, was partitioned into sources representing linear regression on year-of-release and deviations from regression. The coefficient of regression served as an estimate of genetic progress for a given attribute in a specific environment. Heterogeneity of regression coefficients between systems was determined from the significance of system × cultivar linear interactions. Similarly, the heterogeneity of regression coefficients between fungicide and no-fungicide treatments was determined from the significance of the fungicide × cultivar linear interaction in the analysis of variance across years for each system. Corresponding residual mean squares for each interaction served as error terms in the *F*-tests. Least significant difference (LSD) values were calculated to compare means for the same cultivar between the two systems, using year × system × cultivar mean squares as the error term.

RESULTS AND DISCUSSION

Genetic variation for grain yield and test weight was highly significant (P<0.01), as expected from a diverse genotypic sample spanning nearly 80 yr of genetic improvement (Table 2). Means across years for the two systems were not declared significantly different for yield (P=0.24) or for test weight (P=0.83), given the presence of large system × year interactions. Fungicide application did not affect grain yield, nor did the fungicide treatment interact with other factors. Fungicide application did influence test weight and show interactions with systems and cultivars.

Environmental Conditions

The 3-yr test period provided diverse environmental conditions from which differences in mature plant development were readily detected. The grazing period during the first year, when demand often exceeded forage availability (Table 1), was followed by an unusually late freeze (average daily temperature $\leq 1.4^{\circ}$C) from 10 to 13 April 1997, when early maturing cultivars were either in the late-boot stage or at heading. This sequence of severe defoliation and freeze conditions was followed by the lowest grain yield among the three years. For the 1998 crop, weather conditions were excellent for wheat growth, resulting in record statewide grain yields (Oklahoma Agric. Stat. Serv., 1998). Grain yields were likely influenced by barley yellow dwarf virus infection. Symptoms appeared more visible in the dual-purpose system for all cultivars. Good moisture and mild winter temperatures during the 1999 crop year led to high forage production. Symptoms of soil-borne mosaic were observed in the grain-only system but not in the dual-purpose system. This disease likely impacted grain yield, except for the resistant cultivars 2157, 2163, Karl 92, and 2174. Summarizing across the three years, grazing-induced defoliation varied from extremely severe in 1997, with negligible green vegetation remaining at the time of cattle removal, to mild in 1999, with little discernible difference in canopy height between systems at cattle removal.

Grain Yield Responses

During the first two years of this study (1997, 1998), no cultivar produced greater yield in the dual-purpose system than in the grain-only system (Fig. 1). The grain yield reduction in the dual-purpose system varied among cultivars from 30 to 60% in 1997, averaging 49%, and from 4 to 35% in 1998, averaging 22% (Table 3). For the third year (1999), yields were virtually identical between systems for each cultivar (Fig. 1, Table 3). Forage production that year exceeded the demand imposed by grazing leaving ample vegetative reserves for grain production following cattle removal (Table 1). This disparity in yearly patterns was reflected in the significant year × system and year × system × cultivar interactions shown in Table 2. When a consistent yield difference was observed between systems for each cultivar, as it was in 1997 and 1998, the dual-purpose system showed less yield.

Averaging across years for each cultivar, the reduction in grain yield varied from 12% for TAM 105 to 33% for 2163. These two cultivars represent semidwarf genotypes, released only 10 yr apart. Yield reductions were not highly correlated with year of release ($r = 0.50$, $P = 0.10$), nor did they appear to be accentuated in the newer semidwarf genotypes. Yield reductions for the three tall, non-semidwarf cultivars (Turkey, Scout 66, and Triumph 64) varied from 15 to 20% and were within the range observed for the semidwarf cultivars. With a limited sample of one tall and two semidwarf cultivars, Winter et al. (1990) suggested a possible adaptive advantage for non-semidwarf cultivars in a dual-purpose system. Their greater height was believed to offer comparatively more leaf area at heading than the semidwarf cultivars, and potentially greater recovery from grazing. Leaf area index of these three cultivars at anthesis and grain yields of the two semidwarf cultivars increased linearly with increasing biomass at anthesis, while grain yield of the tall cultivar did not increase beyond an anthesis biomass of 1300 g m^{-2} (Winter and Musick, 1991).

With cultivars treated as a qualitative factor, the non-significant system × cultivar mean square in Table 2 would imply that management system had no significant effect on separation of cultivars. The phenotypic correlation between systems was high ($r = 0.89$, $P < 0.01$), indicating similarity of cultivar responses. However, using year of release as a quantitative indicator of their expected level of improvement, linear functions of cultivar yields (i.e., rate of genetic improvement) differed markedly between systems, again with year effects (Table 2, system × cultivar linear, year × system × cultivar linear terms, $P < 0.05$). Rates were significantly greater in the grain-only system than the dual-purpose system in 1997 and 1998 (Table 3, Fig. 1). Recent cultivars performed better than older ones, but the rate of improvement was clearly suppressed under dual-purpose management. Only in 1999 were rates similar between systems, when grazing pressure was low relative to forage availability. Interestingly, no significant progress was detected as a linear trend in the dual-purpose system in 1997, when average yield in that system was greatly reduced compared to other years. These 12 cultivars were included in another experiment in 2000, and treated entirely with propiconazole fungicide. Rates of improvement estimated under the fungicide treatment in 2000 (not shown) were 30.2 (grain-only) and 20.9 kg ha^{-1} yr^{-1} (dual-purpose), and these differed between systems.

Genetic improvement in the grain-only system averaged across the 3-yr period was 18.8 kg ha^{-1} yr^{-1}, equivalent to 1.3% of the mean yield for Turkey, or 0.7% of the mean of all cultivars. Improvement in the dual-purpose system was significantly lower at 11.3 kg ha^{-1} yr^{-1}, equivalent to 0.9% of the mean for Turkey, or 0.6% of the mean of all cultivars. We also estimated genetic improvement without the cultivar Turkey included in the regression analysis, because of the potentially inordinate influence it may have on least-squares estimates of the regression coefficient. The 45-year gap between Turkey and Triumph 64 well exceeded the average 3.3-yr gap between subsequent pairs of consecutive cultivars. Exclusion of Turkey did not change the regression coefficient in the grain-only system, whereas the average rate in the dual-purpose system was even further reduced from 11.3 to 8.8 kg ha^{-1} yr^{-1} ($P < 0.05$, $r^2 = 0.30$).

The genetic superiority of contemporary cultivars is derived not only from their higher yield potential per se but also their greater resistance to foliar diseases. Cultivars developed in the Great Plains routinely express some degree of resistance to the most prevalent fungal disease, leaf rust. Leaf rust resistance has been shown to provide a significant yield advantage in the southern Great Plains (Cox et al., 1997; Martin et al., 1999) and elsewhere (Drijepondt et al., 1990). Cultivars known in this study to possess effectively higher levels of resistance were Custer and 2174. The foliar fungicide, propiconazole, was applied prior to the kernel filling period to provide equal protection to all cultivars from leaf rust and from Septoria leaf blotch. Symptoms of these diseases were observed in all years in the absence of fungicide. Even with those diseases mitigated, the fungicide treatment provided no significant yield benefit (Tables 2 and 4), nor were interactions with systems or cultivars significant (Table 2). Genetic improvement measured in the grain-only system was almost identical in the absence or presence of fungicide (about 19 kg ha^{-1} yr^{-1}, $P < 0.01$), and similar between fungicide treatments in the dual-purpose system (9.5 to 13.1 kg ha^{-1} yr^{-1}, $P < 0.01$, Table 4). Hence, management for grazing had a more profound influence on estimates of yield progress than did management for fungal disease protection.

Yield losses in the dual-purpose system, either as an average across cultivars or as an estimate of genetic improvement, could not be attributed to physical removal of reproductive tissues by grazing, expressed as reduced spike density. Cattle removal always preceded the first appearance of hollow stem above the crown, as defined by Redmon et al. (1996). Considering the two extremes for yield loss (TAM 105 and 2163), each cultivar produced similar numbers of fertile spikes between the two systems: 507 vs. 531 spikes m^{-2} for TAM 105 in grain-only vs. dual-purpose systems, and 459 vs. 448 spikes m^{-2} for 2163. System means for all cultivars were equal (approx. 515 spikes m^{-2}, Table 5). In contrast, changes in the number of kernels per spike and kernel weight were both unidirectional, with lower values consistently found in the dual-purpose system. Each cultivar produced 1 to 4 fewer kernels per spike in the dual-purpose system, and the two systems averaged 27 (grain-only) vs. 25 (dual-purpose) kernels per spike ($P = 0.26$). Each cultivar also had lower 1000-kernel weight by 0.5 to 2.7 g, with system means of 32.2 (grain-only) vs. 30.5 g (dual-purpose) ($P = 0.11$).

While no single yield component may account for the different yield patterns between systems, the discussion above would imply that the combination of, or product of, kernel number per spike and kernel weight, i.e., grain weight per spike, is a key yield determinant in the dual-purpose environment. Losses in the dual-purpose system varied from 87 to 161 mg per spike among cultivars, with average grain weights of 880 for the grain-only system and 758 mg per spike for the dual-purpose system (Table 5). Genetic improvement was significant, averaging 3.2 and 2.8 mg per spike yr^{-1} in the grain-only and dual-purpose systems across years, respectively. Indeed, the lower yields in the dual-purpose system reflected lower spike weights for all cultivars, yet the rate of progress was parallel between systems. The lack of response in spike density, combined with a reduction in grain weight per spike, would seem plausible if the dual-purpose system did not reduce tiller survival but decreased photosynthate production during kernel filling as a consequence of reduced biomass and source capacity at heading. Further research is in progress to quantify source-sink interactions responsible for the differential yield gains.

Test Weight Responses

Cultivar differences were observed for test weight, but these differences varied depending on the system or year in which they were measured (Table 2). During the first two years, test weights of all cultivars tended to be higher (1 to 3%) in the grain-only system than the dual-purpose system, but the reverse was true in 1999. Hence, no difference was found between system means averaged across years (Table 3). Test weights were highly correlated ($r = 0.96$, $P < 0.01$) between systems, indicating a high level of consistency. The benefit of a foliar fungicide application was observed only in the grain-only system, where test weight increased by 3% (Table 4). No significant change was detected in the dual-purpose system.

Genetic improvement in test weight was significant, and greater in the grain-only system than the dual-purpose system in 1997 and 1998 (Table 3); but, in 1999, a genetic decline occurred in the grain-only system. Results from 2000, only with the fungicide treatment, showed zero gains in both systems (data not shown). Averaged across years (1997-1999), improvement in test weight was not evident in either system (Table 3). Gains in test weight were likewise zero, either with or without fungicide protection (Table 4). While test weight did not show the same level of improvement as grain yield, it did not suffer the same degree of reduction in the dual-purpose system. The general lack of progress could be attributed to a lower emphasis on test weight than grain yield during cultivar development, the difficulty in improving both grain yield and test weight simultaneously, or selection practices which traditionally emphasize a constant threshold level rather than incremental increases in test weight.

CONCLUSIONS

With the addition of improved semidwarf cultivars commercialized in the past decade (2157, 2163, Karl 92, Custer, and 2174), our estimate of breeding progress for grain yield in the conventional grain-only system—18.8 kg ha^{-1} yr^{-1}, or 1.4% per year of the mean of Turkey—was consistent with an estimate by Cox et al. (1988) of 16.2 kg ha^{-1} yr^{-1}, or 1.0 % of Turkey. Hence, genetic progress continues for grain yield of HRW wheat, particularly in an environment managed strictly for grain production. Progress in test weight was not detected in this genetic sample. Long-term trends in the Oklahoma State University wheat breeding program generated the same conclusion (Khalil et al., 1995).

Superiority in the grain-only system among contemporary cultivars was similarly expressed in the dual-purpose system, but with a yield penalty as high as 33% and no penalty for test weight. Continued selection in a grain-only system will likely deliver benefits (for grain yield) to a producer using newly developed cultivars in a dual-purpose system. Reducing the yield penalty will, however, require a targeted approach of selection for adaptive characteristics unique to a dual-purpose environment. Among those discussed in more detail by Carver et al. (2001, p. 463), the capacity to recover rapidly from defoliation immediately preceding culm elongation appears to warrant special attention. Rather than establish independent breeding programs for each management system, we suggest an integrative approach of identifying populations, and lines derived from those populations, that are best adapted to a dual-purpose management system, but express high yield potential under a grain-only system.

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Table 1. Features of the dual-purpose management system applied to wheat pastures at Marshall, OK for 3 yr.

Item	1996-1997	1997-1998	1998-1999
Total pasture area, ha†	7.3	9.7	8.5
Grazing initiation	25 Oct. 1996	25 Oct. 1997	17 Nov. 1998
Grazing termination	24 Feb. 1997	20 Feb. 1998	6 Mar. 1999
Grazing period, d	122	118	109
Stocking rate, steer ha^{-1}	2.30	2.06	1.65
Stocking rate, kg steer ha^{-1}‡	651	593	449
Available dry matter forage, kg ha^{-1}	1871 (23 Oct.)	1723 (24 Oct.)	--
	2450 (5 Dec.)	3363 (12 Dec.)	2358 (9 Dec.)
	1154 (20 Jan.)	1211 (20 Jan.)	3022 (11 Jan.)
	651 (14 Feb.)	566 (17 Feb.)	2818 (5 Feb.)
Available dry matter forage per 100 kg steer body wt., kg	402 (23 Oct.)	389 (24 Oct.)	--
	355 (5 Dec.)	611 (12 Dec.)	697 (9 Dec.)
	174 (20 Jan.)	180 (20 Jan.)	626 (11 Jan.)
	96 (14 Feb.)	80 (17 Feb.)	401 (5 Feb.)
Steer wt. gain, kg d^{-1}	0.95	1.08	1.08
Steer wt. gain, kg steer^{-1}	116	127	118
Beef gain, kg ha^{-1}	276	262	194

†Includes experimental plot area of 0.14 ha.
‡Based on mean weight of the cattle during the entire grazing trial.

Table 2. Mean squares for grain yield, and test weight of 12 winter wheat cultivars evaluated under grain-only and dual-purpose systems with and without fungicide for 3 yr at Marshall, OK.

Source of variation	df	Grain yield	Test weight
		$(\mathrm{kg\ ha^{-1}})^2 \times 10^4$	$(\mathrm{kg\ hL^{-1}})^2$
Year (Y)	2	15856	176981
System (S)	1	6167	952
Y x S	2	1270**	18041**
Reps (Y x S)	24 (16)†	70	1728
Fungicide (F)	1	433	13018*
Y x F	2	24	667
S x F	1	110	343**
Y x S x F	2	52	7
F x Reps (Y x S)	24 (16)	19	367
Cultivar (C)	11	776**	11338**
C linear	1	6616**	2088
Y x C	22	189**	874
Y x C linear	2	480**	204
S x C	11	90	446
S x C linear	1	410*	1
F x C	11	21	773*
F x C linear	1	20	1139
Y x S x C	22	60**	941**
Y x S x C linear	2	268**	4952**
Pooled interactions‡	55	76	784
Pooled error	528 (352)	19	278
C.V. (%)		19.2	2.2

*, ** Significant at $P = 0.05$ and 0.01, respectively.

†Degrees of freedom for test weight.

‡Includes (with df) Y x F x C (22) + S x F x C (11) + Y x S x F x C (22), which were non-significant.

Table 3. Means and genetic improvement, estimated by linear regression on year of cultivar release, for grain yield and test weight for 12 winter wheat cultivars evaluated under grain-only (GO) and dual-purpose (DP) systems for 3 yr at Marshall, OK.

		Mean				Rate of improvement per year			
Characteristic	System†	1996-1997	1997-1998	1998-1999	All years	1996-1997	1997-1998	1998-1999	All years
Grain yield (kg ha^{-1})	GO	2240	3560	1800	2533	13.0**	24.5**	18.8**	18.8**
	DP	1140	2790	1910	1947	1.6	9.1**	23.2**	11.3**
P-value for comparing systems‡					0.24	0.01	0.01	0.23	0.02
Test weight (kg hL^{-1})	GO	77.7	79.3	71.9	76.3	0.23**	0.30**	-0.19*	0.05
	DP	75.7	78.4	73.7	75.9	-0.13	0.06	0.37**	0.15
P-value for comparing systems					0.83	0.01	0.01	0.01	0.52

*, ** Significant at $P = 0.05$ and 0.01, respectively.

†Each system included foliar fungicide and no-fungicide treatments in its average.

‡Statistical comparison of within-year means were not attempted due to lack of true error term; comparison of regression coefficients based on significance of system x cultivar linear interaction.

Table 4. Means and genetic improvement, estimated by linear regression on year of cultivar release, for grain yield and test weight for 12 winter wheat cultivars with or without foliar fungicide and evaluated in grain-only (GO) and dual-purpose (DP) systems for 3 yr at Marshall, OK.

		Mean		Rate of improvement per year	
Characteristic	Treatment	GO	DP	GO	DP
Grain yield (kg ha^{-1})	No-fungicide	2420	1910	18.9**	9.5**
	Fungicide	2650	1990	18.6**	13.1**
Comparison between treatments†		NS	NS	NS	NS
Test weight (kg hL^{-1})	No fungicide	75.4	75.6	0.01	0.00
	Fungicide	77.2	76.2	0.08	0.30
Comparison between treatments		*	NS	NS	NS

*,** Significant at $P = 0.05$ and 0.01, respectively.

†Comparison of regression coefficients based on significance of fungicide x cultivar linear interaction across years under each system.

Table 5. Means and genetic improvement, estimated by linear regression on year of cultivar release, for spike density and spike weight for 12 winter wheat cultivars evaluated under grain-only (GO) and dual-purpose (DP) systems for 3 yr at Marshall, OK.

		Mean				Rate of improvement per year			
Characteristic	System†	1996-1997	1997-1998	1998-1999	All years	1996-1997	1997-1998	1998-1999	All years
Spike density (spikes m^{-2})	GO	462	568	511	514	-1.1	-1.2	-0.9	-1.0
	DP	413	529	604	516	-0.2	-0.6	-0.8	-0.5
P-value for comparing systems‡					0.97	NS	NS	NS	NS
Spike weight (mg)	GO	691	894	1056	880	3.2**	3.7**	2.8**	3.2**
	DP	527	887	860	758	1.1	3.4**	3.9**	2.8**
P-value for comparing systems					0.17	0.01	NS	NS	NS

** Significant at *P* = 0.01.

†Each system included foliar fungicide and no-fungicide treatments in its average.

‡Statistical comparison of within-year means were not attempted due to lack of true error term; comparison of regression coefficients based on significance of system x cultivar linear interaction.

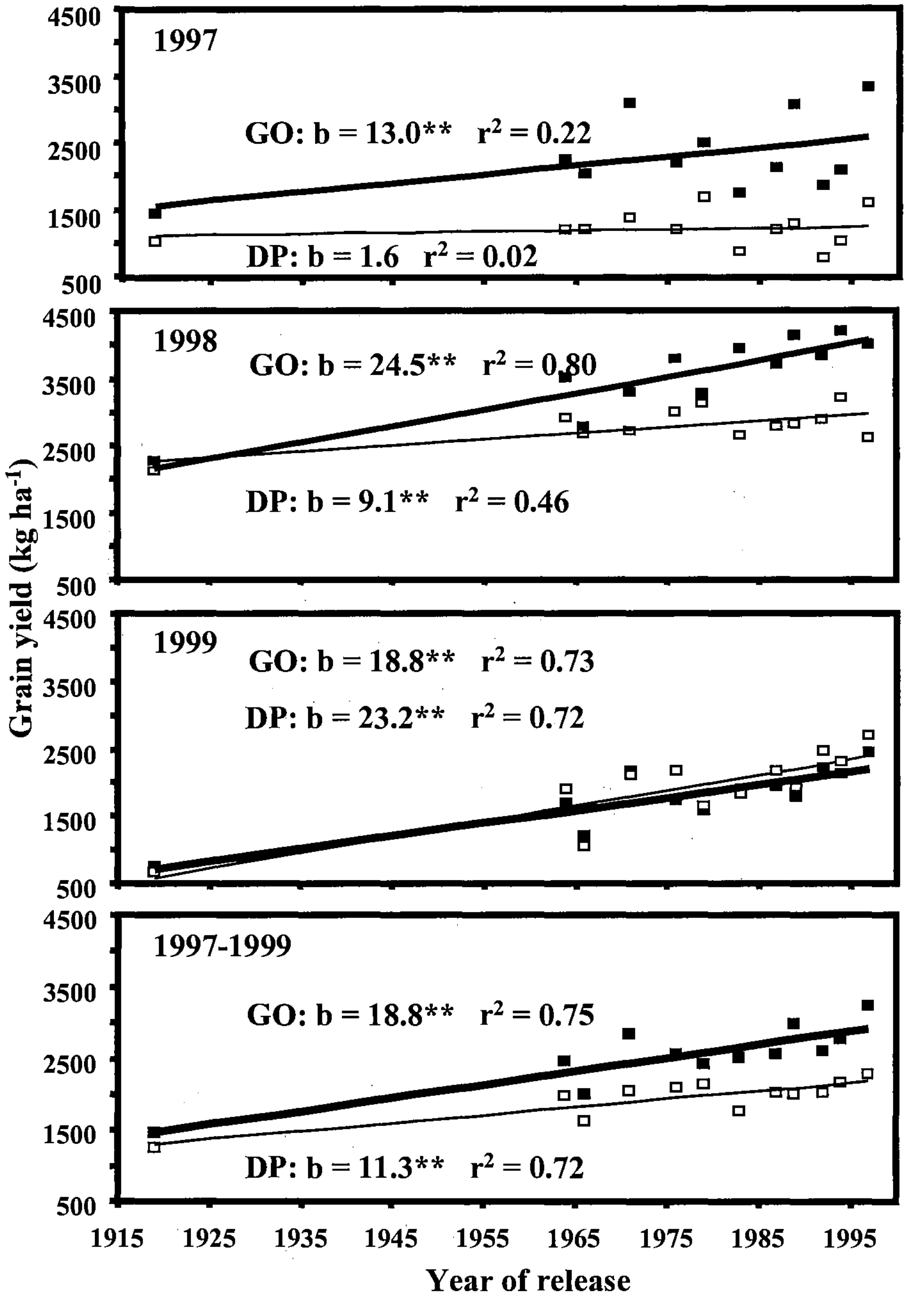

Fig. 1. Linear regression on year of release for grain yield of 12 hard red winter wheat cultivars (averaged across fungicide treatments) under grain-only (GO, solid squares and thick line) and dual-purpose (DP, open squares and thin line) systems in 1997, 1998, 1999, and averaged across 3 yrs at Marshall, OK.

CHAPTER III

GENETIC TRENDS IN WINTER WHEAT GRAIN QUALITY UNDER DUAL-PURPOSE AND GRAIN-ONLY MANAGEMENT SYSTEMS

Genetic Trends in Winter Wheat Grain Quality Under Dual-Purpose and Grain-only Management Systems

Iftikhar H. Khalil, Brett F. Carver*, Eugene G. Krenzer, Charles T. MacKown,

Gerald W. Horn, and Patricia Rayas-Duarte

I.H. Khalil, B.F. Carver, and E.G. Krenzer, Dep. of Plant and Soil Sciences; G.W. Horn, Dep. of Animal Sci.; P. Rayas-Duarte, Dep. of Biochem. and Molecular Biol., Oklahoma State Univ., Stillwater, OK 74078; C.T. MacKown, USDA-ARS, Grazinglands Res. Lab., El Reno, OK 73036. Work supported by USDA-CSREES agreement no. 97-34198-3970 and 99-34198-7481. Published with approval of the Director, Oklahoma Agric. Exp. Stn. Part of a dissertation submitted by I.H. Khalil in partial fulfillment of the Ph.D. degree requirements at Oklahoma State Univ. Received ______________

*Corresponding author (bfc@mail.pss.okstate.edu)

ABSTRACT

Winter wheat (*Triticum aestivum* L.) grain harvested from a dual-purpose crop (forage plus grain) is often perceived by users to have inferior end-use quality compared to that of a grain-only crop. Scientific proof of that perception is lacking, and it is unknown if long-term genetic changes in grain quality are differentially influenced by these management systems. Our objectives were to measure grain and flour quality characteristics of wheat from grain-only and dual-purpose systems for a sample of hard red winter (HRW) cultivars spanning nearly 80 yr of genetic improvement. Separate experiments were established for each system, featuring whole-plot treatments of a foliar fungicide and split-plot treatments of 12 cultivars from Turkey (oldest) to 2174 (newest). The study was conducted for 4 yr at the Wheat Pasture Research Center near Marshall, OK. Dual-purpose experiments were grazed from November through late February or early March of each year. Traits examined were kernel hardness, grain protein, flour yield, mixing time and tolerance, large-kernel fraction, kernel weight, and kernel diameter. The effect of fungicide treatment was not significant, and cultivar × system interactions were generally absent. The correlation between management systems for all traits varied from r=0.74 to 0.99 (P<0.01), indicating a high level of consistency in quality between systems. Kernel weight for the dual-purpose system failed to maintain the same level as the grain-only system for some cultivars, though kernel diameter was not negatively affected. Grain protein and dough strength, measured by mixing time and tolerance, were unaffected by management system. Significant genetic progress was

observed with both systems for only the kernel physical attributes of quality (weight, diameter, and percent large kernels). Detrimental effects of the dual-purpose management system were generally absent for several characteristics commonly used to estimate bread wheat quality.

INTRODUCTION

Hard red winter wheat is the most abundantly produced and exported wheat class in the USA, amounting to approx. 50 million metric tons annually (USDA, 2000). A major part of the crop is produced in the southern Great Plains. In Oklahoma alone, where 10% of the U.S. winter wheat is produced (USDA, 2000), about two-thirds of the wheat acreage may be used for the dual purpose of forage and grain from the same crop (Epplin et al., 1998). Depending on moisture availability, dual-purpose wheat is planted usually in late August or early September to supply ample fall forage for grazing from November to early March. However, early planting, combined with grazing, intensifies drought, insect, and disease pressures (Krenzer, 2000; Kelley, 2001; Lyon et al., 2001). Consequently, studies in the southern Great Plains have concluded that sometimes grain yield declines in a dual-purpose system, depending on stocking rate or the degree of defoliation, relative to a grain-only system (Winter et al., 1990; Winter and Thompson, 1990; Winter and Musick, 1991). Associated effects on wheat quality are not documented but are key to our understanding if hard winter wheat is to continue as a world supplier of bread wheat.

Wheat grain harvested from a dual-purpose crop is often perceived to have inferior quality compared to that of a grain-only crop. Several physical and compositional characteristics of grain influence bread wheat quality that are considered critical in the domestic and international wheat trade. These characteristics are greatly affected by genotype as well as the production environment (Peterson et al., 1998; Guttieri et al., 2000; Marry et al., 2001; Zhu and Khan, 2001), leading to large variation in end-use quality parameters. Kernel weight and size, and protein content, may be reduced in the dual-purpose system, possibly due to reduced photosynthetic assimilation and nitrogen available for redistribution during grain filling after forage removal (MacKown and Rao, 1998). Both protein content and composition are critical to several physical characteristics of dough, which in turn influence bread volume and texture (Finney et al., 1987).

Several high yielding wheat cultivars have replaced their predecessors during the past decade, but genetic improvement in quality attributes has not been evaluated since the report by Cox et al. (1989). We attempted to ascertain genetic changes in quality, but in the context of how such changes might be influenced by dual-purpose management, a system unlikely used in the selection of cultivars. Therefore, this study was conducted to: (i) determine selected grain and flour quality characteristics of wheat harvested from grain-only and dual-purpose systems, and (ii) compare levels of genetic improvement for quality expressed in the two systems.

MATERIALS AND METHODS

Field experiments were conducted at the Wheat Pasture Research Center near Marshall, OK, during the 1996-1997, 1997-1998, 1998-1999, and 1999-2000 (hereafter 1997, 1998, 1999, and 2000, respectively) crop seasons. Experimental methods were described completely by Khalil et al. (2001), but are repeated here in part for reader convenience. Twelve HRW wheat cultivars (with their assigned year of release)—Turkey (1919), Triumph 64 (1964), Scout 66 (1966), TAM W-101 (1971), Vona (1976), TAM 105 (1979), Chisholm (1983), 2157 (1987), 2163 (1989), Karl 92 (1992), Custer (1994), and 2174 (1997)—were grown in grain-only and dual-purpose management systems in adjacent areas of the pasture. A split-plot treatment design with five replicates was used in each system, wherein foliar fungicide vs. no-fungicide treatments were assigned to whole-plots and the 12 cultivars to sub-plots. The 2000 experiment employed a randomized complete block design using the fungicide treatment only, due to the absence of fungicide × system and fungicide × cultivar interactions for grain yield and test weight in the previous 3 yr (Khalil et al., 2001). Each sub-plot consisted of five 3.0-m long rows spaced 0.23 m apart.

The dual-purpose experiments were planted during early to mid-September using a seeding rate of 77 kg ha^{-1}, while the grain-only experiments were planted during mid-October with a seeding rate of 58 kg ha^{-1}. The dual-purpose plots were continuously grazed each year from late-October or early-November until the appearance of hollow stem (early jointing) during late-February or early-March, determined in ungrazed plants of an early maturing cultivar with the same planting date (Redmon et al., 1996). Grazing duration and average stocking rate were 122 d and 2.30 steer ha^{-1} (≈ 651 kg steer ha^{-1}) in 1997, 118 d and 2.06 steer ha^{-1} (≈ 593 kg steer ha^{-1}) in 1998, 109 d and 1.65 steer ha^{-1} (≈ 449 kg steer ha^{-1}) in 1999, and 90 d and 1.38 steer ha^{-1} (≈ 414 kg steer ha^{-1}) in 2000, respectively. Other features of the dual-purpose system were described by Khalil et al. (2001). Nitrogen fertilizer (anhydrous NH_3) was applied according to Oklahoma State University soil-test recommendations for grain and dry forage yield targets of 3000 and 3500 kg ha^{-1}, respectively. Actual amount of N applied varied over years due to adjustment for residual N in the top 60 cm of soil.

All plots of both systems were harvested the same day each year. Immediately preceding harvest, 15 random spikes were collected per plot and threshed to determine 1000-kernel weight. A 200-g grain sample from the bulk harvest of each plot was sifted for 1 min through a Tyler seive no. 7 (2.82 mm-wide slots) using a Tyler Ro-tap sieve shaker (W.S. Tyler Co., Mentor, OH). Percent large kernels was calculated from the weight of grain retained on the sieve. Average kernel diameter was determined using the Perten Single Kernel Characterization System (SKCS, Perten Instruments, Reno, NV).

Quality analyses were performed at the Oklahoma State University Wheat Quality Lab. using procedures described by Carver (1994). Kernel hardness and grain protein content were determined by near-infrared reflectance (NIR) spectroscopy using a 9 g whole ground-wheat sample from each plot (method 39-70, AACC, 1995). Hardness index score was measured on a scale of 0 (extremely soft) to 100 (extremely hard). Extraction rate or flour yield was determined using AACC method 12-10A (AACC, 1995 in a 125 g grain sample, after cleaning and tempering the grain to 155 g kg^{-1} moisture and milling on a Brabender Quadrumat senior mill (C.W. Brabender Instruments, South

Hackensack, NJ). Flour yield and grain protein were adjusted to a 140 g kg^{-1} moisture basis. Mixing characteristics were determined with a computer-assisted mixograph (National Manufacturing Co., Lincoln, NE) using a 10 g bowl (method 54-40, AACC, 1995). Mixing time was the number of minutes needed for optimal dough development and was adjusted for flour samples with <120 g kg^{-1} protein. Mixing tolerance was rated subjectively on a scale of 1 to 10 based on visual comparison of the mixogram with 10 standard tracings for each of three ranges of flour protein (<10%, 10-13%, and >13%). Scores of 1 to 2 were considered as poor mixing tolerance, 3 to 6 as moderate, and 7 to 10 as strong. Mixing tolerance was also determined as the width of the mixogram curve at 2 min past peak development.

Percent large kernels was measured in four to five replicates (fungicide treatment only) in 1998, 1999, and 2000, while kernel diameter was determined in one or three replicates (fungicide treatment only) in 1999 and 2000. Kernel weight was measured on all replicates, while remaining quality traits were determined on three of the five replicates (both fungicide and no-fungicide treatments) in 1997, 1998, and 1999.

Data across years and systems were analyzed using a mixed-effects model for each attribute, wherein systems, fungicide treatments, and cultivars represented fixed effects, while replicates and years were random. Cultivar means for the two systems were compared using least significant difference (LSD) values. To determine genetic improvement over time, the cultivar sum of squares in the analysis of variance across years for each system was partitioned into terms presenting linear regression on year of release and deviations from regression. The regression coefficient was considered as an estimate of genetic progress for that trait. Heterogeneity of regression coefficients between two systems was based on the significance of system × cultivar linear interaction in the combined analysis of variance across years and systems (Khalil et al., 2001).

RESULTS AND DISCUSSION

The analysis of variance across years and the two management systems showed significant genetic variation among cultivars for all traits, except for NIR hardness and grain protein (Table 1). Averaged across cultivars and years, the management system main effect was not significant for any quality trait. The general lack of cultivar × system interactions (except for kernel diameter) and the strong relationship between management systems for all traits ($r = 0.74$ to 0.99, $P < 0.01$) indicated that cultivars with desirable quality in the grain-only system showed similar quality in the dual-purpose system. The main effect of fungicide treatment, as well as interactions with other factors, were not significant for any trait. Subsequent discussion of cultivar trends will derive from means across fungicide treatments.

Kernel weight and size (kernel diameter) are widely used quality indicators in the wheat trade due to their reported influence on wheat milling performance. Wheat breeders often set targets of >28 g for 1000-kernel weight and >2.1 mm for average kernel diameter, even though standards for these traits are not enforced within wheat markets. Turkey and TAM W-101 showed lowest and highest kernel weights, respectively, in both systems, ranging from 27.0 to 37.4 g in the grain-only system and from 25.6 to 36.2 g in the dual-purpose system (Fig. 1a). System means across all cultivars and years (Table 2) were still about 3 to 4 g above the minimum target value of 28 g. Chisholm and 2163 were two cultivars that showed a significant reduction (P=0.05) in the dual-purpose system. No cultivar showed any increase in kernel weight. The moderate correlation between kernel weight and test weight in the dual-purpose system ($r = 0.62$, P=0.03) and in the grain-only system ($r = 0.55$, P=0.06) indicated that kernel weight only partly influenced test weight. Moderate to strong association of kernel weight with test weight was previously reported for Karl 92 (Gibson et al., 1998) and for a set of several hard winter wheat cultivars and experimental lines (Merkle et al., 1969).

The complete absence of any cultivar showing increased kernel weight under the dual-purpose system contrasted with several cultivars showing increased kernel diameter (Table 2). The two cultivars with significantly lesser kernel weight under the dual-purpose system, Chisholm and 2163, had greater kernel diameter in the dual-purpose system (Fig. 1b), as did five other cultivars (Scout 66, Vona, TAM 105, Custer, and 2174). Increases in kernel diameter in the dual-purpose system could be related to formation of slightly fewer kernels (Khalil et al., 2001) and spikelets per spike (C.T. MacKown, unpublished data). However, average kernel diameters in the grain-only and dual-purpose systems across all cultivars were similar (Table 2). On a phenotypic basis, kernel diameter was positively correlated with kernel weight ($r \geq 0.77$, $P < 0.01$) in either system. Thus, those cultivars having a genetic tendency toward heavier kernels also had larger kernels. Examples of this association were Triumph 64 and TAM W-101.

International buyers of U.S. HRW wheat are placing more demand on uniform kernel size to better assure optimal flour yields (Oades, 1997). Kernel size distribution may be determined as the proportion of kernels retained over various wire-mesh screens. We used the Ro-tap sifter as the shaking device and a Tyler sieve no. 7 to separate and quantify the proportion of "large" kernels. All cultivars, except Turkey and Vona, contained a minimum of 50% large kernels in both systems (Fig. 1c). Kernel size distribution was not affected by management system, averaging 59% large kernels in the grain-only vs. 57% in the dual-purpose system (P=0.50, Table 2). Triumph 64 had the largest reduction in large-kernel fraction from the grain-only (70%) to the dual-purpose system (59%), but differences shown by other cultivars were minor and ambi-directional. The proportion of large kernels was highly correlated among cultivars with 1000-kernel weight, both in the grain-only and dual-purpose systems ($r \geq 0.85$, $P < 0.01$), and with kernel diameter ($r \geq 0.90$, $P < 0.01$). Contemporary cultivars did not necessarily have the highest proportion of large kernels. TAM W-101, released 30 years ago, conspicuously had heavier kernels and a higher proportion of large kernels in both systems.

Both domestic and foreign millers prefer wheat grain that produces a high yield of flour. Genetic variation in flour yield may result from differences in the proportion of endosperm in the kernel (Bergman et al., 1998), and can be influenced by physical characteristics of the grain, such as kernel weight and size, for which these cultivars had genetic variation (Table 1). Flour yield varied from 595 (Vona) to 631 g kg^{-1} (Scout 66) in the grain-only system and from 584 (Chisholm) to 631 g kg^{-1} (both Triumph 64 and Karl 92) in the dual-purpose system, producing a negligible difference in means (P =0.75) between the grain-only (614 g kg^{-1}) and the dual-purpose systems (608 g kg^{-1}). These values are low compared to commercial extraction rates, but are representative of samples milled on a laboratory-scale flour mill equipped with only one break and reducing roll. These results are useful for a comparative purpose but do not equal the extraction rate obtained with an industrial mill.

We found no association of flour yield with 1000-kernel weight or large-kernel fraction under either system. For example, TAM W-101 had the highest kernel weight and a high proportion of large kernels both in the grain-only and dual-purpose systems, but its flour yield was 10 to 20 g kg^{-1} lower than Turkey (lowest in kernel weight and large-kernel fraction) in the two systems. A similar trend occurred for Custer. In contrast, Scout 66 and 2157 had a relatively low kernel weight and large-kernel fraction, but yielded maximum flour across systems (630 and 625 g kg^{-1}, respectively). Though a comparable experiment with HRW wheat is lacking, Gains et al. (1997) sieved non-shriveled grains of seven soft wheat cultivars into large, medium, and small kernels. Kernel weight decreased with decreasing kernel size, without any change in flour extraction. However, only a moderate level of kernel shriveling significantly reduced flour yield.

All cultivars, other than Turkey, span five former and current breeding programs in the southern Great Plains, but surprisingly, genetic or system differences were absent for kernel hardness and wheat protein (Table 1). Averaged across cultivars, hardness showed identical scores of 50 in both systems. Grain protein varied only one percentage unit from 121 (Chisholm) to 132 (Triumph 64 and Scout 66) g kg^{-1} under either management system (data not shown), or about 6 to 17 g kg^{-1} higher than what is often considered the minimum target value of 115 g kg^{-1} for HRW wheat. The two systems averaged 127 (grain-only) and 128 (dual-purpose) g kg^{-1} (P=0.87), even though yield performance was influenced by management systems (Khalil et al., 2001). A decrease in wheat protein under the dual-purpose system would have agreed with preliminary observations reported by MacKown and Rao (1998) and the greater potential for N deficiency with greater forage production and removal. Our results agree with those reported by Royo and Pares (1996) and Royo and Tribo (1997), who observed no differences in grain protein content of mechanically clipped dual-purpose and grain-only treatments in barley and triticale.

Dough strength, an indication of protein quality, was evaluated using mixing time, mixing tolerance score from visual ratings of the mixogram, and mixogram curve width at 2 min past peak development. Commercial bakeries produce best yeast products with a flour having moderate mixing time (3 to 7 min) and good mixing tolerance (>3, 1-10 scale). Mixing time varied among cultivars from 4.4 to 7.0 min in the grain-only system and 4.3 to 6.8 min in the dual-purpose system (Fig. 2a), with only a 6-sec difference between system means (*P*=0.31, Table 2). Mixing tolerance scores also were within the commercially acceptable range in both systems (3 to 6, Fig. 2b), with no difference between systems (Table 2). Mixogram curve width among cultivars varied from 9.5 to 14.4 mm in the grain-only system and from 10.9 to 15.3 mm in the dual-purpose system (Fig. 2c), also with no difference between system means. Triumph 64 actually had significantly larger curve width in the dual-purpose system (11.9 mm) than the grain-only system (9.5 mm). Mixing time and mixing tolerance may increase with protein content, but such an association did not exist in either system, given the low cultivar variation for protein. Triumph 64 and Karl 92 tended to have highest grain and flour protein (data not shown) content in both systems, but their mixing times varied by 3 min (4 and 7 min, respectively). The same disparity was observed for mixing tolerance. TAM 105 tended to have lowest grain and flour protein (109 g kg^{-1}) in both systems, but had the highest mixing tolerance score (Fig. 2b); however, the reverse was true for Triumph 64. These observations underscore the significance of compositional factors, such as glutenin and gliadin structure, that influence protein functionality.

Genetic selection for improved milling and bread baking characteristics is an integral component of all wheat breeding programs in the southern Great Plains. Selection often takes the form of adopting industry-recommended standards for physical (kernel size and texture) and analytical (dough quality) attributes among breeding lines chosen for superior agronomic potential. Progress in grain yield was previously shown for this set of cultivars, albeit at a reduced level in the dual-purpose system (Khalil et al., 2001). Significant progress was also observed for kernel size attributes, except for kernel diameter in the grain-only system (Table 2). Rates of progress for 1000-kernel weight were 0.05 to 0.06 g yr^{-1} in both systems, although an older cultivar, TAM W-101, showed the highest kernel weight in both systems. These estimates for kernel weight were similar in magnitude to those reported by Cox et al. (1988). Increases in kernel weight corresponded to significant increases in the large-kernel fraction, with no negative impact of the dual-purpose system. No trends were observed in kernel hardness, protein content, flour yield, or mixograph attributes over time under either system (Table 2). With a larger set of HRW wheat cultivars, Cox et al. (1989) observed a significant increase in flour protein and in mixing time. Despite slight improvements in average kernel size, flour yield has not substantially increased in hard red winter wheat (Cox et al., 1989; Peterson et al., 1997) and hard red spring wheat (Souza et al., 1993).

With the exception of kernel weight, we found no obvious detrimental influence of the dual-purpose management system on several characteristics commonly used to describe end-use quality of hard winter wheat. If managed properly for seeding rate and date, grazing initiation and termination, and nitrogen application, this management system should allow the same expression of genetically improved quality traits expected under a grain-only system. Recognizing that actual production practices may depart from those employed in this study, communication among breeders, consultants, growers, handlers, and processors is important to a better understanding of quality expectations following recommended practices.

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Table 1. Summary of selected F-tests for physical and chemical grain quality attributes of 12 hard red winter wheat cultivars evaluated under grain-only and dual-purpose systems at Marshall, OK from 1997 to 2000.

	Kernel size			Wheat attributes			Mixograph attributes		
Source	Kernel weight	% large kernels†	Kernel diameter †	NIR hardness	Grain protein	Flour yield	Mixing time	Mixing tolerance	Curve width‡
	g	%	mm	1-100	g kg^{-1}	g kg^{-1}	min	1-10	mm
System (S)	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fungicide (F)	NS	--	--	NS	NS	NS	NS	NS	NS
S x F	NS	--	--	NS	NS	NS	NS	NS	NS
Cultivar (C)	**	**	**	NS	NS	**	*	*	*
S x C	NS	NS	*	NS	NS	NS	NS	NS	NS
F x C	NS	--	--	NS	NS	NS	NS	NS	NS
S x F x C	NS	--	--	NS	NS	NS	NS	NS	NS
Mean	31.3	58.0	2.2	50.1	127	611	5.1	4.5	12.4
C.V. (%)	9.4	13.4	2.8	25.3	6.8	4.4	14.8	19.6	17.4

*, ** F-test significant at $P = 0.05$ and 0.01, respectively; NS: not significant ($P > 0.05$).

† % large kernels determined in 1998, 1999, and 2000 under fungicide treatment only, and kernel diameter determined in 1999 and 2000 under fungicide treatment only. All other attributes determined in 1997, 1998, and 1999 under fungicide and no-fungicide treatments.

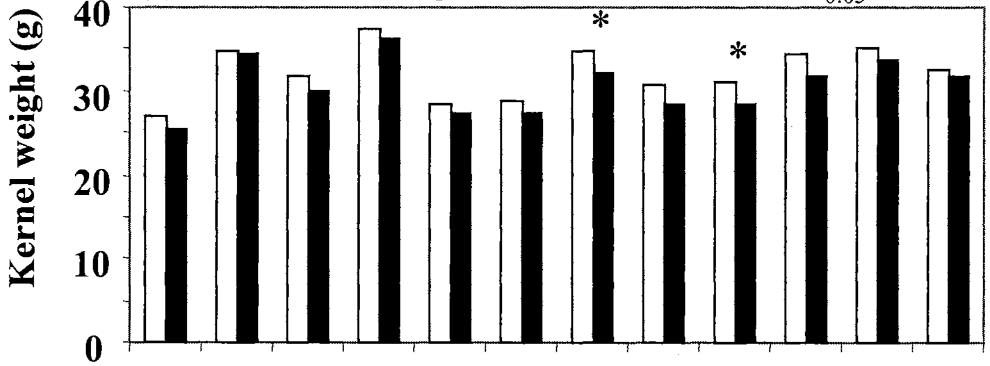
‡Measured at 2 min past peak development.

Table 2. Means ($\overline{X}$) and regression coefficients (*b*), estimated by linear regression on year of cultivar release, for kernel size and mixograph attributes of 12 hard red winter wheat cultivars grown in grain-only (GO) and dual-purpose (DP) systems at Marshall, OK from 1997 to 2000.

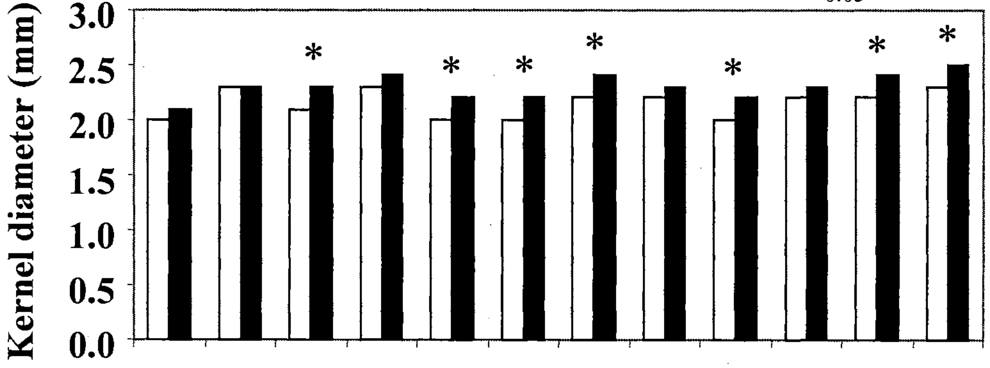
Trait	System	($\overline{X}$)	*b*†
1000-kernel weight (g)	GO	32.2	0.06**
	DP	30.5	0.05**
P value		0.11	NS
Large kernel fraction (%)‡	GO	59.0	0.22*
	DP	57.2	0.34*
P value		0.50	NS
Avg. kernel diameter (mm)‡	GO	2.16	0.002
	DP	2.29	0.004*
P value		0.23	0.05
Mixing time (min)	GO	5.2	0.01
	DP	5.1	0.01
P value		0.31	NS
Mixing tolerance score (1-10)	GO	4.6	0.006
	DP	4.4	0.003
P value		0.50	NS
Mixogram curve width (mm)§	GO	12.2	0.018
	DP	12.7	-0.003
P value		0.62	NS

*,** Significant at $P = 0.05$ and 0.01, respectively; NS: not significant ($P > 0.05$).
†Comparison of regression coefficients based on significance of system x cultivar linear interaction.
‡Evaluated under fungicide treatment only.
§ Measured at 2 min past peak development.

(a) 1000-kernel weight LSD$_{0.05}$=2.5



(b) Kernel diameter LSD$_{0.05}$=0.2



(c) Percent large kernels LSD $_{0.05}$=11

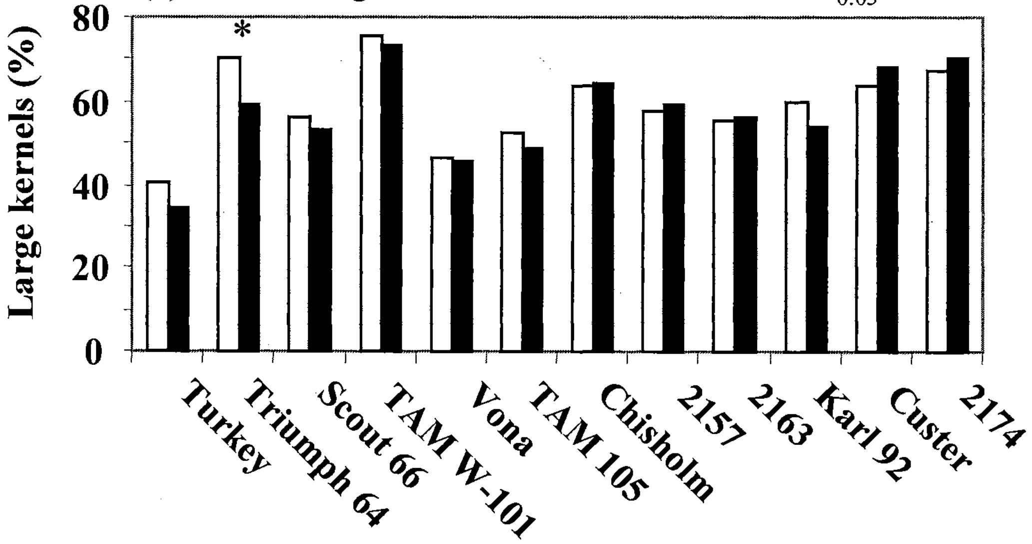


Fig. 1. 1000-kernel weight (a), kernel diameter (b), and percent large kernels (c), of 12 hard red winter wheat cultivars evaluated under grain-only (open bars) and dual-purpose (closed bars) systems at Marshall, OK. LSD given for comparing means for the same cultivar between systems.

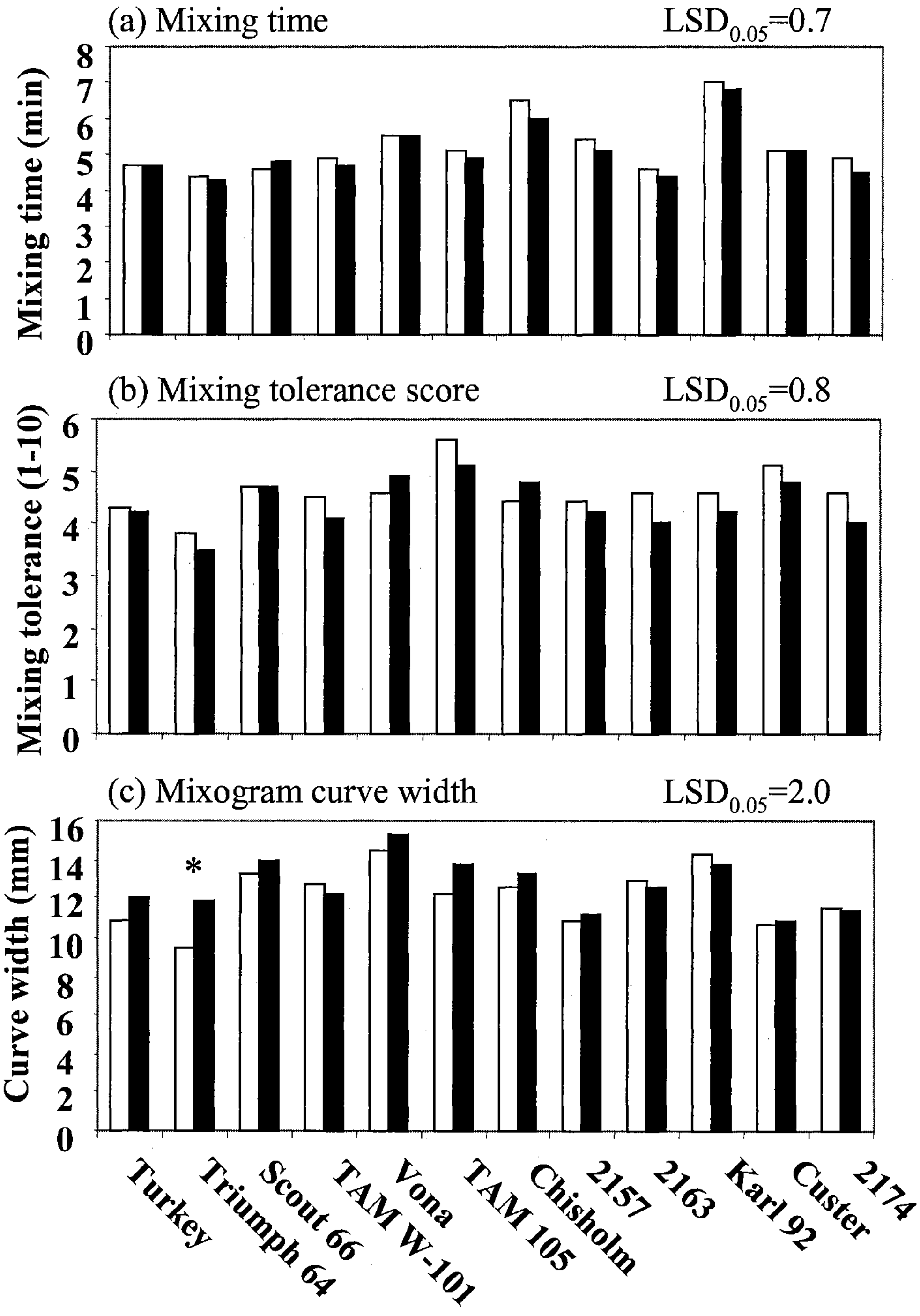


Fig. 2. Mixing time (a), mixing tolerance score (b), and mixogram curve width (c), of 12 hard red winter wheat cultivars evaluated under grain-only (open bars) and dual-purpose (closed bars) systems at Marshall, OK. LSD given for comparing means for the same cultivar between systems.

CHAPTER IV

GENETIC PARAMETER ESTIMATION FOR AGRONOMIC TRAITS IN GRAIN-ONLY AND FORAGE-PLUS-GRAIN WINTER WHEAT SYSTEMS

Genetic Parameter Estimation for Agronomic Traits in Grain-only and Forage-plus-grain Winter Wheat Systems

Iftikhar H. Khalil, Brett F. Carver*, and Eugene G. Krenzer

I.H. Khalil, B.F. Carver, and E.G. Krenzer, Dep. of Plant and Soil Sciences, Oklahoma State Univ., Stillwater, OK 74078. Published with approval of the Director, Oklahoma Agric. Exp. Stn. Part of a dissertation submitted by I.H. Khalil in partial fulfillment of the Ph.D. degree requirements at Oklahoma State University. Received ________________

*Corresponding author (bfc@mail.pss.okstate.edu)

ABSTRACT

More than 3.2 million hectares of hard winter wheat (*Triticum aestivum* L.) are managed for the dual purpose of forage-plus-grain in the southern Great Plains of USA, yet no cultivars to date were bred specifically under a dual-purpose management system. This discrepancy between cultivar selection environment and target environment prompted an investigation, beginning with the 1996-97 crop season, to determine whether breeders should select winter wheat genotypes in a forage-plus-grain system, or continue the current practice of indirect selection in the grain-only system. Thirty-seven random winter wheat lines were evaluated in three experiments in a randomized complete block design for 3 yr at the North Central Research Station, Lahoma, OK. Each experiment represented either an early-planted forage-plus-grain (FG) system, a normal-planted grain-only (GO) system, or a forage-plus-grain control (FGC) system, in which the forage was not removed. To simulate continuous grazing, the FG experiments were mechanically clipped three to four times from November until first-hollow-stem development in late-February. Though significant genetic variation was observed among random wheat lines for all traits under each system, the genotype × system interactions were not significant due to strong genetic ($r_G \geq 0.94$) and phenotypic ($r_P \geq 0.71, P < 0.01$) correlations. Genetic variances and heritability estimates for all traits were equal to or slightly higher in the GO system than those in FG and FGC systems. Indirect selection in the GO system was just as effective as direct selection for trait improvement in the FG system. These results do not imply that separate selection efforts be applied in FG and GO systems.

INTRODUCTION

Breeders are often faced with the dilemma to either conduct selection under conditions to which selected genotypes are targeted, or under conditions which optimize expression of the selected traits. This scenario bears relevance to wheat breeding programs in the southern Great Plains, where cultivars are usually bred in a grain-only system but are mostly cultivated for the dual purpose of forage-plus-grain production (Redmon et al., 1995). This imbalance between cultivar development and usage is more apparent in Oklahoma, where up to 66% of the winter wheat acreage is used for the dual purpose of forage plus grain, 25% for grain only, and 9% for forage production only (Epplin et al., 1998).

Most breeding programs in the southern Great Plains use a modified bulk-population scheme for cultivar development. Each year, several hundred populations are bulk-tested in the F_2 to F_4 generations, from which 20,000 to 40,000 head rows are selected for observation under a grain-only system. The selected head progenies are ultimately submitted to one or more of the USDA-ARS supported regional nurseries, including the Southern Regional Performance Nursery (SRPN), for further evaluation before release as a cultivar. As such, the newly released cultivars in the region are hardly exposed to the potential stresses associated with early planting and forage removal—two main features of the dual-purpose system. A selection environment that features early planting would appear essential to selecting genotypes adapted to a dual-purpose system. Reductions in grain yields of currently used cultivars with early planting in August or September compared to a mid-October planting clearly demonstrate this requirement

(Krenzer et al., 2000; Heer and Krenzer, 1989). Besides crown and root rots (Lyon et al., 2001), early planting also increases exposure to insects vectoring wheat streak mosaic (Wiese, 1991) and barley yellow dwarf viruses (Kelley, 2001), which newly released cultivars do not encounter to the same degree with most breeding regimes. Additionally, the removal of forage, either by clipping or grazing, would be advantageous for selecting genotypes with optimum recovery from defoliation and grain production. Perhaps, cultivar selection is conducted under the grain-only system, because it is not only easily manageable but also more economical than the forage-plus-grain system, especially one that involves actual grazing.

Selection under the grain-only system may produce genotypes with acceptable yield performance in the forage-plus-grain system if the genetic correlation between grain yield in the grain-only and forage-plus-grain systems is large and positive and if heritability of grain yield is greater in the grain-only system than in the forage-plus-grain system. Research evidence indicates that rates of genetic gain for grain yield are smaller or even nonexistent in the dual-purpose system as compared to the grain-only system (Khalil et al., 2001), suggesting that selection be strictly conducted under the target system (Ceccarelli, 1989). However, past research in the Great Plains and elsewhere have mainly focused on cultivar response to forage removal (Redmon et al., 1995), rather than testing breeding strategies for maximizing cultivar performance in a forage-plus-grain system.

Therefore, the objectives of this study were to 1) estimate and compare genetic parameters relevant to genetic improvement in grain-only and forage-plus-grain systems, and 2) suggest an optimum selection strategy for simultaneous genetic improvement of grain yield in the two management systems.

MATERIALS AND METHODS

This study was conducted at the North Central Research Station, Lahoma, OK, during the 1996-1997, 1997-1998, and 1998-1999 crop seasons (hereafter referred to as 1997, 1998, and 1999, respectively). Thirty-seven experimental winter wheat lines and three widely adopted hard red winter (HRW) wheat cultivars were evaluated in three management systems: i) forage-plus-grain (FG); ii) forage-plus-grain control, in which the forage was not removed (FGC); and, iii) grain-only (GO). The experimental entries were random S_2 (1997), S_3 (1998), and S_4 (1999) lines from a recurrent selection population, originally developed to compare grain yield and protein under a grain-only system. The check cultivars were, Tomahawk, Jagger, and 2174, all recognized for their adaptation to forage-plus-grain management systems.

To minimize environmental bias, the three systems were treated as independent experiments and planted adjacently in the field, using a randomized complete block design with four replicates per system. Each plot had five rows, spaced 0.23 m apart and 3 m long. Both the FG and FGC experiments were planted 9 Sept. 1996, 28 Aug. 1997, and 18 Sept. 1998, using a seeding rate of 77 kg ha^{-1}, while the GO experiments were planted 14 Oct. 1996, 2 Oct. 1997, and 23 Oct. 1998, with a seeding rate of 58 kg ha^{-1}. To simulate continuous grazing, the FG experiments were mechanically clipped three to four times with a rotary mower to approximately 5 cm aboveground. Clipping commenced in November and was terminated when the non-clipped Jagger plots in the FGC system reached hollow stem (early jointing) development. Jagger is reputed to be very early in hollow stem development (mid to late February) among the current hard winter wheat cultivars in the southern Great Plains (Krenzer, 2000); hence, clipping termination was often early for the experimental lines. The FGC system was included to determine if results similar to the FG system might be obtained without the added expense of forage removal. Nitrogenous fertilizer was applied according to the Oklahoma State University soil-test recommendations for a grain yield target of 3000 kg ha^{-1} in each system. The FG experiments were also topdressed immediately following the last cutting based on a dry forage target of 3500 kg ha^{-1}, using 15 kg N for each 500 kg of harvested dry forage. All five rows of a plot in each system were combine-harvested the same day. Grain yields were measured in all replicates, while 1000-kernel weight and test weight were measured in two to three of the four replicates.

Data collected for the 37 experimental lines were analyzed across years and systems using a mixed-effects model, with systems considered as a fixed effect, while replicates, years, and genotypes were considered random. Variance components across years in each system and their standard errors were estimated using the MIXED procedure and Covtest option in SAS (SAS Institute, 1996). Heritability estimates were computed on an entry-mean basis in each system from the components of variance combined across years to reduce genotype-by-year bias. Exact 90-percent confidence intervals for heritabilities were determined according to Knapp et al. (1985). The estimate of genetic correlation, r_G, for a trait between two systems was obtained as, $r_G = COV_{G(XY)}/ \sigma_{G(X)} \sigma_{G(Y)}$, where $COV_{G(XY)}$ is the genetic covariance among systems X and Y, and $\sigma_{G(X)}$ and $\sigma_{G(Y)}$ are the square roots of the genetic variance of the same trait in systems X and Y, respectively. The genetic covariances were estimated using the

MANOVA option in PROC ANOVA. Standard errors for the genetic correlations were determined according to Falconer and Mackay (1996).

Direct response, DR, to selection for a trait in system X was predicted as, $DR_X = i_X h^2_X \sigma_{PX}$, wherein i_X is the selection intensity, h^2_X is the heritability, and σ_{PX} is the square root of the phenotypic variance of the trait in system X. The correlated or indirect response for a trait in system X to selection in system Y, $CR_{X(Y)}$, was determined as, $CR_{X(Y)} = i_Y h_X h_Y r_G \sigma_{PX}$, where i_Y is the selection intensity in system Y, h_X and h_Y are square roots of heritabilities of the trait in systems X and Y, respectively, and r_G is genetic correlation for the trait between the two systems. A similar selection intensity of 15% ($i = 1.55$; Falconer and Mackay, 1996) was assumed in predicting both direct and indirect selection responses.

RESULTS AND DISCUSSION

The three management systems did not differ for average grain yield (P=0.28), kernel weight (P=0.33), or test weight (P=0.47), though significant interactions with years indicated that grain yield and test weight comparisons for the three systems varied during the 3-yr period (Table 1). Grain yields in the FGC system were consistently lower than the FG and GO systems during all years: 15 and 17% less in 1997, 2 and 18% less in 1998, and 24 and 3% less in 1999. The FG system yielded 3 and 16% less than the GO system in 1997 and 1998, respectively, but in 1999, grain yield in the GO system was 22% lower than the FG system (data not shown). Averaged across years, grain yields both in the FG and GO systems were about 2700 kg ha^{-1} vs. 2324 kg ha^{-1} in the FGC system, or a 14% reduction due to non-removal of excess forage or due to early planting in the FGC system (Table 2). Early planting in August or September often leads to reduced grain yields compared to the recommended early to mid-October planting dates for winter wheat (Kelley, 2001; Heer and Krenzer, 1989).

Significant genetic variation was found among experimental lines for all traits, while genotype × system interactions were not significant (Table 1). Indeed, phenotypic correlations among systems were high ($r_P \geq 0.71$, $P < 0.01$) for all traits, indicating consistent performance of wheat lines across systems. Mean grain yield of experimental lines ranged from 2189 to 3111 kg ha^{-1} in FG, 1848 to 2827 kg ha^{-1} in FGC, and 2266 to 3044 kg ha^{-1} in the GO system. Genetic variances tended to be larger in the FG and FGC systems than the GO system, but these differences were minor (Table 2). In contrast, genetic variances for 1000-kernel weight and test weight were 2- to 3-times greater in the

GO system than the early-planted FG and FGC systems, while error variances for grain yield and test weight were reduced by about 30 to 60% in the GO system.

There was no consistent relationship between genetic variance and the magnitude of heritability (Table 3). As noted above, genetic variances for grain yield were numerically greater in the early-planted FG and FGC systems, but the resultant heritabilities were comparatively smaller than the GO system due to higher genotype-by-year and/or error variances. The differences in heritability estimates for all traits were indistinguishable based on their confidence intervals except for test weight in the GO system, which was 49% greater compared to the FGC system. Genetic correlations among the three systems were high ($r_G \geq 0.94$) for all traits (Table 3), indicating that at least 88% or more of the genetic variation for a trait was common in any given pair of the three systems. Interestingly, the heritabilities for test weight under the GO (0.85) and FGC (0.57) systems differed significantly, but the genetic correlation between the two systems was 1.03. Thus, the grain-only environment might not only be more conducive to improving test weight but also serve as a proxy to improving test weight in the early-planted forage-plus-grain system. A genetic correlation coefficient exceeding 1.0 between selection environments was previously reported for yield in white clover (Rowe and Brink, 1993) and for several yield components in sugarcane (De Sousa-Vieira and Milligan, 1999).

The perfect genetic ($r_G = 0.94\text{-}1.0$) and phenotypic ($r_P \geq 0.71$, $P < 0.01$) correlations among the three systems for all traits indicate that selection in this population of wheat lines in any system is likely to produce similar responses in other systems. This was evident from the relatively small differences in predicted direct and indirect selection responses for each system (Table 4). Assuming a similar selection intensity of 15%, responses to indirect selection in the FGC system were always lower for all traits than direct selection in the FG system, excluding the possibility of considering this system as a substitute for the clipped FG system. Direct selection for grain yield in the GO system was 10% more effective than indirect selection in the FGC system, while only 2% more effective for the FG system. Similarly, direct selection for kernel weight and test weight was 6 and 8% higher in the GO, while 8 and 5% higher in the FG system, than indirect selection in the FGC system. In contrast, selection in the GO system for indirect improvement of grain yield in the FG system was 5% more effective than direct selection in the FG system; however, by assuming a selection intensity of 13% (i= 1.63) instead of 15% (i=1.55) in the FG system, this difference in direct and indirect responses dissipated. The direct responses for other traits (kernel weight and test weight) in the FG system were virtually identical in magnitude to that of indirect selection for these traits in the GO system, and vice versa.

The strong relationship among management systems was also evidenced by that at least four out of six high yielding lines (15% selection intensity) were common to all three systems. The same commonality among systems was also observed by selecting the 15% lowest yielding lines in each system. Selection differentials, calculated as the difference in mean grain yield of the six highest yielding lines and the overall mean of 37 lines, from direct selection in the GO (264 kg ha^{-1}) and FG (304 kg ha^{-1}) systems were 43 and 40% greater than selection differentials from indirect selection in the FGC system (Table 5). Interestingly, the selection differential for the FG system through indirect selection in the GO system was 97 kg ha^{-1}, or 32% less than that from direct selection in FG (304 kg ha^{-1}), suggesting efficiency of direct selection under the FG system.

Results from a companion study indicated that yield potential of a historical set of winter wheat cultivars bred in a grain-only system was not fully realized in a dual-purpose grazing system (Khalil et al., 2001). Our results here would suggest that progress should be expected in FG system following selection in a GO system. This discrepancy in results may be due to lower levels or different types of stresses in the forage-plus-grain system (where forage is mechanically clipped) than in a dual-purpose grazing system. To achieve maximum response under the target forage-plus-grain production system, indirect selection of early segregating generations under the grain-only system might be supplemented with simultaneous evaluation and selection in a dual-purpose system with actual grazing. This approach will increase the probability of selecting genotypes with optimum adaptation to stresses encountered in the target dual-purpose system, though a high degree of genetic spillover is expected between systems.

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Table 1. Mean squares for grain yield, 1000-kernel weight, and test weight of 37 hard winter wheat lines evaluated in three management systems for 3 yr at Lahoma, OK.

Source of variation	df	Grain yield	1000-kernel weight	Test weight
		$(\text{kg ha}^{-1})^2 \times 10^3$	g^2	$(\text{kg hL}^{-1})^2$
Year (Y)	2	17263	271	127815**
System (S)	2	20628	64	4160
Y x S	4	11648**	43	4554*
Reps (Y x S)	27, 15, 9†	924	28	1162
Genotypes (G)	36	1317**	32**	953**
G x Y	72	374**	3**	125**
G x S	72	146	2	81
G x S x Y	144	139**	2	66
Error	972, 540, 324†	95	1	68
Coefficient of variation (%)		12.0	4.0	1.1

†Degrees of freedom for grain yield, 1000-kernel weight, and test weight, respectively.

Table 2. Estimates of genotypic (σ^2_G), genotype × year (σ^2_{GY}), and residual error (σ^2_E) variances, and means for grain yield, kernel weight, and test weight measured on 37 hard winter wheat lines in three management systems for 3 yr at Lahoma, OK.

		Management system†		
Trait	Parameter	FG	FGC	GO
Grain yield	σ^2_G	25734‡	29239‡	24817‡
	σ^2_{GY}	25428‡	37545‡	28577‡
	σ^2_E	128941	93188	63865
	Mean (kg ha^{-1})	2701	2324	2693
1000-Kernel weight	σ^2_G	0.9‡	1.0‡	1.8‡
	σ^2_{GY}	0.1	0.2	0.3‡
	σ^2_E	1.3	1.7	1.3
	Mean (g)	28.9	29.3	29.8
Test weight	σ^2_G	43‡	26‡	73‡
	σ^2_{GY}	0	10	20‡
	σ^2_E	68	98	39
	Mean (kg hL^{-1})	76.3	75.8	76.7

† FG = Forage-plus-grain; FGC = Forage-plus-grain control, forage not removed; GO = Grain-only.

‡ Variance component significantly greater than zero if the variance estimate is twice its standard error.

Table 3. Heritabilities and genetic correlations among three management systems for grain yield, 1000-kernel weight, and test weight measured on 37 hard winter wheat lines for 3 yr at Lahoma, OK.

		Management system†		
Parameter	Trait	FG	FGC	GO
Heritability	Grain yield	0.57	0.59	0.63
(90% CI)		(0.32, 0.73)	(0.34, 0.74)	(0.40, 0.77)
	Kernel weight	0.84	0.79	0.88
		(0.64, 0.86)	(0.71, 0.89)	(0.80, 0.92)
	Test weight	0.79	0.57	0.85
		(0.71, 0.89)	(0.32, 0.73)	(0.75, 0.90)
Genetic Correlation		FG vs. FGC	FG vs. GO	FGC vs. GO
	Grain yield	0.96±0.02	1.04±-0.02	0.94±0.03
	Kernel weight	1.04±-0.01	0.97±0.01	0.98±0.01
	Test weight	1.05±-0.02	0.97±0.01	1.03±-0.01

† FG = Forage-plus-grain; FGC = Forage-plus-grain control, forage not removed; GO = Grain-only.

Table 4. Predicted direct and indirect responses for grain yield, 1000-kernel weight, and test weight at 15% selection intensity for 37 hard winter wheat lines in the grain-only and forage-plus-grain systems at Lahoma, OK.

Response system	Type of selection†	Grain yield	Kernel weight	Test weight
		kg ha^{-1}	g	kg hL^{-1}
FG	Direct in FG	187	1.4	2.3
	Indirect in FGC	183	1.3	2.2
	Indirect in GO	197	1.4	2.3
GO	Direct in GO	195	1.9	2.6
	Indirect in FGC	177	1.8	2.4
	Indirect in FG	185	1.8	2.6

† FG = Forage-plus-grain; FGC = Forage-plus-grain control, forage not removed; GO = Grain-only

Table 5. Mean grain yields of six selected winter wheat lines ($\overline{X}_s$) and of the entire population ($\overline{X}_o$), selection differential (S), and expected direct and indirect responses (R) to selection in grain-only and forage-plus-grain systems at Lahoma, OK.

Response system	Type of selection†	$\overline{X}$s	$\overline{X}$o	S‡	R§
		----------	kg ha^{-1}	----------	
FG	Direct in FG	3005	2701	304	173
	Indirect in FGC	2918	2701	217	124
	Indirect in GO	2908	2701	207	118
GO	Direct in GO	2957	2693	264	166
	Indirect in FGC	2877	2693	184	116
	Indirect in FG	2948	2693	255	161

† FG = Forage-plus-grain; FGC = Forage-plus-grain control, forage not removed; GO = Grain-only.
‡S = $\overline{X}$s - $\overline{X}$o, wherein each mean computed across 3 yr.
§R = S × h^2 (from Table 3).

APPENDIX

SUPPLEMENTAL DATA ABOUT 12 HRW WHEAT CULTIVARS EVALUATED AT MARSHALL, AND 37 WINTER WHEAT EXPERIMENTAL LINES AND 3 CHECK CULTIVARS EVALUATED AT LAHOMA

Appendix Table 1. Mean grain yield of 12 winter wheat cultivars (averaged over fungicide treatments) evaluated under grain-only (GO) and dual-purpose (DP) systems for 3 yr at Marshall, OK.

		1996-1997		1997-1998		1998-1999		All years	
Cultivar	Year of release	GO	DP	GO	DP	GO	DP	GO	DP
		kg ha^{-1}							
Turkey	1919	1376	961	2255	2123	758	663	1463	1249
Triumph 64	1964	2192	1133	3517	2898	1699	1892	2470	1974
Scout 66	1966	1972	1140	2788	2665	1210	1047	1990	1617
TAM W-101	1971	3025	1321	3297	2707	2173	2108	2832	2045
Vona	1976	2122	1133	3783	2989	1745	2178	2550	2100
TAM 105	1979	2429	1624	3274	3124	1574	1646	2426	2131
Chisholm	1983	1677	818	3931	2645	1900	1827	2503	1763
2157	1987	2055	1141	3695	2788	1933	2164	2561	2031
2163	1989	3003	1223	4127	2833	1785	1925	2972	1994*†
Karl 92	1992	1802	728	3826	2889	2208	2467	2612	2028
Custer	1994	2006	958	4189	3211	2121	2313	2772	2161
2174	1997	3270	1525	4015	2610	2445	2695	3244	2276*
Mean	--	**2244**	**1142**	**3558**	**2790**	**1796**	**1910**	**2533**	**1947**

†LSD$_{0.05}$ = 850 for comparing means (averaged over 3 yr) for the same cultivar between systems.

Appendix Table 2. Means of 12 winter wheat cultivars (averaged over fungicide treatments and years) for test weight, spike density, kernels per spike, and spike weight evaluated under grain-only (GO) and dual-purpose (DP) systems for 3 yr at Marshall, OK.

Cultivar	Year of release	Test weight		Spike density		Kernels/spike		Spike weight	
		GO	DP	GO	DP	GO	DP	GO	DP
		--kg hL^{-1}--		-- no. m^{-2} --		---- no ----		---- mg -----	
Turkey	1919	75.0	74.3	567	535	25	24	697	610
Triumph 64	1964	78.0	77.6	514	517	25	22	889	737
Scout 66	1966	75.5	75.6	557	550	24	23	793	683
TAM W-101	1971	76.0	75.8	511	464	24	22	886	795
Vona	1976	74.2	75.0	544	570	31	27	870	743
TAM 105	1979	71.9	72.9	507	531	30	26	876	716
Chisholm	1983	76.5	76.0	508	545	26	24	908	776
2157	1987	76.9	76.8	477	488	30	26	907	746
2163	1989	72.5	72.5	459	448	30	30	920	862
Karl 92	1992	76.4	76.9	579	613	24	21	834	701
Custer	1994	75.7	76.2	462	449	28	24	979	820
2174	1997	77.3	76.8	481	477	31	29	1006	908
Mean	**--**	**76.3**	**75.9**	**514**	**516**	**27**	**25**	**880**	**758**

Appendix Table 3. Means of 12 winter wheat cultivars for kernel size, and other quality attributes evaluated under grain-only (GO) and dual-purpose (DP) systems for 3 yr at Marshall, OK.

	Year of	TK weight		Large kernels		Kernel diam.		Gr. protein		Flour yield		Mixing time		Mixing Tolerance	
Cultivar	release	GO	DP	GO	DP	GO	DP	GO	DP	GO	DP	GO	DP	GO	DP
		---- g ----		----- % -----		---- mm ----		-- g kg^{-1} --		-- g kg^{-1} --		-- min --		-- 1-10 --	
Turkey	1919	27.0	25.6	41	35	2.0	2.1	128	127	618	621	4.7	4.7	4.3	4.2
Triumph 64	1964	34.9	34.4	70	59	2.3	2.3	130	132	622	613	4.4	4.3	3.8	3.5
Scout 66	1966	31.9	29.8	56	53	2.1	2.3	132	124	631	627	4.6	4.8	4.7	4.7
TAM W-101	1971	37.4	36.2	75	73	2.3	2.4	130	129	608	601	4.9	4.7	4.5	4.1
Vona	1976	28.3	27.3	46	46	2.0	2.2	123	126	595	598	5.5	5.5	4.6	4.9
TAM 105	1979	28.8	27.4	52	48	2.0	2.2	124	125	606	597	5.1	4.9	5.6	5.1
Chisholm	1983	34.6	32.0	64	64	2.2	2.4	121	122	612	584	6.5	6.0	4.4	4.8
2157	1987	30.5	28.4	58	59	2.2	2.3	130	130	620	628	5.4	5.1	4.4	4.2
2163	1989	31.0	28.3	55	56	2.0	2.2	127	128	600	601	4.6	4.4	4.6	4.4
Karl 92	1992	34.4	31.9	60	54	2.2	2.3	129	131	626	631	7.0	6.8	4.6	4.2
Custer	1994	35.3	33.5	64	68	2.2	2.4	125	126	599	586	5.1	5.1	5.1	4.8
2174	1997	32.5	31.8	67	71	2.3	2.5	126	130	630	610	4.9	4.5	4.6	4.0
Mean	**--**	**32.2**	**30.5**	**59**	**57**	**2.2**	**2.3**	**127**	**128**	**614**	**608**	**5.2**	**5.1**	**4.6**	**4.4**

Appendix Table 4. Grain yield of 37 winter wheat experimental lines and three check cultivars under three management systems at Lahoma, OK.

	Management system†								
	FG			FGC			GO		
Genotypes	1997	1998	1999	1997	1998	1999	1997	1998	1999
	---------- kg ha^{-1} ----------								
Exptl. lines									
Mean	2746	2584	2772	2335	2524	2112	2827	3082	2171
Minimum	2017	2021	2174	1531	1878	1708	2344	2430	1798
Maximum	3492	3091	3129	3214	3324	2497	3303	3990	2624
Check cultivars									
Tomahawk	3732	3090	2877	3419	2961	2564	2963	3684	2323
Jagger	3139	2987	3299	2708	3354	2582	3644	4387	3028
2174	3203	2687	2958	3191	3019	2320	3393	3424	2730
LSD $_{(0.05)}$‡	301	477	677	328	486	462	305	419	369

†FG = Forage-plus-grain; FGC = Forage-plus-grain, forage not removed;
GO = Grain-only.
‡LSD value for comparing individual genotype means in the same year.

Appendix Table 5. 1000-kernel weight of 37 winter wheat experimental lines and three check cultivars under three management systems at Lahoma, OK.

	Management system†								
	FG			FGC			GO		
Genotypes	1997	1998	1999	1997	1998	1999	1997	1998	1999
	------------------- g -------------------								
Exptl. lines									
Mean	27.5	29.0	29.8	28.1	30.6	28.9	28.6	30.6	29.9
Minimum	24.8	26.2	27.4	24.5	27.8	26.8	25.8	27.5	26.4
Maximum	30.8	32.3	31.8	32.2	33.3	32.2	32.5	33.2	33.2
Check cultivars									
Tomahawk	28.3	30.7	28.0	29.8	31.3	28.4	30.0	31.8	27.5
Jagger	27.5	28.0	29.9	27.4	29.3	28.7	30.4	32.2	30.8
2174	28.2	29.2	30.0	29.3	32.3	30.0	29.8	31.3	29.0
LSD $_{(0.05)}$‡	2.1	1.7	2.1	2.3	2.4	1.8	2.5	1.7	2.0

†FG = Forage-plus-grain; FGC = Forage-plus-grain, forage not removed;
GO = Grain-only.
‡LSD value for comparing individual genotype means in the same year.

Appendix Table 6. Test weight of 37 winter wheat experimental lines and three check cultivars under three management systems at Lahoma, OK.

	Management system†								
	FG			FGC			GO		
Genotypes	1997	1998	1999	1997	1998	1999	1997	1998	1999
	kg hL^{-1}								
Exptl. lines									
Mean	75.0	78.6	75.2	75.8	78.7	73.0	76.0	79.5	74.6
Minimum	72.4	76.6	73.1	73.5	77.0	70.8	73.5	77.7	71.5
Maximum	76.8	79.9	76.4	77.5	80.4	74.4	78.0	80.7	76.5
Check cultivars									
Tomahawk	74.3	77.5	73.4	74.6	75.0	71.4	75.3	77.9	72.3
Jagger	74.5	78.0	75.3	74.3	75.8	73.5	75.1	79.4	75.0
2174	75.8	78.9	76.2	77.5	80.6	73.4	77.7	81.4	75.5
LSD $_{(0.05)}$‡	3.0	3.3	2.9	3.5	3.4	3.1	2.8	2.3	2.8

†FG = Forage-plus-grain; FGC = Forage-plus-grain, forage not removed; GO = Grain-only.

‡LSD value for comparing individual genotype means in the same year.

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VITA

Iftikhar Hussain Khalil

Candidate for the Degree of

Doctor of Philosophy

Thesis: GENETIC IMPROVEMENT FOR WINTER WHEAT YIELD AND QUALITY UNDER DUAL-PURPOSE AND GRAIN-ONLY MANAGEMENT SYSTEMS

Major Field: Crop Science

Biographical:

Personal Data: Born in village Sufaid Dheri, Peshawar, Pakistan, February 1, 1965, the son of Muhammad Hussain and Bibi Saira.

Education: Graduated from Islamia Collegiate School, Peshawar University, Peshawar, Pakistan in 1979; received Fellow of Science diploma from Islamia College, Peshawar, Pakistan in 1982; received B.S. and M.S. degrees in Plant Breeding and Genetics from Agricultural University, Peshawar, Pakistan, in 1986 and 1988, respectively; received M.S. degree in Agronomy from Oklahoma State University, Stillwater, Oklahoma, in 1993; and completed the requirements for the Doctor of Philosophy degree in Crop Science at Oklahoma State University in August, 2001.

Professional Experience: Research Officer, Sugar Crops Research Institute, Mardan, Pakistan, March to Sept. 1989. Research officer, ARI, Tarnab, Peshawar, Pakistan, Oct. 1989 to Dec. 1991. Graduate research assistant, Dep. of Agronomy, Oklahoma State University, Jan. 1992 to Dec. 1993. Research Officer, ARI, Tarnab, Peshawar, Pakistan, Jan. 1994 to Oct. 1994. Planning Officer, Directorate of Research Planning, Agricultural University, Peshawar, Pakistan, Nov. 1994 to Dec. 1997. Graduate research assistant, Dep. of Plant and Soil Sciences, Oklahoma State University, Jan. 1998 to Aug. 2001.

Professional Membership: Crop Science Society of America. Frontier Agricultural Research Scientists Association (FARSA), Pakistan.