Published April 27, 2017

JOURNAL OF PLANT REGISTRATIONS

CULTIVAR

Registration of 'Pritchett' Soft White Winter Club Wheat

Kim Garland-Campbell,* Arron H. Carter, Stephen S. Jones, Xianming Chen, Patricia DeMacon, Ryan Higginbotham, Doug Engle, Stephen O. Guy, Chris C. Mundt, Timothy D. Murray, Craig F. Morris, and Deven See

Abstract

Soft white club wheat (*Triticum aestivum* ssp. *compactum*) is a unique component of wheat production in the Pacific Northwest, comprising 10 to 12% of the wheat crop. It is valued for milling and baking functionality and marketed for export in a 10 to 30% blend with soft white wheat known as western white. Our goal was to develop a club wheat cultivar for the traditional club wheat-growing region of central Washington, with better soilborne disease resistance than currently grown cultivars. The bulk pedigree breeding method was used to select Pritchett (Reg. No. CV-1123, PI 678944) from the cross: 'Chukar'/2*'Bruehl'. Pritchett has significantly better grain yield and grain volume weight in environments receiving less than 30 cm annual precipitation than Bruehl, the cultivar that it is targeted to replace. Pritchett has better milling quality, producing larger diameter cookies and greater volume sponge cake. Pritchett has effective adult plant resistance to stripe rust, has moderate resistance to Cephalosporium stripe, and carries the *Pch1* gene for moderate resistance to eyespot. Pritchett carries the *Rht-B1b* allele for reduced plant height but has excellent emergence from deep sowing. Pritchett was released because of its superior agronomic productivity in the targeted region, combined with resistance to multiple diseases and superior end use quality.

Journal of Plant Registrations 11:152–158 (2017).
doi:10.3198/jpr2016.04.0018crc
Received 4 Apr. 2016.
Accepted 22 Oct. 2016.
Registration by CSSA.
5585 Guilford Rd., Madison, WI 53711 USA
*Corresponding author (kgcamp@wsu.edu)

Club wheat (*Triticum aestivum*. ssp. *compactum*) is grown commercially exclusively in the Pacific Northwest of the United States and represents 6 to 10% of the total wheat crop in that region annually (US Wheat Associates, 2015). It is prized in the export market for its characteristic end use functionality in a 10 to 30% blend with soft white winter wheat, known as western white. Club wheat is valued for its low gluten strength, low water absorption, and low batter viscosity, resulting in high quality cookies and high volume sponge cakes. Club wheat cultivars have consistently been bred to have greater flour extraction and break flour yields, higher starch concentration, and less starch damage than soft white winter wheat (Lin and Czuchajowska, 1997; Morris et al., 2005). Club wheat has unique spike morphology, conditioned by the dominant *compactum* (*C*) locus on chromosome 2DL (Johnson et al., 2008) that results in redistribution of yield components. The cultivar Bruehl (Jones et al., 2001) has been predominant in the traditional club wheat-growing region of central Washington State. Bruehl has excellent resistance to stripe rust (caused by *Puccinia striiformis* Westend f. sp. *tritici*) and is moderately resistant to speckled snow mold (caused by *Typhula* spp.), but it is susceptible to eyespot, caused by *Oculimacula yallundae* (Wallwork & Spooner) Crous & W. Gams and *O. acuformis* (Boerema, R. Pieters, & Hamers) Crous & W. Gams. Bruehl also has lower flour extraction and break flour yields than other club wheat cultivars. This research was undertaken to improve milling and baking quality, resistance to soilborne diseases, specifically eyespot, and grain yields of club wheat targeted to the traditional club wheat growing areas in Douglas, Grant, Adams, and Lincoln counties in Washington State. Pritchett club wheat (Reg. No. CV-1123, PI 678944) was released because it met these criteria. Pritchett was named after John Pritchett, who served the

K. Garland-Campbell , X. Chen, D. Engle, C.F. Morris, and D. See, USDA-ARS Wheat Health, Genetics and Quality Research Unit, 209 Johnson Hall, Washington State Univ., Pullman WA 99164-6420; A.H. Carter, S.S. Jones, P. DeMacon, and S.O. Guy, Dep. of Crop and Soil Sciences, Box 646420, Washington State Univ., Pullman WA, 99164-6420; R. Higginbotham, Washington State Univ. Extension, Box 646420, Washington State Univ., Pullman WA, 99164-6420; C.C. Mundt, Dep. of Botany and Plant Pathology, 2082 Cordley Hall, Oregon State Univ., Corvallis, OR 97331-2902; T.D. Murray, Dep. of Plant Pathology, Box 646430, Washington State Univ., Pullman WA, 99164-6430.

Abbreviations: HTAP, high-temperature adult-plant; IT, infection type; KASP, Kompetitive Allele Specific PCR; WSU, Washington State University.

USDA-ARS wheat breeding and genetics program from 1957 to 2000 and is fondly remembered for his work ethic, dedication, and positive influence on many student employees.

Methods

The pedigree of Pritchett is 'Chukar'/2*'Bruehl', with the final cross made by Kerry Balow in 2006 (Garland-Campbell et al., 2005; Jones et al., 2001). Pritchett was evaluated under the experimental number 4J071366-1. Pritchett was evaluated in the Washington State Soft Wheat Variety Trials 4J071366C and 4J0713366C, due to transcription errors.

Generation Advance

The F_1 through F_3 were advanced without selection. The F_3 bulk population was planted in a 5.5-m^2 plot in the field at the Washington State University (WSU) Spillman Agronomy Farm, Pullman WA, in fall 2008. In summer 2009, 150 heads were randomly harvested from the F_3 bulk population, threshed separately, and planted as F_4 head rows in sets of four rows, 1 m long, spaced 0.3 m apart with 0.1 m between sets of rows at Spillman Agronomy Farm. The F_4 head rows were selected in 2010 on the basis of plant height, maturity, and resistance to stripe rust under natural infection. From the F_5 generation on, the breeding line designated as 4J071366-1 was evaluated in yield trials, initially at Spillman Agronomy Farm and then at other locations (see below).

Yield Trials

Pritchett was evaluated in USDA-ARS field trials from 2013 to 2015 at Pendleton, OR, Genesee, ID, and Central Ferry, Farmington, Harrington, Lind, Pullman, Ritzville, and St. Andrews, WA, for a total of 17 environments over the 3 yr. Selection was based on agronomic characteristics (heading date, height, standability), disease resistance, grain yield, grain volume weight, and end use quality. Experimental designs at each location were either unreplicated designs with multiple replicated checks or α lattice designs with two replications. Pritchett was entered into the Washington State Extension Cereal Variety Testing Soft Winter Wheat Nursery in 2014 in the <40-cm precipitation zone trials and at all testing locations for the same nursery in 2015.

Heading date was recorded as days from 1 January to 50% of full spike emergence from the boot (Zadoks growth stage 60) on a plot basis (Zadoks et al., 1974). Height was measured after senescence and recorded as the average distance from the base of the plant to the top of the spike on a plot basis. Grain was harvested with a Wintersteiger Classic small plot combine (Wintersteiger Inc., Salt Lake City), and grain yield was measured on a plot basis with correction for grain moisture and converted to kilograms per hectare. Grain volume weight was recorded based on a cleaned, 600-g sample using AACC International Approved Method 55-10.01 (AACC International, 2008). Procedures for the Washington State Extension Cereal Variety Testing nurseries are detailed at http://variety.wsu.edu/.

Disease Resistance Evaluations

Resistance to *P. striiformis* races PSTv-4, PSTv-14, PSTv-37, PSTv-40, and PSTv-51 was evaluated on 28-d-old seedlings in a growth chamber operating at 16 h light and 8 h dark with diurnal temperatures gradually changing from 4°C at 2:00 AM to 20°C at 2:00 PM. Disease was rated as infection type on a 0-to-9 scale where 0 = most resistant and 9 = most susceptible as described in Line and Qayoum (1992). The race PSTv-51 is the most virulent race identified so far in the United States. The greenhouse seedling tests to specific races were conducted in 2014 to 2016, October to December, for each race without replication. For adult-plant tests to specific races, seed was planted in the greenhouse in late November and seedlings of about 3 to 5 cm were vernalized at 4°C for 6 to 9 wk, transplanted into pots and grown in the greenhouse (10–25°C diurnal temperature cycle, 16 h light) from January to March. Plants at boot to flowering stages (Zadoks growth stage 45) were inoculated with urediniospores of a particular race mixed with talcum powder at about 1:20 ratio, incubated for 20 to 24 h in a dew chamber (dark, 10°C) and then grown in a greenhouse growth chamber at the 10 to 30°C diurnal temperature cycle with 16 h light. Infection type (IT) was recorded for each plant 18 to 20 d after inoculation. Disease severity was rated as percentage leaf area infected, using the modified Cobb scale as in Peterson et al. (1948). The three replications for each adult plant race test were conducted during different time periods. Entries with a high IT in the seedling low-temperature test but with a low IT to all tested races in the adult-plant tests under high temperatures were considered to have high-temperature adult-plant (HTAP) resistance. The club wheat breeding line WA7821, which possesses no known genes for stripe rust resistance, was included in all trials as a susceptible check. Stripe rust was evaluated in the field at Mt. Vernon, Pullman, and Walla Walla, WA, under natural infection from 2013 through 2015, except at Pullman in 2014, where field trials were inoculated with a mixture of predominant races PSTv-14 and PSTv-37. These races represent different race groups and, in combination, are virulent to all resistance genes in the set of 18 *Yr* single-gene lines used to differentiate the pathogen races, except for *Yr5* and *Yr15* (Wan and Chen, 2014). Predominant races in Pacific Northwest wheat fields at the time were PSTv-14 and PSTv-37.

Response to eyespot was evaluated as described in Sexton and Murray (2016b). Response to Cephalosporium stripe disease (caused by *Cephalosporium gramineum* Y. Nisik. & Ikata) was evaluated as described in Sexton and Murray (2016a) and by Vazquez et al. (2015).

Abiotic Stress Evaluations

The coleoptile length of Pritchett was evaluated using 10 plants per genotype and two replications per trial in 2014 and 2015, according to Hakizimana et al. (2000). Percentage fall emergence from deep sowing was rated serendipitously on 15 Sept. 2015 after a rainfall event on 5 Sept 2015 that occurred 5 d after the seeds were sown to a depth of 12 cm. Two replications were rated at Kahlotus and Ritzville, WA.

Cold tolerance was evaluated in artificial freezing trials conducted at the WSU Plant Growth Facility in Pullman, WA, in three to four replications of 20 plants per block for each of five trials from 2013 to 2015 as described in Skinner and Bellinger (2011). Spring survival was rated in the Washington State Extension Cereal Variety Testing Soft Winter Wheat Nursery at St. Andrews, WA, in 2015 after severe freezes that occurred in Washington in the fall and winter of 2014–2015.

End Use Quality

End use quality of Pritchett was evaluated by the USDA-ARS Western Wheat Quality Laboratory on grain samples from a total of 11 nurseries grown in Oregon and Washington from 2011 to 2014. Quality analyses for milling, baking, and product tests were performed according to AACC International protocols (AACC International, 2008).

Genotype Data

Pritchett was assayed with Kompetitive Allele Specific PCR (KASP) markers (LGC Genomics, Beverly MA) developed on the basis of analysis of specific genes, including *Glu-D1-1-GluD1-2*, *Lr37-Yr17-Sr38*, *Pch1*, *Rht-B1*, and *Rht-D1* (Chapman et al., 2008; Ellis et al., 2002; Helguera et al., 2003; Liu et al., 2008; McIntosh et al., 2014). For additional details see MAS-Wheat (2016).

Data Analysis

Comparisons between Pritchett and check cultivars grown in the USDA-ARS trials, 2013 to 2015, were made after environments were grouped into those with ≤40 and >40 cm annual precipitation to minimize variance heterogeneity. Data were analyzed using mixed models with environment, genotype, and their interaction considered fixed and replications and blocks within environments considered random. Least squares means were calculated for genotypes within precipitation zones and significant differences among genotypes determined using Fisher's protected F-test at the $\alpha = 0.05$ level. The actual number of environments (n) included in each analysis depended on whether the data for a given trait were recorded in individual trials.

Pritchett has been evaluated in the Washington State Extension Trials since 2014. Environments were grouped and analyzed within four annual precipitation zones. Each zone comprised four to six environments in each year. Data were analyzed using mixed models with all factors considered fixed. Least squares means were calculated for genotypes within precipitation zones and significant differences among genotypes determined using Fisher's protected F-test at the $\alpha = 0.10$ level. Quality data for Pritchett were compared with the predominant club cultivars, Bruehl and 'ARS-Crescent' (PI 664048), using t tests paired over a total of 11 environments.

All disease screening data and the coleoptile experiments were analyzed using mixed models over testing environments with either the MIXED procedure of SAS/STAT V. 9.2 (SAS Institute, Cary NC) or the *nlme* package of R (Pinheiro et al., 2016), with all genotypes and environments considered fixed and replications considered random.

Characteristics and Discussion

Grain Yield, Grain Volume Weight, and Agronomic Data

In USDA-ARS trials from 2013 to 2015, the average yield of Pritchett was significantly greater than that of Bruehl in the <40-cm precipitation environments (Table 1). The heading date of Pritchett was earlier than club wheat cultivars ARS-Crescent and Bruehl over all environments. Pritchett's plant height was similar to other cultivars but shorter than Bruehl in the high precipitation environments (Table 2). The grain volume weight of Pritchett was significantly greater than Bruehl in the high rainfall environments. Grain yields of Pritchett were competitive with the major soft white cultivars 'Otto' (Carter et al., 2013) and 'Xerpha' (Jones et al., 2010) in low and high rainfall environments.

In the WSU Variety Testing trials, the grain yield of Pritchett was significantly greater than the club wheat cultivars Bruehl, 'Coda' (Allan et al., 2000), and 'Cara' (Garland-Campbell et al., 2013) but equal to ARS-Crescent over all 25 site-years (Table 3). In the 30- to 40-cm precipitation zone, grain yield of Pritchett was significantly greater than Bruehl and Cara and Coda but equal to ARS-Crescent, whereas in the 40- to 50-cm zone, the grain yield of Pritchett was significantly greater than Bruehl but equal to the other check cultivars. In the >50-cm zone, Pritchett yielded significantly greater than Bruehl and Coda, equal to Cara, and significantly less than ARS-Crescent.

Club wheat cultivars traditionally have lower grain volume weight than other soft wheat classes, and the US grain grading system allows no. 1 grade club wheat to be as much as 2.5 kg hL^{-1} lower than other soft wheat classes (USDA, 2006). Even

Table 1. Comparisons of club wheat cultivar Pritchett to check cultivars from 2013 to 2015 in the <40 cm precipitation zones of Washington.†

Name	Grain yield	Heading date‡	Plant height	Grain vol. weight
	kg ha^{-1}	d	cm	kg hL^{-1}
Pritchett	4070	145	79	74.5
ARS-Crescent	3788	150	76	75.1
Bruehl	3450	150	80	73.0
Otto	3977	147	79	75.2
Xerpha	3698	148	76	74.3
LSD (0.05)	471	1	5	3.5
No. of environments	5	1	4	4

† Environments included Harrington, 2013, 2015, 2015; Lind, 2013; and Ritzville, 2014.

‡ Days from 1 January. Heading data were only recorded at one environment in the <40-cm precipitation zone.

Table 2. Comparisons of club wheat cultivar Pritchett to check cultivars from 2013 to 2015 in the >40-cm precipitation zones of Washington, Idaho, and Oregon.†

Name	Grain yield	Heading date‡	Plant height	Grain vol. weight
	kg ha^{-1}	d	cm	kg hL^{-1}
Pritchett	5085	155	88	70.3
ARS-Crescent	5372	158	89	68.4
Bruehl	5416	156	94	68.3
Otto	5332	157	–§	–§
Xerpha	5392	154	92	71.9
LSD (0.05)	336	2	3	1.2
No. of environments	12	3	10	11

† Environments include Central Ferry, WA, 2013, 2014, 2015; Farmington, WA, 2014; Genesee, ID, 2013, 2014, 2015; Pendleton, OR, 2013, 2014, 2015; and Pullman, WA, 2013, 2015.

‡ Days from 1 January.

§ Otto was not evaluated in all environments.

Table 3. Agronomic comparisons of Pritchett with other club wheat cultivars in the Washington State Cereal Variety Testing Soft Winter Wheat Nursery, 2014 and 2015.

Entry	<30-cm precipitation (8 site-years)					30–40 cm precipitation (9 site-years)					40–50 cm precipitation (5 site-years)					All zones (25 site-years)				
	Yield	GVW†	Prot‡	Ht§	HD¶	Yield	GVW	Prot	Ht	HD	Yield	GVW	Prot	Ht	HD	Yield	GVW	Prot	Ht	HD
	kg ha^{-1}	kg hL^{-1}	g kg^{-1}	cm	d	kg ha^{-1}	kg hL^{-1}	g kg^{-1}	cm	d	kg ha^{-1}	kg hL^{-1}	g kg^{-1}	cm	d	kg ha^{-1}	kg hL^{-1}	g kg^{-1}	cm	d
ARS-Crescent	2381	76.4	123	65	145	5257	73.9	109	87	151	5516	71.8	117	96	147	4739	74.4	114	83	149
Bruehl	2268	75.8	121	72	144	5134	73.1	114	90	151	4972	69.4	124	95	148	4404	73.2	118	87	149
Cara	2056	74.3	127	59	145	4847	72.4	114	83	150	5611	70.3	123	97	145	4336	72.6	120	79	148
Coda	2093	78.1	128	65	144	5241	76.6	116	90	151	5515	74.6	123	100	146	4497	76.7	121	85	148
Pritchett	2453	77.5	123	66	143	5387	74.6	111	88	150	5596	71.8	118	94	147	4730	74.6	116	84	148
LSD (0.10)	83	0.5	2	1	0.3	137	0.3	2	2	0.3	212	0.7	4	2	1	78	0.2	1	1	0.3

† GVW, grain volume weight.

‡ Prot, protein concentration.

§ Ht, plant height.

¶ HD, heading date as days from 1 January.

so, grain volume weight is a major selection criterion for club wheat breeding. The grain volume weight of Pritchett, across 25 site-years, was significantly less than Coda, equal to ARS-Crescent, and significantly greater than Bruehl and Cara. Grain protein concentration of Pritchett across all zones was greater than ARS-Crescent, and heading date was slightly earlier than ARS-Crescent and Bruehl but equal to Cara and Coda. The plant height of Pritchett was slightly shorter than Bruehl. Because Pritchett has greater grain volume weight and greater grain yields than Bruehl in every precipitation zone, it is recommended by the USDA-ARS and WSU as a replacement for Bruehl.

Disease Resistance

The target growing area of Pritchett experiences regular epidemics of stripe rust, so resistance is essential. Pritchett has been rated for resistance to stripe rust in field nurseries since 2010. It was highly resistant in all of the field tests (data for 13 locations from 2013 to 2015 shown in Table 4), except for an IT score of 5 in 2015 at the WSU Whitlow Farm in Pullman. This was attributed to a low frequency of segregating off-types in the breeding line, which were subsequently removed during breeder seed purification (see below). In the same trials, the susceptible check, WA7821, had a susceptible reaction with high IT and severity at every environment.

Pritchett was evaluated for all-stage resistance to multiple races of the stripe rust pathogen in the greenhouse as 3-wk-old seedlings under low temperatures and as adult plants under high temperatures. In the seedling tests from 2014 to 2016, Pritchett was highly resistant to races PSTv-4 and PSTv-51 but susceptible to PSTv-14, Pstv-37, and PSTv-40 (Table 5). In the adult-plant tests at high temperatures, Pritchett was highly resistant to tested races PSTv-14, PSTv-37, and PSTv-40 in both 2014 and 2015 (data not shown). For comparison, susceptible check WA7821 had a susceptible reaction in all seedling and adult-plant tests. The seedling susceptibility to PSTv-14,

Table 4. Reaction of Pritchett and WA7821 club wheat to natural infection of stripe rust in field trials at Mt. Vernon, Pullman, and Walla Walla WA, 2013–2016.

Year	Entry	Location and Zadoks growth stage (GS) when rated: Mt. Vernon GS 35		Mt. Vernon GS 65		Spillman Farm, Pullman GS 75		Plant Pathology Farm, Pullman GS 75		Northern Farms, Pullman GS 75		Walla Walla GS 65		Summary rating§	Possible HTAP resistance¶
		IT†	Sev‡	IT	Sev	IT	Sev	IT	Sev	IT	Sev	IT	Sev		
		1–9	1–100	1–9	1–100	1–9	1–100	1–9	1–100	1–9	1–100	1–9	1–100		
2013	Pritchett	2	10	2	5					2	1				
	WA7821	8	80	8	100					8	100				
2014	Pritchett	2	10	2	5	2	5	2	2	2	10			R	High
	WA7821	8	80	8	100	8	100	8	100	8	100			S	No
2015	Pritchett	2	20	2	1	2	5	2	5	2	2	3	5	R	Moderate
	WA7821	8	60	8	80	8	100	8	10	8	75	8	80	S	No
2016	Pritchett	2	30	3	10	5	10	2	1	3	10	3	10	MR	Moderate
	WA7821	8	80	8	90	8	100	8	80	8	100	8	10	S	No

† IT, infection type, rating on a 0-to-9 scale according to Line and Qayoum (1992), where 0 is the absence of symptoms.

‡ Sev, disease severity, rated on a plot basis, on a 0-to-100 scale, where 0 is the absence of disease, as described in Naruoka et al. (2015).

§ Summary rating assigned by X. Chen according to analysis of multiple testing environments.

¶ Possible high-temperature adult-plant (HTAP) resistance. Determined by comparing IT and Sev rated at an early growth stage to those same ratings rated at a later growth stage. If the scores at an early growth stage are higher than those at a later growth stage, HTAP is assumed to be present.

Table 5. Evaluation of all-stage resistance of Pritchett and WA7821 club wheat to multiple races of stripe rust, rated on seedlings under controlled conditions, 2014–2016.

Name	Infection types produced by PST races†				
	PSTv-4	PSTv-14	PSTv-37	PSTv-40	PSTv-51
Pritchett	2	8	8	8	2
WA7821	8	8	8	8	8

† Virulence/avirulence formula of races used for screening: Pstv-4, 1,6,9,17,27,SP,Tye/5,7,8,10,15,24,32,43,44,Tr1,Exp2; Pstv-14, 1,6,7,8,9,17,27,43,44,Tr1,Exp2,Tye/5,10,15,24,32,SP; Pstv-37, 6,7,8,9,17,27,43,44,Tr1,Exp2/1,5,10,15,24,32,SP,Tye; Pstv-40, 6,7,8,9,10,24,27,32,43,44,Tr1,Exp2/1,5,15,17,SP,Tye; Pstv-51, 1,6,7,8,9,10,17,24,27,32,43,44,SP,Tr1,Exp2,Tye/5,15.

Pstv-37, and PSTv-40 combined with adult-plant resistance to those same races indicate that Pritchett has HTAP resistance. In summary, Pritchett has a combination of all-stage resistance to some races and a moderate to high level of HTAP resistance to stripe rust. Pritchett carries unknown genes for resistance to stripe rust. Sources carrying the resistant alleles at *Yr5* and *Yr15* are not present in Pritchett's pedigree. The allele for resistance at *Lr37-Yr17-Sr38* is also not present in Pritchett, based on the KASP assay for that gene.

Pritchett carries the *Pch1* gene for resistance to eyespot derived from Chukar. In an inoculated nursery, Pritchett had a disease index of 60.4, significantly better than the susceptible check 'Eltan' (Peterson et al., 1991) at 74.2, but less than the resistant check 'Madsen' (Allan et al., 1989) at 54.5 ($LSD_{0.05}$ = 13.2) (Sexton and Murray, 2016b). Pritchett is moderately resistant to Cephalosporium stripe. In inoculated trials at Pullman in 2015, Pritchett had a disease index of 36.2 compared with the moderately resistant Eltan (21.0) and Bruehl (42.4) and the susceptible check Stephens (77.7) ($LSD_{0.05}$ = 18.7) (Sexton and Murray, 2016a). In trials inoculated with Cephalosporium stripe at Corvallis, OR, from 2013 to 2015 using a disease index of 1 to 5, where 1 = no disease and 5 = severe stunting and interveinal leaf stripe symptoms, Pritchett was rated as 1.78, compared with Bruehl (2.40), ARS Crescent (1.98), Otto (0.95), Xerpha (2.15), and the susceptible cultivar SY Ovation (PVP201100387) (5.0) ($LSD_{0.05}$ 4.0). Snow mold is a critical but sporadic disease in the Pacific Northwest. Despite several attempts to obtain good disease pressure, only the 2015 trial at Waterville, WA, was uniform enough to compare entries for resistance to snow mold using a 1-to-10 disease index where 1 = dead water-soaked leaves and lack of regrowth and 10 = no disease symptoms, green leaves, and actively growing plants. The survival score of Pritchett was 2.50, similar to that of Bruehl (2.17), less than the resistant check Eltan (7.00) and Otto (6.33), but better than the susceptible cultivar Madsen (1.5).

Abiotic Stress

The average coleoptile length of Pritchett was similar to Bruehl and equal to the other club and soft white winter wheat cultivars grown in the targeted region. Emergence after deep sowing of Pritchett was better than that of other cultivars targeted to the dry and intermediate precipitation zones of Washington as rated after a rain event that caused crusting of the topsoil (Table 6). In freezing tests conducted in the WSU Plant Growth Facility and in the field at St. Andrews, WA, Pritchett exhibited cold tolerance equal to ARS Crescent and Bruehl, better than the susceptible check 'Stephens' (Kronstad et al., 1978), but not as good as the resistant check Eltan (Peterson et al., 1991) (Table 6).

Milling and Baking Quality

Pritchett has displayed milling properties better than Bruehl and equal to the very high quality ARS Crescent. The flour yield of Pritchett was 701 g kg^{-1}, which was 10 g kg^{-1} greater than Bruehl ($p < 0.001$); the break flour yield of Pritchett was 436 g kg^{-1}, which was 20 g kg^{-1} greater than Bruehl ($p < 0.001$), and the four ash of Pritchett was 3.85 g kg^{-1}, which was 0.13 g kg^{-1} less than Bruehl, contributing to a milling score index 2.3% better than Bruehl ($P < 0.001$). These differences, while small in absolute value, are significant in the milling industry. The flour sedimentation volume for Pritchett was 6.7 mL g^{-1} which was 1.5 mL g^{-1} lower than for Bruehl. The lactic acid

Table 6. Emergence and cold tolerance of club wheat cultivar Pritchett compared with check cultivars.

Name	Fall emergence after rain and crusting, 2015		Coleoptile growth		Survival in artificial freeze trials†	Spring survival at St. Andrews, WA
	Kahlotus	Ritzville	2013	2015	2013–2014	2014
	———— %‡ ————		— mm after 14 d —		% (SE)	1–10§
Pritchett	45	75	96.0	90.5	0.27 (0.06)	5.67
ARS-Crescent	8	25	85.5	79.5	0.22 (0.03)	6.00
Bruehl	33	60	92.5	87.0	0.16 (0.03)	5.33
Otto	35	72	NA	79.5	0.19 (0.04)	7.33
Eltan					0.34 (0.01)	8.33
Stephens					0.03 (0.01)	4.00
LSD (0.05)	17	31	10.2	19	NA¶	0.72

† Trials were conducted according to Skinner and Bellinger (2011). Data were unbalanced and analyzed using mixed models.

‡ % emergence over two replications.

§ Spring survival on a 1-to-10 scale, where 10 = complete stand.

¶ LSD not applicable due to differences in SE among genotypes.

solvent retention capacity (SRC-L) was 737 g kg $^{-1}$ for Pritchett compared with 844 g kg^{-1} for Bruehl. Pritchett has the Dx2Dy12 subunit at the *Glu-D1-1-Glu-D1-2* gene as assayed using the *Glu-D1* KASP marker. These differences indicate that Pritchett has weak gluten strength, a preferred trait for products made from flour in the western white market class. The mixograph water absorption for both Pritchett and Bruehl was 510 g kg^{-1}, and the water solvent retention capacity was 521 g kg^{-1} for Pritchett and 531 g kg^{-1} for Bruehl. These results indicate that Pritchett has low water absorption, desired for soft wheat products. The baking performance of Pritchett was greater than Bruehl with excellent quality of both sugar cookie and Japanese sponge cake. In product tests, the cookie diameter of Pritchett was 9.56 cm, significantly wider than Bruehl (9.44 cm) ($p < 0.01$). The sponge cake volume of Pritchett was 1311 cm^3, significantly greater than Bruehl (1247 cm^3) ($p < 0.03$).

Pritchett is an awned, white chaffed, club wheat with white kernels. The thousand kernel weight of Pritchett was 33.9 g, significantly less than Bruehl at 37.3 g ($p < 0.001$) and similar to ARS Crescent (33.4 g). Samples of Pritchett sent for grading to the Federal Grain Inspection Service were rated as white club in 87% of samples in 2014 and 2015. The others were graded as western white.

In summary, Pritchett is agronomically competitive with other soft white wheat cultivars in the Pacific Northwest, has excellent adult plant resistance to stripe rust and resistance to Cephalosporium stripe disease, and has excellent soft club wheat end use quality characteristics. The excellent emergence of Pritchett from deep sowing will make this cultivar competitive in the driest wheat-growing regions of Washington.

Availability

Purification of Pritchett for breeder seed was initiated in 2014 when 1500 heads were selected from a bulk increase of 4J071366C at Central Ferry, WA. Those head rows were planted as above at Spillman Agronomy Farm and selected for uniformity, resistance to stripe rust, and standability. Approximately 30% of the rows were removed; these remaining rows were harvested by hand and bulk threshed using a Vogel thresher. Breeder seed was planted at Moses Lake, WA, in fall 2015. Pritchett will be sold as foundation, registered, and certified seed through a licensing arrangement managed by the Washington State Research Foundation, Pullman, WA. Multiplication of certified seed classes of Pritchett will be done by the Washington State Crop Improvement Association, Pullman, WA, 99163. Small amounts (5 g) of seed are available from the corresponding author for research purposes. Plant Variety Protection (PVP) will be applied for. Pritchett has been deposited in the National Small Grains Collection and the National Plant Germplasm system, where seed will be available on expiration of PVP.

Acknowledgments

The authors thank Frank Ankerson, Jocelyn Bowser, Vadim Jitkov, and Stephen Johnson for their work managing testing nurseries.

References

AACC International. 2008. Approved methods of the AACCI. 11th ed. AACC Int., St. Paul, MN. http://methods.aaccnet.org/toc.aspx (accessed 30 Nov. 2015).

Allan, R.E., C.F. Morris, R.F. Line, J.A. Anderson, M.K. Walker-Simmons, and E. Donaldson. 2000. Registration of Coda club wheat. Crop Sci. 40:578. doi:10.2135/cropsci2000.0028rcv

Allan, R.E., C.J. Peterson, G.L. Rubenthaler, R.F. Line, and D.E. Roberts. 1989. Registration of Madsen wheat. Crop Sci. 29:1575. doi:10.2135/cropsci1989.0011183X002900060068x

Carter, A.H., S.S. Jones, Sr., K.A. Lyon, G.B. Balow, R.W. Shelton, X.M. Higginbotham, X.M. Chen, D.A. Engle, B. Baik, S.O. Guy, T.D. Murray, and C.F. Morris. 2013. Registration of 'Otto' wheat. J. Plant Reg. 7:195–200. doi:10.3198/jpr2012.07.0013crc

Chapman, N.H., C. Burt, H. Dong, and P. Nicholson. 2008. The development of PCR-based markers for the selection of eyespot resistance genes *Pch1* and *Pch2*. Theor. Appl. Genet. 117:425–433. doi:10.1007/s00122-008-0786-3

Ellis, M.H., W. Spielmeyer, K.R. Gale, G.J. Rebetzke, and R.A. Richards. 2002. 'Perfect' markers for the *Rht-B1b* and *Rht-D1b* dwarfing genes in wheat. Theor. Appl. Genet. 105:1038–1042. doi:10.1007/s00122-002-1048-4

Garland-Campbell, K., R. Allan, J. Anderson, A. Burke, N. Blake, C. Hoagland, C. Walker, J. Chatelain, L. Little, J. Pritchett, X. Chen, C. Morris, D. See, S. Guy, T. Murray, D. Engle, H. Wetzel, and D. Wood. 2013. Registration of 'Cara' soft white winter club wheat. J. Plant Reg. 7:81–88. doi:10.3198/jpr2012.01.0005crc

Garland-Campbell, K.A., R.E. Allan, J. Anderson, J.A. Pritchett, L.M. Little, C.F. Morris, R.F. Line, X. Chen, M.K. Walker-Simmons, B.P. Carter, J.W. Burns, S.S. Jones, and P.E. Reisenauer. 2005. Registration of 'Chukar' wheat. Crop Sci. 45:1657–1659. doi:10.2135/cropsci2004.0342

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

Helguera, M., I.A. Khan, J. Kolmer, D. Lijavetzky, Z. Li, and J. Dubcovsky. 2003. PCR assays for the *Lr37-Yr17-Sr38* cluster of rust resistance genes and their use to develop isogenic hard red spring wheat lines. Crop Sci. 43:1839–1847. doi:10.2135/cropsci2003.1839

Johnson, E.B., V.J. Nalam, R.S. Zemetra, and O. Riera-Lizarazu. 2008. Mapping the compactum locus in wheat (*Triticum aestivum* L.) and its relationship to other spike morphology genes of the Triticeae. Euphytica 163:193–201. doi:10.1007/s10681-007-9628-7

Jones, S.S., T.D. Murray, S.R. Lyon, C.F. Morris, and R.F. Line. 2001. Registration of Bruehl wheat. Crop Sci. 41:2006. doi:10.2135/cropsci2001.2006

Jones, S.S., S.R. Lyon, K.A. Balow, M.A. Gollnick, K.M. Murphy, J.S. Kuehner, T.D. Murray, X.M. Chen, D.A. Engle, and K.G. Campbell. 2010. Registration of 'Xerpha' wheat. J. Plant Reg. 4:137–140. doi:10.3198/jpr2009.06.0306crc

Kronstad, W.E., C.R. Rohde, M.F. Kolding, and R.J. Metzger. 1978. Registration of Stephens wheat. Crop Sci. 18:1097. doi:10.2135/cropsci1978.0011183X001800060060x

Lin, P.-Y., and S. Czuchajowska. 1997. Starch properties and stability of club and soft white winter wheats from the Pacific Northwest of the United States. Cereal Chem. 74:639–646. doi:10.1094/CCHEM.1997.74.5.639

Line, R., and A. Qayoum. 1992. Virulence, aggressiveness, evolution, and distribution of *Puccinia striiformis* (the cause of stripe rust in wheat) in North America 1960–1987. US Department of Agriculture Technical Bull. 1788. USDA, Washington, DC.

Liu, S., S. Chao, and J.A. Anderson. 2008. New DNA markers for high molecular weight glutenin subunits in wheat. Theor. Appl. Genet. 118:177–183. doi:10.1007/s00122-008-0886-0

MASWheat. 2016. MASWheat protocols. http://maswheat.ucdavis.edu/protocols/index.htm (accessed 30 Sept. 2016).

McIntosh, R.A., J. Dubcovsky, W.J. Rogers, C. Morris, R. Appels, and X.C. Xia. 2014. Catalogue of gene symbols for wheat: 2013–2014 supplement. National BioResource Project http://shigen.nig.ac.jp/wheat/komugi/genes/symbolClassList.jsp.

Morris, C.F., K.G. Campbell, and G.E. King. 2005. Kernel texture differences among US soft wheat cultivars. J. Sci. Food Agric. 85:1959–1965. doi:10.1002/jsfa.2202

Naruoka, Y., K.A. Garland-Campbell, and A.H. Carter. 2015. Genome-wide association mapping for stripe rust (*Puccinia striiformis* F. sp. *tritici*) in US Pacific Northwest winter wheat (*Triticum aestivum* L.). Theor Appl Genet. 128: 1083–1101.

Peterson, C.J., R.E. Allan, G.L. Rubenthaler, and R.F. Line. 1991. Registration of 'Eltan' wheat. Crop Sci. 31:1704.

Peterson, R.E., A.B. Campbell, and A.E. Hannah. 1948. A diagrammatic scale for estimating rust intensity on leaves and stems of cereals. Can. J. Res. 21:10–17. 10.1139/cjr48c-033

Pinheiro, J., D. Bates, S. DebRoy, D. Sarkar, and R Core Team. 2016. nlme: Linear and nonlinear mixed effects models. R package version 3.1-128. R Project. http://CRAN.R-project.org/package=nlme (accessed 30 Sept. 2016).

Sexton, Z.F., and T.D. Murray. 2016a. Reaction of winter wheat cultivars and breeding lines to Cephalosporium stripe, 2015. Plant Dis. Manage. Rep. 10:CF047. https://www.plantmanagementnetwork.org/pub/trial/PDMR/volume10/abstracts/CF047.asp (accessed 30 Sept. 2016).

Sexton, Z.F., and T.D. Murray. 2016b. Reaction of winter wheat cultivars and breeding lines to eyespot, 2015. Plant Dis. Manage. Rep. 10:CF048 https://www.plantmanagementnetwork.org/pub/trial/pdmr/volume10/abstracts/cf048.asp (accessed 30 Sept 2016).

Skinner, D.Z., and B.S. Bellinger. 2011. Differential response of wheat cultivars to components of the freezing process in saturated soil. Crop Sci. 51:69–74. doi:10.2135/cropsci2010.05.0286

USDA. 2006. Subpart M. United States standards for wheat. US Standards for Grain. https://www.gipsa.usda.gov/fgis/standards/810wheat.pdf.

US Wheat Associates. 2015. 2015 harvest: US Pacific Northwest soft white wheat quality report. US Wheat Associates, Idaho Wheat Commission, Oregon Wheat Commission, Washington Grain Commission. US Wheat Associates Grain Marketing Center, Portland. OR. http://www.uswheat.org/cropQuality/doc/FB95A0DAEFA8EC3085257EE400426B22/$File/SW2015.pdf?OpenElement# (accessed 30 Sept. 2016).

Vazquez, D.M., R. Zemetra, C.J. Peterson, and C.C. Mundt. 2015. Identification of Cephalosporium stripe resistance quantitative trait loci in two recombinant inbred line populations of winter wheat. Theor. Appl. Genet. 128:329–341. doi:10.1007/s00122-014-2433-5

Wan, A.M., and X.M. Chen. 2014. Virulence characterization of *Puccinia striiformis* f. sp. *tritici* using a new set of *Yr* single-gene line differentials in the United States in 2010. Plant Dis. 98:1534–1542. doi:10.1094/PDIS-01-14-0071-RE

Zadoks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415–421. doi:10.1111/j.1365-3180.1974.tb01084.x