Stand establishment and emergence from deep planting are important traits for winter wheat (Triticum aestivum L.) cultivars produced in the US Pacific Northwest. The objective of this research was to develop an adapted winter wheat cultivar with a long coleoptile and the ability to emerge well from deep planting conditions in the dryland (<300 mm annual precipitation) regions of Washington State. ‘Sequoia’ (Reg. No. CV-1125, PI 678966) hard red winter wheat was developed and released by the Agricultural Research Center of Washington State University. Sequoia was tested under the population designations 2J040720, 3J040720, 2J061383, 3J061383, 4J061383, and 5J061383 and experimental designation WA8180, which were assigned through progressive generations of advancement. Sequoia is a tall cultivar adapted to the low-precipitation, rainfed wheat production regions of Washington with excellent emergence from deep planting. Sequoia has high-temperature, adult-plant resistance to stripe rust, average grain protein, high grain volume weight, high yield potential, and excellent end-use quality properties.

Most wheat (Triticum aestivum L.) production in the Pacific Northwest region of the United States is conducted under rainfed (i.e., nonirrigated) conditions. Annual precipitation varies greatly across the region, ranging from as little as 150 mm of precipitation to >700 mm. In areas where annual precipitation is <300 mm, growers practice a winter wheat–summer fallow rotation. Optimum planting date for winter wheat is late August to early September, as delays in planting past this date result in decreasing seed-zone soil moisture (Donaldson, 1996) and lower grain yield potential (Higginbotham et al., 2011). In the driest years, seed-zone soil moisture is frequently very marginal. Thus, seed is sometimes placed as deep as 18 cm below the soil surface to reach moisture for germination and emergence.

Winter wheat seedling emergence in the dry areas is a major concern. Seeds planted deep should ideally have a long coleoptile with sufficient ability to push the coleoptile through the soil (Rebetzke et al., 2007; Schillinger et al., 1998). One frequent complication of seedling emergence is soil crusting caused by rain showers after planting and prior to emergence. One method to enhance wheat emergence from deep planting is to breed cultivars with very long coleoptiles, done primarily by selecting lines with wild-type alleles of the major dwarfing genes (Rebetzke et al., 2007; Schillinger et al., 1998; Whan, 1976). Another method is to speed up plant emergence, thereby limiting the number of days from planting to when a rain event could occur and induce crusting. To mitigate risk to growers, cultivars must have the ability to emerge from deep planting as quickly as possible (Mahdi et al., 1998). The objective of our cultivar development effort was to develop a hard red winter (HRW) wheat cultivar that could consistently emerge from planting depths greater than 15 cm.

‘Sequoia’ HRW wheat (Reg. No. CV-1125, PI 678966), which has excellent emergence from deep planting, was released in 2015 by the Agricultural Research Center of Washington State University (WSU) in cooperation with the USDA-ARS.
**Methods**

**Breeding Design**

Sequoia, tested under the population designations 2J040720, 3J040720, 2J061383, 3J061383, 4J061383, 5J061383, and experimental designation WA8180 (assigned through progressive generations of advancement), is a selection from a bulk population advanced under field conditions to the F6 generation. The pedigree of Sequoia is ‘Finley’/‘Bauermeister’, and the cross was made in the WSU Plant Growth Facility (greenhouses) in Pullman, WA, in 2004. Finley (Donaldson et al., 2000) is a HRW wheat cultivar released in 1995 by WSU in cooperation with the USDA-ARS with the pedigree ‘Weston’/‘Hatton Sib’/‘Short Wheat’/‘Scout’. Bauermeister (Jones et al., 2007) is a HRW cultivar with the pedigree ‘Eltan’/‘Tam200’/‘Eltan-Sib’/‘Short Wheat’/‘Scout’. Bauermeister was made in the WSU Plant Growth Facility (greenhouses) in Pullman, WA, in 2004. Finley (Donaldson et al., 2000) is a HRW wheat cultivar released in 1995 by WSU in cooperation with the USDA-ARS with the pedigree ‘Weston’/‘Hatton Sib’/‘Short Wheat’/‘Scout’. Bauermeister (Jones et al., 2007) is a HRW cultivar with the pedigree ‘Eltan’/‘Tam200’/‘Eltan-Sib’/‘Short Wheat’/‘Scout’.

The following modified bulk breeding method was used to advance early generation progeny. Bulked seed (38.4 g) from F3-3/Eltan that was released by WSU in 2005. is a HRW cultivar with the pedigree ‘Eltan’/‘Tam200’/‘Eltan-Sib’/‘Short Wheat’/‘Scout’. Bauermeister (Jones et al., 2007) is a HRW wheat cultivar released in 1995 by WSU in cooperation with the USDA-ARS with the pedigree ‘Weston’/‘Hatton Sib’/‘Short Wheat’/‘Scout’. Bauermeister was made in the WSU Plant Growth Facility (greenhouses) in Pullman, WA, in 2004. Finley (Donaldson et al., 2000) is a HRW wheat cultivar released in 1995 by WSU in cooperation with the USDA-ARS with the pedigree ‘Weston’/‘Hatton Sib’/‘Short Wheat’/‘Scout’. Bauermeister (Jones et al., 2007) is a HRW cultivar with the pedigree ‘Eltan’/‘Tam200’/‘Eltan-Sib’/‘Short Wheat’/‘Scout’.

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**Field Evaluations**

Using seed from a nonreplicated field trial, Sequoia was evaluated in replicated field trials for 36 location-years in preliminary (two locations) and advanced (12 locations) trials from 2011 through 2015 in low- (<300 mm average annual precipitation), intermediate- (300–500 mm average annual precipitation), and high-precipitation zones (>500 mm average annual precipitation) in Washington State. All years of field testing used the same data collection strategy using a general α-lattice design (three replications) (Mason et al., 2003). 5J061383 had very high yield potential in single replicated yield plot testing in 2010 and was advanced to a preliminary replicated yield trials at Lind (low precipitation zone) and Pullman (high precipitation zone) and evaluated in 2011. This line was entered into advanced replicated trials at multiple locations from 2012 through 2015. On the basis of agronomic performance in 2012 trials, 5J061383 was selected for testing on a regional basis and assigned the identification number WA8180. WA8180 was entered in the WSU Extension Uniform Cereal Variety Testing Program and tested at seven locations from 2013 through 2015 throughout eastern Washington.

Dry seeding conditions in fall 2013 and 2015 required seed to be planted between 180 and 200 mm deep to reach moisture. Advanced yield trials that year were planted in Klahotus, Ritzville, and Lind, WA. Soil types at each location are Ritzville silt loam (coarse-silty, mixed, superactive, mesic Haploxerolls) in Klahotus and Ritzville and Shano silt loam in Lind. Plots were planted using a custom-built plot planter. The plot planter has four rows on 31-cm centers with John Deere (Deere & Company) RZ openers and split packer wheels. The cropping system was a winter wheat–summer fallow rotation. In the summer fallow year, rod weeding pulverizes the top 10 to 15 cm of soil to control weeds and limit evapotranspiration of water. Seed placement must be below this level and into a moisture zone to germinate seeds. Soil water potential in the seeding zone was estimated between −0.6 and −0.7 MPa using a WP4C Water Potential Meter (Decagon Devices). In 2015, 5 d after planting, Klahotus received 2.8 cm of rain, Lind received 2 cm of rain, and Ritzville received 3.3 cm of rain, causing a crust to form on top of the soil, further impeding seedling emergence. Data at these three locations were collected on percentage plants emerged based on visual observations approximately 21 d after planting.

**End-Use Quality Evaluations**

Beginning 2011, WA8180 was evaluated for end-use quality by the USDA-ARS Western Wheat Quality Laboratory, Pullman, WA, according to approved methods of the American Association of Cereal Chemists (AACC, 2000). Traits included grain volume weight (Approved Method 55-10; kg m−3), grain protein concentration (Approved Method 39-10 adjusted with Dumas combustion method; g kg−1), single kernel hardness (single kernel characterization system [SKCS]; Approved Method 55-31.01), total flour yield (g kg−1 by weight of the total products recovered as straight-grade white flour), flour ash respectively. In 2010, population 5J061383 was advanced to single replicated yield testing as a F6 bulk selection.
content (Approved Method 08-01; g kg⁻¹), flour protein concentration (Approved Method 39-11; g kg⁻¹), mixograph water absorption (Approved Methods 54-40.02; g kg⁻¹), and mixing time (minutes), bake water absorption (g kg⁻¹), and pup-loaf volume (L; Approved Methods 10-10.03). A derived trait, milling score, was calculated as follows:

\[
(100 - (0.5 \times (16 - \text{temper level})) + (80 - \text{flour yield}) + (50 \times (\text{flour ash} - 0.30))) \times 1.274 - 21.602
\]

WA8180 was evaluated by the Pacific Northwest Wheat Quality Council in 2015.

**Biotic and Abiotic Stress Screening**

WA8180 was tested for stripe rust resistance in naturally infected field trials conducted by the USDA-ARS, Wheat Health, Genetics, and Quality Research Unit. Field screening was done on the Whitlow and Spillman Farms near Pullman, at the Lind Dryland Research Station, and at Walla Walla and Mt. Vernon, WA, in breeding nurseries in 2013 to 2015 and in various breeding nurseries throughout eastern Washington from 2010 to 2015. Artificial infection under field conditions was done using field-collected spores with a mixture of races, but predominately PSTv-52 and PSTv-37. Greenhouse seedling tests for stripe rust resistance were conducted from 2013 through 2015 under low-temperature cycles (diurnal temperature cycle gradually changing from 4 to 20°C; Chen and Line, 1992), using races PSTv-4, 14, 37, 40, and 51, and adult-plant tests were conducted at high temperatures (diurnal temperature cycle gradually changing from 10 to 30°C; Chen and Line, 1995), using races PSTv-14, 37, and 40. Data were collected on infection type (IT) on a scale of 1 to 9 (McNeal et al., 1971; Line and Qayoum, 1992) and disease severity on a scale of 0 to 100% (Peterson et al., 1948).

In addition to field testing, replicated laboratory pot seedling emergence experiments were conducted using procedures developed by W.F. Schillinger et al. (unpublished data). In these experiments, seeds of Sequoia and three check cultivars were planted at three soil water potentials (−0.75, −0.60, and −0.40 MPa) with 125 mm of Shano silt loam soil collected from the field covering the seeds. The cultivars used as checks were ‘Moro’ (Rohde, 1966), Finley (Donaldson et al., 2000), and Eltan (Peterson et al., 1991). Seeds of Sequoia and the three checks were obtained from harvested grain from the same nursery grown under rainfed conditions at the Lind Station. Laboratory temperature during the experiment was kept at a constant 21°C. No additional water was given to the plants during this experiment. Percentage emergence was recorded daily starting at 8 d after planting until 14 d after planting, and then once again at 21 d after planting. All emergence data were analyzed using analysis of variance with PROC GLM (SAS v. 9.3; SAS Institute, Cary, NC). At the same time, 50 seeds of Sequoia, Farnum, and Finley were evaluated for coleoptile length using the method cited above.

**Seed Purification**

Breeder seed of WA8180 (Sequoia) was produced by headrow purification, on the basis of phenotypic uniformity, of 1200 headrow selections from the F₉ bulk population grown under irrigation in Othello, WA, in 2014. Selected headrows (2%) were discarded based on plant height, maturity, and leaf color were bulked at harvest, resulting in the production of 771 kg of breeder seed. A 1.2-ha and a 4.8-ha foundation seed increase was planted under irrigation in Othello, WA and Moses Lake, WA, respectively, in the fall of 2015. Foundation fields were rogued for phenotypic uniformity and <1% of the plants were removed due to plant height differences.

**Statistical Analysis**

Replicated data generated from 2011 to 2015 were analyzed with the general lattice procedure in Agrobase Generation 2, version 37.2.4 (Agromomix Software), and unreplicated data were analyzed using the moving means procedure with replicated check cultivars every 10 entries. Since four major wheat-producing regions with distinct agroclimatic conditions are present in Washington State, data were analyzed across locations within regions instead of over all locations. Location means and ranks from 2011 to 2015 were generated via the arithmetic mean of the general lattice adjusted mean and were subjected to analysis of variance. Breeding lines were advanced on the basis of excellent performance within each location, across locations within a region, and across regions within a year. Once Sequoia was selected for release, the final data analysis used only entries common to the trials across all years in the target production region. For all data except end-use quality, significant differences were determined at α = 0.05; for end-use quality, significance was determined at α = 0.01. End-use quality data were analyzed using analysis of variance with PROC GLM (SAS v9.3; SAS Institute, Cary, NC). Data were only analyzed from site-year locations where both Sequoia and the respective check cultivar were in the same trial.

**Characteristics**

**General Description**

Sequoia is a standard height (does not contain a dwarfing gene) cultivar adapted to the low- to intermediate-rainfall (<300 mm average annual precipitation) HRW wheat growing regions of Washington State. It has a dense, tapering, erect inflorescence with tan awns and tan glumes that are long and narrow, with square shoulders and narrow acuminate beaks. Sequoia has elliptical kernels that are red and hard (SKCS value 69.2). The seed of Sequoia has a large germ with a crease width 80% as wide as the kernel and depth that is 35% of that of the kernel, angular cheeks, and a long, noncollared brush. Sequoia lacks anthocyanin pigmentation in the coleoptile and displays a semi-erect juvenile plant growth habit. The flag leaf of Sequoia is green, with 50% erect and 50% recurved, nontwisted, with wax absent at Feekes growth stage 10.0 (Large, 1954). The stem of Sequoia lacks a waxy bloom, anthocyanin pigmentation is absent, the last internode of the rachis is solid, the auricle lacks pigmentation and pubescence, and the peduncle is erect and has an average length of 38 cm.

In the target production region (<300 mm average annual precipitation) of eastern Washington, the heading date of Sequoia was earlier (P < 0.05) than ‘Farnum’ (PI 638535) (3 d) and Bauermeister (2 d) but later than Finley (2 d) (Table 1). The plant height of Sequoia (80 cm) was similar (P > 0.05) to Farnum.
Sequoia is moderately susceptible to Cephalosporium stripe (caused by *Cephalosporium gramineum* Nisik. & Ikata), susceptible to strawbreaker foot rot (caused by *Oculimacula yallundae* Crous & W. Gams and *O. acuformis* Crous & W. Gams), and susceptible to speckled snow mold (caused by *Typhula ishikariensis* Imai var. *idahoensis*).

### Agronomic Performance

Sequoia was selected because of its long coleoptile, an important component of improving emergence, weed suppression, and grain yield in low-precipitation regions. Sequoia was released, in part, for its excellent emergence abilities and stand establishment potential in low moisture and deep planting condition. Since 2012, Sequoia has been tested for emergence potential at three locations (Kahlotus, Lind, and Ritzville, WA) using yield testing plots. In fall 2011, 2012, and 2014, adequate moisture was found at all locations, and Sequoia had 100% plant emergence based on visual observations, as did the check cultivars Farnum, Finley, and Bauermeister. In 2013, dry seeding conditions hindered plant emergence. Averaged across all locations that year (Table 2), Sequoia averaged 93% emergence, which was the same (*P > 0.05*) as Finley (93%), but better (*P < 0.05*) than Farnum (85%) and Bauermeister (80%). The fall 2015 seeding conditions were very dry at all locations and seed was placed 18 cm deep to reach moisture. Five days after planting, a rain event at all three locations caused severe crusting. Many cultivars and breeding lines were not able to emerge due to the combination of the dry conditions and soil crusting event. Despite the extreme planting conditions in 2015, Sequoia emergence was better than check cultivars. Averaged over all three locations, Sequoia had an emergence of 70% (Table 2). This was higher (*P < 0.05*) than Finley (52%), Farnum (43%), and Bauermeister (23%).

To further investigate the emergence performance of Sequoia under dry conditions, replicated laboratory testing was done. At 14 d after planting, Sequoia seedling emergence averaged 31% at −0.75 MPa, 45% at −0.60 MPa, and 64% −0.40 MPa, (Fig. 1). Moro, a club wheat (*Rht-B1a and Rht-D1a alleles*), which has long been considered one of the best emerging cultivars, had emergence values of 20% at −0.75 MPa, 39% at −0.60 MPa, and 55% −0.40 MPa. The HRW cultivar Finley, widely planted by growers in the driest areas and known for good seedling emergence from deep planting, had emergence values of 12% at −0.75 MPa, 29% at −0.60 MPa, and 36% −0.40 MPa. The

### Disease Resistance

Sequoia, together with its parental cultivars Finley and Bauermeister, was evaluated for stripe rust resistance in various field locations in Washington State under natural infection and under controlled greenhouse conditions with selected races of *P. striformis* f. sp. *tritici* from 2013 to 2015. In 2013, stripe rust developed to adequate levels in the fields for evaluation where the check ‘WA7821’ was susceptible (infection type [IT] 8; severity 80–100%) in the flowering and soft dough stage. Sequoia (IT 2–5; severity 10%) and Finley (IT 3–5; severity 20–30%) were rated as resistant, whereas Bauermeister (IT 5–8; severity 40–60%) was rated as moderately susceptible. Again in 2014 and 2015, stripe rust developed to adequate levels for field evaluation where WA7821 (IT 8; severity 80–100%) was rated as highly susceptible. Bauermeister (IT 5–8; severity 20–40%) again displayed moderately susceptible reactions, whereas Sequoia (IT 2–5; severity 5–10%) and Finley (IT 2–5; severity 5–20%) displayed resistant reactions. In greenhouse seedling tests conducted in 2014 and 2015 under low-temperature cycles, Sequoia was resistant (IT 2) to races PSTv-4, PSTv-14, PSTv-37, and PSTv-51 yet was susceptible (IT 8) to PSTv-40. These seedling reactions indicate that Sequoia has race-specific, all-stage resistance that is not effective against all of the predominant races currently in the region. When tested at the adult-plant stage using high-temperature cycles, Sequoia demonstrated that it had resistance to PSTv-14 and PSTv-37 but had intermediate reactions (IT 5) to PSTv-40, indicating a moderate level of high-temperature, adult-plant resistance.

Sequoia has been tested under natural field infection for resistance to other diseases that are not commonly found in the target production region and has been found to be susceptible.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Heading date</th>
<th>Plant height</th>
<th>Grain volume weight</th>
<th>Grain protein concentration</th>
<th>Grain yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;300 mm†</td>
<td>300–400 mm‡</td>
<td>&lt;300 mm</td>
<td>300–400 mm</td>
<td>&lt;300 mm</td>
</tr>
<tr>
<td></td>
<td>— d after 1 Jan. —</td>
<td>cm</td>
<td>cm</td>
<td>kg m⁻¹</td>
<td>g kg⁻¹</td>
</tr>
<tr>
<td>Sequoia</td>
<td>143</td>
<td>152</td>
<td>80</td>
<td>108</td>
<td>798</td>
</tr>
<tr>
<td>Farnum</td>
<td>146</td>
<td>155</td>
<td>78</td>
<td>104</td>
<td>763</td>
</tr>
<tr>
<td>Finley</td>
<td>141</td>
<td>149</td>
<td>78</td>
<td>108</td>
<td>811</td>
</tr>
<tr>
<td>Bauermeister</td>
<td>145</td>
<td>154</td>
<td>71</td>
<td>92</td>
<td>785</td>
</tr>
<tr>
<td>LSD (n = 0.05)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

† Means averaged over trials from 2013 through 2015 in locations receiving <300 mm of average annual precipitation including Connell, Horse Heaven, Lind, Ritzville, and St. Andrews, WA (14 site-years).
‡ Means averaged over trials from 2013 through 2015 in locations receiving 300–400 mm of average annual precipitation including Almira and Lamont, WA (6 site-years).
semidwarf (Rht-B1b and Rht-D1a alleles) soft white winter cultivar Eltan had emergence values of 6% at −0.75 MPa, 20% at −0.60 MPa, and 19% −0.40 MPa. The emergence of Sequoia was greater ($P < 0.05$) than Eltan and equal ($P > 0.05$) to Moro and Finley at the water potentials of −0.75 and −0.40 MPa. There were no significant differences at the water potential of −0.60 MPa.

Averaged over multiple location-years of field testing in breeding nurseries, the grain yield of Sequoia was not different ($P > 0.05$) than Farnum but was greater ($P < 0.05$) than Finley and Bauermeister (Table 2). The average grain volume weight and grain protein concentration of Sequoia was not different than any of the three check cultivars (Table 2). In 20 rainfed location-years of the WSU Extension Uniform Cereal Variety Testing Program winter wheat performance trials conducted from 2013 through 2015, the grain yields of Sequoia were higher than Finley and not different than Farnum and Bauermeister in the <300-mm precipitation zone (Table 1). Average grain volume weight of Sequoia in the <300-mm precipitation zone was higher than Bauermeister and Farnum but lower than Finley (Table 1). The average grain protein concentration of Sequoia was not different from that of Finley and Bauermeister but was lower than that of Farnum (Table 1).

**End-Use Quality**

End-use quality of Sequoia was assessed using grain produced in 23 breeding and commercial variety testing trials in Washington from 2011 through 2015. Farnum, Finley, and Bauermeister were used as checks in these evaluations. The flour protein concentration of Sequoia was not different from those of the three check cultivars ($P > 0.01$) (Table 3). Single kernel hardness of Sequoia was higher ($P < 0.01$) than those of Farnum and Finley but not different from that of Bauermeister (Table 3). Milling properties of Sequoia are an improvement over the check cultivars. Sequoia has higher total flour yield than Bauermeister and Farnum, with similar values for flour ash content and overall milling score (Table 3). Bake mixing time is similar to Bauermeister, Farnum, and Finley (Table 3). Mixograph water absorption and bake water absorption of Sequoia were also similar to the check cultivars (Table 3). The bread loaf volume of Sequoia was lower than that of the check cultivars Farnum and Finley (Table 3). The HMW glutenin profile of Sequoia contains the Ax1 or the AxNull subunit at the Glu-A1 locus and the Dx5/Dy10 subunits at the Glu-D1 locus.

In 2015, Sequoia was evaluated by the Pacific Northwest Wheat Quality Council, where commercial millers and bakers concluded that Sequoia has acceptable milling, dough handling, and baking properties and is equal to or superior to other HRW wheat cultivars that are currently in production in the Pacific Northwest (data not shown).

**Availability**

Foundation seed of Sequoia will be maintained by the Washington State Crop Improvement Association under supervision of the WSU Department of Crop and Soil Sciences and the Washington State Agricultural Research Center. Small quantities of seed may be obtained for research purposes from the corresponding author for at least 5 yr from the date of publication. A seed sample has been deposited with the National Plant
Table 3. Mean grain protein concentration, single kernel hardness, flour yield, flour ash, mixing time, milling score, flour protein, mixograph water absorption, bake water absorption, and pup loaf volume of hard red winter wheat cultivars from winter wheat trials in eastern Washington.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Grain protein concentration g kg⁻¹</th>
<th>Single kernel hardness g kg⁻¹</th>
<th>Total flour yield g kg⁻¹</th>
<th>Flour ash content g kg⁻¹</th>
<th>Mixing time min</th>
<th>Milling score 1 g kg⁻¹</th>
<th>Flour protein g kg⁻¹</th>
<th>Mixograph water absorption L</th>
<th>Bake water absorption g kg⁻¹</th>
<th>Pup loaf volume L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequoia</td>
<td>129</td>
<td>68.4</td>
<td>676</td>
<td>37</td>
<td>3.5</td>
<td>84.1</td>
<td>111</td>
<td>620</td>
<td>656</td>
<td>0.963</td>
</tr>
<tr>
<td>Bauermeister</td>
<td>127</td>
<td>69.0</td>
<td>664</td>
<td>37</td>
<td>3.2</td>
<td>82.6</td>
<td>111</td>
<td>614</td>
<td>650</td>
<td>0.985</td>
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<tr>
<td>LSD (α = 0.01)</td>
<td>5</td>
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<td>5</td>
<td>2</td>
<td>0.6</td>
<td>1.2</td>
<td>7</td>
<td>11</td>
<td>17</td>
<td>0.72</td>
</tr>
<tr>
<td>N</td>
<td>17</td>
<td>11</td>
<td>13</td>
<td>11</td>
<td>11</td>
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<td>11</td>
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Germplasm System, where it will thereafter be available for distribution.

Acknowledgments

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References


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