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# Establishment and Trends in Persistence of Selected Perennial Cool-Season Grasses in Western United States☆

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ABSTRACT

Restoring western US rangelands from a site dominated by invasive annuals, such as cheatgrass and medusahead, to a diverse, healthy, perennial plant — dominated ecosystem can be difficult with native grasses. This study describes the establishment and trends in persistence (plant/m$^2$) of native grass cultivars and germplasm compared with typically used crested and Siberian wheatgrasses at four locations in Idaho (one), Wyoming (one), and Utah (two) that range in mean average annual precipitation (MAP) from 290 to 415 mm. Sites were cultivated and fallowed 1 yr before planting using two glyphosate applications to control weeds. We monitored seedling establishment of 10 perennial cool-season grass species and plant persistence over 5 yr. Precipitation during the seeding year varied with the Utah sites locations reviving below MAP (4% and 14%), while the Wyoming and Idaho sites received above MAP at 8% and 26%, respectively. Across these four sites, native grass seedling establishment of bottlebrush squirreltail (29 ± 0.08 [standard error] seedling/m$^2$), bluebunch (28 ± 0.05), slender (30 ± 0.05), and Snake River wheatgrasses (28 ± 0.08) was similar to "Vavilov II" Siberian wheatgrass (36 ± 3.20). By yr 5, western, Snake River, and thickspike wheatgrasses were the only native grasses to have plant densities similar to Vavilov II (37 ± 0.29) Siberian and "Hycrest II" (36 ± 0.29) crested wheatgrasses. On sites receiving between 290 and 415 mm MAP, our data suggest that native grasses are able to establish but in general lack the ability to persist except for western, Snake River, and thickspike wheatgrasses, which had plant densities similar to crested and Siberian wheatgrasses after 5 yr.

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## Introduction

Large-scale conversion of western US rangelands from a diverse, healthy, perennial plant — dominated ecosystem such as the lower-elevation Basin and Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *tridentata* and *A. tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) rangelands to invasive annual grasses, particularly cheatgrass (*Bromus tectorum* L.), has been attributed to wildfires, human activities, and drier, hotter growing conditions (Davies, 2011; Hardegree et al., 2016). In the Great Basin, for example, cheatgrass is estimated to have displaced approximately 10 million ha of native perennial vegetation (Menakis et al., 2003; Boyte et al., 2016). Dominance of cheatgrass in Wyoming sagebrush ecosystems, especially at high abundance, results in crossing a biotic threshold where ecosystem function and stability is impaired (Pellant, 1990; Monsen, 1992; Brooks and Pyke, 2001; Chambers et al., 2014).

Revegetation of semiarid rangelands is complicated by the intrinsic high interannual and intra-annual variability in climatic and environmental conditions (Bleak et al., 1965) overlaid on a fabric of heterogeneous soils and topographic combinations (Robertson and Pearce, 1945; Evans, 1961; Melgoza et al., 1990). Above 250 mm mean average annual precipitation (MAP) (Mangla et al., 2011), the competitive nature of cheatgrass presents additional challenges for successful revegetation efforts. Cheatgrass has the ability to germinate under most conditions in fall, winter, and early spring (Allen et al., 1994), creating a competitive advantage over perennial cool-season grasses (Boyte et al., 2016).

Plant traits affecting the success of arid-land restoration include seed germination, seedling emergence, seedling survival (Davies and Sheley, 2011; Atwater et al., 2015), and adult plant survival (Howard and Goldberg, 2001). Researchers have proposed that over time, native plants growing within invasive plant populations confer increased tolerance to and competition against invasive species (Leger, 2008; Rowe

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and Leger, 2012). Rowe and Leger (2011) reported that seedlings of bottlebrush squirreltail collected from cheatgrass-invaded areas had increased early seedling root-to-shoot ratio, root fork number, and fine root length compared with seedlings originating from adjacent uninvaded areas. Gibson et al. (2018) reported that population rather than experience type (invader vs. noninvader) was more important in bluebunch wheatgrass suppression of spotted knapweed (*Centaurea stoebe*). Howard and Goldberg (2001) concluded that the competitive ability of adult plants and size is less correlated to final community abundance than seed germination and seedling growth. Atwater (2012) suggested that when three or more plants interact, selection favors the ability to tolerate neighbors but not to suppress them. Fletcher et al. (2016) questioned the ability of native grasses, when grown in invaded areas, to develop a competitive ability as defined by Miller and Werner (1987) as the ability to suppress competitors compared with tolerating them. In a meta-analysis including 34 field sites, Robins et al. (2013) concluded that above 310 mm MAP, both native and introduced grasses were able to establish and persist; however, below 310 mm MAP, there are fewer species that establish and persist over time. These examples emphasize the difficulty in restoring native perennial species and indicate the need to find restoration solutions that avoid inaccurate expectations and expenditure of limited dollars on efforts that are likely not going to work.

Revegetation efforts in the early 1900s (Pickford, 1932) focused on introduced grasses such as crested (*Agropyron cristatum* [L.] Gaertn) or *Agropyron desertorum* [Fish. Ex Link] J. A. Schultes) and Siberian (*Agropyron fragile* [Roth] Candargy) wheatgrasses because of better stand establishment, persistence, and weed suppression than native grass species, particularly on rangelands receiving < 310 mm MAP (Evans and Young, 1978; MacDonald, 1997; Asay et al., 2001; Ott et al., 2001; Robins et al., 2013). Due to an increased desire and need for revegetation with perennial native grass, shrub, and forb species (Richards et al., 1998), efforts have focused on development of improved native plant materials, particularly grasses, with enhanced seedling establishment in the following species: bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey), basin wildrye (*Leymus cinereus* [Scribn. & Merr.] Á. Löve), slender wheatgrass (*Elymus trachycaulus* [Link] Gould ex Shinners), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh.] A. Löve), Snake River wheatgrass (*Elymus wawawaiensis* J. Carlson & Barkworth), thickspike wheatgrass (*Elymus lanceolatus* [Scribn. & Sm.] Gould), and western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve) (Table 1).

There is a need to evaluate newly developed native grasses over multiple environments (Table 2) and years. The purpose of this study is to evaluate stand establishment and trends in plant persistence 5 yr post seeding for native dryland range grasses comparing native grasses with crested and Siberian wheatgrasses on rangelands. The hypothesis is that some of the newer native range grasses will establish better and persist longer compared with crested and Siberian wheatgrasses.

**Table 1**
Description of entries by species including cultivar or germplasm name with reference to corresponding release notice. Sites where entries were included are indicated by the corresponding site number.

| Species | Entry | Status | Site | | | | Reference |
|---|---|---|---|---|---|---|---|
| | | | 1[1] | 2[2] | 3[3] | 4[4] | |
| Bottlebrush squirreltail | Fish Creek | Germplasm | 1 | | 3 | 4 | Jones et al. (2004a) |
| *Elymus elymoides* | Sand Hollow | Germplasm | 1 | | 3 | | Jones et al. (1998b) |
| | Toe Jam Creek | Germplasm | 1 | | 3 | 4 | Jones et al. (2004b) |
| Bluebunch wheatgrass | Anatone | Germplasm | 1 | 2 | 3 | 4 | Monsen et al. (2003) |
| *Psuedoroegneria spicata* | Goldar | Cultivar | 1 | | 3 | 4 | Gibbs et al. (1991) |
| | [5]*P-7 | Germplasm | 1 | 2 | 3 | 4 | Jones et al. (2002) |
| Basin wildrye | *Continental | Cultivar | 1 | | | 4 | Jones et al. (2009) |
| *Leymus cinereus* | Magnar | Cultivar | 1 | | | 4 | Howard (1979) |
| | Trailhead | Cultivar | 1 | 2 | | 4 | Cash et al. (1998) |
| | *Trailhead II | Cultivar | | 2 | | 4 | Robins and Bushman (2016) |
| Crested wheatgrass | *Hycrest II | Cultivar | 1 | 2 | 3 | 4 | Jensen et al. (2009a) |
| *Agropyron cristatum* | | | | | | | |
| Indian ricegrass | Nezpar | Cultivar | 1 | | 3 | | Booth et al. (1980) |
| Achnatherum hymendoides | Rimrock | Cultivar | 1 | | 3 | | Jones et al. (1998a) |
| | *White River | Cultivar | 1 | | 3 | | Jones et al. (2010) |
| Siberian wheatgrass | *Vavilov II | Cultivar | 1 | 2 | 3 | 4 | Jensen et al. (2009b) |
| *Agropyron fragile* | | | | | | | |
| Slender wheatgrass | *Charleston Peak | Germplasm | 1 | | 3 | | Jensen et al. (2016) |
| *Elymus trachycaulus* | *FirstStrike | Cultivar | 1 | 2 | 3 | 4 | Jensen et al. (2007) |
| | Pryor | Cultivar | 1 | 2 | 3 | 4 | Majerus et al. (1991) |
| | Revenue | Cultivar | 1 | | | | Crowle (1970) |
| | San Luis | Cultivar | 1 | | 3 | 4 | USDA-SCS (1984) |
| Snake River wheatgrass | *Discovery | Cultivar | 1 | 2 | | 4 | Jones (2008) |
| *Elymus wawawaiensis* | Secar | Cultivar | 1 | 2 | 3 | 4 | Morrison and Kelley (1981) |
| Thickspike wheatgrass | Bannock | Cultivar | 1 | 2 | | 4 | John and Blaker (1998) |
| *Elymus lanceolatus* | *Bannock II | Cultivar | 1 | 2 | | 4 | Robins et al. (2015) |
| | Critana | Cultivar | 1 | 2 | | 4 | Stroh et al. (1972) |
| | Schwendimar | Cultivar | 1 | | | | USDA NRCS (2016b) |
| | Sodar | Cultivar | 1 | | | | Douglas and Ensign (1954) |
| Western wheatgrass | Arriba | Cultivar | 1 | | 3 | 4 | Anonymous (1977) |
| *Pascopyrum smithii* | Barton | Cultivar | 1 | | 3 | | Alderson and Sharp (1994) |
| | *Recovery | Cultivar | 1 | 2 | 3 | 4 | Waldron et al. (2011) |
| | Rodan | Cultivar | 1 | | 3 | | Barker et al. (1984) |
| | Rosana | Cultivar | 1 | 2 | 3 | 4 | Alderson and Sharp (1994) |

[1] Entry included at Site 1, Beaver, Utah.
[2] Entry included at Site 2, Cheyenne, Wyoming.
[3] Entry included at Site 3, Malta, Idaho.
[4] Entry included at Site 4, Eureka, Utah.
[5] Indicates newly developed plant materials.

**Table 2**
Summary of environmental characteristics at four locations used for analysis of establishment and persistence of range grasses.

| | Beaver, UT | Cheyenne, WY | Malta, ID | Tintic, UT |
|---|---|---|---|---|
| Latitude (°N) | 38°20'51.72" | 41°10'36.84" | 42°18'6.84" | 39°54'12.6" |
| Longitude (°W) | 112°35'20.76" | 104°54'3.96" | 113°11'41.99" | 112°8'58.92" |
| Soil | Murdock silt loam (coarse-loamy, mixed, mesic arid petrocalcic palexerolls)[1] | Altvan loam (fine-loamy over sandy or sandy-skeletal, mixed mesic aridic argiustolls) | Declo silt loam (Coarse-loamy, mixed, mesic xerollic calciorthids) | Doyce silt loam (fine-loamy, mixed, esic aridic calcic argixerolls) |
| Elevation (asl) | 1 981 m | 1 901 m | 1 480 m | 1 789 m |
| Level III ecoregion | Central Basin and Range | High Plains | Northern Basin and Range | Central Basin and Range |
| Level IV ecoregion | Woodland and shrub-covered low mountains | Moderate relief rangeland | Northern basin and range and saltbush dominated valleys | Sagebrush basins and slopes |
| Associated species | Utah juniper, singleleaf pinyon, bluebunch wheatrass, bottlebrush squirreltail, Indian ricegrass, black sagebrush, and Wyoming big sagebrush | Needleand thread grass and western wheatgrass. | Wyoming big sagebrush, and bluebunch wheatgrass with greasewood on the more sodic soils | Utah juniper, black sagebrush, Wyoming big sagebrush, bluebunch wheatgrass, western wheatgrass, bottlebrush squirreltail, and Indian ricegrass |
| Minimum average temperature (°C) | −9.3 | −8.6 | −8.3 | −10.3 |
| Maximum average temperature (°C) | 30.2 | 28.2 | 30.5 | 31.3 |
| Annual precipitation (mm)[2] | | | | |
| Seeding yr | 352 (2006) | 433 (2009) | 397 (2004) | 355 (2009) |
| Yr_1 | 366 | 390 | 269 | 439 |
| Yr_2 | 290 | 394 | 201 | 419 |
| Yr_3 | 269 | 240 | 175 | 343 |
| Yr_4 | 272 | 477 | 285 | 307 |
| Yr_5 | 475 | 433 | 290 | 367 |
| Long-term MAP | 365 | 397 | 292 | 415 |

MAP, mean annual precipitation.
[1] USDA-NRCS, 2016a. Ecological Site Description.
[2] PRISM Climate Group, 2016.

## Methods

Each year the US Department of Agriculture (USDA)—Agriculture Research Service (ARS) Forage and Range Research Laboratory in Logan, Utah, establishes a series of rangeland plantings to evaluate the establishment and persistence of new plant materials under different environments compared with older plant materials. A meta-analysis describing 34 of those sites can be found in Robins et al. (2013) for site information. Because the focus of this paper is to look at persistent trends in native grasses compared with crest and Siberian wheatgrasses, we identified four locations with ≥ 5 yr of plant density data with common plant materials. Beaver and Tintic, Utah sites experienced 4% and 14% less MAP, while Cheyenne, Wyoming and Malta, Idaho sites received 26% and 8% above MAP for the area, respectively (Table 2). Plant materials used in this study, including species, cultivar or germplasm designation and reference, Latin name and authority, and study location, are listed in Table 1. Environmental characteristics of the four study sites—Beaver, Utah, Cheyenne, Wyoming, Malta, Idaho, and Tintic, Utah—are described in Table 2 to include soil type, ecoregions level III and IV (Omernik, 1987), associated species, minimum and maximum temperatures, and yearly rainfall.

### *Site Preparation and Planting*

Each site was mechanically cultivated 1 yr before planting, followed by two subsequent applications of glyphosate (1 518 g a.i $ha^{-1}$) the summer before planting. Just before planting, sites were lightly cultivated followed by a harrow or cultipacker to firm the seedbed. Each of the sites was weed free at planting (a condition rarely obtained on typical rangeland seedings); however, after planting, weed control was not practiced. Fall dormant seedings were accomplished during November (see Table 2). In addition, all sites were planted using a Hege 6-row cone seeder with double disc openers and depth control press wheels (Wintersteiger Inc. Salt Lake City, UT) at a rate of one pure live seed $cm^{-1}$ and a seeding depth of 0.63 − 1.27 cm. The double disc openers and depth control pressure wheels ensure good seed-to-soil contact at planting. Plots were 1.5 m × 6 m long, except at Cheyenne, Wyoming and Malta, Idaho, where they were 3 m × 6 m and 1.5 m × 12 m, respectively. Row spacing was 25.4 cm spacing between rows with six rows per plot and 25.4 cm spacing between plots. Plots were arranged in a randomized-complete-block design with four replications at each site.

### *Seedling Establishment and Stand Persistence*

Frequency of plant occurrence during the establishment year and subsequent plant persistence 4 yr post establishment was determined by counting the number of 12.5 × 12.5 cm quadrats that contained at least one seedling along 2.3 m of the four inner rows of each plot divided by the total number of possible quadrats (USDI BLM, 1999; Vogel and Masters, 2001). Multiplying the frequency of occurrence by 0.51 (see Vogel and Masters for details) provides a conservative estimate of the number of plants/$m^2$ because only a single count is made per grid cell even though a cell may contain several plants. Vogel and Masters (2001) suggest that 20 or more plants/$m^2$ would be classified as a successful stand with between 10 and 20 plants/$m^2$ as marginal and

**Table 3**
Significance levels by year for seedling establishment and stand persistence (% frequency).

| Source | Seedling establishment | | Stand persistence | | | |
|---|---|---|---|---|---|---|
| | df | Y1 | Y2 | Y3 | Y4 | Y5 |
| Species (Sp) | 12 | < .0001 | < .0002 | < .0001 | < .0001 | < .0001 |
| Cult (Species) (CS) | 35 | < .0001 | < .0001 | < .0001 | < .0001 | 0.0006 |
| Location (L) | 3 | < .0001 | 0.0019 | 0.0002 | < .0001 | < .0001 |
| Sp X L | 28 | < .0001 | < .0001 | < .0001 | < .0001 | < .0003 |
| CS X L | 44 | < .0001 | < .0001 | < .0001 | < .0001 | 0.0023 |

anything below 10 plants/$m^2$ as unsuccessful. Dates of plant frequency data collection are in Table 2.

### Statistical Analysis

Due to the data being counted and not normally distributed, all data were square-root transformed before data analysis and then back transformed for the tables (McDonald, 2014). Initially, years and locations were included in the statistical model, but there were numerous significant interactions of species and cultivars within species with years and locations; therefore, data were subsequently reanalyzed by year and location using PROC MIXED procedures (SAS, 1999) and reported in that manner. Effects due to grass species, as well as cultivars within species, were considered fixed effects with replications (blocks) as a random effect (Table 3). Main effects and interactions were tested with their first-order interactions with replications as the error terms. Species mean separations were based on species averages in accordance with Fisher's protected least significant difference (LSD) at the $P < 0.05$ level of probability. Intercharacter correlations were computed on entry by rep means using PROC CORR (SAS, 1999). Linear, quadratic, and cubic trends of plant-frequency percentage were determined for each species and cultivars within species using orthogonal polynomials with equal-year intervals (Gomez and Gomez, 1984).

## Results

### Beaver, Utah

#### Seedling Establishment

Significant ($P < 0.05$) differences for seedlings/$m^2$ were observed among species (Tables 3 and 4). Between species, seedlings/$m^2$ ranged from 48 ± 0.01 for Siberian wheatgrass to 19 ± 0.07 (standard error) in

**Table 4**
Means and trends in plant/$m^2$ of 10 grass species across 5 yr at Beaver, UT from 2007 to 2011.

| Species | Plants $m^{-2}$ | | | | | Slope[1] | Trends† | |
|---|---|---|---|---|---|---|---|---|
| | 2007 | 2008 | 2009 | 2010 | 2011 | b | Linear | Quad. |
| Bottlebrush ST | 40 AB | 46 AB | 45 AB | 45 AB | 42 AB | 0.3 | 39 ** | 38 ** |
| Fish Creek | 41 ab | 47 a | 47 A | 48 a | 46 a | 1.1 | 63 ** | 30 ** |
| Sand Hollow | 35 b | 41 b | 39 B | 39 b | 33 b | −0.7 | 9 ns | 27 * |
| Toe Jam Creek | 44 a | 48 a | 48 A | 48 a | 46 a | 0.4 | 54 ** | 37 * |
| Bluebunch WG | 38 AB | 44 ABC | 45 AB | 46 A | 44 AB | 1.3 | 76 ** | 24 ** |
| Anatone | 36 a | 44 a | 46 A | 46 a | 44 a | 1.9 | 79 ** | 17 ** |
| Goldar | 39 a | 44 a | 47 A | 45 a | 44 a | 1.2 | 66 ** | 32 * |
| P-7 | 39 a | 45 a | 47 A | 46 a | 43 a | 0.8 | 71 ** | 23 * |
| Basin WR | 28 C | 36 CD | 37 C | 39 BC | 34 BC | 1.6 | 83 ** | 14 ** |
| Continental | 31 a | 40 a | 41 A | 39 a | 39 a | 1.6 | 49 ** | 44 ** |
| Magnar | 21 b | 36 ab | 34 A | 36 a | 28 ab | 1.5 | 56 ** | 27 ** |
| Trailhead | 31 a | 36 ab | 39 A | 41 a | 37 b | 1.8 | 95 ** | 3 ns |
| Crested WG − Hycrest II | 46 AB | 46 AB | 47 AB | 48 A | 46 AB | 0.2 | 80 ns | 1 ns |
| Indian ricegrass | 35 BC | 41 BCD | 39 BC | 35 C | 28 D | −2.1 | 0 ns | 23 ** |
| Nezpar | 29 a | 36 b | 29 b | 26 b | 11 b | −4.6 | 1 ns | 4 ns |
| Rimrock | 36 a | 43 a | 44 A | 35 ab | 32 a | −1.8 | 1 ns | 53 ** |
| White River | 40 a | 44 a | 44 A | 44 a | 40 a | 0.1 | 41 ns | 24 ns |
| Siberian WG - Vavilov II | 48 A | 50 A | 49 A | 51 A | 48 A | 0.1 | 48 ** | 3 ns |
| Slender WG | 35 BC | 42 ABC | 41 BC | 36 C | 32 DE | −1.4 | 0 ns | 49 ** |
| Charleston Peak | 22 b | 33 b | 31 B | 22 b | 24 b | −0.6 | 1 ns | 94 ** |
| FirstStrike | 43 a | 48 a | 46 A | 41 a | 36 a | −1.9 | 1 ns | 30 * |
| Pryor | 43 a | 45 ab | 45 A | 44 a | 41 a | −0.6 | 3 ns | 12 ns |
| Revenue | 44 a | 47 a | 46 A | 37 a | 29 ab | −4.2 | 11 ns | 12 * |
| San Luis | 26 b | 38 ab | 38 Ab | 33 a | 29 ab | 0.3 | 24 ns | 59 ** |
| Snake River WG | 35 BC | 41 ABC | 43 ABC | 43 AB | 37 CD | 0.5 | 63 ** | 14 * |
| Discovery | 40 a | 44 a | 45 A | 45 a | 36 a | −0.8 | 17 * | 4 ns |
| Secar | 30 a | 38 b | 41 A | 41 b | 38 a | 1.8 | 79 ** | 20 ns |
| Thickspike WG | 36 B | 42 ABC | 48 A | 47 A | 48 A | 2.9 | 70 ** | 9 * |
| Bannock | 37 ab | 43 a | 47 A | 49 a | 49 a | 3.0 | 73 ** | 5 ns |
| Bannock II | 30 b | 42 a | 47 A | 48 a | 49 a | 4.5 | 71 ** | 13 ns |
| Critana | 38 ab | 42 a | 46 A | 48 a | 47 a | 2.6 | 82 ** | 2 ns |
| Sodar | 39 a | 43 a | 48 A | 45 a | 48 a | 2.00 | 52 ** | 14 ns |
| Schwendimar | 34 ab | 40 a | 46 A | 44 a | 45 a | 2.6 | 62 ** | 19 ns |
| Western WG | 19 D | 37 D | 44 AB | 45 AB | 46 AB | 6.4 | 72 ** | 13 ** |
| Arriba | 11 c | 32 bc | 38 A | 38 a | 35 a | 5.4 | 71 ** | 27 * |
| Barton | 18 bc | 37 abc | 44 A | 44 a | 48 a | 6.7 | 63 ** | 19 ** |
| Recovery | 28 a | 43 a | 49 A | 50 a | 51 a | 5.4 | 71 ** | 14 ** |
| Rodan | 12 c | 30 c | 42 A | 44 a | 48 a | 8.6 | 70 ** | 9 ** |
| Rosana | 26 ab | 41 ab | 48 A | 51 a | 50 a | 5.7 | 76 ** | 11 * |

Values followed by different letters significantly differ at $P < 0.05$.
† Orthogonal polynomial trends expressed as a percent of years' sum of squares due to linear effects. Values followed by a different letter are significantly different at $P < 0.05$. Uppercase letters denote significance among species. Lowercase letters denote significance within species.
* Significant at the 0.05 level of probability.
** Significant at the 0.01 level of probability.
[1] Regression coefficients of plants $m^{-2}$.

**Table 5**
Correlations for frequency of seedling establishment (Y1) and stand persistence in yr 2 (Y2), yr 3 (Y3), yr 4 (Y4), and yr 5 (Y5). Top diagonal is the Beaver, UT location, and bottom diagonal is the Cheyenne, WY location.

| | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|
| Y1 | 1.0000 | 0.8340 | 0.6275 | 0.4541 | 0.3097 |
| | | < .0001 | < .0001 | < .0001 | < .0001 |
| Y2 | 0.5290 | 1.0000 | 0.0762 | 0.5948 | 0.4712 |
| | < .0001 | | < .0001 | < .0001 | < .0001 |
| Y3 | 0.1450 | 0.6500 | 1.0000 | 0.8035 | 0.7547 |
| | 0.2687 | < .0001 | | < .0001 | < .0001 |
| Y4 | −0.1006 | 0.3293 | 0.6240 | 1.0000 | 0.8579 |
| | 0.4441 | 0.0102 | < .0001 | | < .0001 |
| Y5 | −0.2575 | 0.1087 | 0.5539 | 0.8465 | 1.0000 |
| | 0.0469 | 0.4081 | < .0001 | < .0001 | |

western wheatgrass. Basin wildrye (28 ± 0.05 seedlings/m$^2$), Indian ricegrass (35 ± 0.05), slender (35 ± 0.04), Snake River (35 ± 0.07), and thickspike (36 ± 0.02) wheatgrasses had fewer seedlings/m$^2$ ($P <$ 0.05) than Siberian wheatgrass.

Differences ($P < 0.05$) in seedling frequency between cultivars within species were observed in bottlebrush squirreltail, basin wildrye, slender, thickspike, and western wheatgrasses (see Table 4). Toe Jam Creek and Fish Creek bottlebrush squirreltail had greater ($P < 0.05$) seedlings/m$^2$ than Sand Hollow (35 ± 0.12). “Continental” and “Trailhead” basin wildrye had greater seedlings/m$^2$ than “Magnar” at 21 ± 0.18. Seedling density in Vavilov II (48 ± 0.01) was similar to Hycrest II at 46 ± 0.02 seedlings/m$^2$. Seedlings/m$^2$ of slender wheatgrass cultivars FirstStrike, Pryor, and Revenue slender wheatgrasses were similar but greater ($P < 0.05$) than observed Charleston Peak (22 ± 0.96) and San Luis (26 ± 0.12). “Recovery” western wheatgrass had more seedlings/m$^2$ than cultivars Arriba (11 ± 0.34), Rodan (12 ± 0.01), and Barton (18 ± 0.53).

### *Stand Persistence*

All species studied saw an increase in plants/m$^2$ from 2007 to 2008. Positive linear trends ($P < 0.05$) in plants/m$^2$ were observed in thickspike and western wheatgrasses from 2007 to 2011, each increasing in plant density 2.9 and 6.4 plants/yr, respectively (see Table 4). Negative linear trends ($P < 0.05$) in plants/m$^2$ were observed in Indian ricegrass and slender wheatgrass from 2007 to 2011, each declining by 2.1 and 1.4 plants/yr, respectively.

Cultivars that exhibited a linear decline in plants/m$^2$ from Y1 to Y5 were Sand Hollow bottlebrush squirreltail (−0.7), Nezpar (−4.6), and Rimrock (−1.8) Indian ricegrass, slender wheatgrass cultivars Charleston Peak (−0.6), FirstStrike (−1.9), Pryor (−0.6), and Revenue (−4.2), and Discovery Snake River wheatgrass (−0.8). Observed correlations between 2007 and 2008 ($r = 0.83$), 2009 ($r = 0.63$), 2010 ($r = 0.45$), and 2011 ($r = 0.31$) were all significant ($P < 0.001$) (Table 5).

## *Cheyenne, Wyoming*

### *Seedling Establishment*

Significant ($P < 0.05$) differences for seedlings/m$^2$ were observed among species (Tables 3 and 6). Between species, seedlings/m$^2$ ranged from 8 ± 0.30 in western wheatgrass to 35 ± 0.04 in basin wildrye (see Table 6). Species with fewer ($P < 0.05$) seedlings/m$^2$ than Siberian wheatgrass (33 ± 0.30) were thickspike (22 ± 0.34), Snake River (19 ± 0.21), bluebunch (19 ± 0.40), and western (8) wheatgrasses. Cultivars within species differed ($P < 0.05$) in seedlings/m$^2$ in slender and thickspike wheatgrasses (see Table 6). Slender wheatgrass cultivar FirstStrike (45 ± 0.02) had greater seedlings/m$^2$ than Pryor (6 ± 0.53). Thickspike wheatgrass cultivar Critana had fewer ($P < 0.05$) seedlings/m$^2$ than Bannock (35 ± 0.08) and Bannock II (25 ± 1.28).

### *Stand Persistence*

Negative linear trends ($P < 0.05$) in plants/m$^2$ were observed between 2010 and 2014 in basin wildrye and slender wheatgrass, each decreasing by 5.8 and 1.4 plants/m$^2$, respectively (see Table 6). Trailhead basin wildrye declined more rapidly than Trailhead II by 41%. Plants/m$^2$ in FirstStrike slender wheatgrass declined by 6.6 plants m$^{-2}$ compared with an increase of 3.8 plants/m$^2$ observed in Pryor slender wheatgrass. Plants/m$^2$ of western wheatgrass increased by 7.9 plants/yr. Contributing to a quadratic ($P < 0.05$) trend in all species but basin wildrye and Siberian wheatgrass was the increase in plants/m$^2$ from 2010 to 2011, suggesting that seeds were possibly germinating 1 yr post planting. Observed correlations between seedlings/m$^2$ in 2010 and plants m$^{-2}$ in 2011 ($r = 0.53$; $P < 0.0001$), 2012 ($r = 0.15$; $P =$ 0.268), 2013 ($r = -0.101$; $P = 0.444$), and 2014 ($r = -0.258$; $P =$

**Table 6**
Means and trends in plants/m$^2$ of 8 grass species across 5 yr at Cheyenne, WY from 2007 to 2011.

| Species | Plants m$^{-2}$ | | | | | Slope[1] | Trends† | |
|---|---|---|---|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 | 2014 | b | Linear | Quad. |
| Bluebunch WG | 19 BC | 39 AB | 39 A | 33 BC | 43 A | 4.3 | 33 ** | 44 ** |
| Anatone | 12 a | 32 b | 32 b | 28 a | 40 a | 5.0 | 36 ** | 38 ** |
| P-7 | 25 a | 45 a | 45 a | 38 a | 46 a | 3.5 | 29 ** | 55 ** |
| Basin WR | 35 A | 39 AB | 22 B | 20 D | 17 C | −5.8 | 47 ** | 1 ns |
| Trailhead | 34 a | 37 a | 12 a | 14 a | 10 a | −7.0 | 51 ** | 0 ns |
| Trailhead II | 37 a | 41 a | 31 b | 27 a | 23 a | −4.1 | 36 * | 8 ns |
| Crested WG − Hycrest II | 30 AB | 46 A | 46 A | 47 A | 51 A | 4.3 | 51 ** | 23 ** |
| Siberian WG − Vavilov II | 33 AB | 45 AB | 44 A | 48 A | 51 A | 3.9 | 55 ** | 10 ns |
| Slender WG | 25 AB | 46 A | 42 A | 26 CD | 29 BC | −1.4 | 1 ns | 92 ** |
| FirstStrike | 45 a | 49 a | 45 a | 23 a | 26 a | −6.6 | 40 * | 25 ns |
| Pryor | 6 b | 42 b | 38 a | 28 a | 32 a | 3.8 | 35 ** | 56 ** |
| Snake River WG | 19 B | 37 B | 38 A | 35 ABC | 39 AB | 3.9 | 48 ** | 37 ** |
| Discovery | 20 a | 39 a | 40 a | 37 a | 43 a | 4.6 | 45 ** | 35 ** |
| Secar | 18 a | 35 a | 36 a | 34 a | 34 a | 3.2 | 52 ** | 39 ** |
| Thickspike WG | 22 B | 41 AB | 40 A | 32 BCD | 40 A | 2.6 | 21 * | 66 ** |
| Bannock | 35 a | 47 a | 44 a | 41 a | 40 a | 0.3 | 12 ns | 75 * |
| Bannock II | 25 ab | 35 a | 33 a | 17 b | 32 a | −0.5 | 11 ns | 82 ns |
| Critana | 7 b | 40 a | 42 a | 40 a | 47 a | 8.0 | 51 ** | 32 ** |
| Western WG | 8 C | 39 AB | 41 A | 45 A | 44 A | 7.9 | 64 ** | 23 ** |
| Recovery | 7 a | 38 a | 40 a | 45 a | 41 a | 7.4 | 66 ** | 23 ** |
| Rosana | 8 a | 40 a | 43 a | 46 a | 47 a | 8.5 | 62 ** | 23 ** |

†Orthogonal polynomial trends expressed as a percent of years' sum of squares due to linear effects.
Values followed by a different letter are significantly different at $P < 0.05$. Uppercase letters denote significance among species. Lowercase letters denote significance within species.
*,** Significant at the 0.05 and 0.01 levels of probability, respectively.
[1]Regression coefficients of plants m$^{-2}$.

**Table 7**
Means and trends in plants/m$^2$ of 8 grass species across 5 yr at Malta, ID from 2007 to 2011.

| Species | Plants m$^{-2}$ | | | | | Slope[1] | Trends[2] | |
|---|---|---|---|---|---|---|---|---|
| | 2005 | 2006 | 2007 | 2008 | 2009 | b | Linear | Quad. |
| Bottlebrush ST | 30 BC | 25 BC | 18 D | 14 B | 4 BC | −6.4 | 23 ** | 0 ns |
| Fish Creek | 32 ab | 31 a | 26 a | 20 a | 6 a | −6.9 | 15 ** | 1 ns |
| Sand Hollow | 24 b | 20 a | 14 a | 8 a | 2 a | −5.5 | 43 ** | 0 ns |
| Toe Jam Creek | 35 a | 25 a | 15 a | 14 a | 6 a | −6.8 | 53 ** | 5 ns |
| Bluebunch WG | 42 A | 26 BC | 25 CD | 13 B | 5 BC | −8.6 | 39 ** | 0 ns |
| Anatone | 41 b | 30 a | 31 a | 19 a | 9 a | −7.4 | 34 ** | 0 ns |
| Goldar | 40 b | 12 b | 11 b | 1 b | 0 a | −9.1 | 66 ** | 8 ** |
| P-7 | 45 a | 35 a | 32 a | 18 a | 8 a | −9.2 | 41 ** | 1 ns |
| Crested WG − Hycrest II | 48 A | 49 A | 47 A | 46 A | 18 A | −6.3 | 1 ns | 0 ns |
| Indian ricegrass | 30 BC | 15 CD | 5 E | 2 C | 0 C | −7.3 | 73 ** | 6 * |
| Nezpar | 16 c | 7 b | 2 b | 6 b | 1 a | −4.0 | 76 ** | 8 * |
| Rimrock | 31 b | 12 b | 2 b | 0 b | 0 a | −7.3 | 75 ** | 11 ** |
| White River | 44 a | 27 a | 11 a | 0 a | 0 a | −10.6 | 68 ** | 3 * |
| Siberian WG − Vavilov II | 48 A | 51 A | 50 A | 48 A | 21 A | −5.7 | 0 ns | 1 ns |
| Slender WG | 34 BC | 11 D | 7 E | 2 C | 0 C | −7.7 | 68 ** | 10 * |
| FirstStrike | 44 a | 20 a | 17 a | 5 a | 0 a | −10.3 | 62 ** | 3 ns |
| Pryor | 18 b | 5 b | 4 ab | 0 a | 0 a | −4.2 | 70 ** | 10 ns |
| San Luis | 39 a | 8 b | 0 c | 0 a | 0 a | −8.6 | 70 ** | 21 ** |
| Snake River WG | 40 AB | 40 AB | 42 AB | 41 A | 12 AB | −5.5 | 0 ns | 0 ns |
| Western WG | 27 C | 25 BC | 26 BC | 19 B | 10 AB | −3.9 | 13 ns | 3 ns |
| Arriba | 21 b | 16 cd | 26 a | 19 a | 16 a | −0.8 | 2 ns | 1 ns |
| Barton | 28 ab | 28 ab | 22 a | 16 a | 6 a | −5.6 | 25 ns | 3 ns |
| Recovery | 35 a | 37 a | 29 a | 19 a | 10 a | −6.7 | 30 * | 7 ns |
| Rodan | 28 ab | 25 bc | 30 a | 22 a | 11 a | −3.7 | 5 ns | 3 ns |
| Rosana | 23 b | 16 d | 23 a | 19 a | 8 a | −2.7 | 2 ns | 1 ns |

NOTE: Uppercase letters denote significance among species. Lowercase letters denote significance within species. Differing letters are significantly different at $P < 0.05$.
[1] Regression coefficients of plants m$^{-2}$.
[2] Orthogonal polynomial trends expressed as a percent of years' sum of squares because of linear effects.
* Significant at the 0.05 level of probability.
** Significant at the 0.01 levels of probability.

0.047) were not good indicators of stand persistence 4 and 5 yr post seeding (Table 5).

## Malta, ID

### Seedling Establishment

Significant ($P < 0.05$) differences for seedlings/m$^2$ were observed between species (see Tables 3 and 7). At 42 ± 0.01 seedlings/m$^2$, bluebunch wheatgrass was similar to crested and Siberian wheatgrass. Species with ≤ 34 seedlings/m$^2$ were bottlebrush squirreltail, Indian ricegrass, slender wheatgrass, and western wheatgrass (see Table 7). Sand Hollow bottlebrush squirreltail (24 ± 0.11 seedlings/m$^2$) had fewer ($P < 0.05$) seedlings/m$^2$ than Toe Jam Creek (35 ± .01) and Fish Creek (32 ± 0.08). Seedlings/m$^2$ of White River Indian ricegrass (44 ± 0.01) were greater ($P < 0.05$) than Nezpar (16 ± 0.06) and Rimrock (31 ± 0.14). Bluebunch wheatgrass germplasm P-7 at 45 ± .01 seedlings/m$^2$ had more ($P < 0.05$) than Anatone (41 ± 0.01) and Goldar (40 ± 0.01). Pryor slender wheatgrass had fewer seedlings/m$^2$ than FirstStrike and San Luis slender wheatgrass, with 44 ± 0.01 and 39 ± 0.02, respectively. Western wheatgrass cultivars Barton, Recovery, and Rodan had ≥ 28 seedlings/m$^2$ (see Table 7).

**Table 8**
Correlations for frequency in yr 1 establishment (Y1), yr 2 (Y2), yr 3 (Y3), yr 4 (Y4), yr 5 (Y5). Top diagonal is the Malta, ID location. The bottom diagonal is the Tintic, UT location.

| Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|
| 0.4783 | 0.3407 | 0.3098 | 0.0634 |
| <.0001 | 0.0020 | 0.0052 | 0.5758 |
| 1.0000 | 0.8364 | 0.7407 | 0.3605 |
| | <.0001 | <.0001 | 0.0010 |
| 0.6089 | 1.0000 | 0.8719 | 0.5690 |
| <.0001 | | <.0001 | <.0001 |
| 0.4770 | 0.5364 | 1.0000 | 0.6637 |
| <.0001 | <.0001 | | <.0001 |
| 0.2586 | 0.2541 | 0.7882 | 1.0000 |
| 0.0175 | 0.0197 | <.0001 | |

### Stand Persistence

Plants/m$^2$ declined ($P < 0.05$) in all species from 2005 to 2009 (see Table 7). Within species, the decline in plants/m$^2$ ranged from 3.9 to 7.7 in western and slender wheatgrasses, respectively. By 2009, plants/m$^2$ in crested (18 ± 1.85), Siberian (21 ± 1.64), Snake River (12 ± 1.06), and western wheatgrass (10 ± 0.22) were similar (see Table 7). Five yr post planting, no differences were observed between cultivars within species (see Table 7). Observed correlations between 2005 and 2006 ($r = 0.48$; $P < 0.0001$), 2007 ($r = 0.34$; $P = 0.002$), 2008 ($r = 0.31$; $P = 0.005$), and 2009 ($r = 0.06$; $P = 0.576$) were observed (Table 8).

## Tintic, Utah

### Seedling Establishment

Differences ($P < 0.05$) were observed between species for seedlings/m$^2$ (see Tables 3 and 9). Slender wheatgrass at 20 ± 0.06 seedlings/m$^2$ had more ($P < 0.05$) than bluebunch wheatgrass (13 ± 0.13), basin wildrye (13 ± 0.02), crested wheatgrass (8 ± 0.04), Siberian wheatgrass (12 ± 0.37), thickspike wheatgrass (10 ± 0.02), and western wheatgrass (10 ± 0.06) (see Table 9). Seedlings/m$^2$ varied ($P < 0.05$) within bluebunch, slender, Snake River, western wheatgrasses, and basin wildrye cultivars (see Table 9). Bluebunch wheatgrass P-7 at 22 ± 0.13 seedlings/m$^2$ had more ($P < 0.05$) than Anatone (5 ± 0.19) and Goldar (12 ± 0.05). FirstStrike slender wheatgrass had more ($P < 0.05$) seedlings/m$^2$ than either Pryor (17 ± 0.09) or San Luis (15 ± 0.14) wheatgrass. Secar Snake River wheatgrass had significantly more ($P < 0.05$) seedlings/m$^2$ compared with that of Discovery. Western wheatgrass cultivars Arriba and Rosana had greater ($P < 0.05$) seedlings/m$^2$ than Recovery (Table 8). Trailhead II basin wildrye had more seedlings/m$^2$ (24 ± 0.14) than Trailhead (12 ± 0.03), Magnar (2 ± 0.16), or Continental (12 ± 0.13).

**Table 9**
Means and trends in plants/m$^2$ of 9 grass species across 5 yr at Tintic, UT from 2010 to 2014.

| Species | Plants m$^{-2}$ | | | | | Slope[1] | Trends† | |
|---|---|---|---|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 | 2014 | b | Linear | Quad. |
| Bottlebrush ST | 16 AB | 38 AB | 35 AB | 20 CD | 18 EF | −1.4 | 1 ns | 79 ** |
| Toe Jam Creek | 17 a | 39 a | 31 a | 28 a | 26 a | 0.6 | 12 ns | 59 ** |
| Fish Creek | 15 a | 38 a | 39 a | 13 b | 10 b | −3.4 | 0 ns | 75 ** |
| Bluebunch WG | 13 B | 30 BC | 27 BCD | 32 B | 32 B | 3.9 | 57 ** | 16 ** |
| Anatone | 5 b | 15 b | 15 b | 24 b | 24 b | 4.7 | 64 ** | 0 ns |
| Goldar | 13 a | 35 a | 33 a | 32 ab | 37 a | 4.4 | 38 ** | 36 ** |
| P-7 | 22 a | 40 a | 35 a | 40 a | 34 a | 2.4 | 52 ** | 20 ns |
| Basin WR | 13 B | 29 C | 23 D | 26 BC | 25 CD | 2.3 | 40 ** | 29 ** |
| Continental | 12 b | 31 a | 27 a | 32 a | 29 a | 3.5 | 60 ** | 18 ns |
| Magnar | 2 c | 15 b | 5 b | 8 b | 11 b | 1.3 | 3 ns | 22 ns |
| Trailhead | 12 b | 30 a | 27 a | 31 a | 26 a | 2.8 | 60 ** | 24 ** |
| Trailhead II | 24 a | 39 a | 35 a | 34 a | 34 a | 1.5 | 27 * | 49 ** |
| Crested WG − Hycrest II | 8 B | 32 CD | 22 CD | 24 BC | 28 BCD | 3.3 | 22 * | 34 ** |
| Siberian WG − Vavilov II | 12 B | 30 ABC | 28 ABCD | 22 BC | 27 BCDE | 2.2 | 16 ns | 69 ** |
| Slender WG | 20 A | 41 A | 38A | 27 BC | 15 F | −2.3 | 3 ns | 53 ** |
| FirstStrike | 27 a | 48 a | 38 a | 37 a | 24 a | −1.7 | 5 ns | 34 ** |
| Pryor | 17 b | 37 b | 40 a | 28 a | 15 b | −1.2 | 13 ** | 51 ** |
| San Luis | 15 b | 37 b | 36 a | 15 b | 6 c | -3.9 | 0 ns | 60 ** |
| Snake River WG | 16 AB | 32 ABC | 33 ABC | 32 AB | 32 ABC | 3.2 | 58 ** | 33 ** |
| Discovery | 9 b | 33 a | 31 a | 32 a | 34 a | 4.9 | 49 ** | 31 ** |
| Secar | 23 a | 30 a | 35 a | 32 a | 29 a | 1.5 | 67 * | 31 ns |
| Thickspike WG | 10 B | 29 BC | 32 ABC | 32 B | 23 DE | 3.0 | 68 ** | 28 ** |
| Bannock | 11 a | 29 a | 38 a | 40 a | 29 a | 4.8 | 87 ** | 13 * |
| Bannock II | 11 a | 34 a | 29 a | 37 a | 28 a | 3.5 | 65 ** | 15 * |
| Critana | 8 a | 25 a | 28 a | 19 b | 14 b | 0.7 | 26 ** | 64 ** |
| Western WG | 10 B | 39 A | 41 A | 42 A | 42 A | 6.5 | 63 ** | 25 ** |
| Arriba | 14 a | 36 b | 41 b | 41 a | 41 a | 5.9 | 67 ** | 23 ** |
| Recovery | 6 b | 38 ab | 36 ab | 42 a | 41 a | 7.4 | 62 ** | 19 ** |
| Rosana | 12 a | 43 a | 46 a | 43 a | 43 a | 6.4 | 57 ** | 34 ** |

† Orthogonal polynomial trends expressed as a percent of years' sum of squares due to linear effects. Values followed by a different letter are significantly different at $P < 0.05$. Uppercase letters denote significance among species. Lowercase letters denote significance within species.
* Significant at the 0.05 level of probability.
** Significant at the 0.01 level of probability.
1 Regression coefficients of plants m$^{-2}$.

*Stand Persistence*

Plants/m$^2$ increased from 2010 to 2014 in all species except bottlebrush squirreltail and slender wheatgrass (see Table 9). Contributing to the decreasing plants/m$^2$ were Fish Creek bottlebrush squirreltail (−3.4 plants/year), FirstStrike (−1.7), Pryor (−1.2), and San Luis (−3.9) slender wheatgrass. Improved bluebunch wheatgrass plant materials P-7 and Goldar had more plants/m$^2$ than source-identified Anatone bluebunch wheatgrass (see Table 9). Magnar basin wildrye had fewer ($P < 0.05$) plants/m$^2$ than the other basin wildrye cultivars. Newer cultivars of thickspike wheatgrass Bannock and Bannock II had more plants/m$^2$ in 2014 than Critana. Despite being significant ($P \leq 0.025$), correlation values were all less than $r = 0.60$ when comparing 2010 with 2011, 2012, 2013, and 2014 (see Table 8). As with other locations, observed correlations in yr 1 and 2 are not good indicators of plants/m$^2$ in yr 4 and 5 (see Table 8).

## Discussion

Establishing perennial bunchgrasses from seed has proven difficult, particularly at low elevations and with native species (Robertson et al., 1966; Clements et al., 2017), and attempts to establish most species are often unsuccessful (Pyke et al., 2003; Clements et al., 2017). Evans (1961) and later others (Chambers et al., 2007; Davies, 2008; Hardegree et al., 2016) attributed the lack of success in bunchgrass establishment to their inability to compete for water and nutrients with invasive annual grasses at the seedling stage. Factors affecting seedling establishment include germination, seed placement, and the frequent occurrence of soil crusts (Madsen et al., 2012) observed frequently on range sites. Madsen et al. (2012) reported that agglomerating multiple seeds of bluebunch wheatgrass into a single pellet increased emergence and biomass when seeded in clay soils in the greenhouse. Site preparation via cultivation combined with two herbicide applications, which initially removed competing vegetation before planting, likely contributed to the high density of observed seedlings in the first yr after planting. We observed an increase in seedling density from Y1 to Y2 at all locations but Malta, Utah. The observed decline likely resulted from a 26% increase in MAP during 2004 (seeding) followed by 3 yr of 8%, 31%, and 40% reduction in MAP during Y1, Y2, and Y3, respectively. Observed declining trends in plants/m$^2$ at Malta, Utah correspond to reports by Humphrey and Schupp (2004), where at 192 mm MAP site bottlebrush squirreltail plants failed to survive after Y2. Conversely, near-average or above AAP (see Table 2; Fig. 1) following seeding at Beaver, Utah, Tintic, Utah, and Cheyenne, Wyoming likely influenced the observed increase in plants/m$^2$ from Y1 to Y2. In our study, plants/m$^2$ in Y1 and Y2 were not strong predictors of plants/m$^2$ at Y4 and Y5 (see Tables 5 and 8), suggesting that to adequately measure seeding success, observations need to be made at a minimum of 4 yr post planting.

Still one of the most frequently asked questions by practitioners is what species should I seed on arid and semiarid rangelands? Failure to seed species that lack rapid establishment and long-term persistence frequently results in the lack of cheatgrass suppression in many regions of the Great Basin (Menakis et al., 2003; Boyte et al., 2016; Clements et al., 2017) and Wyoming sagebrush ecosystems, leading to once-native plant communities crossing a biotic threshold where ecosystem function and stability is impaired (Pellant, 1990; Monsen, 1992; Brooks and Pyke, 2001; Chambers et al., 2014). In our study, a significant species-by-environment interaction was observed, suggesting that not one species established and/or persisted uniformly across study sites, confounding the question regarding which species to plant. Contributing to the species-by-location interactions are random environmental factors so often observed as described earlier. For example, a 26% increase in precipitation over MAP at the Malta, Idaho site the year of

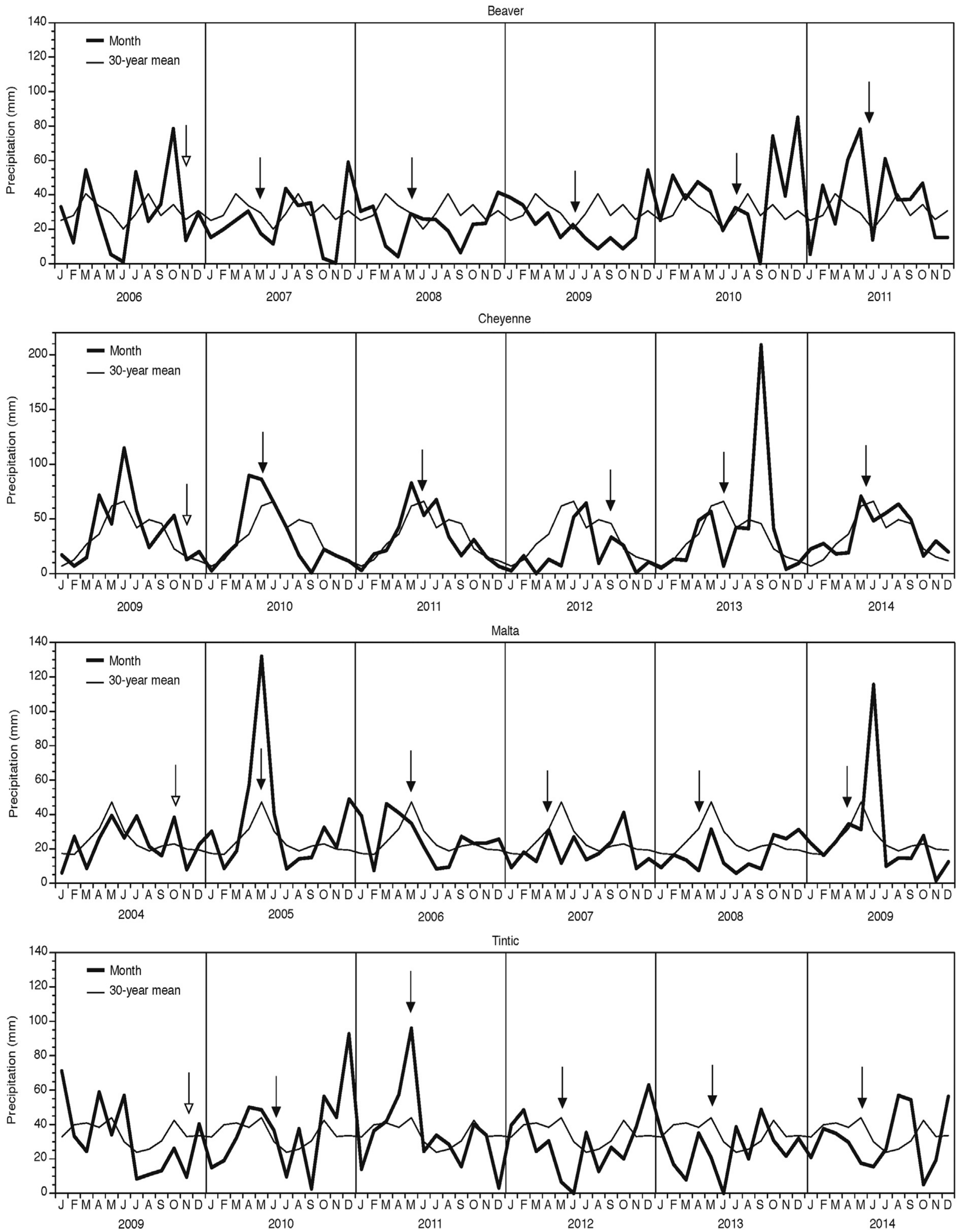


**Figure 1.** Monthly and long-term mean precipitation for the four study locations: Beaver, Cheyenne, Malta, and Tintic. The *thin solid line* represents the 30-yr mean (1981 − 2010), and the *thick solid line* represents the monthly precipitation in the given year. *Open arrows* are planting dates. *Solid arrows* are evaluation dates. Data last accessed 22 January, 2016 at http://prism.oregonstate.edu

seeding resulted in all species establishing; however, this site experienced average or below-average MAP during the next 5 yr (see Table 2), resulting in declining plant densities of all species.

Within our study environment, 290 − 415 mm MAP, there were native grasses that exhibited similar establishment, when Y1 plant/m$^2$ were analyzed over four locations (analysis not shown) when compared with crested (30 ± 0.15 plants/m$^2$) and Siberian (32 ± 0.15) wheatgrasses. They include Indian ricegrass (32 ± 0.10 plants/m$^2$), bottlebrush squirreltail (29 ± 0.07), slender (27 ± 0.05), bluebunch (26 ± 0.05), Snake River (24 ± 0.08), and thickspike (22 ± 0.05) wheatgrasses. Robins et al. (2013) reported stand establishment values of 43 − 79% for 18 grasses across 34 locations and concluded that plant persistence on sites receiving < 310 mm MAP was more of a problem than seedling establishment. Basin wildrye and western wheatgrass had significantly fewer seedlings/m$^2$ than crested and Siberian wheatgrass at Y1. Within species and over locations, cultivars/germplasms with seedling/m$^2$ similar to Vavilov II Siberian wheatgrass (32) were bottlebrush squirreltail (cv. Toe Jam Creek [31 ± 0.17 seedlings/m$^2$], Sand Hollow [29 ± 0.26], and Fish Creek [28 ± 0.17]); bluebunch wheatgrass (cv. P_7 [32 ± 0.13] and Goldar [29 ± 0.17]); slender wheatgrass (cv. FirstStrike [39 ± 0.13], Revenue [44 ± 0.51], and San Luis [25 ± 0.17]); Snake River wheatgrass (cv. Secar [27 ± 0.13]); basin wildrye (cv. Trailhead II [30 ± 0.26], Trailhead [24 ± 0.17], and Continental [20 ± 0.26]); Thickspike wheatgrass (cv. Bannock [26 ± 0.26], Sodar [39 ± 0.51], and Schwendimar [34 ± 0.51]); and Indian ricegrass (cv. White River [44 ± 0.26] and Rimrock [33 ± 0.26]). Cultivars/germplasms with fewer than 20 seedlings/m$^2$ were Discovery Snake River, Bannock II thickspike, Anatone bluebunch, Charleston Peak and Pryor slender, and Rodan, Recovery, Rosana, and Arriba western wheatgrass.

Previous literature has demonstrated the importance of seed germination and seedling establishment, but plant persistence, once established, is just as important. Failure of a seedling to mature into an adult plant will have the same impact (i.e., continued cheatgrass dominance) on the ultimate success of rangeland seedings. Clements et al. (2017) reported that establishment of perennial grasses reduced aboveground cheatgrass densities by > 93%, thus decreasing the chance of reoccurring wildfires and improving the chance that critical browse species can return to the site and improve wildlife resources. In our study, Siberian (cv. Vavilov II) and crested (Hycrest II) wheatgrasses declined in plants/m$^2$ from Y1 to Y5; however, they ranked at the top when compared with the other grasses studied. Increases in plants/m$^2$ from Y1 to Y5 were observed in all western wheatgrass cultivars in part from poor seed germination and seedling vigor during the establishment year (Jensen et al., 2001) and the presence of strong rhizomes, which by Y5 can dominate the site, becoming a monoculture. Native wheatgrasses Snake River, thickspike, and bluebunch experienced little to no change in plants/m$^2$ from Y1 to Y5 across the four locations. Plants/m$^2$ declined significantly in bottlebrush squirreltail, basin wildrye, slender wheatgrass, and Indian ricegrass from Y1 to Y5.

The selection of plant materials, planting procedures, and presite and postsite treatments all influence the success of rangeland seedings and have been well studied with varying viewpoints. This research provides land managers with plant material options on range sites with MAP between 290 and 415 mm. However, further research is needed to achieve greater establishment and persistence of native grasses on rangelands that have MAP < 300 mm.

## Implications

Evaluation of perennial cool-season grass species for establishment and trends in persistence provides important information for land mangers when making decisions concerning what species to plant on revegetation projects, similar to our study sites and land preparations. Within most species, we did not observe significant changes in the ability of selected plant materials to establish and/or persist better than the native grasses not selected. However, within the study we were able to identify species and cultivars/germplasms within species that under our site conditions were able to establish equally to crested and Siberian wheatgrasses.

An appropriate seed mix needs to include a combination of species that as an aggregate have the ability to establish quickly, persist, and be competitive against annual invasive weeds. It is important to note that this study looked at the establishment and persistence of species, not how the different species suppressed cheatgrass or other invasive weeds. Increased stand density is positively correlated with a reduction in cheatgrass density. Clements et al. reported that a crested wheatgrass frequency of 9.6 plants/m$^2$ was successful at reducing cheatgrass cover. Early seral species that establish quickly, such as bottlebrush squirreltail and slender wheatgrass, but are frequently short lived but may play a critical role in stabilizing soils and provide the first line of defense against further increases of cheatgrass. Candidate native grasses capable of rapid establishment include bottlebrush squirreltail cultivars Toe Jam Creek and Fish Creek and slender wheatgrass cultivars FirstStrike and Revenue. Indian ricegrass continues to rank among the lowest in establishment and persistence, in part because it has a narrow geographical adaptation and is frequently planted outside that (Barkworth, 2007). However, if it is going to be used, the cultivar White River establishes and persists better than Rimrock and Nezpar. Native grass cultivars of thickspike wheatgrass (cv. Sodar, Schwendimar, Bannock, Bannock II, and Critana); Snake River wheatgrass (cv. Discovery and Secar); western wheatgrass (cv. Rosana, Recovery, Arriba, Rodan, and Barton); basin wildrye (cv. Continental, Trailhead II, and Trailhead); and bluebunch wheatgrass (cv. P-7, Anatone, and Goldar) had plant densities at Y5 similar to Siberian and crested wheatgrasses. This study provides data describing seedling establishment and plant persistence of native grasses that establish and persist similar to Siberian and crested wheatgrass and should be considered as important seed mix components when MAP ranges between 290 and 415 mm.

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## References

Alderson, J., Sharp, W.C., 1994. Grass varieties in the United States. Agriculture handbook. US Department of Agriculture, Washington, DC, USA.
Allen, P.S., Debaena_Gill, S.B., Meyer, S.E., 1994. Regulation of germination timing in facultatively fall-emerging grasses. In: Monsen, S.B., Kitchen, S.G. (Eds.), Proceedings of Ecology and Management of Annual Rangelands. General Technical Report INT-GTR-313, pp. 215–219 Ogden, UT, USA.
Anonymous, 1977. Arriba western wheatgrass. L. L. P. M. C. USDA-Natural Resources Conservation Service, Los Lunas, NM, USA.
Asay, K.H., Horton, W.H., Jensen, K.B., Palazzo, A.J., 2001. Merits of native and introduced Triticeae grasses on semiarid rangelands. Canadian Plant Science 81, 45–52.
Atwater, D.Z., 2012. Interplay between competition and evolution in invaded and native plant communities. [Ph.D. dissertation]. University of Montana, Missoula, MT, USA.
Atwater, D.Z., James, J.J., Leger, E.A., 2015. Seedling root traits strongly influence field survival and performance of a common bunchgrass. Basic and Applied Ecology 16, 128–140.
Barker, R.E., Berdahl, J.D., Jacobson, E.T., 1984. Registration of Rodan western wheatgrass. Crop Science 24, 1215–1216.
Barkworth, M.E., 2007. Achnatherum P. Beauv. In: Barkworth, M.E., Capels, K.M., Long, S., Anderton, L.K., Piep, M.B. (Eds.), Flora of North America, vol. 24. Magnoliophyta: Commelinidae (in part): Poaceae, part 1. Oxford University Press, Oxford, England, and New York, NY, USA, pp. 114–142.
Bleak, A.T., Frischknecht, N.C., Plummer, A.P., Eckert, R.E., 1965. Problems in artificial and natural revegetation of the arid shadscale vegetation zone of Utah and Nevada. Journal of Range Management 18, 59–65.
Booth, D.T., Howard, C.G., Mowery, C.E., 1980. "Nezpar" Indian ricegrass: description, justification for release, and recommendations for use. Rangelands Archives 2, 53–54.
Boyte, S.P., Wylie, B.K., Major, D.J., 2016. Cheatgrass percent cover change: comparing recent estimates to climate change–driven predictions in the Northern Great Basin. Rangeland Ecology & Management 69, 265–279.
Brooks, M.L., Pyke, D.A., 2001. Invasive plants and fire in the deserts of North America. In: Galley, K.E.M., Wilson, T.P. (Eds.), Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. I I, Tallahassee, FL.
Cash, S.D., Majerus, M.E., Scheetz, J.C., Holzworth, L.K., Murphy, C.L., Wichman, D.M., Bowman, H.F., Ditterline, R.L., 1998. Registration of "Trailhead" basin wildrye. Crop Science 38, 278.
Chambers, J.C., Bradley, B.A., Brown, C.S., D'Antonio, C.M., Germino, M.J., Grace, J.B., Hardegree, S.P., Miller, R.F., Pyke, D.A., 2014. Resilience to stress and disturbance, and resistance to *Bromus tectorum* L. invasion in cold desert shrublands of western North America. Ecosystems 17, 360–375.
Chambers, J.C., Roundy, B.A., Blank, R.R., Meyer, S.E., Whittaker, A., 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? Ecological Monographs 77, 114–145.
Clements, C.D., Harmon, D.H., Blank, R.R., Weltz, M., 2017. Improving seeding success on cheatgrass-infested rangelands of northern Nevada. Rangelands 39, 174–181.

Crowle, W., 1970. Revenue slender wheat-grass. Canadian Journal of Plant Science 50, 748–749.
Davies, K.W., 2008. Medusahead dispersal and establishment in sagebrush steppe plant communities. Rangeland Ecology & Management 61, 110–115.
Davies, K.W., 2011. Plant community diversity and native plant abundance decline with increasing abundance of an exotic annual grass. Oecologia 167, 481–491.
Davies, K.W., Sheley, R.L., 2011. Promoting native vegetation and diversity in exotic annual grass infestations. Restoration Ecology 19, 159–165.
Douglas, D.S., Ensign, R.D., 1954. Sodar wheatgrass. Idaho Ag. Exp. Sta. Bull. 234. Level III and Level IV Ecoregions of the Continental United States, National Health and Environmental Effects Research Laboratory, U.S Environmental Protection Agency. Available at:. http://archive.epa.gov/wed/ecoregions/web/html/level_iii_iv-2.html, Accessed date: 22 March 2016
Evans, R., 1961. Effects of different densities of downy brome *(Bromus tectorum)* on growth and survival of crested wheatgrass *(Agropyron desertorum)* in the greenhouse. Weeds 9, 216–223.
Evans, R.A., Young, J.A., 1978. Effectiveness of rehabilitation practices following wildfire in a degraded big sagebrush downy brome community. Journal of Range Management 31, 185–188.
Gibbs, J., Young, G., Carlson, J., 1991. Registration of 'Goldar' bluebunch wheatgrass. Crop Science 31, 1708.
Gibson, A., Nelson, C.R., Atwater, D.Z., 2018. Response of bluebunch wheatgrass to invasion: differences in competitive ability among invader-experienced and invader-naïve populations. Functional Ecology 32 (7), 1857–1866.
Gomez, K.A., Gomez, A.A., 1984. Statistical procedures for agricultural research. second ed. John Wiley & Sons, Toronto, ON, Canada, pp. 229–233.
Hardegree, S.P., Sheley, R.L., Duke, S.E., James, J.J., Boehm, A.R., Flerchinger, G.N., 2016. Temporal variability in microclimate conditions for grass germination and emergence in the sagebrush steppe. Rangeland Ecology & Management 69, 123–128.
Howard, C., 1979. "Magnar" basin wildrye (Elymus cinereus Scribn. & Merr.) description, adaptation, use, culture, management, and seed production. Proceedings of 19th Annual Meeting of the Nevada Committee on Conservation Plant Materials. Nevada Agricultural Experiment Station, Reno, NV, USA, pp. 28–31.
Howard, T.G., Goldberg, D.E., 2001. Competitive response hierarchies for germination, growth, and survival and their influence on abundance. Ecology 82, 979–990.
Humphrey, L.D., Schupp, E.W., 2004. Competition and other barriers to establishment of a native perennial grass *(Elymus elymoides)* in alien annual grass *(Bromus tectorum)* communities. Journal of Arid Environments 58 (4), 405–422.
Fletcher, R.A., Callaway, R.M., Atwater, D.Z., 2016. An exotic invasive plant selects for increased competitive tolerance, but not competitive suppression, in a native grass. Oecologia 181, 499–505.
Jensen, K.B., Horton, H., Reed, R., Whitesides, R., 2001. Intermountain planting guide. Ag. Exp. Sta., Utah State Univ., Logan, UT, p. 104.
Jensen, K.B., Larson, S.R., Bushman, B.S., Robins, J.G., 2016. Notice of release of Charleston Peak Germplasm: selected class genetically manipulated track pre-variety germplasm. Native Plants Journal 17, 127–133.
Jensen, K.B., Larson, S.R., Waldron, B.L., Robins, J.G., 2009a. "Hycrest II," a new crested wheatgrass cultivar with improved seedling establishment. Journal of Plant Registrations 3, 57–60.
Jensen, K.B., Palazzo, A.J., Waldron, B.L., Bushman, B.S., 2007. Registration of "FirstStrike" slender wheatgrass. Journal of Plant Registrations 1, 24–25.
Jensen, K.B., Palazzo, A.J., Waldron, B.L., Robins, J.G., Bushman, B.S., Johnson, D.A., Ogle, D.G., 2009b. "Vavilov II," a new siberian wheatgrass cultivar with improved persistence and establishment on rangelands. Journal of Plant Registrations 3, 61–64.
John, L.S., Blaker, P., 1998. New native plant releases from the USDA–NRCS. Aberdeen, ID, USA: Plant Materials Center. Proceedings RMRS 138.
Jones, T.A., 2008. Notice of release of "Discovery" Snake River wheatgrass. Native Plants Journal 9, 99–101.
Jones, T.A., Larson, S.R., Nielson, D.C., Young, S.A., Chatterton, N.J., Palazzo, A.J., 2002. Registration of P-7 bluebunch wheatgrass germplasm. Crop Science 42, 754–1755.
Jones, T.A., Majerus, M.E., Scheetz, J.G., Holzworth, L.K., Nielson, D.C., 1998a. Registration of 'Rimrock' Indian ricegrass. Crop Science 38, 539–540.
Jones, T.A., Nielson, D.C., Larson, S.R., Johnson, D.A., Monaco, T.A., Caicco, S.L., Ogle, D.G., Young, S.A., 2004a. Registration of Fish Creek bottlebrush squirreltail germplasm. Crop Science 44, 879–—1880.
Jones, T.A., Nielson, D.C., Larson, S.R., Johnson, D.A., Monaco, T.A., Caicco, S.L., Ogle, D.G., Young, S.A., Carlson, J.R., 2004b. Registration of Toe Jam Creek bottlebrush squirreltail germplasm. Crop Science 44, 1880–1881.
Jones, T.A., Nielson, D.C., Ogle, D.G., Johnson, D.A., Young, S.A., 1998b. Registration of Sand Hollow squirreltail germplasm. Crop Science 38, 286.
Jones, T.A., Parr, S.D., Winslow, S.R., Rosales, M.A., 2009. Notice of release of "Continental" Basin Wildrye. Native Plants Journal 10, 57–61.
Jones, T.A., Winslow, S.R., Parr, S.D., Memmott, K.L., 2010. Notice of release of White River germplasm Indian ricegrass. Native Plants Journal 11, 133–136.
Leger, E.A., 2008. The adaptive value or remnant native plants in invaded communities: An example from the Great Basin. Ecological Applications 18, 1226–1235.
Mangla, S., Sheley, R.L., James, J.J., Radosevich, S.R., 2011. Role of competition in restoring resource poor arid systems dominated by invasive grasses. Journal of Arid Environment 75, 487–493.
Majerus, M., Scheetz, J., Holzowth, L., 1991. Pryor slender wheatgrass, a conservation plant for Montana and Wyoming. Agricultural leaflet. USDA-SCS, Plant Materials Center, Bridger, MT, USA 1 p.
MacDonald, L. 1997. Wildfire rehabilitation in Utah. In: B., M.S., R., S. and [COMPS.] (eds.), Proceedings-Ecology and Management of Pinyon-Juniper communities within the interior West: Sustaining and restoring a diverse ecosystem; Provo, UT, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. P. 410-411.
Madsen, M.D., Davies, K.W., Williams, C.J., Svejcar, T.J., 2012. Agglomerating seeds to enhance native seedling emergence and growth. Journal of Applied Ecology 49, 431–438.
McDonald, J.H., 2014. Handbook of biological statistics. third ed. Sparky House Publishing, Baltimore, MD, USA.
Melgoza, G., Nowak, R.S., Tausch, R.J., 1990. Soil water exploitation after fire: competition between *Bromus tectorum* and 2 native species. Oecologia 83, 7–13.
Menakis, J.P., Osborne, D., Miller, M., 2003. Mapping the cheatgrass-caused departure from historical natural fire regimes in the Great Basin, USA. In: Omi, P.N., Joyce, L.A. (Eds.), Fire, fuel treatments, and ecological restoration: conference proceedings; 16—18 April 2002. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA, pp. 281–287.
Miller, T.E., Werner, P.A., 1987. Competative effects and responses between plant species in a first-year old field community. Ecology 68, 1201–1210.
Monsen, S.B., 1992. The competitive influences of cheatgrass on site restoration. Symposium on Ecology, Management, and Restoration of Intermountain Annual Rangelands, Boise, ID, USA, 18—21 May 1992.
Monsen, S.B., Memmott, K., Shaw, N., Pellant, M., Young, S., Ogle, D., St John, L., 2003. Notice to release *Anatone germplasm* bluebunch wheatgrass (selected class natural population). US Forest Service Rocky Mountain Research Station, Shrub Sciences Laboratory, Provo, UT, USA, p. 10.
Morrison, K.J., Kelley, C.A., 1981. Secar bluebunch wheatgrass. Cooperative Extension, College of Agriculture, Washington State University, Pullman, WA, USA, p. 3 EB 0991.
Omernik J. M. 1987. Ecoregions of the conterminous United States. Map (scale 1: 7,500,000). Annals of the Association of American Geographers 77:118–125.
Ott, J.E., McArthur, E.D., Sanderson, S.C., 2001. Plant community dynamics of burned and unburned sagebrush and pinyon-juniper vegetation in west-central Utah. In: McArthur, E.D., Fairbanks, D.J. (Eds.), Shrubland ecosystem genetics and biodiversity: proceedings; 2000 June 13-15. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, USA, pp. 177–191.
Pellant, M., 1990. The cheatgrass-wildfire cycle—are there any solutions? In: McArthur, E.D., Romney, E.M., Smith, S.D., Tueller, P.T. (Eds.), Proceedings of a symposium on cheatgrass invasion, shrub die-off, and other aspects of shrub biology and management. US Forest Service, International Research Station, General Technical Report. INT-276, Ogden, UT, USA, pp. 11–18
Pickford, G.D., 1932. The influence of continued heavy grazing and of promiscuous burning on spring-fall ranges in Utah. Ecology 13, 159–171.
PRISM Climate Group, O. S. U, 2016. Available at:. http://prism.oregonstate.edu, Accessed date: 22 January 2016.
Pyke, D.A., McArthur, T.O., Harrison, K.S., Pellant, M., 2003. Coordinated Intermountain Restoration Project-fire, decomposition and restoration. In: Palmer, A.R., Milton, S.J., Kirkman, K.P., Kerley, G.I.H., Hurt, C.R., Brown, C.J. (Eds.), Proceedings of the VIIth Intermountain Rangelands Congress. N. Allsopp, Durban, South Africa, pp. 116–124.
Richards, R.T., Chambers, J.C., Ross, C., 1998. Use of native plants on federal lands: Policy and practice. Journal of Range Management 51, 625–632.
Robertson, J.H., Pearce, C.K., 1945. Artificial reseeding and the closed community. Northwest Science 14, 38–66.
Robertson, J.H., Eckert, R.E., Bleak, A.T., 1966. Responses of grasses seeded in an *Artemisia tridentate* habitat in Nevada. Ecology 47, 187–194.
Robins, J.G., Bushman, B.S., 2016. Notice of release of "Trailhead II" basin wildrye. Native Plants Journal 17, 273–280.
Robins, J.G., Jensen, K.B., Bushman, B.S., 2015. Notice of release of "Bannock II" thickspike wheatgrass. Native Plants Journal 16, 259–264.
Robins, J.G., Jensen, K.B., Jones, T.A., Waldron, B.L., Peel, M.D., Rigby, C.W., Vogel, K.P., Mitchell, R.B., Palazzo, A.J., Cary, T.J., 2013. Stand establishment and persistence of perennial cool-season grasses in the Intermountain West and the Central and Northern Great Plains. Rangeland Ecology & Management 66, 181–190.
Rowe, C.L.J., Leger, E.A., 2011. Competitive seedlings and inherited traits: A test of rapid evolution of Elymus mutlisetus (big squirreltail) in response to cheatgrass invasion. Evolutionary Application 4, 485–498.
Rowe, L.J., Leger, E.A., 2012. Seed source affects establishment of *Elymus multisetus* in postfire revegetation in the Great Basin. Western North American Naturalist 72, 543–553.
SAS_Institute, 1999. SAS/STAT users guide version 6. fourth ed. SAS Institute, Cary, NC, USA.
Stroh, J., Thornburg, A., Ryerson, D., 1972. Registration of *Critana thickspike* wheatgrass (Reg. No. 9). Crop Science 12, 394.
USDA-NRCS, 2016a. Ecological Site Description. Available at:. https://esis.sc.egov.usda.gov/Welcome/pgReportLocation.aspx?type=ESD, Accessed date: 22 January 2016.
USDA-NRCS, 2016b. The PLANTS Database. http://plants.usda.gov, Accessed date: 1 February 2016.
USDA-SCS, 1984. Notice of the naming and release of "San Luis" slender wheatgrass *(Agropyron trachycaulus)*.
[USDI BLM] USDI Bureau of Land Management, 1999. Sampling vegetation attributes. Technical reference 1734-4. USDI Bureau of Land Management, Denver, CO, USA.
Vogel, K.P., Masters, R.A., 2001. Frequency grid—a simple tool for measuring grassland establishment. Journal of Range Management 54, 653–655.
Waldron, B.L., Jensen, K.B., Palazzo, A.J., Cary, T.J., Robins, J.G., Peel, M.D., Ogle, D.G., St John, L., 2011. "Recovery," a new western wheatgrass cultivar with improved seedling establishment on rangelands. Journal of Plant Registrations 5, 367–373.