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Abstract

The choice of plant materials is an important component of revegetation following disturbance. To determine the utility and effectiveness of various perennial grass species for revegetation on varied landscapes, a meta analysis was used to evaluate the stand establishment and persistence of 18 perennial cool-season grass species in 34 field studies in the Intermountain and Great Plains regions of the United States under monoculture conditions. Combined across the 34 studies, stand establishment values ranged from 79% to 43% and stand persistence values ranged from 70% to 0%. Intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D. R. Dewey), tall wheatgrass (*Thinopyrum ponticum* [Podp.] Z.-W. Liu & R.-C. Wang), crested wheatgrass (*Agropyron* spp.), Siberian wheatgrass (*Agropyron fragile* [Roth] P. Candargy), and meadow brome (*Bromus riparius* Rehmann) possessed the highest stand establishment (≥ 69%). There were no significant differences among the 12 species with the largest stand persistence values. Basin wildrye (*Leymus cinereus* (Scribn. & Merr.) Á. Löve), Altai wildrye (*Leymus angustus* [Trin.] Pilg.), slender wheatgrass (*Elymus trachycaulus* [Link] Gould ex Shinners), squirreltail (*Elymus* spp.), and Indian ricegrass (*Achnatherum hymenoides* [Roem. & Schult.] Barkworth) possessed lower stand persistence (≤ 32%) than the majority of the other species, and Indian ricegrass (0%) possessed the lowest stand persistence of any of the species. Correlations between environmental conditions and stand establishment and persistence showed mean annual study precipitation to have the most consistent, although moderate effect ($r = \sim 0.40$) for establishment and persistence. This relationship was shown by the relatively poor stand establishment and persistence of most species at sites receiving less than 310 mm of annual precipitation. These results will be a tool for land managers to make decisions concerning the importance of stand establishment, stand persistence, and annual precipitation for revegetation projects on disturbed sites.

Key Words: environmental conditions, grass species, precipitation, revegetation

INTRODUCTION

Attempts to revegetate degraded lands in western North America began in the early 1900s and resulted in varying levels of success (Pickford 1932). Ecosystem degradation resulted in weakened ecological health and function, including loss of soil resources from erosion and loss of plant species diversity. This fed into the cycle of increasing annual plant invasion and fire disturbance. Invasive annual plants such as cheatgrass (*Bromus tectorum* L.) create unfavorable conditions for perennial vegetation by changing soil structure and properties (Norton et al. 2004, 2007). Reseeding these disturbed sites with genetically improved cultivars that establish in the presence of undesirable vegetation is often the most effective and economically feasible way to improve such sites (Asay et al. 2003).

Revegetation with introduced grasses, such as crested wheatgrass, became common because of better stand establishment, persistence, and weed suppression than perennial native grass species (Aguirre and Johnson 1991; Asay et al. 2001; Thacker et al. 2009). However, due to increasing desire and need for revegetation with perennial native grass species, efforts began to focus on development of improved plant materials of these species (Jones et al. 1991; Asay 1992).

Research entities from various US and state government agencies share a long history of developing and evaluating improved plant materials for rangeland revegetation in the western United States. Among the work carried out over the years, stand establishment and stand persistence data is available from over 30 studies at diverse ecological sites across the Great Plains and Intermountain regions of the United States. Although small components of these studies have been reported previously (Asay et al. 2001; Robins et al. 2007), a comprehensive analysis has not yet been published. Thus, the objectives of this study were to: 1) use a meta analysis to compile and analyze stand establishment and persistence of various plant materials of 18 cool-season, perennial grasses from 34 field studies; 2) determine the effect of climatic and environmental conditions on the stand establishment and persistence of these species; and 3) where possible, evaluate the performance of improved compared to standard plant materials.

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METHODS

Evaluation Sites and Data Collection

The dataset evaluated came from 34 field studies located at sites across the Intermountain West and northern and central Great Plains areas of the United States. A few of the sites were used for more than one study (Table 1). Although the repeated use of some sites likely introduced covariance structure into the model, the studies at each site were not identical because studies were separated by years, different varieties were included in the different studies, and the climatic conditions were often very different for the studies at the same site (Table 1). Thus, the covariance created in the model by some repeated use of sites was considered less important than including the additional data from varieties and climatic conditions. The sites were located in seven states in the Intermountain and Great Plains regions of the United States and represented 12 plant adaptation regions (PARs; Vogel et al. 2005). The sites included a wide range of climatic and environmental conditions including precipitation, elevation, latitude, longitude, temperature, and soil type. The data set spans more than 20 yr (1983–2006).

Typical site preparation consisted of rototilling in the fall for degradation and removal of native plant vegetation, chemical fallow (glyphosate $2.3 \cdot L \cdot ha^{-1}$) the following summer, and cultivation followed by a roller or harrows prior to seeding in the fall. The majority of sites were seeded using either a John Deere flex planter with depth bands (Deere and Co, Moline, IL) or a Hegge cone seeder with depth control (Wintersteiger, Inc, Salt Lake City, UT). Sites were seeded in fall using a pure live seed seeding rate (based on germination) of one seed $linear \cdot cm^{-1}$ at a 0.64-cm depth. Using equal numbers of seeds for each species is commonly used in seeding evaluations with multiple species (Asay et al. 2001; Palazzo et al. 2005). Actual seeding rates ranged from 9 $kg \cdot ha^{-1}$ (Siberian wheatgrass) to 29 $kg \cdot ha^{-1}$ (Altai wildrye) with a mean of 16 $kg \cdot ha^{-1}$. The larger-seeded species, such as Altai wildrye, meadow brome, and RS wheatgrass (*Elymus hoffmannii* K. B. Jensen & K. H. Asay), had higher seeding rates on a $kg \cdot ha^{-1}$ basis. Emergence occurred in fall of the seeding year for the Nebraska sites, or the following spring for all other sites. Plot size varied depending on location, but ranged from approximately 4 m^2 to 6 m^2. Each trial was comprised of a randomized complete block design with either three or four blocks. Common seed sources could not be used for the same variety in each study due to the span of years involved in the work. However, in all cases seed was tested for germination to ensure proper seed rate on a pure live seed basis.

Stand establishment and stand persistence data were collected from 34 and 22 studies, respectively. Stand establishment was measured the first year after seeding and persistence was measured in the third year after seeding. Values for both measurements pertained just to the seeded species corresponding to each plot and were representative of monocultures. Prior to 1999, all data were collected using visual estimates of percent stand based on a 1 to 9 rating. Visual estimates were converted to a percentage by increasing the percentage by 12.5% for each numeric increase (1=0%, 5=50%, 9=100%). Subsequently, the method of Vogel and Masters (2001) was employed. A square frame with interior grids (15 cm^2) was used by counting the number of square grids within the frame that contained live, rooted plant material that had been seeded in each plot. This procedure was repeated twice in each plot and the value was then converted to a proportion. Because the visual and grid methods were not used simultaneously at a site, there was no way to estimate the correlation between the two methods.

Plant Materials

Eighteen cool-season grass species were included at some or all of the studies (Table 2). Not all species were included in each study. The number of species included in a study ranged from 2 to 16. Species were chosen according to seed availability and their expected adaptation to each site. The species were big squirreltail (*Elymus multisetus* M. E. Jones), bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), basin wildrye, Indian ricegrass, slender wheatgrass, Snake River wheatgrass (*Elymus wawawaiensis* J. Carlson & Barkworth), thickspike wheatgrass (*Elymus lanceolatus* [Scribn. & J. G. Sm.] Gould), western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), Altai wildrye, crested wheatgrass, intermediate wheatgrass, meadow brome, RS wheatgrass, Russian wildrye (*Psathyrostachys juncea* [Fisch.] Nevski), Siberian wheatgrass, smooth brome (*Bromus inermis* Leyss.), and tall wheatgrass. Crested wheatgrass and Russian wildrye were the only species included in all studies. Sixty-nine varieties (varieties or germplasms) were included in the analysis (Table 3). With the exception of Kazak Siberian wheatgrass, each of the varieties is officially released from a public or private entity and is (or has been) commercially available for rangeland revegetation.

Data Analysis

Data were analyzed using mixed model procedures. The main effects of species and variety nested within species (variety) were considered fixed. The main effects of study, blocks nested within study, and all interactions were considered random. The mixed procedure of the SAS Statistical software (Vers. 9.3, SAS, Inc, Cary, NC) was used for analysis. Statistical models for stand establishment and stand persistence were analyzed both within each study and across all studies. Due to nonnormality, data were arcsin-transformed prior to analysis and then reverse-transformed for presentation and discussion.

Least significant differences were estimated for each study individually and for the overall across study analysis. Due to the unbalanced nature of the data, least significant differences were estimated using the standard errors of a mean difference of each species when compared to crested wheatgrass, similar to the proposed methods of Jones (1988) and Dourleijn (1993). Crested wheatgrass was chosen as the check because it was one of only two species included in each study. All discussions of significance are based on a minimum critical value of $\alpha = 0.05$ unless otherwise noted.

RESULTS

Species and Varieties

Combined across the 34 studies, stand establishment values ranged from 79% (intermediate wheatgrass) to 43% (Indian

Table 1. Environmental and climatic characteristics for the 34 studies from which establishment and persistence data was collected for the species included in the study from 1983–2006.

Location	PAR[1]	Year planted	Soil type	Latitude	Longitude	Mean annual precipitation (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Elevation (m)
Colorado									
Turkey Creek	GPPDS5	1996	Neville–Rednun complex/ Rizozo–Neville complex	38.62	−104.88	446 (219–593)	16.7 (14.8–17.5)	0.9 (−0.1 to 1.4)	1 898
Idaho									
King Hill	IS6	2003	Lankbush–Lanktree complex	43.07	−115.14	300 (292–308)	17.2 (16.6–17.8)	3.8 (3.4 to 4.2)	1 131
Malta	IS5	1985	Declo silt loam	42.30	−113.20	280 (210–357)	16.6 (14.7–17.4)	0.2 (−1.6 to 0.6)	1 468
Malta	IS5	2004	Declo silt loam	42.30	−113.20	274 (193–376)	16.2 (15.7–17.1)	0.4 (−0.1 to 0.9)	1 468
Picabo	IS5	1985	Gooding–Gooding eroded– Hamrub complex	43.24	−114.24	330 (325–335)	13.4 (11.9–14.8)	−3.3 (−4.9 to −1.6)	1 507
Stone	IS5	1984	Mellor–Freedom complex	42.04	−112.67	337 (295–373)	15.5 (14.2–16.4)	−1.1 (−2.5 to 0.2)	1 408
Stone	IS5	1989	Mellor–Freedom complex	42.04	−112.67	258 (186–339)	16.2 (15.4–17.4)	−0.7 (−2.1 to 0.1)	1 408
Stone	IS5	2002	Mellor–Freedom complex	42.04	−112.67	310 (233–482)	16.0 (15.4–17.4)	0.2 (−0.8 to 1.2)	1 408
Montana									
Decker	GPPDS4	1984	McRae loam/ Midway silty clay loam	45.11	−106.93	300 (277–316)	15.7 (14.1–17.3)	−1.1 (−2.8 to 0)	1 109
Miles City	GPPDS3	1994	Havre loam	46.39	−105.89	296 (247–324)	15.4 (13.5–16.1)	0.5 (−0.8 to 1.4)	736
Miles City	GPPDS3	1999	Havre loam	46.39	−105.89	306 (271–363)	15.8 (15.1–16.7)	1.3 (0.5 to 2.3)	736
Nebraska									
Mead	PP5	1999	Sharpsburg silt loam	41.22	−96.48	689 (625–798)	17.0 (16.6–17.2)	3.9 (3.6 to 4.3)	364
Sidney	GPPDS4	1999	Duroc loam	41.38	−103.00	428 (274–528)	17.1 (16.8–17.7)	1.7 (1.1 to 2.2)	1 310
North Dakota									
Mandan	GPPDS4	1999	Parshall fine sandy loam	46.80	−100.77	474 (286–643)	12.9 (12.5–13.3)	−0.4 (−0.8 to 0.3)	510
Utah									
Beaver	NUM6	2006	Murdock silt loam	38.35	−112.59	312 (273–377)	17.0 (16.6–17.5)	0.8 (0.4 to 1.1)	1 971
Blue Creek	IS5	1984	Timpanogos silt loam	41.93	−112.44	397 (323–470)	14.4 (14.0–14.9)	−1.1 (−1.1 to −0.7)	1 564
Blue Creek	IS5	1989	Timpanogos silt loam	41.93	−112.44	306 (226–402)	16.5 (14.6–17.6)	0.1 (−1.1 to 1.1)	1 564
Blue Creek	IS5	1999	Timpanogos silt loam	41.93	−112.44	313 (278–356)	16.8 (15.8–17.4)	0.7 (−0.1 to 1.7)	1 564
Dugway	ISD6	1990	Medburn fine sandy loam	40.27	−112.82	209 (169–245)	17.4 (16.2–18.4)	2.1 (1.3 to 2.7)	1 615
Monticello	ISD6	1984	Begay fine sandy loam	38.30	−109.39	328 (155–416)	17.0 (15.8–17.9)	1.7 (1.3 to 2.5)	1 879
North Logan	SRM4	1986	Green Canyon gravelly loam/ Parley's silt loam	41.77	−111.78	426 (301–653)	15.1 (14.0–15.7)	2.2 (1.7 to 2.7)	1 509
North Logan	SRM4	1999	Green Canyon gravelly loam/ Parley's silt loam	41.77	−111.78	399 (357–437)	15.5 (14.5–16.1)	1.6 (0.7 to 3.0)	1 509
Promontory	ISD5	2003	Kearns silt loam	41.67	−112.48	310 (216–404)	17.1 (16.2–18.0)	2.2 (1.1 to 2.9)	1 287
Scipio	NUM6	2003	Unmapped	39.20	−112.24	397 (345–463)	17.4 (16.8–18.6)	2.4 (1.4 to 3.2)	1 772
Scipio	NUM6	2004	Unmapped	39.22	−112.20	409 (348–477)	16.9 (16.7–17.3)	2.3 (1.0 to 3.3)	1 831
Skull Valley #1	ISD6	1983	Tooele fine sandy loam	40.33	−112.78	254 (207–310)	16.7 (15.6–17.9)	2.1 (1.1 to 2.9)	1 435
Skull Valley #2	ISD6	1983	Berent–Hiko Peak complex	40.32	−112.90	372 (292–486)	16.1 (15.2–17.3)	2.4 (1.4 to 3.5)	1 689
Spring City	ISD5	2003	Denmark gravelly loam	39.51	−111.53	274 (249–298)	17.3 (16.7–17.9)	0.6 (0.2 to 1.0)	1 734
Washington									
Yakima	IS6	2002	Selah silt loam	46.85	−120.37	264 (177–347)	15.2 (14.9–15.6)	2.2 (1.5 to 2.8)	699
Wyoming									
Guernsey	GPPDS4	2002	Deight–Thirtynine–Glendo very fine sandy loam	42.40	−104.81	324 (265–384)	16.3 (16.2–16.5)	−0.1 (−0.5 to 0.3)	1 494
Guernsey	GPPDS4	2004	Mainter–Keeline fine sandy loam	42.25	−104.73	316 (248–401)	17.7 (16.8–18.1)	0.5 (−0.2 to 0.8)	1 323
Guernsey	GPPDS4	2005	Mitchell very fine sandy loam	42.24	−104.74	312 (248–401)	17.8 (16.8–18.1)	0.5 (−0.2 to 0.8)	1 396
Granger	IS4	1998	Unmapped	41.41	−110.38	194 (122–292)	13.6 (12.8–14.4)	−2.8 (−3.3 to −2.0)	2 101
Soda Lake	IS3	1991	Pinedale very bouldery– Noclios, extremely bouldery complex	42.94	−109.85	390 (280–490)	9.6 (7.9–10.9)	−6.3 (−7.6 to −5.7)	2 360

[1]PAR indicates Plant Adaptation Region (Vogel et al. 2005).

Table 2. Mean stand establishment and 3-yr stand persistence values with corresponding standard errors in parentheses for cool-season perennial grass species evaluated in a varying number of studies across the Great Plains and Intermountain regions of the United States. Mean values followed by different letters significantly differ at $P \leq 0.05$.

Species	Stand persistence (%)	Stand establishment (%)
Intermediate wheatgrass	70 (9) a	79 (7) a
Siberian wheatgrass	69 (8) a	70 (6) a–d
Crested wheatgrass	69 (7) a	71 (6) abc
Tall wheatgrass	66 (12) a	75 (9) ab
Meadow brome	64 (12) a	69 (9) a–d
Russian wildrye	60 (8) a	59 (6) c–g
Western wheatgrass	59 (8) a	58 (7) c–g
Smooth brome	55 (13) a	52 (9) d–h
Bluebunch wheatgrass	53 (10) ab	57 (7) d–g
RS wheatgrass	52 (10) ab	60 (8) c–f
Thickspike wheatgrass	51 (9) abc	64 (7) b–e
Snake River wheatgrass	49 (10) abc	52 (9) d–h
Basin wildrye	32 (11) bcd	46 (8) f–h
Slender wheatgrass	29 (12) cd	64 (9) b–e
Altai wildrye	29 (11) cd	49 (8) e–h
Squirreltail	25 (25) d	59 (12) c–g
Indian ricegrass	0 (25) e	43 (10) h

ricegrass) and stand persistence values ranged from 70% (intermediate wheatgrass) to 0% (Indian ricegrass) (Table 2). Intermediate wheatgrass, tall wheatgrass (75%), crested wheatgrass (71%), Siberian wheatgrass (70%), and meadow brome (69%) possessed the highest stand establishment (Table 2). There were no significant differences among the 12 species with the largest stand persistence values (Table 2). Basin wildrye (32%), Altai wildrye (29%), slender wheatgrass (29%), squirreltail (25%), and Indian ricegrass (0%) possessed lower stand persistence than the majority of the other species, and Indian ricegrass possessed the lowest stand persistence of any of the species (Table 2). Likely due to its rhizomatous nature, western wheatgrass was the only species that exhibited a marked increase of stand persistence (69%) compared to stand establishment (58%).

'Beefmaker' intermediate wheatgrass (86%) possessed higher stand establishment than 48 of the individual varieties (Table 3). This included higher stand establishment than each of the varieties corresponding to Altai wildrye, bluebunch wheatgrass, basin wildrye, Indian ricegrass, RS wheatgrass, Russian wildrye, smooth brome, Snake River wheatgrass, squirreltail, thickspike wheatgrass, and western wheatgrass. 'NU-ARS AC2' crested wheatgrass (80%) possessed higher stand persistence than 26 varieties, including all varieties corresponding to Altai wildrye, basin wildrye, Indian ricegrass, RS wheatgrass, slender wheatgrass, squirreltail, and thickspike wheatgrass (Table 3). 'Whitmar' bluebunch wheatgrass possessed stand persistence of 79%, but was only measured for stand persistence at one location, which limited the inference of this result.

Intermediate wheatgrass, tall wheatgrass, crested wheatgrass, Siberian wheatgrass, and meadow brome possessed the best potential to maximize both stand establishment and stand persistence. Although the majority of the varieties corresponding to these species possessed high stand establishment and persistence, there were exceptions. For example, 'Douglas' crested wheatgrass did not possess high stand establishment or persistence. Thus, care must be taken to choose not only the appropriate species, but also the appropriate variety for revegetation.

Influence of Climatic and Environmental Conditions

Although results from the overall analysis across all sites provide a baseline for comparisons, the underlying interaction between sites and species and varieties resulted in confounded findings. The sites for this analysis comprise a wide range of climatic and environmental conditions and represented 12 plant adaptation regions (Table 1).

Stand establishment was correlated ($P \leq 0.05$) with mean annual precipitation (r=0.42) and longitude (0.46), and stand persistence was correlated with mean annual precipitation (r=0.44), elevation (r=–0.51), longitude (0.49), and the year planted (0.63). Thus, more eastern, higher precipitation sites at lower elevations tended to have higher stand establishment and persistence values. For instance, the Mead, Nebraska site was the most eastern, received the highest precipitation, had the lowest elevation, and resulted in the highest stand establishment (98%) and stand persistence (83%) of any site. Although intuitively the most critical year would seem to be the establishment year, precipitation during the establishment at each site in this analysis was not associated with either stand establishment or stand persistence (data not shown). Because the correlation values were moderate to low, from a biological standpoint they suggested that environmental conditions affected stand establishment and persistence, but that they were not sufficient to explain differences in stand establishment and persistence.

Site Precipitation

The individual site results for each species are reported in Tables 4 and 5. However, due to the significant correlations between stand establishment and persistence and annual site precipitation, sites were partitioned into groups based on annual precipitation to allow further species performance inferences. The groups were low (< 310 mm), intermediate (310–389 mm), and high (> 389 mm) annual precipitation.

Crested wheatgrass, Siberian wheatgrass, RS wheatgrass, Russian wildrye, and thickspike wheatgrass were among the species with the highest stand establishment at a majority of the low precipitation sites where they were evaluated (Table 4). Intermediate wheatgrass, tall wheatgrass, and thickspike wheatgrass were the only species evaluated at multiple low precipitation sites that were not among the species with the lowest stand establishment at any site. Indian ricegrass, Snake River wheatgrass, western wheatgrass, and Altai wildrye were among the species with the lowest stand establishment at all, or the majority, of the low precipitation sites where they were evaluated. Bluebunch wheatgrass, crested wheatgrass, intermediate wheatgrass, and Siberian wheatgrass possessed high stand establishment at the majority of intermediate precipitation sites where they were evaluated. Slender wheatgrass, Snake River wheatgrass, western wheatgrass, basin wildrye and Russian

Table 3. Mean stand establishment and 3-yr stand persistence values with corresponding standard errors in parentheses for 69 cool-season perennial grass cultivars or prevariety germplasms evaluated in a varying number of evaluations across the Great Plains and Intermountain regions of the United States. Mean values followed by different letters significantly differ at $P \leq 0.05$.

Cultivar/Germplasm	Stand persistence (%)	Stand establishment (%)
NU-ARSAC2 Crested wheatgrass	80 (10) a	74 (9) a–i
Whitmar Bluebunch wheatgrass	79 (28) a	45 (17) p–v
Recovery Western wheatgrass	78 (10) a	65 (9) c–m
Beefmaker Intermediate wheatgrass	77 (11) a	86 (9) a
Manska Intermediate wheatgrass	76 (11) ab	79 (9) a–e
Jose Tall wheatgrass	76 (13) ab	79 (10) a–e
Hycrest II Crested wheatgrass	75 (8) ab	79 (7) a–e
CD II Crested wheatgrass	75 (9) ab	80 (7) abc
Hycrest Crested wheatgrass	74 (8) abc	77 (7) a–g
Vavilov II Siberian wheatgrass	74 (10) abc	78 (8) a–f
Rush Intermediate wheatgrass	74 (11) abc	81 (9) abc
Haymaker Intermediate wheatgrass	73 (11) abc	82 (9) ab
Flintlock Western wheatgrass	72 (10) a–d	68 (8) b–m
Mankota Russian wildrye	72 (10) a–d	66 (8) b–m
Oahe Intermediate wheatgrass	71 (11) a–e	82 (9) ab
Cache Meadow brome	71 (12) a–e	75 (11) a–i
Ephraim Crested wheatgrass	70 (9) a–e	64 (8) d–n
Manifest Intermediate wheatgrass	70 (11) a–e	78 (9) a–f
Fairway Crested wheatgrass	69 (9) a–f	63 (7) e–n
Reliant Intermediate wheatgrass	68 (11) a–g	80 (9) abc
P27 Siberian wheatgrass	68 (9) a–g	59 (7) i–r
Arriba Western wheatgrass	68 (9) a–g	55 (8) l–t
Vavilov Siberian wheatgrass	67 (9)a–h	70 (7) a–l
Lincoln Smooth brome	67 (14) a–h	57 (10) j–s
Kazak Siberian wheatgrass	66 (9) a–i	71 (7) a–l
Bozoisky II Russian wildrye	65 (8) a–i	65 (7) c–m
Nordan Crested wheatgrass	65 (8) a–i	64 (7) d–n
Rosana Western wheatgrass	65 (8) a–i	60 (7) h–q
Bozoisky-Select Russian wildrye	65 (8) a–i	57 (7) j–s
Rodan Western wheatgrass	65 (9) a–i	55 (8) l–t
Roadcrest Crested wheatgrass	64 (10) a–j	64 (8) d–n
Greenar Intermediate wheatgrass	63 (10) a–k	70 (8) a–l
Tetra-1 Russian wildrye	62 (10) a–k	67 (8)b–m
Barton Western wheatgrass	62 (11) a–k	44 (9) q–v
Regar Meadow brome	62 (13) a–k	65 (11) c–m
Vinall Russian wildrye	60 (9) a–l	53 (8) m–u
Alkar Tall wheatgrass	60 (12) a–l	73 (9) a–j
Platte Tall wheatgrass	60 (13) a–l	72 (10) a–k
Cabree Russian wildrye	59 (13) a–l	60 (13) h–q
Discovery Snake River wheatgrass	59 (15) a–l	62 (14) f–o
Tetracan Russian wildrye	58 (9) a–l	57 (8) j–s
Fleet Meadow brome	57 (13) a–m	68 (11) b–m
Luna Intermediate wheatgrass	56 (10) a–m	77 (8) a–g
Critana Thickspike wheatgrass	52 (10) b–n	61 (8) g–p
NewHy RS wheatgrass	52 (10) b–n	60 (8) h–q
Sodar Thickspike wheatgrass	52 (11) b–n	64 (8) d–n
Douglas Crested wheatgrass	50 (9) c–n	63 (7) e–n
Bannock Thickspike wheatgrass	48 (10) d–o	67 (8) b–m
Anatone Bluebunch wheatgrass	47 (10) e–o	64 (8) d–n
Continental Basin wildrye	45 (14) f–o	56 (10) k–s
Mustang Altai wildrye	44 (13) g–o	66 (9) b–m
P7 Bluebunch wheatgrass	43 (10) h–p	55 (8) l–t
Firststrike Slender wheatgrass	42 (12) i–p	76 (10) a–h
Manchar Smooth brome	42 (13) i–p	46 (10) o–v
Fish Creek Bottlebrush squirreltail	40 (28) j–p	62 (15) f–o
Secar Snake River wheatgrass	39 (8) k–q	42 (7) s–v
Goldar Bluebunch wheatgrass	37 (9) l–q	63 (7) e–n
Swift Russian wildrye	33 (13) m–r	41 (10)s–v
Trailhead Basin wildrye	31 (11) n–r	43 (8) r–v
Pryor Slender wheatgrass	24 (12) o–s	48 (10) n–v
Prairieland Altai wildrye	24 (12) o–s	32 (9) vw
Magnar Basin wildrye	19 (12) p–s	38 (9) uvw
Pearl Altai wildrye	19 (13) p–s	48 (10) n–v
San Luis Slender wheatgrass	19 (15) p–s	65 (12) c–m
Toe Jam Creek Bottlebrush squirreltail	19 (28) p–s	69 (15) b–m
Sand Hollow Big squirreltail	15 (28) qrs	46 (12) o–v
White River Indian ricegrass	9 (28) rs	66 (15) b–m
Rimrock Indian ricegrass	0 (28) s	39 (11) tuv
Nezpar Indian ricegrass	0 (28) s	22 (11) w

wildrye possessed consistently low stand establishment at the intermediate precipitation sites. Many species possessed generally high stand establishment at the high precipitation sites. Nevertheless, smooth brome, Indian ricegrass, squirreltail, bluebunch wheatgrass, slender wheatgrass, Snake River wheatgrass, and the three wildrye species possessed low or moderate stand establishment at these sites.

For stand persistence, crested wheatgrass, Siberian wheatgrass, western wheatgrass, and Russian wildrye were the only species to possess consistently high values at the majority of low and intermediate precipitation sites (Table 5). Smooth brome, Indian ricegrass, bluebunch wheatgrass, slender wheatgrass, Snake River wheatgrass, Altai wildrye, and basin wildrye possessed consistently low stand persistence at the low precipitation sites. RS wheatgrass, Snake River wheatgrass, and basin wildrye were the only species to possess consistently low stand persistence at the intermediate precipitation sites. With the exceptions smooth brome, bluebunch wheatgrass, Snake River wheatgrass, Altai wildrye, and basin wildrye, the species all possessed generally high stand persistence at the high precipitation sites.

Although the site precipitation groupings indicated general trends in the data, not all sites followed these trends for a particular precipitation level (Tables 4 and 5). For instance, crested wheatgrass had low stand establishment at the Guernsey, Wyoming 2004 site. This was an intermediate precipitation site where, based on other similar sites, crested wheatgrass would have been expected to establish well. Additionally, the unbalanced nature of the data resulted in the evaluation of the different species at differing numbers of sites. Thus, some species were included at all sites in a particular precipitation grouping, whereas other species were

Table 4. Mean stand establishment (%) species values for each of the 34 studies included in the evaluations. Sites are sorted by mean precipitation from low to high. Mean values followed by different letters significantly differ. Regions are sorted in descending order based on precipitation, whereas sites within regions are sorted in ascending order based on precipitation.

Location[1]	Meadow brome	Smooth brome	Indian ricegrass	Big/bottlebrush squirreltail	Bluebunch wheatgrass	Crested wheatgrass	Intermediate wheatgrass	RS wheatgrass	Siberian wheatgrass	Slender wheatgrass	Snake River wheatgrass	Tall wheatgrass	Thickspike wheatgrass	Western wheatgrass	Altai wildrye	Basin wildrye	Russian wildrye	Mean
Prairie Parkland Hardiness Zone 5																		
Mead (H)	100 a	100 a			95 a	98 a	100 a	100 a	99 a		74 b	99 a	98 a	100 a	100 a	96 a	99 a	97
Great Plains–Palouse Dry Steppe, Hardiness Zones 3, 4, and 5																		
Miles City 94 (L)	—	—	—	—	55 b	80 a	—	—	83 a	—	32 c	—	67 ab	69 ab	—	—	78 a	66
Decker (L)	—	—	—	—	—	100 a	100 a	100 a	100 a	—	86 ab	—	99 ab	25 c	10 c	—	100 a	80
Miles City 99 (L)	82 ab	72 bc	—	—	66 c	78 abc	89 a	86 ab	81 abc	—	48 d	85 ab	87 ab	89 a	76 abc	76 abc	89 a	79
Guernsey 05 (I)	—	—	—	—	57 ab	48 ab	—	—	67 a	50 ab	44 ab	—	51 ab	38 b	—	53 ab	58 ab	52
Guernsey 04 (I)	—	—	—	—	46 ab	5 d	—	—	46 ab	61 a	6 d	—	51 ab	58 a	—	14 cd	34 bc	36
Guernsey 02 (I)	—	—	—	—	98 a	96 a	—	—	87 abc	73 bc	99 a	—	—	67 c	—	95 ab	81 abc	87
Sidney (H)	75 a–e	61 dfg	—	—	72 b–e	59 efg	97 a	75 a–e	65 c–f	—	47 fg	91 ab	81 a–e	82 a–d	71 b–e	40 g	75 a–e	71
Turkey Creek (H)	—	—	4 d	—	—	67 bc	—	—	49 c	—	—	—	41 c	100 a	—	—	85 ab	58
Mandan (H)	82 a–e	57 fg	—	—	45 g	77 cde	95 a	71 def	85 a–d	—	43 g	88 abc	79 b–e	93 ab	72 def	67 ef	81 a–e	74
Southern Rocky Mountains Hardiness Zone 4																		
North Logan 99 (H)	78 a–d	48 f	47 f	53 ef	74 bcd	68 de	95 a	78 a–d	71 cde	—	27 g	78 a–d	78 a–d	92 ab	48 f	36 fg	47 f	64
North Logan 86 (H)	—	—	—	—	13 c	79 a	74 a	52 b	21 c	—	—	—	55 b	—	—	—	53 b	50
Nevada–Utah Mountains Hardiness Zone 6																		
Beaver (I)	—	54 ef	70 bcd	80 b	75 bc	78 b	74 bc	—	92 a	76 bc	60 def	—	75 bc	38 g	—	52 f	66 cde	68
Scipio 03 (H)	—	—	—	—	61 bc	74 ab	74 ab	—	85 a	60 bc	38 d	—	—	76 ab	48cd	—	64 bc	64
Scipio 04 (H)	—	20 de	—	—	56 ab	68 a	69 a	—	70 a	54 ab	36 cd	—	—	49 bc	—	15 e	26 de	46
Intermountain Semidesert Hardiness Zones 3, 4, 5, and 6																		
Granger (L)	—	—	—	—	38 b	41 b	—	—	73 a	—	13 c	—	60 a	25 bc	—	—	38 b	41
Stone 89 (L)	—	—	—	—	28 c	66 a	—	—	25 cd	—	14 de	—	33 bc	11 e	—	—	45 b	32
Yakima (L)	—	—	—	—	32 de	35 cde	—	—	39 b–e	68 a	40 b–e	—	—	58 ab	—	22 e	55 ab	44
Malta 04 (L)	—	—	63 cd	60 cd	83 b	94 a	—	—	93 ab	69 c	85 ab	—	—	54 d	—	—	65 c	74
Malta 85 (L)	—	—	—	—	70	57	81	37	—	—	75	—	—	68	—	—	63	64
King Hill (L)	—	—	16 c	—	—	77 a	—	—	80 a	—	—	—	—	—	—	—	42 b	54
Blue Creek 89 (L)	—	—	—	—	72 ab	79 a	61 bc	79 a	66 abc	—	35 d	—	55 c	28 d	32 d	—	66 abc	57
Stone 02 (I)	—	—	—	—	68 ab	76 a	—	—	58 b	—	—	—	—	42 c	—	—	63 b	61
Blue Creek 99 (I)	65 a–d	57 cde	21 h	44 efg	66 a–d	67 abc	71 ab	41 fg	61 bcd	—	17 h	76 a	61 bcd	37 g	56 cde	23 h	53 def	51
Picabo (I)	—	—	—	—	—	94 a	—	—	—	—	—	—	—	—	—	—	29 b	62
Stone 84 (I)	—	—	—	—	—	37 a	3 c	1 c	5 c	—	15 b	—	—	3 c	—	—	19 b	12
Soda Lake (H)	—	—	—	—	70 ab	76 a	—	57 ab	53 b	—	—	—	56 ab	—	—	—	71 ab	64
Blue Creek 84 (H)	—	—	—	—	—	73	69	61	—	—	67	—	—	78	—	—	79	71
Intermountain Semidesert and Desert Hardidness Zones 5 and 6																		
Dugway (L)	—	—	—	—	—	44 a	—	—	7 bc	—	0 c	—	16 b	—	—	—	16 b	17
Skull Valley #1 (L)	—	—	—	—	—	40 a	24 b	3 c	—	—	—	24 b	—	—	—	—	7 c	20
Spring City (L)	—	—	—	—	—	25	22	—	14	—	—	—	—	—	—	—	20	20
Promontory (I)	—	—	—	—	—	87	—	—	87	—	—	91	—	—	85	—	74	85
Monticello (I)	—	—	—	—	—	99 a	97 ab	85 bc	97 ab	—	—	—	—	70 d	—	—	75 cd	87
Skull Valley #2 (I)	—	—	—	—	—	47 a	41 a	3 c	—	—	—	24 b	—	—	—	—	3 c	24

[1]H indicates High (> 389 mm); I, Intermediate (310–389 mm); L, Low (< 310 mm) annual precipitation.

Table 5. Mean 3-yr stand persistence (%) species values for each of the 22 studies included in the evaluations from stand persistence was taken. Sites are sorted by mean precipitation from low to high. Mean values followed by different letters significantly differ. Regions are sorted in descending order based on precipitation, whereas sites within regions are sorted in ascending order based on precipitation.

Location[1]	Meadow brome	Smooth brome	Indian ricegrass	Big/bottlebrush squirreltail	Bluebunch wheatgrass	Crested wheatgrass	Intermediate wheatgrass	RS wheatgrass	Siberian wheatgrass	Slender wheatgrass	Snake River wheatgrass	Tall wheatgrass	Thickspike wheatgrass	Western wheatgrass	Altai wildrye	Basin wildrye	Russian wildrye	Study Mean
Prairie Parkland, Hardiness Zone 5																		
Mead (H)	90 ab	99 a	—	—	31 d	91 ab	98 ab	100 a	89 ab	—	93 ab	94 ab	81 bc	100 a	64 c	81 bc	87 ab	83
Great Plains–Palouse Dry Steppe, Hardiness Zones 3, 4, and 5																		
Miles City 94 (L)	—	—	—	—	54 c	87 a	—	—	90 a	—	53 c	—	73 b	69 b	—	—	85 a	73
Decker (L)	—	—	—	—	—	100 a	33 b	0 c	95 a	—	0 c	—	21 b	20 b	0 c	—	100 a	41
Miles City 99 (L)	83 a–e	72 b–e	—	—	67 e	78 a–e	78 a–e	79 a–e	87 abc	—	71 cde	77 a–e	77 a–e	91 a	69 de	72 b–e	92 a	78
Guernsey 05 (I)	—	—	—	—	56 b	84 a	—	—	90 a	28 c	68 ab	—	46 bc	67 ab	—	31 c	81 a	61
Guernsey 04 (I)	—	—	—	—	48 bcd	21 de	—	—	66 abc	49 bd	23 de	—	75 ab	85 a	—	12 e	52 a–d	48
Sidney (H)	90 a–d	61 efg	—	—	81 a–d	59 fgh	98 a	95 abc	75 def	—	47 gh	91 a–d	81 a–d	94 a–d	78 b–ef	40 h	76 c–f	76
Mandan (H)	84 ab	75 bcd	—	—	36 e	72 bcd	100 a	95 a	80 bc	—	31 e	88 ab	72 bcd	100 a	60 d	63 cd	76 bcd	74
Nevada–Utah Mountains, Hardiness Zone 6																		
Scipio 03 (H)	66 bc	—	—	—	70 abc	87 ab	84 ab	—	85 ab	72 abc	53 c	—	—	91 a	30 d	—	75 abc	71
Scipio 04 (H)	73ab	42 de	—	—	66 abc	81 a	54 bcd	—	77 a	47 cde	62 abc	—	—	75 a	—	28 e	47 cde	59
Intermountain Semidesert, Hardiness Zone 4, 5, and 6																		
Granger (L)	—	—	—	—	10 c	35 a	—	—	39 a	—	3 c	—	23 b	32 ab	—	—	33 a	25
Stone 89 (L)	—	—	—	—	11 d	72 a	—	—	28 c	—	11 d	—	11 d	11 d	—	—	49 b	27
Yakima (L)	—	—	—	—	40 bcd	60 ab	—	—	63 a	24 d	57 ab	—	—	72 a	—	32 cd	75 a	53
Malta 04 (L)	—	—	10 d	37 c	50	92 a	—	—	95 a	14 d	85 a	—	—	52 b	—	—	60 b	55
Malta 85 (L)	—	—	—	—	76	48	68	25	—	—	72	—	—	59	—	—	62	59
Blue Creek 89 (L)	—	—	—	—	38 de	85 a	32 e	48 d	69 bc	—	41 de	—	66 c	82 ab	38 de	—	78 abc	58
Stone 02 (I)	—	—	—	—	83	82	—	—	73	—	—	—	—	75	—	—	76	78
Stone 84 (I)	—	—	—	—	—	49 a	0 c	0 c	11 bc	—	3 c	—	—	5 c	—	—	24 b	13
Intermountain Semidesert and Desert, Hardiness Zones 5 and 6																		
Dugway (L)	—	—	—	—	—	37 a	—	—	7 c	—	10 bc	—	22 b	—	—	—	19 bc	19
Skull Valley #1 (L)	—	—	—	—	—	33 a	19 b	0 c	—	—	—	19 b	—	—	—	—	5 c	15
Spring City (L)	—	—	—	—	—	57	54	—	53	—	—	—	—	—	—	—	51	54
Skull Valley #2 (I)	—	—	—	—	—	44 a	36 a	0 c	—	—	—	18 b	—	—	—	—	2 c	20

[1]H indicates High (> 389 mm); I, Intermediate (310–389 mm); L, Low (< 310 mm) annual precipitation.

evaluated at only one or two of the sites in a particular grouping.

Plant Adaptation Regions

In conjunction with the grouping of sites by precipitation, the sites were also located in 12 PARs (Table 1). Results from individual evaluations are grouped under the corresponding PARs in Tables 4 and 5. Some trends concerning the appropriateness of the various species to PARs can be noted in the data. Crested, Siberian, thickspike, and intermediate wheatgrass are more widely adapted as indicated by their stand establishment values throughout the regions. Other species established well in some regions, but not in others. Meadow brome possessed consistently high stand establishment, but was only evaluated at two sites west of the Great Plains. Bluebunch wheatgrass, which is native to many of the Intermountain Semidesert sites, established well in this region, but outside the Guernsey, Wyoming sites possessed only low to moderate establishment in the other regions. RS, tall, thickspike, and western wheatgrass and Russian wildrye established well in the eastern regions and the North Logan sites, but established poorly elsewhere. Smooth brome, Indian ricegrass, squirreltail, Snake River wheatgrass, and Altai and basin wildrye possessed generally low establishment across the regions.

Crested and Siberian wheatgrass possessed high stand persistence across most of the regions. Meadow brome generally persisted well, but its evaluation in western regions was limited. Intermediate, RS wheatgrass, and tall wheatgrass persisted well in the eastern regions, but not in the western regions. Western wheatgrass and Russian wildrye persisted well in all regions but the Intermountain Semidesert and Desert. The stand persistence of western wheatgrass is consistent with its center of origin, corresponding to higher rainfall and humidity locations in the northern and central Great Plains, where many of the high precipitation sites were located. All remaining species rarely exhibited high persistence. Thus, some grasses are simply not adapted to some regions. As an example, and consistent with the precipitation groups, bluebunch wheatgrass, slender wheatgrass, Snake River wheatgrass, thickspike wheatgrass, and basin wildrye from the Intermountain West possessed low persistence in the eastern Great Plains as typified by the Mead, Nebraska location, probably due to root, crown, and foliar diseases that exist in high rainfall regions of the eastern Great Plains.

Results of Selection

Although differences were not always significant there was a strong trend for more recent plant releases to possess higher stand establishment than older releases of the same species. (Table 3). This is likely due to the limited evaluation and selection that accompanied the release of many of the older plant materials. However, the improvements in stand establishment did not necessarily correspond to improvements in stand persistence (Table 3). 'Mustang' Altai wildrye (66%) possessed higher stand establishment than either of the of Altai wildryes, 'Pearl' (48%) and 'Prairieland' (32%). White River Indian ricegrass (66%) possessed higher stand establishment than 'Rimrock' (39%) or 'Nezpar' (22%). 'Discovery' Snake River wheatgrass possessed higher stand establishment (62%) than 'Secar' (42%).

DISCUSSION

Successful revegetation of a site requires establishment of seeded species and subsequent growth by the species on available resources (reviewed in Seabloom et al. 2003). The synthesis of studies described herein addressed both of these requirements through the evaluation of species stand establishment and persistence under monoculture conditions. The 18 species and corresponding varieties evaluated herein represent the majority of perennial grass species currently or historically used in revegetation of degraded landscapes in the United States (e.g., US Department of the Interior–Bureau of Land Management 2009). Although few of the species possessed stand establishment values similar to species such as intermediate or crested wheatgrass, the majority established at values greater than 50% across all of the studies. However, species with stand establishment values less than 50% reflect revegetation sites with substantial areas of bare soil that remain unprotected from soil erosion and annual plant invasion. Nevertheless, only three species had stand establishment less than 50%. Thus, most species established at acceptable levels, particularly at precipitation levels higher than 310 mm annual precipitation. Stand persistence was the trait for which more species fell short, particularly at low-precipitation sites. Therefore, the main distinction between the species evaluated in these studies was stand persistence rather than stand establishment. This result is consistent with earlier findings on a more limited number of species and sites (Bleak et al. 1965).

In a dynamic landscape where stands can reestablish from seedling recruitment, and populations successionally move from one perennial plant community to another, long-term persistence might not be that important. Moreover, if long-term persistence prevents successional progression of species on a site, it could be a negative. This is particularly true if greater plant diversity is desirable, such as in the case of assisted succession (Cox and Anderson 2004). Unfortunately, the data presented did not allow persistence of species in mixtures to be determined. However, in the case of many revegetation projects where potentially large seed banks of annual, invasive species exist (Humphrey and Schupp 2001), failure of revegetation species to persist for at least moderate amounts of time will lead to annual plant dominance and increased wildfire frequency. Therefore, on severely degraded sites with annual plant invasion and at low precipitation levels, the importance of longer-term persistence is of paramount importance. This can become an even more important consideration if plant adaptation profiles for specific ecoregions change due to the expected changes in climate. Site stability could be dependent upon having species at a site that have the broad adaptative capacity to be able to thrive under changing climatic conditions. Ultimately, land managers will need to determine the relative importance of stand persistence for their long-term site goals for biodiversity and their needs to balance soil stabilization and limit annual plant invasion. Public and private land managers make revegetation decisions based on criteria such as topography and size of the disturbance, seed prices, seed availability, and regulatory requirements (Richards et al. 1999).

These results should provide further information to make more informed site decisions.

Mean annual precipitation and longitude were moderately correlated with stand establishment and persistence, although it is likely that precipitation and longitude are confounded due to the higher rainfall pattern of the more eastern sites. A larger proportion of the species had higher stand establishment and persistence at sites that received higher levels of precipitation. Thus, the results suggested, as has been noted previously (Bleak et al. 1965), that precipitation was the predominant environmental factor underlying stand establishment and persistence. Nevertheless, none of the correlations were sufficient to explain the differences in stand establishment and persistence among the species across the sites. It is likely that differences in stand establishment and persistence were due to inherent biological and genetic differences among the species and varieties, environmental conditions at the study sites, and interactions between biology/genetics and environment, or genotype by environment interaction (Falconer and Mackay 1996).

From a biological standpoint, differences in seed size and rhizomatous nature among the species were possible causes of response differences. The effect of seed size on seedling establishment is unclear. In some instances there has been evidence of correlation between large seed size and increased establishment (Lawrence 1963; Berdahl and Barker 1984), whereas in other instances there was no correlation (Waldron et al. 2006). Additionally, these studies encompassed only single species, rather than a comparison among species. Among the species with the largest seeds included in this study (Altai wildrye, meadow brome, RS wheatgrass, and tall wheatgrass) there was no obvious relationship to increased establishment. Altai wildrye and RS wheatgrass possessed generally low stand establishment values, and meadow brome and tall wheatgrass possessed generally high stand establishment values. On the other extreme, Siberian wheatgrass and Indian ricegrass were the species with the smallest seeds. Siberian wheatgrass possessed generally high stand establishment, but Indian ricegrass possessed low stand establishment.

When considering growth habit (Asay and Jensen 1996), the rhizomes of intermediate wheatgrass and western wheatgrass might have been beneficial for their stand persistence, but there appeared to be less benefit from rhizomes for the stand persistence of either RS or thickspike wheatgrass. Although it was unclear which growth or morphological traits correlated with stand establishment or persistence, there was evidence that the selection underlying the development of the newer varieties had in several instances resulted in increased stand establishment, which is consistent with previous selection studies for seedling establishment (Asay and Johnson 1980; Berdahl and Barker 1984; Waldron et al. 2006).

IMPLICATIONS

The evaluation of perennial, cool-season grass species for stand establishment and persistence provides an important baseline for land managers when making decisions for revegetation projects. The important findings for land managers are: 1) that many of the available perennial, cool-season grass species will result in acceptable establishment, particularly at higher precipitation sites; 2) at low precipitation sites there are fewer species that consistently produced adequate stands; and 3) the relative importance of stand persistence must be determined by the land managers when they determine priorities for biodiversity, soil stabilization, and invasive annual species competition.

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