Colorado Division of Parks and Wildlife
January 2013 – August 2016

WILDLIFE RESEARCH REPORT

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Author: D. B. Johnston

Personnel: B. deVergie, J.T. Romatzke, J.C. Rivale, and R. Velarde (CPW)
Phillip L. Chapman (Colorado State University)

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EXTENDED ABSTRACT

Healthy sagebrush-steppe areas of western Colorado are characterized by a diverse mixture of shrubs, forbs, and grasses. Restoring such habitats following oil and gas disturbances is often difficult because of the variety of impacted precipitation zones and the threat of weed invasion. An area of particular concern is the Piceance Basin gas field because of its value to mule deer (*Odocoileus hemionus*), greater sage-grouse (*Centrocercus urophasianus*), and other wildlife. In 2008, 2009, and 2012, a series of six experiments was implemented on simulated well pads and pipelines covering the wide range of precipitation and ecological conditions represented in the Piceance Basin gas field.

The experiments conducted at lower elevations emphasize weed control, particularly that of cheatgrass (*Bromus tectorum*), which presents a serious obstacle to effective reclamation (Knapp 1996, Chambers et al. 2007, Reisner et al. 2013). The four lower elevation experiments are the Pipeline experiment (implemented at six sites ranging from 1561 to 2216 m in elevation), the Competition and Competition 2 Experiments (implemented at two sites of elevations 2004 and 2216 m), and the Gulley experiment (implemented at four sites ranging from 1561 to 2084 m in elevation). The remaining two experiments, conducted at high or middle elevations, emphasized maximizing plant diversity. The Mountain Top experiment was implemented at the four highest elevation sites, ranging from 2342 to 2676 m. The Strategy Choice experiment was implemented at four moderate elevation sites ranging from 1662 to 2216 m.

Sites were prepared in 2008 by simulating pipeline disturbances and well pad disturbances. These two disturbance types differ in the length of time topsoil is stored, an important variable for restoration. The Pipeline Experiment was implemented in 2008, three weeks after the disturbances. All other experiments were implemented on well pad disturbances. These experiments were implemented in 2009 immediately after the well pads were reclaimed, except for the Competition 2 Experiment, which was implemented in 2012. Results and analysis for at least 3 post-treatment years for all experiments is now available, either within this report or via the included links to publications.

Although the complexity of elevation, soil type, and prior land use history make finding general recommendations for improving restoration for wildlife challenging, a general theme did emerge over the seven years these six experiments have been studied. This general theme is the importance of controlling weed seed propagule pressure. Propagule pressure is the number of weed seeds per area per unit of time. Even the experiments that were not explicitly designed to address propagule pressure ultimately provided lessons about its importance, and what we can do about controlling it. This corroborates research in other ecosystems which has demonstrated that controlling propagule pressure is more important than other factors managers might try to influence, such species diversity (Von Holle and Simberloff 2005, Eschtruth and Battles 2009) herbivory (Eschtruth and Battles 2009), or abiotic conditions (Von Holle and Simberloff 2005). Controlling propagule pressure during vulnerable periods such as after disturbances is especially important (DiVittorio et al. 2007, Eschtruth and Battles 2009).

In the Pipeline Experiment, we learned that in limited circumstances, pipeline disturbances can reduce cheatgrass density compared to unimpacted areas (Johnston 2015). When combined with Plateau ® (ammonium salt of imazapic) herbicide, enough cheatgrass control can be achieved to allow establishment of big sagebrush (*Artemisia tridentata*). While Plateau is a useful herbicide, using it alone is sometimes ineffective because applying it at high enough rates to get sufficient cheatgrass control results in unacceptable injury to desirable plants (Owen et al. 2011). By causing cheatgrass seeds to be buried too deeply to germinate, ground disturbances can work additively with herbicides to reduce cheatgrass propagule pressure. The timing of the disturbance is important. We quantified the seasonality of cheatgrass propagule pressure using seed traps (Appendix 1). Most cheatgrass seeds arrive between May and June, but seeds continued to arrive until September. The disturbances in the Pipeline Experiment occurred in September, which maximized burial of seeds from the prior growing season. A disturbance earlier in the growing season may not be as helpful for limiting cheatgrass.

In the Competition and Competition 2 Experiments, cheatgrass propagule pressure was intentionally controlled in order to look for other factors that may limit cheatgrass during restoration. These experiments had mixed results. We focused on abiotic manipulations which might exploit cheatgrass's weaknesses: lower competitive ability under higher, more stable soil moisture (Chambers et al. 2007, Bradley 2009), and inability to germinate through compacted soils (Thill et al. 1979, Beckstead and Augspurger 2004). In the Competition Experiment, the treatments were super-absorbent polymer (SAP) application (to increase water retention), a soil binding agent designed to increase water infiltration (DirtGlue ®), and compaction with a heavy roller. Rolling was not helpful. SAP increased initial perennial grass density and reduced subsequent cheatgrass cover at one of two sites, and the binding agent increased perennial grass density and reduced cheatgrass cover at one of two sites. Because the binding agent application was more expensive, the Competition 2 Experiment focused on SAP. In Competition 2, SAP had beneficial effects at one site (increasing perennial grass cover and reducing cheatgrass), but detrimental effects at the other site, causing a five-fold increase in cheatgrass. The limitations on cheatgrass germination and the nature of competitive interactions between cheatgrass and desirable perennial plants appears to be a complex interaction of site conditions, treatment timing, and treatment choice. Right now, clear management recommendations on how to use SAP or binding agent are not available, although this may be improved through further study.

The Gulley Experiment focused on identifying which sources of propagule pressure are important to control: the seed bank, new seeds entering from the surrounding landscape, or both. The treatments were application of Plateau herbicide at 140 g ai/ha (8 oz/ac) just prior to seeding, fallowing for one year with the broad-spectrum pre-emergent herbicide Pendulum™ (pendamethilin, BASF Corporation), and surrounding plots with seed dispersal barriers of aluminum window screen. The barriers had slight effects which were entirely positive: lower annual forb cover at some sites where Russian thistle (*Salsola tragus*) was dominant, and higher perennial grass and forb cover. The herbicide treatments were a lesson in the dangers of over application. The pendamethilin treatment was especially detrimental. Both herbicides in combination so suppressed perennial vegetation that by four years post-treatment, there was a trend for higher cheatgrass cover where both had been applied, in spite of both herbicides effectively controlling cheatgrass in the initial years of the experiment. The barriers did not reduce cheatgrass cover, possibly because cheatgrass seeds passed under the barriers or blew over them. The Mountain Top and Strategy Choice Experiments examined a treatment that had more success at reducing cheatgrass cover.

The Mountain Top Experiment was initially designed to address how to maximize plant diversity in restoration. This is critical because restored areas are often dominated by grasses, even after decades of recovery. Unexpectedly, this experiment also demonstrated that high elevation sites in Piceance are vulnerable to cheatgrass invasion, and revealed a useful technique for combating that invasion. The treatments were: seeding (17.8 kg/ha PLS native species including 60% grass or no seed), soil surface (roughened with 50 cm-deep holes or flat), and brush mulch replacement (0.024 m^3/m^2 or no brush). Unseeded plots were initially dominated by annual forbs, while seeded plots were dominated by perennial grasses. After five years, unseeded plot annual forb cover had declined to 10%, perennial grass cover had increased to 24% (about two-thirds of that of seeded plots), and perennial forb cover was 6.8% (about one-third that of seeded plots). Cover of shrubs (mostly big sagebrush, *Artemisia tridentata*) in unseeded plots was 26% (almost double that of seeded plots), highlighting the degree to which competition by seeded species can slow the recovery of sagebrush. Brush mulch benefitted shrubs, perennial grasses, and perennial forbs, and also slightly reduced annual forbs. Contrary to expectations, the rough soil surface did not have any large effects on cover of perennial grasses, forbs, or shrubs, but it did have an effect on cheatgrass. By five years post-treatment, cheatgrass had become established in unseeded plots at two sites, especially Scandard. At Scandard, the rough surface reduced unseeded plot cheatgrass cover from 13% to 3% (Figure MountainTop 5). We hypothesize that cheatgrass seeds become entrapped in the bottom of holes, limiting their spatial distribution, and forcing them to compete under wetter conditions under which they are less competitive.

The Strategy Choice Experiment also included a rough vs. flat soil surface treatment, although in this experiment the rough surface was always applied with brush (and broadcast seeded), while the flat surface was always applied with straw mulch (and primarily drill-seeded). The Strategy Choice Experiment was conducted at middle elevations where the threat of weed invasion was moderate or ambiguous, in order to find optimal strategies in uncertain circumstances. The other treatments included Plateau (8 oz/ac vs. none) and a seed mix treatment. There were two seed mixes compared: one that had about equal numbers of forb, shrub, and grass seeds, and one that was about 75% forbs, 17% shrubs, and only 8% grass. Cheatgrass established at two of the four sites, one each with high (GVM) and low (MTN) cheatgrass propagule pressure. The Plateau treatment successfully controlled cheatgrass, but caused an increase in annual forbs, and had either neutral or negative effects on perennials. At GVM, the rough surface augmented the effect of Plateau, reducing cheatgrass biomass six-fold. At MTN, the rough surface reduced cheatgrass biomass 10-fold in the absence of Plateau and reduced weedy annual forbs 100-fold in the presence of Plateau. Across sites, there was no difference in cheatgrass due to seed mix, and forb and shrub biomass were higher with the high-forb mix.

Looking across the Mountain Top and Strategy Choice experiments, the rough surface helped control cheatgrass at three of four sites where cheatgrass became established. The one site where it had no effect, the Sprague site in Mountain Top, had only sparse and patchy cheatgrass. As an extension of this project, we implemented a rough surface treatment along with a light (4 oz/ac) Plateau application to 7 acres at Horsethief SWA, and successfully turned a cheatgrass near-monoculture into a diverse stand of grasses, forbs, and shrubs (Johnston 2014). Weedy species, almost by definition, produce large numbers of rapidly dispersing seeds to quickly exploit any open or disturbed areas. From prior research we know that holes entrap many kinds of seeds (Chambers 2000), and that cheatgrass seeds disperse 10 to 50-fold farther over bare soils than in intact ecosystems (Kelrick 1991, Johnston 2011, Monty et al. 2013). Our research supports the conclusion that landscapes which permit rapid seed dispersal foster weeds; landscapes which slow seed dispersal favor less weedy species.

Altered seed dispersal is one reason why cheatgrass responds so well to fire. Even though a fire may kill 97% of cheatgrass seeds (Humphrey and Schupp 2001), fire also removes vegetation, which allows cheatgrass seeds to travel farther (Monty et al. 2013). The few surviving seeds grow in the absence of competition, which enables them to produce 40 times more seed than they might have within a dense stand (Hulbert 1955). These seeds disperse readily over the burned surface, producing a second generation of plants which are also relatively free from competition. By two years after the fire, cheatgrass is fully recovered from the 97% reduction (Humphrey and Schupp 2001). A rough soil surface can entrap seeds near the parent plant, preventing the growth of isolated, highly productive cheatgrass plants. This may slow the cheatgrass recovery cycle enough for perennial plants to establish. A rough soil surface is a practical tool managers can use to limit cheatgrass and other weedy invasives after disturbances including fire and development.

The two experiments which addressed seeding practices demonstrate the costs of including too much grass seed in seed mixes: forb and shrub growth is delayed. Including at least a little grass in seed mixes is probably wise, as research has shown that the best competitors for invasive species are native species of the same functional group (i.e. grasses compete best with grass, and forbs with forbs) (Fargione et al. 2003). Even so, the high-forb seed mix performed well at the GVM site, which had high cheatgrass propagule pressure. The recent investments made by CPW through the Uncompagre Project to make additional forb species available at low cost are critical, and additional resources should be devoted to this task.

Results of Plateau application in this series of experiments are mixed, generating beneficial results in one experiment (Pipeline), mixed results in another experiment (Gulley), and largely detrimental results a third experiment (Strategy Choice). Successful use of this herbicide requires accurately applying a light rate, focusing on areas with cheatgrass cover prior to disturbance, and combining Plateau with other measures to reduce cheatgrass propagule pressure, such as a rough soil surface or a well-timed ground disturbance.

Restoring oil and gas disturbances to fully functional, diverse wildlife habitat in northwestern Colorado is possible. Making use of a higher proportion of forbs and shrubs in seed mixes, considering the timing of weed seed dispersal, combining herbicides with other factors to reduce weed propagule pressure, and seeding over a rough soil surface are strategies which can be used over a wide range of elevations and ecological conditions to the benefit of wildlife.

WILDLIFE RESEARCH REPORT

RESTORING ENERGY FIELDS FOR WILDLIFE

DANIELLE B. JOHNSTON

INTRODUCTION

Preserving wildlife habitat quality in oil and gas fields requires effective restoration of impacted areas. Successful restoration entails preventing soil loss, overcoming the threat of weed invasion, and promoting natural plant successional processes so that a diverse mixture of native perennial grasses, forbs, and shrubs are established. A detailed knowledge of soils, climate, topography, land use history, and plant competition is needed to accomplish this goal, and optimal choices of reclamation techniques are site-specific. The need for site-specific knowledge often prompts local reclamation trials by organizations which cause large-scale disturbances, such as coal mining companies. In oil and gas fields, however, local reclamation trials are difficult to implement due to the spatial pattern of disturbance.

In contrast to coal mines, which typically result in a small number of large disturbances, oil and gas fields result in a large number of smaller disturbances, each connected by a web of pipelines and access roads which may extend across hundreds of thousands of acres. The complexities of gathering knowledge at the appropriate scales, administering recommendations for the multitude of sites involved, and enforcing appropriate standards over such large areas often results in reclamation that falls short of the most basic standards (Avis 1997, Pilkington and Redente 2006).

Addressing these challenges is imperative, as the fragmented pattern of development means that wildlife and wildlife habitat are affected over a much larger area than that directly occupied by development activities. For instance, greater sage-grouse (*Centrocercus urophasianus*) populations and mule deer (*Odocoileus hemionus*) habitat use may decline within large buffer areas surrounding development (Sawyer et al. 2006, Walker et al. 2007). Furthermore, non-native species establishment due to development (Bergquist et al. 2007) could reduce wildlife habitat quality over large areas if disturbances are allowed to provide vectors for weed invasion into otherwise undisturbed habitat (Trammell and Butler 1995). Because of this threat, preventing weed invasion through successful restoration of all impacted areas is a top management priority for wildlife. The goal of this study is to promote such restoration by replicating tests of promising techniques at the scale of an oil field.

The Piceance Basin in northwestern Colorado provides an ideal laboratory for conducting a large-scale study of restoration techniques. The area is rich in natural gas and periodically experiences intense pulses of resource development. It also provides critical habitat for the largest migratory mule deer herd in the United States, and has a complex topography which ensures that a wide range of precipitation, soil development, and plant community types are represented.

Because elevation is an important driver of precipitation, plant community composition, and weed prevalence in the area, experiments were assigned according to elevation zone. Twelve study sites, ranging in elevation from 1561 to 2676 m, house six experiments, each repeated at two to six sites. Each experiment tests three to six treatments, and some treatments are tested in multiple experiments. Overlap of treatments allows the experiments to relate to one another in a way that will permit broad-scale conclusions, if appropriate, while the differences in the experiments permit tailoring of particular treatments to those portions of the landscape where they are potentially useful.

The experiments conducted at lower elevations emphasize weed control, particularly that of cheatgrass (*Bromus tectorum*), which presents a serious obstacle to effective reclamation in the study area

(Pilkington and Redente 2006, Reisner et al. 2013). The four lower elevation experiments are the Pipeline experiment (implemented at six sites ranging from 1561 to 2216 m in elevation), the Competition and Competition 2 Experiments (implemented at two sites of elevations 2004 and 2216 m), and the Gulley experiment (implemented at four sites ranging from 1561 to 2084 m in elevation). The remaining two experiments, conducted at high or middle elevations, emphasized maximizing plant community diversity. The Mountain Top experiment was implemented at the four highest elevation sites, ranging from 2342 to 2676 m. The Strategy Choice experiment was implemented at four moderate elevation sites ranging from 1662 to 2216 m.

The Pipeline experiment, which has been completed and published (Johnston 2015) evaluated the effectiveness of tillage treatments versus an herbicide treatment at controlling cheatgrass and promoting establishment of a diverse, predominately perennial, native plant community. Oil and gas disturbances are amenable to tillage manipulations, as the ground is already disturbed and access routes for heavy equipment have already been created. In agricultural settings, combining lower levels of herbicide with tillage treatments, such as disk cultivation, has proven effective for controlling weeds (Mulugeta and Stoltenberg 1997, Mohler et al. 2006). Cheatgrass is sensitive to seed burial (Wicks 1997), does not germinate well in even slightly compacted soil surfaces (Thill et al. 1979), and is less competitive in denser soils (Kyle et al. 2007). Tillage manipulations examined were disking, rolling with a static roller, rolling with a vibratory drum roller, or disking plus compaction with a static roller. The herbicide investigated was Plateau ™ (ammonium salt of Plateau, BASF Corporation, Research Triangle Park, NC, *hereafter* Plateau), as it has been shown to reduce annual grasses with little effect on some perennial grasses (Kyser et al. 2007).

The Competition experiment also examines compaction by rolling, but does so in conjunction with soil additives, in an environment where the density of cheatgrass seeds is controlled. Earlier work has shown that the density of weed seeds, or propagule pressure, has a large influence on the likelihood that a weed will become dominant when an ecosystem is disturbed (Thomsen et al. 2006). Therefore, variation in propagule pressure can confound attempts to study which reclamation techniques promote desirable species, particularly if the effects are subtle. Cheatgrass propagule pressure was controlled in the Competition experiment by adding a known quantity of cheatgrass seeds to areas that were previously free of cheatgrass, (and then surrounding the research area by physical and chemical barriers to prevent cheatgrass from leaving the area). The first soil additive examined is a super-absorbent polymer called Luquasorb® 1280 RM (BASF Corporation, Ludwigshafen, Germany). When added to degraded soils, super-absorbent polymers absorb and then gradually release water, reducing the effects of water stress (Huttermann et al. 2009). This may hinder cheatgrass, as cheatgrass has been shown to be a more effective invader when soil moisture is more variable (Chambers et al. 2007). The second soil additive examined is a soil binding agent called DirtGlue® (DirtGlue® Enterprises, Amesbury, MA). Soil binding agents are commonly used to stabilize soil and facilitate binding of seed to the soil surface, but their effect on competitive interactions is unknown. DirtGlue® is used in this study because of its purported ability to bind soil particles while increasing water infiltration. The combination of soil binding agent with rolling was of interest because of the potential for creating a crust that might hinder cheatgrass emergence.

The original Competition experiment utilized small plot sizes and a very simple seed mix containing only wheatgrasses. In 2012, the Competition 2 experiment was implemented which examined the effects of super-absorbent polymer with larger plots and a more complex seed mix.

The Gulley experiment focuses on identifying which potential sources of weeds are important to control: those which originate from within the soil seed bank of the reclamation area, those which enter from the surrounding landscape, or both. Like the Pipeline experiment, the Gulley experiment includes a test of Plateau herbicide as a strategy to control certain species in the soil seed bank. A second herbicide is also tested: Pendulum® AquaCap™ (pendamethilin, BASF Corporation, Research Triangle Park, NC;

hereafter Pendulum). Pendulum is a broad-spectrum pre-emergent herbicide, is effective for about six months, and is a drastic measure designed to eliminate as much of the existing seed bank as possible. To control seeds originating from areas surrounding the reclamation area, seed dispersal barriers were constructed of aluminum window screen, using a design that had been effective in a Utah seed bank study (Smith et al. 2008). This is of interest because a recent CPW study demonstrated that a sufficient number of cheatgrass seeds may disperse from the edges of disturbance to compromise reclamation efforts (Johnston 2011).

The Mountain Top experiment sites were surrounded by perennial, predominately native plant communities (Table Intro 1); therefore weed control was not a great concern. At sites such as these, the goal of reclamation should be to re-create the desirable mixture of grasses, forbs, and shrubs found in the undisturbed habitat. However, prior studies have shown that even after decades of recovery, reclamation areas may remain dominated by grasses (Newman and Redente 2001). Explanations for grass dominance include a loss of variability in soil resources when topsoil is redistributed, and a disproportionate influence of the grasses included in the reclamation seed mix (Redente et al. 1984). Creating treatments which re-establish resource heterogeneity, encourage native seed dispersal, and avoid undue competition from seeded grasses may result in a plant community which better serves the needs of wildlife. In this study, we examine three such treatments: creating a rough soil surface of mounds and holes, spreading brush mulch, and foregoing seeding. A rough soil surface may be helpful because it creates variability in soil depth, creates microsites of higher moisture availability, and traps dispersing seeds (Chambers 2000). Similarly, brush mulch creates favorable germination conditions by causing snow to drift, creates shade, entraps seeds (Kelrick 1991), and perhaps also provides a source of seed. These two treatments are applied with and without seeding in order to address the question: If the adjacent undisturbed area is desirable, how important is seeding versus creating soil heterogeneity and encouraging natural seed dispersal in order to establish a diverse plant community?

The Strategy Choice experiment was conducted at middle-elevation sites where the degree of threat from invasive weeds is ambiguous. Such situations raise the question: should one take a conservative strategy by seeding a highly competitive seed mix, using aggressive weed control measures, and avoiding contaminating the site with seed from the surrounding area? Such measures often come at a price of reduced plant diversity and forb establishment (Marlette and Anderson 1986, Chambers 2000, Krzic et al. 2000, Baker et al. 2009). Therefore, one might wish to adopt an optimistic strategy by seeding a high-forb/high diversity seed mix with a minimal fraction of rhizomatous grasses, avoiding the use of herbicide, and entrapping seeds via brush mulch, holes, or other mechanisms. An optimistic strategy is the obvious choice when the surrounding plant community is desirable, and the risks of soil erosion and weed invasion are low. This study compares the results of these two strategies in situations where the risk of weed invasion is moderate, and the surrounding plant community contains both desirable and undesirable species. The treatments examined include use of Plateau, creation of a rough soil surface with holes and brush mulch, and comparison of a balanced versus high-forb seed mix.

In all experiments, establishment of native, perennial plants was emphasized. Perennial plants are critical for wildlife because they provide nutritious forage for a longer portion of the growing season, their overall productivity is higher, and their productivity is less variable from year to year than that of annual plants (DiTomaso 2000). The experiments focus on big sagebrush communities, because of the need for better techniques for re-establishing these communities (Lysne 2005), their widespread distribution, and their importance to wildlife (Davies et al. 2011).

Study area. The Piceance Basin study area is in Rio Blanco and Garfield Counties, Colorado, USA (Figure Intro 1). Elevation increases gradually from north to south as one travels from Piceance Creek (~1,800 m) to the top of the Roan Plateau (~2,500 m), then drops off sharply at the Book Cliffs to the Colorado River Valley (~1,500 m). Precipitation and temperature vary across the region with both elevation and latitude; more northerly sites are colder and receive less precipitation than southerly sites of similar elevation. Northernmost sites receive approximately 280 mm per year, 40% as snow. The southerly Colorado River Valley sites receive approximately 340 mm of precipitation per year, 25% as snow. The wettest, highest elevation sites are at the southern edge of the Roan Plateau, and receive approximately 500 mm per year, 60% as snow. Lower elevations are characterized by Wyoming big sagebrush, cheatgrass, Indian ricegrass (*Achnatherum hymenoides*), western wheatgrass (*Pascopyrum smithii*), prairie junegrass (*Koeleria macrantha*), and globemallow (*Sphaeralcea coccinea*) in flatter areas with a mixture of pinyon pine (*Pinus* sp.) and Utah juniper (*Juniperus utahensis*) on steeper slopes and greasewood (*Sarcobatus vermiculatus*) in floodplains. Higher elevations are characterized by mountain big sagebrush, mountain brome (*Bromus marginatus*) and diverse forbs in flatter areas, serviceberry (*Amelanchier alnifolia*), snowberry (*Symphoricarpos rotundifolius*), Gambel's oak (*Quercus gambelii*) on slopes, and aspen (*Populus tremuloides*) mixed with Engleman spruce (*Picea engelmanii*) in the highest elevation, north-facing slopes.

Twelve research locations were chosen within the Piceance Basin in sagebrush habitats (Figure Intro 1, Table Intro 1). These 12 locations span most of the range of elevation, soil type, and precipitation to be found in the area. The lowest elevation site, SK Holdings (SKH) lies at 1561 m (5120 ft), has alkaline, clayey soils, and is characterized by high cheatgrass cover with interspersed Basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*). The highest elevation site, Square S (SQS), lies at 2676 m (8777 ft), has a sandy loam soil, and has a mixture of non-noxious forb, grass, and mountain big sagebrush cover.

Disturbance Creation. Two types of disturbances, simulated pipelines and simulated well pads, were created in order to provide templates for the experiments. Pipeline disturbances measured 11 m X 52 m and were simulated using a bulldozer and a backhoe. Vegetation was scraped and discarded, the top 20 cm of topsoil was scraped and stockpiled, and then a 1 m wide x 1 m deep trench was dug. Trenches were left open three weeks, and then the subsoil was replaced and the topsoil spread evenly over the site. This work was completed in six locations in August and September of 2008. The Pipeline experiment was immediately implemented on these disturbances.

Well pads differ from pipelines in the length of time topsoil is stockpiled and in the degree to which subsoil disturbance occurs. Well pad disturbances measured 31 m x 52 m and were simulated using a bulldozer. Vegetation was cleared, the top 20 cm of topsoil was scraped and stockpiled in windrows less than 2 m in height, and then the subsoil was cut and filled to create a level surface. The initial work was completed in July and August of 2008, and the surface was kept weed-free for one year by repeated hand-spraying of emerging plants with 2% (v/v) glyphosate. In August of 2009, the subsoil was recontoured to approximate the original contour, and the stockpiled topsoil spread evenly across the surface of the site. Simulated well pads were created in 12 locations, each with slopes of 5% or less. The Gulley, Strategy Choice, Competition, and Mountain Top experiments were implemented on the well pad disturbances in 2009 and 2010. The Competition 2 experiment was implemented on the well pad disturbance in 2012 in areas which had been seeded in 2009. The vegetation which had grown between 2009 and 2012 was removed by ripping, disking, and raking the soil in early September, 2012.

All sites were fenced with 2.4 m (8 ft) fencing in late fall 2009. This eliminated variability from site to site in the degree of browsing and grazing pressure from wildlife and livestock.

RG3-M data logging rain gauges (Onset® Computer Corporation, Bourne, MA, USA) were installed on guyed posts at each study site in late 2009 or early 2010. These were downloaded twice a year 2010-2016 and summarized by season for each experiment.

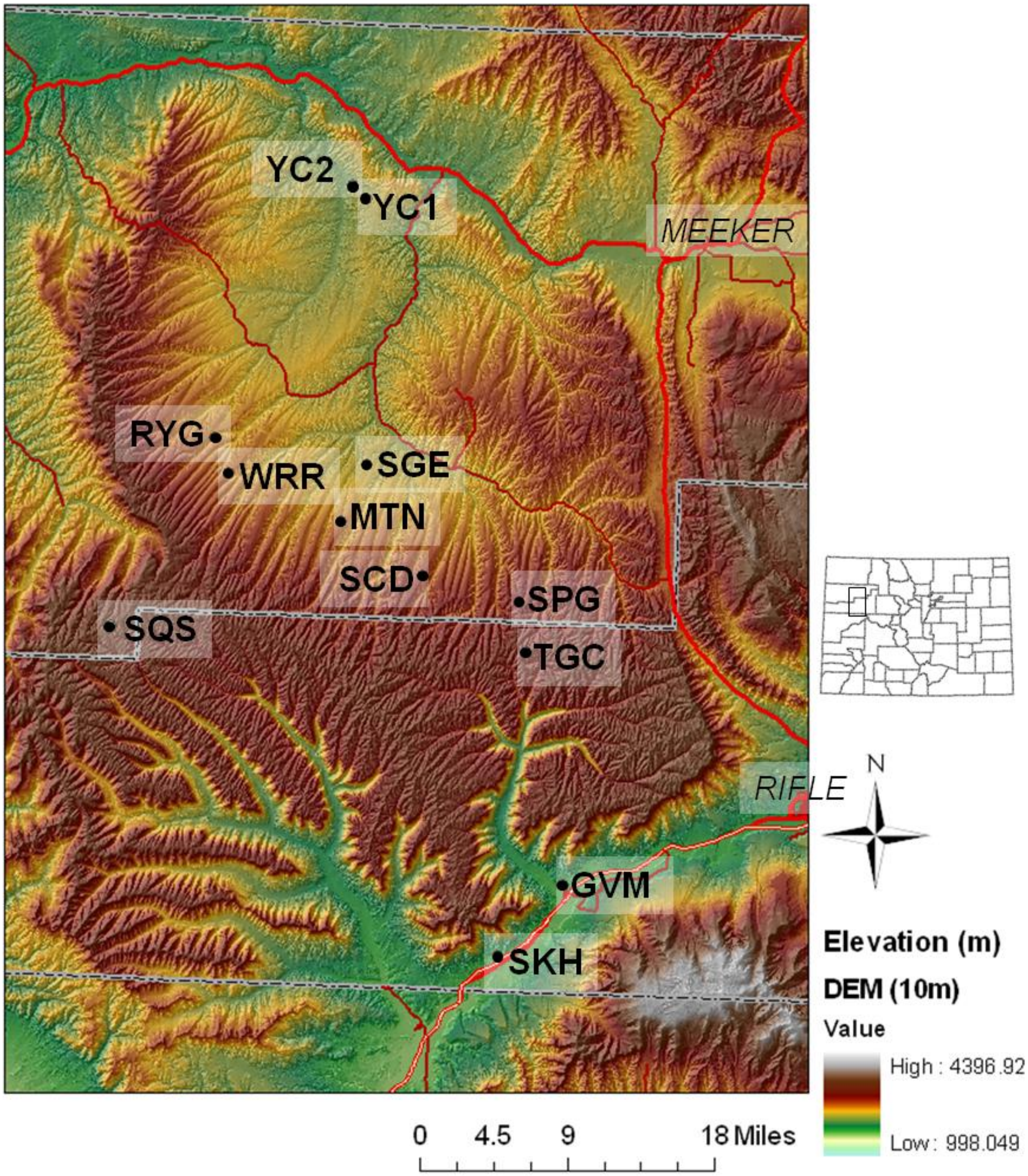
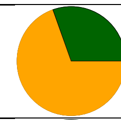
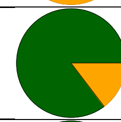
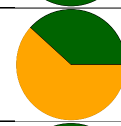
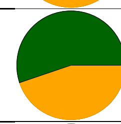
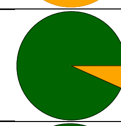
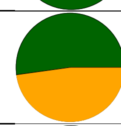
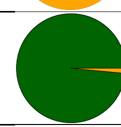
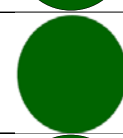
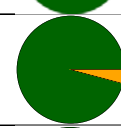
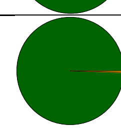
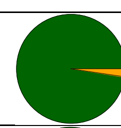
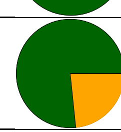


Figure Intro 1. Locations of the 12 research sites in Rio Blanco and Garfield counties, Colorado.

Table Intro 1. Study site information. Pie charts are baseline (2009) relative cover from undisturbed areas assessed by 4-6 10m-long line-point intercept transects arrayed around each site (200+ hits per site).

code	Name	landowner	elev. m (ft)	experiment(s) conducted	cover NonNative Native
SKH	SK Holdings	WPX Energy	1561 (5120)	Pipeline Gulley	
GVM	Grand Valley Mesa	WPX Energy	1662 (5451)	Pipeline Strategy Choice	
YC2	Yellow Creek 2	CPW	1829 (5999)	Pipeline Gulley	
YC1	Yellow Creek 1	CPW	1905 (6248)	Pipeline Gulley	
SGE	Sagebrush	BLM	2004 (6573)	Strategy Choice Competition/ Comp. 2	
RYG	Ryan Gulch	WPX Energy	2084 (6835)	Pipeline Gulley	
MTN	Mountain Shrub	BLM	2183 (7160)	Strategy Choice	
WRR	Wagon Road Ridge	WPX Energy	2216 (7268)	Pipeline Strategy Choice Competition / Comp.2	
SCD	Scandard	BLM	2342 (7681)	Mountain Top	
SPG	Sprague (formerly called Snowpile)	Conoco	2445 (8019)	Mountain Top	
TGC	The Girls' Claims	Encana Oil and Gas, Inc.	2527 (8288)	Mountain Top	
SQS	Square S	CPW	2676 (8777)	Mountain Top	

PIPELINE EXPERIMENT

Overview

- Goal: Compare effectiveness of Plateau herbicide and tillage treatments for controlling cheatgrass and promoting perennial plants.
- Conducted at 6 sites: YC1, YC2, RYG, WRR, GVM and SKH (Figure Intro1, Table Intro1).
- Treatments:
  - Herbicide (two levels): Plateau applied (Plateau) or no Plateau applied (no Plateau)
  - Tillage (five levels): disking, compaction with a static roller, compaction with a vibratory drum roller, disking plus compaction with a static roller, or control
- Design: Factorial split-plot. Herbicide treatments were randomly assigned to whole plots, and tillage treatments were randomly assigned to subplots.
- Plot size: 11 m X 10 m
- Responses measured: seedling density (2009) and plant cover (2010, 2011, and 2014)

Publication. For complete methods, results and discussion of the initial phase (through 2011) of this experiment please see:

Johnston, D. B. (2015). "Downy brome (*Bromus tectorum*) control for pipeline restoration." Invasive Plant Science and Management **8**(2): 181-192.

Available at: http://www.wssajournals.org/doi/pdf/10.1614/IPSM-D-14-00001.1.

Key results. Cheatgrass often increases after disturbances, but disturbances which turn the soil over can also be used to help control cheatgrass, as cheatgrass seeds are sensitive to burial and soil compaction (Thill et al. 1979, Wicks 1997). Success may depend on the timing of the disturbance, and on coupling the disturbance with other measures to help control cheatgrass.

In this experiment, we assessed the effectiveness of 6 oz/ac Plateau® (105 g ai^{-1} imazapic) plus 280 g ai ha^{-1} glyphosate when coupled with simulated pipeline disturbances. Disturbances occurred in September 2008. Herbicide application was crossed with tillage treatments (control, disked, rolled, rolled plus disked, and rolled by vibratory drum) applied within pipelines to further examine how soil compaction affects cheatgrass.

As disturbances occurred in areas already compromised by cheatgrass, the initial effect of the disturbance was a 10-fold reduction in cheatgrass density. Where Plateau was applied, this reduction persisted through the first growing season. Where Plateau was not applied, cheatgrass densities rebounded to values similar to undisturbed areas by July. Three years post-treatment, cheatgrass cover was 2-fold lower and shrub cover was 8-fold higher where Plateau had been applied than where it was not applied. The tillage treatments had little effect on cheatgrass density or cover, possibly because the disturbances themselves had already achieved the goal of burying cheatgrass seed under slightly compacted soil.

In the study area, cheatgrass seeds distributed from early May through September (Appendix 1 Figure A1-2). Prior work has shown that cheatgrass seeds distribute readily over bare soils such as oil and gas disturbances (Johnston 2011). By turning the soil over in September, the pipeline disturbances may have buried the majority of cheatgrass seeds which had fallen on the soil surface during the 2008 growing season. This reduction in propagule pressure likely acted additively with the herbicide to provide enough cheatgrass control for desirable perennial plants to establish. Prior work has shown that

Plateau is more effective on annual grasses when applied after disturbances such as burning (Sheley et al. 2007, Davies and Sheley 2011). This study indicates that a well-timed soil disturbance can serve a similar function.

Plant communities disturbed in early spring or summer may be less easily restored, as cheatgrass seeds from pipeline edges would distribute over the bare soil of the restoration area for a longer period of time prior to the germination of desirable species. In practice, it may be impossible to time disturbances at the end of the growing season. When that is the case, one or more of the following strategies may be helpful prior to fall seeding: 1) treat cheatgrass patches prior to disturbance, in a manner that successfully reduces seed production in the area to be disturbed, 2) as soon as the disturbance occurs, line the edges of the disturbed area with a seed dispersal barrier, such as brush or a trench, 3) control weeds which emerge in the disturbed area before they produce seed, and 4) disk and firm the soil just prior to planting to bury weed seeds. Actions such as these may complement an application of Plateau by reducing the density of viable cheatgrass seeds.

The Plateau had no effect on forb or grass cover, a result which contrasts with some other studies in Wyoming big sagebrush plant communities, in which cheatgrass cover in plots where Plateau was applied rebounded to levels as high (Owen et al. 2011) or higher (Morris et al. 2009) than that of control plots in 2-3 years, or in which Plateau negatively affected forbs (Baker et al. 2009, Owen et al. 2011). The effects of Plateau on shrub and cheatgrass cover are likely intertwined. In a study of competitive dynamics between cheatgrass and big sagebrush, sagebrush and cheatgrass competed for soil water, and cheatgrass cover increased when sagebrush was removed (Prevey et al. 2010). In plots where Plateau was applied, sagebrush appears to have established well enough to limit cheatgrass cover, resulting in a long-term effect of Plateau on the composition of the plant community.

The disking treatment was only moderately effective at reducing cheatgrass seedling density and improving perennial grass cover, and the rolling treatments were not effective. The second phase of this experiment will consist of monitoring plant cover in all plots every third year. Data was collected in 2014, and the next data collection year is planned for 2017.

COMPETITION EXPERIMENT

Overview

- Goal: Test novel techniques for minimizing the competitive advantage of cheatgrass under a condition of controlled cheatgrass propagule pressure.
- Conducted at two sites: WRR and SGE (Figure Intro 1, Table Intro 1)
- Treatments:
  - Binding agent (three levels): a low level of binding agent applied (low BA), a high level of binding agent applied (high BA), or no binding agent applied (no BA)
  - Super-absorbent polymer (two levels): super-absorbent polymer applied (SAP) or no polymer applied (no SAP)
  - Rolling (two levels): rolled with a static heavy roller (rolled) or not rolled (not rolled)
- Design: Factorial split-split plot, with completely randomized whole plots. The whole plot factor was rolling, subplot factor was super-absorbent polymer, and the sub-subplot factor was binding agent (Figure Competition 1).
- Plot size: 2.4 m X 2.4 m
- Five replicates per site
- Responses measured: Cover of perennial grasses and cheatgrass

Methods

Cheatgrass seed was collected using a lawnmower with a bagging attachment from monocultures or near-monocultures in four locations, each within 50 miles of the study sites. Collections were made in late June or early July 2009, when most or all of the cheatgrass in a location had fully ripened seed heads. Seed was allowed to dry and after-ripen in shallow containers in a dry, warm location for approximately three months. The density of apparently viable cheatgrass seeds was determined by gathering five 5 g subsamples from each collection, and then counting and weighing all of the fully developed, hard-coated cheatgrass seeds for each subsample. Equal quantities of seeds from each collection were mixed together, and then a volume of seed sufficient to supply 300 seeds/m^2 was prepared for each sub-subplot. Seed was hand-broadcast in early October, 2009, and then immediately lightly raked to incorporate seed into the soil. The 300 seeds/m^2 seeding rate is about 25% of the 2009 cheatgrass seed production at heavily cheatgrass-infested sites quantified for the Pipeline experiment, and therefore thought to be a reasonable seed density for a Piceance Basin site in the initial phases of invasion.

A mixture of native wheatgrasses (Table Competition1) was drill-seeded using a Plotmaster™ 400 (Tecomate Wildlife Systems, San Antonio, TX) in mid-October, 2009. Seed was mixed 1:1 by volume with rice hulls to maintain suspension of the seed mixture. For SAP plots, Luquasorb® 1280 RM granulated super-absorbent polymer (a cross-linked copolymer of Potassium acrylate and acrylic acid in granulated form; BASF Corporation, Ludwigshafen, Germany), was added to the seed/rice hull mixture. At SGE, 6.7 g/m^2 of polymer was added, and at WRR, 30.8 g/m^2 was added. These rates are near the lower and upper limits, respectively, of recommended application rates for agricultural purposes.

Next, whole plots receiving the rolling treatment were rolled 10 times with a static roller supplying a linear load of 36.5 N/cm (20.8 lbs/in). Binding agent sub-subplots were then treated by sprinkling plots using hand watering cans. High BA plots received 4100 li/ha (440 gal/ac) of binding agent, diluted 6:1 with water. Low BA plots received 1600 li/ha (175 gal/ac) of binding agent, diluted 17:1 with water. No BA plots received 21000 li/ha (3200 gal/ac) of plain water, an amount equivalent to the total amount of liquid applied to other plots.

Following implementation, the entire treatment area was surrounded by a barrier to prevent dispersal of cheatgrass seed out of the experiment area. A physical barrier of 0.6 m-high aluminum window screen supported by oak stakes was constructed adjacent to the plots. Outside of this, we applied a chemical barrier of Pendulum, a broad spectrum pre-emergent herbicide, at 3200 g ai/ha (0.75 gal/ac) to a 1m wide strip of bare ground.

Two to three soil moisture readings were made in random locations within each plot on 21 May 2010, 7 June 2010, 3 June 2011, 19 July 2011, 15 May 2012, and 28 June 2012. Readings were taken to 12 cm using a Hydro Sense® Soil Water Measurement System (Campbell Scientific, Inc, Logan, Utah) and were averaged for each plot on each date.

Cheatgrass and perennial grass responses to treatments were assessed by seedling density in 2010, by percent cover 2011-2013, and by aboveground biomass in 2013. Seedling density was assessed late July/early August within a 1m X 1m area centered within each plot. Cover was quantified in between June 25 and August 8 using a 1m x 1m sampling frame centered within each plot. The sampling frame was a grid containing thirty-six intersections, and point-intercept hits were measured at each intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT). All layers of vegetation were identified to species at each hit. When calculating percent cover of perennial grasses, overlapping hits of different species were counted as a single instance of the functional group. Aboveground biomass was quantified by clipping current-year growth to the ground level in July in one 0.5 X 1m frame centered in each plot. Entire plants were clipped if rooted in the plot. Plant material was dried to a constant weight and weighed to the nearest 0.1g.

Density, cover, biomass, and soil moisture data were analyzed using ANOVA in SAS PROC MIXED for a split-split plot structure with completely randomized whole plots nested within sites, and sites considered as fixed effects. Data were transformed if needed to improve normality and residual plots were inspected to ensure adherence to ANOVA assumptions [density and cover: arcsine (square root [x]); cheatgrass biomass: log + constant; perennial grass biomass: no transformation]. The three years of cover data were analyzed as repeated measures with an autoregressive covariance structure with a lag of 1. Soil moisture data was analyzed separately by date. Where significant site by treatment interactions occurred (cutoff $\alpha = 0.10$), separate analyses by site were also conducted. A significance level of $\alpha = 0.05$ was used to determine significantly different means, and a level of $\alpha = 0.10$ for interactions was used to determine which means to compare. Means are presented ± SE. Effect sizes were calculated using LSMESTIMATE in SAS PROC MIXED.

Results

Across sites and treatments, 100% of perennial grass cover was native, and 100% of annual grass cover was non-native cheatgrass. Perennial grasses at both sites consisted of a heterogeneous mix of slender wheatgrass (*Elymus trachycaulus*), western wheatgrass, bluebunch wheatgrass (*Pseudoroegneria spicata*), and needle-and-thread grass (*Hesperostipa comata*).

Perennial grass seedling density in 2010 differed by site ($p = 0.015$) and SAP treatment ($p = 0.016$) as well as a 4-way interaction involving site, SAP, rolling, and BA ($p = 0.004$). Upon breaking the analysis down by site, no significant effects were found at the SGE site, although a trend for higher perennial grass density in rolled plots occurred ($p = 0.09$; Figure Competition 2a). At WRR, SAP treatment had an effect ($p = 0.006$; Figure Competition 2a), and there was also a 3-way interaction involving rolling, BA and SAP ($p = 0.008$). In plots that were rolled, SAP increased perennial grass density ($p = 0.015$), while in plots that were not rolled, there were no significant effects ($p > 0.11$). The effect in rolled plots was further modified by an interaction with the BA treatment ($p = 0.020$) whereby the effect of SAP was non-significant in plots with the high level of BA (SAP effect in high BA plots:

11.2 seedlings/m^2, $p = 0.26$; SAP effect in low BA plots: 41.2 seedlings/m^2, $p = 0.0006$; SAP effect in no-BA plots: 38.8 seedlings/m^2, $p = 0.001$). Also at WRR, in the absence of SAP and with rolling, the high BA treatment increased perennial grass seedlings by 21.1 seedlings/m^2 versus low or no BA treatments ($p = 0.004$). There was a slight effect of BA in the absence of SAP without rolling ($p = 0.041$), and no effects of BA in the presence of SAP ($p > 0.1081$).

Perennial grass cover was influenced by site, year, and their interaction ($p < 0.0002$) as well as by a three-way interaction between rolling treatment, SAP, and year ($p = 0.032$). When breaking the analysis down by site, and subsequently by year, no contrasts of means were significantly different ($p > 0.18$). Across years, perennial grass cover averaged 46.7 ± 0.01% at SGE and 60.9 ± 0.01% at WRR (Figure Competition 2b). Perennial grass biomass in 2013 was influenced by site ($p < 0.0001$) and an interaction between BA and site ($p = 0.021$). When breaking the analysis down by site, there were no significant effects ($p > 0.10$). Perennial grass biomass averaged 22.8 ± 1.2 g/m^2 at SGE and 48.4 ± 1.7 g/m^2 at WRR.

Cheatgrass seedling density in 2010 differed by site ($p < 0.0001$), with 11.1 ± 0.8 seedlings/m^2 at SGE and 24.4 ± 1.9 seedlings/m^2 at WRR (Figure Competition 3a). There was also an interaction between SAP and BA treatments ($p = 0.051$) whereby SAP had no detectable effect in low-BA or no-BA plots ($p > 0.19$), but increased cheatgrass density by 9.0 seedlings/m^2 in high-BA plots ($p = 0.035$). Cheatgrass cover was influenced by site, year, and their interaction ($p < 0.002$) as well as by SAP ($p = 0.026$), and a three-way interaction between site, year, and SAP ($p = 0.036$). At SGE, cheatgrass cover varied by year ($p < 0.0001$), falling from 11.2 ± 1.3% in 2011 to 2.0 ± 0.6% in 2012, then rebounding to 5.4 ± 0.7% in 2013. There was an interaction between SAP and BA at SGE ($p = 0.051$) whereby in the absence of SAP, the high-BA treatment reduced cheatgrass cover about 2-fold relative to either the no-BA or low BA treatments ($p < 0.01$) but had no effect in the presence of SAP ($p > 0.42$; Figure Competition 4). At WRR, cheatgrass cover varied by year ($p < 0.0001$), with 28.1 ± 2.4% in 2011, 1.7 ± 0.05% in 2012, and 19.1 ± 2.5% in 2013 (Figure Competition 3b). Cheatgrass cover at WRR was also influenced by SAP ($p = 0.035$) and an interaction between SAP and year ($p = 0.059$). SAP reduced cheatgrass cover 11.4 percentage points in 2011 ($p = 0.028$), and 12.3 percentage points in 2013 ($p = 0.002$), but did not have a significant effect in 2012 (Figure Competition 3b). Cheatgrass 2013 biomass was influenced by site ($p = 0.017$), SAP ($p = 0.020$), and their interaction ($p = 0.052$). At SGE, cheatgrass biomass averaged 0.58 g/m^2 and there was no significant effect of SAP. At WRR, SAP reduced cheatgrass biomass from 4.14 ± 0.73 g/m^2 to 1.53 ± 0.41 g/m^2 ($p = 0.004$; Figure Competition 3c).

Soil moisture differed by site on every date measured ($p < 0.0001$), with SGE averaging 24 .3 ± 15.2 % soil moisture across dates and treatments, and WRR averaging only 13.7 ± 10.4%. Binding agent had a consistent effect at increasing soil moisture, with a significant effect across sites on 21 May 2010 ($p < 0.0001$), 3 June 2011 ($p = 0.0070$), 15 May 2012 ($p < 0.0001$), and 28 June 2012 ($p = 0.0220$; see Figure Competition 5 for site-specific effects). On the highest soil moisture date measured, 21 May 2010, the high BA treatment averaged 37.1 ± 9.4% while the no-BA treatment averaged 32.9 ± 8.9%. On the lowest soil moisture date measured, 28 June 2012, the high BA treatment averaged 2.1 ±1.3%, and the no BA treatment averaged 1.9 ± 1.4%. Precipitation data for the two study sites is summarized in Table Competition 2.

Discussion

Both SAP and binding agent treatments showed some utility for promoting perennial grasses and discouraging growth of cheatgrass, although results were not consistent across sites. SAP, by its ease of application and somewhat more pronounced effects, seems the more promising treatment. Effects were only noted at the WRR site, where SAP had been applied near the upper end of the recommended range for agricultural purposes (30.8 g/m^2). At WRR, SAP increased 2010 perennial grass density by about

40%, with effects most apparent in plots with low or no BA which had been rolled. SAP slightly increased cheatgrass seedling density in high-BA plots the first year post-treatment, but over the longer term, the effect of SAP on cheatgrass was negative. SAP reduced cheatgrass cover in 2011 and 2013, and cheatgrass biomass four years post-treatment was about three times lower where SAP had been applied. At the SGE site, where SAP was applied at 6.7 g/m^2, no significant effects were apparent. Across treatments, the SGE site had two to three times lower cheatgrass density and cover than the WRR site. Two possible explanations for the differences between sites are that the application rate of SAP was too low at the SGE site to be effective, and that cheatgrass did not establish well enough at SGE for an effect of SAP to be apparent.

Cheatgrass utilizes near-surface water early in the growing season, causing soils to dry prematurely and hindering the establishment of perennial plants (Kulmatiski et al. 2006). A possible mechanism for the effect of SAP in this study is that it extended the duration of moist soils, allowing better establishment of perennial grasses in the first post-treatment year. Increased competition from perennial grasses then limited cheatgrass cover and biomass in subsequent years. It is also possible that SAP has some direct negative effect on cheatgrass, such as reducing nitrogen or water availability when cheatgrass is most actively growing. The lack of effect of SAP on perennial grass cover or biomass two to four years post-treatment supports this second possibility. Further studies which track the effects of SAP on the timing of water and nutrient availability in cheatgrass-invaded versus uninvaded areas are warranted.

The BA treatment had generally positive effects. For instance, the high BA treatment increased perennial grass density in the absence of SAP, and the high BA treatment also reduced cheatgrass cover at the SGE site in the absence of SAP. Binding agent increased soil moisture, especially at the highest application rate, supporting the manufacturer's claims that the product increases water infiltration. Binding agent application is expensive; in order to apply the binding agent in the manner tested in this study, 3200 gal/ac of water is needed, requiring a water truck. Even so, the benefit of the product may warrant further study for the limited applications where implementation is feasible.

SAP and BA treatments often interacted, such that the effect of one treatment was less prominent in the presence of the other. Binding agent impeded the effect of SAP at increasing perennial grass density, and SAP impeded the effects of binding agent at increasing perennial grass density and reducing cheatgrass cover. The reasons for this are not entirely clear. It would seem that the increased soil moisture provided by the binding agent and increased storage of soil moisture provided by SAP would have synergistic effects by providing sufficient moisture over sufficient time to support perennial plant growth. However, this was not what was generally observed. The exception was for cheatgrass seedlings in 2010, wherein the combination of SAP and the high BA increased density. It is possible that such a synergism did occur, but only initially, with timing that benefitted cheatgrass. Over the long term, as SAP particles swelled to absorb moisture or shrunk as moisture was released, the resulting heaving action could have interfered with the ability of the binding agent to hold soil particles together.

There was no interaction between BA and rolling treatments, and no benefit of the rolling treatment for either cheatgrass or perennial grass. It can be concluded that the strategy of creating a crust of compacted soil in order to limit cheatgrass growth, either by applying a binding agent, rolling, or the two together, was not successful.

Cheatgrass has adapted to complete its life cycle before the dry period of the summer in the intermountain west (Rice et al. 1992), making it an effective competitor in arid ecosystems with variable soil moisture (Chambers et al. 2007). By absorbing water and then gradually releasing it into the soil, SAPs can reduce the variability in soil moisture over time. SAPs have long been shown to aid in perennial plant growth and establishment, and this study supports the idea that SAPs may also help in cheatgrass control. Granulated SAP can easily be applied through a drill seeder or combined into a pellet with seed, making SAP application a potentially practical tool for managers seeking to establish perennial grasses in competition with cheatgrass.

Figures

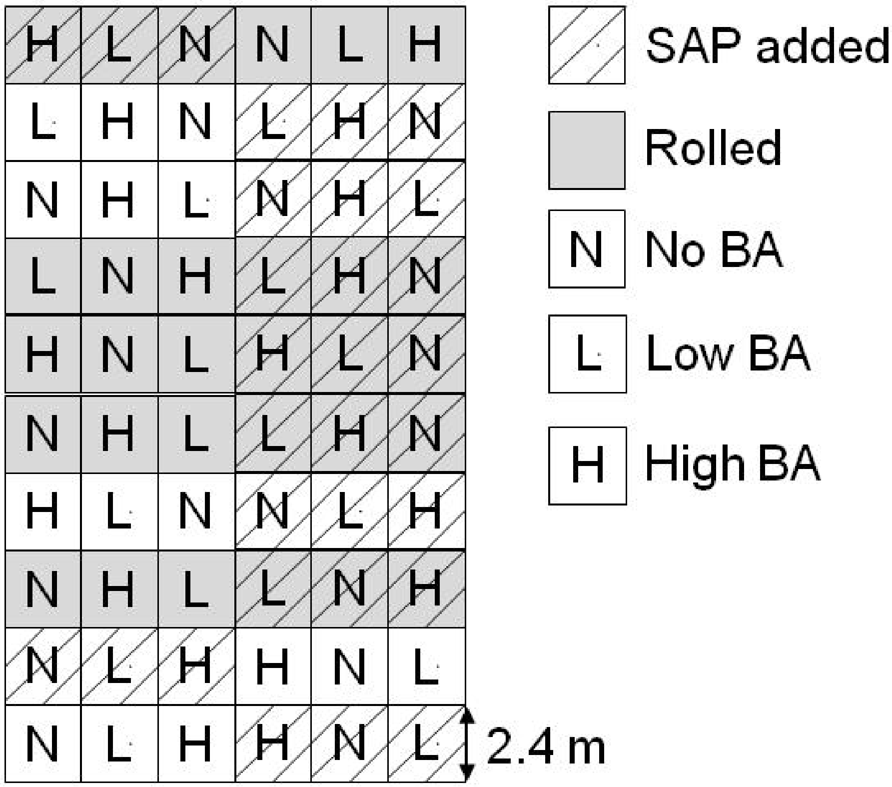


Figure Competition 1. Layout of the Competition experiment at one of 2 research sites. SAP = super-absorbent polymer. BA = soil binding agent DirtGlue ®.

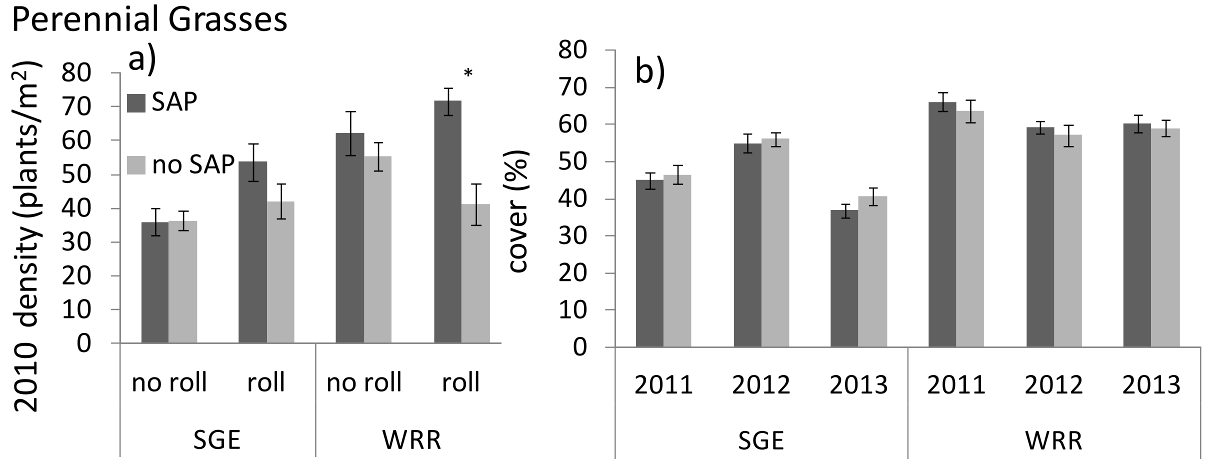


Figure Competition 2. Response of perennial grasses to super-absorbent polymer addition (SAP) at two sites: SGE and WRR. In 2010 (a) SAP interacted with a rolling treatment to influence seedling density. In 2011-2013 (b) only site effects were evident on cover. Error bars = SE. Stars indicate significantly different means at $\alpha = 0.05$.

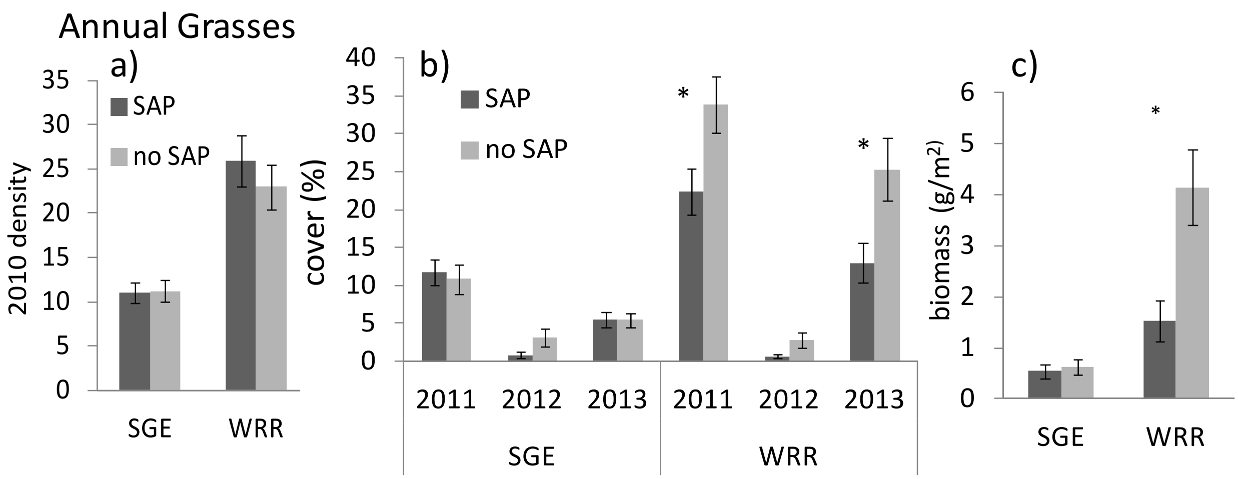


Figure Competition 3. Response of cheatgrass (*Bromus tectorum*) to super-absorbent polymer addition (SAP) at two sites: SGE and WRR. In 2010 (a) only site effects were evident on annual grass density. In 2011-2013 (b), SAP reduced annual grass cover at the WRR site in 2 of 3 years. In 2013 (c), SAP reduced annual grass biomass at the WRR site. Error bars = SE. Stars indicate significantly different means at $\alpha = 0.05$.

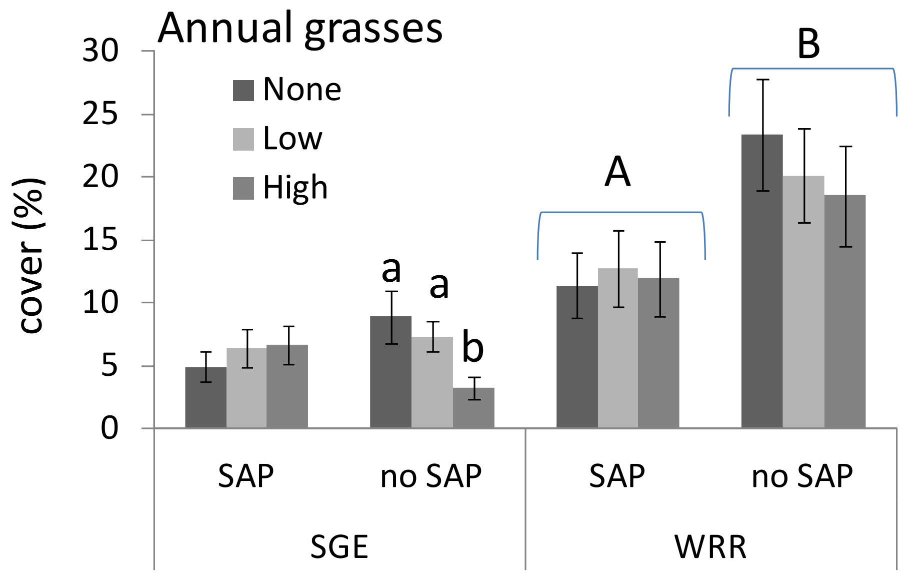


Figure Competition 4. Response of cheatgrass (*Bromus tectorum*) to super-absorbent polymer addition (SAP) and DirtGlue ® soil binding agent (3 levels: None, Low, or High) at two sites: SGE and WRR. Data are averaged over 3 years, 2011-2013. Error bars = SE. Bars not sharing letters are significantly different at α = 0.05.

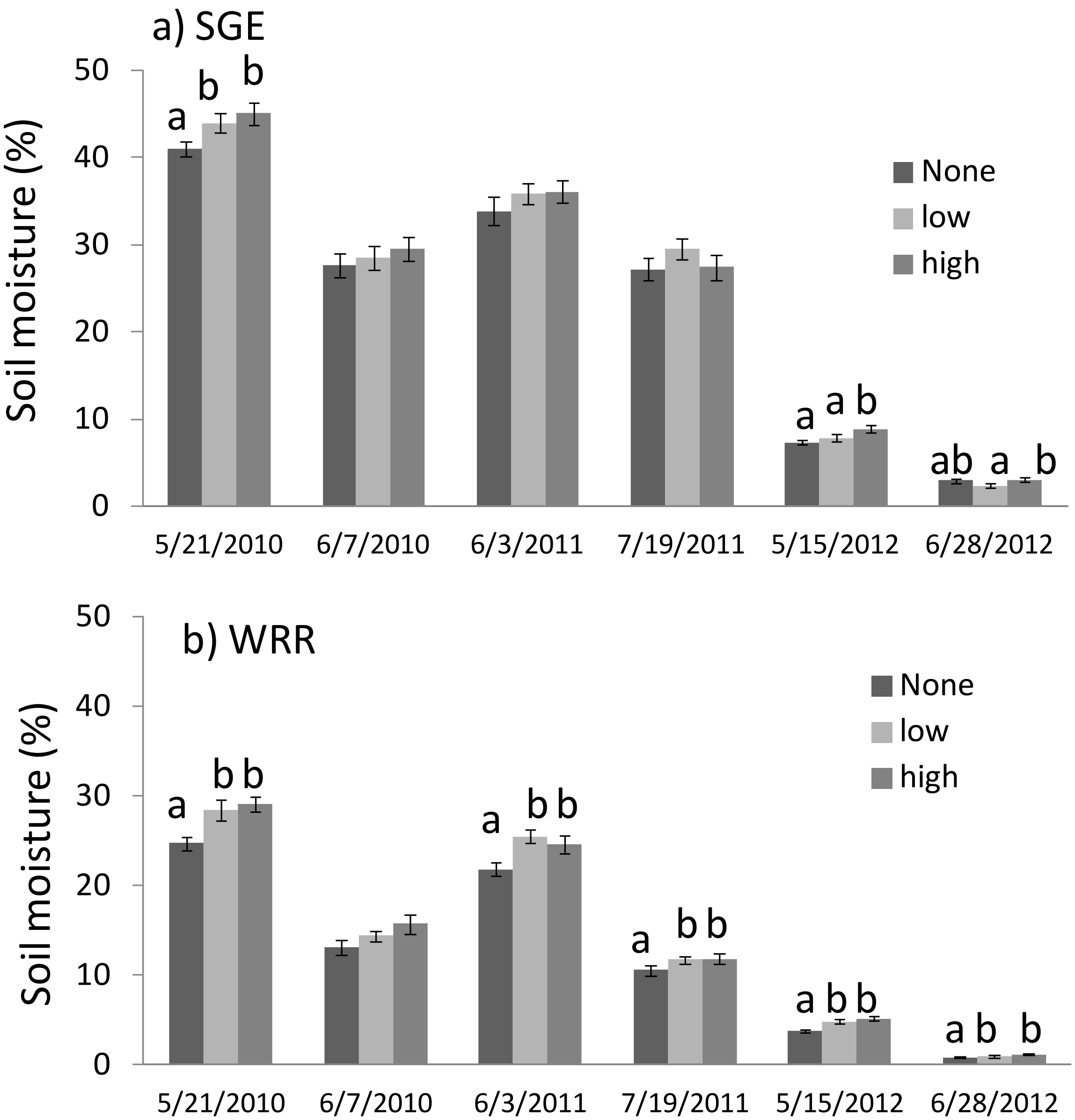


Figure Competition 5. Percent volumetric soil moisture in response to DirtGlue ® soil binding agent (3 levels: None, Low, or High) at two sites: SGE (a) and WRR (b) on 6 measurement dates. Error bars = SE. Bars not sharing letters are significantly different at $\alpha = 0.05$.

Tables

Table Competition1. Seed mix of grasses used in the Competition experiment. Cheatgrass (*Bromus tectorum*) was also seeded at 300 seeds/m2.

Scientific Name	Common Name	Variety	Seeds/ m2	PLS (kg/ha)	Seeds/ ft2	PLS (lbs/ac)
Elymus lanceolatus spp. lanceolatus	thickspike wheatgrass	Critana	150.7	4.5	14	4.0
Elymus trachycaulus spp. trachycaulus	slender wheatgrass	San Luis	150.7	5.1	14	4.5
Pascopyrum smithii	western wheatgrass	Rosana	150.7	5.8	14	5.2
		TOTAL	**452.1**	**15.3**	**42**	**13.7**

Table Competition 2. Precipitation information recorded using RG3-M data logging rain gauges (Onset® Computer Corporation, Bourne, MA, USA) installed on guyed posts at each site: SGE and WRR. Summer data is June - August, fall data is September - November, and winter/spring data is December - May.

		site	
	season	**SGE**	**WRR**
2010	summer	111.4	106.2
	fall	69.2	66
2011	winter/spring	102.6	189
	summer	84	110.8
	fall	44.6	81
2012	winter/spring	8.6	44.4
	summer	48.8	77
	fall	39.4	57.8
2013	winter/spring	109	121
	summer	93.2	76.6
	fall	151.4	142.8
2014	winter/spring	102.8	88.4
	summer	89.2	103.4
	fall	145.2	125.4
2015	winter/spring	167.8	180.8
	summer	86.2	107.8
AVG	**winter/spring**	**98.2**	**124.7**
	summer	**85.5**	**97.0**
	fall	**90.0**	**94.6**

COMPETITION 2 EXPERIMENT

Overview

- Goal: Test effectiveness of super-absorbent polymer at reducing the competitive ability of cheatgrass when applied with complex seed mix of desirable perennials. Use a larger plot size than that used in the Competition experiment so that edge effects are less likely to influence vegetation within plots. Use a higher seeding rate of cheatgrass than that used in the Competition experiment to test the effect of polymer under higher cheatgrass propagule pressure.
- Conducted at two sites: SGE and WRR (Figure 1, Table 1)
- Treatment:
    - Super-absorbent polymer (two levels): super-absorbent polymer applied (SAP) or no polymer applied (no SAP)
- Design: completely randomized, with three replications per site
- Plot size: 6.4 X 8.1 m
- Three replications per site

Methods

The vegetation which had grown on the well pad surface between 2009 and 2012 was characterized at each site using six systematically arrayed 12.8 m point-intercept transects per site, with hits every 20 cm, for a total of 384 hits per site.

Cheatgrass seed was collected using a lawnmower with a bagging attachment from monocultures or near-monocultures from two locations, one within 10 miles of the study sites, and another about 50 miles from the study sites. Collections were made in late June or early July 2012, when most or all of the cheatgrass in a location had fully ripened seed heads. Seed was allowed to dry and after-ripen in shallow containers in a dry, warm location for approximately three months. The density of apparently viable cheatgrass seeds was determined by gathering five 5 g subsamples from each collection, and then counting and weighing all of the fully developed, hard-coated cheatgrass seeds for each subsample. The collection from the location nearer the study sites was sufficient to supply about 2/3 of the number of seeds needed for the experiment. The remaining 1/3 of seeds were drawn from the collection from the further location, and this material was mixed thoroughly with that of the other collection. Next, a volume of seed sufficient to supply 600 seeds/m^2 was prepared for each plot.

Site preparation and seeding occurred in early to mid September, 2012. Existing vegetation was removed by ripping to 30 cm, then disking to 15 cm with a Plotmaster. Uprooted vegetation was then removed by hand or with rakes. Next, the plots were rolled with the Plotmaster to create a firm, level surface. Next, we simulated a drill seeding by creating furrows with the Plotmaster, then hand-sprinkling seed into these furrows and pressing soil over them. We chose this method because it allowed for the seeding and polymer application rates to be precisely known. The seed mix in Table Comp2_1 was applied to all plots. In plots randomly selected for the polymer treatment, Tramfloc® 1001 granulated polymer (a cross-linked copolymer of acrylamide and potassium acrylate; Tramfloc®, Inc, Tempe, AZ, USA) was applied at 45 g/m^2 to furrows, after seed application but before pressing soil over the seed. The Tramfloc® product was used because Luquasorb® 1280 RM (which was used in the Competition experiment) was no longer available.

Directly after desirable species were seeded, cheatgrass seed was hand-broadcast at 600 seeds/m^2 then lightly raked to incorporate it into the soil in all plots. In mid-November, 2012, locally-collected Wyoming big sagebrush was hand-broadcast over snow at 270 seeds/m^2.

Vegetation was assessed by seedling density in 2013 and by percent cover in 2014 and 2015. Seedling counts were done using 5 0.5 X 1.0 m miniplots per plot, and seedlings were identified to species. Cover data was done using 5 1.0 X 1.0 m miniplots, over which we placed a sampling frame. The frame was a grid containing thirty-six intersections, and point-intercept hits were measured at each intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT). All layers of vegetation were identified to species at each hit. When calculating percent cover of perennial grasses, overlapping hits of different species were counted as a single instance of the functional group. Soil moisture data was also taken in 2013-2014 using the same sampling locations as vegetation data. At each location, one soil moisture reading was taken within a drill-seeded row, and one reading was taken between rows on each of these dates: 6/19/13, 8/21/13, 5/16/14, 6/23/14, 7/19/14, and 8/21/14. Readings were taken to 12 cm using a Hydro Sense® Soil Water Measurement System (Campbell Scientific, Inc, Logan, Utah) and were averaged for row and between row placements for each plot on each date. Initial analysis indicated that placement in rows or between rows did not affect soil moisture; therefore data were averaged over placement for subsequent analysis.

Density, cover, and soil moisture data were analyzed using ANOVA in SAS PROC MIXED for a completely randomized design nested within sites, and sites considered as fixed effects. Species were grouped by functional group for analysis (perennial grass, perennial forb, annual forb, and annual grass). Annual grass was entirely cheatgrass, and there were insufficient shrubs for analysis. Data were transformed to improve normality and residual plots were inspected to ensure adherence to ANOVA assumptions [density: log (x); perennial grass cover and perennial forb cover: arcsine (square root [x]); annual forb cover and cheatgrass cover: square root (x)]. Cover and soil moisture data were analyzed as repeated measures with an autoregressive covariance structure with a lag of 1. Where significant site by treatment interactions occurred (cutoff $\alpha = 0.10$), separate analyses by site were also conducted. A significance level of $\alpha = 0.05$ was used to determine significantly different means, and a level of $\alpha = 0.10$ for interactions was used to determine which means to compare. Means are presented ± SE. Effect sizes were calculated using LSMESTIMATE in SAS PROC MIXED.

Results

Perennial grass density in 2013 was not significantly affected by site, SAP or their interaction ($p > 0.11$; Figure Comp2_a). Perennial grass cover was affected by year ($p = 0.023$), an interaction between site and year ($p = 0.006$), and by SAP treatment ($p = 0.031$; Figure Comp2_b; for complete ANOVA results see Table Comp2_2). Grass cover was similar between sites in 2014, but was higher at SGE (29.4 ± 5.4%) than at WRR (16.2 ± 4.8%) in 2015 ($p = 0.044$). Over half of perennial grass cover at SGE was in 2014 was needle-and-thread grass, which was not seeded. At WRR, this species was not prevalent, and about 4/5 of grass cover was comprised of seeded species. The SAP treatment roughly doubled perennial grass cover, from 13.4 ± 2.8% to 26.3 ± 3.1% across sites and years.

Perennial forb density in 2013 was influenced by SAP ($p = 0.003$) and by site ($p = 0.002$), but not by their interaction ($p = 0.386$). Perennial forb density was 5.1 ± 1.1 plants/m^2 in SAP plots and 11.3 ± 2.4 plants/m^2 in no-SAP plots (for site-specific results see Figure Comp2_c). Perennial forb cover increased with year ($p = 0.001$) and was higher at SGE than WRR ($p = 0.034$) but was not affected by SAP treatment (Figure Comp2_d). The seeded species Lewis flax (*Linum lewisii*) comprised about half of 2013 perennial forb density and 2/3 of forb cover in subsequent years at both sites.

Annual forb density was not significantly affected by any factors ($p > 0.32$; Figure Comp2_e). Annual forb cover declined from 2014 to 2015 ($p = 0.007$) and was affected by a three-way interaction between site, year, and SAP treatment ($p = 0.081$). SAP treatment had an effect only in 2015 at WRR, where it reduced annual forb cover from 16.3 ± 5.3% to 3.1 ± 1.0% ($p = 0.0394$; Figure Comp2_f). At SGE, annual forbs were dominated by desert alyssum (*Alyssum desertorum*). At WRR, plots without

SAP were co-dominated by tall tumble mustard (*Sisymbrium altissimum*) and small tumbleweed mustard (*Sisymbrium loeselii*), while plots with SAP contained a diversity of non-native annual forbs at low cover values.

Annual grass density was not affected by any factors ($p > 0.21$). Annual grass cover differed by site ($p < 0.0001$) and year ($p = 0.006$), and was influenced by a site by SAP treatment interaction ($p = 0.011$; Figure Comp2_h). Annual grass cover increased from 2014 to 2015, and was higher at WRR, averaging 53.6 ± 6.4% in 2015, than at SGE, which averaged 9.8 ± 3.2%. SAP had opposite effects depending on site. At WRR, there was a trend for lower annual grass cover with SAP ($p = 0.0845$), while at SGE, SAP increased annual grass cover from a mean of 3.0 ± 1.1% to 16.7 ± 5.0% ($p = 0.0281$).

Soil moisture differed by site ($p < 0.0001$), with SGE averaging 11.9 ± 10.1% across dates and treatment, and WRR averaging only 8.3 ± 7.6%. Soil moisture was also influenced by date ($p < 0.0001$), a site*date interaction ($p < 0.0001$), and an SAP treatment by date interaction ($p = 0.004$; Figure Comp2_2). SAP increased soil moisture on May 16, 2014 ($p < 0.0001$), but had no detectible effect on any other date in the analysis across sites ($p > 0.1852$; for site-specific effects see Figure Comp2_2).

Discussion

The study provides some insight into the complex ways in which SAP may affect plant communities. Desirable effects included a doubling of perennial grass cover, and a 5-fold reduction in annual forb cover at WRR in 2015. Undesirable consequences of SAP application were also noted. SAP had a negative effect on perennial forb density the first year post-treatment at both sites, although this negative effect on forbs was not evident in the cover data taken in later years. Cheatgrass established to a greater degree at the WRR than at the SGE site, and opposite effects of SAP on cheatgrass were noted at the two sites. The trend at the WRR site was for lower cheatgrass cover where SAP had been applied. At the SGE site, however, SAP increased cheatgrass cover over 5-fold in 2015.

Comparison of this study with the Competition Experiment illustrates the need for precaution with promising treatments which may impact plant communities in complex ways. Few undesirable effects of SAP application were evident in the Competition Experiment, but conducting a subsequent, similar study at the same two sites revealed the potential for SAP to increase cheatgrass cover dramatically. In the Competition Experiment, SAP was applied at a lower rate at the SGE site than at the WRR site, while in the Competition 2 Experiment, the same application rate was used at both sites. This may explain why the effect of SAP was evident at SGE only in the second study.

Why the two sites differed in how they responded to SAP is unclear. The sites were similar in precipitation (Table Competition 2) and both sites are classified has having sandy loam soils in the Piceance Soil series. However, slight differences existed between sites. WRR soils appeared darker in color and had slightly higher organic matter in an agricultural soil test (Appendix 2). The SGE site has ~ 3%, west-facing slope, while the WRR site is flat. The SGE is slightly lower in elevation. Soils at SGE were wetter in both this experiment and in the Competition Experiment, and SAPs had an effect on soil moisture on 19 June 2013 at WRR which was not evident at SGE (Figure Comp2_2).

SAP appeared to benefit perennial grasses to a greater degree at WRR than at SGE, as SAP improved perennial grass density at WRR but not at SGE in the Competition Experiment, and had a larger effect on perennial grass cover at WRR in Comp2. In the second experiment, grass establishment dynamics differed from the first. Grass cover three years post treatment in Competition 2 vs. Competition experiments was much lower at WRR (~20% vs. ~60%) and somewhat lower at SGE (~30% vs. ~55%), possibly due to the addition of forbs and shrubs to the seed mix. In the second experiment, grass cover at SGE was dominated by needle-and-thread grass, an unseeded native perennial. As the SAP was applied near the seed within drill-seeded rows, it is possible that the lack of response of perennial grasses to SAP at SGE was because conditions were favorable for needle-and-thread grass, but it did not have as much access to the SAP.

The WRR was apparently more favorable for cheatgrass, as WRR had two to three-fold higher cheatgrass cover in both Competition and Competition 2 experiments. Site differences in cheatgrass response to SAP may have been influenced by interannual changes in precipitation. 2011-13 had dry preceding autumns, averaging just 68 mm of precipitation. In contrast, 2014 and 2015 had wet preceding autumns, averaging 148mm of precipitation (Table Competition 2). Cheatgrass typically germinates in September in the study area and completes its life cycle the following May. High precipitation in late fall through early spring is favorable for cheatgrass growth and seed production (Prevey and Seastedt 2015). At the SGE site, the higher application rate in the second experiment may have interacted positively with higher precipitation to promote cheatgrass in spite of the site being generally less favorable. At WRR, however, the large positive effect of SAP on perennial grasses allowed perennial grasses to suppress cheatgrass, in spite of a possible direct benefit of SAP on cheatgrass.

Apparently, the type of plant which is most benefitted by SAP application is determined by some complex combination of site, precipitation, and species composition factors. A working hypothesis is that when the timing and amount of soil moisture is nearly adequate for seedling establishment of a particular species, then SAP application may benefit that species, allowing it to have a larger impact on competitive dynamics than it would have had otherwise. In other words, SAP application may 'promote the underdog' when otherwise soil moisture patterns would be predominately favorable for a different plant type. The fact that SAP increased the cover of the functional group which had lower cover at both WRR and SGE supports this hypothesis. If this hypothesis is true, then SAP application may be beneficial for establishing perennial grass when conditions generally favor cheatgrass, but not when conditions generally favor perennial grass.

SAP application had a negative effect on perennial forb seedling density at both sites in the Competition 2 Experiment. The seeded species Lewis flax was responsible for 50 to 70% of this response, but the direction of response was the same for the seeded species Utah sweetvetch (*Hedysarum boreale*), as well as the unseeded species multi-lobed groundsel (*Packera multilobata*), hollyleaf clover (*Trifolium gymnocarpon*), and lesser rushy milkvetch (*Astragalus convallarius*). All of these are taproot-developing species, and SAP was applied only in the top 5-10 cm of soil. The morphology of the root systems of these forbs may preclude benefits from shallowly-incorporated SAP. The primary effect of SAP may then be increased competition from either annual or perennial grass. By two years post-treatment, there was no effect of SAP on forb cover, indicating that in this study, sufficient forbs nonetheless established to prevent a long-term negative effect of SAP on forbs.

In summary, this study indicates that SAP may be beneficial for increasing perennial grass establishment, but also may increase cheatgrass. The relative benefits appear to be site-specific. A deeper understanding of these site-specific factors is needed to inform management.

Figures

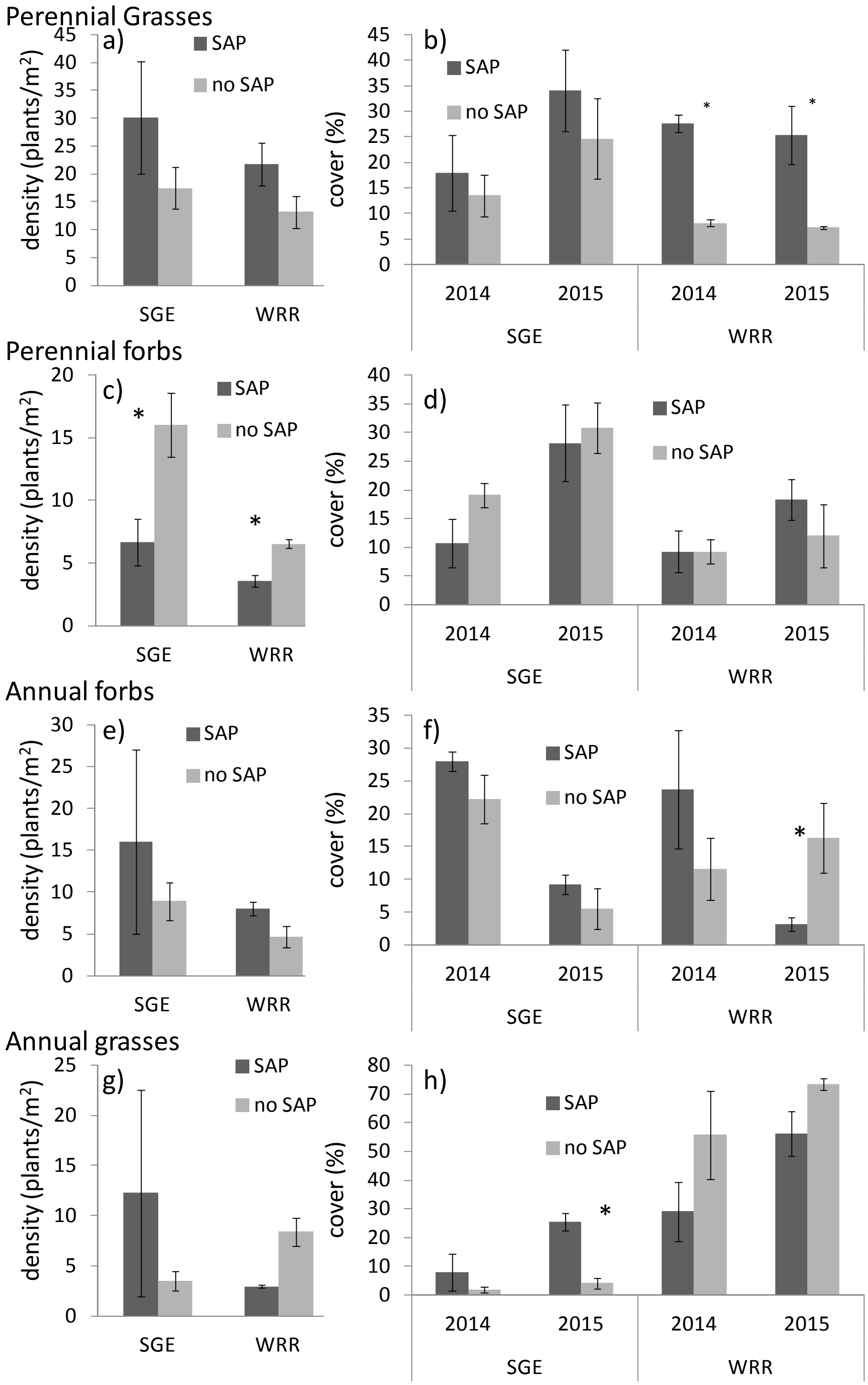


Figure Comp2_1. Response of 4 functional groups, perennial grasses (a, b), perennial forbs (c, d), annual forbs (e, f), and annual grasses (g, h) in 2013 (a, c, e, g) and 2014-5 (b, d, f, h) to a super-absorbent polymer soil amendment (SAP) at two sites: SGE and WRR. Error bars = SE. Stars indicate significantly different means at $\alpha = 0.05$.

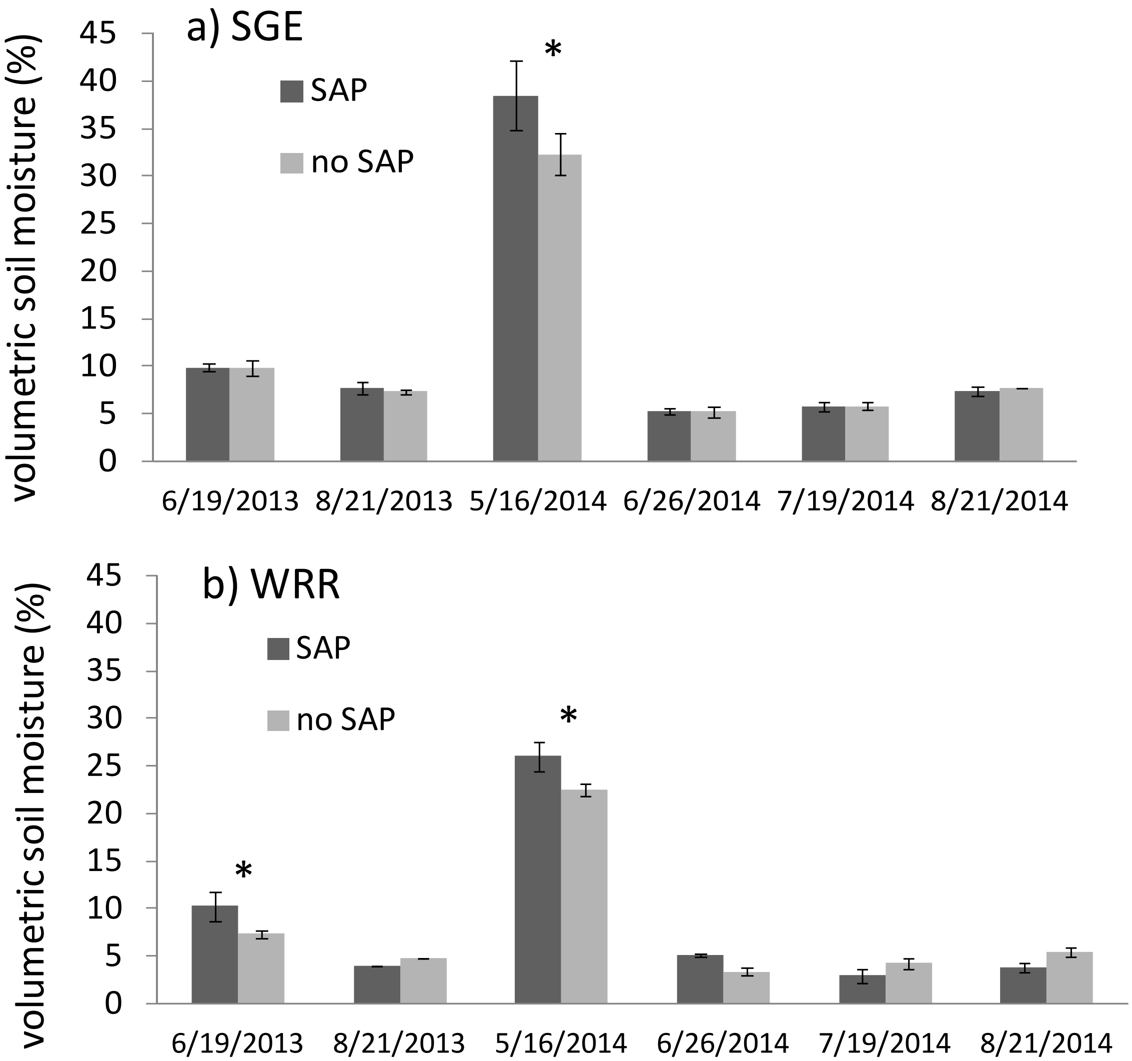


Figure Comp2_2. Volumetric soil moisture in response to super-absorbent polymer soil amendment (SAP) at two sites: a) SGE and b) WRR. Error bars = SE. Stars denote significantly different means at α = 0.05.

Tables

Table Comp2_1. Seed mix used in the Competition 2 experiment. Cheatgrass (*Bromus tectorum)* was also seeded at 600 seeds/m^2.

Scientific Name	Common Name	Variety	Seeds/ m^2	PLS (kg/ha)	Seeds/ ft^2	PLS (lbs/ ac)
forbs						
Eriogonum umbellatum	sulphur flower buckwheat	VNS	130	3.5	12.1	3.1
Hedysarum boreale	Utah sweetvetch	Timp	26	3.5	2.4	3.1
Linum lewisii	Lewis flax	Maple Grove	91	1.4	8.5	1.2
Penstemon palmeri	Palmer penstemon	Cedar	104	0.8	9.7	0.7
grasses						
Pascopyrum smithii	western wheatgrass	Arriba	39	1.6	3.6	1.4
Achnatherum hymenoides	Indian ricegrass	Nezpar	130	4.1	12.1	3.6
Bouteloua gracilis	blue gramma	Hachita	65	0.4	6.0	0.4
Elymus elymoides	bottlebrush squirreltail	Toe Jam Creek	65	1.5	6.0	1.4
Elymus trachycaulus	slender wheatgrass	San Luis	52	1.8	4.8	1.6
Poa sandbergii	Sandberg bluegrass	Cedar	182	0.9	16.9	0.8
Pseudoroegneria spicata	bluebunch wheatgrass	Anatone	104	3.4	9.7	3.0
shrubs						
Atriplex canescens	fourwing saltbush	Colorado source	195	32.2	18.1	28.7
Artemisia tridentata	big sagebrush	local collection	150	0.6	13.9	0.5

Table Comp2_2. ANOVA results for perennial grass, perennial forb, annual forb, and annual grass cover over 2 years (2014 and 2015) in response to site (SGE or WRR) and super absorbent polymer treatment (SAPTrt).

		grasses		forbs		annual forbs		annual grasses	
Factor	df	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
site	1, 8	1.128	0.319	6.510	**0.034**	0.770	0.406	61.720	**0.000**
year	1, 8	7.821	**0.023**	26.011	**0.001**	12.861	**0.007**	13.366	**0.006**
site*year	1, 8	13.604	**0.006**	3.330	0.105	1.794	0.217	0.001	0.980
SAPTrt	1, 8	6.831	**0.031**	0.107	0.753	0.324	0.585	0.251	0.630
site*SAPTrt	1, 8	2.002	0.195	1.480	0.258	2.887	0.128	10.792	**0.011**
year*SAPTrt	1, 8	0.263	0.622	3.721	**0.090**	2.230	0.174	2.416	0.159
site*year*SAPTrt	1, 8	0.577	0.469	0.008	0.930	3.990	**0.081**	0.234	0.642

GULLEY EXPERIMENT

Overview

- Goal: identify which potential sources of weeds are important to control: those that originate from within the soil seed bank of the reclamation area, those that enter from the surrounding landscape, or both.
- Conducted at four sites: RYG, SKH, YC1, and YC2 (Figure Intro 1, Table Intro 1)
- Treatments:
    - Fallowing (two levels): fallowed with Pendulum™ herbicide for one year prior to seeding (fallowed) or seeded immediately (unfallowed)
    - Plateau application (two levels): Plateau applied (Plateau) or no Plateau applied (no Plateau)
    - Seed barriers (two levels): surrounded by a seed dispersal barrier (barrier) or not surrounded (no barrier)
- Design: Factorial split-split plot, with completely randomized whole plots. The whole plot factor was fallowing, the subplot factor was seed barriers, and the sub-subplot factor was Plateau (Figure Gulley1). Whole plots were completely randomized.
- Plot size: 9 m X 6 m
- Three replicates per site

Methods

In late August and early September, 2009, fallowed plots were treated with Pendulum at 3200 g ai/ha (3 qt/ac), applied with a boom sprayer with 330 li/ha (35 gal/ac) of water. At the time of application, no germinated plants of any kind were evident at any of the sites. Once dry, the product was immediately incorporated into the soil with light disking to 5 cm (2 in) to prevent breakdown due to UV radiation. Next, the mixture of native grasses, forbs, and shrubs in Table 4 (except big sagebrush) was hand-broadcast. Even seed distribution was ensured by preparing batches of the seed mix for each sub-subplot and seeding them individually. Seed was mixed 1:1 by volume with rice hulls to aid in even distribution of species. Seed was lightly raked to incorporate it into the soil after broadcasting. The same day as seeding, Plateau was applied at 140 g ai/ha (8 oz/ac) with 655 li/ha (70 gal/ac) of water using a backpack sprayer to unfallowed, Plateau plots. Dye indicator was used to ensure even application.

To prevent wind and water erosion, DirtGlue soil binding agent was applied to all plots in September 2009. Soil binding agent was applied with a boom sprayer at 190 li/ha (50 gal/ac) diluted 10:1 with water. Next, barrier subplots were surrounded by aluminum window screen seed dispersal barriers. Barriers were 0.6 m high and were secured to oak stakes with staples. One meter wide buffer strips separated barrier subplots. Finally, locally collected big sagebrush seed was hand-broadcast on top of snow in unfallowed plots in December of 2009.

During the 2010 growing season, fallowed plots were maintained in a nearly unvegetated condition by applying glyphosate at 560 g/ac (8 oz./ac) in early June, and hand-pulling any plants nearing seed production in late June. In early September, 2010, soil compaction was relieved in fallowed plots by ripping to 30 cm with a Plotmaster 400. This necessitated removing and then rebuilding the seed dispersal barriers in fallowed plots. Following ripping, fallowed, Plateau plots were treated with Plateau at 140 g ai/ha (8 oz/ac) applied with 655 li/ha (70 gal/ac) of water with a backpack sprayer. Fallowed plots were seeded in late September using the same seed mixture and techniques as had been used in 2009 for unfallowed plots. Locally collected big sagebrush seed was hand-broadcast on top of snow in fallowed plots in December of 2010.

Some cheatgrass seed that had been caught in the dispersal barriers in 2009 germinated and grew through the barrier. In order to fortify the barriers, we applied Plateau at 140 g ai/ha (8 oz/ac) in a 0.1 m strip between 9/14/10 and 9/28/10 at the base of the barrier.

A difficulty with constructing a fair test of the barriers is that subplots on the edge of the experiment area are likely to be subject to more seed blowing in from the surrounding landscape than are subplots in the interior. We moderated this effect by hand-broadcasting cheatgrass seed within the buffer strips separating subplots in 2009 and again in 2010. To determine how much seed to scatter, we used annual data on ambient cheatgrass seed rain known from our seed rain traps (Appendix 1). Because the traps were sticky and did not allow the seeds to redistribute, we scattered only half as much seed per unit area as these traps had caught. This compensated for the fact that under normal conditions roughly half of cheatgrass seeds landing in a particular location move again (Kelrick 1991). The scattered cheatgrass seed had been collected from near-monocultures within 100 m of each site in June and July, when the seed was dry and nearly ready to fall. Seed was collected using a lawnmower with a bagging attachment. Viable cheatgrass seed content was estimated for each collection by gathering five 5g subsamples, and then counting and weighing all of the fully developed, hard-coated cheatgrass seeds from each subsample.

At two of the sites, RYG and SKH, barriers were badly damaged by cow trampling after the cheatgrass seed had been broadcast in 2009. The barriers were rebuilt, and lath secured with wood screws was added to the oak stakes at all sites to better secure the windowscreen. The barrier treatments at RYG and SKH are best viewed as being functionally implemented in 2010, while those at YC1 and YC2 were effective for 2009 growing season. All of the sites were fenced to prevent further damage.

Vegetation was assessed by percent cover using five 1m^2 miniplots per sub-subplot. One miniplot was located in the center of the sub sub-plot, and the remaining miniplots were equidistant from the center miniplot and a sub sub-plot corner. A grid containing thirty-six intersections was held over each miniplot, and point-intercept hits were measured at each grid intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT). All layers of vegetation were identified to species at each hit. When calculating percent cover of a given functional group, such as perennial grasses, overlapping hits of different species within a functional group (for instance, western wheatgrass overlying Sandberg bluegrass) were counted as a single instance of the functional group.

The cover of perennial grasses, perennial forbs, annual forbs, annual grasses, and shrubs in response to site, fallow treatment, Plateau treatment, and barrier treatment was analyzed using repeated measures ANOVA in SAS PROC MIXED. All factors were considered fixed. Site and fallowing were considered between-subject effects for whole plots, and barriers and Plateau treatment (nested within barriers) were considered within-subject effects. The repeated measures covariance structure was autoregressive with a lag of 1. Biennial forbs were lumped with annual forbs. Cover data was transformed by an arcsine [square root (x)] transformation to improve normality. A significance level of $\alpha = 0.05$ was used to determine significantly different means, and a level of $\alpha = 0.10$ for interactions was used to determine which means to compare. I limit my discussion of site effects to site×treatment (and site×treatment×treatment) interactions which had larger F-values than those of the corresponding treatment (or treatment×treatment interaction). When site×treatment interactions occurred which had larger F-values than the corresponding treatment, I conducted analyses separately by site. The SKH site was lost to a natural gas development in late 2012, therefore there were only two years of cover data analyzed for SKH.

The percentage of native versus non-native species was calculated for all functional groups.

Results

Across sites treatments, and years 96.8% of perennial grass cover was native, 99.9% of perennial forb cover was native, 100% of shrub cover was native, 7.2 % of annual forb cover was native, and 0% of annual grass cover was native. Big sagebrush accounted for 86.3% of all shrub cover. Bulbous bluegrass (*Poa bulbosa*) was the only non-native perennial grass detected, and it was confined to the SKH site. Russian thistle (*Salsola tragus*) and blue mustard (*Chorispora tenella*) were the most dominant annual forbs. Cheatgrass accounted for 99.9% of annual grass cover. The most dominant perennial forbs were Utah sweetvetch and Lewis flax. Squirreltail (*Elymus elymoides*), western wheatgrass, and bluebunch wheatgrass were the most common perennial grasses.

Fallowing greatly reduced shrub cover ($F_{1,16}$ = 198.93, P < 0.0001) from a mean of 18.4 ± 1.2% to 1.7 ± 0.3%. The effect of fallowing has grown greater over time (fallowing*year: $F_{2,112}$ = 4.58, P = 0.0122), as shrub cover increase in no-fallow plots has outpaced that in fallow plots (Figure Gulley2a). Plateau increased shrub cover ($F_{1,32}$= 46.33 P < 0.0001), especially in the absence of the fallow treatment (fallowing*Plateau: $F_{1,32}$= 20.77 P < 0.0001; Figure Gulley 3).

Fallowing greatly reduced perennial grass cover ($F_{1,16}$ = 83.39, P < 0.0001), but the effect grew smaller with time (fallowing*year: $F_{2, 112}$ = 91.45, P < 0.0001; Figure Gulley 2b). Plateau also slightly reduced perennial grass cover ($F_{1,32}$= 4.93 P = 0.0337), from a mean of 17.4 ± 1.5% to a mean of 15.4 ± 1.6%. Barriers increased perennial grass cover ($F_{1,16}$= 18.37 P = 0.0006) from a mean of 13.8 ± 1.5% to 19.0 ± 1.6%.

The effect of fallowing on perennial forb cover depended on time (fallowing*year: $F_{2,112}$ = 40.67, P < 0.0001). In 2011, no significant effect of fallowing was observed, but in 2012 and 2013, perennial forb cover was higher in fallowed plots (P < 0.0095**;** Figure Gulley 2c). Plateau negatively impacted forbs ($F_{1,32}$= 20.04 P < 0.0001), but the effect grew smaller with time (Plateau*year: $F_{2, 112}$ = 6.72, P = 0.0016); in 2011 Plateau reduced forbs from 9.8 ± 1.5% to 3.5 ± 0.4%, while in 2013 the difference was 8.9 ± 1.7% vs. 5.2 ± 0.8%. Barriers increased forb cover from ($F_{1,16}$= 8.34 P = 0.0107) from a mean of 4.8 ± 0.5% to 7.4 ± 0.7%.

Both fallowing ($F_{1,16}$ = 19.56, P = 0.0004; Figure Gulley 2d) and Plateau ($F_{1,32}$= 74.29 P < 0.0001) controlled annual grasses. An interaction occurred because the effectiveness of each herbicide was much more apparent in the absence of the other ($F_{1,32}$= 61.36 P < 0.0001; Figure Gulley 4). The interaction differed by year (fallowing*Plateau*year $F_{2,112}$= 12.54 P < 0.0001). In 2013, the trend for the direction of the Plateau effect in the presence of fallowing was opposite that of prior years (compare the last set of bars in Figure Gulley 4 to the first set). Though the means were not significantly different, in 2013 plots with both herbicides had a trend for higher annual grass cover than those with either herbicide alone.

Fallowing increased annual forbs ($F_{1,16}$ = 196.26, P < 0.0001) and the effect grew greater with time (fallowing*year: $F_{2, 112}$ = 83.31, P < 0.0001; Figure Gulley 2e). Plateau reduced annual forbs ($F_{1,32}$= 74.29 P < 0.0001), although the effect was constrained to certain combinations of year, site, and fallowing treatment (Plateau*year: $F_{2, 112}$ = 6.72, P = 0.0016; fallowing*Plateau*year $F_{2,112}$= 12.54; site*fallowing*Plateau*year: $F_{5, 112}$ = 6.72, P = 0.0016). In 2011, Plateau reduced annual forbs at all 4 sites (p < 0.0483) and both in the presence and absence of fallowing (p < 0.0001) from a mean of 37.2 ± 3.6% to 10.3 ± 1.7%. In 2012 and 2013, site*Plateau*fallowing interactions occurred which had higher F-values than the corresponding Plateau*fallowing interaction. At RYG, Plateau continued to reduce annual forb cover in 2012 and 2013 in fallow plots (p < 0.0045) from 39.4 ± 8.7% to 15.8 ± 5.0%, but had no detectible effect in no-fallow plots (p > 0.1635). At SKH in 2012, a similar pattern to RYG occurred: Plateau reduced annual forb cover in fallow plots from 30.6 ± 1.7% to 10.9 ± 2.5% (p = 0.0002) but had no detectible effect in no-fallow plots. At the Yellow Creek sites, cases occurred where Plateau increased annual forb cover: in fallow plots at YC1 in 2012 and 2013 (from 38.9 ± 9.0% to 50.7 ± 8.5% , p < 0.0037), and in no-fallow plots at YC2 in 2012 (from 0.2 ± 0.2% to 2.6 ± 0.7%, p = 0.0099).

Barriers reduced annual forb cover from 24.0 ± 27.4% to 19.3 ± 23.4% ($F_{1, 16}$ = 6.83, P = 0.0188) but the effect was constrained to certain combinations of site, Plateau and Fallow treatments (site*Plateau*fallow*barrier: $F_{3, 32}$ = 5.95, P = 0.0024). Barriers significantly reduced annual forb cover in Plateau, fallow plots at YC1; no plateau, fallow plots at YC1, no Plateau, fallow plots at YC2, and no Plateau, no fallow plots at YC2 (p < 0.0489). Russian thistle was the dominant annual forb in all of the combinations in which barriers had a significant effect on annual forbs.

Discussion

The fallow treatment greatly reduced perennial grasses, annual grasses, and shrubs, while increasing perennial forbs and annual forbs. The Plateau treatment slightly decreased perennial grasses and forbs, greatly decreased annual grasses, and annual forbs, and increased shrubs. The Barrier treatment decreased annual forbs in some cases, and increased perennial grasses and forbs.

Neither herbicide produced a desirable long-term outcome, but the chemical fallow with Pendulum herbicide was far more detrimental than the Plateau application. Although the fallow treatment successfully controlled annual grasses, the effects on perennial grasses and shrubs were devastating (Figure Gulley 5). We expected some lag effects because fallowed plots were planted one year after no-fallow plots. However, the degree of difference between fallow and no-fallow plots was much greater than could be accounted for by lag effects. Pendulum herbicide is a meristematic inhibitor, reducing cell division in the growing tips of roots and shoots (BASF 2009). The product label indicates control of a wide variety of grasses and forbs, with effects lasting 4 to 6 months at the application rate tested (BASF 2009). Although we waited 12 months before planting desirable species, it is evident that this herbicide was still active under the tested conditions. While the label indicates that the herbicide may be used for 'site preparation', it seems as though it is not a good choice for a chemical fallow to control cheatgrass due to its lasting effects on desirable species. Interestingly, however, perennial forbs increased in response to the fallow treatment. This was due mainly to the response of Utah sweetvetch, which had four times the cover in fallow plots as in no-fallow plots in 2013, and to Lewis flax, which had 10 time higher cover (in contrast, western yarrow (*Achillea millefolium*) had only one-fifth as much cover in fallow plots). Utah sweetvetch also seemed to tolerate the Plateau application in the Strategy Choice experiment, which had detrimental effects on many other species. It seems likely that the reduced competition from shrubs and grasses allowed the few tolerant perennial forbs to flourish in fallow plots. These plants were sparse, however, and it does not seem that they will prevent long-term dominance by cheatgrass, as cheatgrass cover in fallow plots increased steadily between 2011- 2013 (Figure Gulley 2d).

Plateau controlled annual grasses and annual forbs, and had less dramatic negative consequences on perennial plants than the fallow treatment. In contrast to the fallow treatment, the Plateau treatment increased shrubs, and, similar to some prior studies (Baker et al. 2009, Owen et al. 2011), decreased perennial forbs. The increase in shrubs (mostly big sagebrush) with Plateau was similar to the effect seen in the Pipeline Experiment (Johnston 2015). The combination of Plateau with the fallowing treatment had an interesting effect on annual grasses. By 2013, there was a trend for higher annual grass cover where both herbicides had been applied than where either had been applied singly (Figure Gulley 4, last set of bars). A reasonable hypothesis is that the combination of herbicides so suppressed perennial plants that over the long term, annual grasses were able to dominate in spite of the immediate negative effect of the herbicides on annual grasses. A testable theory resulting from this experiment is that the ultimate effect of herbicides on annual plants is related to their initial effects on perennials.

In contrast to both herbicides, the effects of barriers, while slight, were entirely positive. Perennial grasses and forbs had higher cover in barrier plots, and annual forbs were reduced, at least in some combinations of site, Plateau, and fallow treatments. The barriers seemed to be effective at reducing annual forbs in those cases where Russian thistle was the dominant annual forb. The barriers may have worked well for this species because it is a tumbleweed, with large plant skeletons easily stopped by the barriers. The barriers were not effective on annual grasses, even though we observed many cheatgrass seeds getting stuck in the barriers (Figure Gulley 6) It has long been known that cheatgrass plants compensate well for low density by increasing seed productivity; stands with 50 plants/m^2 can produce as much seed as stands with 2000 plants/m^2 (Hulbert 1955). The barriers tested in this study may simply not have been effective enough to suppress cheatgrass. Wind and cow trampling compromised the barriers at RYG and SKH in 2009, and design modifications improved the barriers over time, as we learned how to prevent weeds from passing beneath the barriers or growing through them. A more effective treatment was identified in the Mountain Top and Strategy Choice Experiments, which used a surface of large mounds and holes. Such holes are known to entrap seeds (Chambers 2000), and it seems reasonable that having an entire surface which impedes seed movement may be more effective than a barrier.

The positive effect of barriers on perennial grass and forb cover may have been related to the reduction in annual forbs, which allowed better establishment because of reduced competition. It is also possible that barriers caused snow drifting and thereby increased soil moisture, or that shading improved plant establishment. In a few plots, plants, especially shrubs, appeared more robust very near barriers, indicating that a moisture and/or shading effect may have occurred. Even so, subplots for cover measurements were located at least 0.5m from the 0.45m-high barriers, and in most cases were more than 1m from barriers. Also, study sites were located in gulley bottoms where snow drifting was not apparent on those occasions were sites were visited in winter.

In summary, this study demonstrated that a chemical fallow with Pendulum herbicide is not an effective means of reducing cheatgrass and promoting perennial plant establishment, that Plateau herbicide may help in shrub establishment but also may harm perennial grasses, and that impeding the dispersal of undesirable annuals through the use of seed dispersal barriers may improve restoration outcome by hindering weedy annual plants.

The Gulley experiment is not planned for long-term monitoring. Barriers were removed in 2015, and the experiment is planned for decommissioning in 2017.

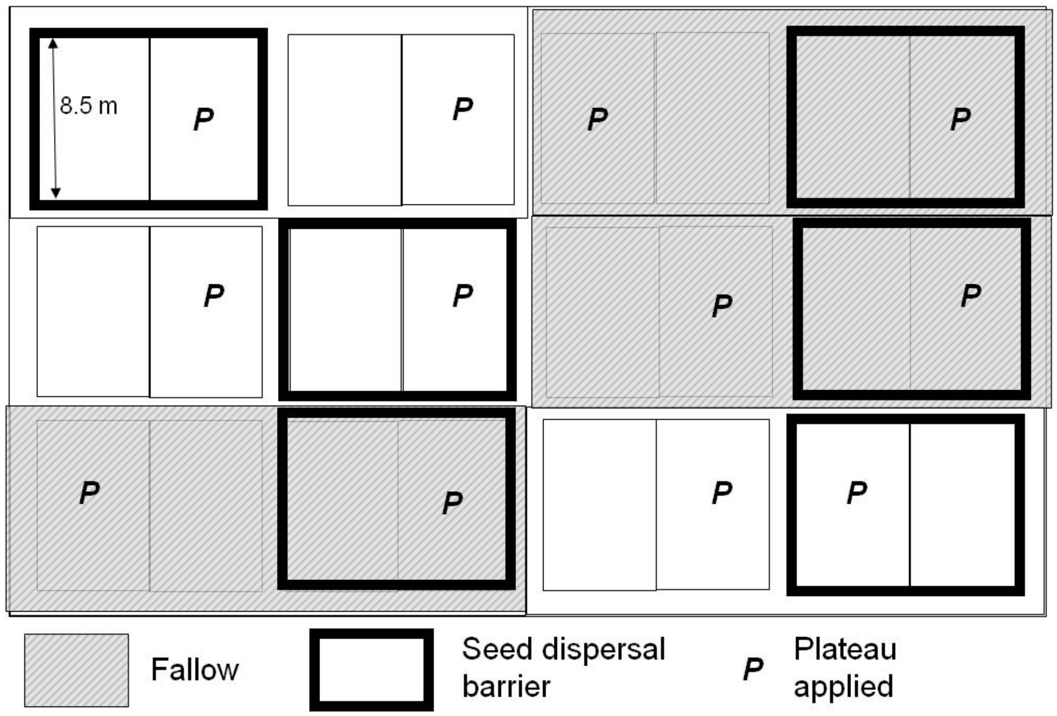


Figure Gulley 1. Layout of the Gulley experiment at one of 4 research sites.

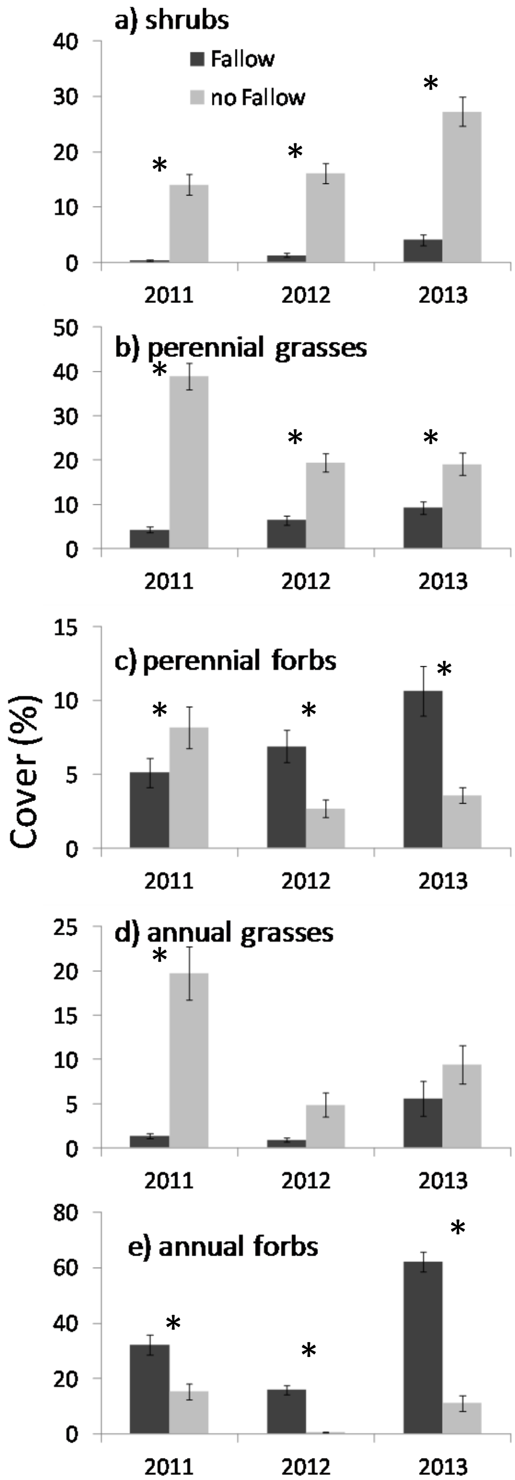


Figure Gulley 2. Percent cover of a) shrubs, b) perennial grasses, c) perennial forbs, d) annual grasses and e) annual forbs for three years (2011- 2013) in response to chemical fallowing with Pendulum™ herbicide applied in 2009. Plots were seeded in 2010 if fallowed and 2009 if not fallowed. Data are averages over 4 sites, a Plateau treatment, and a seed barrier treatment. Error bars = SE. Stars indicate significantly different means at $\alpha = 0.05$.

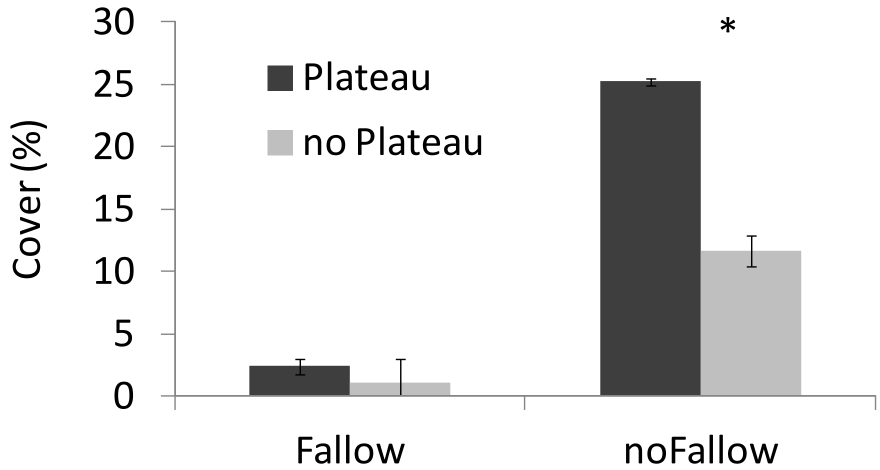


Figure Gulley 3. Shrub cover in response to chemical fallowing with Pendulum™ herbicide (Fallow) and Plateau™ herbicide applied in 2009. Plots were seeded in 2010 if fallowed and 2009 if not fallowed. Data are averaged over three years (2011- 2013), 4 sites, and a seed barrier treatment. Error bars = SE. Star indicates a significantly different mean at α = 0.05.

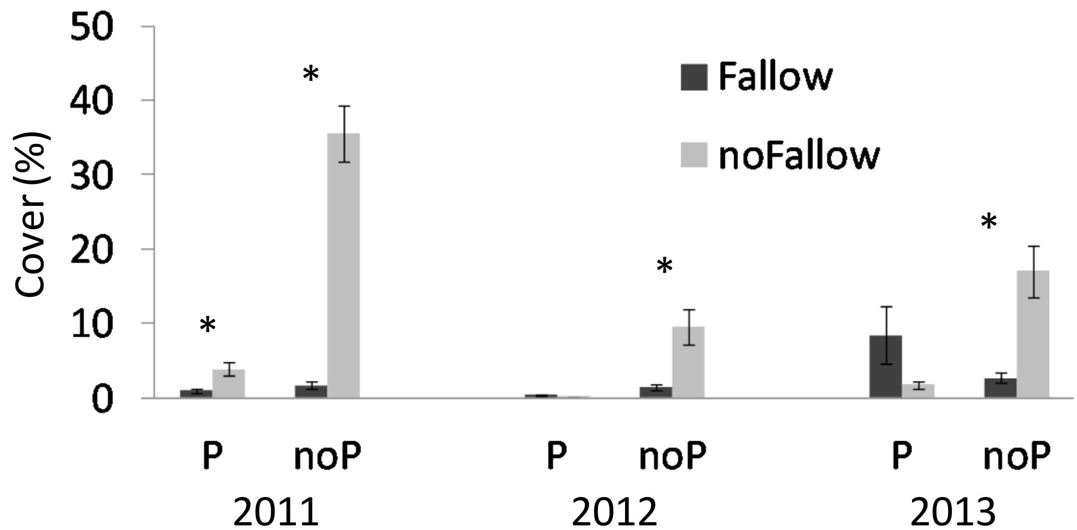


Figure Gulley 4. Annual grass cover (nearly 100% of which was cheatgrass, *Bromus tectorum*) over three years (2011- 2013) in response to chemical fallowing with Pendulum™ herbicide (Fallow) and Plateau™ herbicide (P) applied in 2009. Data are averages over 4 sites, and a seed barrier treatment. Error bars = SE. Stars indicate significantly different means at α = 0.05.

Figure Gulley 5. Overview of the Gulley experiment at the Ryan Gulch site in 2012, three years post-treatment. Plots right of the white line received a chemical fallowing treatment with Pendulum™ herbicide.

Figure Gulley 6. Cheatgrass seeds caught in aluminum windowscreen barrier.

Table Gulley 1. Seed mix used in the Gulley experiment.

Scientific name	Common Name	Variety	Seeds/ m2	PLS (kg/ha)	Seeds/ ft2	PLS (lbs/ac)
forbs						
Achillea millefolium	western yarrow	VNS	183	0.3	17	0.3
Hedysarum boreale	Utah sweetvetch	Timp	22	2.1	2	1.9
Linum lewisii	Lewis flax	Maple Gr.	54	0.8	5	0.7
grasses						
Achnatherum hymenoides	Indian ricegrass	Rimrock	108	3.0	10	2.7
Elymus elymoides	squirreltail	Toe Jam Ck.	108	2.5	10	2.3
Elymus lanceolatus spp. lanceolatus	thickspike wheatgrass	Critana	65	1.9	6	1.7
Elymus trachycaulus spp. trachycaulus	slender wheatgrass	San Luis	65	2.2	6	1.9
Leymus cinereus	basin wild rye	Trailhead	43	1.3	4	1.2
Pascopyrum smithii	western wheatgrass	Rosana	65	2.5	6	2.2
Pleuraphis jamesii	galleta grass	Viva	54	1.6	5	1.4
Poa fendleriana	muttongrass	VNS	323	0.7	30	0.7
Pseudoroegneria spicata spp. spicata	bluebunch wheatgrass	Anatone	108	3.9	10	3.5
shrubs						
Artemisia tridentata spp. Wyomingensis	Wyo. big sagebrush	VNS	250	0.6	23	0.5
Atriplex canescens	fourwing saltbush	VNS	32	3.3	3	3.0
Ericameria nauseosa	rubber rabbitbrush	VNS	22	0.2	2	0.2
Krascheninnikovia lanata	winterfat	VNS	16	0.6	1.5	0.5
		TOTAL	**1514**	**28**	**141**	**25**

MOUNTAIN TOP EXPERIMENT

Overview

- Goal: Identify techniques to maximize plant diversity, shrub establishment, and forb establishment in areas where the threat of weed invasion is low.
- Conducted at four sites: SCD, SPG, TGC and SQS (Figure Intro 1, Table Intro 1)
- Locations had predominately native and desirable surrounding plant communities, and varied in elevation from 2342 m (7681 ft) to 2676m (8777 ft; Table Intro 1).
- Treatments:
  - Seeding (two levels): seeded or unseeded
  - Soil surface (two levels): roughened with holes and mounds (rough) or left flat (flat)
  - Brush mulch (two levels): mulched with brush (brush) or not mulched with brush (no brush)
- Design: Completely randomized factorial (Figure MtnTop1)
- Plot size: 9.1 m X 6 m
- Three replications per site

Methods

Treatments. Treatments were implemented in August and September of 2009. The rough surface treatment was created using a mini excavator to dig holes approximately 100 cm x 60 cm x 50 cm deep. Material removed was mounded next to each hole, and approximately 18 holes were dug per plot. This resulted in approximately 20% of the ground being allocated to holes, 30% to mounded soil, and 50% to interspaces.

Seed (Table MtnTop1) was mixed 1:1 by volume with rice hulls to help ensure even distribution of species in seeded plots. In flat plots, seed was drilled approximately 1 cm deep using a Plotmaster™ 400 with a drill attachment. In rough plots, seed was broadcast and then lightly raked to incorporate the seed into the soil. Seeding rates were the same for both seeding methods.

The brush mulch treatment was achieved by distributing approximately 1.2 m^3 of stockpiled woody debris to each plot receiving the brush treatment. Because some topsoil was mixed with stockpiled brush, and this likely contained viable seed, an effort was made to distribute equal amounts of this topsoil. Approximately four liters of topsoil from brush stockpiles was scattered over each brush plot.

Mountain big sagebrush seed was collected within 10 miles of each study site in November 2009 and broadcast seeded in November and December of 2009 in seeded plots.

Data collection. Percent cover of vegetation was assessed July or early August of 2011- 2014 within experimental plots and 2011-2013 in reference, undisturbed locations adjacent to each site. Within plots, five 1m^2 miniplots were arrayed systematically, with one miniplot located in the center of the plot, and the remaining miniplots equidistant from the center miniplot and a plot corner. A grid containing 36 intersections was held over each miniplot, and point-intercept hits were measured at each grid intersection. Reference plant communities were sampled using 6, 10m long transects arrayed systematically around each site, with 50 point-intercept hits per transect. Hits were measured using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT) and all layers of vegetation were identified to species at each hit. When calculating percent cover of a given functional group, such as perennial grasses, overlapping hits of different species within a functional group (for instance, western wheatgrass overlying Sandberg bluegrass (*Poa secunda*) were counted as a single instance of the functional group.

Data analysis. Repeated measures analysis of variance in SAS PROC MIXED was used to analyze differences in responses to treatments. Site was included as a fixed effect, and the covariance structure was autoregressive with a lag of 1. Cover data was analyzed separately by the following functional groups: shrubs, perennial grasses, perennial forbs, annual grasses, and annual forbs. Biennial forbs were lumped with annual forbs. Insufficient annual grasses grew at the TGC and SQS sites to permit analyses; analysis of annual grasses is restricted to the SPG and SCD sites. Data were transformed to improve normality and residual plots were inspected to ensure adherence to ANOVA assumptions. Tests for significant contrasts of means were calculated using LSMESTIMATE statements in SAS PROC MIXED. Means are presented ± SE.

The order in which I discuss results is guided by the F-values in the ANOVA table (Table MtnTop 2). For all functional groups, seeding treatment and year effects had very large main effect F-values; I discuss these first. For most functional groups, the microtopography treatment had larger F-values than the brush mulch treatment; I discuss the microtopography treatment followed by the brush mulch treatment. For each treatment, I discuss the main effect first if it had larger F-values than interactions. I limit my discussion of site effects to site×treatment (and site×treatment×treatment) interactions which had larger F-values than those of the corresponding treatment (or treatment×treatment interaction). This is to focus the discussion on the pattern of responses to treatments, when sites responded in the same direction but differed in the magnitude of their responses. When site×treatment interactions occurred which had larger F-values than the corresponding treatment, I conducted analyses separately by site.

Results

Reference plant communities. Undisturbed vegetation was dominated by native shrubs and perennial grasses at the 4 research sites (Figure MtnTop 2). Averaged over years, shrub cover varied from 40.8% at TGC to 47.3% at SQS. Mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) was the most dominant shrub, followed by snowberry, serviceberry, and bitterbrush (*Purshia tridentata*). 100% of shrub cover was native. Perennial grass cover varied from 15.3% at SPG to 59.4% at SQS, and dominant species included Sandberg bluegrass, Kentucky bluegrass (*Poa pratensis*), muttongrass (*Poa fendleriana*), and green needlegrass (*Nassella viridula*). 94.4% of perennial grasses were native. Perennial forb cover varied from 5.0% at SCD to 19.1% at TGC. Common species included silvery lupine (*Lupinus argenteus*), sulfur-flower buckwheat (*Eriogonum umbellatum*), white locoweed (*Oxytropis sericea*), American vetch (*Vicia Americana*), and northern bedstraw (*Galium septentrionale*). 98.3% of perennial forbs were native. Annual forbs varied from 0.5% at TGC to 2.9% at SQS. Slender phlox (*Microsteris gracilis*) and stickseed (*Lappula redowskii*) were the most common annual forbs. 76% of annual forbs were native. Annual grasses were not found in reference plant communities. Detailed precipitation data is included in Table MtnTop3.

Shrubs. Shrub cover increased with time ($F_{3,192}$ = 439.10, P < 0.0001), seeding reduced shrub cover ($F_{1,64}$ = 27.35, P < 0.0001), and the effect of seeding grew greater with time (seeding × year: $F_{3,192}$ = 13.85, P < 0.0001; Figure MtnTop3a). In 2011, a significant difference in seeded vs. unseeded plots was not apparent (P = 0.1535), but by 2014, unseeded plots averaged 27.0 ± 2.0% while seeded plots averaged only 16.3 ±1.9% [$t(192)$ = 7.73, P < 0.0001; Figure MtnTop3a]. Big sagebrush was the dominant shrub in both seeded and unseeded plots, followed by yellow rabbitbrush (*Chrysothamnus viscidiflorus*). In unseeded plots, snowberry, rubber rabbitbrush (*Ericameria nauseosus*), and bitterbrush were also prevalent. 100% of shrub cover was native.

For shrubs, there was no main effect or interactions involving microtopography. The brush mulch treatment increased shrub cover ($F_{1,64}$ = 9.11, P = 0.0036) from a mean of 9.5 ± 0.8% to 12.1 ± 0.9%.

Perennial Grasses. Seeding increased perennial grass cover ($F_{1,64}$ = 212.24, P < 0.0001), but the difference between seeded and unseeded plots grew smaller with time (seeding × year: $F_{3,192}$ = 40.45, P < 0.0001). In 2011, seeding increased perennial grass cover from 7.7% to 34.7%, but by 2014, the difference was only 23.5% vs. 32.8% (Figure MtnTop 3b). Mountain brome (*Bromus marginatus*) was dominant in seeded plots, accounting for 50.1% of all grass cover. Bluebunch wheatgrass and slender wheatgrass (*Elymus trachycaulus*) were also common in seeded plots. In unseeded plots, the most common grass was needle-and-thread (26.2% of all grass cover), followed by mountain brome and Sandberg bluegrass. 99.7% of perennial grass cover was native in seeded plots, and 96.8% was native in unseeded plots.

Microtopography had differing effects on perennial grasses depending on site (site × topo: $F_{3,64}$ = 4.95, P = 0.0038). Perennial grass cover was higher with the flat surface at SCD [t(64) = 2.01, P = 0.0482] , but higher with the rough surface at SQS [t(64) = 2.45, P = 0.0170]. At TGC there was a trend for higher grass cover with the rough surface [t(64) = 1.80, P = 0.0766], while at SPG there was no significant effect.

Perennial grass cover increased from a mean of 23.5 ± 1.1% to 26.2 ± 1.0% with the brush mulch treatment ($F_{1,64}$ = 4.79, P = 0.0323).

Perennial forbs. Perennial forb cover increased with seeding ($F_{1,64}$ = 80.43, P < 0.0001), and the effect of seeding grew greater with time (seeding × year: $F_{3,192}$ = 7.20, P = 0.0001; Figure MtnTop 3c). In 2011, seeding increased perennial forb cover from 5.4 ± 0.1% to 9.0 ± 1.0%, and by 2014, this difference had grown to 6.7 ± 0.9% vs. 18.1 ± 1.4% (Figure MtnTop 3c). In seeded plots, Rocky Mountain penstemon (*Penstemon strictus*; 42.2% of all perennial forb cover) and western yarrow (*Achillea millefolium*; 23.9%) were dominant, followed by white locoweed, Utah sweetvetch, and Palmer's penstemon (*Penstemon palmeri*). In unseeded plots, the most common species was *O. sericea* (38.3% of perennial forb cover), followed by silvery lupine and Rocky Mountain penstemon. 99.6% of perennial forbs were native in seeded plots, and 96.3% were native in unseeded plots.

For perennial forbs, microtopography had different effects depending on site (site × topo: $F_{3,64}$ = 8.48, P < 0.0001) and on seeding (topo × seeding: $F_{1,64}$ = 11.04, P = 0.0015). At SCD, the effect of microtopography depended on seeding treatment (seeding × topo: $F_{1,16}$ = 6.64, P = 0.0202). In seeded plots, forb cover was more than 2-fold higher with the rough surface, while in unseeded plots, there was no effect of microtopography (Figure MtnTop 4). At SPG, the rough surface increased forb cover from 13.9 ± 4.0% to 19.2 ± 4.4%. At TGC, the effect of microtopography depended on seeding treatment (seeding × topo: $F_{1,16}$ = 6.18, P = 0.0243). In seeded plots, there was no effect of microtopography, while in unseeded plots, forb cover was higher with the flat surface (Figure MtnTop 4).

The effect of the brush mulch treatment on perennial forbs depended on a three way interaction with site and seeding (site × seeding × litter: $F_{3,64}$ = 2.74, P = 0.0503). At SCD, brush mulch increased year-averaged forb cover from 6.0 ± 0.8 % to 10.4 ± 1.4% ($F_{1,16}$ = 6.74, P = 0.0197). At SPG, TGC, and SQS brush mulch had no detected effect. The two-way interaction between brush mulch and seeding was not significant at any site.

Annual grasses. Seeding reduced annual grass cover at the two sites where annual grasses established in sufficient density to permit analysis ($F_{1,32}$ = 18.38, P = 0.0002). The effect of seeding grew greater with time (seeding × year: $F_{3,96}$ = 23.54, P < 0.0001; Figure MtnTop 3d). In 2011, a significant difference in seeded vs. unseeded plots was not apparent (p = 0.1226), but by 2014, unseeded plots averaged 10.4 ± 1.2 % annual grass cover, while seeded plots averaged only 2.2 ± 0.4% [$t(128)$ = 8.51, P < 0.0001; Figure MtnTop 3d].

The effect of microtopography on annual grasses depended on 3-way interactions with site and seeding (site × topo × seeding : $F_{1,32}$ = 6.12, P = 0.0189) as well as with site and year (site × topo × year : $F_{3,96}$ = 6.07, P = 0.0008). At SCD, there was no detected effect of microtopography in the presence of seeding, either overall or within any specific year (P > 0.7087. In unseeded plots, annual grass cover was lower with the rough soil surface ($F_{1,16}$ = 10.42, P = 0.0053), and this effect grew greater with time ($F_{3,48}$ = 6.91, P = 0.0016); Figure MtnTop 5]. In 2011, there was no significant effect detected, but by 2014 flat surface plots averaged 13.0 ± 3.8% annual grass cover, while rough surface plots averaged only 2.5 ± 1.4%. At SPG, there was no detected effect of surface treatment or any interactions involving surface treatment (P > 0.2321).

The brush mulch treatment had no significant main effect, although a 3-way interaction with year and seeding occurred ($F_{3,96}$ = 2.94, P = 0.0372). In unseeded plots in 2014, annual grass cover was 3.1 ± 0.9% with brush mulch, and 2.1 ± 1.3% without brush mulch (averaged over sites). Other combinations of year and seeding treatment were not significant.

The non-native cheatgrass was the only annual grass detected.

Annual forbs. Seeding reduced annual forb cover ($F_{1,64}$ = 317.27, P < 0.0001), annual forb cover declined strongly with time ($F_{3,192}$ = 521.19, P < 0.0001), and the effect of seeding grew smaller with time (seeding × year: $F_{3,192}$ = 6.64, P = 0.0003; Figure MtnTop 3e). In 2011, seeding reduced annual forb cover from 55.6 ± 1.8% to 28.9 ± 2.6%, and by 2014, the difference was 10.4 ± 1.2% vs. 2.2 ± 0.4%. In both seeded and unseeded plots, the native mountain knotweed (*Polygonum douglasii*) was the most common annual forb, followed by the non-native prostrate knotweed (*Polygonum aviculare*). 58.6% of annual forbs were native in seeded plots, and 42.0% of annual forbs were native in unseeded plots.

For annual forbs, the effect of microtopography depended on seeding (topo × seeding: $F_{1,64}$ = 4.85, P = 0.0313). In seeded plots, there was a trend for slightly higher annual forb cover with the flat surface, while in unseeded plots, there was a trend for lower annual forb cover with the flat surface.

The brush mulch treatment reduced annual forb cover from 20.3 ± 1.5% to 17.4 ± 1.4% ($F_{1,64}$ = 10.04, P = 0.0023). The effect of brush mulch on annual forbs was modified by a 2-way interaction with site (site × litter: $F_{3,64}$ = 3.20, P = 0.0292), a 3-way interaction with site and year (site × year× litter: $F_{9,192}$ = 3.56, P = 0.0004), and a 4-way interaction (site × seeding × topo × litter: $F_{3,64}$ = 3.03, P = 0.0355). Litter had a pronounced effect at reducing annual forb cover at SQS in 2013 and 2014, and at SCD in 2014 (P < 0.006). At SPG in 2014, an opposite effect occurred: annual forb cover 9.5% ± 3.2% with brush mulch, and 3.5% ± 1.2% without brush mulch (P = 0.0135). The 4-way interaction may have been driven by unseeded, rough surface plots at SPG, and seeded, rough surface plots at TGC , where annual forb cover was higher with brush mulch (P < 0.0324). In the other 14 combinations of seeding, surface, and site, the brush mulch treatment either had a negative effect on annual forb cover, or was neutral with respect to annual forb cover.

Discussion

Mountain big sagebrush communities were resilient to disturbance in the study area, but the recovery time of the shrub community, the vulnerability of the community to invasion by cheatgrass, and the species composition of perennial grasses and forbs were heavily influenced by seeding, microtopography, and brush mulch replacement.

Shrubs recovered most quickly in unseeded plots which included brush mulch. After six years, shrub cover in these plots averaged 31.0 % , which neared the average of the reference plant communities, which was 44.1%. In seeded, no-litter plots, shrub cover after six years averaged only 15.6 %. . The effect of seeding at limiting shrub dominance grew greater with time. It has long been known that seeding non-native grasses limits shrub establishment (Redente et al. 1984). Our study concurs with recent research which indicates that seeding native grasses may limit shrub establishment as well (Porensky et al. 2014). Big sagebrush was the most dominant shrub in our study plots, comprising 94% of all shrub cover. The small size of big sagebrush seeds relative to those of perennial grasses may limit their competitive abilities. Brush mulch may have improved big sagebrush establishment by creating favorable microsites for germination, increasing availability of symbiotic mycorrhizae, providing a source of locally-adapted seed, or some combination of these factors. By 2014, plots with brush mulch averaged 24.0% shrub cover, while those without it averaged 19.3%. The effect was consistent across sites and across seeded versus unseeded plots. In many areas, shrub establishment, particularly that of big sagebrush, is desired as quickly as possible in order to improve habitat quality for sagebrush-obligate species such as greater sage-grouse. Addition of locally-collected brush mulch to restoration areas may be an effective treatment for promoting rapid recovery of big sagebrush.

Although the seeding treatment limited big sagebrush, it had beneficial effects as well. Perennial grass and perennial forb cover were higher in seeded plots, while annual forb and cheatgrass cover were lower. Perennial grasses in unseeded plots have continued to increase through time, such that the discrepancy between seeded and unseeded plot grass cover may eventually be negligible. However, this is not true for perennial forbs. Western yarrow, Rocky Mountain penstemon, and Palmer's penstemon were the seeded species which accounted for the majority of difference in forb cover between seeded and unseeded plots. Seeding also reduced annual forb cover, an expected response, as annual plants are typically prolific seed producers and tend to dominate whenever competition is lessened. Seeding effectively controlled cheatgrass at the two sites, SCD and SPG, where it became established.

Cheatgrass establishment was not anticipated in this study, due to the high elevations and mesic climates of the study sites. The SCD site is at 7681 ft (2341m), and the SPG site is at 8019 ft (2444 m). Over the past 20-40 years, cheatgrass has expanded to montane as well as warm desert habitats, and this expansion is due to specialist genotypes adapted for these habitats (Merrill et al. 2012). As these genotypes become more dispersed, cheatgrass invasion may become an increasing concern for restoration of high elevation mountain big sagebrush sites. Because of this threat, seed mixes which can prevent cheatgrass establishment while allowing establishment of keystone species such as big sagebrush are needed. In the Strategy Choice Experiment of this study, conducted at sites ranging from 5451 ft (1662m) to 7268 ft (2216m), a seed mix comprised of 10.9 PLS (kg/ha) of forb and shrub seeds with only 1.7 PLS of grass seeds performed as well as a seed mix containing 7.8 PLS of forb and shrub seeds with 9.8 PLS of grass seeds at limiting establishment of cheatgrass and weedy annual forbs (Johnston and Chapman 2014). The high-forb seed mix also promoted higher shrub biomass. While seeding may be necessary to limit invasion of undesirable annuals, seed mixes can be formulated which foster recovery of big sagebrush, provided sufficient resources are spent on forb and shrub seeds.

Rough microtopography is another tool which should be considered for control of cheatgrass during the restoration process. In unseeded plots at SCD, cheatgrass cover was over five-fold lower with rough versus flat microtopography. These results concur with the Strategy Choice Experiment, which found that cheatgrass biomass was 10-fold lower with the rough surface at a site of 7160 ft (2182m), and six-fold lower with the rough surface in Plateau-treated plots at a site of 5154 ft (1662m) (Johnston and Chapman 2014). The reasons why rough microtopography is effective at controlling cheatgrass is not known, but the mechanism likely involves a combination of restricted dispersal and altered competitive environment. Cheatgrass seeds are likely entrapped in large holes, as is the case for many other types of seeds (Chambers 2000). There, they encounter wetter, more stable soil moisture, conditions under which cheatgrass is known to be less competitive (Bradford and Lauenroth 2006, Chambers et al. 2007, Shinneman and Baker 2009). The action of creating the holes likely also buries some cheatgrass seeds too deeply to germinate. Although creating rough microtopography with a backhoe, as was done in this study, is too labor intensive for large scale implementation, a modified disk is under development which creates a similar effect much more cost effectively (Johnston 2014).

Microtopography also had site-specific effects on perennial grasses and forbs. Perennial grass cover was higher with flat microtopography at SCD, but higher with rough microtopography at SQS. Perennial forb cover was higher in most cases with rough microtopography, with the notable exception of unseeded plots at TGC, where forb cover was over two-fold higher in flat surface plots. This may have resulted from imperfect well pad disturbance simulation. The deeply rooted, unseeded species white locoweed Silvery lupine accounted for about 75 percent of 2014 forb cover in unseeded, flat surface plots at TGC. TGC was flatter than other sites, and required very little cut-and-fill to create a level surface during the well pad simulation. The topsoil layer was deep and was not completely disturbed. The year after the disturbance, mature White Locoweed plants were noted at the site. In rough microtopography treatment plots, the action of digging holes and mounding soil disturbed these plants, but in flat surface plots, deeply-rooted forb species appears to have survived treatment implementation.

The Mountain Top experiment contrasts extreme treatments: seeding with a high density of perennial grasses, shrubs, and forbs, versus not seeding at all, in order to gauge the ecological resiliency of higher-elevation sites. The results indicate that although these sites have high resiliency to disturbance, seeding may still be necessary to control undesirable invasive species. However, the seed mix used in this study compromised development of mature big sagebrush. A seed mix with lower grass density would likely be a better choice. Additional treatments which can promote restoration of big sagebrush and other shrubs include using microtopography to aid in cheatgrass control, and applying locally-collected brush mulch to restoration areas. Reference plant communities were dominated by shrubs and grasses. Recreating this type of plant community following a disturbance is possible with a careful choice of seeding and soil preparation techniques.

Figures

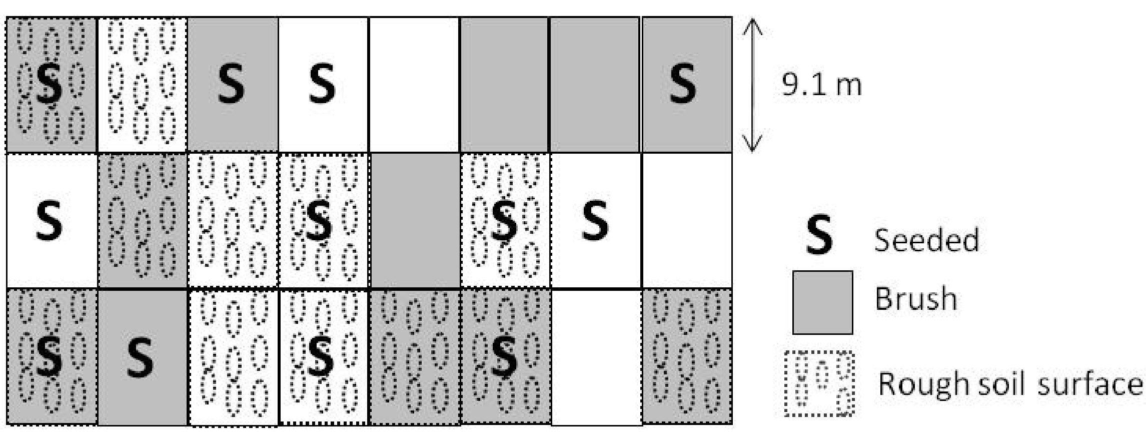


Figure MtnTop 1. Layout of the Mountain Top experiment at one of 4 research sites.

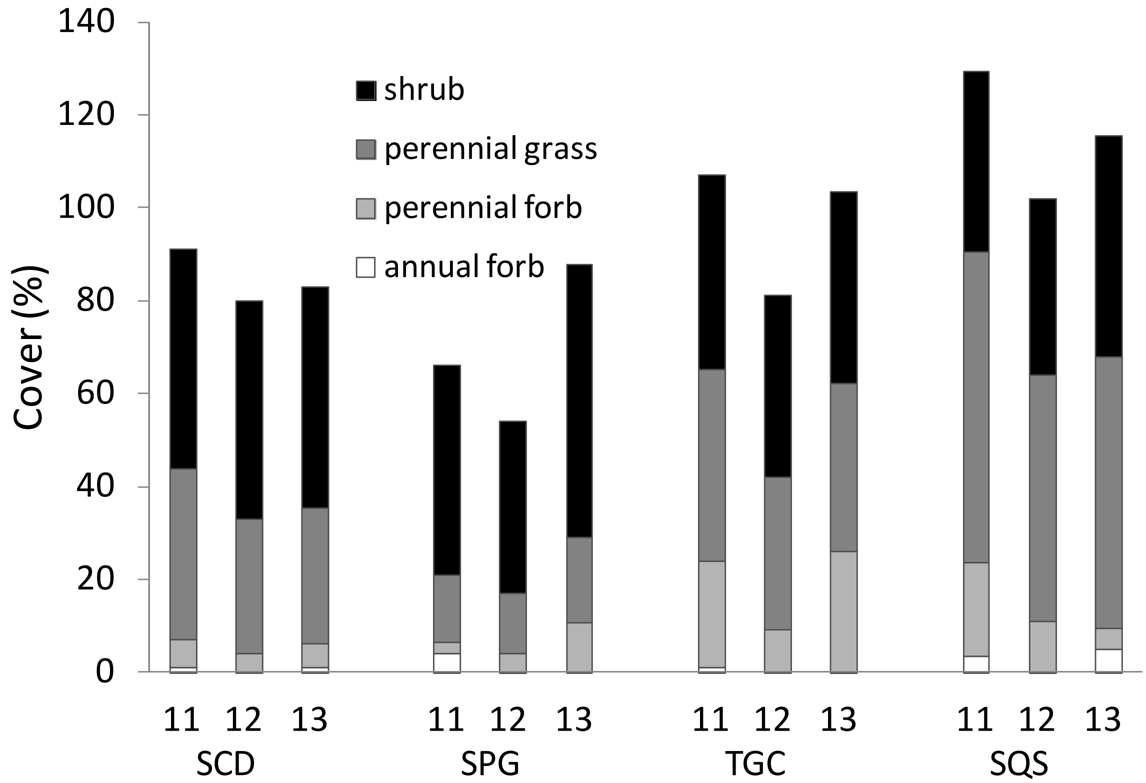


Figure MtnTop 2. Percent cover through time (2011-2013) for undisturbed, reference transects surrounding each of four study sites: Scandard Ridge (SCD), Sprague Gulch (SPG), The Girls' Claims (TGC), and Square S (SQS). Cover values can exceed 100% due to overlap of functional groups.

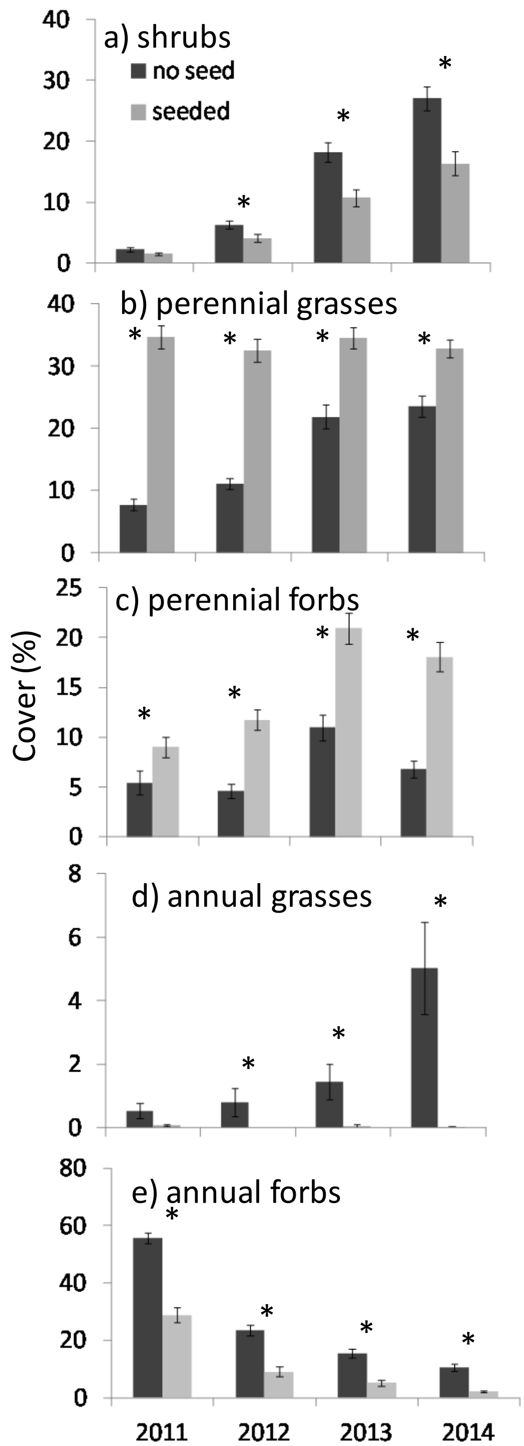


Figure MtnTop 3. Percent cover of five functional groups: (a) shrubs, (b) perennial grasses, (c) perennial forbs, (d) annual grasses, and (e) annual forbs, in response to seeding 2 to 5 years post-treatment. Error bars are standard errors. Stars denote significant differences at $\alpha = 0.05$.

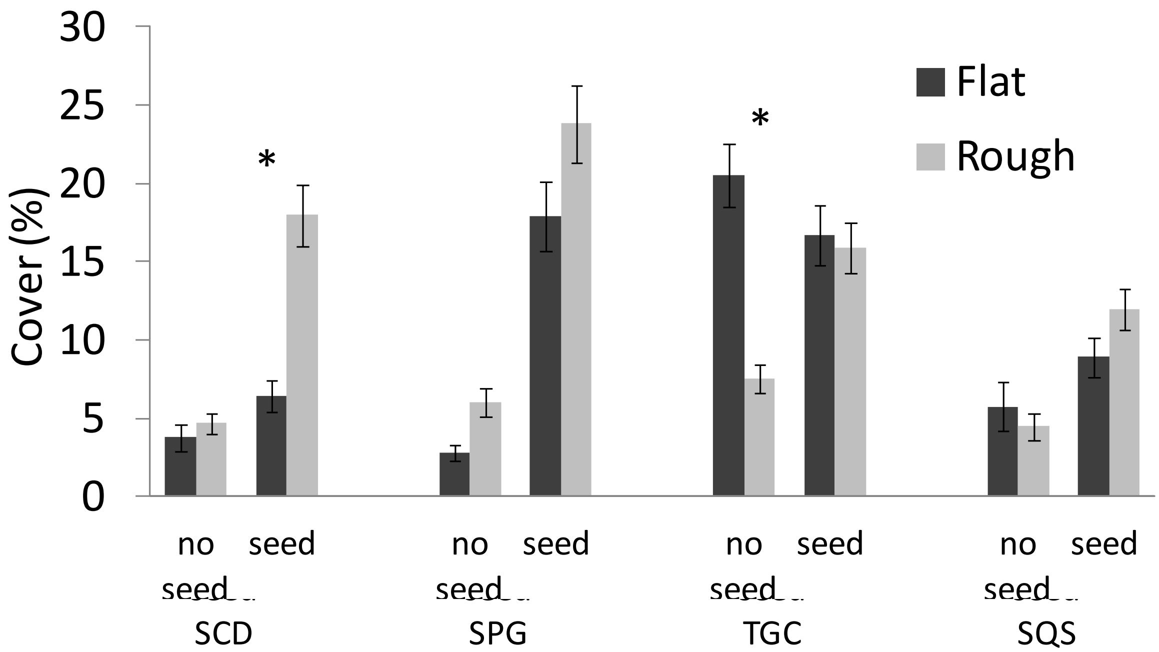


Figure MtnTop 4. Percent cover of perennial forbs in response to seeding and microtopography treatments at four study sites: Scandard Ridge (SCD), Sprague Gulch (SPG), The Girls' Claims (TGC) and Square S (SQS). Error bars are standard errors of means taken over 4 years (2011-2014), one other treatment (brush mulch replacement), and 3 replications. Stars denote significant differences at $\alpha = 0.05$.

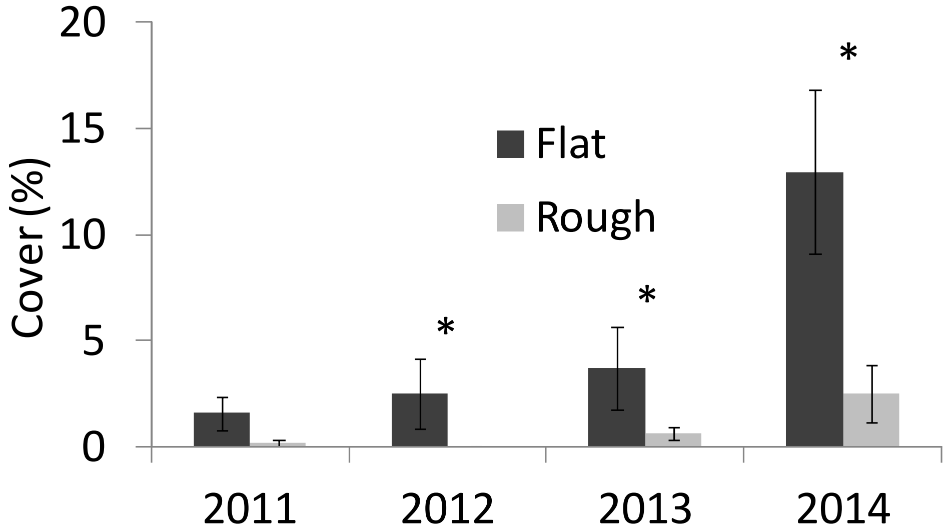


Figure MtnTop 5. Percent cover of annual grass (cheatgrass) in response to microtopography treatment in unseeded plots at the Scandard Ridge study site 2- 5 years post-treatment. Error bars are standard errors of means taken over the brush mulch treatment and 3 replications. Stars denote significant differences at $\alpha = 0.05$.

Tables

Table MtnTop 1. Seed mix used in seeded plots of the Mountain Top Experiment.

Scientific Name	Common Name	Variety	Seeds/ m^2	PLS (kg/ha)
forbs				
Achillea millefolium	western yarrow	Eagle Mtn.	161	0.3
Hedysarum boreale	Utah sweetvetch	Timp	15	1.5
Penstemon palmeri	palmer penstemon	Cedar	215	1.7
Penstemon strictus	Rocky Mtn. penstemon	Bandera	108	1.7
grasses				
Bromus marginatus	mountain brome	Garnet	54	3.8
Elymus lanceolatus spp. lanceolatus	thickspike wheatgrass	Critana	22	0.6
Elymus trachycaulus spp. trachycaulus	slender wheatgrass	San Luis	65	2.2
Nassella viridula	green needlegrass	Lowdorm	43	1.2
Poa fendleriana	muttongrass	VNS	215	0.5
Pseudoroegneria spicata spp. spicata	bluebunch wheatgrass	Anatone	65	2.3
shrubs				
Artemisia cana	silver sage	VNS	323	1.3
Artemisia tridentata spp. vaseyana	mtn. big sagebrush	VNS	250	0.6
Ericameria nauseosa	rubber rabbitbrush	VNS	22	0.2
		TOTAL	**1556**	**17.8**

Table MtnTop 2. Analysis of variance results examining responses of five functional groups to a factorial experiment crossing seeding (Seed), microtopography (Topo), and brush mulch replacement (Lit) at 4 sites over 4 years (yr), 2011-2014

		shrubs		grasses		forbs		annual forbs		annual grasses	
Factor	df	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Seed	1, 64	27.349	**<0.000**	212.241	**<0.000**	80.434	**<0.000**	317.271	**<0.000**	18.385	**<0.000**
Topo	1, 64	0.737	0.394	0.210	0.648	2.757	0.102	<0.000	0.985	2.188	0.149
Lit	1, 64	9.110	**0.004**	4.787	**0.032**	1.709	0.196	10.041	**0.002**	0.711	0.405
Seed*Topo	1, 64	0.196	0.660	1.826	0.181	11.038	**0.001**	4.846	**0.031**	1.580	0.218
Seed*Lit	1, 64	2.632	0.110	0.304	0.584	0.242	0.624	0.013	0.908	0.629	0.434
Topo*Lit	1, 64	1.008	0.319	2.001	0.162	0.770	0.383	1.861	0.177	0.002	0.964
Seed*Topo*Lit	1, 64	0.120	0.731	1.955	0.167	0.003	0.953	0.536	0.467	0.115	0.737
site	3, 64	37.165	**<0.000**	25.535	**<0.000**	15.158	**<0.000**	63.187	**<0.000**	3.423	0.074
site*Seed	3, 64	2.077	0.112	7.583	**<0.000**	8.765	**<0.000**	16.620	**<0.000**	2.988	0.094
site*Topo	3, 64	0.100	0.960	4.945	**0.004**	8.476	**<0.000**	0.825	0.485	5.529	**0.025**
site*Lit	3, 64	2.263	0.090	1.212	0.312	3.661	**0.017**	3.197	**0.029**	0.249	0.621
site*Seed*Topo	3, 64	1.356	0.264	1.211	0.313	1.800	0.156	2.364	0.079	6.116	**0.019**
site*Seed*Lit	3, 64	0.874	0.460	2.743	**0.050**	1.522	0.217	2.591	0.060	0.302	0.586
site*Topo*Lit	3, 64	0.614	0.608	0.551	0.649	0.594	0.621	0.862	0.466	0.194	0.662
site*Seed*Topo*Lit	3, 64	2.706	0.053	0.402	0.752	0.171	0.916	3.035	**0.035**	0.022	0.884
yr	3, 192	439.104	**<0.000**	42.100	**<0.000**	96.458	**<0.000**	521.190	**<0.000**	22.600	**<0.000**
yr*Seed	3, 192	13.848	**<0.000**	40.446	**<0.000**	7.195	**<0.000**	6.642	**<0.000**	23.545	**<0.000**
yr*Topo	3, 192	1.291	0.279	1.340	0.263	0.532	0.661	0.137	0.938	3.090	**0.031**
yr*Lit	3, 192	2.176	0.092	1.377	0.251	0.696	0.556	0.802	0.494	2.390	0.073
yr*Seed*Topo	3, 192	0.839	0.474	1.726	0.163	0.366	0.777	1.554	0.202	1.734	0.165
yr*Seed*Lit	3, 192	0.754	0.521	0.855	0.465	1.202	0.310	0.229	0.876	2.936	**0.037**
yr*Topo*Lit	3, 192	1.673	0.174	0.860	0.463	2.230	0.086	0.309	0.819	0.764	0.517
yr*Seed*Topo*Lit	3, 192	0.562	0.641	0.280	0.840	0.287	0.834	0.020	0.996	0.771	0.513
site*yr	9, 192	13.168	**<0.000**	5.402	**<0.000**	6.940	**<0.000**	24.280	**<0.000**	2.930	**0.038**
site*yr*Seed	9, 192	1.589	0.121	3.640	**<0.000**	2.599	**0.008**	3.464	**0.001**	2.440	0.069
site*yr*Topo	9, 192	0.997	0.444	1.369	0.205	1.214	0.289	0.743	0.669	6.070	**0.001**
site*yr*Lit	9, 192	1.377	0.201	0.507	0.869	0.763	0.651	3.561	**<0.000**	0.509	0.677
site*yr*Seed*Topo	9, 192	1.053	0.400	0.695	0.713	1.843	0.063	0.894	0.531	2.891	**0.039**
site*yr*Seed*Lit	9, 192	0.761	0.653	1.090	0.372	1.601	0.117	0.584	0.809	0.173	0.914
site*yr*Topo*Lit	9, 192	0.602	0.795	1.169	0.317	0.689	0.718	0.871	0.552	2.346	0.078
site*yr*Seed*Topo*Lit	9, 192	0.750	0.663	1.374	0.202	0.630	0.770	1.189	0.304	1.196	0.316

Table MtnTop 3. Precipitation information recorded using RG3-M data logging rain gauges (Onset® Computer Corporation, Bourne, MA, USA) installed on guyed posts at each site: Scandard ridge (SCD), Sprague gulch (SPG), Square S (SQS), and The Girls' Claims (TGC). Summer data is June - August, fall data is September - November, and winter/spring data is December - May.

		Precipitation (mm)			
	season	***SCD***	***SPG***	***SQS***	***TGC***
2010	*summer*	.	134.6	.	.
	fall	.	57.6	57.4	.
2011	*winter/spring*	.	170.4	154.4	.
	summer	103	101.4	133.8	85.2
	fall	82.8	77.8	86.4	85.4
2012	*winter/spring*	41.2	41	.	51.8
	summer	87.4	105.8	.	81.4
	fall	52.4	52.6	52.8	52.4
2013	*winter/spring*	90.4	101.2	68.2	.
	summer	78.2	86.2	76	.
	fall	160	180.4	134	.
2014	*winter/spring*	72.4	84.2	72.8	.
	summer	.	138.8	143	.
	fall	.	94.8	144.2	.

STRATEGY CHOICE EXPERIMENT

Overview

- Goal: compare two mutually exclusive reclamation strategies (one which maximizes plant diversity and one which minimizes weed invasion) in situations where the threat of weed invasion is ambiguous.
- Conducted at four sites: WRR, SGE, GVM, MTN (Figure Intro 1, Table Intro 1)
- Treatments include:
  - Seed mix (two levels): seeded with a balanced seed mix (called ‘high competition’ or ‘HC’ in prior reports) or a high-forb seed mix (called ‘low competition’ or ‘LC’ in prior reports)
  - Soil surface/mulch type (two levels): flat with straw mulch (flat/straw) or rough surface with brush mulch (rough/brush)
  - Herbicide (two levels): Plateau applied (Plateau) or no Plateau applied (no Plateau)
- Completely randomized factorial
- Plot size: 9 m x 6 m
- Three replications per site
- The four locations had 0-15% non-native cover prior to the start of the experiment

Publication. For complete results and discussion of the initial phase (through 2012) of this experiment, please see:

> Johnston, D. B. and P. L. Chapman (2014). "Rough surface and high-forb seed mix promote ecological restoration of simulated well pads." *Invasive Plant Science and Management* **7**: 408-424.
>
> *Available at*: http://www.bioone.org/doi/pdf/10.1614/IPSM-D-13-00087.1

Key results. Restoring cheatgrass-invaded ecosystems is difficult because many effective cheatgrass control measures, such as seeding competitive grasses or applying herbicides, impair the growth of desirable forbs and shrubs. The goal of the Strategy Choice Experiment was to address optimal weed control strategies in middle-elevation zones where the threat of cheatgrass invasion is moderate or unclear. Three treatments were implemented: 1) a rough soil surface, comprised of pothole-sized holes and mounds with brush mulch vs. a flat soil surface with straw mulch, 2) a high-forb seed mix, containing nearly 75% forbs by seed number, vs. a mix containing roughly equal numbers of forb, grass, and shrub seeds, and 3) Plateau herbicide at 8 oz/ ac (140 g ai ha^{-1}) vs. no herbicide. The premise of the experiment was that there is a tradeoff between security against weeds and maximizing plant diversity. In actuality, only one of the three treatments, the herbicide application, exhibited such a tradeoff. The soil surface treatment had surprising benefits applicable to areas of both high and low weed threat, and the seed mix treatment demonstrated that seed mixes dominated by forbs can control weeds as well as traditional grass-dominated seed mixes at a variety of sites.

The soil surface treatment compared traditional drill-seeding and straw-mulching over a flat soil surface versus a rough soil surface. The rough surface had holes approximately 130 cm by 80 cm by 50 cm deep. Material removed from holes was mounded next to each hole, plots were broadcast-seeded, and sagebrush skeletons were used as brush mulch. The treatment was created to provide heterogeneity in the hopes that slower-growing functional groups valuable to wildlife, forbs and shrubs, could find microsites and establish more readily. However, we found no consistent or large influence of soil surface type on cover of shrubs, forbs, or grasses. Unexpectedly, we found that the rough soil surface prevented dominance by cheatgrass at the two sites where cheatgrass became a problem. At GVM, a site with preexisting cheatgrass, the rough/brush treatment augmented the effectiveness of Plateau, reducing cheatgrass biomass six-fold. At MTN, a site previously uninvaded by cheatgrass, the rough/brush surface reduced cheatgrass biomass 10-fold in the absence of Plateau, and also reduced weedy annual forbs 100- fold in the presence of Plateau. We hypothesize that the rough surface makes cheatgrass less competitive because cheatgrass seeds get trapped in the holes, limiting their spatial distribution, and forcing them to compete in a wetter environment, where cheatgrass is typically less competitive.

A key difference between the mixes is in the number and type of grass seeds used. In the balanced mix, 344 grass seeds/m^2 (32 seeds/ft^2) were used, and these were mostly rhizomatous wheatgrasses. In the high-forb mix, 156 grass seeds/m^2 (15 seeds/ft^2) were used, and these were mostly bunchgrasses. The high-forb mix had nearly 75% forb seeds. The high-forb seed mix resulted in higher forb and shrub establishment, and lower grass establishment, than the balanced mix. There was no difference in cheatgrass or weedy annual forbs due to seed mix, and the high forb and shrub cover produced by the high-forb mix is beneficial for habitat restoration. Seeding mostly forbs and shrubs at a high rate, 1600 seeds m^{-2}, should be considered in areas where erosion is not a concern.

Plateau plots were sprayed with 140 g ai/ha of Plateau (8 oz /ac) The Plateau treatment did control cheatgrass, but it also had a negative impact on grasses, forbs, and shrubs. The lack of perennial plant establishment led to higher annual forb cover in Plateau plots three years post-treatment. Extending the plant-back interval, applying at a lower rate, and restricting application to areas with cheatgrass presence prior to disturbance are recommended.

Percent cover data was collected in 2014, and the next data collection year is planned for 2017.

CONCLUSION

Restoring fully functional wildlife habitat following oil and gas disturbances is possible in northwest Colorado, and in the case of degraded habitat, improvements should be the goal. Promising ideas include timing disturbances to maximize weed seed burial, judicious use of Plateau herbicide, seeding over a roughened surface of large holes, utilizing obstructions to prevent weed seed dispersal, and using a seed mix focused on perennial forbs and shrubs. With the exception of Plateau, which should be used only lightly in areas where cheatgrass is already a problem, these treatments may aid restoration over a wide range of ecological conditions. Two treatments which warrant further study are the use of a soil binding agent which increases water infiltration (DirtGlue®), and treating soil with granulated super-absorbent polymer, which increases water retention. An idea which is not promising is increasing soil density to hinder cheatgrass. Many of the promising treatments involve considering or influencing cheatgrass propagule pressure.

We found that cheatgrass propagule pressure peaks in late June and continues until mid-September (Figure Appendix 1_2). At the weediest site measured, cheatgrass propagule pressure peaked at 160 seeds/m^2 per day. For comparison, 40 cheatgrass seeds/m^2 is enough to hinder the growth of crested wheatgrass (*Agropyron cristatum*; (Evans 1961)). Many times more cheatgrass seed may arrive *in a single day* than is acceptable for establishing native plants on restoration sites. Furthermore, cheatgrass seeds can travel far when there are no ground obstructions to stop them, hopping along in the direction of prevailing winds for up to 20m (65ft.)(Johnston 2011). To restore small or linear disturbances such as well pads or pipelines, one must consider not only the weeds in the seed bank, but dispersal of weeds from the edge of the disturbance (Johnston 2011). Given the timing of cheatgrass propagule pressure, the worst scenario is if a disturbance occurs in spring, is left bare over the summer, and then is seeded in the fall. On the other hand, a fall disturbance which is planted immediately provides little opportunity for cheatgrass seeds to arrive before seeded species germinate. Because cheatgrass seeds are sensitive to burial (Wicks 1997), a fall disturbance may partially control cheatgrass in invaded areas. This was the case in the Pipeline experiment, where cheatgrass density was five times lower in the disturbed area than in the adjacent undisturbed area the spring following disturbance.

The disturbance combined with Plateau herbicide provided enough cheatgrass control to keep cheatgrass densities low throughout the first growing season, allowing establishment of sagebrush. Three years post-disturbance, sagebrush cover was 8 times higher and cheatgrass cover two times lower where Plateau had been applied. Controlling cheatgrass may require simultaneous complimentary methods (Davies and Sheley 2011, Johnston 2015). Cheatgrass is not only a high seed producer, but it is capable of bouncing back from 97% reduction in as little as two years (Humphrey and Schupp 2001). A few sparse cheatgrass plants can be especially productive, equaling the seed production of much denser stands (Hulbert 1955). Many studies have found that a single application of Plateau may not provide enough cheatgrass control to establish native plants (Morris et al. 2009, Elseroad and Rudd 2011, Owen et al. 2011, Munson et al. 2015). Increasing the application rate provides better control, but injury to desirable plants may become unacceptable (Baker et al. 2009, Morris et al. 2009, Munson et al. 2015).

This report details three experiments were Plateau was applied. Results were positive in the Pipeline experiment where Plateau was applied at 6 oz/ac (105 g ai/ha), and less desirable in the Gulley and Strategy Choice Experiments, were Plateau was applied at 8 oz/ac (140 g ai/ha). Plateau injured perennial grasses and forbs in both the Gulley and Strategy Choice Experiments. In the Gulley experiment, where Plateau was tested in combination with pendamethilin, the combined effect of both herbicides was so detrimental to perennial species that by three years post treatment, a trend for higher cheatgrass cover occurred where both had been applied, even though both herbicides were very effectively controlled cheatgrass in the initial years of the experiment. Where only Plateau was applied, shrubs benefitted in a similar manner to that seen in the Pipeline Experiment. In the Strategy Choice experiment, detrimental effects of Plateau were worse at the MTN site, which lacked cheatgrass prior to disturbance, than at the GVM site, which was much weedier. At GVM as well as at the Gulley Experiment sites, cheatgrass was a major component of the plant community prior to disturbance, and the positive effects of cheatgrass control may have counteracted the direct negative effect of the herbicide on perennials. Recommendations for using Plateau include: restrict application to weedy sites, use a rate no higher than 6 oz./ac, wait three months or more after seeding before applying herbicide (Sbatella et al. 2011), and couple the herbicide with a complimentary strategy for reducing cheatgrass.

One such complimentary strategy is seeding over a rough soil surface of large mounds and holes. We examined this technique in two experiments which included a total of four sites where cheatgrass was evident or became evident following the disturbance. Cheatgrass was reduced six- to 10-fold at three of these sites (with the remaining site having very light and patchy cheatgrass cover). The success of the rough surface treatment probably includes a combination of altered seed dispersal and altered competitive dynamics. In a study of many kinds of seeds, Chambers (2000) found that large holes capture seeds effectively (Chambers 2000). Cheatgrass seeds trapped in the bottom of holes encounter more stable soil moisture, and cheatgrass is known to compete less effectively when soil moisture is higher and less variable (Chambers et al. 2007). The effect of the rough soil surface on cheatgrass dispersal at a larger scale is probably also important. If seeds are dispersing from the perimeter of the treatment area or from a few surviving cheatgrass plants within it, the holes may entrap seeds near their source. Weedy plants rely on high seed production and rapid dispersal to colonize vulnerable areas. Getting to a good site first is critical; one study found that a native grass could outcompete an invader if given a head start of only three weeks (Firn et al. 2010). Therefore, a landscape which slows seed dispersal even to a small degree may provide a measurable benefit to seeded perennial species.

In the Gulley experiment, we looked explicitly at creating obstructions to seed dispersal, in the form of windowscreen barriers placed around plots. The barriers increased perennial grass and forb cover, and reduced annual forbs in certain combinations of treatments. The instances where the barriers were effective on annual forbs were ones in which Russian thistle was dominant. Although we observed cheatgrass seeds being caught in the barriers, we did not find an effect of barriers on cheatgrass cover, and we also observed cheatgrass seeds passing under the barriers. As a tumbleweed, Russian thistle was probably more easily caught by the barriers than cheatgrass. It seems reasonable that an entire landscape which impedes seed movements, as in the rough surface treatment, is a better choice than a barrier. Even so, we should seek improved barrier designs for applications where a rough surface treatment is not practical, such as in steep or rocky conditions.

For flatter, less rocky areas, we have worked to make the rough soil surface treatment economical. With the help of Rob Raley, Ivan Archer, and Derek Lovoi, we produced a modified disk with a mounted broadcast seeder which would create the rough surface and seed in one pass. In 2012, we treated seven acres of cheatgrass near-monoculture at Horsethief State Wildlife area this way after a 4 oz./ac Plateau application. Now, the area supports diverse native grasses, forbs, and shrubs (Johnston 2014). The first design of this modified disk had structural weaknesses and is no longer functional, and we are in the process of producing a second version. We expect equipment mobilization and per-acre costs of rough surface seeding to be similar to that of drill seeding, and we have found that establishment of forbs, grasses, and shrubs to be similar between the two techniques as well. These results confirm and extend those of Eldridge (2011) who found that a rough soil surface treatment improved the cover of native plants at low elevation sites in the Colorado River Valley (Eldridge et al. 2011).

Two experiments examined the consequences of seed mix choices. In the Strategy Choice experiment, we compared a high-forb seed mix containing only 1.7 PLS kg/ha (1.5 lbs/ac) of grass to a seed mix with fewer forbs and a typical amount of grass (9.8 kg/ha or 8.7 lbs/ac). In the Mountain Top experiment, we compared a typical seed mix to the extreme of not seeding at all. In Strategy Choice, the high-forb mix produced higher forb cover and controlled cheatgrass similarly to the high-grass mix. The unseeded plots in the Mountain Top experiment had more weedy annual forbs than the seeded plots, but annual forbs decreased to 10% cover by five years post-treatment, and shrub cover was nearly double in unseeded plots as in seeded plots. Both studies underscore the costs of seeding too much grass: forb and shrub growth is delayed. Completely eliminating grass from seed mixes is not recommended, as other research has shown that the most effective competitors for invasive species are native species of the same type (Fargione et al. 2003). Results from the Strategy Choice experiment show that to compete with cheatgrass as well as a grass-dominated mix, a diverse seed mix requires only a small amount of grass seed- on the order of 1-2 PLS (lbs/acre). To be most effective, high diversity mixes should be seeded at a high rate (Carter and Blair 2012). We used about 1200 seeds/m^2, which is high in terms of seed density, but reasonable in terms of weight (12.6 kg/ha or 11.2 lbs/ac).

The idea that seed mixes should limit the proportion of rhizomatous grasses in order to promote a mixed plant stand was proposed nearly 30 years ago (Redente et al. 1984). However, most seed mixes continue to be dominated by competitive grasses, probably out of a fear of weed invasion, a lack of availability of appropriate forb seeds, and/or a need for an inexpensive seed mix. This study made use of several forb species provided by the Uncompagre Partnership (UP). Several of these species established well, including local cultivars of many-lobed groundsel, hairy golden aster (*Heterotheca villosa*), sulfur flower buckwheat, bluestem penstemon (*Penstemon cyanocaulis*), and western yarrow. We applaud the efforts of the UP to make more forb species economically practical.

Three studies attempted to manipulate soil density and/or soil moisture in ways that might favor native species over cheatgrass: the Pipeline, Competition, and Competition2 studies. Manipulations of soil density, attempted in Pipeline and Competition, were not successful, and sometimes harmed perennial plants. Manipulations of water infiltration and water holding capacity, attempted in Competition and Competition2 experiments, had mixed results. In the Competition Experiment, we found that a soil binding agent designed to increase water infiltration, DirtGlue, did indeed increase soil moisture. It also reduced cheatgrass cover at one of two sites. While DirtGlue is a promising treatment, a large volume of liquid is needed to administer the product- 21000 li/ha (3200 gal/ac), limiting its potential applications. The Competition and Competition2 experiments tested use of granulated super-absorbent polymer (SAP), which increases soil moisture retention. In the Competition Experiment, SAP dramatically reduced cheatgrass cover and biomass at one of two sites, but in Competition 2, administered at the same two sites as the Competition Experiment, SAP increased cheatgrass cover at one of two sites.

Research tells us that the best competitors for a particular invasive have traits similar to the invasive: the competitor should belong to the same functional group, have similar root morphology, and have similar timing of germination and flowering to the invasive (Fargione et al. 2003, Brown and Rice 2010). This can make finding abiotic manipulations that will favor natives over invasives tricky (Hulvey and Aigner 2014). The inconsistent results we found with abiotic manipulations in the Pipeline, Competition, and Competition2 Experiments support this argument. In contrast, the manipulations in the Strategy Choice, Mountain top, Gulley, and Pipeline Experiments which affected seed dispersal or seed propagule pressure were very successful. Differential reliance on seed production may be the most easily exploitable trait for favoring desirable plants over weeds.

In summary, excellent restoration of wildlife habitat following oil and gas disturbances is possible over a wide range of elevations in northwestern Colorado. Where cheatgrass is a problem prior to disturbance, using a light application of Plateau several months prior to planting, taking measures to reduce dispersal of cheatgrass from the borders of the disturbance, and burying as many cheatgrass seeds as possible are recommended. Over the entire range of ecological zones in Piceance, cheatgrass invasion appears to be possible following disturbance. However, Plateau use is not recommended where cheatgrass is not evident prior to disturbance, due to potential injury to desirable plants. Instead, making use of a rough soil surface to impede the movements of cheatgrass seeds is recommended. Across elevations, use of a dense, diverse seed mix containing a small proportion of grass seed is recommended.

APPENDIX 1. CHEATGRASS PROPAGULE PRESSURE METHODS

The study sites chosen for these experiments had cheatgrass present in varying quantities. Prior work has shown that the quantity of weed seeds, or "propagule pressure", is important in understanding the outcome of revegetation (Lockwood et al. 2005, DiVittorio et al. 2007). Therefore, cheatgrass propagule pressure is an important covariate for the experiments. We quantified cheatgrass propagule pressure at the 8 sites where cheatgrass was present: SKH, GVM, RYG, YC1, YC2, WRR, SGE, and MTN.

We quantified cheatgrass propagule pressure at each study site using 0.1 m^2 seed rain traps constructed of poster board covered with Tree Tanglefoot (The Tanglefoot Company, Grand Rapids, MI), a sticky resin (Figure A1-1). Eight traps were set in systematically chosen locations in undisturbed vegetation surrounding each site. Cheatgrass seeds were counted and removed from traps a mean of every 12 days from mid-May to late September, 2009- 2011. Tanglefoot was reapplied as necessary to ensure a sticky surface. Total growing season cheatgrass propagule pressure (seeds/m^2) was calculated by summing the seeds on each trap, and then taking an average for the site. The time course of cheatgrass propagule pressure over the course of the season (Figure A1-2) was calculated by finding the average number of seeds caught per Julian date, averaging this data over three years, and then applying a cubic spline smoothing function with an nn value of 15 (Reinsch 1967).

Figure A1-1. A seed trap.

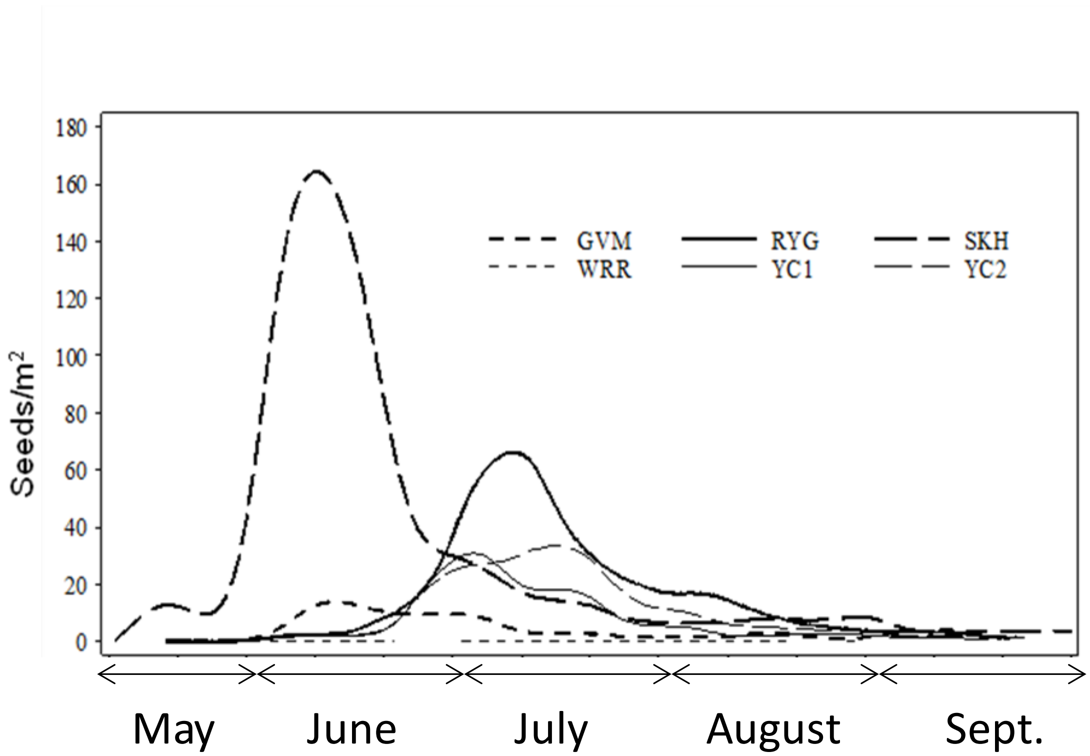


Figure A1-2. Propagule pressure of cheatgrass seeds between May and September in undisturbed locations near 6 sites: GVM, RYG, SKH, WRR, YC1, and YC2, which varied in elevation from 1561-2216 m (5120-7268 ft.) and cheatgrass cover from 70% to 0%. Data are averages over 3 years, 2009-11.

APPENDIX 2. SOIL TEST RESULTS

Soil characteristics were determined by sampling the top 20 cm from eight undisturbed locations within 10 m of each research area in June, 2009. Samples were aggregated for each site and analyzed by the Soil, Water, and Plant testing laboratory at Colorado State University, Fort Collins, CO. Map Units are USDA Natural Resources Conservation Service designations. Abbreviations: EC, electrical conductivity; OM, organic matter; SAR, sodium adsorption ratio.

					ppm						
SITE	**pH**	**EC (mmhos/cm)**	**Lime Estimate**	**OM (%)**	**NO_3-N**	**P**	**K**	**Zn**	**Fe**	**Mn**	**Cu**
GVM	8.1	0.2	Very High	1.8	0.7	1.8	125	0.417	4.58	4.25	4.35
MTN	7.7	0.2	Low	1.3	2.6	2.5	155	0.333	7.76	2.61	2.42
RYG	7.8	0.2	Medium	2.2	4.5	4.9	238	0.469	17.0	4.03	3.66
SCD	7.3	0.2	Low	2.5	3.0	1.8	113	0.390	17.3	2.57	2.29
SGE	7.9	0.3	High	1.4	4.6	1.5	77.1	0.146	4.05	3.56	1.80
SKH	8.3	0.3	Very High	0.9	3.4	3.1	213	0.308	2.68	0.79	3.00
SPG	7.8	0.3	High	2.5	12.0	2.1	79.7	0.340	12.3	0.82	2.87
SQS	6.5	0.2	Low	1.9	11.6	3.4	336	1.280	68.3	1.89	2.23
TGC	7.0	0.1	Low	2.8	6.8	4.6	166	0.618	36.2	0.60	2.04
WRR	7.3	0.3	Low	1.8	2.4	2.8	93.2	0.269	7.27	3.27	2.19
YC1	8.1	0.3	Very High	1.8	5.8	2.5	166	0.699	6.52	3.15	2.61
YC 2	7.8	0.3	Very High	3.2	11.3	6.2	200	0.526	12.8	6.55	3.10

	meq/L					%			
SITE	**Ca**	**Mg**	**Na**	**K**	**SAR**	**Sand**	**Silt**	**Clay**	**Texture**
GVM	2.1	0.5	0.4	0.1	0.3	50	30	20	Loam
MTN	2.1	0.6	0.4	0.1	0.3	52	26	22	Sandy Clay Loam
RYG	2.6	0.3	0.4	0.5	0.3	68	16	16	Sandy Loam
SCD	1.8	0.6	0.3	0.1	0.3	66	14	20	Sandy Loam
SGE	2.8	0.6	0.5	0.2	0.4	60	22	18	Sandy Loam
SKH	1.4	0.2	1.8	0.3	2.0	52	22	26	Sandy Clay Loam
SPG	3.1	0.7	0.4	<0.1	0.3	70	12	18	Sandy Loam
SQS	1.2	0.3	0.3	0.4	0.4	68	20	12	Sandy Loam
TGC	0.5	0.1	0.4	0.1	0.6	72	12	16	Sandy Loam
WRR	3.7	0.8	0.4	<0.1	0.3	56	26	18	Sandy Loam
YC1	1.7	0.1	2.6	0.2	2.8	62	24	14	Sandy Loam
YC 2	3.9	0.5	0.4	0.5	0.3	70	16	14	Sandy Loam

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