ESTABLISHMENT AND TRENDS IN PERSISTENCE OF SELECTED PERENNIAL COOL-SEASON GRASSES

by

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ABSTRACT

Establishment and Trends in Persistence of Selected Perennial Cool Season Grasses

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The choice of plant materials is an important factor in restoration or revegetation of disturbed rangelands. To better identify plant materials that could be adapted to increased competition from invasive grasses and fluctuations in temperature and precipitation, there is a need to understand potential seedling establishment, plant persistence, and dry-matter yield (DMY) as a measure of plant vigor in the newly developed varieties across a wide range of environmental conditions. Experiments were conducted on four semiarid range sites to compare these traits in 14 perennial cool-season grass species currently used for revegetation in the Western U.S.A. There were location differences, with overall seedling establishment ranging from 28 to 70% seedling frequency at Malta, ID and Tintic, UT sites, respectively. No one species was statistically highest for seedling frequency at all four locations. However, there were four species that had higher seedling frequency at three of the four locations: Siberian wheatgrass (*Agropyron fragile* [Roth] Candargy), crested wheatgrass (*Agropyron cristatum* [L.]

Gaertn), and (*Agropyron desertorum* [Fish. ex Link] J. A. Schultes), intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D.R. Dewey) and Snake River wheatgrass (*Elymus wawawaiensis* J. Carlson & Barkworth). The newer varieties, in most instances, had increased seedling frequency vs. older varieties. Intermediate wheatgrass had the highest dry matter yields (DMY) at the Beaver location while crested and Siberian wheatgrass were highest for DMY at the Cheyenne location. Plant frequency was evaluated every year for five years after planting to determine stand persistence. Trends in plant persistence showed that, although difficult to establish, stands of western wheatgrass increased in the years after establishment due to rhizome development. Slender wheatgrass had a negative linear trend in stand persistence at the four tested locations. These results can help land managers make informed decisions concerning the choice of plant materials for revegetation projects, as related to potential seedling establishment, stand persistence, and relative biomass production.

(67 pages)

PUBLIC ABSTRACT

Establishment and Trends in Persistence of Selected Cool-Season Perennial Grasses

Craig W. Rigby

The choice of plant materials is an important component of restoration or revegetation following disturbance. To better identify plant materials that could be adapted to increased competition from invasive grasses and fluctuations in temperature and precipitation, there is a need to understand potential seedling establishment, plant persistence, and dry-matter yield (DMY) as a measure of plant vigor in the newly developed varieties across a range of environmental conditions. Experiments were conducted on four semiarid range sites to compare these traits in perennial cool-season grasses currently used for revegetation in the Western U.S.A. Overall seedling establishment ranging from 70 to 28% seedling frequency at Malta, ID and Tintic, UT sites, respectively. No one species was statistically highest for seedling frequency at all four locations. However, there were four species that had higher seedling frequency at three of the four locations: Siberian wheatgrass, crested wheatgrass, intermediate wheatgrass and Snake River wheatgrass. The newer varieties, in most instances, had increased seedling frequency vs. older varieties. Intermediate wheatgrass had the highest dry matter yields (DMY) at the Beaver location while crested and Siberian wheatgrass were highest for DMY at the Cheyenne location. Plant frequency was evaluated every year for five years after planting to determine stand persistence. Trends in plant

persistence showed that, although difficult to establish, stands of western wheatgrass increased in the years after establishment due to rhizome development. Slender wheatgrass had a negative linear trend in stand persistence at the four tested locations. These results can help land managers make informed decisions concerning the choice of plant materials for revegetation projects, as related to potential seedling establishment, stand persistence, and relative biomass production.

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CONTENTS

Page

ABSTRACT ii

PUBLIC ABSTRACT iv

ACKNOWLEDGMENTS vi

LIST OF TABLES viii

LIST OF FIGURES x

INTRODUCTION 1

MATERIALS AND METHODS 6

RESULTS 26

DISCUSSION 44

IMPLICATIONS 48

REFERENCES 49

LIST OF TABLES

Table Page

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...................................... 7

2 Sampling dates for stand frequency counts at four locations all sites were evaluated every year for five years after planting.. 23

3 Probability of a > F (based on type III sums of squares, non additive) from the analysis of variance for seedling establishment (% frequency year 1), plant persistence (% frequency year 5), and dry-matter yield (DMY) in year 3 and 5 after planting. Based on fixed effects.. 25

4 Means and trends in stand persistence of 13 grass species across five years at Site 1 (Beaver) from 2007 to 2011. Ranked by species 2007 seedling frequency. Values followed by different letters significantly differ at P<0.05 (LSD)... 31

5 Means of Dry-matter yield (DMY) of 13 grass species across three years at Site 1 (Beaver) from 2009 to 2011. Ranked by 2009 DMY. Values followed by different letters significantly differ at P<0.05 (LSD). Uppercase letters denote significance among species; lowercase letters denote significance within species... 32

6 Correlations for frequency in year one establishment (Est), year two (Y2), year three (Y3), year four (Y4), year five (Y5), dry matter yield year three (DMY_Y3), dry matter yield year four (DMY_Y4), and dry matter yield year five (DMY_Y5). Top diagonal is the Beaver, UT location; the bottom diagonal is the Cheyenne, WY location.. 35

7 Means and trends in seedling establishment and stand persistence of 12 grass species across five years at Site 2 (Cheyenne) from 2010 to 2014. Ranked by species 2010 frequency. Values followed by a different letter are significantly different at P<0.05 (LSD). Uppercase letters denote significance among species; lowercase letters denote significance within species. 36

8 Means in Dry-matter yield (DMY) of 12 grass species across five years at Site 2 (Cheyenne) from 2011, 2013, and 2014. Ranked by species 2011 DMY. Values followed by different letters differ at P<0.05 (LSD), uppercase letter denote significance among species, lowercase letter denote significance within species. 37

9 Correlations for frequency in year one establishment (Est), year two (Y2), year three (Y3), year four (Y4), and year five (Y5). Top diagonal is the Malta, ID location; the bottom diagonal is the Tintic, UT location. 39

10 Means and trends in seedling establishment and plant persistence of 10 grass species across five years at Site 3 (Malta) from 2005 to 2009. Ranked by species 2005 seedling frequency. Values followed by different letters differ at P<0.05 (LSD), uppercase letter denote significance among species, lowercase letter denote significance within species. 40

11 Means and trends in seedling establishment and stand persistence of 13 grass species across five years at Site 4 (Tintic), from 2010 to 2014. Ranked by 2010 seedling frequency. Values followed by different letters differ at P<0.05 (LSD), uppercase letter denote significance among species, lowercase letter denote significance within species. 43

LIST OF FIGURES

Figure Page

1 Monthly and long-term mean precipitation for the four study locations: (a) Beaver, (b) Cheyenne, (c) Malta, and (d) Tintic. The thin solid line represents the 30 year 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 January 22, 2016 at http://prism.oregonstate.edu 21

INTRODUCTION

Disturbances by wildfire, livestock, wildlife, and humans have contributed to degraded conditions on much of the western United States semiarid rangelands (Asay et al., 2003; Davison, 1996). These disturbances have resulted in widespread loss of native perennial vegetation (Pickford, 1932; Whisenant, 1992) and replacement by invasive annual weeds such as cheatgrass, (*Bromus tectorum L.*) and medusahead, (*Taeniatherum caput-medusae* [L.] Nevski) (Billings, 1990; Davies, 2011). It has been estimated that cheatgrass alone has displaced approximately 10 million ha of native perennial vegetation within the Great Basin (Menakis et al., 2003), where it remains a major factor in the deterioration of ecosystem function, natural resources, and productivity of western rangelands of North America (Young and McLain, 1997).

As a consequence of this invasion and other factors, the frequency and size of wildfires has increased (Brooks et al., 2004; Dantonio and Vitousek, 1992; Whisenant, 1992), soil structure has been lost (Norton et al., 2004), soil erosion has increased, watershed function has declined, and biological diversity has decreased (Brooks and Chambers, 2011). In addition, there has been a loss in wildlife habit and economic profitability (DiTomaso, 2000; Evans and Young, 1978; Mack, 1981; Mosley et al., 1999). Undesirable invasive weeds continue to spread to new areas and increasingly threaten most rangelands (Brooks and Pyke, 2000; Monsen, 1992; Pellant, 1990). Hence, today much of our western U.S. rangelands have either lost their ecosystem stability or are on the cusp of doing so.

Many of the attempts to restore or revegetate these degraded sites have not been successful (Bleak et al., 1965; Davies et al., 2015; Monsen, 1992; Pellant, 1990; Stoddart et al., 1975). To reclaim these disturbed or otherwise damaged sites requires plant materials with good stand establishment (Wolf et al., 1996), persistence, and forage production to provide ecological function and protect the soils from erosion. Efforts to restore former shrublands now dominated by cheatgrass require re-establishing plant communities and key ecosystem processes for long-term stability (McIver and Starr, 2001). A competitive plant community will maximize the capture of soil moisture and nutrients, and restrict the invasion of noxious weeds (Svejcar, 2003; Thacker et al., 2009).

The correct choice of plant materials is an important component of restoration or revegetation following disturbance (Asay et al., 2003; Booth and Jones, 2001). Seedling establishment on damaged intermountain rangelands is generally considered the most limiting factor for revegetation of these lands (Asay and Johnson, 1983; Robins et al., 2007). Reclamation of arid and semiarid rangelands is complicated by the extreme fluctuations in environmental and site conditions. Climatic factors, primarily low and erratic precipitation, and seasonal temperature variability have a large effect on the success or failure of a seeding practice (Bleak et al., 1965). The weather cannot be controlled, but the type of plant materials seeded can be. One way to enhance the possibility of a successful seeding is to use genetically improved plant materials both native and introduced that are competitive (i.e., seedling establishment and persistence) with annual grasses, while restoring a perennial plant community (Asay et al., 2001; Waldron et al., 2005). Most improved grasses have been selected for increased seed germination, rapid seedling establishment, and subsequent plant persistence, and have been shown to provide ecological function and reduce soil erosion (Asay et al., 2003).

Revegetation with introduced grasses such as crested wheatgrass (*Agropyron cristatum* [L.] Gaertn) or (*Agropyron desertorum* [Fish. ex Link] J. A. Schultes) and Siberian wheatgrass (*Agropyron fragile* [Roth] Candargy), became common in the early 1900's (Pickford, 1932) because of better stand establishment, persistence, and weed suppression than perennial native grass species, particularly on rangelands receiving less than 310 mm of annual precipitation (Asay et al., 2001; Evans and Young, 1978; MacDonald, 1997; Ott et al., 2001; Robins et al., 2013). Recurrent selection for increased seed germination, seedling establishment, and persistence within crested and Siberian wheatgrasses and Russian wildrye (*Psathyrostachys juncea* [Fisch.] Nevski) has resulted in cultivars able to establish, persist, and compete with invasive annual weeds on arid and semi-arid rangelands (Jensen et al., 2006; Jensen et al., 2009a; Jensen et al., 2009b).

Due to increased desire and need for revegetation with perennial native grass species (Richards et al., 1998), efforts have focused on development of improved native grasses (Asay, 1992; Jones et al., 1991). These include the following new releases: bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey) (Jones et al., 2004a; Jones et al., 2004b; Jones et al., 1998b), basin wildrye (*Leymus cinereus* [Scribn. & Merr.] Á. Löve) (Jones et al., 2009), slender wheatgrass (*Elymus trachycaulus* [Link] Gould ex Shinners) (Jensen et al., 2007), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh.] Á. Löve) (Jones et al., 2002), Snake River wheatgrass (*Elymus wawawaiensis* J. Carlson & Barkworth) (Jones, 2008), thickspike wheatgrass (*Elymus lanceolatus* [Scribn. & Sm.] Gould) (Robins et al., 2015), Sandberg bluegrass (*Poa secunda* Presl.) (Waldron et al., 2006), and western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve) (Waldron et al., 2011).

In a meta-analysis that included over 34 field sites, Robins et al. (2013) concluded that seeding many of the available native and introduced perennial cool-season grass species, will result in acceptable stand establishment, particularly at sites with average annual precipitation (AAP) above 310 mm. However, at low precipitation sites (i.e., below 310 mm AAP) there are fewer species that persisted over time.

Asay et al. (2001) reported that on six U.S. rangeland sites, crested and Siberian wheatgrass were among the easiest to establish, more persistent and productive, and more defoliation-tolerant under severe water stress compared with other rangeland grasses. Asay et al. (2001) further found that native grasses were more difficult to establish, less persistent, and less productive than non-native grasses on sites with less than 300 mm of AAP. Fifteen years after seeding, Siberian, bluebunch, and Snake River wheatgrass co-existed on a range site near Yakama, WA (Asay et al., 2001). Young and McLain (1997) concluded that to not consider the use of these potentially valuable grasses because they are improved or not native is to condemn much of our rangelands to weed dominance and often disastrous loss of our soil resources.

To better identify plant materials that could be adapted to increased competition from invasive grasses and fluctuations in temperature and precipitation, there is a continuing need to understand seedling establishment, plant persistence, and dry-matter yield (DMY) as a measure of plant vigor in the newly developed varieties across a wide range of environmental conditions. The purpose of this study was to evaluate comparative stand establishment, trends in plant persistence, and biomass production of major cool-season grasses used for restoration and revegetation efforts on the rangelands of the western U.S.A.

MATERIALS AND METHODS

Plant Materials

Fourteen perennial cool-season grass species and cultivar or germplasm within species included in this study with their common name, Latin name, location, and reference of release are listed in Table 1. A brief description of the species included in the study is given below. These accessions or germplasms were seeded as monocultures at four sites located across the Intermountain West and Central Great Plains areas of the United States. Not all entries were included at each site. Species were included according to seed availability and expected adaptation to each site. The species included were: crested wheatgrass, Siberian wheatgrass, Intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D.R. Dewey), smooth brome (*Bromus inermis* Leyss), meadow brome (*Bromus riparius* Rehm.), bottlebrush squirreltail, thickspike wheatgrass, slender wheatgrass, Snake River wheatgrass, Basin wildrye, Indian ricegrass (*Achnatherum hymenoides* [Roemer & J.A. Shultes] Barkworth), western wheatgrass, Bluebunch wheatgrass, and Russian wildrye (Table 1).

Crested wheatgrass is indigenous to the Steppe region of European Russia and southwestern Siberia (Knowles, 1990). Since its introduction from Asia in the early 1900s, crested wheatgrass has become the major cool-season grass used to improve semiarid rangelands of western North America. Most early plantings of crested wheatgrass were made with unimproved introductions or mixes consisting of both ‘Fairway’ (*A. cristatum* [L.] Gaertn) and ‘Standard’ (*A. desertorum* [Fisch. ex Link] Schultes) types (Asay and Jensen, 1996).

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	Site 1[1]	2[2]	3[3]	4[4]	Reference
Bottlebrush squirreltail	Fish Creek	1		3	4	(Jones et al., 2004a)
Elymus elymoides	Sand Hollow	1		3		(Jones et al., 1998b)
	Toe Jam Creek	1		3	4	(Jones et al., 1998b)
Bluebunch wheatgrass	Anatone	1	2	3	4	(Monsen, 2003)
Psuedoroegneria spicata	Goldar	1		3	4	(Gibbs et al., 1991)
	P-7	1	2	3	4	(Jones et al., 2002)
Basin wildrye	Continental	1			4	(Jones et al., 2009)
Leymus cinereus	Magnar	1			4	(Howard, 1979)
	Trailhead	1	2		4	(Cash et al., 1998)
	Trailhead II		2		4	(Robins et al., 2015)
Crested wheatgrass	Hycrest	1		3	4	(Asay et al., 1985b)
Agropyron cristatum X	CD II	1		3	4	(Asay et al., 1997)
A. desertorum	Hycrest II	1	2	3	4	(Jensen et al., 2009a)
Agropyron cristatum	Douglas	1				(Asay et al., 1995a)
Agropyron desertorum	Nordan	1			4	(Rogler, 1954)
Indian ricegrass	Nezpar	1		3		(Booth et al., 1980)
Achnatherum hymendoides	Rimrock	1		3		(Jones et al., 1998a)
	White River	1		3		(Jones et al., 2010)
Intermediate wheatgrass	Luna		2		4	(Niner, 1967)
Thinopyrum intermedium	Oahe	1	2		4	(Ross and Bullis, 1962)
	Rush				4	(Alderson and Sharp, 1994)
Meadow bromegrass	Cache		2		4	(Jensen, 2004)
Bromus riparius	Arsenal		2		4	(Jensen et al., 2015)
	Regar				4	(Foster et al., 1966)
Russian wildrye	Bozoisky-Select	1		3	4	(Asay et al., 1985a)
Psathyrostachys juncea	Bozoisky II	1	2	3	4	(Jensen et al., 2006)
	Swift	1				(Lawrence, 1980)
Smooth bromegrass	Manchar	1	2		4	(Hein, 1960)
Bromus inermis						
Siberian wheatgrass	Vavilov	1		3	4	(Asay et al., 1995b)
Agropyron fragile	Vavilov II	1	2	3	4	(Jensen et al., 2009b)
	Stabilizer	1		3	4	(Jensen et al., 2013)
Slender wheatgrass	Charleston Peak	1		3		(Jensen, In Press)
Elymus trachycaulus	FirstStrike	1	2	3	4	(Jensen et al., 2007)
	Pryor	1	2	3	4	(Majerus et al., 1991)
	Revenue	1				(Crowle, 1970)
	San Luis	1		3	4	(USDA-SCS, 1984)
Snake River wheatgrass	Discovery	1	2		4	(Jones, 2008)
Elymus wawawaiensis	Secar	1	2	3	4	(Morrison and Kelley, 1981)
Thickspike wheatgrass	Bannock	1	2		4	(John and Blaker, 1998)
Elymus lanceolatus	Bannock II	1	2		4	(Robins et al., 2015)
	Critana	1	2		4	(Stroh et al., 1972)
	Schwendimar	1				(USDA-NRCS, 2016b)
	Sodar	1				(Douglas and Ensign, 1954)
Western wheatgrass	Arriba	1		3	4	(Anonymous, 1977)
Pascopyrum smithii	Barton	1		3		(Alderson and Sharp, 1994)
	Recovery	1	2	3	4	(Waldron et al., 2011)
	Rodan	1		3		(Barker et al., 1984)
	Rosana	1	2	3	4	(Alderson and Sharp, 1994)

[1]Site 1, Beaver, UT, [2]Site 2, Cheyenne, WY, [3]Site 3, Malta, ID, [4]Site 4, Eureka, UT

‘Nordan’, the earliest tetraploid cultivar was released in 1953. Nordan was selected for its upright growth form, relatively large seeds, and good seedling vigor (Rogler, 1954). ‘Hycrest’ was the first interspecific hybrid of crested wheatgrass to be released (Asay et al., 1985b). The most noteworthy attributes of Hycrest are its increased seedling establishment, forage production, and ability to compete with invasive annual weeds (Asay et al., 2001). In an attempt to increase the leafiness and absence of purple leaves during the early spring growth in Hycrest, two cycles of recurrent selection were conducted, resulting in the release of the cultivar ‘CD-II’ crested wheatgrass (Asay et al., 1997). ‘Douglas’ is the only hexaploid ($2n=6x=42$) crested wheatgrass cultivar and was released based on its exceptionally broad leaves and comparatively improved seedling vigor (Asay et al., 1995a). ‘Hycrest II’ was released with improved seedling establishment over Hycrest (Jensen et al., 2009a).

Siberian Wheatgrass is an introduced bunchgrass similar in appearance and distribution to the Fairway and Standard crested wheatgrasses. Siberian wheatgrass is more drought-resistant and it is better adapted to sandy soils than crested wheatgrasses (Jensen et al., 2001). Siberian wheatgrass has narrow awnless inflorescences, finer leaves, and thinner stems than standard crested wheatgrass (Jensen et al., 2009b).

The original cultivar P-27 was released in 1953 where it was derived directly from a 1934 collection from the Institute of Plant Industry, St. Petersburg, Russia (Alderson and Sharp, 1994). ‘Vavilov’, released in 1995, underwent three cycles of recurrent selection for improved vegetative vigor, response to drought, diseases and insects, seedling vigor (emergence from deep seedings), seed yield and upright plant type

(Asay et al., 1995b). ‘Vavilov II’ released in 2008 was selected for improved seedling establishment and persistence under drought (Jensen et al., 2009b). Parental lines for Vavilov II included plants from Vavilov and collections made from the Steppes of Kazakhstan in 1988. ‘Stabilizer’ is the most recent release of Siberian wheatgrass and is noted for its low growth habit, rapid establishment for use on rangelands and roadsides, and as a grass component in "fire-strip" plantings in the Intermountain West, Great Basin, and Northern Great Plains regions of western U.S.A. Selection emphasis to produce Stabilizer was for seedling establishment, persistence, seed production, pubescence, and reduced forage yield (Jensen et al., 2013).

Smooth brome is a long-lived, highly rhizomatous, sod forming grass adapted to moist well drained soils but, grows under a wide range of soil and moisture conditions (Jensen et al., 2001). It has been traditionally used for hay and pasture. Because of its sod forming nature, it has been effectively used for erosion control (USDA-NRCS, 2016b). Although it is best adapted to cooler climates receiving 400 to 500 mm AAP, it has been shown to establish at 300 to 350 mm AAP (Jensen et al., 2001). ‘Manchar’ originated from PI 109812 from Manchuria. Manchar is a mild, sod-forming, Northern-type bromegrass that produces high DMY during the growing season (Hein, 1960).

Bottlebrush and big squirreltails (*Elymus multisetus* JG. Smith [M.E. Jones]) are native short-lived perennial bunch grasses 15 to 55 cm tall (Jensen et al., 2001). They have relatively high seedling vigor, establishing well in a variety of soils and conditions from desert alkali flats to high mountain slopes. The squirreltails are adapted to areas that support sagebrush, shadscale, and pinyon-juniper which receive 200 to 450 mm of AAP.

Early season forage is classified as fair but becomes unpalatable at maturity, where the long sharp awns of the florets and glumes may cause injury to soft tissue of grazing animals during mid- to late-spring into summer (USDA-NRCS, 2016b). ‘Sand Hollow’, a pre-variety germplasm, was collected in Gem County, ID from a west-facing slope consisting of loamy coarse sand where the AAP is about 280 mm (Jones et al., 1998b). Pre-variety germplasm ‘Fish Creek’ was selected for high seedling emergence rates and late maturity (Jones et al., 2004a). ‘Toe Jam Creek’, a pre-variety germplasm, was collected in northwestern Elko County, Nevada, about eight miles west of the town of Tuscarora at 1846 m above sea level (asl) with an AAP of 305 mm (Jones et al., 2004b).

Thickspike wheatgrass is a long-lived native of the Northern Great Plains and Intermountain regions of North America. It possesses relatively high seeding vigor and is rhizomatous. It is adapted to a wide range of soils and has been shown to establish in areas receiving 200 mm or more AAP. Its seeding vigor, drought tolerance, and rhizomatous nature make it well suited for reclaiming disturbed low rainfall areas (USDA-NRCS, 2016b). ‘Sodar’ thickspike (streambank) wheatgrass originated from a collection near Canyon City, OR, and was selected for low-growth habit and narrow and smooth leaves (Douglas and Ensign, 1954). ‘Critana’ thickspike wheatgrass originated from collections along roadside cuts near Havre, MT (Stroh et al., 1972). ‘Schwendimar’ (USDA-NRCS, 2016b) originated from a collection made on windblown sands along the banks of the Columbia River, east of The Dalles, OR and was subjected to several cycles of mass selection to reduce the frequency of aberrant plants. ‘Bannock’ (USDA-NRCS, 2012) thickspike wheatgrass is a composite of six collections originating near Pocatello, ID; The Dalles, OR; and Quincy, WA. Six individual plants were selected based on visual vigor and DMY and then seed was increased. ‘Bannock II’ was selected for increased seed production and seedling establishment (Robins et al., 2015).

Slender wheatgrass has been one of the most widely used native grasses in revegetation programs on the rangelands of western U.S.A. and Canada (Asay and Jensen, 1996). It is a relatively short-lived native bunchgrass with good seedling vigor and moderate palatability (Jensen et al., 2001). Slender wheatgrass maintains high forage production for the first three to four years, then generally declines thereafter (Smoliak et al., 1990). Due to its seeding vigor, rapid establishment, moderate salt tolerance, and compatibility with other species, slender wheatgrass is a valuable component of reclamation seed mixes. The cultivar ‘Revenue’ originated from a single plant selected near Revenue, Saskatchewan in 1961 (Crowle, 1970). ‘San Luis’ slender wheatgrass released in 1984, originated from the direct seed increase of a collection made near Center, San Luis Valley, Rio Grande County, CO (USDA-SCS, 1984). ‘Pryor’ slender wheatgrass resulted from a collection made on a dry drainage within a saline-upland range site located in Carbon County, MT (Majerus et al., 1991). ‘FirstStrike’ slender wheatgrass is a multi-origin composite of four collections from Colorado and Wyoming with increased seedling emergence from a deep planting depth (Jensen et al., 2007). ‘Charleston Peak’, a selected class, genetically manipulated track pre-variety germplasm, originated from a collection near Charleston Peak, NV, and exhibits short rhizomes not typically found in standard slender wheatgrass (Jensen et al., In Press).

Morphologically Snake River wheatgrass is similar to bluebunch wheatgrass

(USDA-NRCS, 2016b). The variety 'Secar' was originally released as a bluebunch wheatgrass in 1981. It is adapted to most areas suitable for bluebunch wheatgrass, but it is more vigorous and drought tolerant (Jensen et al., 2012). Secar originated from the Lewiston Grade in the Snake River gorge, near Lewiston, ID and was selected for divergent awns, early maturity, and drought resistance (Morrison and Kelley, 1981). 'Discovery' originated from four accessions that showed improved vigor compared to Secar. Collections used to develop Discovery trace to Whitman and Asotin counties in southeastern Washington and Idaho County. These collections were crossed and seed harvested in bulk to generate Discovery (Jones, 2008).

Basin wildrye is a native long-lived cool-season bunchgrass that can become very large and coarse. Because of its large stature it can provide shelter from the wind and is considered excellent wildlife habitat (USDA-NRCS, 2016b). In sagebrush ecosystems, it is often found on well-drained riverbanks, in ravines, and other sites with higher water holding capacity. It is moderately tolerant of saline and alkaline conditions (Jensen et al., 2001). It can be hard to establish however, once established it provides excellent soil stabilization and surface erosion control. Early cultivars of basin wildrye originated as selections made from superior collections, followed by seed increase. 'Magnar' is blue-green in color, tall growing, with broad coarse leaves, and is frequently used for winter forage and wind barriers (Howard, 1979). 'Trailhead' basin wildrye originated from a seed collection near Roundup, MT which was subsequently selected for its superiority in DMY and stand longevity (Cash et al., 1998). 'Continental' was developed by hybridizing Magnar ($2n$=56) and a chromosome-doubled version of Trailhead followed by selection for seedling and mature-plant vigor (Jones et al., 2009). ‘Trailhead II’ was directly selected from Trailhead followed by two-cycles of selection for rapid seedling emergence from a deep planting depth (Robins, In Press).

Indian ricegrass is a perennial bunchgrass that is native to the arid and semiarid regions of the western United States (USDA-NRCS, 2016b). It has a large area of adaptation, and is found on a wide range of soils. However, it is dominant on sandy, stony, gravelly, and shallow soils found in the upland and semiarid climactic zones (Ogle et al., 2011). It is valued as high quality forage by many classes of livestock and wildlife and is especially important as a winter forage. ‘Nezpar’ was collected south of Whitebird, ID and was released based on low seed dormancy and ease of establishment (Booth et al., 1980). ‘Rimrock’ originated from a collection 1 km north of Billings, MT and was released for its ability to retain mature seed better than ‘Paloma’ and Nezpar (Jones et al., 1998a). ‘White River’, a selected pre-variety germplasm genetically manipulated track was selected from a collection originally made about 24 miles east of the town of Rangely, CO for high germination and seed yield (Jones et al., 2010).

Western Wheatgrass is a sod forming grass with strong spreading rhizomes (USDA-NRCS, 2016b). It is native to North America and is distributed throughout western North America. Although it is able to grow on a wide variety of soils, it prefers the heavier but well drained soils. It is most adapted to regions receiving 300 mm or more of AAP (Jensen et al., 2001). Above 500 mm AAP, it acts as an increaser on rangelands (USDA-NRCS, 2016b) and can become very aggressive. It is associated with blue grama (*Bouteloua gracilis* [Willd. ex Kunth.] Lag. ex Griffiths) and needlegrasses

(*Achnatherum* sp.) of the Great Plains and with bluebunch wheatgrass and various shrubs of the Intermountain region. Western wheatgrass germinates poorly and typically has poor seedling vigor. It requires 2 to 3 years to develop well established stands (Waldron et al., 2011).

‘Barton’ was a direct seed increase from a collection made along Walnut Creek near Heizer, KS (Alderson and Sharp, 1994). Seed harvested commercially from native meadows along Porcupine Creek, northwest of Forsyth, MT in 1959 with subsequent seed increase, resulted in the cultivar ‘Rosana’ (Alderson and Sharp, 1994). ‘Arriba’ was derived from a collection near Flager, CO in 1957 that received five seed increase cycles to improve seed production (Anonymous, 1977). Parental materials for ‘Rodan’ came from a commercial seed field of unknown origin grown in the Missouri River valley near Mandan, ND. Based on progeny performance for density, foliage cover, leafiness, and stem rust, 13 half-sib families were intercrossed and bulked. This population received continued selection over the next seven generations to remove off types (Barker et al., 1984). ‘Recovery’ combined germplasm from Rosana (28%), D2945 (50%), a different seed lot of the same population that gave rise to Rodan, and WW117FC (22%), a native collection made near Fort Carson, CO. The original population underwent two cycles of recurrent selection for seedling emergence from a deep planting depth (Waldron et al., 2011).

Bluebunch wheatgrass is an important native grass of the Palouse Prairie and the Intermountain sagebrush zones (USDA-NRCS, 2016b). Because of its high nutritional value and palatability, it is considered one of the most valuable native range grasses.

However, it will not tolerate intensive prolonged grazing (USDA-NRCS, 2016b). It is adapted to most soils, but is predominantly found on well-drained medium to coarse textured soils. It is a typical component of dry mountain slopes, sagebrush, ponderosa pine, mountain brush, and pinyon-juniper ranges receiving 250-500 mm AAP (Jensen et al., 2001).

‘Anatone’ a source identified germplasm originated from East of Anatone, Asotin County, WA (Monsen, 2003). ‘Goldar’ bluebunch wheatgrass (PI 5399873) a collection from the Malley Ridge, Umatilla National Forest, Asotin, WA resulted from several cycles of mass selection for establishment and persistence prior to release (Gibbs et al., 1991). Pre-variety germplasm genetically manipulated, P-7, was constructed as a multiple-origin polycross, it was developed by intermating 24 individual populations from Washington (13), Idaho (3), Oregon (3), Utah (2), Nevada (1), Montana (1), and British Columbia (1) (Jones et al., 2002).

Russian wildrye is an introduced, densely tufted bunchgrass. Most of the forage produced is contained in the basal leaves. Because of its tolerance to drought, cold, and saline soils it has been widely used throughout the Northern Great Plains and the Intermountain West of the United States in areas receiving between 200 to 400 mm AAP (USDA-NRCS, 2016b). It is most productive on fertile loam and clay soils (Ogle et al., 2011) but, produces acceptable stands on all major soil types. Relatively slow seedling growth and development is the most serious limitation in obtaining acceptable stands of Russian wildrye (Jensen et al., 2001).

‘Swift’, a 26 clone synthetic traces back to the cultivar ‘Sawki’, and was selected for establishment vigor, seed quality, DMY, and seed yield (Lawrence, 1980). 'Bozoisky-Select' was developed from PI 406468 (Bozoisky) originating in the USSR, it is the result of two cycles of recurrent phenotypic selection for improved vigor, leafiness, seed yield, coleoptile length (i.e., correlated to seedling vigor), and seedling establishment (Asay et al., 1985a). 'Bozoisky-II' included parental germplasm from Bozoisky-Select, 'Vinall', and plant introductions from Kazakhstan. Selection emphasis on Bozoisky-II was for increased seedling establishment and DMY (Jensen et al., 2006).

Intermediate wheatgrass is one of the higher producing grasses on upland and mountain sites (USDA-NRCS, 2016b). It is a moderate sod forming, late maturing, long-lived grass well suited for grazing use. It will establish and grow at AAP between 300 to 350 mm but, has increased production at 400 to 500 mm AAP (Jensen et al., 2001). It prefers well-drained loam to clay soils at elevations of 1050 to 2750 m asl. It is palatable to livestock and wildlife and is considered good forage throughout the growing season and into fall and winter. Due to its rhizomatous root system, this species has been used as a reclamation plant for soil stabilization (USDA-NRCS, 2016b).

Intermediate wheatgrass has probably had the most direct selection for agronomic traits of any of the range grasses. 'Oahe' is a four-clone synthetic derived directly from the cultivar 'Ree' it was selected for high seed-set, DMY, and rust resistance (Ross and Bullis, 1962). 'Luna' pubescent wheatgrass originated from a collection found in the former USSR and Turkey, was selected for increased leafiness and DMY (Niner, 1967). 'Rush', a selection originating from the German Botanical Garden, Berlin, Germany was selected for superior seedling emergence and DMY on sites with AAP of 300 mm or above (USDA-NRCS, 2013).

Meadow bromegrass is a long-lived perennial with moderately creeping rhizomes, early season forage production, and rapid regrowth after defoliation (USDA-NRCS, 2016b). It is grown on both irrigated and non-irrigated pastures. It is extremely winter hardy, typical "green up" is two to three weeks earlier in the spring than other pasture grasses, increasing its grazing season as well as forage production under reduced irrigation. It is adapted to slightly acidic to mildly alkaline soils on dryland pastures, where annual precipitation exceeds 380 mm. Meadow brome is adapted to the mountain brush, aspen, conifer forests, and subalpine environments. ‘Regar’ originated from the Kars Province of Turkey and was selected for regrowth characteristics under irrigation (Foster et al., 1966). ‘Cache’ originated from selections within the cultivars Regar, Fleet, and Paddock followed by three cycles of selection for enhanced seedling establishment and increased DMY on irrigated and semi-irrigated pastures (Jensen, 2004). ‘Arsenal’ resulted from five cycles of selection for plant vigor, rapid seedling establishment, increased DMY and seed yield, and seed mass under dryland environments ranging between 250 to 450 mm AAP (Jensen et al., 2015).

Although several experimental entries were included at each study location described herein, only commercially available varieties or germplasms that have been officially released from a public or private entity were included in the analysis.

Site Characteristics

Site 1 - (Beaver) located 9 km northeast of Beaver UT (38° 20' 51.72" N, 112° 35' 20.76" W) at 1,981 m above sea level (asl), where average annual precipitation (AAP) is 365 mm (PRISM Climate Group, 2016). This site is located in the Level III ecoregion Central Basin and Range; Level IV ecoregion woodland and shrub-covered low mountains (EPA, 2016). Ecological site descriptions (ESD) classify the site as upland shallow hardpan (Pinyon-Utah Juniper) with Utah juniper (*Juniperus osteosperma* [Torr.] Little), singleleaf pinyon (*Pinus monophylla* Torr. and Frem), bluebunch wheatgrass, bottlebrush squirreltail, Indian ricegrass, black sagebrush (*Artemisia nova* A. Nels), and Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp.) as associated species (USDA-NRCS, 2016a). The soil is classified as Murdock silt loam, where soil family is designated as coarse-loamy, mixed, mesic aridic petrocalcic palexerolls (Soil Survey Staff, 2016). The temperature ranges from a mean January Low of -9° Celsius (C) to a mean July high of 30° C. Precipitation from October to September of the establishment year was 352 mm, or 97% of the 30 year AAP. During 2007, 2008, 2009, 2010, and 2011 precipitation was 101, 80, 74, 75, and 131% of long-term AAP respectively (Figure 1).

Site 2 - Cheyenne is positioned 8 km northwest of Cheyenne, WY (41° 10' 36.84" N, 104° 54' 3.96" W) at 1,901 m asl, where AAP is 397 mm. This site is situated in the Level III ecoregion High Plains, Level IV ecoregion Moderate Relief Rangeland. Based on ESD this site is classified as "Loamy 15-17 ppt.". The typical plant community is dominated by cool-season grasses including needle and thread grass (*Hesperostipa comata* [Trin. & Rupr.] Barkworth) and western wheatgrass. The soil type is described as

Altvan loam where soil family is designated as fine-loamy over sandy or sandy-skeletal, mixed, mesic aridic argiustolls (Soil Survey Staff, 2016). The mean January low is -9° C and the mean July high is 28° C. Precipitation from October to September of the establishment year was 433 mm, or 109% of AAP. For the years, 2010 to 2014 annual precipitation was 99, 100, 61, 121, and 109% of AAP respectively (Figure 1).

Site 3 - Malta is located on the Bureau of Land Management (BLM), Lee A. Sharp Experimental Area 14 km East of Malta, ID (42° 18' 6.84" N, 113° 11' 41.99" W) at 1,480 m asl where AAP is 292 mm. Level III and IV ecoregion description are Northern Basin and Range and Saltbush Dominated Valleys. Associated plant species consists of Wyoming big sagebrush and bluebunch wheatgrass with greasewood (*Sarcobatus vermiculatus* [Hook.] Torr.) on the more sodic soils. The soil is described as Declo silt loam, soil family: Coarse-loamy, mixed, mesic xerollic calciorthids (Soil Survey Staff, 2016). The mean January low is -8° C and the mean July high is 30° C. Precipitation from October to September of the establishment year was 397 mm, or 136% of AAP. The subsequent calendar year annual precipitation for 2006 to 2010 was 106, 79, 69, 112, and 114%. of AAP. (Figure 1)

Site 4 - Tintic is located approximately 6 km southwest of Eureka, UT (39° 54' 12.6" N, 112° 8' 58.92" W) at 1,789 m asl where AAP is 415 mm. This site is situated in the level III ecoregion Central Basins and Range. The Level IV ecoregion is Sagebrush Basins and Slopes. Utah Juniper is the dominant species with black sagebrush and Wyoming big sagebrush and an understory of bluebunch wheatgrass, western wheatgrass, bottlebrush squirreltail, and Indian ricegrass. Soil series is Doyce silt loam where soil family is designated as fine-loamy, mixed, mesic aridic calcic argixerolls (Soil Survey Staff, 2016). The mean January low is -10° C and the mean July high is 31° C. Precipitation for October to September of the establishment year was 335 mm, or 81% of AAP. In the years of the study from 2010-2014 the annual precipitation was 110, 105, 86, 77, and 92 of AAP (Figure 1).

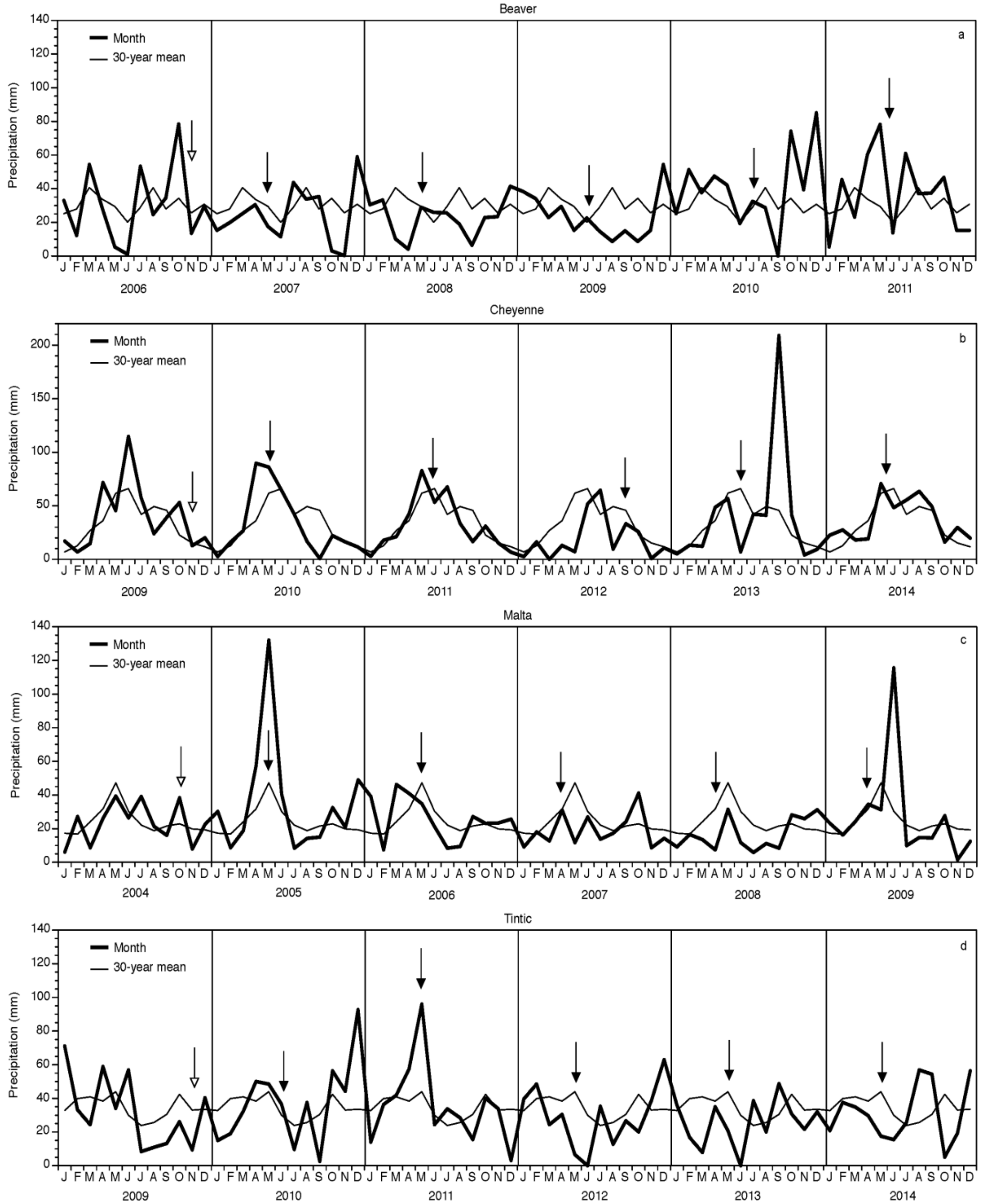

Figure 1. Monthly and long-term mean precipitation for the four study locations: (a) Beaver, (b) Cheyenne, (c) Malta, and (d) Tintic. The thin solid line represents the 30 year mean (1981-2010) and the thick solid line represents the monthly precipitation in the given year. Open arrows are planting dates,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

Site Preparation and Planting

Each site was mechanically tilled one year prior to planting, followed by two subsequent applications of glyphosate (1518 g a.i. ha $^{-1}$) the summer before planting. Just prior to planting, sites were prepared with a field cultivator followed by a harrow or cultipacker to firm the seedbed. Fall dormant seedings were accomplished during November 2006 (Site 1), 2009 (Site 2), 2004 (Site 3), and 2009 (Site 4). 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 0.6 to 1.3 cm. Row spacing was 25.4 cm spacing between rows with six rows per plot and 25.4 cm spacing between plots. Plots were separated length-wise by a 1.5 m border of CD-II crested wheatgrass. Seeded plots were 1.5 m x 6 m long, except at Cheyenne and Malta sites where plots were 3 m x 6 m and 1.5 m x 12 m, respectively. Plots were arranged in a randomized complete block design (RCBD) with four replications at each site.

Seedling Establishment

Seedling frequency percentage, hereafter referred to as seedling frequency, and plant frequency percentage, hereafter referred to stand frequency, is defined as the number of times a species is present in a given number of sampling units expressed as a percentage (Interagency_Technical_Team, 1996). Frequency counts were initiated the spring after planting approximately two months after emergence when the seedling was considered established (Ries and Svejcar, 1991). This was accomplished using the grid system described by Vogel and Masters (2001). Seedling frequency was determined by laying a 12 by 7 grid of 6.25- by 12.5- cm quadrats over the drilled rows. The grid covered four drilled rows (48 quadrats) with three empty grid rows covering the interspaces between rows (36 quadrats) not counted. This was repeated three times over the plot for a total of 144 possible quadrats. Each square containing one or more live seedlings of the seeded entry was scored as present versus absent. Counts were converted to percentage frequency by dividing the number of cells that contained at least one seedling of the target species by the total number of cells. If a plant occurred in every possible quadrat, seedling establishment was considered to be 100%. To avoid border effects only the four center rows were measured. The lineal row length measured in each drilled row was 2.25 m over four rows for a total of measurement length of 9 m of lineal row.

The same procedure was used to determine plant frequency in years two through five, except that the quadrats were 12.5- by 12.5-cm for a total 72 quadrats per plot due to plant size. Frequency counts were taken each year thereafter for the duration of the study (Table 2).

Table 2
Sampling dates for stand frequency counts at four locations all sites were evaluated every year for five years after planting.

Location	Establishment Year	Year 2	Year 3	Year 4	Year 5
Beaver	24-May-2007	6-May-2008	23-Jun-2009	1-Jul-2010	20-Jun-2011
Cheyenne	27-May-2010	15-Jun-2011	18-Sep-2012	4-Jun-2013	20-May-2014
Malta	16-May-2005	19-May-2006	17-Apr-2007	24-Apr-2008	27-Apr-2009
Tintic	1-Jun-2010	16-May-2011	2-May-2012	20-May-2013	1-May-2014

Dry-matter yield (DMY)

Determinations of DMY (kg ha^{-1}) were based on a plot mean basis and were taken at the Cheyenne, WYand Beaver, UT sites. The entire plot was harvested to an 8-cm stubble height by a Swift Current sickle bar harvester or flail chopper (Swift Machining & Welding LTD, Swift Current, SK Canada). Plots were harvested beginning in the third year and were harvested once a year for three years at Cheyenne, WY on 15-Jun-2011, 4-Jun-2013, and 20-May-2014 and at Beaver, UT on 23-Jun-2009, 1-Jul-2010, and 20-Jun-2011. All plots were mowed in October to remove any regrowth prior to the next harvest. Due to drought in Cheyenne, WY during 2012 and subsequent lack of forage growth, a DMY harvest was not taken. Forage samples used to estimate DMY were dried at 60°C in a forced-air oven to constant weight.

Statistical analysis

Data were analyzed within years and locations using the PROC MIXED procedure of SAS statistical software (Vers. 9.4 SAS Inc. Cary, NC). Initially, years and locations were included in the statistical model, but there were numerous interactions of species and cultivars within species with years and locations (Table 3); therefore, data was subsequently re-analyzed by year and location and reported in that manner. Effects due to grass species, and 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 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_Institute, 1999).

This study was conducted to monitor species trends in stand persistence defined as positive or negative changes in plant-frequency percentage from the year after establishment (Y2) to five years after establishment (Y5). Thus, 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). The rate of change in plant frequency percentage from Y2 to Y5, as an estimate of plant persistence, was determined using regression analysis (PROC REG) (SAS_Institute, 1999) procedure with plant frequency percentage as the dependent variable and years as the independent variable.

Table 3
Probability of a > F (based on type III sums of squares, non-additive) from the analysis of variance for seedling establishment (% frequency year 1), plant persistence (% frequency year 5), and dry-matter yield (DMY) in year 3 and 5 after planting. Based on fixed effects.

Source	DF	Seedling Establishment (Y1)	Stand Persistence (Y5)	DF	DMY (Y3)	DMY (Y5)
Species (Sp)	12	<0.0001	<0.0001	12	<0.0001	<0.0001
Cult(Species) (CS)	38	<0.0001	<0.0001	33	<0.0001	<0.0001
Location (L)	3	<0.0001	<0.0001	1	0.0009	0.0445
Sp X L	28	<0.0001	<0.0001	9	0.0001	0.0514
CS X L	40	<0.0001	<0.0001	6	0.0492	0.3418

RESULTS

Location differences

Significant differences between locations were observed for seedling frequency in year one (Y1) ($P < 0.0001$) and plant frequency from year two (Y2) to year five (Y5) ($P < 0.0001$). Seedling frequency averaged 70, 68, 53, and 28% across Malta ID, Beaver UT, Cheyenne WY, and Eureka UT, respectively. At Y5, plant frequency averaged 81, 80, 55, and 23% at Beaver UT, Cheyenne WY, Eureka UT, and Malta, ID respectively. Dry-matter yield averaged 651 and 389 kg ha^{-1} ($P < 0.08$) at Beaver UT and Cheyenne WY, respectively. Location, and its 2^{nd} order interaction with species and cultivars within species were significant ($P < 0.01$) for seedling frequency, plant frequency, and DMY in Y3 (Table 3).

Beaver, UT site

Seedling frequency

Significant ($P < 0.05$) differences for seedling frequency were observed among species in Y1 (Table 4). Among species, seedling frequency ranged from 89% for Siberian wheatgrass to 37% in western wheatgrass. Significantly similar to Siberian wheatgrass was bottlebrush squirreltail (79%). Species with lower seedling frequency than Siberian wheatgrass were crested (77%), bluebunch (75%), intermediate (73%), slender (70%), thickspike (70%), Snake River (69%), and western (37%) wheatgrasses, Indian ricegrass (69%), basin wildrye (54%), and smooth bromegrass (53%). Western wheatgrass (37%) was the only species under 50% seedling frequency at Beaver, UT and had lower seedling frequency than all other species (Table 4).

Differences ($P < 0.05$) in seedling frequency among cultivars within species were observed in bottlebrush squirreltail, basin wildrye, Indian ricegrass, and crested, Siberian, slender, thickspike, and western wheatgrasses (Table 4). Toe Jam Creek bottlebrush squirreltail was similar to Fish Creek (81%) but, had greater seedling frequency compared to Sand Hollow (68%). In basin wildrye, the cultivar Magnar at 41% had less seedling frequency than the cultivars Continental and Trailhead at 61% each, followed by the germplasm Gund at 54%. Nordan crested wheatgrass at 57%, had lower seedling frequency than all other crested wheatgrasses. At 89%, Hycrest II crested wheatgrass had greater seedling frequency compared to CD II (74%) and Douglas (78%), but was similar to Hycrest (86%). Within Indian ricegrass, Nezpar (57%) was similar to Rimrock (72%), in seedling frequency but less than White River (79%). Siberian wheatgrass cultivars Vavilov II (94%) and Stabilizer (90%) had greater seedling frequency than Vavilov at 82%. Seedling frequency between FirstStike, Pryor, and Revenue slender wheatgrasses were similar to each other, but greater than Charleston Peak and San Luis (Table 4). Within western wheatgrass, cultivars Arriba (21%), Rodan (25%), and Barton (36%) had seedling frequency lower than Recovery (54%).

Plant frequency/stand persistence

All species studied saw an increase in plant frequency from Y1 to Y2. Contributing to this difference was the change in frequency gird size from 78 cm^2 to 156 cm^2 used in subsequent years to quantify plant frequency. Hence, trends in plant frequency were calculated between 2008 (Y2) and 2011 (Y5) when the grid size remained constant (Interagency_Technical_Team, 1996).

Positive linear trends ($P < 0.05$) in plant frequency were observed in thickspike and western wheatgrasses from Y2 to Y5 each increasing in plant frequency by 4 and 6% per year, respectively. Negative linear trends ($P < 0.05$) in plant frequency were observed in bottlebrush squirreltail, Indian ricegrass, slender, and Siberian wheatgrasses from Y2 to Y5 each declining by 2, 9, 7, and 1% per year, respectively.

A significant ($P < 0.01$) negative linear trend in plant frequency observed in bottlebrush squirreltail germplasm Sand Hollow of 5% per year between Y2 and Y5 contributed to the overall negative decline in bottlebrush squirreltail. Plant frequency in Indian ricegrass declined from 80 to 54% from Y2 to Y5. Within cultivars of Indian ricegrass, a negative trend in plant frequency was observed in Nezpar and Rimrock declining by 15% ($P < 0.01$) and 8% ($P < 0.01$) a year, respectively. White River Indian ricegrass showed non-significant trends in plant frequency. (Table 4). As expected in slender wheatgrass, a short-lived perennial, plant frequency declined from 83 to 62% from Y2 to Y5. Significant ($P < 0.05$) negative linear trends in plant frequency from Y2 to Y5 were observed in Charleston Peak, FirstStrike, Revenue, and San Luis at 7, 8, 13, and 6%, respectively (Table 4). A negative decline in plant frequency observed in Vavilov Siberian wheatgrass of 2% per year between Y2 and Y5 contributed to a significant ($P < 0.05$) overall negative trend of 1% in Siberian wheatgrass. Non-significant linear trends in plant frequency were observed in basin and Russian wildryes, crested, intermediate, bluebunch, and Snake River wheatgrasses, and smooth bromegrass (Table 4).

Dry-matter yield

Significant ($P < 0.05$) differences between species was observed for mean DMY in 2009 ranging from 2029 kg ha^{-1} in intermediate wheatgrass to 493 kg ha^{-1} in bottlebrush squirreltail (Table 5). By 2011, intermediate wheatgrass still ranked first with 887 kg DMY ha^{-1}, however, crested, bluebunch, and western wheatgrass, basin and Russian wildryes, and smooth bromegrass had statistically ($P < 0.05$) similar DMY (Table 5).

Differences ($P < 0.05$) in DMY between cultivars within species were observed within thickspike, western, Siberian, and slender wheatgrasses, Indian ricegrass, and bottlebrush squirrtail (Table 5). Within thickspike wheatgrass in 2009, Bannock (1062 kg ha^{-1}) and Bannock II (978 kg ha^{-1}) had significantly higher DMY than Critana (482 kg ha^{-1}). In 2009 the Siberian wheatgrass cultivar Stabilizer (341 kg ha^{-1}) had lower ($P < 0.05$) DMY than Vavilov (812 kg h^{-1}) and Vavilov II (719 kg ha^{-1}). Among slender wheatgrass cultivars, FirstStrike (861 kg ha^{-1}) and Pryor (1059 kg ha^{-1}) had significantly higher DMY than Charleston Peak (318 kg ha^{-1}), Revenue (231 kg ha^{-1}), or San Luis (447 kg ha^{-1}). In Indian ricegrass, White River (1131 kg ha^{-1}) had significantly greater DMY than Rimrock (407 kg ha^{-1}) in 2009 and had significantly higher DMY than Nezpar in all three years of harvesting (Table 5).

Correlations between both seedling frequency (Y1) and DMY or plant frequency (Y2-Y5) and DMY were non-significant except between plant frequency at Y5 and DMY in 2011 ($r = 0.66$; $P = 0.0139$) (Table 6). Mean species ranking for rate of DMY decline between 2009 and 2011 were intermediate wheatgrass > Snake River wheatgrass >

crested wheatgrass > slender wheatgrass > Russian wildrye > Indian ricegrass > thickspike wheatgrass > Siberian wheatgrass > bluebunch wheatgrass > basin wildrye > smooth bromegrass > bottlebrush squirreltail > western wheatgrass.

Table 4

Means and trends in stand persistence of 13 grass species across five years at Site 1 (Beaver) from 2007 to 2011. Ranked by species 2007 seedling frequency. Values followed by different letters significantly differ at P<0.05 (LSD).

	Establishment %	Years after Establishment Frequency %				Slope	Trends†	
Species	2007	2008	2009	2010	2011	bŦ	Linear	Quadratic
Siberian WG	88 A	96 A	97 A	97 A	93 AB	-1	32 *	63 **
Stabilizer	90 ab	97 a	99 a	98 ab	98 a	0	4 ns	6 ns
Vavilov	82 b	92 b	95 b	95 b	85 b	-2	30 **	67 **
Vavilov II	94 a	99 a	97 ab	100 a	95 a	-1	27 ns	15 ns
Bottlebrush ST	79 AB	89 AB	88 ABC	88 B	82 CD	-2	80 **	15 ns
Fish Creek	81 ab	93 a	93 a	93 a	91 a	-1	39 ns	52 ns
Sand Hollow	68 b	81 b	77 b	76 b	64 b	-5	86 **	9 ns
Toe Jam Creek	87 a	94 a	94 ab	94 a	91 a	-1	69 ns	28 ns
Crested WG	77 B	86 B	90 AB	90 AB	85 BC	-1	0 ns	99 *
CD II	74 c	83 a	87 ab	82 b	82 a	-1	21 ns	22 ns
Douglas	78 bc	90 a	92 a	94 a	88 a	-1	7 ns	82 ns
Hycrest	86 ab	91 a	93 a	92 a	86 a	-1	41 ns	59 ns
Hycrest II	89 a	91 a	92 a	94 a	90 a	0	1 ns	81 ns
Nordan	57 d	74 b	85 b	86 ab	81 a	2	26 ns	73 *
Bluebunch WG	75 B	87 AB	91 AB	90 B	86 ABC	-1	2 ns	97 **
Anatone	71 a	86 a	89 a	91 a	87 a	-1	7 ns	87 *
Goldar	76 a	86 a	92 a	89 a	87 a	0	0 ns	68 ns
P-7	77 a	88 a	92 a	91 a	84 a	-1	21 *	79 **
Intermediate WG	73 BC	87 AB	88 ABCD	86 ABC	89 ABC	1	28 ns	26 ns
Slender WG	70 BC	83 B	81 CDE	70 D	62 FG	-7	95 **	2 ns
Charleston Peak	43 b	65 b	61 b	44 b	47 b	-7	76 *	5 ns
FirstStrike	84 a	93 a	91 a	81 a	71 a	-8	94 **	5 ns
Pryor	84 a	88 a	88 a	86 a	80 a	-3	80 ns	22 ns
Revenue	87 a	93 a	90 a	73 a	56 a	-13	93 **	6 ns
San Luis	50 b	75 ab	74 ab	66 a	58 a	-6	94 *	5 ns
Thickspike WG	70 BC	82 B	92 AB	92 AB	94 A	4	76 **	17 ns
Bannock	73 ab	84 a	92 a	95 a	97 a	4	88 **	11 ns
Bannock II	59 b	82 a	92 a	95 a	97 a	5	84 *	14 ns
Critana	74 ab	82 a	91 a	94 a	93 a	4	71 *	29 ns
Sodar	77 ab	84 a	92 a	89 a	94 a	3	68 *	2 ns
Schwendimar	67 ab	78 a	91 a	85 a	89 a	3	37 ns	23 ns
Indian ricegrass	69 BC	80 BC	77 DE	69 D	54 G	-9	93 **	7 ns
Nezpar	57 b	71 b	57 b	52 b	22 b	-15	91 **	5 ns
Rimrock	72 ab	84 a	86 a	68 ab	62 a	-8	85 **	3 ns
White River	79 a	86 a	87 a	86 a	79 a	-2	56 ns	42 ns
Snake River WG	69 BC	81 BC	84 BCD	85 BC	72 DE	-3	31 ns	61 *
Discovery	79 a	86 a	88 a	89 a	70 a	-5	48 **	44 **
Secar	60 a	75 b	80 a	81 b	74 a	0	1 ns	96 ns
Russian WR	62 C	80 BC	82 BCDE	88 AB	84 BCD	1	33 ns	40 ns
Bozoisky-Select	72 a	88 a	92 a	95 a	88 a	0	0 ns	92 *
Bozoisky II	70 a	87 a	89 a	95 a	90 a	2	37 *	30 *
Swift	54 a	73 a	74 a	82 a	79 a	3	65 ns	7 ns
Basin WR	54 D	70 D	73 E	76 CD	67 EF	0	4 ns	80 **
Continental	61 a	79 a	80 a	77 a	77 a	-1	49 ns	2 ns
Gund	54 a	58 b	69 a	75 a	60 ab	1	5 ns	86 *
Magnar	41 b	71 ab	67 a	71 a	56 ab	-4	57 *	18 ns
Trailhead	61 a	71 ab	76 a	81 a	73 b	1	12 ns	77 *
Smooth bromegrass	53 D	80 BCD	76 CDE	82 BC	83 ABCD	3	37 ns	22 ns
Western WG	37 E	72 CD	87 BC	89 AB	91 AB	6	79 **	18 **
Arriba	21 c	63 bc	74 a	74 a	68 a	2	14 ns	84 ns
Barton	36 bc	72 abc	87 a	86 a	94 a	7	82 **	5 ns
Recovery	54 a	84 a	95 a	99 a	100 a	5	84 **	15 ns
Rodan	24 c	59 c	83 a	87 a	95 a	11	87 **	9 ns
Rosana	51 ab	81 ab	94 a	99 a	98 a	6	74 *	26 ns

Uppercase letters denote significance among species, lowercase letters denote significance within species.

† Orthogonal polynomial trends expressed as percent of year sums of squares due to linear and quadratic effects.

Ŧb Regression coefficients of % frequency from 2008 to 2011.

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

Table 5

Means of Dry-matter yield (DMY) of 13 grass species across three years at Site 1 (Beaver) ranked by 2009 DMY. Values followed by different letters significantly differ at P<0.05 (LSD). Uppercase letters denote significance among species; lowercase letters denote significance within species.

	DMY (kg ha^{-1})					
Species	2009 (Y3)		2010 (Y4)		2011 (Y5)	
Intermediate WG	2029	A	1045	AB	887	A
Snake River WG	1009	BC	746	BCD	339	DEF
Discovery	1079	a	523	a	403	a
Secar	939	a	970	a	274	a
Crested WG	1003	BC	817	B	584	ABCD
CD II	1098	a	810	ab	427	a
Douglas	570	b	795	ab	730	a
Hycrest	1157	a	817	ab	485	a
Hycrest II	972	a	644	b	635	a
Nordan	1219	a	1017	a	643	a
Russian WR	976	BC	715	BCD	637	ABC
Bozoisky-Select	994	ab	662	a	530	a
Bozoisky II	1242	a	849	a	850	a
Swift	692	b	633	a	532	a
Thickspike WG	783	BCD	430	F	563	BCD
Bannock	1062	a	472	a	974	a
Bannock II	978	a	373	a	517	ab
Critana	482	b	611	a	394	b
Sodar	503	b	307	a	465	ab
Schwendimar	890	a	389	a	646	ab
Bluebunch WG	782	BCD	707	BCDE	648	ABC
Anatone	777	a	714	a	557	a
Goldar	756	a	739	a	784	a
P-7	813	a	668	a	605	a
Basin WR	735	CDE	1088	A	628	ABC
Continental	801	a	1211	a	686	a
Gund	539	a	931	a	671	a
Magnar	942	a	1079	a	524	a
Trailhead	659	a	1126	a	633	a
Western WG	672	DE	790	BC	765	AB
Arriba	702	ab	1200	a	728	ab
Barton	807	a	814	ab	938	a
Recovery	891	a	846	ab	903	ab
Rodan	657	ab	647	b	708	ab
Rosana	304	b	442	b	549	b
Indian ricegrass	630	DE	526	DEF	314	EF
Nezpar	351	b	80	c	49	b
Rimrock	407	b	41	b	240	b
White River	1131	a	1090	a	654	a
Smooth bromegrass	628	DE	938	AB	609	ABCD
Siberian WG	624	DE	555	CDEF	451	CDEF
Stabilizer	341	b	333	b	310	b
Vavilov	812	a	604	ab	590	a
Vavilov II	719	a	727	a	453	ab
Slender WG	583	DE	123	G	222	F
Charleston Peak	318	b	0	a	175	ab
FirstStrike	861	a	186	a	48	b
Pryor	1059	a	277	a	369	a
Revenue	231	b	17	a	173	ab
San Luis	447	b	134	a	347	a
Bottlebrush ST	493	E	444	EF	560	BCDE
Fish Creek	304	a	451	a	464	b
Sand Hollow	485	a	407	a	144	c
Toe Jam Creek	691	a	474	a	787	a

Cheyenne, WY site

Seedling frequency

Significant ($P < 0.05$) differences were observed between species for seedling frequency (Table 7). Between species, seedling frequency ranged from 15% in western wheatgrass to 82% in Russian wildrye. Seedling frequencies in meadow bromegrass (81%), intermediate (78%) and Siberian (65%) wheatgrasses, and basin wildrye (69%) were similar to Russian wildrye. Species with less seedling frequency than Russian wildrye were crested (59%), slender (50%), smooth bromegrass (48%), thickspike (44%), Snake River (37%), bluebunch (36%), and western (15%) wheatgrasses.

Differences ($P < 0.05$) between cultivars within meadow bromegrass, slender and thickspike wheatgrasses were observed for seedling frequency (Table 7). Arsenal (88%) meadow bromegrass had greater seedling frequency than did the cultivar Cache (75%). Slender wheatgrass cultivar, FirstStrike (89%) had higher seedling frequency compared to Pryor (11%). Seedling frequency of Critana thickspike wheatgrass (14%) was lower than Bannock (69%) and Bannock II (49%).

Plant frequency/stand persistence

Trends in plant frequency as an estimate of stand persistence were taken between 2011 through 2014. Positive linear relationships ($P < 0.05$) between 2011 and 2014 in plant frequency were observed in crested, Siberian, and western wheatgrasses each increasing by 3, 4, and 4% plant frequency per year, respectively (Table 7). Species experiencing a significant ($P < 0.05$) linear decline in plant frequency were Basin wildrye and slender wheatgrass, each declining by 13% per year. Plant frequency declined 15 and

11% per year in basin wildrye cultivars Trailhead and Trailhead II, respectively. Plant frequency in FirstStrike slender wheatgrass declined by 18% per year from 2011 to 2014 compared to an 8% decrease per year observed in Pryor slender wheatgrass.

Significant ($P < 0.05$) quadratic trends were observed in basin wildrye, smooth bromegrass, and bluebunch wheatgrass (Table 7). A 45% decrease in plant frequency between 2011 and 2012 in basin wildrye contributed to the quadratic effect. Smooth bromegrass plant frequency declined by 13% between 2011 and 2012 followed by a 21% increase from 2013 to 2014. A decline of 14% in bluebunch wheatgrass plant frequency from 2012 to 2013 followed by a 23% increase between 2013 and 2014 contributed to the observed quadratic effects.

Seedling frequency in 2010 was correlated with plant frequency in 2011 ($r = 0.69$; $P = 0.0003$). There were no correlations between seedling frequency and plant frequency in subsequent years 2012, 2013, and 2014. Correlations between plant frequency and the following year were always the strongest and declined each succeeding year (Table 6).

Significant ($P < 0.05$) differences between species were observed for mean DMY in 2011, 2013, and 2014 (Table 8). Crested wheatgrass mean DMY ranked highest in 2011 (1946 kg ha^{-1}), 2013 (844 kg ha^{-1}), and 2014 (472 kg ha^{-1}), which was similar to Siberian wheatgrass in all three years and Russian wildrye and bluebunch wheatgrass in 2014 (Table 8). As plant stands matured, a decrease in DMY from 2011 to 2014 was observed across all species and ranged from 17 to 500 kg ha^{-1} per year reduction in DMY in bluebunch and Siberian wheatgrasses, respectively. With the exception of bluebunch wheatgrass cultivars in 2011 and western wheatgrass cultivars in 2014, there were no observed differences between cultivars within species (Table 8). In 2011, P-7 (496 kg ha^{-1}) had greater DMY than Anatone at 237 kg ha^{-1} but had similar DMY in 2013 and 2014. By 2014 western wheatgrass cultivar, Recovery (172 kg ha^{-1}) had greater ($P < 0.05$) DMY than Rosana (105 kg ha^{-1}).

Significant correlations between plant frequency in 2013 (Y4) and 2014 (Y5) and DMY in 2013 (Y4) ($r = 0.63$; $P = 0.0021$ and $r = 0.52$; $P = 0.0148$) and 2014 (Y5) ($r = 0.64$; $P = 0.0018$ and $r = 0.62$; $P = 0.0025$) were observed. (Table 6).

Table 6
Correlations for frequency in year one establishment (Est), year two (Y2), year three (Y3), year four (Y4), year five (Y5), dry matter yield year three (DMY_Y3), dry matter yield year four (DMY_Y4), and dry matter yield year five (DMY_Y5). Top diagonal is the Beaver, UT location; the bottom diagonal is the Cheyenne, WY location

	Est	Y2	Y3	Y4	Y5	DMY_Y3	DMY_Y4	DMY_Y5
		0.8899	0.62231	0.4260	0.2462	0.1191	-0.2357	-0.2005
Est	1.0000	< 0.0001	< 0.0001	0.0049	0.1160	0.4526	0.1329	0.2088
	0.6898		0.7679	0.5669	0.4205	0.1461	-0.2075	-0.0736
Y2	0.0003	1.0000	<0.0001	<0.0001	0.0056	0.3558	0.1873	0.6473
	0.2263	0.7003		0.8708	0.8230	0.2214	0.0020	0.2910
Y3	0.2990	0.0002	1.0000	<0.0001	<0.0001	0.1588	0.9901	0.0649
	0.0967	0.5577	0.7709		0.9109	0.3178	0.3054	0.5263
Y4	0.6606	0.0057	<0.0001	1.0000	<0.0001	0.0403	0.0492	.0004
	-0.0219	0.4409	0.7982	0.8852		0.3119	0.2633	0.5966
Y5	0.9211	0.0352	<0.0001	<0.0001	1.0000	0.0443	0.0920	<0.0001
	0.4669	0.6211	0.4498	0.3476	0.3435		0.5151	0.4749
DMY_Y3	0.0329	0.0027	0.0408	0.1226	0.1274	1.0000	0.0005	0.0017
	0.2342	0.3429	0.4694	0.6286	0.6396	0.7191		0.6240
DMY_Y4	0.3068	0.1281	0.0318	0.0021	0.0018	0.0002	1.0000	<0.0001
	0.2536	0.3499	0.4794	0.5238	0.6235	0.4924	0.8194	
DMY_Y5	0.2673	0.1200	0.0279	0.0148	0.0025	0.0234	<0.0001	1.000

Table 7
Means and trends in seedling establishment and stand persistence of 12 grass species across five years at Site 2 (Cheyenne) from 2010 to 2014. Ranked by species 2010 frequency. Values followed by a different letter are significantly different at P<0.05 (LSD). Uppercase letters denote significance among species; lowercase letters denote significance within species.

	Establishment %	Years after Establishment Frequency %				Slope	Trends†	
Species	2010	2011	2012	2013	2014	b‡	Linear	Quadratic
Russian WR								
Bozoisky II	82 A	98 A	96 A	98 AB	100 A	1	33 ns	62 ns
Meadow BG	81 A	98 A	96 A	99 A	99 A	1	57 ns	5 ns
Cache	75 a	96 a	94 a	100 a	100 a	2	66 ns	2 ns
Arsenal	88 a	98 a	97 a	98 a	98 a	0	0 ns	48 ns
Intermediate WG	78 AB	94 A	88 ABC	78 BC	88 AB	-3	43 ns	29 ns
Luna	79 a	91 a	86 a	78 a	80 a	-4	78 ns	13 ns
Oahe	77 a	97 a	90 a	78 a	95 a	-2	6 ns	67 *
Basin WR	69 AB	77 CD	42 E	40 E	33 D	-13	78 **	16 **
Trailhead	66 a	73 a	23 b	28 a	20 a	-15	64 **	24 **
Trailhead II	72 a	80 a	61 a	53 a	45 a	-11	95 **	5 ns
Siberian WG								
Vavilov II	65 ABC	89 ABC	86 ABCD	95 AB	100 A	4	75 *	14 ns
Crested WG								
Hycrest II	59 BCD	91 AB	91 ABC	93 AB	100 A	3	77 *	20 ns
Slender WG	50 CDE	90 AB	82 BCD	50 DE	56 C	-13	78 **	4 ns
FirstStrike	89 a	96 a	89 a	45 a	50 a	-18	80 **	2 ns
Pryor	11 b	83 b	75 a	55 a	63 a	-8	71 *	13 ns
Smooth BG								
Manchar	48 CDE	88 ABC	77 CD	78 BC	98 AB	3	16 ns	84 **
Thickspike WG	44 DE	80 BCD	78 CD	63 CD	78 B	-2	13 ns	33 ns
Bannock	69 a	91 a	87 a	80 a	78 a	-5	97 ns	1 ns
Bannock II	49 a	69 a	66 a	78 a	63 a	-5	16 ns	32 ns
Critana	14 b	79 a	82 a	32 b	93 a	4	45 ns	23 ns
Snake River WG	37 E	72 D	74 D	69 C	76 B	1	1 ns	23 ns
Discovery	38 a	76 a	78 a	73 a	85 a	2	26 ns	34 ns
Secar	35 a	68 a	70 a	65 a	68 a	-1	17 ns	1 ns
Bluebunch WG	36 E	76 CD	76 CD	65 CDE	84 AB	1	5 ns	47 *
Anatone	24 a	63 b	64 b	55 a	78 a	3	23 ns	46 ns
P-7	49 a	88 a	89 a	75 a	90 a	-1	2 ns	36 *
Western WG	15 F	76 CD	81 BCD	89 AB	86 AB	4	76 **	13 ns
Recovery	14 a	75 a	78 b	88 a	80 a	2	36 ns	29 ns
Rosana	16 a	78 a	84 a	90 a	93 a	5	97 *	2 ns

† Orthogonal polynomial trends expressed as percent of year sums of squares due to linear and quadratic effects.
‡b Regression coefficients of % stand frequency from 2011 to 2014.
*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

Table 8
Means in Dry-matter yield (DMY) of 12 grass species across five years at Site 2 (Cheyenne) from 2011, 2013, and 2014. Ranked by species 2011 DMY. Values followed by different letters differ at P<0.05 (LSD), uppercase letter denote significance among species, lowercase letter denote significance within species.

	DMY (kg ha^{-1})					
Species	2011		2013		2014	
Crested WG (Hycrest II)	1946	A	844	A	472	A
Siberian WG (Vavilov II)	1329	AB	696	A	393	ABC
Meadow BG	1064	BC	381	B	221	BCD
Cache	960	a	390	a	188	a
Arsenal	1167	a	371	a	255	a
Slender WG	961	BC	78	E	114	D
FirstStrike	1092	a	89	a	110	a
Pryor	830	a	70	a	118	a
Intermediate WG	846	C	240	CD	224	BCD
Luna	701	a	245	a	177	a
Oahe	991	a	234	a	270	a
Smooth BG (Manchar)	845	CD	253	BCD	251	BCD
Russian WR (Bozoisky II)	456	DE	400	B	408	AB
Snake River WG	400	E	291	BC	200	CD
Discovery	419	a	286	a	225	a
Secar	380	a	295	a	174	a
Basin WR	394	E	27	E	74	D
Trailhead	336	a	14	a	49	a
Trailhead II	459	a	39	a	99	a
Bluebunch WG	385	E	281	BC	348	ABC
Anatone	237	b	317	a	332	a
P-7	496	a	237	a	365	a
Thickspike WG	381	E	117	DE	171	D
Bannock	472	a	177	a	286	a
Bannock II	375	a	64	a	165	a
Critana	295	a	113	a	63	a
Western WG	223	E	130	DE	140	D
Recovery	239	a	140	a	172	a
Rosana	206	a	119	a	105	b

Malta, ID site

Seedling frequency

Significant ($P < 0.05$) differences in seedling frequency (2005) were observed between species (Table 10). At 93% seedling frequency, crested and Siberian wheatgrasses had greater seedling frequency than all other species (Table 6). Seedling frequency between Snake River (79%) and bluebunch (82%) wheatgrasses were similar but greater ($P < 0.05$) than slender (66%) and western (53%) wheatgrasses, Russian wildrye (64%), bottlebrush squirreltail (60%), and Indian ricegrass (60%) (Table 10).

Significant ($P < 0.05$) differences in seedling frequency were observed between cultivars of bottlebrush squirreltail, Indian ricegrass, bluebunch, slender, and western wheatgrasses (Table 10). Sand Hollow bottlebrush squirreltail (46%) had lower seedling frequency compared to Toe Jam Creek (69%) and Fish Creek (64%). White River Indian ricegrass (86%) had higher seedling frequency than Nezpar (32%) and Rimrock (61%). Bluebunch wheatgrass germplasm P-7 at 88% had higher ($P < 0.05$) seedling frequency than Anatone (80%) and Goldar (79%). Pryor slender wheatgrass had less ($P < 0.05$) seedling frequency (36%) compared to 86 and 76% for FirstStrike and San Luis slender wheatgrass, respectively. Recovery western wheatgrass (68%) had greater ($P < 0.05$) seedling frequency than Arriba (41%), Barton (55%), Rodan (56%), and Rosana (45%) (Table 10).

Plant frequency/stand persistence

Negative linear trends ($P < 0.05$) were observed for plant frequency from 2006 to 2009 in all species examined (Table 10). The rate of decline within species for plant frequency ranged from 8 to 16% per year in slender and Snake River wheatgrass, respectively (Table 10). By 2009, plant frequency in crested, Siberian, and Snake wheatgrasses and Russian wildrye were similar at 48, 39, 49, and 24%, respectively (Table 10). Other species showed a larger decrease in plant frequency by 2009 (Y5), including: bluebunch wheatgrass (11%), slender wheatgrass (0%), bottlebrush squirreltail (7%), and Indian ricegrass (1%).Five years after planting no differences were observed between cultivars within species (Table 10).

Significant ($P > 0.0166$) correlations between percentage seedling frequency and subsequent percentage plant frequency from 2006 ($r = 0.73$; $P < 0.0001$), 2007 ($r = 0.62$; $P = 0.0008$), 2008 (r 0.59; $P = 0.0015$), and 2009 ($r = 0.47$; $P = 0.0166$) were observed (Table 9). This suggests that initial seedling frequency is a predictor of plant frequency percentage, particularly, 2 to 3 years post planting.

Table 9
Correlations for frequency in year one establishment (Est), year two (Y2), year three (Y3), year four (Y4), and year five (Y5). Top diagonal is the Malta, ID location; the bottom diagonal is the Tintic, UT location.

	Est	Y2	Y3	Y4	Y5	
Est	1.0000	0.7265 <0.0001	0.6168 0.0008	0.5907 0.0015	0.4652 0.0166	
Y2	0.7114 <0.0001	1.0000	0.9384 <0.0001	0.92739 <0.0001	0.8019 <0.0001	
Y3	0.5430 0.0005	0.7313 <0.0001	1.0000	0.9706 <0.0001	0.8610 <0.0001	
Y4	0.3612 0.0281	0.5355 0.0006	0.5724 0.0002	1.0000	0.8895 <0.0001	
Y5	0.2425 0.1482	0.4162 0.0104	0.3693 0.0245	0.8326 <0.0001	1.0000	

Table 10

Means and trends in seedling establishment and plant persistence of 10 grass species across five years at Site 3 (Malta) from 2005 to 2009. Ranked by species 2005 seedling frequency. Values followed by different letters differ at P<0.05 (LSD), uppercase letter denote significance among species, lowercase letter denote significance within species.

	Establishment %	Years after Establishment Frequency %				Slope	Trends†	
Species	2005	2006	2007	2008	2009	b‡	Linear	Quadratic
Crested WG	93 A	95 A	91 A	87 A	48 A	-15	74 **	22 *
CD II	93 a	94 a	92 a	88 a	55 a	-12	73 **	24 ns
Hycrest	92 a	93 a	89 a	82 a	52 a	-13	81 **	17 ns
Hycrest II	94 a	97 a	93 a	90 a	36 a	-18	69 **	25 *
Siberian WG	93 A	96 A	94 A	92 A	49 A	-14	67 **	27 **
Stabilizer	92 a	99 a	95 a	96 a	71 a	-17	68 **	23 *
Vavilov	92 a	91 a	89 b	86 a	36 a	-18	67 **	27 *
Vavilov II	95 a	100 a	98 a	95 a	42 a	-8	67 **	28 *
Bluebunch WG	82 B	50 CD	48 BC	25 C	11 CD	-14	92 **	3 ns
Anatone	80 b	58 a	61 a	38 a	17 a	-15	86 **	11 ns
Goldar	79 b	23 b	22 b	2 b	0 a	-9	86 **	0 ns
P-7	88 a	69 a	62 a	35 a	15 a	-19	96 **	2 ns
Snake River WG	79 B	78 AB	82 A	80 A	24 ABCD	-16	57 **	38 **
Slender WG	66 C	22 E	14 D	3 D	0 D	-8	96 *	2 ns
FirstStrike	86 a	38 a	34 a	9 a	0 a	-14	93 *	0 ns
Pryor	36 b	10 b	7 ab	0 a	0 a	-4	90 ns	3 ns
San Luis	76 a	16 b	0 b	0 a	0 a	-5	60 ns	33 ns
Russian WR	64 C	68 BC	60 B	49 B	39 AB	-10	99 **	0 ns
Bozoisky-Select	61 a	57 b	55 a	45 a	45 a	-5	86 ns	1 ns
Bozoisky II	67 a	79 a	66 a	53 a	33 a	-15	99 **	1 ns
Bottlebrush ST	60 CD	49 CD	36 C	28 C	7 CD	-13	97 **	1 ns
Fish Creek	64 ab	60 a	51 a	40 a	6 a	-17	90 **	9 *
Sand Hollow	46 b	39 a	27 a	17 a	3 a	-12	100 **	0 ns
Toe Jam Creek	69 a	49 a	29 a	28 a	13 a	-11	91 **	1 ns
Indian ricegrass	60 CD	30 E	10 E	4 D	1 CD	-9	82 **	14 **
Nezpar	32 c	14 b	3 b	0 b	0 a	-5	76 **	23 *
Rimrock	61 b	23 b	5 b	1 b	1 a	-7	74 **	25 *
White River	86 a	54 a	21 a	12 a	2 a	-16	90 **	8 ns
Western WG	53 D	48 D	51 B	37 BC	20 BC	-10	82 **	17 ns
Arriba	41 c	32 a	51 a	38 a	31 a	-2	5 ns	68 ns
Barton	55 b	55 a	44 a	31 a	12 a	-14	98 **	2 ns
Recovery	68 a	73 a	56 a	38 a	20 a	-18	100 **	0 ns
Rodan	56 b	49 a	59 a	43 a	22 a	-10	64 ns	33 ns
Rosana	45 c	32 a	45 a	37 a	17 a	-6	37 ns	63 ns

† Orthogonal polynomial trends expressed as percent of year sums of squares due to linear and quadratic effects.

‡b Regression coefficients of % stand frequency from 2006 to 2009.

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

Tintic, UT site

Seedling frequency

Differences ($P < 0.05$) between species for seedling frequency were observed (Table 11). Overall, seedling frequency at this site was less than the other sites with a mean overall seedling frequency of 27% and ranged from 15% in Russian wildrye to 46% in intermediate wheatgrass (Table 11). Similar to intermediate wheatgrass in seedling frequency was meadow bromegrass at 42%. Unlike previous locations, crested (17%) and Siberian (21%) wheatgrasses had seedling frequency less ($P < 0.05$) than intermediate wheatgrass, meadow bromegrass, and slender wheatgrass (39%), but similar to bottlebrush (31%), bluebunch (26%), Snake River (32%), thickspike (19%), and western (21%) wheatgrasses and basin (25%) and Russian wildryes (15%) (Table 11).

Cultivars differences ($P < 0.05$) within bluebunch, slender, Snake River, and western wheatgrasses, basin wildrye, meadow bromegrass were observed. Bluebunch wheatgrass germplasm, P-7 (43%), had greater seedling frequency compared to Anatone (10%) and Goldar (26%). Seedling frequency for FirstStrike (53%) was greater than either Pryor (33%) or San Luis (29%) slender wheatgrass. Secar Snake River wheatgrass (45%) had greater seedling frequency than Discovery (18%) but, by the second year, they were similar in plant frequency at 61 and 65% stand respectively. Western wheatgrass cultivars Arriba (28%) and Rosana (22%) had greater seedling frequency than Recovery at 11% (Table 11). By Y4, all western wheatgrass cultivars were similar with greater than 80% plant frequency. Trailhead II (48%) basin wildrye had greater seedling frequency than Trailhead (23%), Magnar (3%), or Continental (24%). Arsenal meadow bromegrass at 57% seedling frequency was greater than cultivars Cache (37%) and Regar (32%).

Plant frequency/stand persistence

Based on orthogonal polynomials, trends in plant frequency were less informative at this site. Negative linear ($P < 0.05$) trends from 2011 to 2014 for plant frequency were observed in Bottlebrush squirreltail and intermediate and slender wheatgrasses, each declining by 15, 4, and 17% plant frequency per year, respectively (Table 11). Significant ($P < 0.05$) quadratic trends were observed in smooth bromegrass, Siberian, and thickspike wheatgrasses. Contributing to this effect was an increase in plant frequency from 2011 to 2012 followed by a decline in plant frequency from 2012 to 2014 in smooth bromegrass and thickspike wheatgrass (Table 11).

Within bottlebrush squirreltail germplasm, Toe Jam Creek had greater plant frequency in 2014 than did Fish Creek. Similarly, P-7 and Goldar bluebunch wheatgrass had greater plant frequency compared to Anatone (Table 11). Magnar basin wildrye had lower plant frequency than the other basin wildrye cultivars (Table 10). FirstStrike slender wheatgrass had higher plant frequency than cultivars Pryor or San Luis (Table 11). Bannock and Bannock II thickspike wheatgrass had greater plant frequency in 2014 than Critana (Table 11).

As with previous locations, observed correlations between seedling frequency (2010) and subsequent plant frequency from 2011 ($r = 0.71$; $P < 0.0001$), 2012 ($r = 0.54$; $P = 0.0005$), 2013 (r 0.36; $P = 0.0015$), and 2014 ($r = 0.24$; $P = 0.1482$) decreased with each succeeding year (Table 9)

Table 11

Means and trends in seedling establishment and stand persistence of 13 grass species across five years at Site 4 (Tintic), from 2010 to 2014. Ranked by 2010 seedling frequency. Values followed by different letters differ at P<0.05 (LSD), uppercase letter denote significance among species, lowercase letter denote significance within species.

	Establishment %	Years after Establishment Frequency %				Slope	Trends†	
Species	2010	2011	2012	2013	2014	b[ᵀ]	Linear	Quadratic
Intermediate WG	46 A	81 A	67 ABC	69 B	67 B	-4	59 *	27 ns
Luna	40 a	88 a	72 ab	70 a	73 a	-5	56 ns	41 ns
Oahe	60 a	82 a	84 a	70 a	73 a	-4	60 ns	0 ns
Rush	54 a	85 a	55 b	70 a	58 a	-7	39 **	14 *
Meadow BG	42 AB	69 BCD	69 ABCD	62 BC	61 BCDE	-3	82 ns	1 ns
Arsenal	57 a	83 a	74 a	75 a	75 a	-2	50 ns	39 ns
Cache	37 b	61 a	60 a	50 a	53 a	-4	70 ns	3 ns
Regar	32 b	62 a	73 a	60 a	55 a	-3	35 ns	36 ns
Slender WG	39 B	80 A	75 AB	53 CD	30 H	-17	94 **	5 ns
FirstStrike	53 a	94 a	75 a	73 a	48 a	-14	92 **	1 ns
Pryor	33 b	73 b	79 a	55 b	30 b	-15	80 **	17 **
San Luis	29 b	73 b	70 a	30 c	13 c	-22	92 **	2 ns
Snake River WG	32 BC	62 DE	66 BCDE	63 BC	63 BCD	0	0 ns	44 ns
Discovery	18 b	65 a	61 a	63 a	68 a	1	18 ns	82 ns
Secar	45 a	61 a	68 a	63 a	58 a	-1	6 ns	78 ns
Bottlebrush ST	31 BC	75 ABC	68 ABCD	40 D	35 GH	-15	92 **	0 ns
Toe Jam Creek	34 a	76 a	60 a	55 a	50 a	-8	90 *	8 ns
Fish Creek	29 a	74 a	76 a	25 b	20 b	-21	83 **	0 ns
Bluebunch WG	26 CD	59 DE	54 EF	63 BC	63 BC	2	32 ns	16 ns
Anatone	10 c	30 b	29 b	48 b	48 b	7	78 **	0 ns
Goldar	26 b	69 a	64 a	63 ab	73 a	1	4 ns	91 ns
P-7	43 a	79 a	68 a	78 a	68 a	-2	26 ns	0 ns
Basin WR	25 CD	56 E	46 F	51 CD	49 F	-2	21 ns	32 ns
Continental	24 b	60 ab	53 a	63 a	58 ab	0	0 ns	2 ns
Magnar	3 c	28 b	9 b	15 b	23 c	-1	3 ns	83 ns
Trailhead	23 b	59 ab	54 a	60 a	50 b	-2	34 ns	7 ns
Trailhead II	48 a	77 a	68 a	68 a	68 a	-3	66 ns	30 ns
Siberian WG	21 CDE	62 DE	52 EF	51 CD	54 CDEF	-2	38 ns	60 *
Vavliov	24 a	60 a	54 a	45 a	53 a	-3	35 ns	60 ns
Vavilov II	21 a	63 a	51 a	43 a	53 a	-4	44 ns	42 ns
Stabilizer	18 a	64 a	49 a	65 a	58 a	0	0 ns	8 ns
Western WG	21 CDE	77 AB	81 A	83 A	82 A	3	72 ns	28 ns
Arriba	28 a	71 b	81 ab	80 a	80 a	3	54 ns	37 ns
Recovery	11 b	75 ab	71 b	83 a	80 a	3	46 ns	1 ns
Rosana	22 a	84 a	90 a	85 a	85 a	0	2 ns	38 ns
Thickspike WG	19 DE	58 E	63 CDE	63 BC	46 F	-4	34 ns	62 *
Bannock	21 a	57 ab	74 a	78 a	58 a	1	1 ns	98 **
Bannock II	21 a	67 a	58 a	73 a	53 a	-3	18 ns	11 ns
Critana	15 a	49 b	56 a	38 b	28 b	-8	73 **	15 ns
Crested WG	17 DE	59 DE	49 F	55 C	53 DEF	-1	20 ns	27 ns
CD II	14 a	50 b	48 a	53 a	48 a	0	2 ns	25 ns
Hycrest	22 a	72 a	58 a	70 a	63 a	-2	11 ns	8 ns
Hycrest II	15 a	63 ab	42 a	48 a	55 a	-2	7 ns	81 *
Nordan	18 a	53 b	47 a	50 a	45 a	-2	65 ns	0 ns
Russian WR	15 DE	63 CDE	56 DEF	59 BC	64 BC	0	2 ns	92 ns
Bozoisky-Select	14 a	52 b	49 a	60 a	63 a	4	77 ns	5 ns
Bozoisky II	16 a	75 a	60 a	58 a	65 a	-3	39 ns	60 ns
Smooth BG (Manchar)	10 E	49 E	70 ABCD	65 BC	48 EFG	-1	1 ns	96 **

† Orthogonal polynomial trends expressed as percent of year sums of squares due to linear and quadratic effects.

[ᵀ]b Regression coefficients of % stand frequency from 2011 to 2014.

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

DISCUSSION

No one species was highest for seedling frequency at all four locations. However, there were four species that had significantly higher seedling frequency at three of the four locations: Siberian wheatgrass, crested wheatgrass, intermediate wheatgrass, and Snake River wheatgrass. This data is consistent with previous studies (Asay et al., 2001; Robins et al., 2013). All of these species maintained high stand persistence, being some of the highest for plant frequency five years after planting. Bottlebrush squirreltail and Meadow bromegrass also had significantly higher seedling frequency but were not included at all four locations. Bottlebrush squirreltail had a significant negative linear trend in plant frequency at the three included locations. Western wheatgrass was one of the lowest for initial seedling frequency, but had some of the highest plant frequencies five years after planting, due to rhizome development. Russian wildrye was low for seedling frequency in Y1 at all but one location. However, by Y2 it was one of the higher species for plant frequency and remained so through Y5.

Generally, after the second year rankings for plant frequency did not change significantly. The species with the highest plant frequency in year two were still highest after five years. Two exceptions were slender wheatgrass and western wheatgrass. Slender wheatgrass always had a significant decreasing linear trend in persistence, decreasing in stand frequency at all four locations with a combined plant frequency of 69% in Y2 to a combined plant frequency of 37% in Y5. Western wheatgrass was always one of the lowest for initial seedling frequency, having a combined initial seedling frequency of 32% but increased to greater than 82% plant frequency at three of the four locations.

The newer varieties, in most instances, had increased stand establishment vs. check varieties. At the Beaver and Malta sites, Recovery western wheatgrass had significantly higher seedling frequency then Arriba, Barton, Rodan, or Rosana. Hycrest II and Vavilov II established better at the Beaver location than Hycrest or Vavilov but no significant difference in seedling frequency were observed at the other locations. In Indian ricegrass, White River had much better seedling and plant frequency than either Rimrock or Nezpar. P-7 bluebunch wheatgrass had higher seedling frequency than Anatone. Within slender wheatgrass, Firststike had increased seedling frequency vs. Pryor at three of the four locations. This data is consistent with previous studies for seedling establishment (Jensen et al., 2009a; Jensen et al., 2007; Jensen et al., 2009b; Waldron et al., 2011).

Intermediate wheatgrass had the highest dry matter yields (DMY) at the Beaver location with crested and Siberian wheatgrass highest for DMY at the Cheyenne location. Crested wheatgrass had some of the highest DMY at both locations and all three years of harvesting, but it also had a significant decreasing trend in DMY from the first year harvest to the third year harvest. Most other species also declined in DMY from the first year of harvesting to the third year. Exceptions to this declining trend were Russian wildrye and bluebunch wheatgrass, both of these species remained relatively consistent in DMY over the three years of harvesting. Russian wildrye and Bluebunch wheatgrass had some of the highest DMY in the third year of harvesting. Siberian wheatgrass had high DMY at Cheyenne but lower at the Beaver location. The cultivar Stabilizer was included at the Beaver location but not at Cheyenne. Stabilizer was selected for reduced biomass production (Jensen et al., 2013). Stabilizer had almost half the DMY of Vavilov in all three years of harvesting. Intermediate wheatgrass had high DMY at Beaver but lower DMY at Cheyenne. In Indian ricegrass, the germplasm White River had significantly higher DMY than Nezpar or Rimrock, however the stand frequency was not significantly different between White River (87%) and Rimrock (86%), indicating the superior vigor of White River.

Climactic variability is a well-recognized factor in seeding success or failure (Hardegree et al., 2011). There were significant location differences in the first year seedling frequency and subsequent years plant frequency. At these locations, average annual precipitation was not a good predictor of potential seeding success. The Malta site had the lowest AAP at 292 mm yet had the highest overall seedling frequency at 70%. The Tintic site had the highest AAP but had the lowest overall seedling frequency at 23%.

After control or reduction of invasive annual weeds, it is critical to establish perennial vegetation to limit reinvasion and improve ecosystem services and function (Nafus and Davies, 2014). Mature perennial species can be highly competitive with invasive annual weeds and their presence provides significant resistance to annual weed invasion (Chambers et al., 2014). In our studies, the perennial grass species were planted in prepared seedbeds with weed control before planting. Even under these favorable conditions, the establishment of some species was consistently lower than the best establishing species. If seedlings had a difficult time establishing in prepared seedbeds they likely have little chance of success under less optimum conditions or in competition with cheatgrass. There is some debate as to what constitutes the "best" plant material for any given site. Genetic appropriateness is very important, but seed availability, budget constraints, and relative competitive ability of plant materials must be considered as well (Brown et al., 2008)

Public and private land managers choose plant materials for revegetation projects based on several criteria including: climate, topography of the site, seed price and availability, expected plant performance, and regulatory requirements. The evaluation of perennial cool-season grass species for establishment and trends in persistence provides important information for land mangers when making decisions concerning revegetation projects. These results should provide further information to make knowledgeable decisions.

IMPLICATIONS

1. Crested, Siberian, intermediate, and Snake River wheatgrass had some of the highest initial seedling frequencies and high plant frequencies in subsequent years, but were not the highest at every location.

2. At the most xeric site (Malta) with AAP less than 300mm, there were declining trends in plant persistence for all species. With bluebunch wheatgrass, slender wheatgrass, bottlebrush squirreltail and Indian ricegrass dropping to below 20% plant frequency.

3. Western Wheatgrass was difficult to establish, having some of the lowest seedling frequency percentages, however stands of this rhizomatous grass increased over time at all locations except the Malta site.

4. Crested, intermediate, and Siberian wheatgrasses had some of the highest dry matter yields in all three years of harvesting, but dropped in total yield from Y1 to Y3. Russian wildrye and bluebunch wheatgrass had relatively consistent yields over the three years of harvesting. By Y5 they were similar to the highest yielding species.

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