Crested Wheatgrass Control and Native Plant Establishment in Utah

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Abstract

Effective control methods need to be developed to reduce crested wheatgrass (Agropyron cristatum [L.] Gaertner) monocultures and promote the establishment of native species. This research was designed to determine effective ways to reduce crested wheatgrass and establish native species while minimizing weed invasion. We mechanically (single- or double-pass disking) and chemically (1.1 L \cdot ha\(^{-1}\) or 3.2 L \cdot ha\(^{-1}\) glyphosate—Roundup Original Max) treated two crested wheatgrass sites in northern Utah followed by seeding native species in 2005 and 2006. The study was conducted at each site as a randomized block split plot design with five blocks. Following wheatgrass-reduction treatments, plots were divided into 0.2-ha subplots that were either unseeded or seeded with native plant species using a Truax Rough Rider rangeland drill. Double-pass disking in 2005 best initially controlled wheatgrass and decreased cover from 14% to 6% at Lookout Pass and from 14% to 4% at Skull Valley in 2006. However, crested wheatgrass recovered to similar cover percentages as untreated plots 2–3 yr after wheatgrass-reduction treatments. At the Skull Valley site, cheatgrass cover decreased by 14% on herbicide-treated plots compared to an increase of 33% on mechanical-treated plots. Cheatgrass cover was also similar on undisturbed and treated plots 2 yr and 3 yr after wheatgrass-reduction treatments, indicating that wheatgrass recovery minimized any increases in weed dominance as a result of disturbance. Native grasses had high emergence after seeding, but lack of survival was associated with short periods of soil moisture availability in spring 2007. Effective wheatgrass control may require secondary treatments to reduce the seed bank and open stands to dominance by seeded native species. Manipulation of crested wheatgrass stands to restore native species carries the risk of weed invasion if secondary treatments effectively control the wheatgrass and native species have limited survival due to drought.

Resumen

Se necesitan desarrollar métodos eficaces de control para reducir los monocultivos del triguillo crestado (Agropyron cristatum [L.] Gaertner) y promover el establecimiento de especies nativas. Esta investigación se diseñó para determinar formas efectivas de reducir el triguillo crestado y establecer especies nativas y a la vez minimizar la invasión de malezas. Dos sitios de triguillo crestado al norte de Utah se trataron mecánicamente (pasando un disco un ves o dos veces) y químicamente (1.1 L \cdot ha\(^{-1}\) o 3.2 L \cdot ha\(^{-1}\) glyphosate—Roundup Original Max) seguido por la siembra de especies nativas en 2005 y 2006. El estudio se hizo en cada sitio como un diseño de bloques al azar con parcelas divididas con cinco bloques. Después de los tratamientos de la reducción del triguillo crestado, las parcelas se dividieron en sub-parcelas de 0.2 ha que fueron sembradas o no sembradas con especies nativas utilizando una sembradora para pastizales Truax Rough Rider. El pasar dos veces los discos en 2005 controló el triguillo crestado mejor inicialmente y disminuyó la cubierta del 14% a 6% en Lookout Pass y del 14% a 4% en Skull Valley en 2006. Sin embargo, el triguillo crestado volvió a los porcentajes de cobertura similar a las parcelas sin tratar 2 a 3 años después de los tratamientos de reducción del triguillo. En el sitio de Skull Valley, la cobertura del bromillo disminuyó de 14% en las parcelas tratadas con herbicidas comparadas con las parcelas tratadas mecánicamente que se incrementaron un 33%. La cobertura del bromillo fue también similar en las parcelas sin disturbio y las parcelas tratadas 2 años y 3 años después de los tratamientos de reducción indicando que la recuperación del triguillo crestado minimiza cualquier incremento en el dominio de las malezas como resultado del disturbio. Los pastos nativos presentaron una alta aparición después de la siembra, pero la falta de sobrevivencia fue asociada con los periodos cortos de humedad disponible en el suelo durante la primavera del 2007. El control efectivo del triguillo crestado quizás requiera de tratamientos secundarios para reducir el banco de semillas y favorecer el dominio de las especies nativas sembradas. La manipulación de las áreas para restaurar las especies nativas lleva el riesgo de la invasión de malezas si los tratamientos secundarios controlan efectivamente el triguillo crestado y las especies nativas tienen limitada sobrevivencia debido a la sequía.

Key Words: Agropyron cristatum, assisted succession, bridging communities, mechanical and chemical control, Roundup Original Max

INTRODUCTION

Crested wheatgrass (Agropyron cristatum [L.] Gaertner) is a C\(_3\) perennial caespitose bunchgrass from Eurasia that has been seeded on 6–11 million ha of rangeland in North America (Lesica and DeLuca 1996; Henderson and Naeth 2005; Vaness and Wilson 2008). Crested wheatgrass is widely seeded...
following wildfires because it establishes well, suppresses weeds, provides cover that significantly decreases runoff, and increases forage for grazing (Pellant and Lysne 2005; Romo 2005; Waldron et al. 2005; Hansen and Wilson 2006). Crested wheatgrass is drought and cold resistant, making it widely adapted, and it has relatively few disease problems (Rogler and Lorenz 1963). Despite these benefits crested wheatgrass often exists in large manmade monocultures that support limited plant and wildlife diversity (Looman and Heinrichs 1973; Christian and Wilson 1999; Heidenga and Wilson 2002; Davison and Smith 2005).

By increasing native plant cover in crested wheatgrass monocultures, we expect to improve wildlife habitat, enhance species richness and community diversity, increase soil cover, and improve the aesthetics of the landscape (Shelley et al. 1996; Pellant and Lysne 2005). Converting crested wheatgrass stands to more native-plant–dominated communities requires an understanding of the response of crested wheatgrass to control methods (Pellant and Lysne 2005), potential weed invasion, and native plant establishment. Because crested wheatgrass dominates communities (both vegetation and seedbank) for decades following establishment in mixed-grass prairies, Henderson and Naeth (2005) suggest that controlling crested wheatgrass 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.

In a study conducted in the Great Basin, Cox and 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 crested wheatgrass, 2) reduce crested wheatgrass using mechanical or herbicide treatments, and 3) reseed the site with native species. Pellant and Lysne (2005) saw crested wheatgrass monocultures as “bridge” plant communities that would replace cheatgrass-dominated lands for future restoration to a more diverse plant community. We sought to evaluate revegetation of native species in crested wheatgrass stands by determining 1) which wheatgrass-reduction methods best reduce crested wheatgrass, 2) the effects of wheatgrass-reduction methods on weed invasion, and 3) how wheatgrass-reduction methods affect native plant revegetation success.

METHODS

Study Area

Two crested wheatgrass stands in Tooele County, Utah, were selected for crested wheatgrass–reduction treatments and native species seeding. Both sites were previously seeded by the Bureau of Land Management following wildfires. The Skull Valley site (lat 40°18’N, long 112°51’W) was drill seeded with 3.36 kg·ha⁻¹ A. cristatum “Fairway” and 3.36 kg·ha⁻¹ intermediate wheatgrass (Thinopyrum intermedium [Host] Barkworth and D. R. Dewey) following the Spoonbill fire in the fall of 1982. The stand is predominantly crested wheatgrass, with some Sandberg bluegrass (Poa secunda [J. Presl] Barkworth) and very few intermediate wheatgrass plants observed 24 yr after seeding. Skull Valley is 1,524 m above sea level, receives 200–254 mm of precipitation annually, has Medburn fine sandy loam, mixed (Calcareous) mxic, and xeric Torriorthents soil (Trickler 2001), and has an abundance of cheatgrass surrounding and within patches on the site. The Lookout Pass site (lat 40°09’N, long 112°28’W) is approximately 72 km southeast of the Skull Valley site and located on the eastern side of the Onaqui Mountains. Lookout Pass was drill seeded following the Aqueduct fire with 3.36 kg·ha⁻¹ A. cristatum “Hycrest,” 1.12 kg·ha⁻¹ western wheatgrass (Pascopyrum smithii [Rydb.] A. Love), and 1.12 kg·ha⁻¹ yellow sweetclover (Melilotus officinalis [L.] Lam.) in the fall of 1996. By 2006, western wheatgrass was recorded on <5% of plots, and no yellow sweetclover was observed. The Lookout Pass site is 1,673 m above sea level, receives 254–305 mm of precipitation annually, and has Taylorsflat fine-loamy, mixed, mesic, xeric Calciorithents soil (Trickler 2001). Both sites were fenced to exclude livestock grazing for the duration of the experiment.

Experimental Design

Each study site was on approximately 24 ha. The experiment was installed as a randomized block split plot with five blocks. Blocks were divided in half and randomly assigned to be treated in 2005 or 2006. Within each block, 0.4-ha main plots were either left undisturbed (UD) or received a single-pass disk treatment (SPD), double-pass disking treatment (DPP), partial rate herbicide treatment (1.1 L·ha⁻¹ glyphosate–Roundup Original Max; PRH), or full-rate herbicide treatment (3.2 L·ha⁻¹ glyphosate–Roundup Original Max; FRH) to partially or substantially reduce crested wheatgrass. Following wheatgrass-reduction treatments, all treatment plots were further divided into 0.2-ha subplots that were either seeded or left unseeded. In both 2005 and 2006, herbicide treatments were applied in late May, and mechanical treatments were applied in early June. The DPP treatment was implemented by disking 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, New Hope, MN) in October 2005 or 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. Chains dragging behind the packer wheel covered drilled seeds with soil.

Species Seeded

A mixture of 10 species (four grasses, three shrubs, and three forbs) was seeded in each seeded subplot (Table 1). 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, “Eagle” yarrow (Achillea millefolium [L.]), which was provided by Landmark Seed Company (Spokane, WA). The seed mixture included species adapted to the sites and readily available in sufficient quantities for operational scale revegetation.
Vegetation Sampling
Data were collected in early June 2006, late May 2007, and May 2008. We used a stratified random sampling design. Starting points for initial transects were located randomly for each site. 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, which ran the length of the subplot.

Data were recorded from 0.25-m²-square quadrats placed six times (in 3-m intervals) along each 30-m transect, totaling 30 samples per subplot. Within each quadrat, density was recorded for all species including a row each of the drilled and broadcast species. Percentage cover for perennial species and cheatgrass was estimated ocularly using cover classes (Dau, 1959; Bailey and 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 and averaged across subplots.

Precipitation and Soil Moisture Sampling
In summer 2005, thermocouples and gypsum blocks (Delmhorst, Stamford, CT) were buried in small plots adjacent to our 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 with three wheatgrass-reduction treatments (undisturbed, partial rate herbicide, and full-rate herbicide). Thermocouple and gypsum-block outputs were read every minute, and hourly averages were recorded using Campbell Scientific CR-10× microloggers (Campbell Scientific, Logan, UT). Soil water potentials down to −1.5 MPa were estimated from gypsum block electrical resistance using a standard calibration curve (Campbell Scientific, 1983). Total hourly precipitation was monitored from an electronic tipping bucket rain gage (Texas Electronics, Dallas, TX) at each study site. Precipitation data for January 2005–July 2005 and mean precipitation were taken from the Western Regional Climate Center (2005) weather stations with the closest proximity to individual sites. Lookout Pass data were taken from Utah station #429133 VERNON; Skull Valley data were taken from Utah station #422257 DUGWAY.

Table 1. Seed mix species. Pure live seed (PLS) and bulk seeding rates (kg·ha⁻¹). Seeded October 2005 and 2006.

<table>
<thead>
<tr>
<th>Species names</th>
<th>PLS</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudoroegneria spicata (Pursh) A. Love</td>
<td>3.36</td>
<td>3.54</td>
</tr>
<tr>
<td>(Bluebunch wheatgrass—“Anatone”)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elymus elymoides (Raf.) Swezey</td>
<td>2.24</td>
<td>3.16</td>
</tr>
<tr>
<td>(Squirreltail—“SID Sanpete”)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Achthatherum hymenoides (Roemer &amp; J. A. Schultes) Barkworth</td>
<td>2.24</td>
<td>2.39</td>
</tr>
<tr>
<td>(Indian Ricegrass—“Nezpar”)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atriplex canescens (Pursh) Nutt</td>
<td>1.12</td>
<td>3.9</td>
</tr>
<tr>
<td>(Fourwing saltbush)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linum lewisii Pursh (Lewis flax—“Appar”)</td>
<td>0.84</td>
<td>0.93</td>
</tr>
<tr>
<td>Sphaeralcea munroana (Dougl. ex Lindl.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spach ex Gray (Munro’s globemallow)</td>
<td>0.56</td>
<td>0.94</td>
</tr>
<tr>
<td>Total</td>
<td>10.36</td>
<td>14.86</td>
</tr>
<tr>
<td>Broadcast mix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poa secunda J. Presl</td>
<td>0.84</td>
<td>1.06</td>
</tr>
<tr>
<td>(Sandberg bluegrass—“SID OR”)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ericameria nauseosa (Pallas ex Pursh) Nesom &amp; Baird (White stemmed rabbitbrush)</td>
<td>0.28</td>
<td>0.84</td>
</tr>
<tr>
<td>Artemisia tridentata Nutt. subsp. wyomingensis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beetle &amp; Young (Wyoming big sagebrush)</td>
<td>0.22</td>
<td>1.05</td>
</tr>
<tr>
<td>Achillea millefolium L. (Yarrow—“Eaglebrush”)</td>
<td>0.22</td>
<td>0.27</td>
</tr>
<tr>
<td>Total</td>
<td>1.56</td>
<td>3.22</td>
</tr>
</tbody>
</table>

RESULTS
Precipitation and Soil Moisture
Yearly precipitation at Lookout Pass was at or below average (265 mm last 35 yr) while that at Skull Valley was at or above average (197 mm last 46 yr) during the 2005–2008 study period (Fig. 1). An important exception was 2008, which was extremely dry at Skull Valley (51% below average; Fig. 1). In 2007 at Lookout Pass, yearly precipitation was overall 40% lower than the 35-yr 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. At Lookout Pass and at a soil depth of 1–3 cm, soil moisture after 1 March was available 25 more days in 2006 than in 2007 (Fig. 2). Spring soil moisture availability at Skull Valley was less than that at Lookout Pass all three years, but was greater in 2006 than 2007 or 2008 (Fig. 2). For both sites, subsurface (13–30 cm) soil water availability in spring 2007 ranged from 6 d to 42 d less, with a mean of 24 d less, than in 2006 and 2008 (Fig. 2).
Crested Wheatgrass Control
Mechanical treatments were initially more effective than herbicide treatments in reducing mature crested wheatgrass cover, but 3 yr after treatment, wheatgrass cover was similar for all treatments (Fig. 3). Double disking in 2005 decreased wheatgrass cover significantly in 2006 at Lookout Pass (14–6%) and at Skull Valley (14–4%; Fig. 3; P < 0.05). Double disking in 2006 reduced wheatgrass cover significantly at Skull Valley (7–1%; P < 0.05), but not at Lookout Pass (Fig. 3). The full herbicide rate applied in 2005 also significantly reduced mature wheatgrass cover at Lookout Pass (14–5%; P < 0.05), but not at Skull Valley (Lookout Pass × Skull Valley: F$_{1,8}$ = 5.63, P = 0.0451; 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).

No wheatgrass-reduction treatments significantly reduced densities of mature crested wheatgrass plants at Lookout Pass or Skull Valley compared to UD plots (Table 2; Lookout Pass × Skull Valley: F$_{1,8}$ = 22.59, P = 0.0014; treatment × sample year interactions for Lookout Pass: F$_{4,16}$ = 1.78, P = 0.1817; Skull Valley: F$_{4,16}$ = 1.64, P = 0.2140). At Lookout Pass, double disking in 2006 actually increased wheatgrass density compared to UD plots in 2008 (Table 2; P < 0.05). Crested wheatgrass produced high seedling densities on both undisturbed and treated plots in 2006 and 2007, but much lower densities in 2008 (Table 2; site × sample year interaction: F$_{4,32}$ = 5.26, P = 0.0023). Seedling densities peaked in spring 2007. Over the course of the study, mature crested wheatgrass increased in density to the maximum measured in 2008 as new seedlings from previous years filled in both untreated and treated stands (Table 2).

Cheatgrass and Annual Forbs
Cheatgrass cover and density were much higher at Skull Valley than at the Lookout Pass site, while exotic annual forbs (mainly desert madwort (Alyssum desertorum Stapf) were more dense at Lookout Pass than at Skull Valley (Fig. 4; Table 2; Lookout Pass × Skull Valley: F$_{1,8}$ = 126.87, P < 0.0001). Double disking in 2005 increased cheatgrass density at Lookout Pass in 2006 (Table 2), while herbicide applications in 2005 decreased...
cheatgrass cover at Skull Valley in 2006 (Fig. 4). At Lookout Pass, cheatgrass cover and density remained low throughout the study, with small increases associated with disking (Fig. 4; Table 2). At Skull Valley cheatgrass cover and density were high on all plots, with highest values in wetter years and on disked plots (Fig. 4; Table 2; treatment \times sample year interactions for Lookout Pass: $F_{16,160} = 3.47, P \leq 0.0001$; Skull Valley: $F_{16,160} = 5.36, P \leq 0.0001$).

Exotic annual forb density was highest at Lookout Pass in spring of 2007 because of the high amount of desert madwort and was associated with the FRH wheatgrass-reduction treatment applied in 2005 (Table 2; treatment \times sample year interaction for Lookout Pass: $F_{16,160} = 3.47, P \leq 0.0001$). Except for curvseeded buttwort (Ceratocephala testiculata [Cranz] Roth), annual forbs were limited at Skull Valley, with prickly Russian thistle (Salsola tragus L.) most frequently encountered (Lookout Pass \times Skull Valley: $F_{1,8} = 57.13, P < 0.0001$). Because of large quantities of curvseeded buttwort at both sites, we did not sample its density; however, we estimated it to have covered approximately 40% of the ground for 2–3 wk at both sites each spring, and it was considered to be the dominant annual forb.

**Seeding Success**

There were no significant differences in seeded species density associated with any wheatgrass-reduction method, except that double disking in 2005 at Skull Valley was associated with lower seeded species density than UD plots in 2006 (Fig. 5; treatment: $F_{4,32} = 1.62, P = 0.1942$). Density of seeded species was greater at Lookout Pass than at Skull Valley both the first year after sowing and on subsequent years (Fig. 5; $P < 0.05$). Survival of seeded species continually decreased throughout the study period, especially after 2007 (Figs. 5 and 6).

At both sites, seeded grasses had greater emergence than either shrubs or forbs (Table 3; $P < 0.0001$). Drill-seeded species encountered most frequently were bluebunch wheatgrass (Pseudoroegneria spicata [Pursh] A. Love), Indian ricegrass (Achnatherum hymenoides [Roem. and Schult.] Barkworth), and squirreltail (Elymus elymoides [Raf.] Swezey). The forb encountered most often was Lewis flax (Linum lewisii

![Figure 2. Average number of wet days (soil water potential $\geq -1.5$ MPa) \pm SE from 1 March until soil was dry ($\leq -1.5$ MPa) for A, Lookout Pass and B, Skull Valley, Utah.](image-url)
of the species that were broadcast, Sandberg bluegrass was most common; “Eagle” yarrow (Achillea millefolium L.) was noted occasionally. Only a few shrub seedlings of Wyoming big sagebrush (Artemisia tridentata Nutt. subsp. wyomingensis Beetle and Young), white stemmed rabbitbrush (Ericameria nauseosa [Pallas ex Pursh] Nesom and Baird), and fourwing saltbush (Atriplex canescens [Pursh] Nutt.) were observed.

**DISCUSSION**

Two major restoration concepts that apply to restoring native species in crested wheatgrass stands are described by Sheley and Krueger-Mangold (2003) and Davis et al. (2000). The first concept in replacing less desirable species with native species in rangeland improvement and restoration projects is to reduce the less desirable species to free resources for the establishment of revegetation species (Sheley and Krueger-Mangold 2003). The second concept is the fluctuating resource hypothesis of Davis et al. (2000), which states that weeds with sufficient propagule pressure will invade environments where they can use resources made available by disturbances, pulses, or both. Davis et al. (2000) also imply that environments with highly fluctuating resource availability are more invasible because their resources are not consistent enough to support sufficient populations of resident plants to preempt resources, especially on a pulse year. The disturbance of mechanical or herbicide treatments was “designed” to free up resources for the “controlled colonization” (Sheley and Krueger-Mangold 2003) of native plants. However, if the “designed disturbance” does not reduce the target plants, desired plant establishment may be reduced. If the disturbance does reduce the target plants and desired plants do not establish well enough to preempt resources, weeds may invade.
In our study, double-pass disking best controlled crested wheatgrass; however, all mechanical treatment effects had disappeared by the third year posttreatment. Disking may have “broken” up larger clumps of mature crested wheatgrass plants contributing to higher densities posttreatment (Table 2) instead of reducing crested wheatgrass cover and density. The resilience of crested wheatgrass to mechanical treatments is associated with its late seasonal growth and productive seedbanks and seedheads (Lodge 1960; Hull and Klomp 1966; McCaughey and Simons 1998).

Our full-rate herbicide treatment reduced crested wheatgrass cover more than the partial rate herbicide treatment. Responses of crested wheatgrass to herbicide treatments vary with timing and quantity of application and the phenological stage of the plants (Bakker et al. 1997; Ambrose and Wilson 2003; Wilson and Partel 2003; Hansen and Wilson 2006). Highest mortality should be expected when herbicides are applied in the spring when leaves are expanded and actively growing before lack of soil moisture results in water stress. As with mechanical treatments, all herbicide treatment effects had disappeared by the third year posttreatment as new seedlings restocked the stand (Table 2; Fig. 3). Density of crested wheatgrass increased as seedlings survived and added to the population of plants in both undisturbed and disturbed plots (Fig. 6). Our results support previous work noting that crested wheatgrass residuals and seedlings from the seedbank rapidly negate control efforts and that effective control requires successive wheatgrass-reduction treatments (Marlette and Anderson 1986; Pyke 1990; Romo et al. 1994; Bakker et al. 2003; Vaness and Wilson 2008).

Cheatgrass density was increased by disturbance (Brown et al. 2008), but densities decreased as crested wheatgrass density increased and after the dry spring-summer period of 2007 (Fig. 6). By 2008, cheatgrass density and cover were both similar on undisturbed and treated plots (Table 2; Figs. 4 and 6), indicating that disturbance did not lead to increased weed dominance. The practical conclusion is that while sown native species seedlings were dying, enough crested wheatgrass seedlings were surviving to restock the stand and suppress cheatgrass.

The differential effects of fluctuating resources on crested wheatgrass seedlings, cheatgrass, and sown native species help explain the 3-yr results of this experiment. Soil water availability in spring 2006 and 2007 was sufficient to support seedling emergence of cheatgrass at Skull Valley and of sown species and crested wheatgrass at both sites. The relatively dry winter of 2006–2007, followed by the dry spring of 2007, resulted in an average of 24 fewer days of subsurface water availability in spring 2007 compared to spring 2006 and 2008 (Fig. 2). In our sampling categorization, crested wheatgrass seedlings emerging in a given year were counted as 1 yr old or older the following year (Table 2). At the same time that crested wheatgrass was increasing in density, sown native grasses were decreasing in density (Fig. 6). 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 high mortality of sown native seedlings after the spring 2007 count (Fig. 5). In a small-plot study conducted adjacent to our study, Rawlins (2009)
also found high seedling mortality associated with limited soil moisture availability in the spring and summer months of 2007 (Fig. 2). Because crested wheatgrass recovery and drought both occurred simultaneously, it is not known how much each of these factors affected the high mortality of seeded native species or if better wheatgrass control would have supported higher native species seedling survival.

Revegetation success is highly variable on arid and semiarid rangelands where seasonal precipitation frequently limits or prevents plant establishment and growth (Call and Roundy 1991). Seeded species establishment was probably constrained in our study by lack of recurrent precipitation (Fig. 1), limited days of soil moisture availability (Fig. 2), and the recovery of crested wheatgrass (Table 2; Fig. 3). Nevertheless, native seeded species, including shrubs, were observed in all treated areas. Hull and Klomp (1966) found that when sagebrush seed was available in crested wheatgrass sites during the year of establishment, crested wheatgrass seedlings would be unable to suppress the brush. In a study similar to ours, Fansler (2007) found that wheatgrass-reduction treatments will decrease crested wheatgrass cover adequately to increase site availability for establishment of native species. More time is needed to observe how well the few surviving seeded plants persist on the crested wheatgrass-dominated plots.

Crested wheatgrass continues to dominate big sagebrush communities once occupied by native species, resulting in decreased biological diversity where it is predominately seeded following wildfire. Evidence is mounting that native grasses may successfully establish in many postfire seedings (Asay et al. 2001; Huber-Sannwald and Pyke 2005; Thompson et al. 2006). Although promising success, increased seed availability, and lower costs are leading to more use of native grasses in fire rehabilitation, crested wheatgrass will continue to be seeded because of its lower cost and high resistance to weed invasion. Our study indicates that resistance of crested wheatgrass to control measures and susceptibility of sown native species to

Figure 4. Cheatgrass mean cover (%) ± SE at A, Lookout Pass and B, Skull Valley, Utah, on undisturbed (UD), single-pass disk (SPD), double-pass disk (DPD), partial rate herbicide (PRH), and 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).
mortality during dry years both constrain restoration of native species into crested wheatgrass stands.

**IMPLICATIONS**

Our study has four important management implications. First, control of crested wheatgrass to restore native species will require primary and secondary wheatgrass-reduction treatments to reduce both residuals and seedbank plants. Second, native species establishment is highly dependent on seedling survival even if emergence is high. The dry spring of 2007 was likely associated with the high mortality of 1–2-yr-old sown native plants in our study. Third, crested wheatgrass has a valuable role in range seeding because of its ability to establish and survive when native plant seedling survival is low. Fourth, because native species success may be less dependable than that of crested wheatgrass, full control of crested wheatgrass carries the risk of weed invasion. Because both a dry year and lack of crested wheatgrass control occurred simultaneously in our study, we do not know if successful wheatgrass control would have supported greater sown native species survival. Therefore, native species establishment should be investigated where crested wheatgrass is successfully controlled.

**ACKNOWLEDGMENTS**

The authors would like to thank the USDA-Natural Resources Conservation Service for help in seeding the experiment and Jennifer Rawlins for substantial field support as well as other Brigham Young University students.
Figure 6. Mean density ± SE of crested wheatgrass plants >1-yr-old, seeded native grasses, and cheatgrass at A, Lookout Pass and B, Skull Valley, Utah, after treatments to control crested wheatgrass and sowing native species in 2005.

Table 3. Mean density ± SE of seeded species 1–3 yr after sowing into stands of Agropyron cristatum (L.) Gaertner, averaged across A. cristatum undisturbed, mechanical, and herbicide control treatments.

<table>
<thead>
<tr>
<th>Seeded species</th>
<th>Lookout Pass mean value (plants · m⁻² ± SE)</th>
<th>Skull Valley Mean Value (Plants · m⁻² ± SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TG (PSSP6, ACHY, ELE5)</td>
<td>14.83 ± 0.02</td>
<td>7.34 ± 0.09</td>
</tr>
<tr>
<td>POSE</td>
<td>4.65 ± 0.07</td>
<td>2.14 ± 0.06</td>
</tr>
<tr>
<td>LILE3</td>
<td>5.32 ± 0.06</td>
<td>1.86 ± 0.03</td>
</tr>
<tr>
<td>SPMU2</td>
<td>0.13 ± 0.01</td>
<td>0.11 ± 0.05</td>
</tr>
<tr>
<td>ACM12</td>
<td>0.63 ± 0.02</td>
<td>0.58 ± 0.02</td>
</tr>
<tr>
<td>ARTRW8</td>
<td>0.10 ± 0.00</td>
<td>0.12 ± 0.08</td>
</tr>
<tr>
<td>ERNA10</td>
<td>0.03 ± 0.00</td>
<td>0.01 ± 0.00</td>
</tr>
<tr>
<td>ATCA2</td>
<td>0.04 ± 0.00</td>
<td>0.01 ± 0.00</td>
</tr>
</tbody>
</table>

¹TG indicates Pseudoroegneria spicata (Pursh) A. Love, Achnatherum hymenoides (Roemer & J. A. Schultz) Barkworth, Elymus elymoides (Raf.) Swezey; POSE, Poa secunda J. Presl; LILE3, Linum lewisii Pursh; SPMU2, Sphaeralcea munroana (Doug. ex Lindl.) Spach ex Gray; ACM12, Achillea millefolium L.; ARTRW8, Artemisia tridentata Nutt. subsp. wyomingensis Beetle & Young; ERNA10, Ericameria nauseosa (Pallas ex Pursh) Nesom & Baird; ATCA2, Atriplex canescens (Pursh) Nutt.
LITERATURE CITED


