Population and Environmental Effects on Seed Production, Germination, and Seedling Vigor in Western Wheatgrass (Pascopyrum smithii [Rydb.] A. Löve)


ABSTRACT

Western wheatgrass (Pascopyrum smithii [Rydb.] A. Löve) has low seed production and poor germination and seedling vigor, limiting its use when quick establishment is needed to stabilize degraded rangelands. This study examined differences among germplasm sources and seed production environments on western wheatgrass seed traits. Seed was harvested from 10 western wheatgrass populations grown in three environments. Seed yield, seed weight, seedling germination, and seedling vigor were then determined. Seedling vigor was measured by greenhouse evaluation of seedling emergence percentage and rate from a planting depth of 6.35 cm. There were significant population × environment interactions for seed yield and seed weight. However, high Spearman’s rank correlations between environments within each trait (r = 0.64 to 0.85, P = 0.048 to 0.002) suggested that environment had only a moderate effect on ranking of populations. Mean seed yield and 100-seed weight varied significantly among populations, ranging from 2.6 to 25.4 g plant⁻¹ and 0.43 to 0.54 g, respectively. Seed germination was high, ranging from 78.4 to 94.4%; however, population performance was not consistent across environments. Environment had no effect on seedling emergence rate, whereas emergence among populations ranged from 2.4 to 4.2 seedlings d⁻¹. Germination rate and seed weight were both correlated with seedling emergence rate (r = 0.57, P = 0.001 and r = 0.49, P = 0.01, respectively). These results indicated that seed production environment had little effect on western wheatgrass seed yield or seedling vigor and that it may be possible to breed for improvement in these traits by selecting among and within western wheatgrass populations.

Western wheatgrass is a perennial, cross-pollinating native grass that is an important component of rangelands in the mixed grass prairies throughout the central and northern Great Plains and in some areas of the Intermountain West (Asay and Jensen, 1996; Hart et al., 1996). Because of its sod-forming characteristics, it is widely recommended for use in rangeland improvement and revegetation after disturbances such as mining, construction, and fire (Asay and Jensen, 1996). Western wheatgrass is found naturally throughout central and southern Colorado, including the Fort Carson United States Army base headquartered in Colorado Springs, CO, where it is used to reseed 200 to 1215 ha per year following military training and rangeland fires (J.D. Kulbeth, Rangeland Management Specialist, Natural Resources Division, Fort Carson, personal communication, 2002). Western wheatgrass has low seed yields and is difficult and slow to establish because of seed dormancy and poor seedling vigor; however, thick stands may result over time from extensive rhizome development (Asay and Jensen, 1996). The inherent slow establishment of western wheatgrass limits its effectiveness in reducing erosion and controlling invasive weeds in areas with frequent, severe disturbances. The development of new western wheatgrass cultivars with improved seed production and seedling vigor would greatly enhance the value of this species for revegetation of frequently disturbed rangelands, military training lands, and areas with repeated wildfires.

Seed weight and ability to emerge from a deep planting depth have been used as selection criteria for improving seedling vigor in grasses (Andrews et al., 1997; Asay and Johnson, 1983a; Johnson and Asay, 1993; Kalton et al., 1959; Lawrence, 1963). Lawrence (1963) suggested that high seed test-weight and faster emergence rate from deep depths were effective selection criteria for improving seedling vigor in Russian wildrye [Psathyrostachys juncea (Fisch.) Nevski]. This strategy was successfully used to evaluate Russian wildrye and crested wheatgrass [Agropyron desertorum (Fisch. ex Link) Schultes] breeding populations (Asay and Johnson, 1980, 1983a; Johnson and Asay, 1993) resulting in the release of ‘Bozoisky-Select’ Russian wildrye (Asay et al., 1985a), Tetra-1 Russian wildrye germplasm (Jensen et al., 1998), ‘Hycrest’ crested wheatgrass (Asay et al., 1985b), and ‘Vavilov’ Siberian wheatgrass (Asay et al., 1995). These cultivars and germplasms are known for their improved seedling vigor and establishment ease in comparison to older cultivars. A recent Russian wildrye cultivar, Mankota, was also selected, in part, for its ability to emerge from a depth of 5 cm (Berdahl et al., 1992). Lafond and Baker (1986) also found that seed size and speed of emergence were associated with seedling vigor in wheat (Triticum aestivum L.).

Ries and Hofmann (1995) reported that western wheatgrass emergence significantly decreased when planted deeper than 5.2 cm. Their study lends support to the hypothesis that variation for seedling vigor in western wheatgrass can be evaluated by seedling emergence from deep seeding. In this study we evaluated differences among 10 germplasm sources and the effect of three seed production environments on seed production, seed weight, germination, and seedling emergence in western wheatgrass.

MATERIALS AND METHODS

Seed for this study came from plants grown in two locations. One location was the Utah State University Evans Research...
Farm located approximately 2 km south of Logan, UT (41°45′ N, 111°8′ W, 1350 m above sea level). Soil type at this site is a Nibley silty clay loam series (fine, mixed, active, mesic Aquic Argix- 
roll). The long-term mean annual precipitation at Evans farm is 475 mm with approximately 50% received April through September. The other site was located at the Fort Carson, Turkey Creek Recreation area approximately 20 km south of Colorado Springs, CO (38°37′20″ N, 104°52′40″ W). Soil type at Turkey Creek is a Neville fine sandy loam (fine-loamy, mixed, 
superactive, calcareous, mesic Ustic Torriorthent). Colorado Springs mean annual precipitation is 383 mm with 80% re- 
ceived April through September.

Plant materials were 10 western wheatgrass populations comprised of cultivars and germplasms in common between 
two large western wheatgrass evaluation nurseries at each site. 
Descriptions of the plant materials are as follows: ‘Arriba’ 
originated from a collection near Flagler, CO, and was released 
in 1973 for its improved seedling establishment, aggressive 
rhizomes, and superior seed production (U.S. Department of 
Agriculture, 1995); ‘Barton’ traces to a 1947 collection on a clay 
bottomland in Barton County, KS, and was released in 1970 as 
an intermediate between northern and southern types with 
improved rust resistance, seed culm development, and forage 
yield (U.S. Department of Agriculture, 1995); EPC181 is germ- 
plasm collected from Taos County, NM; ‘Flintlock’ originated 
from collections on native grasslands in central and southwes- 
tern Nebraska and northwestern Kansas and was released in 
1975 after selection for forage yield, seed yield, and rhizomatous 
spread (U.S. Department of Agriculture, 1995); KJ48 is a col- 
mation made by Kevin Jensen near Rio Blanco, CO; MAN3459 
is a breeding population that originated from bulking seed of 
the western Canadian collections described by Johnston et al. 
(1975) and used in the development of ‘Walsh’ western wheat- 
gress (Smoliak and Johnston, 1983, 1984); NE1 is a Nebraska 
herb plant and used in the seed weight, germination, and 
seeding vigor evaluations. In 1999, seed production at Fort 
Carson was erratic and essentially zero and, thus, seed from 
this site was not included in the tests. We were unable to 
determine what biotic or abiotic (e.g., insects, frost, etc.) events 
causethisresult.Therefore,seed production environments in 
this study were comprised of 2 yr at Logan and 1 yr at Fort 
Carson.

Percentage of germination was determined by standard pro- 
cedures outlined in the rules for testing seeds (Association of 
Official Seed Analysts, 2002). Briefly, three replicates of 100 
seeds were placed on blotter paper moistened with 0.2% 
KNO₃ solution and placed in an RCB design in an a dark 
incubator with alternating temperatures of 15 and 30°C for 
periods of 16 and 8 h d⁻¹, respectively. Germination counts 
were made 7, 14, 21, and 28 d after initiation. Viability of dorm- 
mand seed was not tested. Germination was evaluated during 
the winter of 1999 and again during the winter of 2002 and 
2003 to correspond with seedling vigor tests. The 1999 evalu- 
at results suggested that a high amount of dormancy re- 
mained in the seed, and the data were not used in the analyses 
in an effort to reduce the confounding effect of dormant seed. 
Germination rate was measured using the method of Maguire (1962).

Seeding vigor was evaluated as percentage and rate of seed- 
ing emergence from a planting depth of 6.35 cm. This evalu- 
at was initiated during the winter of 2002 and repeated in 
2003 in a greenhouse at Logan, UT. Each of four replications 
were in separate, cement-encased sand benches filled with 3:1 
sandy-soil/peat medium. One hundred seeds of each popula- 
tion were placed at the bottom of a trench and then covered to 
a uniform depth of 6.35 cm to comprise an experimental unit. 
Sand benches were gently watered daily to near field capacity 
of the soil. Number of seedlings emerged were counted 10, 12, 
13, 15, 17, 18, 21, and 24 d after planting in 2002 and 10, 12, 13, 
16, 19, 21, and 26 d after planting in 2003. Seedling emergence 
rate was again measured using the method of Maguire (1962).

In the statistical model, population, environment (i.e., the 
three location–seed production year combinations), and their 
interaction were fixed effects, whereas, replicate and run (i.e., 
year of test) were considered random. All analyses were done 
using the MIXED procedure (SAS Institute Inc., 1999). In 
addition, simple correlations among seed traits and Spear- 
man’s rank correlations among populations within seed traits 
were calculated using the CORR procedure of SAS (SAS 

RESULTS AND DISCUSSION

Seed Yield and 100-Seed Weight

Population, environment, and the population × envi- 
ronment interaction were all significant for seed yield (Table 1). Mean seed yield at Fort Carson-1998 was only 
43 and 48% of the yield at Logan-1998 and Logan-1999,
respectively. Several rank changes among populations for seed yield occurred for the different environments. However, seed yield among populations was moderately to highly correlated between the environments with Spearman’s rank correlation coefficients of 0.64 ($P = 0.048$), 0.85 ($P = 0.002$), and 0.66 ($P = 0.038$), for comparisons between Logan-1998 and Fort Carson-1998, Logan-1998 and Logan-1999, and Logan-1999 and Fort Carson-1998, respectively. Most notable of the rank changes resulted from Flintlock’s lower yield in Logan-1998 as compared to being one of the top yielders at Logan-1999 and Fort Carson-1998, and greater than 80% seed yield reduction in Rosana at Fort Carson as compared with both Logan environments (Table 2). Western wheatgrass is not considered susceptible to seed shattering, but minor shattering at Fort Carson was observed during harvest. Rosana, in particular, may have been more susceptible to shattering, perhaps helping to explain its large seed yield reduction.

Limited literature is available concerning genotype × environment effects on seed production in perennial grasses. Stratton and Ohm (1989) reported significant genotype × location interaction and low phenotypic correlations between Oregon and Indiana for seed yield in orchardgrass (*Dactylis glomerata* L.). They concluded that breeding for increased orchardgrass seed production must occur in the area targeted for commercial seed production. Our relatively high parallel ranking between environments is more in agreement with Barker et al. (1997), who found that orchardgrass seed production in Oregon could be improved by selection for seed yield in multiple midwest environments. Overall, our results support the hypothesis that evaluating western wheatgrass in any one of the three environments in this study would be indicative of relative seed yield for all environments.

The population effect was highly significant for seed yield with mean yields ranging from 2.6 to 24.5 g plant$^{-1}$ (Table 2). Asay and Jensen (1996) listed poor seed production as one of the major limitations of western wheatgrass. The range among populations for seed yield expressed in this study suggests that there may be opportunity to select for increased seed yield in western wheatgrass. Additional studies will be needed to verify the heritability of seed production in western wheatgrass.

Population and population × environment had significant effects for differences in 100-seed weight values (Table 1); whereas, environment had no effect, with mean 100-seed weights nearly identical among the three production environments (Table 2). As observed with seed yield, ranking of populations was similar, but not identical, among environments (Spearman’s rank correlations of 0.68, 0.81, and 0.76, and corresponding $P$ values of 0.029, 0.005, and 0.011, respectively). On average, Arriba had the highest 100-seed weight; whereas, seed weight for EPC181 was approximately 20% less and ranked lowest (Table 2). The range observed among these germplasm sources again suggests the possibility of selection for increased seed mass in western wheatgrass.

### Germination

Population, environment, and population × environment effects were all significant for germination percentage (Table 1). Logan-1999 had the highest mean germination of 90.9%, but all environments had relatively high germination with a difference of only 3% between the highest and lowest environment (Table 3). Unlike seed yield and 100-seed weight, Spearman’s rank correlations were not significant indicating that individual population performance was not consistent across environments. Few general patterns in germination percentage were observed, with the exception that D2945 was consistently among the highest populations (Table 3).

These results were not altogether surprising. Percentage of germination is often used as an indicator of seed quality, and it is common knowledge that seed production environment plays a role in seed quality. However, with few exceptions, germination percentage for any given population–environment combination in this study would be considered high for western wheatgrass, and we can conclude that all three environments produced high quality western wheatgrass seed. It is possible that differences in lingering seed dormancy resulted in differences among populations. However, average germination percentages of 45.0, 88.8, and 89.5, in the 1999, 2002, and 2003 germination tests, respectively, suggested that most seed had broken dormancy by 2002.

Maguire (1962) first suggested evaluating germination rate to test seedling vigor in grasses. In our study we found

| Table 2. Seed yield and 100-seed weight of open-pollinated seed grown in three environments (1998 and 1999 near Logan, UT, and 1998 at Fort Carson, CO) of 10 western wheatgrass populations. |
|---------------------------------|----------------|----------------|----------------|----------------|
| **Population**                  | **Logan 1998** | **Logan 1999** | **Fort Carson 1998** | **Mean**       |
| NE1                             | 33.8           | 26.6           | 15.8           | 25.4           |
| D2945                           | 33.0           | 27.4           | 14.1           | 24.8           |
| Rodan                           | 34.1           | 22.6           | 12.0           | 22.9           |
| Flintlock                       | 46.7           | 22.3           | 16.2           | 18.4           |
| Arriba                          | 25.5           | 18.5           | 7.5            | 17.2           |
| Rosana                          | 22.7           | 23.3           | 3.5            | 16.5           |
| EPC181                          | 16.0           | 13.6           | 8.0            | 12.5           |
| Barton                          | 13.1           | 15.8           | 7.6            | 12.2           |
| MAN3459                         | 6.3            | 10.3           | 2.5            | 6.4            |
| KJ48                            | 2.3            | 4.9            | 0.7            | 2.6            |
| Mean                            | 20.4           | 18.5           | 8.8            | 15.9           |
| **LSV(α,0.05)**                 | 9.6            | 7.1            | 5.3            | 4.1            |
| **Population**                  | **Logan 1998** | **Logan 1999** | **Fort Carson 1998** | **Mean**       |
| NE1                             | 0.54           | 0.54           | 0.55           | 0.54           |
| D2945                           | 0.47           | 0.53           | 0.55           | 0.52           |
| Rodan                           | 0.54           | 0.51           | 0.46           | 0.50           |
| MAN3459                         | 0.50           | 0.47           | 0.53           | 0.50           |
| Arriba                          | 0.49           | 0.50           | 0.47           | 0.49           |
| Barton                          | 0.46           | 0.47           | 0.47           | 0.46           |
| EPC181                          | 0.46           | 0.44           | 0.45           | 0.45           |
| KJ48                            | 0.43           | 0.48           | 0.44           | 0.45           |
| Mean                            | 0.47           | 0.48           | 0.48           | 0.48           |
| **LSV(α,0.05)**                 | 0.03           | 0.05           | 0.04           | 0.02           |
significant effects among populations and for the population × environment interaction for germination rate (Table 1). As was the case for germination percentage, Spearman’s rank correlations for germination rate were not significant indicating that individual population performance was not consistent across environments. Accession D2945 was consistently among the highest populations and had a faster mean germination rate than all other populations (Table 3). Barton had the slowest germination rate, although no significant differences existed between the five slowest populations (Table 3).

**Seedling Emergence from Deep Seeding**

Rate of seedling emergence from deep seeding has been used to improve and evaluate seedling vigor in grasses (Johnson and Asay, 1993). In this study, the population × environment interactions were not significant for seedling emergence percentage or seedling emergence rate (Table 1), indicating consistency among populations for seedling vigor, regardless of seed production environments. The significance among environments was due to higher \( P < 0.0001 \) seedling emergence (percentage and rate) of seed produced from Logan-1999 as compared to seed from Logan-1998 or Fort Carson-1998 (Table 4).

Variation range among populations was evident with Rosana, D2945, and Arriba having the highest mean seedling emergence (percentage and rate); whereas, Barton had the lowest (Table 4). Rosana and Arriba were both released as western wheatgrass cultivars with improved seedling vigor (U.S. Department of Agriculture, 1995). The fact that they ranked high for seedling emergence in our study supports previous reports (Asay and Johnson, 1983a; Johnson and Asay, 1993; Kalton et al., 1959; Lawrence, 1963) that rate of emergence from deep planting is a reliable indirect measure of seedling vigor in rangeland grasses. The cultivar Barton is traditionally used in reseeding projects at Fort Carson (J.D. Kulbeth, Rangeland Management Specialist, Natural Resources Division, Fort Carson, personal communication, 2002), but had the lowest seedling emergence of all populations. This suggests that other germplasm sources may be better adapted for rapid establishment at Fort Carson. Overall, the large range in emergence rate from 2.4 to 4.2 seedlings \( d^{-1} \) among these populations suggests that selection and breeding for improved seedling vigor in western wheatgrass may be possible.

**Correlations Among Seed Characteristics**

Correlations among seed characteristics are shown in Table 5. Of most interest were the correlations or lack of correlation with seedling emergence rate, which would indicate which characteristics might be associated with seedling vigor. Seed yield and germination percentage were not associated with seedling emergence rate, whereas, germination rate and 100-seed weight were...
Table 5. Pearson’s correlation coefficients between seed traits of 10 western wheatgrass populations. Seed was produced in three environments (1998 and 1999 near Logan, UT, and 1998 at Fort Carson, CO). Mean performance of each population at each location was used for correlation analysis (N = 30).

<table>
<thead>
<tr>
<th>Seed yield</th>
<th>100-seed wt</th>
<th>Germination %</th>
<th>Germination rate</th>
<th>Emergence %†</th>
<th>Emergence rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NS</strong></td>
<td>0.56**</td>
<td>NS</td>
<td>0.43*</td>
<td>NS</td>
<td>0.49**</td>
</tr>
<tr>
<td>Germination %</td>
<td>NS</td>
<td>0.46*</td>
<td>0.39*</td>
<td>NS</td>
<td>0.57***</td>
</tr>
<tr>
<td>Germination rate</td>
<td>0.44*</td>
<td>0.50**</td>
<td>0.97***</td>
<td></td>
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<tr>
<td>Emergence %†</td>
<td></td>
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* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Emergence from a planting depth of 6.25 cm in a greenhouse test.

moderately correlated with emergence rate (Table 5). Percentage of emergence was highly correlated ($r = 0.97, P = 0.001$) with emergence rate, and was similar to the results ($r = 0.92$) found by Asay and Johnson (1980) of Russian wildrye emerging from a 7.6-cm depth.

Maguire (1962) showed that germination rate was predictive of emergence differences between Kentucky bluegrass cultivars (*Poa pratensis* L.). Similar to our study, Lawrence (1963) reported moderate correlations ($r = 0.57$ to $0.66$) between speed of germination and greenhouse evaluation of Russian wildrye emergence from depths of 1.3 to 3.8 cm. In comparison, Kitchen and Monsen (1994) reported that germination rate was not significantly correlated with bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Løve) seedling emergence from a 4-cm depth. Overall, it appears that germination rate per se is only partially predictive of emergence, especially when evaluating emergence from a deep seeding.

There are many studies reporting the relationship between seed test weight and seedling vigor in grasses. We found that seed weight and seedling emergence from deep seeding (6.35 cm) were only moderately associated ($r = 0.49, P = 0.01$), although there were some consistencies. For example, Arriba had the highest 100-seed weight and also one of the fastest emergence rates, and EPC181 had the lowest 100-seed weight and one of the slowest emergence rates. In comparison, Lawrence (1963) and Trupp and Carlson (1971) showed highly positive correlations ($r > 0.70$) between seed weight and seedling emergence in Russian wildrye and smooth bromegrass (*Bromus inermis* Leyss.), respectively. Asay et al. (1996) and Berdahl and Ries (1997) both reported that seedling emergence and vigor were highly affected by the increased seed weight of tetraploid Russian wildrye. Similar to our results, others have reported more moderate associations between seed weight and seedling vigor tests. Kitchen and Monsen (1994) reported a correlation of $r = 0.62$ between seed weight and emergence from a depth of 4.0 cm for wild collections of bluebunch wheatgrass, and Asay and Johnson (1983b) found that seed weight was moderately associated ($r = 0.48$) with field emergence in half-sib families of crested wheatgrass.

In recent research, Doganlar et al. (2000) reported that seed size of many domesticated species was as much as 10-fold greater than their wild counterparts due to domestication and subsequent plant breeding to improve germination and vigor. They found that just a few QTL were responsible for the majority of variability in seed weight in tomato (*Lycopersicon esculentum* Mill.) thus, helping to explain the heritable nature of seed mass. Asay and Johnson (1983b) and Berdahl and Barker (1984) both indicated that seed size could be useful in preliminary screening for seedling vigor in grasses, but suggested that sustained selection for greater seed size may not continue to improve seedling vigor. This may be especially true in western wheatgrass with only a moderate association between seed weight and seedling emergence. Hence, Lawrence’s (1963) suggested method of “selecting large-seeded lines and subjecting them to deep seeding” greenhouse evaluation seems to have obvious merit. Since western wheatgrass is a cross-pollinating octaploid ($2n = 56$) we can assume populations are extremely heterogeneous composed of highly heterozygous individual genotypes. Hence, heritability and genetic correlation studies are needed to determine the potential to directly and indirectly select for improved seedling vigor in western wheatgrass.

In conclusion, seed production environment had minimal effect on relative performance and ranking of western wheatgrass populations for seed yield and seedling vigor as measured by rate of seedling emergence from a deep seeding. In addition, there was a large range in seed yield and seedling vigor among evaluated germplasm sources, suggesting that it may be possible to breed for improvement in these traits. Our data also confirmed earlier reports that germination rate and seed weight are often associated with increased seedling vigor in grasses.

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**REFERENCES**


