DIVERSIFICATION OF CRESTED WHEATGRASS STANDS IN UTAH

By

April Hulet

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Plant and Wildlife Sciences

Brigham Young University

April 2009

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

April Hulet

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	Bruce A. Roundy, Chair
Date	Val Jo Anderson
Date	Loreen A. Woolstenhulme

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of April Hulet in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

Date	Bruce A. Roundy Chair, Graduate Committee
Date	Loreen A. Woolstenhulme Graduate Coordinator
Date	Rodney Brown Dean, College of Life Sciences

ABSTRACT

DIVERSIFICATION OF CRESTED WHEATGRASS STANDS IN UTAH

April Hulet

Department of Plant and Wildlife Sciences

Master of Science

Agropyron cristatum [L.] Gaertner (crested wheatgrass) continues to be seeded on burned wildlands. Effective control methods need to be developed to convert these seedings to more diverse native plant communities. This research was designed to determine effective ways to control *A.cristatum* and establish native species while minimizing weed invasion. We mechanically and chemically treated two sites followed by seeding native species. The study was replicated for 2 years as a randomized block split plot design with five blocks. Within each block, 0.4 ha main plots were either left undisturbed or received a mechanical (single or double-pass disking) or herbicide treatment (1.1 L/ha or 3.2 L/ha. Roundup Original Max) to partially or substantially reduce *A. cristatum*. Following wheatgrass control, main plots were divided into 0.2 ha subplots that were either unseeded or seeded with a Truax Rough Rider rangeland drill in October 2005 and 2006. Density and cover data were collected in spring 2006, 2007 and 2008 for *A. cristatum, Bromus tectorum* L. (cheatgrass), perennial grasses and forbs, annual weeds, and sown species. Double disking was initially most effective in controlling *A. cristatum*. When compared to the undisturbed plots in 2006, double disking decreased wheatgrass cover significantly ($P < 0.05$) at Lookout Pass (14 to 6%) and at Skull Valley (14 to 4%). At the Skull Valley site, *B. tectorum* cover on herbicide-treated plots decreased by 14% compared to mechanical-treated plots where *B. tectorum* cover increased by 33%. Native grasses and *Linum lewisii* Pursh (Lewis flax) emerged best from seeding although survival of seeded species was limited. *Agropyron cristatum* on all treated plots recovered to similar cover percentages as untreated plots 2 to 3 years after treatment. Effective plant control may require primary and secondary treatments to reduce the seed bank and open stands to dominance by seeded native species.

Key words: *Agropyrum cristatum*, mechanical treatment, Roundup Original Max, Truax Rough Rider, brillion packer wheel, invasion, emergence, survival

ACKNOWLEDGEMENTS

This project was funded through the USDI Bureau of Land Management Native Plant Selection and Increase Project with additional support provided by Brigham Young University undergraduate mentoring funds.

I would like to thank Dr. Bruce Roundy for his guidance, support, and encouragement as a graduate committee chair and his willingness to expand my understanding of wildland plant ecology and restoration; and my committee, Dr. Loreen Woolstenhulme and Dr. Val Anderson for their direction and continued support throughout my academic career; Brad Jessop for implementing the study and offering constructive criticism, and Jennifer Rawlins and students from BYU who assisted with data collection and made my graduate experience enjoyable and memorable.

I would also like to thank my family for their continued love, support, and encouragement as I am pursuing something that I love.

TABLE OF CONTENTS

LISTS OF TABLES

LISTS OF FIGURES

Figure 5. Total seeded species density (plants/m^2) at (A) Lookout Pass and (B) Skull Valley, Utah on undisturbed (UD), single-pass disking (SPD), double-pass disking (DPD), partial rate herbicide (PRH), full rate herbicide (FRH) treatments. Means with different letters within each site are significantly different using Tukey-Kramer honestly significant difference multiple comparison procedure ($p < 0.05$). *Significantly different from UD treatment.

Introduction

Agropyron cristatum [L.] Gaertner (crested wheatgrass) is a C_3 perennial caespitose bunchgrass from Eurasia that is intentionally introduced for agriculture and revegetation of wildlands in North America (Vaness & Wilson 2008; Henderson & Naeth 2005; Rogler & Lorenz 1963). *Agropyron cristatum* has been seeded on 6 to 11 million hectares of rangeland in western North American (Hansen & Wilson 2006; Ambrose & Wilson 2003; Lesica & DeLuca 1996), including thousands of hectares in the Intermountain West. *Agropryon cristatum* is widely seeded following wildfires because it establishes well, suppresses weeds, provides cover which significantly decreases runoff, and increases forage for grazing (Waldron et al. 2005; Pellant & Lysne 2005; Romo 2005; Hansen & Wilson 2006). *Agropyron cristatum* is drought and cold resistant making it widely adapted, and has relatively few disease problems (Rogler & Lorenz 1963). Although *A. cristatum* has many desirable competitive characteristics and provides many benefits, it often exists in large man-made monocultures that support limited plant and wildlife diversity (Looman & Heinrichs 1973; Christian &Wilson 1999; Davison & Smith 2005). Heidinga and Wilson (2002) found that richness of native plant species decreases as cover of *A. cristatum* increases, and cover of several native species is negatively correlated with cover of *A. cristatum*.

By increasing plant diversity in *A. cristatum* monocultures we expect to improve wildlife habitat, enhance species richness and community diversity, increase soil cover, capture a large proportion of the resources in the system to preempt weeds, and improve the aesthetics of the landscape (Sheley et al. 1996; Pellant & Lysne 2005). Along with developing strategies to increase plant diversity through native seedings in areas dominated by *A. cristatum*, it is essential to understanding the response of *A. cristatum* to control methods (Pellant & Lysne 2005), potential weed invasion, and native plant establishment. Henderson & Naeth (2005) found that *A. cristatum* dominates communities (both vegetation and seedbank) for decades following establishment in mixed-grass prairies. To deal with this dominance, they suggest that controlling *A. cristatum* and restoring mixed-grass prairie ideally will require suppression of crested wheatgrass seed production, eradication of crested wheatgrass plants, and the addition of native grass and forb seeds to increase plant diversity.

Cox & Anderson (2004) suggested a way to increase plant diversity through assisted succession to meet native plant restoration goals. Assisted succession includes three steps: (1) "capture" the site from weeds with *A. cristatum*; (2) reduce *A. cristatum* using mechanical or herbicide treatments; (3) reseed the site with native species. Along those same lines, Pellant & Lysne (2005) saw *A. cristatum* monocultures as a "bridge" plant community that would replace *Bromus tectorum* L.-dominated lands for future restoration to a more diverse plant community. Our goal was then to test effective control strategies to reduce *A. cristatum* and establish native species while minimizing weed invasion at an operational scale. To evaluate this goal, we had three objectives: (1) determine which treatments best control *A. cristatum*; (2) determine effects of wheatgrass control followed by native revegetation on weed invasion; (3) determine how wheatgrass control methods affect native plant revegetation success.

Methods

Site description

Two sites in Tooele Co., Utah were selected for large-scale manipulation of *Agropryon cristatum* [L.] Gaertner stands. Both sites were seeded with *A. cristatum* following wildfires and are currently managed by the Bureau of Land Management Salt Lake Field Office. The Skull Valley site (lat 40°18'N, long 112°51'W) borders the U.S. Army Dugway Proving Ground and was drill seeded with 3.36 kg/ha (3 lbs/ac) *A. cristatum* 'Fairway' and 3.36 kg/ha (3 lbs/ac) *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey (intermediate wheatgrass) following the Spoonbill fire in the fall of 1982. Skull Valley is at an elevation of 1524 m, receives 200-254 mm of precipitation annually, has Medburn fine sandy loam, mixed (Calcareous) mexic, xeric Torriorthents soil (Trickler 2001) and has an abundance of *Bromus tectorum* L. surrounding the site. The Lookout Pass site (lat 40°09'N, long 112°28'W) is approximately 45 miles southeast from the Skull Valley site and located on the eastern side of the Onaqui Mountains. Lookout Pass was drill seeded following the Aquaduct fire with 3.36 kg/ha (3 lbs/ac) *A. cristatum* 'Hycrest', 1.12 kg/ha (1 lb/ac) *Pascopyrum smithii* (Rydb.) A. Love (western wheatgrass) and 1.12 kg/ha (1 lb/ac) *Melilotus officinalis* (L.) Lam. (yellow sweetclover) in the fall of 1996. The Lookout Pass site is slightly higher in elevation (1673 m), receives 254-305 mm of precipitation annually, and has Taylorsflat fine-loamy, mixed, mesic, xerolic Calciorthids soil (Trickler 2001).

Experimental design

Each study site is on approximately 24 hectares (60 acres) and was installed as a randomized block split plot design with five blocks. Each block is divided into two treatment areas that allow the study to be replicated in both time (2005 and 2006) and space. Within each block, 0.4 ha (1 acre) main plots were either left undisturbed (UD) or received a single-pass disking treatment (SPD); double-pass disking treatment (DPD); partial rate herbicide treatment (1.1 L/ha Roundup Original Max; PRH); or full rate herbicide treatment (3.2 L/ha Roundup Original Max; FRH) to partially or substantially reduce *A. cristatum*. Following wheatgrass control treatments, main plots were divided into 0.2 ha (0.5 acre) subplots that were either seeded or left unseeded. In both 2005 and 2006, herbicide treatments were applied in late May, while mechanical treatments were applied in early June. The DPD treatment was implemented by doing a single-pass one way and then disking perpendicular to the first pass. Plots were seeded with a Truax Rough Rider rangeland drill (Truax Company, Inc., New Hope, MN, U.S.A.) in October 2005 and 2006.

Seeding method

The Truax Rough Rider rangeland drill is specially configured to drill and broadcast seed in alternate rows and sow seeds at the optimal depth for germination and emergence (no deeper than 1.3 cm). Brillion packer wheels placed immediately after the drop tubes press broadcast seeds into the ground. A packer wheel followed by a chain covers drilled seeds.

Species seeded

Due to the depleted native species seedbank, a mixture of 10 species (four grasses, three shrubs, and three forbs) was seeded in each seeded subplot (Table 1). With the exception of *Linum lewisii* Pursh (Lewis flax), all species used in the seed mix were native and, where possible collected or grown in proximity to the study site. The Utah

Division of Wildlife Resources supplied all seed for the study except for one species, *Achillea millefolium* L. (‘Eagle’ yarrow) which was provided by Landmark Seed Company out of the state of Washington. The seed mixture included species adapted to the sites and readily available in sufficient quantities for operational scale revegetation.

Vegetation sampling

We used a stratified random sampling design. Starting points for initial transects and quadrats were located randomly. Subsequent transects were located in 12-m intervals at Lookout Pass and 8-m intervals at Skull Valley. In each subplot, five 30 m transects were placed perpendicular to the baseline transect with data recorded in six quadrats placed in 3-m intervals along each transect, totaling 30 samples per subplot.

Data were collected in June 2006, May 2007, and May 2008. Within each 0.25 m^2 square quadrat, density was counted for all species including a 50 cm row each of drilled and broadcast species. Percent cover for perennial species and *B. tectorum* was estimated ocularly using cover classes (Daubenmire 1959; Bailey & Poulton 1968). The eight cover classes were: (1) 0-1% cover, (2) 1-5% cover, (3) 5-15%, (4) 15-25%, (5) 25-50%, (6) 50-75%, (7) 75-95%, and (8) 95-100%. To determine percent cover, the midpoint of each cover class was calculated.

Precipitation and soil moisture sampling

In summer 2005, thermocouples and gypsum blocks (Delmhorst, Inc., Stamford, CT, U.S.A.) were buried in small-plots adjacent to our large-scale study plots at each site. Thermocouples and gypsum blocks were buried at depths of 1-3 cm, 13-15 cm, and 28-30 cm in four replicated plots of three treatments (undisturbed, partial rate herbicide, and full rate herbicide). Thermocouple and gypsum-block output were read every minute and hourly averages were recorded using Campbell Scientific, Inc. CR-10X microloggers (Campbell Scientific, Inc. Logan, UT, U.S.A.). Soil water potentials down to -1.5 MPa were estimated from gypsum block electrical resistance using a standard calibration curve (Campbell Scientific, Inc. 1983). Total hourly precipitation was monitored from an electronic tipping bucket rain gage at each study site. Data were collected from fall 2005 through summer 2008. Precipitation data for January 2005-July 2005 and mean precipitation were taken from the Western Regional Climate Center weather stations (http://www.wrcc.dri.edu) with the closest proximity to individual sites. Lookout Pass data was taken from Utah station #429133 VERNON; Skull Valley data was taken from Utah station #422257 DUGWAY.

Statistical analysis

Data were analyzed using repeated measurements of plots treated in 2005 (data collected 2006, 2007, and 2008) and plots treated in 2006 (data collected 2007 and 2008). *A. cristatum* control variables include density and cover of ≥ 1 year old *A. cristatum*, residual perennial grasses, and *B. tectorum*; and density of *A. cristatum* seedlings and exotic annual forbs. Seeded species density variables included categories of seeded species: drill seeded grasses, broadcast seeded *P. secunda*, drill seeded grasses plus broadcast seeded *P. secunda*, total forbs, total shrubs, and total seeded species.

We used mixed model analysis to determine effects and interactions of treatments with site, control treatments, and seeded species categories considered fixed, year of measurement considered as a repeated measure, and blocks considered random (Littell et al. 1996). Site interactions exhibiting significant differences were separated and analyzed by site. Arcsin squareroot transformation was used to normalize cover data. The Tukey-

Kramer honestly significant difference multiple comparison method ($p < 0.05$) was used to determine significant differences among fixed factors (SAS Institute Inc. 1987). Inferences apply to similar sites and soils as those described.

Diversity Indices

To determine species diversity and evenness, we used Simpson's index of diversity, Simpson's measure of evenness, Shannon-Wiener diversity index, and Shannon-Wiener evenness index. Itô (2007) suggests both indices because Simpson's indices are more sensitive to changes in the number of individuals of dominant species in the sample, and Shannon-Wiener indices are more sensitive to change in the number of rare species.

Results

Precipitation and Soil Moisture

Yearly precipitation at Lookout Pass averaged 265 mm over the last 35 years (Fig. 1A). Precipitation during the 2005-2008 study period was at or below average during most seasons. Although early spring of 2006 was wet (62% above average), winter of 2006-2007 was dry (47% below average) and was followed by a very dry spring, summer, and fall (50% below average). Winter of 2007-2008 was an average winter however, the following months were very dry (49% below average).

Yearly precipitation at Skull Valley averaged 197 mm over the last 46 years (Fig. 1B). Precipitation during the 2005-2008 study period was at or above average during most seasons with the exception of 2008. Spring and fall of 2006 both received above average precipitation (89% and 84%) followed by an average winter. Spring of 2007 was also above average (19%) followed by an average summer and fall. Winter of 2007-2008 was above average (59%) however, the remaining months of the study were extremely dry (51% below average).

In October 2005 when year 1 plots were seeded, Lookout Pass received 46 mm (monthly average 27 mm) of precipitation with Skull Valley only receiving 12 mm (monthly average 18.5 mm) (Fig. 1). In October 2006 when year 2 plots were seeded, both sites received above average precipitation (Lookout Pass 63.5 mm; Skull Valley 64 mm) however, the following month had below average precipitation. In 2007 at Lookout Pass, yearly precipitation was overall 40% lower than the 35-year mean (Fig. 1).

Above average March 2006 precipitation at Lookout Pass resulted in a longer period of soil moisture availability (>-1.5 MPa) at all measured depths in spring 2006 than in 2007 and 2008. The lack of precipitation during the winter of 2006-2007 and the spring of 2007 resulted in limited time of soil water availability in spring 2007. At a soil depth of 1-3 cm, soil moisture in 2006 after 1 March was available 25 more days than in 2007. In 2008 at the same depth, soil moisture was available 7.5 more days. Soil moisture availability was annually more variable at the lower two depths. Soil moisture was available 41.5 more days (13-15 cm) and 42 more days (28-30 cm) in 2006 than 2007. Soil moisture was available 26.5 more days (13-15 cm) and 39 more days (28-30 cm) in 2008 than 2007 (Fig. 2A)

Average precipitation at Skull Valley resulted in available soil moisture (>-1.5 MPa) that was not distinctly different among the years. At a soil depth of 1-3 cm, soil moisture after 1 March was available 8 days in 2006, 2 days in 2007, and 3.5 days in 2008. At the soil depth of 13-15 cm, soil moisture was available 62 days in 2006, 50 days in 2007, and 61 days in 2008. At the soil depth of 28-30 cm, soil moisture was available 70 days in 2006, 63 days in 2007, and 80 days in 2008 (Fig. 2B). Near the surface (1-3 cm), Skull Valley was generally drier than Lookout Pass which may have contributed to the lower numbers of seeded seedlings at Skull Valley than at Lookout Pass. Nevertheless, at both sites there was sufficient soil moisture for seed germination and seedling emergence in both 2006 and 2007 after fall sowing.

Crested Wheatgrass Control

1-year or older (Mature) Crested Wheatgrass Cover.

Initially, mechanical treatments were more effective than herbicide treatments in reducing mature *Agropyron cristatum* [L.] Gaertner cover (Fig. 3). Compared to UD plots in 2006, data collected from treatments implemented in 2005 showed that DPD decreased wheatgrass cover significantly at Lookout Pass (14 to 6%) and at Skull Valley (14 to 4%) (Fig. 3). Compared to UD plots in 2006, data collected from plots treated in 2005 showed that FRH also significantly reduced mature *A. cristatum* cover at Lookout Pass (14 to 5%) with no significant difference observed at Skull Valley. In 2007, data collected from the treatments implemented in 2006 showed that DPD reduced wheatgrass cover significantly at Skull Valley (7 to 1%) with no significant difference at Lookout Pass (Fig. 3) (treatment * sample year interactions for Lookout Pass: $F_{[16,64]} = 5.79$, $p = <0.0001$; Skull Valley: $F_{[16,64]} = 1.91$, $p = 0.0355$). However, 3 years after treatment, there were no treatment effects on *A. cristatum* cover at Lookout Pass or Skull Valley.

1-year or older (Mature) Crested Wheatgrass Density.

Control treatments did not significantly reduce densities of mature *A. cristatum* plants at Lookout Pass or Skull Valley compared to UD plots. In 2008 on plots treated in 2006, *A. cristatum* density was actually greater on DPD than UD plots (14 compared to

34 plants/m^2; Table 2; treatment*sample year interaction for Lookout Pass: $F_{[16, 64]}$ = 2.56, p = 0.0041; Skull Valley: $F_{[16, 64]}$ = 2.36, p = 0.0079). DPD treatments may have 'broken' up larger clumps of mature plants contributing to higher densities. *A. cristatum* density increased (76%) between 2006 and 2007 at Lookout Pass on UD plots treated in 2005. This increase may be contributed to the above average precipitation in the fall of 2006 (Fig. 1). Over the course of the study, *A. cristatum* density generally increased with the highest amounts being counted in 2008 (Table 2). This measured increase in *A. cristatum* density is a result of plant demography and our sampling categories; surviving seedlings from the previous year sample became 'mature' plants the following sample year. *A. cristatum* density on plots treated in 2005 at Lookout Pass increased an average of 45% between 2006 and 2008 (11 to 20 plants/m^2); while density on plots treated in 2006 increased 10% (18 to 20 plants/m^2). At Skull Valley, density on plots treated in 2005 increased an average of 23% (10 to 13 plants/m^2) and density on plots treated in 2006 increased 29% (12 to 17 plants/m^2) (Table 2).

Crested Wheatgrass Seedling Density.

There was little effect of control treatments on *A. cristatum* seedling density at either site during the first year post-treatment (Lookout Pass: $F_{[16, 64]}$ = 1.26, p = 0.2518; Skull Valley: $F_{[16, 64]}$ = 1.21, p = 0.2851); however, response to treatment between implementation years was significantly different at both sites (site * sample year interaction; $F_{[4, 32]}$ = 3.95, p = 0.0102). At Lookout Pass the average *A. cristatum* seedling density on plots treated in 2005 was 5 plants/m^2; on plots treated in 2006, *A. cristatum* seedling density was 24 plants/m^2. At Skull Valley the average *A. cristatum* seedling density on plots treated in 2005 was 6 plants/m^2; on plots treated in 2006, *A.*

cristatum seedling density was 17 plants/m^2 (Table 2). *Agropyron cristatum* seedling density was 79% greater in 2007 at Lookout Pass and 65% greater at Skull Valley in 2007 than in 2006 even though total precipitation was 47% greater at Lookout Pass and 10% greater at Skull Valley in 2006 than in 2007.

Between 2006 and 2007 at Lookout Pass, *A. cristatum* seedling density increased significantly in the UD plots where treatments were implemented in 2005 (5 to 21 plants/m^2) (Table 2). DPD treatments on plots treated in 2006 at Skull Valley significantly increased *A. cristatum* seedling density compared to the UD plots (10 to 24 plants/m^2). *Agropyron cristatum* seedling density decreased on both sites in 2008 which may be due to below average precipitation (Fig. 1) or increased competition with mature *A. cristatum* plants (Table 2).

Weed Invasion

Cheatgrass Cover.

Treatments had significant effects on *Bromus tectorum* L. cover at Lookout Pass and Skull Valley in 2006 (treatment*sample year interaction for Lookout Pass: $F_{[16,64]}$, = 1.94, p = 0.0318; Skull Valley: $F_{[16,64]}$ = 1.76, p = 0.057) (Fig. 4). *B. tectorum* cover was significantly higher in the mechanical-treated plots than in the herbicide-treated plots that were treated in 2005. At Skull Valley, *B. tectorum* cover on the DPD plots was 60% greater than the cover on the herbicide-treated plots. Over the course of the study at the Skull Valley site, *B. tectorum* cover on herbicide-treated plots was decreased by 14% compared to mechanical-treated plots which increased *B. tectorum* cover by 33**%.** In 2007, *B. tectorum* decreased in cover which may be due to above average precipitation in the fall of 2006 leading to a fall germination event (Fig. 1), and due to limited soil moisture availability near the soil surface in 2007 (Fig. 2).

Cheatgrass Density.

At Skull Valley, *B. tectorum* density increased from an average of 25 to 97 plants/m^2 between 2006 and 2007. At both sites, *B. tectorum* density was generally greater in mechanical treatments compared to herbicide treatments (Lookout Pass: $F_{[16, 64]} = 3.35$, $p = 0.0003$; Skull Valley: $F_{[16, 64]} = 3.68$, $p = <0.0001$; Table 2). By 2008, *B. tectorum* density had started to decrease in all treatment plots with no significant differences among treatments at Lookout Pass and Skull Valley.

Annual Forb Density.

Lookout Pass had a higher density of annual species than Skull Valley due to the high amount of *Alyssum desertorum* Stapf (desert madwort) which, over the course of the study, averaged 92% of all annual forbs encountered. Between 2006 and 2007, annual forb density increased significantly at Lookout Pass on the SPD plots (10 to 153 weeds/m^2) and on the FRH plots (7 to 296 weeds/m^2) treated in 2005 (Table 2). In 2007 annual forb density on the FRH plots treated in 2005 was significantly greater than on the UD plots (82 compared to 296 weeds/m^2) (Lookout Pass: $F_{[16, 64]} = 2.79$, $p = 0.0019$; Skull Valley: $F_{[16, 64]} = 1.60$, $p = 0.0952$; Table 2). By 2008 however, annual weeds decreased on all treatments plots for both years with no significant differences among treatments. At Skull Valley the most prevalent annual species was *Salsola tragus* L. (prickly Russian thistle) which comprised 80% of all annual forbs encountered. Due to large quantities of *Ceratocephala testiculata* (Crantz) Roth (curveseed butterwort) at both sites, density data were not collected; however, it is estimated to have approximately 40%

ground cover for 2-3 weeks each spring and was considered to be the dominant annual forb.

Seeded Success

Total Seeded Species Density.

None of the *A. cristatum* control treatments affected seeded species emergence at Lookout Pass ($F_{[16, 64]} = 1.01$, $p = 0.4588$). At Skull Valley there was a significant difference ($F_{[16, 64]} = 2.12$, $p = 0.0181$) between treatments for seeded species density in 2006 on plots treated in 2005. DPD and PRH had on average 44% fewer seedlings than the UD plots (13 compared to 24 plants/m^2). There was greater emergence of seeded species at Lookout Pass compared to Skull Valley and greater emergence following the first-year response to treatment (Fig. 5). Survival of seeded species continually decreased throughout the study period.

At both sites, seeded grasses had greater emergence than either shrubs or forbs. Drill- seeded species encountered most frequently were: *Pseudoroegneria spicata* (Pursh) A. Love (bluebunch wheatgrass), *Achnatherum hymenoides* (Roem. & Schult.) Barkworth (Indian ricegrass), and *Elymus elymoides* (Raf.) Swezey (squirreltail). The forb encountered most often was *Linum lewisii* Pursh (Lewis flax). Of the species that were broadcast, *Poa secunda* J. Presl (Sandberg bluegrass) was most common; *Achillea millefolium* L. (common yarrow) was noted occasionally. Although shrubs were encountered rarely during data collection, seedlings of sown *Artemisia tridentata* Nutt.ssp. *wyomingensis* Beetle & Young (Wyoming big sagebrush), *Ericameria nauseosa* [Pallas ex Pursh] Nesom & Baird (white stemmed rabbitbrush), and *Atriplex canescens* (Pursh) Nutt. (fourwing saltbush) were observed. In 2008, residual and seeded *P.*

secunda was difficult to distinguish; instead of being recorded as a broadcast species it may have been counted with residual perennial species (Table 3).

Species Diversity and Evenness

Seeded plots had more plant species diversity than unseeded plots (Table 4). We encountered on average, 26 plant species in the seeded plots and 23 plant species in the unseeded plots at Lookout Pass. At Skull Valley, we encountered on average 23 plant species on seeded plots and only 14 plant species on unseeded plots, a 39% increase in species richness on seeded plots. At Lookout Pass, the average of both Simpson's measure of evenness (14% even) and the Shannon-Wiener evenness index (19% even) were low indicating the presence of a dominate species. Similar results were found at Skull Valley, Simpson's measure of evenness on average was 9% even and Shannon-Wiener evenness index was 12% even.

Discussion

This study shows the difficulty in controlling monocultures of *Agropyron cristatum* [L.] Gaertner, establishing native species and, minimizing weed invasion simultaneously. Using assisted succession (Cox & Anderson 2004) to accelerate the progressive change in the community composition over time, sites were chosen that were "captured" by *A. cristatum*, then "reduced" through mechanical and herbicide treatments, followed by a "reseeding" with native species.

In our study, mechanical treatments best controlled *A. cristatum*, however, all treatment effects had disappeared by the third year post treatment. Numerous studies have also shown the difficulty in controlling *A. cristatum*. Lodge (1960) found that double disking was the only treatment that significantly reduced *A. cristatum* basal area (from 6.6% on the untreated areas to 2.7% in the disked areas). Within 2 years however, the treatment effects disappeared, showing the competitive effects of *A. cristatum.* McCaughey & Simmon (1998) found that defoliation decreases aboveground *A. cristatum* biomass yield, but also increases late season growth. A study by Hall & Klomp (1966) showed that in many locations across Idaho, *A. cristatum* was heavily used and eaten to the ground level year after year, and though vigor was low, *A. cristatum* still formed a good stand and produced seedheads. In a similar study to our study, Fansler & Mangold (2007) found that control treatments will decrease crested wheatgrass cover adequately to increase site availability for establishment of native species, even though crested wheatgrass control treatments did not decrease crested wheatgrass density.

Full rate herbicide reduced *A. cristatum* cover more than partial rate herbicide. However, all herbicide treatment effects had disappeared by the third year post treatment. Varied responses to herbicide treatments have been found across western North America which may be due to the timing and quantity of application and the phenological stage of the plants. In Canada, a spring application of glyphosphate reduced *A. cristatum* by 50 percent, which was adequate to establish a native warm season grass seeded at a high rate (Bakker et al. 1997). Wilson & Partel (2003) applied multiple (13) glyphosphate applications over 6 years and significantly reduced cover of *A. cristatum* in a 50-year-old stand in the northern Great Plains. However, the surviving plants produced abundant seedheads and crested seedling emergence from the seedbank was not different between the herbicide treatment and untreated areas. Although *A. cristatum* was not eliminated with the herbicide treatments in that study, it was reported that native species diversity and abundance were enhanced on these study sites (Bakker et al. 2003). The work of Hansen & Wilson (2006) in Grasslands National Park in south-western Saskatchewan, Canada indicates that herbicide applications decrease juvenile survival, especially under dry conditions. Ambrose & Wilson (2003) also working in Grassland National Park have shown that *A. cristatum* germination is unaffected by herbicide application, therefore *A. cristatum* populations need to be treated for several years because of their persistent seed bank. Marlette & Anderson (1986) found similar results, large amounts of *A. cristatum* seedlings emerged the year after herbicide treatment, suggesting that the soil has a large reserve of seeds. Across multiple years on our partial rate herbicide treatment, *A. cristatum* cover was greater than our undisturbed cover values which may be due to the persistent seedbank and the increased resource availability captured by surviving residual plants (Fig. 3).

Landscape-scale strategies to control *A. cristatum*, such as disking and herbicide treatments have had short-term results; a few living plants may restock the seedbank. Evidently, successive annual treatments are needed to exhaust the seedbank and control *A. cristatum* (Vaness & Wilson 2008). Pyke (1990) found that *A. cristatum*, on average, produces 68 times more seed than native *Agropyron spicatum* (*Pseudoroegneria spicata* (Pursch) A. Love ssp. *spicata*; bluebunch wheatgrass).

Weed-resistant plant communities effectively use resources over time and space (Sheley et al. 1996). By reducing *A. cristatum* we opened resources for weed invasion and found different treatment effects. Herbicide treatments generally minimized weed invasion in stands where *Bromus tectorum* L. propagule pressure was greatest. The disturbance caused by mechanical treatments complicated revegetation efforts by disturbing the soil which favors weed invasion. Although present at both sites, *B. tectorum* density showed a decrease by the third year post treatment suggesting that *A. cristatum* is a strong competitor with *B. tectorum.* Francis & Pyke (1996) found that *A. cristatum* 'Hycrest' seedlings were better competitors with *B. tectorum* than *A. cristatum* 'Nordan'. When Hycrest densities were increased, reduced biomass and tiller production of *B. tectorum* were observed. Buman et al. (1988) found that 'Hycrest' 6-week-old seedlings were equal to *B. tectorum* seedlings in shoot biomass when competing in a 1:1 mixture. A 3-year experiment conducted by Waldron et al. (2005) evaluated the ability of native and introduced perennial grasses to coexist or mutually exclude each other and weeds. In their experiment, *A. cristatum* had significantly higher introduced perennial grass cover but lower weed cover than Russian wildrye and military seed mixes (mostly native grasses with a small introduced species component). At our study sites, it appears that *A. cristatum* is dominating *B. tectorum* and that *A. cristatum* seedlings are recapturing resources that became available following control treatments.

Davis et. al. (2000) believed that invasibility of many communities changes from year to year and even within a given year, as the amount of available resources fluctuate. Due to drought conditions at Lookout Pass in 2007 and at both sites in 2008, resources were limited for native and introduced species which reduced both invasibility of the site and survival of native species. During this same drought period, a high percentage of *A. cristatum* seedlings survived which increased *A. cristatum* cover and density. This ability to survive drought and replenish the stand when weeds and native species are decreasing is evidence for the competitive nature and drought tolerance of *A. cristatum*.

Due to the depleted native seed bank, a seed supply of native species was introduced into the community. Plots with less-competitive resource use (mechanical treated) were expected to have increased seedling establishment. However, *Agropyron cristatum* control treatments had no effect on seedling emergence. Christian & Wilson (1999) observed that aboveground vegetation competes for light giving *A. cristatum* advantage over native species because of its tall stature and relatively high standing crop. Because *A. critstatum* was only reduced temporarily its recovery and competitiveness may have increased seedling mortality of the seeded native species (Table 3).

Revegetation success is highly variable on arid and semiarid rangelands where seasonal precipitation frequently limits or prevents plant establishment and growth (Call & Roundy 1991). Total seeding success was greater at the Lookout Pass site which is at a higher elevation, receives more precipitation, and has more available soil moisture than the Skull Valley site. However, at both sites, overall lack of recurrent precipitation (Fig. 1) and limited days of soil moisture availability restricted seedling establishment (Fig. 2). At Lookout Pass the relatively dry winter of 2006-2007, followed by the very dry spring resulted in significantly reduced time of soil water availability in spring 2007. Seedling densities were still relatively high in 2007 because counts were made when soil moisture was still available in early spring. However, counts in spring of 2008 indicated subsequent high mortality of seedlings (Fig. 5). In a small-plot study conducted adjacent to our study, Rawlins et al. (2009) also found high seedling mortality associated with limited soil moisture availability in the spring and summer months of 2007 (Fig. 2). Because *A. cristatum* recovery and drought both occurred simultaneously, it is not known how much each of these factors affected the high mortality of seeded native species.

Although seeded species establishment was limited in our study, a few seeded shrubs were observed in all treated areas. Hull & Klomp (1966) found that when sagebrush seed was available in *A. cristatum* sites during the year of establishment, *A. cristatum* seedlings would be unable to suppress the brush. More time is needed to observe if seeded species were able to establish on *A. cristatum* dominated sites and if shrubs will be able to compete.

Species richness was increased initially by seeding. Simpson's index of diversity and Shannon-Wiener diversity index decreased between 2007 and 2008 at Lookout Pass and Skull Valley which may reflect the decrease in total number of individuals (Table 4). The large change in total number of individuals at Lookout Pass reflects the decrease in *Alyssum desertorum* Stapf and *Bromus tectorum* L. between 2007 and 2008 (Table 2). Evenness is <25% at both sites indicating that *A. cristatum* is the dominant species at the end of our study period.

Conclusion

Agropryon cristatum [L.] Gaertner has displaced native species and decreased biological diversity in native communities yet, it is often seeded following wildfire because of its many desirable traits. Thompson et. al. (2006) however did find that native grasses establish as well as introduced grasses in a large-scale fire rehabilitation seeding in Utah, and evidence is mounting that native grasses may successfully establish in many post-fire seedings. Nevertheless, lack of native seed availability and past seeding failures of native species continue to encourage seeding of *A. cristatum* on some rangelands to prevent dominance by *Bromus tectorum* L.

As *A. cristatum* continues to be seeded and considered as an intermediate community, we suggest that primary and secondary control methods may be necessary to treat both residuals and seedbank plants. Long-term sustainable control strategies of *A. cristatum* must reduce seed production and stand renewal from the seedbank. Romo et. al. (1994) recommends mowing, grazing, or the use of growth regulators such as mefluidide for 3 to 5 years before glyphosate application to prevent seed production and thereby deplete the seed reserves in the soil. Aside from using *A. cristatum* as a revegetation species in assisted succession, further determination of native wheatgrass revegetation successes following wildfires and the possibility of native wheatgrass becoming an intermediate community leading to a more diverse community is warranted.

Implications for Practice

- One year treatments, whether mechanical or chemical, will not have continually positive effects over time in reducing crested wheatgrass.
- Follow-up treatments to control residual and seedbank crested wheatgrass, as well as weeds, may be necessary to convert wheatgrass stands to native communities.

LITERATURE CITED

Ambrose, L. G., and S. D. Wilson. 2003. Emergence of the introduced grass *Agropyron cristatum* and the native grass *Bouteloua gracilis* in a mixed-grass prairie restoration. Restoration Ecology **11**:110-115.

Bailey, A. W., and C. E. Poulton. 1968. Plant communities and environmental interrelationships in a portion of the Tillomook burn, Northwest Oregon. Ecology **49**:1-13.

Bakker, J. D., J. Christian, S. D. Wilson, and J. Waddington. 1997. Seeding blue grama in old *A. cristatum* fields in southwestern Saskatchewan. Journal of Range Management **50**:156-159.

Bakker, J. D., S. D. Wilson, J. M. Christian, X. Li, L. G. Ambrose, and J. Waddington. 2003. Contingency of grassland restoration on year, site, and competition from an introduced grass. Ecological Applications **13**:137-153.

Buman, R. D., S. B. Monsen, and R. H. Abernethy. 1988. Seedling competition between mountain rye, 'Hycrest' created wheatgrass and downy brome. Journal of Range Management **41**: 30-34.

Call, C. S., and B. A. Roundy. 1991. Perspectives and processes in revegetation of arid and semiarid rangelands. Journal of Range Management **44**: 543-549.

Campbell Scientific, Inc. 1983. Model 227 Delmhorst cylindrical soil moisture block instruction manual. Logan, UT: Campbell Scientific. 5p.

Christian, J. M. and S. D. Wilson. 1999. Long-term ecosystem impacts of an introduced grass in the northern Great Plains. Ecology **80**:2397-2407.

Cox, R. D., and V. J. Anderson. 2004. Increasing native diversity of *B. tectorum*-dominated rangeland through assisted succession. Journal of Range Management **57**:203-210.

Daubenmire, R. F. 1959. Canopy coverage method of vegetation analysis. Northwest Science **33**:43-64.

Davis, M. A., J. P. Grime, and K. Thompson. 2000. Fluctuating resources in plant communities: a general theory of invisibility. Journal of Ecology **88**:528-534.

Davison, J., and E. Smith. 2005. Living With Fire, *A. cristatum*: Hero or Villain in Reclaiming Disturbed Rangelands. University of Nevada Cooperative Extension Fact Sheet 96-53.

Fansler, V.A., and J. Mangold. 2007. Establishing native plants in crested wheatgrass stands using successional management. M.S. thesis. Oregon State University: Corvallis, OR. 95 pp.

Francis, M. G., and D. A. Pyke. 1996. Crested wheatgrass-cheatgrass seedling competition in a mixed-density design. Journal of Range Management **49**:432-438.

Hansen, M. J., and S. D. Wilson. 2006. Is management of an invasive grass *Agropyron cristatum* contingent on environmental variation? Journal of Applied Ecology **43**:269-280.

Heidinga, L., and S. D.Wilson. 2002. The impact of invading alien grass (*Agropyron cristatum*) on species turnover in native prairie. Diversity and Distributions **8**:249-258.

Henderson, D. C., and M. A. Naeth. 2005. Multi-scale impacts of *A. cristatum* invasion in mixed-grass prairie. Biological Invasions **7**:639-650.

Hull Jr. A. C., and G. J. Klomp. 1966. Longevity of crested wheatgrass in the sagebrush-grass type in Southern Idaho. Journal of Range Management **19**:5-11.

Itô, Y. 2007. Recommendations for the use of species diversity indices with reference to a recently published article as an example. Ecological Research **22**:703-705.

Lesica, P., and T. H. DeLuca. 1996. Long-term harmful effects of crested wheatgrass on Great Plains grassland ecosystems. Journal of Soil and Water Conservation **51**:408-109.

Littell, R. C., G. A. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. SAS systems for mixed models. SAS Institute, Cary, North Carolina, USA.

Lodge, R. W. 1960. Effects of burning, cultivating, and mowing on the yield and consumption of *A. cristatum*. Journal of Range Management **13**:318-321.

Looman, J., and D. H. Heinrichs. 1973. Stability of crested wheatgrass pastures under long-term pasture use. Canadian Journal of Plant Science **53**:501-506.

McCaughey, W. P., and R. G. Simons. 1998. Harvest management and N-fertilization on protein yield, protein content and nitrogen use efficiency of smooth bromegrass, crested wheatgrass and meadow bromegrass. Canadian Journal of Plant Science **78**:281-287.

Pellant, M., and C. R. Lysne. 2005. Strategies to enhance plant structure and diversity in *A. cristatum* seedings. USDA Forest Service Proceedings RMRS-P-38.

Pyke, D. A. 1990. Comparative demography of co-occurring introduced and native tussock grasses: persistence and potential expansion. Oecologia **82**:537-543.

Rawlins, J. K., B. A. Roundy, S. Davis, and B. Jessop. 2009. Wet thermal accumulation of Great Basin species. M.S. thesis. Brigham Young University, Provo, Utah.

Rogler, G. A., and R. J. Lorenz. 1963. *A. cristatum*—Early History in the United States. Journal of Range Management **36**:91-93.

Romo, J. T., P. L. Grilz, and L. Delanoy. 1994. Selective control of crested wheatgrass (*Agropyron cristatum* [L.] Gaertn. and *A. desertorum* Fisch.) in the Northern Great Plains. Natural Areas Journal **14**: 308-309.

Romo, J. T. 2005. Emergence and establishment of *Agropyron desertorum* (Fisch.) (Crested Wheatgrass) seedlings in a Sandhills Prairie of Central Saskatchewan. Natural Areas Journal **25**: 26-35.

SAS Institute Inc. 1987. SAS/STAT™ Guide for personal computers, Version 6 ed. Cary, NC: SAS Institute Inc. 1028 p.

Sheley, R. L., T. J. Svejcar, and B. D. Maxwell. 1996. A theoretical framework for developing successional weed management strategies on rangeland. Weed Technology **10**:766-773.

Thompson, T. W., B. A. Roundy, E. D. McArthur, B. D. Jessop, B. Waldron, and J. N. Davis. 2006. Fire Rehabilitation Using Native and Introduced Species: A Landscape Trial. Rangeland Ecology and Management **59**:237-248.

Trickler, D. L. 2001. Soil survey of Tooele area, Utah: Tooele County and parts of Box Elder, Davis, and Juab Counties, Utah, and parts of White Pine and Elko Counties, Nevada, U.S. Department of Agriculture, Forest Service 269p.

Vaness, B. M., and S. D. Wilson. 2008. Impacts and management of crested wheatgrass (Agropyron cristatum) in the northern Great Plains. Canadian Journal of Plant Science **87**:1023-1028.

Waldron, B. L., T. A. Monaco, K. B. Jensen, R. D. Harrison, A. J. Palazzo, and J. D. Kulbeth. 2005. Coexistence of Native and Introduced Perennial Grasses following Simultaneous Seeding. Agronomy Journal **97**:990-996.

Wilson, S. D., and M. Partel. 2003. Extirpation or coexistence? Management of a persistent introduced grass in a prairie restoration. Restoration Ecology **11**:410-416.

Table 1. Species included in seed mix and seeding rates (kg/ha) to diversify crested wheatgrass stands in Utah. Pure live seed and bulk seeding rates. Plots were seeded October 2005 and 2006.

Drill Mix Species Names	PLS kg/ha	Bulk kg/ha
Pseudoroegneria spicata [Pursh] A. Love (Bluebunch wheatgrass - 'Anatone')	3.36	3.54
Elymus elymoides[Raf.] Swezey (Squirreltail - 'SID Sanpete')	2.24	3.16
Achnatherum hymenoides [Roemer & J.A. Schultes] Barkworth (Indian Ricegrass - 'Nezpar')	2.24	2.39
Atriplex canescens [Pursh] Nutt (Fourwing saltbush)	1.12	3.9
Linum lewisii Pursh (Lewis flax - 'Appar')	0.84	0.93
Sphaeralcea munroana [Dougl. Ex Lindl.] Spach ex Gray (Munro's globemallow)	0.56	0.94
Total	10.36	14.86
Broadcast Mix Species Names	PLS kg/ha	Bulk kg/ha
Poa secunda J. Presl (Sandberg bluegrass - 'SID OR')	0.84	1.06
Ericameria nauseosa [Pallas ex Pursh] Nesom & Baird (White stemmed rabbitbrush)	0.28	0.84
Artemisia tridentata Nutt. ssp. *wyomingensis* Beetle & Young (Wyoming big sagebrush)	0.22	1.05
Achillea millefolium L. (Yarrow - 'Eagle')	0.22	0.27
Total	1.56	3.22

Table 2. Density of *Agropyron cristatum* [L.] Gaertner and weeds after wheatgrass control treatments at Lookout Pass and Skull Valley.

		Lookout Pass Mean Value Plants/m^2					Skull Valley Mean Value Plants/m^2				
			Treated 2005		Treated 2006			Treated 2005		Treated 2006	
Variable	Treatment[t]	2006	2007	2008	2007	2008	2006	2007	2008	2007	2008
Mature *A. cristatum*	UD	11 b	15 b	25 ab	19 ab	14 b	13 abc	15 abc	19 abc	13 abc	15 abc
	PCM	10 b	16 b	16 b	15 b	17 b	8 bc	12 abc	10 abc	16 abc	19 ab
	FCM	10 b	17 b	20 ab	20 ab	34 a*	6 c	10 bc	8 bc	9 bc	23 a
	PCH	10 b	21 ab	14 b	15 b	21 ab	13 abc	14 abc	15 abc	13 abc	16 abc
	FCH	13 b	21 ab	25 ab	21 ab	16 b	10 abc	12 abc	12 abc	10 abc	10 abc
A. cristatum seedlings	UD	5 de	21 abc	0 e	24 ab	1 e	6 cde	9 b-e	0 de	10 b-e	1 de
	PCM	5 de	10 b-e	1 e	30 a	0 e	6 cde	7 cde	0 de	22 ab	2 de
	FCM	5 de	7 cde	1 e	23 ab	2 e	6 cde	6 cde	0 de	24 a*	0 de
	PCH	4 de	12 b-e	0 e	19 a-d	1 e	4 cde	7 cde	0 e	13 a-d	0 e
	FCH	7 cde	8 cde	0 e	24 ab	1 e	6 cde	8 cde	0 de	16 abc	1 de
Bromus tectorum L.	UD	1 b	6 b	2 b	1 b	0 b	34 de	123 a-e	52 cde	154 a-e	65 b-e
	PCM	1 b	11 b	11 ab	1 b	0 b	37 de	232 a	112 a-e	86 b-e	147 a-e
	FCM	2 b	30 a*	13 ab	1 b	1 b	35 de	202 ab	153 a-e	62 cde	191 abc
	PCH	0 b	1 b	0 b	3 b	3 b	9 e	55 b-e	24 de	72 b-e	59 b-e
	FCH	0 b	4 b	1 b	6 b	13 ab	10 e	53 b-e	54 b-e	110 a-e	167 a-d
Exotic annual forbs	UD	8 c	82 bc	11 c	60 bc	3 c	1 a	1 a	1 a	6 a	0 a
	PCM	10 c	153 b	19 bc	29 bc	3 c	1 a	3 a	2 a	3 a	8 a
	FCM	8 c	115 bc	12 c	29 bc	9 c	3 a	13 a	3 a	6 a	13 a
	PCH	4 c	54 bc	2 c	30 bc	6 c	1 a	2 a	1 a	5 a	2 a
	FCH	7 c	296 a*	6 c	46 bc	21 bc	5 a	4 a	2 a	4 a	3 a

[t] Undisturbed (UD), partial control mechanical (PCM), full control mechanical (FCM), partial control herbicide (PCH), full control herbicide (FCH).
Within each variable, site, and year, means with different letters are significantly different using Tukey-Kramer honestly significant difference multiple comparison procedure ($P < 0.05$).
*significantly different from control treatment (UD)

Table 3. Density of seeded species 1-3 years after sowing into stands of *Agropyron cristatum* [L.] Gaertner, averaged across *A. cristatum* undisturbed, mechanical, and herbicide control treatments.

	Lookout Pass Mean Value Plants/m^2 (± SE)					Skull Valley Plants/m^2 (± SE)				
	Sown 2005			Sown 2006		Sown 2005			Sown 2006	
Seeded Species[t]	2006	2007	2008	2007	2008	2006	2007	2008	2007	2008
TG (PSSP6, ACHY, ELEL5)	14.83 ± 0.02	7.34 ± 0.09	0.75 ± 0.02	10.61 ± 0.10	0.77 ± 0.03	9.22 ± 0.09	4.03 ± 0.07	0.20 ± 0.01	7.77 ± 0.08	0.45 ± 0.01
POSE	4.65 ± 0.07	2.14 ± 0.06	0	2.09 ± 0.07	0	4.32 ± 0.06	0.22 ± 0.01	0.44 ± 0.20	0.12 ± 0.009	0.27 ± 0.02
LILE3	5.32 ± 0.06	1.86 ± 0.03	0.84 ± 0.02	2.24 ± 0.04	0.25 ± 0.01	2.49 ± 0.03	0.10 ± 0.006	0.01 ± 0.002	2.83 ± 0.04	0.005 ± 0.001
SPMU2	0.13 ± 0.007	0.11 ± 0.05	0.03 ± 0.003	0.10 ± 0.006	0.03 ± 0.003	0.08 ± 0.005	0.005 ± 0.001	0	0.03 ± 0.003	0
ACMI2	0.63 ± 0.02	0.58 ± 0.02	0.26 ± 0.01	0.01 ± 0.001	0.04 ± 0.006	0.22 ± 0.009	0.08 ± 0.006	0.01 ± 0.002	0.032 ± 0.005	0.01 ± 0.001
ARTRW8	0.10 ± 0.001	0.12 ± 0.08	0.09 ± 0.007	0.09 ± 0.01	0.005 ± 0.001	0.21 ± 0.008	0.02 ± 0.003	0.005 ± 0.001	0.11 ± 0.009	0.016 ± 0.002
ERNA10	0.03 ± 0.003	0.01 ± 0.002	0	0.005 ± 0.001	0	0.20 ± 0.01	0.03 ± 0.003	0.005 ± 0.001	0.02 ± 0.003	0
ATCA2	0.04 ± 0.004	0.01 ± 0.003	0	0.01 ± 0.001	0	0.008 ± 0.002	0	0	0.03 ± 0.003	0

[t] TG (*Pseudoroegneria spicata* [Pursh] A. Love; *Achnatherum hymenoides* [Roemer & J. A. Schultes] Barkworth; *Elymus elymoides* [Raf.] Swezey); POSE (*Poa secunda* J. Presl); LILE3 (*Limun lewisii* Pursh); SPMU2 (*Sphaeralcea munroana* [Dougl. Ex Lindl.] Spach ex Gray); ACMI2 (*Achillea millefolium* L.); ARTRW8 (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young); ERNA10 (*Ericameria nauseosa* [Pallas ex Pursh] Nesom & Baird); ATCA2 (*Atriplex canescens* [Pursh] Nutt.).

Table 4. Number of species *S*, total number of individuals *N*, and values of plant species diversity and evenness indices collected at Lookout Pass and Skull Valley in 2007 and 2008.

Variable	Treatment[t]	*S*	*N*	1 - *D*	$E_{1/D}$	*H'*	*E*
Lookout Pass 2007	S	28	50942	0.66	0.11	1.49	0.16
	US	24	59405	0.56	0.10	1.19	0.14
Lookout Pass 2008	S	24	21109	0.76	0.18	1.64	0.22
	US	22	21357	0.76	0.19	1.62	0.23
Skull Valley 2007	S	25	58115	0.39	0.07	0.83	0.09
	US	14	53874	0.37	0.11	0.72	0.15
Skull Valley 2008	S	20	49674	0.27	0.07	0.58	0.09
	US	14	42849	0.32	0.11	0.67	0.14

[t] Seeded (S) and unseeded plots (US); Simpson's index of diversity (1-*D*), Simpson's measure of evenness ($E_{1/D}$), Shannon-Wiener diversity index (*H'*), Shannon-Wiener evenness index (*E*).

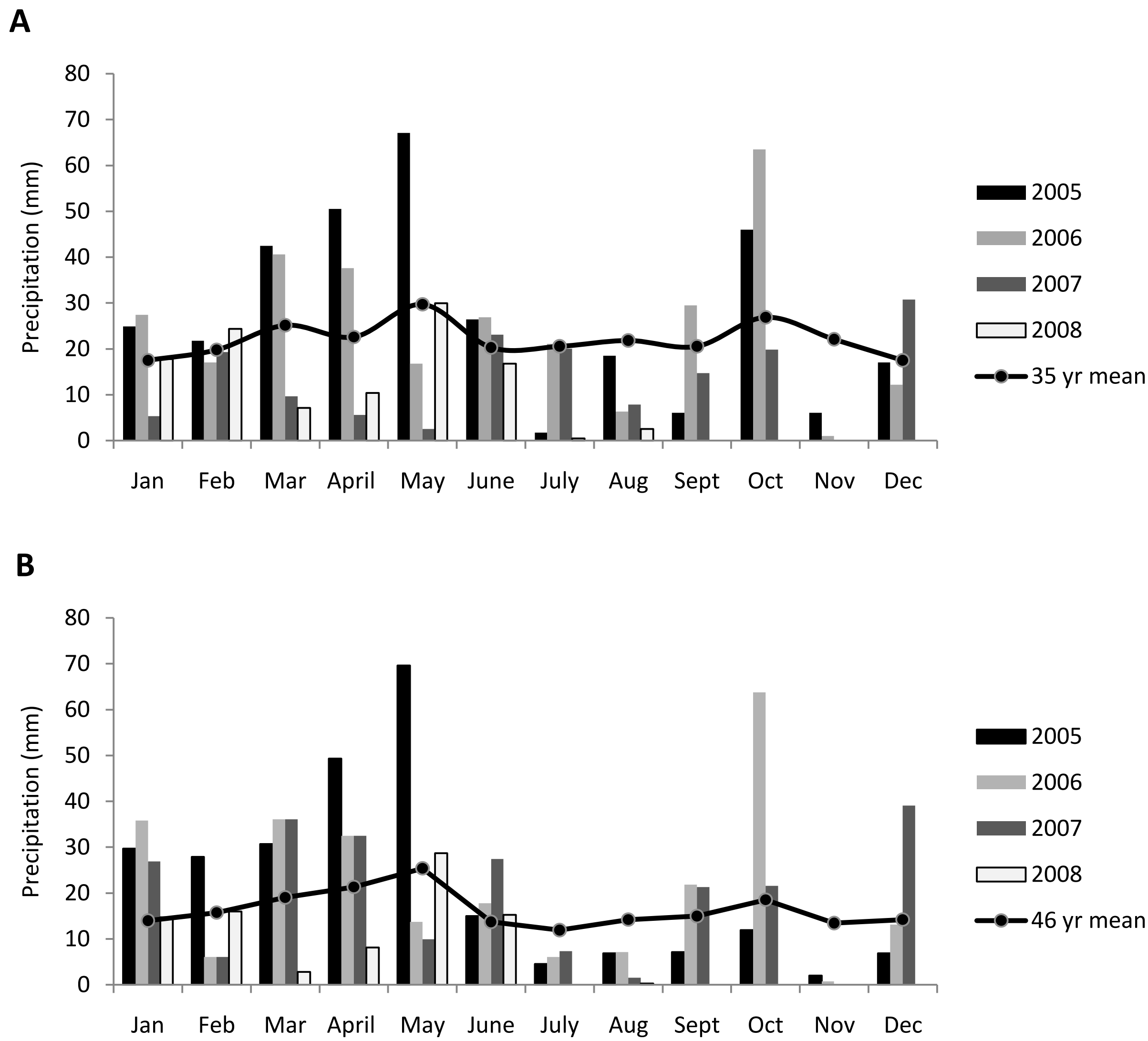

Figure 1. Total monthly precipitation for (A) Lookout Pass and (B) Skull Valley, Tooele Co., Utah from 2005 to August 2008. Lookout Pass yearly totals: 2005-329 mm; 2006-300 mm; 2007-159 mm; 35 Year Mean-265 mm. Skull Valley yearly totals: 2005-262 mm; 2006- 255 mm; 2007- 230 mm; 46 Year Mean-197 mm.

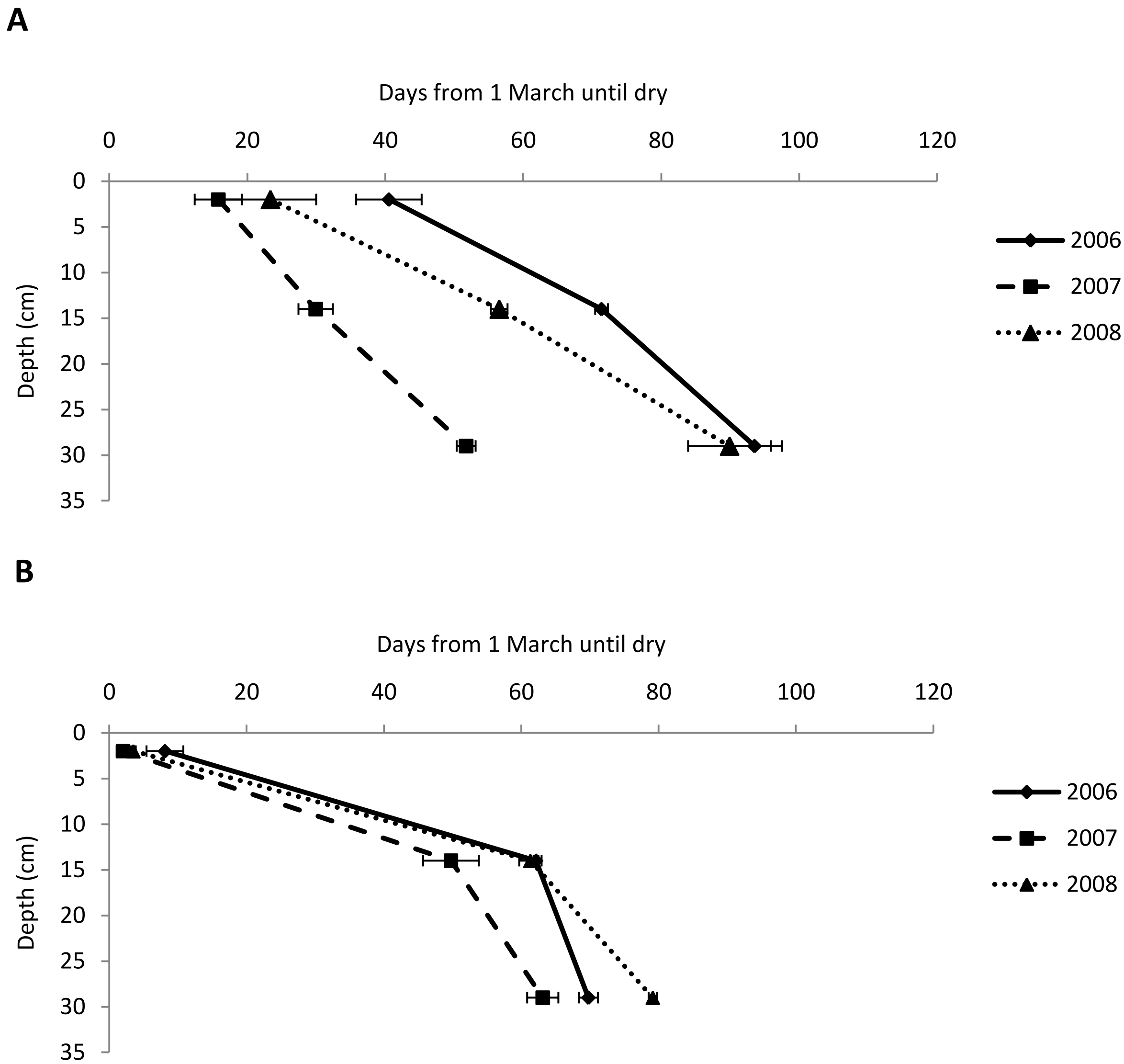

Figure 2. Average number of wet days (soil water potential > -1.5 MPa) from 1 March until soil was dry (< -1.5 MPa) for (A) Lookout Pass and (B) Skull Valley, Utah.

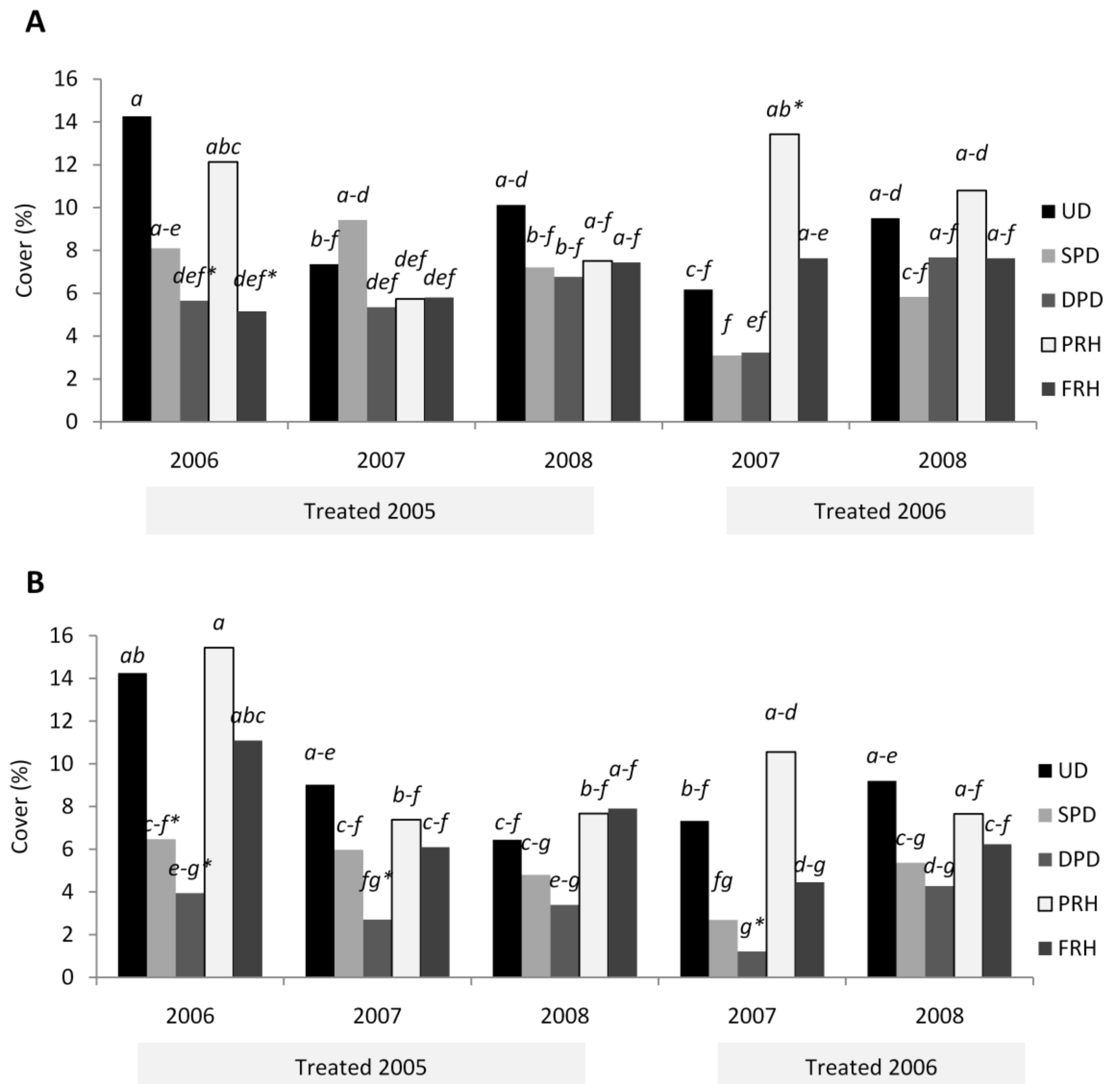

Figure 3. 1-year or older crested wheatgrass cover (%) at (A) Lookout Pass and (B) Skull Valley, Utah on undisturbed (UD), single-pass disking (SPD), double-pass disking (DPD), partial rate herbicide (PRH), full rate herbicide (FRH) treatments. Means with different letters within each site are significantly different using Tukey-Kramer honestly significant difference multiple comparison procedure ($p < 0.05$). *Significantly different from UD treatment.

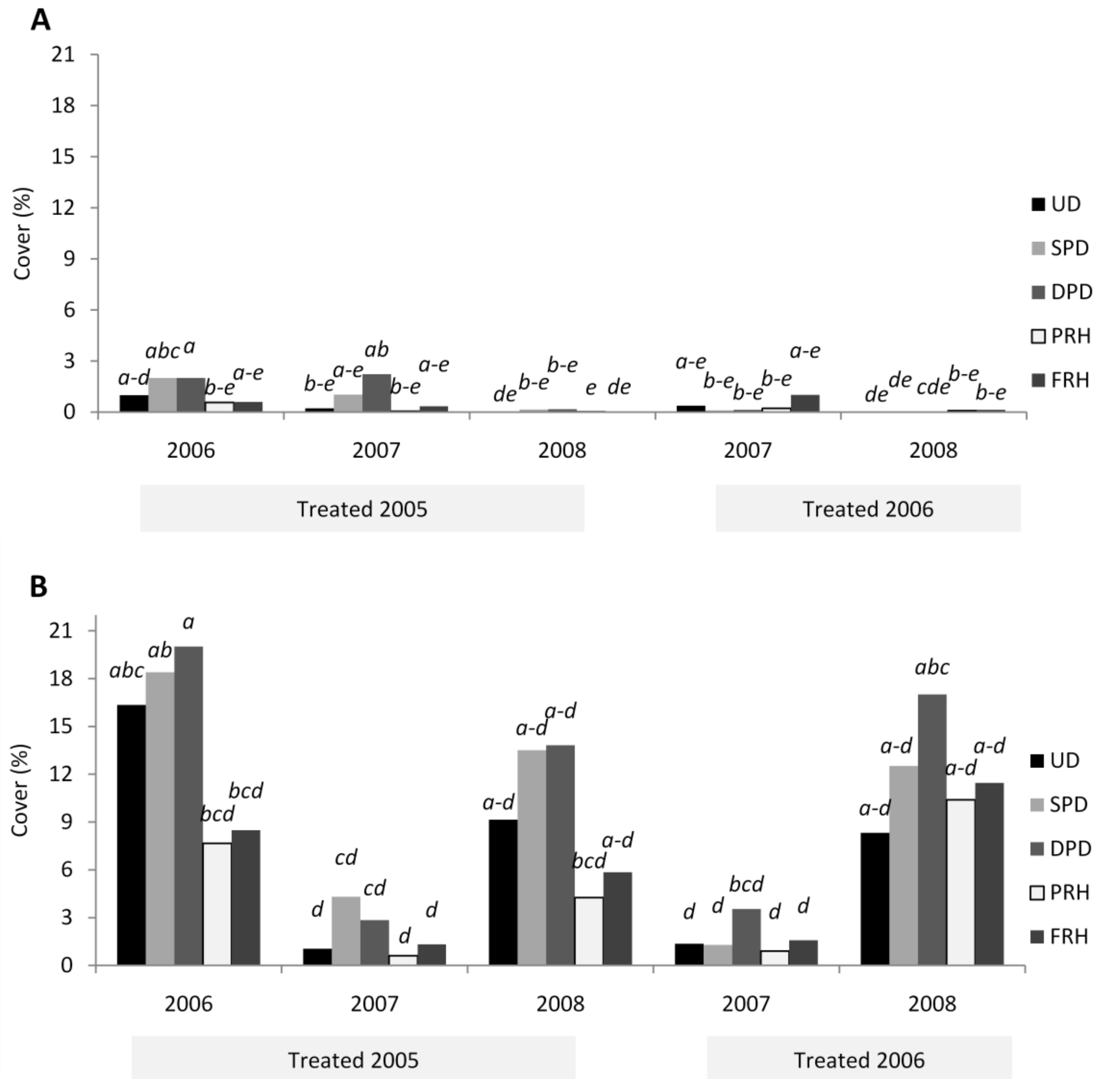

Figure 4. Cheatgrass cover (%) at (A) Lookout Pass and (B) Skull Valley, Utah on undisturbed (UD), single-pass disking (SPD), double-pass disking (DPD), partial rate herbicide (PRH), full rate herbicide (FRH) treatments. Means with different letters within each site are significantly different using Tukey-Kramer honestly significant difference multiple comparison procedure ($p < 0.05$).

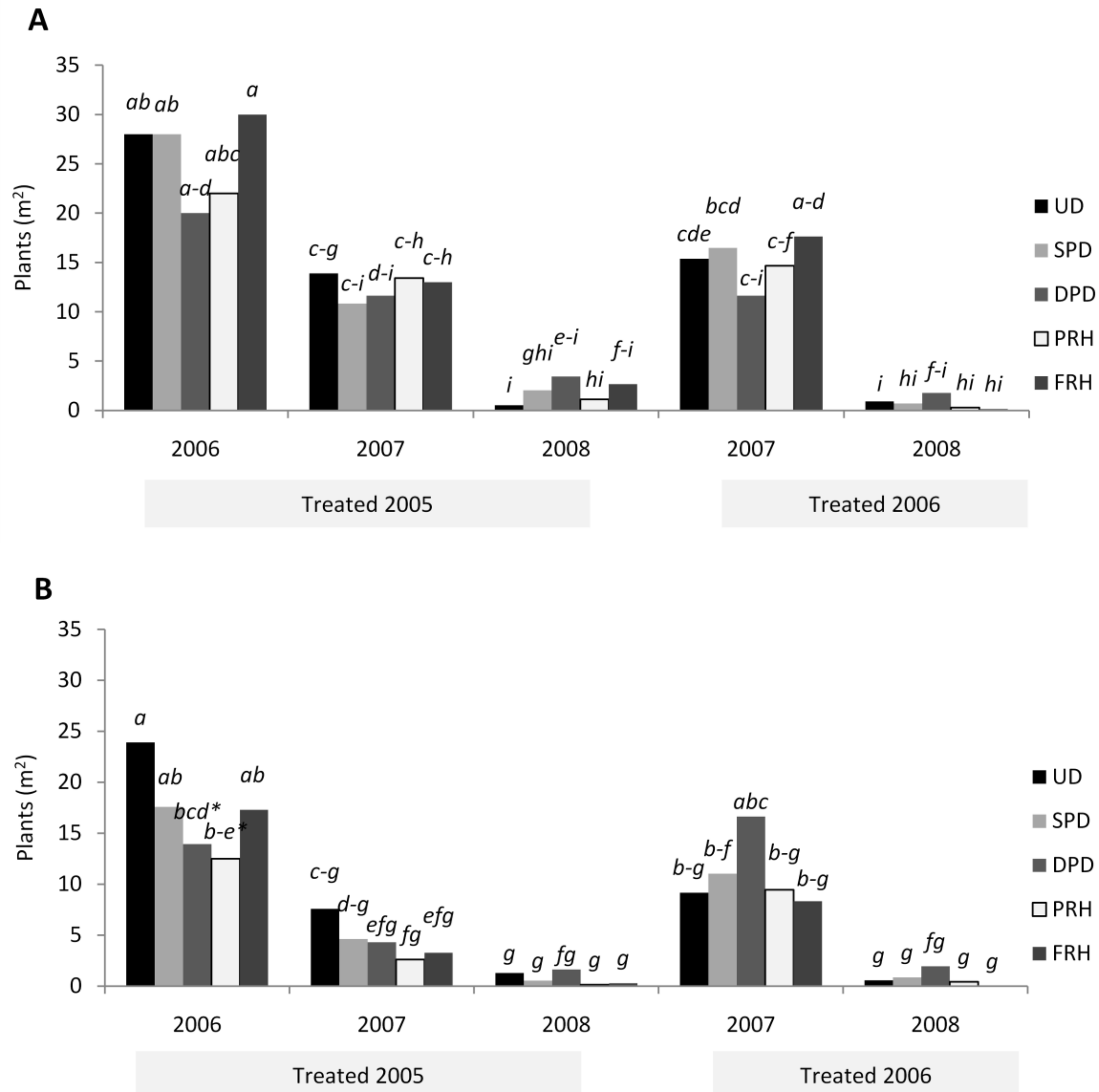

Figure 5. Total seeded species density (plants/m^2) at (A) Lookout Pass and (B) Skull Valley, Utah on undisturbed (UD), single-pass disking (SPD), double-pass disking (DPD), partial rate herbicide (PRH), full rate herbicide (FRH) treatments. Means with different letters within each site are significantly different using Tukey-Kramer honestly significant difference multiple comparison procedure ($p < 0.05$). *Significantly different from UD treatment.