Seed Germination and Early Seedling Growth of Barley at Negative Water Potentials

Tim L. Springer 1,*, and Dolores W. Mornhinweg 2

1 Southern Plains Range Research Station, USDA-ARS, Woodward, OK 73801, USA
2 Wheat, Peanut and Other Field Crops Research Unit, USDA-ARS, Stillwater, OK 74075, USA;
do.mornhinweg@usda.gov
* Correspondence: tim.springer@usda.gov

Received: 11 September 2019; Accepted: 21 October 2019; Published: 23 October 2019

Abstract: The impacts of climate change may increase the duration and frequency of droughts, which would have deleterious effects on crop establishment. The objectives of this study were to determine the effects of moisture stress on seed germination and seedling growth of six winter barley (Hordeum vulgare) lines and discuss how the data are used to select plant materials for rapid germination. Twenty-five seeds of each line were germinated in water of potentials of −2.0, −1.6, −1.2, −0.8, −0.4, and 0 MPa for 4- and 7-days. The experimental design was a factorial arrangement of treatments (barley lines and water potential treatments) in a randomized block replicated four times and repeated twice. The 4- and 7-day percentage seed germination varied with line (p < 0.01), water potential treatment (p < 0.01), and line × treatment interactions (p < 0.01). The seed germination rate varied with water potential treatment (p < 0.01), and line × treatment interactions (p < 0.01). The data indicated that enough variation was present to effectively select and breed cultivars for improved germination at a negative water potential. Studying seed germination under moisture stress is the first step for developing an effective selection pressure for identifying plant materials with rapid seed germination.

Keywords: barley; Hordeum vulgare; seed germination; water potential

1. Introduction

Droughts commonly occur on the landscape and are among the costliest natural hazards in the USA with an estimated annual loss of $9 billion from the loss of crops, water supplies, recreation and tourism, ecosystem services, and human health [1,2]. Future climate projections predict an increase in winter and spring precipitation over much of North America and a decrease in summer precipitation over central and southern North America. Surface temperatures are projected to increase, especially in the winter, at high latitudes, and in the summer throughout southwestern North America. The increase in surface temperature and associated evapotranspiration is expected to have a major impact on the frequency and duration of drought [3]. Many communities have turned to advanced planning to reduce the effects of drought [4].

Although rainfall occasionally occurs during drought periods, it is effectively impossible for seeds to germinate, become established, and survive [5]. Genetic variation can be used to develop plant materials with superior seed germination and establishment characteristics. For example, Springer [6] after two cycles of phenotypic recurrent selection nearly doubled the seven-day laboratory seed germination of sand bluestem (Andropogon hallii) in water of potential −0.8 MPa. The seed germination of the sand bluestem base populations (cycle 0, C0) averaged 21.5% after seven days in water of potential −0.8 MPa compared with 38.4% for seeds of the cycle 2 (C2) populations. Field establishment of C2 sand bluestem populations was 8.6% greater than that of the C0 populations under field conditions [7].
As a result of the research, ‘Centennial’ sand bluestem was released [8]. Centennial has greater seed germination in water of potential −0.8 MPa and greater seedling establishment under field conditions when compared with ‘Chet’ sand bluestem (the C0 population) [8,9]. In addition, Springer [10] has used the genetic variation found in little bluestem (Schizachyrium scoparium) to develop breeding lines with superior seed quality.

In an unrelated crop, Russian dandelion (Taraxacum kok-saghyz), Hodgson-Kratky et al. [11] reported that, after three cycles of recurrent selection for increased seed germination at a negative water potential, the percentage seed germination of breeding lines was increased 34.5% and 42.5%, and the germination time was reduced by three and five days, respectively. They concluded it was possible to increase the laboratory seed germination of Russian dandelion using phenotypic recurrent selection and that this increase had the potential to improve field establishment. Hodgson-Kratky [12] reported average gains per selection cycle for laboratory seed germination of Russian dandelion were greater for family selection compared to phenotypic selection due to greater selection intensity in the families.

As has been demonstrated, phenotypic recurrent selection is extremely effective for developing cross-pollinated species with superior seed germination characteristics under simulated water deficits. Recurrent selection in self-pollinated species, however, may be constrained by the number of hand emasculations and pollinations that need to be made in order to have enough plant materials for selection to be effective. There is evidence that indicates that seed germination is a quantitative trait [13]. When large numbers of genes are segregating for a trait, the frequency of obtaining a specific genotype in a population is low. Palmer [14] suggested a breeding approach to improve self-pollinated crops that is comparable to phenotypic recurrent selection. This approach involves crossing superior lines for the desired trait that were isolated from the same cross thereby increasing the frequency of the desired genotype. Recurrent selection has been used to increase grain yield in barley [15].

Studying seed germination under moisture stress is the first step for developing an effective selection pressure for identifying plant materials with rapid seed germination. Thus, the objectives of this study were to determine the effect of moisture stress on seed germination and seedling growth of six winter barley genotypes and discuss how the data are used to select plant materials for rapid germination.

2. Materials and Methods

2.1. Plant Materials

One barley cultivar, ‘Winternalt’ [16], and five advanced winter barley breeding lines, STARS 13-9, STARS 2606, STARS 2607, MW12 4007 001, and 06ARS 617-25 were used in this study. STARS 13-9, STARS 2606, and STARS 2607 are winter feed barleys developed by the USDA-Agricultural Research Service (ARS) in Stillwater, OK, USA. MW12 4007 001 and 06ARS 617-25 are winter malting barley lines from the University of Minnesota, St. Paul and USDA-ARS, Aberdeen, ID respectively. Seeds of the six genotypes were produced in the same year in a USDA-ARS greenhouse at Stillwater, OK, USA (36°08′ N, 97°04′ W, and elevation 300 m). The greenhouse environment was maintained between 15 and 25 °C under natural and artificial light to provide for a 13-h daylength. The artificial light was provided by light-emitting diode lamps (LumiGrow Pro 325, Emeryville, CA, USA: 440 nm blue light, 650 nm red light, and 480–630 nm white light). Hereafter, line designations STARS 13-9, STARS 2606, STARS 2607, MW12 4007 001, and 06ARS 617-25 will be referred to as 13-9, 2606, 2607, MW12, and 617-25, respectively.

2.2. Seed Germination Assays and Treatments

Forty-eight, 25-seed samples of each line were obtained from each barley genotype, and they were weighed and retained for two germination experiments. For each germination experiment, the 24 samples of each line were randomly assigned to the six water potential treatments. Water potential treatments of −2.0, −1.6, −1.2, −0.8, −0.4, and 0 MPa were prepared by mixing 73.0, 58.4,
43.8, 29.2, 14.6, and 0 g of D-mannitol in 0.5 kg of deionized water, respectively. Deionized water was used as a control. D-mannitol was chosen because it acts as an inert osmotic medium [17,18]. Twenty-five seed of each line were placed in sterile, clear plastic boxes (7.0 × 7.0 × 2.5 cm) on two layers of absorbent paper towel substrates moistened with 8 mL of each water potential solution. Germination was conducted in a seed germinator (Seedburo Equipment Company, Chicago, IL, USA) set for a constant 20 °C in the dark. Cumulative germination counts were made at 4- and 7-days. Germination data were converted to percentages before analysis. The experimental design was a factorial arrangement of treatments (barley line and water potential treatment) in a randomized block replicated four times and repeated twice.

The germination rate (speed of germination) was determined using a modified procedure of Maguire [19]. Maguire [19] stated that, “The germination rate is calculated by dividing the number of normal seedlings per 100 seeds obtained at each counting in the standard germination test by the number of days the seeds have been in the germinator. The values obtained at each count are then summed at the end of the germination test to obtain the germination rate”. Since only 25 seeds were used in each experimental unit, the number of seedlings counted at each germination count were multiplied by 4. In addition, at each germination count, the root and shoot length for up to three random selected seedlings were determined using a millimeter ruler.

2.3. Statistical Analysis

Data for percentage seed germination, seedling root and shoot lengths, germination rate, and 100-seed weight were analyzed as a factorial design analysis of variance using PROC GLIMMIX [20]. Fixed effects were barley line and water potential treatment and their interactions. Blocks within each experiment were random effects. Mean separations of barley lines and water potential treatments were made using a least significant difference (LSD) test at p ≤ 0.05. Correlation coefficients were obtained for germination rate, seedling root and shoot lengths, and 100-seed weight using PROC CORR [20]. In addition, nonlinear regression was used to fit data of each barley line at the 4- and 7-day germination periods using a 4-parameter sigmoidal model using PROC NLIN [20,21]. The modeled equation was:

\[ y = y_0 + \frac{a}{1 + e^{-(x-x_0)/b}} , \]

where \( y \) is the dependent variable percentage four- or seven-day seed germination, \( y_0 \) is the minimum value that can be obtained (i.e., what happens at an infinite negative water potential), \( a \) is the maximum value that can be obtained (i.e., what happens at water potential \( = 0 \)), \( x \) is the independent variable (water potential), \( x_0 \) is the point of inflection of the curve (i.e., the point on the S-curve that is half way between \( y_0 \) and \( a \)), and \( b \) is the slope of the curve or steepness of the curve around point \( x_0 \).

3. Results

3.1. Seed Germination

The percentage 4- and 7-day seed germination varied with barley line (\( p < 0.01 \)), water potential treatment (\( p < 0.01 \)), and line × treatment interactions (\( p < 0.01 \)). Averaged across water potentials, line 617-25 had the highest percentage seed germination at 4- and 7-days (53.3 ± 1.5% at 4-days and 78.5 ± 1.5% at 7-days, Table 1). Conversely, line 2607 had the lowest germination at 4- and 7-days (41.5 ± 2.5% at 4-days and 58.4 ± 1.5% at 7-days). Averaged across lines, the 4- and 7-day seed germination decreased as water potential decreased (Table 1). The 4-day seed germination did not differ in water of potential −0.4 MPa or greater. Similarly, 4-day seed germination did not differ in water of potential −1.6 MPa or less (Table 1). After seven days, the percentage seed germination in water of potential of −0.8 MPa or greater was similar (\( p > 0.05 \)), but differences did occur for percentage seed germination among water potential treatments less than −0.8 MPa (\( p ≤ 0.05 \), Table 1). The line × treatment interaction for percentage 4- and 7-day seed germination were due to differences between the upper
and lower asymptotes and differences of the slopes of the lines near the inflection points on the curve (Figures 1 and 2, Table 2). Although these interactions were considered significant, they accounted for approximately 2% and 8% of the total variation for the percentage 4- and 7-day germination, respectively. After four days of germination, line 617-25 had the steepest slope of 0.008 while lines MW12 and Wintermalt had the gentlest slope of approximately 0.100 (Table 2). After seven days of germination, lines 2606 and 2607 had the steepest slope approximately 0.07 while Wintermalt had the gentlest slope of 0.217 (Table 2).

**Table 1.** Least square means for main effects for barley (*Hordeum vulgare*) lines and germination substrate water potentials for dependent variables percentage 4- and 7-day seed germination, 4-day seedling root and shoot lengths, germination rate, and 100-seed weight.

<table>
<thead>
<tr>
<th>Main Effects</th>
<th>Seed Germination (%)</th>
<th>Root Length (mm)</th>
<th>Shoot Length (mm)</th>
<th>Germination Rate</th>
<th>100-Seed Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barley lines</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06ARS 617-25</td>
<td>53.3 a</td>
<td>23.0 d</td>
<td>13.0 a</td>
<td>16.9 a</td>
<td>5.2 a</td>
</tr>
<tr>
<td>MW12 4007 001</td>
<td>48.9 b</td>
<td>23.9 d</td>
<td>11.8 bc</td>
<td>11.8 a</td>
<td>3.6 c</td>
</tr>
<tr>
<td>STARS 13-9</td>
<td>48.6 b</td>
<td>28.5 c</td>
<td>11.9 bc</td>
<td>14.9 a</td>
<td>3.6 c</td>
</tr>
<tr>
<td>STARS 2606</td>
<td>49.8 b</td>
<td>31.7 b</td>
<td>11.5 c</td>
<td>12.7 a</td>
<td>4.8 b</td>
</tr>
<tr>
<td>STARS 2607</td>
<td>41.5 c</td>
<td>27.0 c</td>
<td>12.7 ab</td>
<td>15.5 a</td>
<td>4.4 b</td>
</tr>
<tr>
<td>Wintermalt</td>
<td>50.1 b</td>
<td>1.0</td>
<td>0.8</td>
<td>1.5</td>
<td>0.1</td>
</tr>
<tr>
<td>SE of mean</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>Water potential (MPa)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>94.7 a</td>
<td>58.5 a</td>
<td>36.6 a</td>
<td>22.9 a</td>
<td>4.2 a</td>
</tr>
<tr>
<td>−0.4</td>
<td>92.6 a</td>
<td>41.9 b</td>
<td>21.7 b</td>
<td>22.5 a</td>
<td>4.1 a</td>
</tr>
<tr>
<td>−0.8</td>
<td>87.5 b</td>
<td>31.0 c</td>
<td>8.8 c</td>
<td>22.1 a</td>
<td>4.2 a</td>
</tr>
<tr>
<td>−1.2</td>
<td>14.1 c</td>
<td>11.5 e</td>
<td>0.8 d</td>
<td>4.5 c</td>
<td>4.2 a</td>
</tr>
<tr>
<td>−1.6</td>
<td>2.0 d</td>
<td>6.7 f</td>
<td>0.5 d</td>
<td>1.0 d</td>
<td>4.1 a</td>
</tr>
<tr>
<td>−2.0</td>
<td>1.4 d</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>SE of mean</td>
<td>1.6</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

1 Means followed by the same letter within main effect (column) and variable are not significantly different at \( p > 0.05 \) (LSD test).

**Figure 1.** Percentage 4-day seed germination of six barley (*Hordeum vulgare*) lines at six water potentials. The standard error (SE) of means is 2.6% and is shown for each data point by the upper and lower bars. Each barley line was fit to a 4-parameter sigmoidal model using nonlinear regression (see text for details).
Figure 2. Percentage 7-day seed germination of six barley (*Hordeum vulgare*) lines at six water potentials. The standard error (SE) of means is 3.3% and is shown for each data point by the upper and lower bars. Each barley line was fit to a 4-parameter sigmoidal model using nonlinear regression (see text for details).

Table 2. Equation parameters for graphing 4-parameter sigmoid plots of 4- and 7-day seed germination of barley (*Hordeum vulgare*) lines. The equation used was: \( y = y_0 + \frac{a}{1 + e^{-(x-x_0)b}} \), where \( x \) is the independent variable water potential (MPa) from -2 to 0, and \( y \) is the dependent variables either percentage 4- or 7-day seed germination.

<table>
<thead>
<tr>
<th>Barley Line</th>
<th>( y_0 )</th>
<th>( a )</th>
<th>( x_0 )</th>
<th>Slope (b)</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-day seed germination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06ARS 617-25</td>
<td>9.75</td>
<td>77.42</td>
<td>-1.19</td>
<td>0.008</td>
<td>0.96</td>
</tr>
<tr>
<td>MW12 4007 001</td>
<td>-0.16</td>
<td>95.89</td>
<td>-1.03</td>
<td>0.100</td>
<td>0.98</td>
</tr>
<tr>
<td>STARS 13-9</td>
<td>-0.04</td>
<td>99.53</td>
<td>-0.95</td>
<td>0.075</td>
<td>0.98</td>
</tr>
<tr>
<td>STARS 2606</td>
<td>0.25</td>
<td>99.25</td>
<td>-1.02</td>
<td>0.048</td>
<td>0.99</td>
</tr>
<tr>
<td>STARS 2607</td>
<td>-0.21</td>
<td>85.29</td>
<td>-0.97</td>
<td>0.028</td>
<td>0.96</td>
</tr>
<tr>
<td>Wintermalt</td>
<td>1.46</td>
<td>94.63</td>
<td>-1.05</td>
<td>0.104</td>
<td>0.98</td>
</tr>
<tr>
<td>7-day seed germination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06ARS 617-25</td>
<td>-14.28</td>
<td>105.10</td>
<td>-1.96</td>
<td>0.180</td>
<td>0.89</td>
</tr>
<tr>
<td>MW12 4007 001</td>
<td>-0.57</td>
<td>97.14</td>
<td>-1.49</td>
<td>0.110</td>
<td>0.97</td>
</tr>
<tr>
<td>STARS 13-9</td>
<td>-0.04</td>
<td>99.88</td>
<td>-1.45</td>
<td>0.071</td>
<td>0.99</td>
</tr>
<tr>
<td>STARS 2606</td>
<td>0.49</td>
<td>99.18</td>
<td>-1.35</td>
<td>0.069</td>
<td>0.99</td>
</tr>
<tr>
<td>STARS 2607</td>
<td>-0.04</td>
<td>87.88</td>
<td>-1.39</td>
<td>0.151</td>
<td>0.94</td>
</tr>
<tr>
<td>Wintermalt</td>
<td>-21.63</td>
<td>118.00</td>
<td>-1.69</td>
<td>0.217</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The germination rate (speed of seed germination) varied with water potential treatment \((p < 0.01)\), and line \(\times\) treatment interactions \((p < 0.01)\). Averaged across water potential treatments, the germination rate did not differ among lines \((p > 0.05)\). Averaged across lines, the germination rate did not differ among water potential treatments of \(-0.8\) MPa or greater averaging \(22.5 \pm 0.9\%\) seeds per day (Table 1). The rate of seed germination did differ among water potential treatments of \(-1.2\) MPa or less (Table 1). The line \(\times\) interaction for germination rate was primarily due to differences among lines in water potentials less than \(-0.8\) MPa and barley line 617-25 (Figure 3). If data for line 617-25 and data for water potentials less than \(-0.8\) MPa were removed from the dataset, the interaction between line and treatment became insignificant \((p > 0.05)\). In addition, the line \(\times\) treatment interactions accounted for approximately 4% of the total variation.
3.2. Seedling Root and Shoot Measurements and 100-Seed Weight

After four days of germination, the seedling root length varied with line \((p < 0.01)\), water potential treatment \((p < 0.01)\), and line \(\times\) treatment interactions \((p < 0.01)\). Averaged across water potential treatments, the seedling root lengths ranged from \(23.9 \pm 1.0\) mm for line 13-9 to \(34.7 \pm 1.0\) mm for line MW12 (Table 1). Averaged across lines, 4-day old seedling root lengths ranged from \(6.7 \pm 1.0\) mm for seedlings grown in water of potential \(-2.0\) MPa to \(58.5 \pm 1.0\) mm for seedlings grown in water of potential \(0\) MPa (Table 1). Seedling root lengths at different water potential treatments were significantly different from each other \((p < 0.05, \text{Table 1})\). Although there was a line \(\times\) treatment interaction for seedling root length, it accounted for approximately 2% of the total variation and was primarily due to the convergence of root length means at water potentials less than \(-0.8\) MPa (Figure 4). Furthermore, if root length data for water potentials less than \(-0.8\) MPa were removed from the dataset, the interaction between line and treatment became insignificant \((p > 0.05)\).
After four days of germination, the seedling shoot length varied with line \((p < 0.01)\), water potential treatment \((p < 0.01)\), and line \(\times\) treatment interactions \((p < 0.01)\). Averaged across water potential treatments, the seedling shoot length ranged from 10.2 ± 0.8 mm for line 13-9 to 13.0 ± 0.8 mm for line 617-25 (Table 1). Averaged across lines, 4-day seedling shoot lengths ranged from 0.5 ± 1.0 mm for seedlings grown in water of potential −2.0 MPa to 36.6 ± 1.0 mm for seedling grown in water of potential 0 MPa (Table 1). Seedling shoot lengths in water potentials less than −0.8 MPa were not significantly different from each other but they were significantly different from each other in water potentials greater than −1.2 MPa \((p < 0.05\), Table 1). Although there was a line \(\times\) treatment interaction for seedling shoot length, it accounted for approximately 1% of the total variation and was primarily due to the interaction between lines 617-25 and Wintermalt (Figure 5). Furthermore, if shoot length data for barley lines 617-25 and Wintermalt were removed from the dataset, the line \(\times\) interaction became insignificant \((p > 0.05)\).

![Figure 5. Seedling shoot length of 4-day old seedlings of six barley (Hordeum vulgare) lines at six water potentials. The standard error (SE) of means is 1.3 mm and is shown for each data point by the upper and lower bars.](image)

The 100-seed weight varied only with barley line \((p < 0.01)\). The 100-seed weight ranged from 3.23 ± 0.1 g per 100 seeds for line 2607 to 5.22 ± 0.1 g per 100 seed for line 617-25 (Table 1). The water potential treatment and line \(\times\) treatment interactions were both insignificant \((p > 0.05)\). Thus, the 100-seed weight averaged across the six lines and water potential treatments were similar.

Seedling root length was correlated strongly with seed germination rate \((r = 0.74, p < 0.01, n = 287)\) as was seedling shoot length \((r = 0.71, p < 0.01, n = 276)\). Seed germination rate was correlated weakly with 100-seed weight \((r = 0.16, p < 0.01, n = 288)\). Seeds that imbibe and germinate quickly during the 4-day germination period had longer roots and shoots compared to those that imbibed and germinated slowly. It is not surprising that seed weight had a weak relationship with seed germination rate. Rapid germination is under physiological control unrelated to seed weight [6,13].

4. Discussion

Seed germination and establishment are affected by weather. When moisture is limited, it can adversely affect seed germination, plant establishment, plant growth, and ultimately plant survival. Several studies, including this study, have shown that water deficits reduce seed germination and seedling growth [17,22–26]. For example, Al-Karaki [25] found the rate of water uptake by barley seed and the percentage seed germination decreased as water potential decreased from 0 to −1.2 MPa. We
also found that percentage 4- and 7-day seed germination of barley decreased with a decreasing water potential from 0 to −2.0 MPa (Table 1). Like the Al-Karaki findings [25], we found that water potentials below −0.8 MPa failed to obtain 50% seed germination. In our study, the x₀ of Table 2 represents the water potential where 50% of the seed are expected to germinate. Among the barley lines represented in our experiment, 50% of the seeds should germinate in four days at a water potential of −1.0 MPa (Table 2, Figure 1). Likewise, 50% of the seed should germinate in seven days at a water potential of −1.6 MPa (Table 2, Figure 2).

Not surprisingly, seedling growth was adversely affected by decreasing water potentials [17,25,27]. Averaged over lines, the 4-day seedling root length decreased linearly as water potential decreased from 0 to −2.0 MPa (Table 1). Al-Karaki [25] found 11-day root length to decrease as water potential decreased from 0 to −1.2 MPa, but the response was curvilinear. The difference found between our studies may be related to the age of the seedlings. There was also a curvilinear decrease in 4-day old seedling shoot length as water potential decreased from 0 to −2.0 MPa, and there was a greater impact on seedling shoot length compared with seedling root length (Table 1). Al-Karaki [25] also found shoot length growth to be affected to a greater extent than root length growth. It should not be a surprise to have roots longer than shoots because, during the seed germination process, the root radicle emerges first and shortly after that the coleoptile emerges followed by the shoot [28].

Rapid germination is an important trait enhancing stand establishment of grasses under variable environmental conditions [29]. The line × water potential interactions for germination rate showed that differences among barley lines at water potentials below −0.8 MPa was primarily due to one line 617-25 (Figure 3). Variation within and among barley lines should make it possible to select and breed for greater 4-day seed germination at a negative water potential. Understanding the seed germination characteristics of plants at negative water potentials is the first step in developing an effective selection pressure for the development of new cultivars with the capacity to germinate and establish under a variable climate.

Palmer [14] suggested a breeding approach to improve self-pollinated crops that is comparable to recurrent selection. This involves crossing superior lines for a desired trait that were isolated from the same cross, thereby increasing the frequency of the desired genotype. Experiments like ours can be used to identify lines that vary for seed germination in water of negative potentials and to identify the water potential (selection pressure) for selection to be effective. In this experiment, a water potential of −1.36 MPa is equivalent to a 5% selection intensity that can be used to select plants that complete germination in four days. These plants can then be used to breed and select new lines with improved seed germination and seedling vigor at a negative water potential—thus improving stand establishment of barley when conditions are less than optimum.

Author Contributions: Conceptualization, T.L.S. and D.W.M.; methodology, T.L.S. and D.W.M.; formal analysis, T.L.S.; resources, T.L.S. and D.W.M.; writing—original draft preparation, T.L.S.; writing—review and editing, T.L.S. and D.W.M. Both authors approved the final draft of the manuscript.

Funding: Funding for this research was provided by the USDA Agricultural Research Service. All programs and services of the USDA are offered on a nondiscriminatory basis, without regard to race, color, national origin, religion, sex, age, marital status or handicap. Mention of a trademark or a proprietary product does not constitute a guarantee or warranty of the product by USDA and does not imply approval to the exclusion of other suitable products.

Conflicts of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References


7. Springer, T.L.; Wynia, R.L.; Rea, G.L. Field emergence and plant density of sand bluestem lines selected for increased seed germination. *Crop Sci.* 2012, 52, 2826–2829. [CrossRef]


10. Springer, T.L. Recurrent selection increases seed germination in little bluestem (*Schizachyrium scoparium*). *Euphytica* 2017, 213, 279. [CrossRef]


