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CULTIVAR

Registration of 'Avery' Hard Red Winter Wheat

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Abstract

'Avery' (Reg. No. CV-1143, PI 676977) hard red winter wheat (*Triticum aestivum* L.) was developed by the Colorado Agricultural Experiment Station and released in August 2015 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, contributed to its development. Avery was developed with the objective of making available a hard red winter wheat cultivar with improved grain yield and end-use quality compared with 'Byrd' hard red winter wheat. Avery is a doubled haploid cultivar developed using the wheat x maize (*Zea mays* L.) wide hybridization method from the cross 'TAM 112'/Byrd made in 2009 at Fort Collins, CO. Following doubled haploid generation in 2010, Avery was selected at Fort Collins in July 2011, assigned experimental line number CO11D174, and evaluated in yield trials in Colorado and other states in the US hard winter wheat region from 2012 to 2015. The name Avery was chosen in honor of early Colorado business and agricultural pioneer Franklin C. Avery (1849–1923).

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Hard winter wheat (*Triticum aestivum* L.) is a key part of dryland (rainfed) and irrigated cropping systems on the eastern plains of Colorado; annual Colorado winter wheat production between 2006 and 2015 averaged 2.05 million metric tons, with an average annual farm-gate value of $444.8 million (USDA–NASS, 2017). The adoption of wheat cultivars with good drought stress tolerance, a high level of winterhardiness, high grain yield potential, adequate host-plant resistance to prevalent diseases and insect pests, and end-use quality characteristics typical of the hard red winter (HRW) wheat market class helps foster successful wheat production and grain marketing in this area.

Avery (Reg. No. CV-1143, PI 676977) hard red winter wheat was developed by the Colorado Agricultural Experiment Station and released in August 2015 through a marketing agreement with the Colorado Wheat Research Foundation. Avery was released as a replacement for 'Byrd' (PI 664257; Haley et al., 2012a), a HRW wheat cultivar that was released in 2011 and by 2015 had become the most widely grown winter wheat cultivar in Colorado (USDA–NASS, 2015). The name Avery was chosen in honor of early Colorado business and agricultural pioneer Franklin C. Avery (1849–1923).

Methods

Avery was developed using the wheat × maize hybridization method (Laurie and Bennett, 1988; Santra et al., 2017) from the cross 'TAM 112' (PI 643143; Rudd et al., 2014)/Byrd made in

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Abbreviations: BLUE, best linear unbiased estimator; CSU, Colorado State University; HCS, heterogeneous compound symmetry; HMWG, high molecular weight glutenin; HRW, hard red winter; SRC, solvent retention capacity.

2009 at Fort Collins, CO. Both parents are HRW wheat cultivars adapted for production in the western areas of the US Great Plains. Doubled haploids were produced in 2010 from the F_1 generation, and seed of the doubled haploid plant was planted in a double "headrow" (two rows, 1 m long, 23 cm row spacing) in February 2011 at Fort Collins. Based on visual observations of overall agronomic appearance, Avery was selected in July 2011 and assigned experimental number CO11D174.

CO11D174 was subsequently evaluated in an unreplicated observation nursery at Fort Collins in 2012, the Colorado State University (CSU) Elite Trial from 2013 to 2015, dryland (rainfed) and irrigated CSU variety trials in 2014 and 2015, the Cooperative USDA–ARS Regional Germplasm Observation Nursery in 2014 and 2015, and the Cooperative USDA–ARS Southern Regional Performance Nursery in 2014. The CSU Elite Trials were arranged in resolvable, latinized row-column designs (John and Williams, 1995) with two replications in 2013 and 2014 and partial replication (Williams et al., 2011) in 2015. The CSU variety trials were arranged in resolvable, latinized row-column designs with three replications. All trial randomizations and statistical analyses were done within the R programming language (R Core Team, 2015); codes are freely available by email request to the corresponding author. Trial randomizations were prepared using version 0.2-31 of the R package *DiGGer* (Coombes, 2009).

Seed purification of Avery began in 2014 using bulk seed increases grown under irrigation at Fort Collins. For each seed increase cycle, purification was accomplished using visual identification and manual removal of tall and red-glumed variants. A subsample of grain harvested from a pre-breeder seed increase in July 2014 was used to plant a 0.4-ha breeder seed increase in September 2014. Breeder seed was used to plant a 5.3-ha foundation seed increase in September 2014. The foundation seed increase was harvested in July 2015.

Agronomic, disease resistance, and end-use quality data were analyzed using the Student's paired *t* test (*t.test* function) in base R. Yield and grain volume weight (test weight) data from the CSU Elite Trial and CSU variety trials were analyzed with the *asreml* package in R (Butler, 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 models specified in the *rcov* argument within the *asreml* call (as described in Butler, 2009). The restricted maximum likelihood (REML) loglikelihood value was used to select the best model for each environment. 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 (covariances) 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 individual environment means within a multienvironment 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 in R (Brien, 2016). The 0.05 α probability level was used for all mean comparisons.

Characteristics

General Description

Avery is an awned, white-glumed, HRW wheat. Avery has medium maturity (time to heading), similar to 'Hatcher' (PI 638512; Haley et al., 2005; n = 28 comparisons), 1.3 d later (n = 28) than Byrd, and 2.0 d earlier than 'Denali' (PI 664256; Haley et al., 2012b; n = 28). Avery is medium-tall at maturity, similar to Denali (n = 63) and about 3.8 cm taller than (n = 78) Hatcher and Byrd. The coleoptile length (evaluated according to Hakizimana et al., 2000) of Avery (77.8 mm; n = 5) is medium-long, similar to Byrd and Denali and longer than that of Hatcher (70.6 mm). Avery's straw strength is fair (5.9 score, n = 16; on a 1 to 9 scale, where 1 = erect and 9 = flat), similar to that of Hatcher (5.7) and less than that of Byrd (5.2) and Denali (4.4). Preharvest sprouting tolerance of Avery, assessed through determination of a germination index (Mares et al., 2005) from field-grown samples, is good (germination index = 0.29; n = 14), similar to that of Byrd and Hatcher (0.21) and greater than that of TAM 112 (0.43). Observations of winter survival ability in eastern Colorado and at two locations of the 2014 Southern Regional Performance Nursery (Mead, NE, and Columbia, MO; USDA–ARS, 2014) suggest that the winterhardiness of Avery is at least adequate for successful production in the west-central Great Plains region of the United States.

Disease and Insect Resistance

Avery has been characterized for disease and insect resistance in Colorado and through cooperative evaluations of the USDA–ARS Coordinated Regional Testing Program (USDA–ARS, 2014). In artificially inoculated field tests at Rossville, KS, in 2013 and 2015, Avery showed a moderately susceptible reaction to stripe rust (caused by *Puccinia striiformis* Westend. f. sp. *tritici* Eriks.), with an average infection type of 4.5 and an average severity of 25% (n = 2 observations). In these same nurseries, the susceptible repeated check line KS89180B-2 showed a highly susceptible reaction, with an average infection type of 7.7 and an average severity of 95%. Observations under natural stripe rust infection in Washington from 2013 to 2015 also showed that Avery is moderately susceptible, with an average infection type of 6.8 and an average severity of 72% (n = 6 observations). In these same nurseries, the susceptible repeated check line PS279 showed an average infection type of 8.0 and an average severity of 97%. Under natural stripe rust infection in Colorado in 2015, Avery showed a moderately susceptible reaction (6.4 score, where 1 = resistant and 9 = susceptible; n = 25), more resistant than Denali (7.6), similar to Byrd (6.7), and more susceptible than Hatcher (4.6).

In greenhouse seedling evaluations at St. Paul, MN, Avery was susceptible to US stem rust (caused by *P. graminis* Pers.:Pers f. sp. *tritici* Eriks. & E. Henn.) races QFCSC, QTHJC, MCCFC, RCRSC, RKQQC, TPMKC, TTTTF, GFMNC, and QCCSM and susceptible to African race TTKSK. Field adult-plant evaluations at St. Paul in 2015 confirmed that Avery is susceptible to the North American stem rust races. Adult plant-evaluation at Njoro, Kenya, in 2014 indicated that Avery is susceptible to Ug99 related races. Greenhouse seedling evaluations with leaf rust (caused by *P. triticina* Eriks.) have shown that Avery is susceptible to most common leaf rust races in the United States (TNBGJ, MCTNB, MFPSB, KFBJG, MBDSD, TFBJQ, MJBJG, MHDSB, TCRKG, PBLRG). In 2014, under natural field infection with unknown leaf rust races at Castroville, TX, Avery showed a susceptible adult-plant reaction.

Other evaluations in Colorado or through the USDA–ARS Coordinated Regional Testing Program (USDA–ARS, 2014) have shown that Avery is resistant to *Soil-borne wheat mosaic virus*, susceptible to a collection of endemic biotypes of the Hessian fly [*Mayetiola destructor* (Say)] (Chen et al., 2009), resistant to greenbug Biotype E [*Schizaphis graminum* (Rondani)], susceptible to Russian wheat aphid (*Diuraphis noxia* Kurdjumov) Biotypes 1 and 2, and tolerant to *Barley yellow dwarf virus*. Avery is moderately susceptible to *Wheat streak mosaic virus* but has shown resistance to a Texas collection of the wheat curl mite (*Aceria tosichella* Keifer; Dhakal et al., 2017). Avery lacks DNA markers *Wsm1* (Qi et al., 2007) and *Wsm2* (Lu et al., 2012) associated with *Wheat streak mosaic virus* resistance.

Field Performance

Avery was tested at 25 rainfed environments of the CSU Elite Trial in Colorado from 2013 to 2015 and 18 rainfed environments of the Colorado Uniform Variety Performance Trial from 2014 to 2015. In the first stage of the analyses for grain yield, a two-dimensional spatial model (AR1xAR1; Gilmour et al., 1997) was the best model for over 76% of the environments (trials). In the combined analysis (second stage) across all rainfed environments (n = 43 environments), the grain yield of Avery was similar to the hard white winter wheat cultivar Antero (PI 667743; Haley et al., 2014) and the HRW wheat cultivar Denali but greater than each of the other cultivars in the trials (Table 1). Compared with Antero, Avery showed similar grain yield in 2013 and 2014 when stripe rust was not a yield-limiting factor in the trials but lower grain yield in 2015 when stripe rust was a significant yield-limiting factor (Table 1). Grain volume weight of Avery across the rainfed environments (Table 1; n = 31) was below average, lower than all of the other HRW wheat cultivars tested except Hatcher.

Across seven irrigated environments, Avery was the top-ranked entry for grain yield, greater than the HRW wheat cultivars Hatcher and ‘Brawl CL Plus’ (PI 664255; Haley et al., 2012c) but not significantly greater than Byrd or Denali (Table 1). The irrigated trials included in these analyses comprise varied geography and production management conditions, which contributed to a greater degree of variation among environments and thus a relatively higher LSD value for mean comparisons. Despite its high yield potential, Avery is not recommended for irrigated production because of its susceptibility to stripe rust and fair straw strength, except where producers are accustomed to include timely fungicide and growth regulator (e.g., Trinexapac-ethyl) applications in their management plans.

Avery was tested in the 2014 Southern Regional Performance Nursery (USDA–ARS, 2014). Averaged across the hard winter wheat region (27 locations), Avery was the highest-yielding entry in the trial (4107 kg ha^{-1}; 40 total entries).

End-Use Quality

Milling and bread-baking characteristics of Avery and the HRW wheat check cultivars Byrd and Denali were determined using approved methods of the American Association of Cereal Chemists (AACC, 2000) in the CSU Wheat Quality Laboratory. Samples from multiple field environments from the 2013 and 2014 growing seasons were used for comparison.

Byrd is known for having relatively strong dough mixing properties, as is common with genotypes that carry the *Glu-D1d* [5+10 high molecular weight glutenin (HMWG) subunits] allele at the *Glu-D1* locus. In spite of its relatively low water absorption, higher values for pup loaf baking volume

Table 1. Grain yield and grain volume weight of hard white winter and hard red winter wheat cultivars in the Colorado State University (CSU) Elite Trial from 2013 to 2015, the Colorado Uniform Variety Performance Trial (UVPT) from 2014 to 2015, and the Colorado Irrigated Variety Performance Trial (IVPT) from 2014 to 2015.

Entry	Type‡	Grain yield†							Grain volume weight
		2013 Elite	2014 Elite	2015 Elite	2014 UVPT	2015 UVPT	Combined Elite and UVPT	Irrigated Elite and IVPT§	
		kg ha^{-1}							kg m^{-3}
Antero	HWW	2318	4540	4823	4046	5156	4023	6373	761
Avery	HRW	2314	4573	4485	4194	4180	4006	6578	755
Denali	HRW	2354	4489	4417	3874	4350	3933	6224	773
Byrd	HRW	2203	4416	4555	3955	4086	3882	6283	761
Hatcher	HRW	2221	4297	3838	3845	4038	3778	5930	756
Brawl CL Plus	HRW	2361	4091	3725	3819	3665	3701	4885	762
Sunshine¶	HWW	2201	4105	4172	3737	4280	3698	5379	750
Snowmass¶	HWW	1991	4039	4320	3705	3988	3626	–	754
Environments		7	10	8	9	9	43	7	31
Mean#		2269	4314	4264	3894	3798	3841	5950	759
LSD (0.05)		179	255	455	222	453	108	636	3

† Individual year and combined data from the CSU Elite Trial and the UVPT are from rainfed environments only.

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

§ Irrigated environments included one for each year of the CSU Elite Trial (2013–2015) and two for each year of the IVPT (2014 and 2015).

¶ Snowmass, Haley et al. (2011); Sunshine, Haley et al. (2017).

Trial mean includes only those entries in the table.

are typical for Byrd. Conversely, Denali is known for having weaker dough mixing properties, as is common with genotypes that carry the *Glu-D1a* (2+12 HMWG subunits) allele at the *Glu-D1* locus, and generally inferior pup loaf baking characteristics (i.e., shorter mixing time, lower mixing tolerance, and lower loaf volume). As expected given its pedigree, Avery carries the *Glu-D1d* allele at the *Glu-D1* locus, the *Glu-A1b* allele (2* HMWG subunit) at the *Glu-A1* locus, and the *Glu-B1b* allele (7+8 HMWG subunits) at the *Glu-B1* locus. Neither Avery or the two check cultivars carry the T1BL-1RS or T1AL-1RS wheat-rye chromosomal translocations.

Overall, Avery showed intermediate values for milling-related characteristics relative to Byrd and Denali (Table 2). Compared with Byrd, Avery had higher kernel weight and kernel diameter, lower grain ash concentration (120 g kg^{-1} moisture basis), and lower break flour extraction (with a modified Brabender Quadrumat Senior, C.W. Brabender). Each of these comparisons suggest a greater potential for improved milling performance of Avery relative to Byrd. Compared with Denali, which is known for better milling performance compared with Byrd, Avery had similar kernel weight and kernel diameter, lower grain ash concentration, and greater total flour extraction.

Values for baking-related characteristics of Avery were also generally intermediate between Byrd and Denali (Table 2). Compared with Byrd, Avery showed lower Mixograph (National Manufacturing) mixing time and mixing tolerance and lower loaf volume in straight-dough pup-loaf baking tests. Although bake water absorption values were similar for Avery and Byrd, likely because of the relative subjectivity and imprecision of water absorption estimation in the pup-loaf bread-baking test, Avery showed greater values than Byrd for solvent retention capacity (SRC; Kweon et al., 2011) using water as a solvent. Given the lower grain protein concentration of Avery compared with Byrd, and the strong positive association between water absorption and protein concentration (Finney and Yamazaki, 1967), we determined the SRC water absorption/flour protein ratio to enable a more objective comparison of water absorption properties of the three cultivars. As observed with SRC water absorption, Avery showed a higher SRC/flour protein ratio (10.5% higher) compared with Byrd and a similar ratio compared with Denali.

Availability

The Colorado Agricultural Experiment Station will maintain breeder seed of Avery. Multiplication and distribution rights of other classes of certified seed have been transferred from the Colorado Agricultural Experiment Station to the Colorado Wheat Research Foundation, 4026 South Timberline Road, Suite 100, Fort Collins, CO, 80525. Avery was granted US Plant Variety Protection (PVP) under Public Law 91-577 with the Certification Only option in June 2016 (PVP Number 201600244). 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 years from the date of publication. Seed of Avery has been deposited with the 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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Table 2. Milling, dough-mixing, and bread-baking characteristics of wheat cultivar Avery and check entries across multiple environments from the 2013 and 2014 growing seasons in Colorado.

Trait and unit of measurement	Environments	Avery	Byrd	Denali
SKCS kernel weight (mg)†	15	30.0	28.3*	30.7 ns‡
SKCS kernel diameter (mm)	15	2.61	2.52*	2.58 ns
SKCS kernel hardness (score)	15	64.0	63.4 ns	62.2 ns
Grain volume weight (kg m^{-3})	15	758	757 ns	773*
Grain ash concentration (g kg^{-1})§	38	14.1	14.8*	14.7*
Total flour extraction (g kg^{-1})	15	727	740*	716*
Break flour extraction (g kg^{-1})	15	481	511*	486 ns
Grain protein concentration (g kg^{-1})§	30	122	132*	122 ns
Mixograph mixing time (min)	25	5.2	6.2*	3.2 ns
Mixograph tolerance (score)¶	25	4.3	4.6*	2.4*
Bake mix time (min)	15	5.1	5.4 ns	3.1*
SRC water absorption (g kg^{-1})#	16	603	586*	596 ns
SRC/flour protein ratio††	16	6.01	5.44*	5.86 ns
Bake water absorption (g kg^{-1})	15	625	634 ns	617 ns
Loaf volume (L)	15	1.06	1.12*	0.85*
Crumb grain (score)¶	15	4.1	3.9 ns	2.8*

* Significance of the difference between Avery 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.

§ Grain ash and protein concentration reported on a 120 g kg^{-1} moisture basis.

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

SRC, solvent retention capacity.

†† SRC/flour protein ratio calculated as SRC water absorption/flour protein.

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References

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

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 25 Oct. 2017).

Butler, D. 2009. asreml: Asreml() fits the linear mixed model. R package version 3.0. https://www.vsni.co.uk/downloads/asreml-r/ (accessed 25 Oct. 2017).

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

Coombes, N.E. 2009. DiGGer design search tool in R. http://nswdpibiom.org/austatgen/software (accessed 25 Oct. 2017).

Dhakal, S., C.-T. Tan, L. Paezold, M.P. Fuentealba, J.C. Rudd, B.C. Blaser, Q. Xue, C.M. Rush, R.N. Devkota, and S. Liu. 2017. Wheat curl mite resistance in hard winter wheat in the US Great Plains. Crop Sci. 57:53–61. doi:10.2135/cropsci2016.02.0121

Finney, K.F., and W.T. Yamazaki. 1967. Quality of hard, soft, and durum wheats. In: K.S. Quisenberry and L.P. Reitz, editors, Wheat and wheat improvement. ASA, CSSA, and SSSA, Madison, WI. p. 471–503.

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.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, 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, F.B. Peairs, J.A. Stromberger, E.E. Hudson-Arns, S.A. Seifert, V.A. Anderson, G. Bai, X. Chen, R.L. Bowden, Y. Jin, J.A. Kolmer, M.-S. Chen, and B.W. Seabourn. 2017. Registration of 'Sunshine' wheat. J. Plant Reg. 11:289–294. doi:10.3198/jpr2016.12.0075crc

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, 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, UK. doi:10.1007/978-1-4899-7220-0

Kweon, M., L. Slade, and H. Levine. 2011. Solvent retention capacity (SRC) testing of wheat flour: Principles and value in predicting flour functionality in different wheat-based food processes and in wheat breeding—a review. Cereal Chem. 88:537–552. doi:10.1094/CCHEM-07-11-0092

Laurie, D.A., and M.D. Bennett. 1988. The production of haploid wheat plants from wheat × maize crosses. Theor. Appl. Genet. 76:393–397. doi:10.1007/BF00265339

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

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

Qi, L.L., B. Friebe, P. Zhang, and B.S. Gill. 2007. Homoeologous recombination, chromosome engineering and crop improvement. Chromosome Res. 15:3–19.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. http://www.R-project.org/ (accessed 25 Oct. 2017).

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

Santra, M., H. Wang, S. Seifert, and S.D. Haley. 2017. Doubled haploid laboratory protocol for wheat using wheat-maize wide hybridization. In: P.L. Bhalla and M.B. Singh, editors, Wheat biotechnology: Methods and protocols. Vol. 1679, Methods in Molecular Biology. Springer, New York. doi:10.1007/978-1-4939-7337-8_14

USDA–NASS. 2015. Colorado winter wheat varieties—2015 crop. https://www.nass.usda.gov/Statistics_by_State/Colorado/Publications/Special_Interest_Reports/ (accessed 25 Oct. 2017).

USDA–NASS. 2017. Quick stats. https://quickstats.nass.usda.gov (accessed 25 Oct. 2017).

USDA–ARS. 2014. Hard winter wheat regional nursery program. https://www.ars.usda.gov/plains-area/lincoln-ne/wheat-sorghum-and-forage-research/docs/hard-winter-wheat-regional-nursery-program/research/ (accessed 25 Oct. 2017).

Williams, E., H.-P. Piepho, and D. Whitaker. 2011. Augmented p-rep designs. Biom. J. 53:19–27. doi:10.1002/bimj.201000102