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CULTIVAR

Registration of 'Sunshine' Hard White Winter Wheat

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Abstract

'Sunshine' (Reg. No. CV-1129, PI 674741) hard white winter wheat (*Triticum aestivum* L.) was developed by the Colorado Agricultural Experiment Station and released in August 2014 through a marketing agreement with the Colorado Wheat Research Foundation. In addition to researchers at Colorado State University, USDA-ARS researchers at Manhattan, KS, St. Paul, MN, and Pullman, WA participated in its development. Sunshine was developed with the objective of making available a hard white winter wheat cultivar with improved grain yield and straw strength and similar milling and baking qualities to 'Snowmass' hard white winter wheat. Both Snowmass and Sunshine are grown in Colorado and adjacent areas of the west-central Great Plains in an identity-preserved marketing system whereby a grower premium is paid through a contract with a flour milling company. Sunshine was developed with a modified-bulk breeding method from the cross KS01HW152-6/HV9W02-267W made in 2005 at Fort Collins, CO. Following two generations (F_2 and F_3) of bulk-population evaluation, Sunshine was selected as an $F_{3:4}$ line in July 2009, assigned experimental line number CO09W293, and evaluated in replicated yield trials from 2012 to 2014 in eastern Colorado.

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Hard white wheat (*Triticum aestivum* L.) is one of five officially recognized market classes for hexaploid wheat in the United States (Federal Grain Inspection Service, 2014). Planted area of hard white wheat is the lowest of the five market classes, representing only about 1% of the US total in both 2014 and 2015 (USDA, 2016). Largely because of limited production, no distinction or separation is currently made in the market between hard white cultivars of spring and winter growth habit. In the west-central Great Plains region of the United States, which includes the wheat production areas of eastern Colorado, all of the hard white wheat production is hard white winter (HWW) wheat.

Despite the general preference for hard white wheat in both export and domestic markets (Taylor et al., 2005), relatively little progress has been made to increase HWW wheat plantings in the US Great Plains since the release of 'Rio Blanco' (PI 531244) by Agripro Biosciences Inc. in 1988. Several largely independent events or circumstances have hindered expansion of hard white plantings, most important, the emergence of stripe rust (caused by *Puccinia striiformis* Westend. f. sp. *tritici* Erikss.) as a significant problem in the region beginning in 2000 (Chen et al., 2002); severe price discounts due to widespread preharvest sprouting that occurred in the western Great Plains in 2004 (Lin and Vocke, 2004); discontinuation of the federal government incentive program for hard white wheat after the 2005 crop year; marginal quality characteristics of high-yielding HWW wheat cultivars, such as 'Trego'

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Abbreviations: BLUE, best linear unbiased estimator; GI, germination index; HCS, heterogeneous compound symmetry; HMWG, high molecular weight glutenin; HRW, hard red winter; HWW, hard white winter.

(Martin et al., 2001) and 'Danby' (PI 648010), particularly when high grain yield and low grain protein concentration occurred throughout the crop in 2007; and inefficiencies in the local grain delivery and handling infrastructure that increase costs of segregating HWW wheat from hard red winter (HRW) wheat.

In recent years, increased domestic demand for whole grain products has helped to maintain the viability of HWW wheat in the US Great Plains winter wheat region (Whole Grains Council, 2016). In several cases, identity-preserved marketing systems have been established to provide economic incentives for producers to help offset segregation costs, manage production, and ensure delivery of specific HWW wheat cultivars with desirable end-use quality characteristics. These programs include Syngenta's Platte Special Value Program (Syngenta, 2017) with 'Platte' (PI 596297) and 'NuGrain' (PI 643090); General Mills' Program (Taylor et al., 2005) with 'NuHorizon' (PI 619198) and 'NuFrontier' (PI 619089); Farmer Direct Foods' program (http://www.farmerdirectfoods.com) with 'Tiger' (Martin et al., 2013); and the Colorado Wheat Research Foundation (CWRF) Ardent Mills Ultragrain Premium Program (Plainsgold, 2017) with 'Thunder CL' (Haley et al., 2009), 'Snowmass' (Haley et al., 2011), and 'Antero' (Haley et al., 2014). In each of these cases, long-term stability and economic viability of the programs have depended to a significant extent on the continual development of cultivars that help to maximize economic returns for the wheat producer and meet the needs of the end-user.

Sunshine HWW (Reg. No. CV-1129, PI 674741) was developed with the objective of making available an improved HWW wheat cultivar suitable for an identity-preserved production system in the rainfed and irrigated winter wheat production areas of the US west-central Great Plains. The name Sunshine was chosen in recognition of Sunshine Peak, one of Colorado's 53 mountains over 4267 m (14,000 ft) elevation.

Methods

Sunshine was developed using a modified bulk-breeding method from the cross KS01HW152-6/HV9W02-267W made in 2005 at Fort Collins, CO. KS01HW152-6 is an experimental line from Kansas State University with the pedigree Trego/'Betty' (PI 612578) Sib. HV9W02-267W is an experimental line from Westbred-Monsanto with the pedigree KS97HW79/Trego. All early-generation population and line development was done in the greenhouse or at an irrigated field-testing location at Fort Collins. The cross, designated as X05058, was made in the greenhouse in spring 2005. The F_1 seed was harvested in June 2005 and then planted at Fort Collins in September 2005. The F_1 plants were hand-harvested in bulk in July 2006, and the F_2 seed was planted in an unreplicated field nursery in September 2006. In July 2007, the F_2 bulk nursery was harvested with a small-plot combine. A subsample of the seed was sieved using a Ro-Tap Test Sieve Shaker (W.S. Tyler) to select larger kernels, which were then planted in September 2007 in an unreplicated F_3 bulk nursery at Fort Collins and under rainfed conditions at Akron, CO. In July 2008, approximately 200 spikes were randomly sampled from the F_3 bulk population growing at Fort Collins. The spikes were threshed individually and planted in a headrow nursery at Fort Collins in September 2008. On the basis of visual observations of uniformity and agronomic appearance, Sunshine was selected as an $F_{3:4}$ line in July 2009 and assigned experimental number CO09W293.

Sunshine was evaluated in eastern Colorado in unreplicated preliminary yield trials in 2010, the advanced yield nursery in 2011, the Colorado State University (CSU) Elite Trial from 2012 to 2014, statewide rainfed and irrigated variety trials in 2014, and the USDA-ARS Coordinated Regional Germplasm Observation Nursery from 2012 to 2014. The CSU Elite Trials were arranged in resolvable, latinized row-column designs (John and Williams, 1995) with two replications, and the statewide variety trials were arranged in resolvable, latinized row-column designs with three replications.

Seed purification of Sunshine was done by headrow progeny purification utilizing DNA marker analysis and a counter-season seed increase in Yuma, AZ. In July 2012, 360 single spike selections ($F_{3:7}$ generation) were randomly sampled from a seed increase growing at Fort Collins. Seed from each spike was divided between a subsample planted in a progeny row in Yuma in November 2012 and a subsample used for DNA marker analysis using the codominant "Bx MAR" (matrix-attachment region) DNA marker that is diagnostic for the *Glu-B1al* ($Bx7^{OE}$+8 subunits) high molecular weight glutenin (HMWG) allele at the *Glu-B1* locus (Butow et al., 2004). A bulk tissue sample from at least 11 seedlings of each spike selection was used to determine heterozygosity or homozygosity of the $F_{3:7}$ plants for the *Glu-B1al* allele. The breeder seed progeny purification rows growing in Yuma were hand-harvested in May 2013. Of the 360 $F_{7:8}$ progeny rows available for purification, 201 were shown to be homogeneous for the *Glu-B1al* allele based on DNA marker analysis, and 94 of these were harvested based on visual observations of uniformity and straw strength (lodging resistance). Seed of the 94 progeny rows was visually inspected for purity of white kernel color and then bulked to form the breeder seed. Breeder seed was used to plant a 4-ha foundation seed increase under irrigation in Yuma in November 2013. The foundation seed increase was rogued for tall and red-glumed variants and harvested in June 2014.

All statistical analyses were done within the R programming language (R Core Team, 2015). All R codes are freely available by email request to the corresponding author. Agronomic, disease resistance, and end-use quality data were analyzed using the Student's paired *t* test (*t.test* function in base R) at the 0.05 α probability level. Yield and grain volume weight (test weight) data from the CSU Elite Trial and statewide variety trials were analyzed with the *asreml* package in R (Butler et al., 2009) using a two-stage procedure (Piepho et al., 2008). In the first stage, individual trials (environments) were analyzed with a series of spatial models that included genotype as a fixed effect, row and column coordinates as random effects, and several different residual error terms specified in the *rcov* argument within the *asreml* call (as described in Butler et al., 2009). The restricted maximum likelihood (REML) loglikelihood value was used to select the best model. Best linear unbiased estimates (BLUEs) from the first stage of the analysis were then subject to a combined analysis over environments using a heterogeneous compound symmetry (HCS) model (Malosetti et al., 2013) with environments and genotypes as fixed effects and the diagonal elements of the genotype × environment matrix specified in the *rcov* argument within the *asreml* call. As discussed by Malosetti et al. (2013), the HCS model efficiently accommodates heterogeneous correlations between environments as often occur when environment means within a multi-environment trial vary greatly due to differing environmental stress conditions. In the second stage of the analysis, only genotypes common to all environments were included. The Fisher's least significant difference (LSD) of the across-environment BLUEs was estimated using the *predictparallel* function in the *asremlPlus* package (Brien, 2016). The 0.05 α probability level was used for all mean comparisons.

Characteristics

General Description

Sunshine is an awned, white-glumed, HWW wheat. Sunshine has medium-early maturity, about 1.5 d earlier (n = 40 comparisons) heading than Antero and 3.0 d earlier (n = 38) heading than Snowmass. Sunshine is medium height, about 2.9 cm shorter than (n = 72) Antero and 3.9 cm shorter than (n = 71) Snowmass. The coleoptile length (evaluated according to Hakizimana et al., 2000) of Sunshine (82.4 mm; $n = 9$) is longer than that of both Antero (66.1 mm) and Snowmass (71.8 mm). Sunshine's straw strength is good (2.1 score, $n = 27$; scale of 1 to 9, where 1 = erect and 9 = flat), better than that of both Antero (5.1) and Snowmass (5.7). Preharvest sprouting tolerance of Sunshine, assessed through determination of a germination index (GI; Mares et al., 2005) from field-grown samples, is good (GI = 0.21; $n = 18$), similar ($P > 0.05$) to that of Antero (GI = 0.18), Snowmass (GI = 0.28), and commonly grown HRW wheat cultivars in Colorado such as 'Hatcher' (Haley et al., 2005) (GI = 0.17) and 'Byrd' (Haley et al., 2012a) (GI = 0.23) and greater than that of the HRW cultivar 'TAM 112' (Rudd et al., 2014) (GI = 0.43). No objective data are available for winter hardiness of Sunshine, but field observations and performance under dry soil conditions during recent winters in Colorado suggest that it is at least adequate for successful production in the west-central Great Plains region of the United States.

Disease and Insect Resistance

Sunshine has been characterized for disease and insect resistance in Colorado and through cooperative evaluations of the USDA-ARS Coordinated Regional Testing Program. In field tests in 2012 and 2013 at Rossville, KS, with artificial inoculation of several endemic Kansas isolates and natural infection with isolates virulent on *Yr17* or QYr.tam-2BL (Basnet et al., 2014), Sunshine showed a moderately susceptible reaction to stripe rust, with an average infection type (Chen and Line, 1992) of 5.2 (on a scale of 1 to 9, where 1 = resistant and 9 = fully susceptible) and an average flag leaf severity of 42% at the soft dough stage (n = 5 observations). In these same nurseries, the susceptible repeated check line KS89180B-2 showed a highly susceptible reaction, with an average infection type of 7.6 and an average severity of 93.6%. Observations under natural stripe rust infection with unknown races in Washington from 2012 to 2014 also showed that Sunshine is moderately susceptible, with an average infection type of 5.8 and an average severity of 52% (n = 10 observations). In these same nurseries, the susceptible repeated check line PS279 showed an average infection type of 8.0 and an average severity of 95 to 100%. Under natural stripe rust infection with unknown races in Colorado from 2010 to 2016, Sunshine showed a moderately susceptible reaction (4.9 score; $n = 38$), more resistant than Snowmass (6.8 score) and less resistant than Antero (2.3 score).

In greenhouse seedling evaluations at St. Paul, MN, Sunshine was resistant to US stem rust (caused by *Puccinia graminis* Pers.:Pers f. sp. *tritici* Erikss. & E. Henn) races QFCSC, QTHJC, QCCSM, RKQQC, and TPMKC and moderately susceptible to race TTTTF and African races TTKSK, TTKST, TTTSK, and TRTTF. Field adult-plant evaluations at St. Paul from 2012 to 2014 confirmed that Sunshine is resistant to the North American stem rust races. Adult plant-evaluation at Njoro, Kenya, in 2013 and 2014 indicated that Sunshine is susceptible to moderately susceptible to Ug99 related races. Under natural field infection with unknown leaf rust (caused by *Puccinia triticina* Erikss.) races at Castroville, TX, Sunshine showed a susceptible adult-plant reaction in both 2013 and 2014.

Other evaluations in Colorado or through the USDA-ARS Coordinated Regional Testing Program have shown that Sunshine is moderately susceptible to *Wheat soilborne mosaic virus* (field evaluation at Stillwater, OK), heterogeneous for resistance to a collection of endemic biotypes of the Hessian fly [*Mayetiola destructor* (Say)] (Chen et al., 2009), and susceptible to Russian wheat aphid (*Diuraphis noxia* Kurdjumov) biotypes 1 and 2 (greenhouse seedling screening at Stillwater; Nkongolo et al., 1989). The reaction of Sunshine to *Barley yellow dwarf virus*, greenbug Biotype E [*Schizaphis graminum* (Rondani)], and *Wheat streak mosaic virus* is not known. Sunshine lacks DNA markers *Wsm1* (Qi et al., 2007) and *Wsm2* (Lu et al., 2012) associated with *Wheat streak mosaic virus resistance*.

Field Performance

Sunshine was tested at 27 rainfed environments of the CSU Elite Trial in Colorado from 2012 to 2014 and nine rainfed environments of the 2014 Colorado Uniform Variety Performance Trial (UVPT). In the first stage of the analyses for grain yield, a two-dimensional spatial model (AR1xAR1; Gilmour et al., 1997) with a nugget effect was the best model for over 50% of the environments (trials). In the combined analysis (second stage) across all rainfed environments (n = 36 environments), the grain yield of Sunshine (3514 kg ha^{-1}) was lower than Byrd (3655 kg ha^{-1}) but similar ($P > 0.05$) to each of the other HRW wheat cultivars in the trials (Table 1). Compared with the other HWW wheat cultivars, the yield of Sunshine was lower than Antero (3699 kg ha^{-1}) and greater than Snowmass (3292 kg ha^{-1}). In the 2 yr with lower mean grain yield (2012 and 2013), influenced by high temperatures and terminal drought stress, the yield of Sunshine was similar ($P > 0.05$) to Antero and greater than Snowmass (Table 1). Across the irrigated environments (n = five environments), Sunshine (5812 kg ha^{-1}) had lower grain yield than Antero (6677 kg ha^{-1}), Byrd (6529 kg ha^{-1}), 'Denali' (Haley et al., 2012b) (6396 kg ha^{-1}), and Hatcher (6287 kg ha^{-1}), and greater yield compared with

Table 1. Grain yield and grain volume weight of hard white winter (HWW) and hard red winter (HRW) wheat entries in the Colorado State University Elite Trial from 2012 to 2014, the Colorado Uniform Variety Performance Trial (UVPT) in 2014, and the Colorado Irrigated Variety Performance Trial (IVPT) in 2014.

Entry	Grain yield†							Grain volume weight
	Type‡	2012 Elite	2013 Elite	2014 Elite	2014 UVPT	Combined Elite and UVPT	Irrigated Elite and IVPT§	
		kg ha^{-1}						kg m^{-3}
Antero	HWW	3522	2318	4540	4046	3699	6677	763
Brawl CL Plus	HRW	3452	2361	4091	3819	3527	5270	772
Byrd	HRW	3891	2203	4416	3955	3655	6529	761
Denali	HRW	3199	2354	4489	3874	3573	6396	776
Hatcher	HRW	3422	2221	4297	3845	3524	6287	757
Ripper¶	HRW	3465	2190	4184	3818	3507	–	748
Snowmass	HWW	3011	1991	4039	3705	3292	–	753
Sunshine	HWW	3553	2201	4105	3737	3514	5812	753
TAM 112	HRW	3528	2199	4020	3672	3480	–	769
Environments		10	7	10	9	36	5	27
Mean#		3449	2227	4242	3830	3530	6162	761
LSD (0.05)		210	179	281	222	98	289	5

† Individual year and combined data from the Colorado State University Elite Trial and 2014 UVPT are from rainfed environments only.

‡ HWW = hard white winter; HRW = hard red winter.

§ Irrigated environments included one for each year of the Colorado State University Elite Trial (2012–2014) and two for the 2014 IVPT.

¶ 'Ripper' (Haley et al., 2007).

Trial mean includes only those entries in the table.

'Brawl CL Plus' (Haley et al., 2012c) (5270 kg ha^{-1}). Grain volume weight of Sunshine across the rainfed trials (Table 1; n = 27 environments) was below average (753 kg m^{-3}), lower than most of the other cultivars tested but not different ($P > 0.05$) than Snowmass HWW wheat.

End-Use Quality

Milling and bread-baking characteristics of Sunshine and the HWW wheat check entries Snowmass and Antero were determined using approved methods of the American Association of Cereal Chemists (AACC, 2000) in the CSU Wheat Quality Laboratory. Multiple samples from the 2011, 2012, and 2013 growing seasons were used for comparison. Snowmass is known for having strong dough mixing properties, influenced to a great degree by the *Glu-B1al* (Bx7^{OE}+8 HMWG subunits) allele at the *Glu-B1* locus (Butow et al., 2004; Cooper et al., 2016), and high water absorption in whole grain flour product applications. The combination of mixing strength and water absorption properties of Snowmass is unique in the flour milling industry and is utilized for the Ultragrain High Performance flour blend marketed by Ardent Mills (Ardent Mills, 2017). Conversely, Antero is known for having much weaker dough mixing properties, despite carrying the *Glu-D1d* (5+10 HMWG subunits) allele at the *Glu-D1* locus, and generally inferior whole grain bread-baking performance relative to Snowmass. Sunshine carries the same *Glu-A1b* (2* HMWG subunit) allele at the *Glu-A1* locus as both Antero and Snowmass and the same *Glu-B1b* (7+8 HMWG subunits) and *Glu-D1d* alleles as Antero. Snowmass and Antero both lack the T1BL-1RS or T1AL-1RS wheat–rye chromosomal translocations based on the TSM0120 microsatellite marker (G. Bai, unpublished data), whereas Sunshine presumably lacks these translocations based on its pedigree.

Overall, Sunshine showed intermediate values for milling-related characteristics relative to Snowmass and Antero (Table 2). Compared with Snowmass, Sunshine had higher kernel weight and lower kernel hardness (determined using a single-kernel characterization system SKCS-4100, Perten Instruments), higher grain volume weight, lower grain and flour ash concentration (determined using a Foss NIRSystems model 6500, Foss North America Inc.), and higher break and total flour extraction (determined with a modified Brabender Quadrumat Senior, C.W. Brabender). Polyphenol oxidase activity (L-Dopa method; AACC method 22-85.01 [AACC, 2000]) of Sunshine was similar ($P > 0.05$) to the check cultivars, and its grain color (L* brightness, measured with Minolta Chroma Meter CR-310, Minolta Camera Co. Ltd.) was slightly brighter (higher L* value) than Snowmass.

Values for baking-related characteristics of Sunshine were also generally intermediate between Snowmass and Antero (Table 2). Compared with Snowmass, Sunshine had lower mixograph (National Manufacturing) mixing time and mixing tolerance and lower bake mix time in straight-dough pup-loaf baking tests (AACC method 10-10B [AACC, 2000]). No differences ($P > 0.05$) between Sunshine and Snowmass were observed, however, for bake water absorption, pup loaf volume, and crumb grain score. The lack of observed differences in bake water absorption between Sunshine and Snowmass—as would be expected based on their differences in kernel hardness and flour milling properties (particularly break flour yield)—may be related to the relative subjectivity and imprecision of water absorption estimation in the pup-loaf bread-baking test.

Availability

The Colorado Agricultural Experiment Station will maintain breeder seed of Sunshine. Multiplication and distribution rights of other classes of certified seed have been transferred from

Table 2. Milling, dough-mixing, and bread-baking characteristics of wheat cultivar Sunshine and check entries across multiple evaluations from the 2011, 2012, and 2013 growing seasons in Colorado.

Trait	Samples	Sunshine	Snowmass	Antero
SKCS† kernel weight (mg)	19	29.6	27.2*	28.3 ns‡
SKCS kernel diameter (mm)	19	2.57	2.53 ns	2.54 ns
SKCS kernel hardness (score)	19	68.8	82.2*	68.1 ns
Grain volume weight (kg m^{-3})	19	762	755*	767 ns
Grain ash (g kg^{-1})	32	14.6	15.2*	14.8*
Break flour extraction (g kg^{-1})	11	452	390*	473*
Flour extraction (g kg^{-1})	11	701	673*	697 ns
Flour ash (g kg^{-1})	22	4.6	4.9*	4.6 ns
Polyphenol oxidase§	15	0.57	0.63 ns	0.54 ns
Grain color (Minolta L*)	11	91.7	91.1*	91.7 ns
Grain protein (g kg^{-1})	32	136	136 ns	129 ns
Mixograph mixing time (min)	11	4.8	7.5*	4.3*
Mixograph tolerance (0–6)¶	15	4.3	5.9*	3.1*
Bake mix time (min)	11	4.9	9.5*	4.2*
Bake water absorption (g kg^{-1})	11	650	651 ns	628*
Loaf volume (L)	11	0.98	0.97 ns	0.86*
Crumb grain (0–6) ¶	11	4.1	4.5 ns	3.3 ns

* Significance of the difference between Sunshine and the check cultivar based on a Student's paired *t* test procedure at the 0.05 probability level.

† SKCS, single kernel characterization system.

‡ ns = not significant.

§ L-Dopa polyphenol oxidase assay, reported as absorption units at 475 nm.

¶ Scale for mixograph tolerance and crumb grain scores: 6 = outstanding, 0 = unacceptable.

the Colorado Agricultural Experiment Station to the Colorado Wheat Research Foundation, 4026 South Timberline Road, Suite 100, Fort Collins, CO, 80525. Sunshine was granted US Plant Variety Protection (PVP) under Public Law 91-577 with the Certification Only option in June 2016 (PVP no. 201500387). Recognized seed classes will include foundation, registered, and certified. Small quantities of seed for research purposes may be obtained from the corresponding author for at least 5 yr from the date of publication. Seed of Sunshine has been deposited with the USDA National Plant Germplasm System, where it will be available for distribution on expiration of Plant Variety Protection, 20 years after publication.

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References

American Association of Cereal Chemists (AACC). 2000. Approved methods. 10th ed. Am. Assoc. Cereal Chem., St. Paul, MN.

Ardent Mills. 2017. Ultragrain. http://www.ardentmills.com/ingredients/whole-grains/ultragrain.html.

Basnet, B.R., A.M.H. Ibrahim, X. Chen, R.P. Singh, E.R. Mason, R.L. Bowden, S. Liu, D.B. Hays, R.N. Devkota, N.K. Subramanian, and J.C. Rudd. 2014. Molecular mapping of stripe rust resistance in hard red winter wheat TAM 111 adapted to the US High Plains. Crop Sci. 54:1361–1373. doi:10.2135/cropsci2013.09.0625

Brien, C. 2016. asremlPlus: Augments the use of 'ASReml-R' in fitting mixed models. R package version 2.0-12. http://CRAN.R-project.org/package=asremlPlus (accessed 27 Dec. 2016).

Butler, D.G., B.R. Cullis, A.R. Gilmour, and B.J. Gogel. 2009. ASReml-R reference manual. https://www.vsni.co.uk/downloads/asreml/release3/asreml-R.pdf (accessed 27 Dec. 2016).

Butow, B.J., K.R. Gale, J. Ikea, A. Juhasz, Z. Bedo, L. Tamas, and M.C. Gianibelli. 2004. Dissemination of the highly expressed Bx7 glutenin sub-unit (*Glu-B1al* allele) in wheat as revealed by novel PCR markers and RP-HPLC. Theor. Appl. Genet. 109:1525–1535. doi:10.1007/s00122-004-1776-8

Chen, M.S., E. Echegaray, R.J. Whitworth, H. Wang, P.E. Sloderbeck, A. Knutson, K.L. Giles, and T.A. Royer. 2009. Virulence analysis of Hessian fly (*Mayetiola destructor*) populations from Texas, Oklahoma, and Kansas. J. Econ. Entomol. 102:774–780. doi:10.1603/029.102.0239

Chen, X.M., M. Moore, E.A. Milus, D.L. Long, R.F. Line, D. Marshall, and L. Jackson. 2002. Wheat stripe rust epidemics and races of *Puccinia striiformis* f. sp. *tritici* in the United States in 2000. Plant Dis. 86:39–46. doi:10.1094/PDIS.2002.86.1.39

Chen, X.M., and R.F. Line. 1992. Inheritance of stripe rust resistance in wheat cultivars used to differentiate races of *Puccinia striiformis* in North America. Phytopathology 82:633–637. doi:10.1094/Phyto-82-633

Cooper, J.K., J.A. Stromberger, C.F. Morris, G. Bai, and S.D. Haley. 2016. End-use quality and agronomic characteristics associated with the *Glu-B1al* high-molecular-weight glutenin allele in U.S. hard winter wheat. Crop Sci. 56:2348–2353. doi:10.2135/cropsci2015.10.0610

Federal Grain Inspection Service. 2014. United States standards for wheat. USDA Grain Inspection, Packers and Stockyards Administration, Federal Grain Inspection Service. https://www.gipsa.usda.gov/fgis/standards/810wheat.pdf (accessed 27 Dec. 2016).

Gilmour, A.R., B.R. Cullis, and A.P. Verbyla. 1997. Accounting for natural and extraneous variation in the analysis of field experiments. J. Agric. Biol. Environ. Stat. 2:269–293. doi:10.2307/1400446

Hakizimana, F., S.D. Haley, and E.B. Turnipseed. 2000. Repeatability and genotype × environment interaction of coleoptile length measurements in winter wheat. Crop Sci. 40:1233–1237. doi:10.2135/cropsci2000.4051233x

Haley, S.D., J.J. Johnson, F.B. Peairs, J.S. Quick, J.A. Stromberger, S.R. Clayshulte, J.D. Butler, J.B. Rudolph, B.W. Seabourn, G. Bai, Y. Jin, and J. Kolmer. 2007. Registration of 'Ripper' wheat. J. Plant Reg. 1:1–6. doi:10.3198/jpr2006.10.0689crc

Haley, S.D., J.J. Johnson, F.B. Peairs, J.A. Stromberger, E.E. Heaton, S.A. Seifert, R.A. Kottke, J.B. Rudolph, G. Bai, R.L. Bowden, M.-S. Chen, X. Chen, Y. Jin, J.A. Kolmer, R. Chen, and B.W. Seabourn. 2011. Registration of 'Snowmass' wheat. J. Plant Reg. 5:87–90. doi:10.3198/jpr2010.03.0175crc

Haley, S.D., J.J. Johnson, F.B. Peairs, J.A. Stromberger, E.E. Hudson-Arns, S.A. Seifert, R.A. Kottke, V.A. Valdez, J.B. Rudolph, G. Bai, X. Chen, R.L. Bowden, Y. Jin, J.A. Kolmer, M.-S. Chen, and B.W. Seabourn. 2014. Registration of 'Antero' wheat. J. Plant Reg. 8:165–168. doi:10.3198/jpr2013.12.0072crc

Haley, S.D., J.J. Johnson, F.B. Peairs, J.A. Stromberger, E.E. Hudson, S.A. Seifert, R.A. Kottke, V.A. Valdez, J.B. Rudolph, G. Bai, X. Chen, R.L. Bowden, Y. Jin, J.A. Kolmer, M.-S. Chen, and B.W. Seabourn. 2012a. Registration of 'Byrd' wheat. J. Plant Reg. 6:302–305. doi:10.3198/jpr2011.12.0672crc

Haley, S.D., J.J. Johnson, F.B. Peairs, J.A. Stromberger, E.E. Hudson, S.A. Seifert, R.A. Kottke, V.A. Valdez, J.B. Rudolph, G. Bai, X. Chen, R.L. Bowden, Y. Jin, J.A. Kolmer, M.-S. Chen, and B.W. Seabourn. 2012b. Registration of 'Denali' wheat. J. Plant Reg. 6:311–314. doi:10.3198/jpr2011.12.0675crc

Haley, S.D., J.J. Johnson, P.H. Westra, F.B. Peairs, J.A. Stromberger, E.E. Heaton, S.A. Seifert, R.A. Kottke, J.B. Rudolph, G. Bai, R.L. Bowden, M.-S. Chen, X. Chen, Y. Jin, J.A. Kolmer, and B.W. Seabourn. 2009. Registration of 'Thunder CL' wheat. J. Plant Reg. 3:181–184. doi:10.3198/jpr2008.12.0727crc

Haley, S.D., J.J. Johnson, P.H. Westra, F.B. Peairs, J.A. Stromberger, E.E. Hudson, S.A. Seifert, R.A. Kottke, V.A. Valdez, J.B. Rudolph, G. Bai, X. Chen, R.L. Bowden, Y. Jin, J.A. Kolmer, M.-S. Chen, and B.W. Seabourn. 2012c. Registration of 'Brawl CL Plus' wheat. J. Plant Reg. 6:306–310. doi:10.3198/jpr2011.12.0673crc

Haley, S.D., J.S. Quick, J.J. Johnson, F.B. Peairs, J.A. Stromberger, S.R. Clayshulte, B.L. Clifford, J.B. Rudolph, B.W. Seabourn, O.K. Chung, Y. Jin, and J. Kolmer. 2005. Registration of 'Hatcher' wheat. Crop Sci. 45:2654–2655. doi:10.2135/cropsci2005.0030

John, J.A., and E.R. Williams. 1995. Cyclic and computer generated designs. 2nd ed. St. Edmundsbury Press, Bury St. Edmunds, Suffolk, UK. doi:10.1007/978-1-4899-7220-0

Lin, W., and G. Vocke. 2004. Hard white wheat at a crossroads. USDA Economic Research Service. https://www.ers.usda.gov/webdocs/publications/39633/48594_whs04k01.pdf?v=42073 (accessed 27 Dec. 2016.

Lu, H., R. Kottke, R. Devkota, P. St. Amand, A. Bernardo, G. Bai, P. Byrne, T.J. Martin, S.D. Haley, and J. Rudd. 2012. Consensus-mapping and identification of markers for marker-assisted selection of Wsm2 in wheat. Crop Sci. 52:720–728.

Malosetti, M., J.-M. Ribaut, and F.A. van Eeuwijk. 2013. The statistical analysis of multi-environment data: Modeling genotype-by-environment interaction and its genetic basis. Front. Physiol. 4:44. doi:10.3389/fphys.2013.00044

Mares, D., K. Mrva, J. Cheong, K. Williams, B. Watson, E. Storlie, M. Sutherland, and Y. Zou. 2005. A QTL located on chromosome 4A associated with dormancy in white- and red-grained wheats of diverse origin. Theor. Appl. Genet. 111:1357–1364. doi:10.1007/s00122-005-0065-5

Martin, T.J., R.G. Sears, D.L. Seifers, T.L. Harvey, M.D. Witt, A.J. Schlegel, P.J. McCluskey, and J.H. Hatchett. 2001. Registration of 'Trego' wheat. Crop Sci. 41:929–930. doi:10.2135/cropsci2001.413929-ax

Martin, T.J., G. Zhang, A.K. Fritz, R. Miller, and M.-S. Chen. 2013. Registration of 'Tiger' wheat. J. Plant Reg. 7:201–204. doi:10.3198/jpr2012.09.0032crc

Nkongolo, K.K., J.S. Quick, W.L. Meyer, and F.B. Peairs. 1989. Russian wheat aphid resistance of wheat, rye, and triticale in greenhouse tests. Cereal Res. Commun. 17:227–232.

Piepho, H.P., J. Möring, A.E. Melchinger, and A. Büchse. 2008. BLUP for phenotypic selection in plant breeding and variety testing. Euphytica 161:209–228. doi:10.1007/s10681-007-9449-8

Plainsgold. 2017. CWRF Ardent Mills Ultragrain premium program. http://plainsgold.com/resources/ultragrain-program-2/.

Qi, L.L., B. Friebe, P. Zhang, and B.S. Gill. 2007. Homoeologous recombination, chromosome engineering and crop improvement. Chromosome Res. 15:3–19. doi:10.1007/s10577-006-1108-8

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. http://www.R-project.org/ (accessed 27 Dec. 2016).

Rudd, J.D., R.N. Devkota, J.A. Baker, G.L. Peterson, M.D. Lazar, B. Bean, D. Worrall, T. Baughman, D. Marshall, R. Sutton, L.W. Rooney, L.R. Nelson, A.K. Fritz, Y. Weng, G.D. Morgan, and B.W. Seabourn. 2014. 'TAM 112' wheat, resistant to Greenbug and Wheat Curl Mite and adapted to the dryland production system in the southern High Plains. J. Plant Reg. 8:291–297. doi:10.3198/jpr2014.03.0016crc

Syngenta. 2017. Platte special value program, https://agriprowheat.com/wheat-variety/central-plains/nugrain.

Taylor, M.R., G.W. Breser, and M.A. Boland. 2005. Hard white wheat and Gold Medal Flour: General Mills' contracting program. Rev. Agric. Econ. 27:117–129. doi:10.1111/j.1467-9353.2005.00211.x

USDA. 2016. Crop production. USDA-NASS. https://www.usda.gov/nass/PUBS/TODAYRPT/crop0816.pdf (accessed 27 Dec. 2016).

Whole Grains Council. 2016. Whole white wheat FAQ. http://wholegrainscouncil.org/whole-grains-101/whats-whole-grain-refined-grain/whole-white-wheat-faq (accessed 27 Dec. 2016).