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ABSTRACT

Restoring disturbed areas as wildlife habitat requires re-establishing a diverse mixture of perennial grasses, forbs, and shrubs. Achieving this goal in Colorado oil and gas fields is often difficult because of the variety of impacted ecological 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, sage-grouse, and other wildlife. At lower elevations in the Piceance Basin, cheatgrass (*Bromus tectorum*) presents a major obstacle to reclamation. At higher elevations, reclamation is easier to achieve, but we lack reliable methods for restoring broadleaf forbs and shrubs. At middle elevations, the choice between minimizing the threat of weed invasion and maximizing the potential for plant community diversity can be difficult to make. In order to test techniques over their full range of potential usefulness, a series of 5 experiments was implemented in 2008 and 2009 on simulated well pads and pipelines covering the wide range of precipitation, soil development, and plant community types represented in the Piceance Basin gas field.

The Pipeline experiment began in 2008 on simulated pipeline disturbances at 6 lower elevation locations. It compares 2 approaches to controlling cheatgrass and promoting native plants: applying Plateau™ herbicide (ammonium salt of imazapic, BASF corporation, *hereafter* Plateau) at 105 g ai/ha (6 oz/ac) just prior to seeding, and using soil tillage. The tillage treatments examined were disking (D), rolling (R), disking+rolling (DR), and vibratory drum rolling (V). The tillage treatments were of interest because cheatgrass has been shown to be sensitive to seed burial and soil compaction. In 2010, vegetation response was quantified by assessing percent cover. Plateau increased perennial grass cover by 60%, reduced annual cover by 58%, and had no discernable effect on perennial forbs. The effect of Plateau on cheatgrass and other annual species differed by site. The tillage treatments were ineffective. These results differed from those in 2009 seeding density estimates, which showed a reduction in cheatgrass density and increase in perennial density with disking.

The Competition experiment began in 2009 on simulated well pad disturbances at 2 middle elevation sites. The goal of the Competition experiment is to examine novel factors which may affect the competitive ability of native wheatgrasses versus cheatgrass. The density of both wheatgrass and cheatgrass seed was controlled. The treatments were: addition of a super-absorbant polymer called Luquasorb® (BASF Corporation), addition of a soil binding agent called DirtGlue® (DirtGlue® Enterprises), and rolling with a heavy lawn roller. In 2010, vegetation response was quantified by seeding density. At an application rate of 30 g/m^2, super-absorbent polymer addition increased perennial

grass density by 34%. Where soils had been compacted by a static roller, super-absorbent polymer had a greater effect. There was no effect of super-absorbent polymer on cheatgrass density. At 1 of 2 sites, binding agent addition increased cheatgrass density slightly. Rolling without other treatments had no significant main effects.

The Gulley experiment began in 2009 on simulated well pad disturbances at 4 low elevation locations with very weedy surrounding landscapes. 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. 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, *hereafter* Pendulum), and surrounding plots with seed dispersal barriers composed of aluminum window screen secured to oak stakes. In 2009, unfallowed plots were treated with Plateau and seeded, and fallowed plots were treated with Pendulum. In 2010, the experiment was completed by applying Plateau and seed to the fallowed plots.

The Mountain Top experiment began in 2009 at 4 high elevation sites surrounded by desirable mixtures of grasses, forbs, and shrubs. In such situations, the best reclamation outcome would be to re-create the surrounding plant community. The Mountain Top experiment examines the relative importance of creating soil heterogeneity and facilitating seed entrapment versus seeding. The treatments were: creating a rough soil surface of mounds and holes, spreading brush mulch, and seeding with native grasses, forbs, and shrubs in quantities typically used in reclamation areas in the Piceance Basin. Vegetation response was quantified in 2010 by measuring seedling density. The rough soil surface reduced the density of annuals by 18%, and, when combined with seeding, increased the density of perennial grasses by 18% and increased the density of perennial forbs by 160%. Seeding brought about a 10-fold increase in perennial grasses and a 4-fold increase in perennial forbs, but had no effect on the density of annuals. There was no effect of the brush mulch on the density of any plant functional group.

The Strategy Choice experiment was implemented in 2009 on simulated well pad disturbances at 4 middle elevation sites with surrounding plant communities which contained both desirable and undesirable species. At sites such as these, the degree of threat from invasive weeds is often unclear. The Strategy Choice experiment combines some elements of the experiments conducted at lower and higher elevations in order to improve our understanding of the optimal reclamation strategies. The treatments were: Plateau herbicide applied just prior to seeding at 140 g ai/ha (8 oz/ac), a rough soil surface with holes and brush mulch versus a flat soil surface with straw mulch, and a high competition versus a low competition seed mix. In 2010, vegetation response was assessed by seedling density. The Plateau treatment dramatically reduced density of all plant functional groups. The seed mix treatment affected the composition of plants: plots with the low competition seed mix had 58% higher perennial forb density and 49% lower perennial grass density than plots with the high competition seed mix. The soil surface/mulch treatment affected many plant groups. Plots with the rough soil surface/brush mulch treatment had 41% lower density of annual forbs, 48% lower density of perennial forbs, and 21% lower density of perennial grasses than plots with the flat soil surface/straw mulch treatment.

One to 2 years after the initiation of experiments, initial results indicate that the outcome of reclamation for wildlife in certain situations may be improved by applying Plateau herbicide, applying super absorbent polymer, seeding a low competition seed mix, and creating a rough soil surface. Plateau herbicide appears to initially hinder growth of both desirable and undesirable species, but the benefit of reduced competition with annuals allows higher perennial grass cover through time. Application of super absorbent polymer appears to improve the competitive ability of perennial grasses when in competition with cheatgrass. Use of a low competition seed mix resulted in a more favorable composition of forbs versus grasses than did a high competition seed mix, and did not incur a cost in terms of increased density of annuals. Creating a rough soil surface greatly increased the density of perennial forbs at high elevations sites, but at middle elevation sites, where the rough soil surface was compared to a flat surface plus straw mulch, the trend was reversed. At both high and middle elevation sites, the rough soil surface reduced the density of annuals, which is a beneficial result as the majority of annuals in the study area are non-native.

All 5 experiments will continue to be monitored in 2011.

RESTORING ENERGY FIELDS FOR WILDLIFE
Annual Progress Report, January 16, 2010- January 15, 2011
Danielle B. Johnston

PROJECT OBJECTIVES

- Develop reclamation techniques for big sagebrush (*Artemisia tridentata* L.) habitats impacted by oil and gas development in northwestern Colorado. Maximize wildlife habitat quality by promoting native, perennial plant communities containing a mixture of grasses, forbs, and shrubs.
- Determine which weed control techniques are effective in reclamation. Test techniques such as application of a selective herbicide, fallowing with a broad-spectrum herbicide, manipulation of soil density, and creation of barriers to weed seed dispersal. Determine where and how these weed control techniques should be applied.
- Determine which techniques are effective at promoting plant community diversity in reclamation. Test techniques such as use of a low competition/high diversity seed mix, creation of a rough soil surface, and use of brush mulch. Determine where and how these techniques should be applied.

SEGMENT OBJECTIVES

This project consists of 5 separate experiments with different objectives for this reporting year:

- *Pipeline Experiment (formerly called Experiment 1):* Assess vegetation response 2 years following herbicide and tillage treatments by measuring plant cover in 10 plots at each of 6 research sites.
- *Competition Experiment:* Assess vegetation one year following soil additive and compaction treatments by measuring seedling density in 60 plots at each of 2 research sites. Assess soil moisture twice in all plots.
- *Gulley Experiment:* Complete implementation of the experiment by seeding 12 plots at each of 4 sites which had received a chemical fallow treatment in 2009.
- *Mountain Top Experiment:* Assess vegetation one year following seeding, soil surface roughening, and brush mulch treatments by measuring seedling density in 24 plots at each of 4 research sites.
- *Strategy Choice Experiment:* Assess vegetation one year following herbicide, soil surface roughening, and seed mix treatments by measuring seedling density in 12-24 plots at each of 4 research sites.
- *All experiments:* Continue to monitor reference conditions at study sites by:
    - Quantifying propagule pressure of cheatgrass (*Bromus tectorum* L.) seed using 8 seed traps placed in undisturbed vegetation near 8 research sites.
    - Collecting rain and temperature data at research sites.

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 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 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 (Walker et al. 2007) and mule deer (*Odocoileus hemionus*) habitat use (Sawyer et al. 2006) may decline within large buffer areas surrounding development. 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 currently experiencing an unprecedented level of natural gas development, it provides critical habitat for the largest migratory mule deer herd in the United States, and it has a complex topography which ensures that a wide range of precipitation, soil development, and plant community types are represented. Furthermore, the Piceance Basin is at the edge of the eastern expansion of cheatgrass (*Bromus tectorum* L.), allowing an opportunity to assess control measures for this weed in an area where such measures may have the most effect.

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 1561to 2676 m, house 5 experiments, each repeated at 2-6 sites. Each experiment tests 3-6 treatments, some of which are tested in multiple experiments. This 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 3 experiments conducted at lower elevations emphasize weed control, particularly that of cheatgrass, which presents a serious obstacle to effective reclamation in the study area (Pilkington and Redente 2006). The 3 lower elevation experiments are the Pipeline experiment (implemented at 6 sites ranging from 1561 to 2216 m in elevation), the Competition experiment (implemented at 2 sites of elevations 2004 and 2216 m), and the Gulley experiment (implemented at 4 sites ranging from 1561 to 2084 m in elevation). The remaining 2 experiments, conducted at high or middle elevations, emphasized maximizing plant community diversity. The Mountain Top experiment was implemented at the 4 highest elevation sites, ranging from 2342 to 2676 m. The Strategy Choice experiment was implemented at 4 moderate elevation sites ranging from 1662 to 2216 m.

The Pipeline experiment evaluates 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). Soil manipulations may be particularly effective for controlling cheatgrass because 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 include disking, rolling with a static roller, rolling with a vibratory drum roller, or disking plus compaction with a static roller. The herbicide investigated is Plateau ™ (ammonium salt of imazapic, BASF Corporation, Research Triangle Park, NC, *hereafter* Plateau), as it has been shown to reduce cheatgrass with little effect on some perennial grasses (Kyser et al. 2007). However, it also reduces the vigor and density of established forbs (Baker et al. 2007), and little is known about its effect on germination of desirable species.

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® (cross-linked copolymer of Potassium acrylate and acrylic acid in granulated form, 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 claimed 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 which might hinder cheatgrass emergence.

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™ (pendimethalin, BASF Corporation, Research Triangle Park, NC; hereafter *Pendulum*). Pendulum is a broad-spectrum pre-emergent herbicide, is effective for about 6 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 DOW study demonstrated that a sufficient number of cheatgrass seeds may disperse from the surrounding plant community to compromise reclamation efforts (Johnston 2011).

The Mountain Top experiment sites were surrounded by perennial, predominately native plant communities (Table 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 3 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, contains microsites of higher moisture availability, and traps dispersing seeds (Chambers 2000). Similarly, brush mulch creates favorable microsites by causing snow to drift and creating shade, entraps dispersing seeds (Kelrick 1991), and also likely contains some viable native seed. These 2 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 establishing a diverse plant community?

At sites similar to those used for the Strategy Choice experiment, the degree of threat from invasive weeds is ambiguous. In such situations, 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. 2007). Therefore, one might wish to adopt an optimistic strategy by seeding a low competition/high diversity seed mix with a minimal fraction of rhizomatous grasses, avoiding using 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 2 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 high competition versus low competition/high diversity seed mix. The goal of the study is to shed light on the question: What conditions mandate a conservative approach to reclamation?

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 is on sagebrush (*Artemesia tridentata*) communities, because of the need for better techniques for re-establishing these communities (Lysne 2005), their widespread distribution, and their importance to wildlife.

STUDY AREA

The Piceance Basin study area is in Rio Blanco and Garfield Counties, Colorado, USA (Figure 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. Low elevations are characterized by Wyoming big sagebrush, cheatgrass, Indian ricegrass (*Oryzopsis hymenoides*), western wheatgrass (*Agropyron smithii*), prairie junegrass (*Koeleria cristata*), and globemallow (*Sphaeralcea coccinea*) in flatter areas with a mixture of pinyon pine (*Pinus* sp.) and Utah juniper (*Juniperous utahensis*) on steeper slopes and greasewood (*Sarcobatus vermiculatus*) in floodplains. High elevations are characterized by mountain big sagebrush, mountain brome (*Bromus marginatus*) and diverse forbs in flatter areas, serviceberry (*Amelanchier alnifolia*), snowberry (*Symphoricarpos albus*), and 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 1, Table 1). These 12 locations span most of the range of elevation, soil type, vegetation, 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. 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.

METHODS: DISTURBANCE CREATION

Two types of disturbances, simulated pipelines and simulated well pads, were created 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 3 weeks, and then the subsoil was replaced and the topsoil spread evenly over the site. This work was completed in 6 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 of subsoil disturbance which 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 respread 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.

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

PIPELINE EXPERIMENT

Overview

- Goal: Compare effectiveness of Plateau herbicide and tillage treatments for controlling cheatgrass.
- Conducted at 6 sites: YC1, YC2, RYG, WRR, GVM and SKH (Figure 1, Table 1).
- Treatments:
    - Herbicide (2 levels): Plateau applied (Plateau) or no Plateau applied (No Plateau)
    - Tillage (5 levels): disking (D), compaction with a static roller (R), compaction with a vibratory drum roller (V), disking plus compaction with a static roller (DR), or control (C)
- Design: Factorial split-plot. Herbicide treatments were randomly assigned to whole plots, and tillage treatments were randomly assigned to subplots (Figure 2).
- Plot size: 11 m X 10 m

Methods

Tillage treatments were implemented shortly after pipeline disturbances were created in the fall of 2008. In C plots, bulldozer and backhoe tracks were left in place. The soil surface varied from smooth to very rough. D plots were disked to 4 inches. R plots were rolled once with a static roller supplying a linear load of 20.8 lbs/in (36.5 N/cm). V plots received 4 passes with a vibratory drum roller (Wacker DH-12). DR plots were disked to 4 inches, then wetted to 1 cm using an ATV tow sprayer, then rolled 5 times with a non-vibratory roller. The DR treatment was an effort to create slight soil compaction at the surface, while avoiding heavy compaction of the rooting zone, which can restrict root growth and compromise establishment of deeply-rooted perennial plants (Thompson et al. 1987). At the Yellow Creek sites, the V treatment was not implemented.

Herbicide was applied in October 2008. At the time of application, cheatgrass was at the 1-leaf stage (~5 cm tall) at WRR and RYG, had just begun emerging at the Yellow Creek sites, and had not emerged at SKH or GVM. Plateau was applied at 105 g ai/ha (420 g/ac or 6 oz/ac) with glyphosate at 210 g ai/ha (8 oz *Roundup Pro* /ac) and methylated seed oil (2% v/v) using an ATV tow sprayer (Agri-Fab 45-0424). The rate of Plateau application was a compromise between the 700 g/ac rate, which has been shown to provide good brome control at the expense of strong negative effects on native forbs (Baker et al. 2007) and the 280 g/ac rate, which has been shown to avoid serious negative effects on most desirable species but provides only moderate brome control (Bekedam 2004). Glyphosate was added because cheatgrass had emerged at some sites at the time of application, and methylated seed soil was added to facilitate bonding of the herbicide to leaf surfaces.

Following herbicide application, sites were drill seeded using a Tye Pasture Pleaser rangeland drill, calibrated to plant seed approximately 1 cm deep in tilled soil. Drill rows were about 25 cm apart, and the drill produced a minimal amount of soil disturbance. All sites received the same seed mixture (Table 2). Grasses and shadscale species were mixed together, as were all forb species. Grass/shadscale and forb mixtures were seeded in separate rows by taping poster board dividers in the seed box, and placing seed mixes in alternating divisions. Rice hulls were added at 50% v/v in order to keep seeds of different sizes suspended evenly in the mixtures (St. John et al. 2005). Wyoming big sagebrush seed collected from Dry Creek Basin, Colorado, an area with similar temperature and moisture characteristics to the study area, was broadcast seeded onto snow in mid-January. Plots were seeded at a rate of 8.6 pounds pure live seed per acre. This low seeding rate was chosen because lower seeding rates facilitate establishment of mixed stands (Redente et al. 1984).

Vegetation response was quantified in 2010 by assessing percent cover by species between 24 June and 19 July. Nine 1m^2 subplots were arrayed systematically per plot, with one subplot in the center of the plot, and the remaining subplots equidistant from the center subplot and either a plot corner or the midpoint of a plot edge. Thirty-six point-intercept hits were measured per subplot, and all layers of vegetation as well as ground cover were identified at each hit. Because of overlapping canopy layers, it is possible for cover to exceed 100%.

Percent cover of functional groups of interest (perennial grasses, perennial forbs, total annuals, annual forbs, annual grasses, total shrubs, big sagebrush, and cheatgrass) was determined. Diversity was calculated from cover data using the Shannon Index, with each hit for a given species considered as an occurrence of that species. When calculated this way, the index reflects the number of species hit and the evenness of cover among those species.

Responses of cover groups and diversity to Plateau treatment, the tillage treatments (D, R, and V), and 2-way interactions among them were analyzed as fixed effects using ANOVA in SAS PROC

MIXED. Site and a site*Plateau Treatment term (to account for the split-plot design) were included as random effects. Biennial forbs were lumped with annual forbs. Models including all possible different combinations of fixed effects and 2-way interactions among fixed effects were compared using Akaike's Information Criterion, adjusted for small sample size (AIC_c). A null model with no fixed effects was also tested. A total of 19 models were tested for each functional group or species-specific response. The magnitude of treatment effects were evaluated using ESTIMATE statements in the model with the lowest AIC_c value. Effect sizes are presented ± 95% confidence intervals.

Results

The Plateau treatment increased cover of perennial grasses, with Plateau plots having 11.3 ± 9.0% higher cover of perennial grasses than plots without Plateau (Figure 3, Table A1). The Plateau treatment exerted a strong effect on the cover of total annuals, with Plateau plots having 39.8 ± 21.5% lower cover of annuals than No Plateau plots (Figure 3, Table A2). The lowest AIC_c model for cheatgrass cover contained the Plateau treatment (Table A3), but the effect of 25.6 ± 33.2% lower cheatgrass in No Plateau plots was only borderline significant ($p = 0.10$).

The lowest AIC_c models for perennial forb cover, annual forb cover, annual grass cover, shrub cover, big sagebrush cover, and species diversity did not contain the Plateau parameter, indicating that our data show little consistent effect of Plateau on these responses (Tables A4- A9).

The tillage treatments had no main effects significant at the 0.05 level, and were rarely represented in the models with the lowest AIC_c value (Appendix 1). The lowest AIC_c models for total shrub cover and Big Sagebrush cover contained a parameter for the rolling treatment, but the effect of the rolling treatment in both cases was only borderline significant and very slight, with Rolled plots having 1.0 ± 1.9 % lower total shrub cover and 0.08 ± 0.10 % lower big sagebrush cover than Not rolled plots ($p < 0.12$; Tables A7- A8). The lowest AIC_c models for perennial grass cover, total annual cover, cheatgrass cover, perennial forb cover, annual forb cover, annual grass cover, and species diversity did not contain any of the tillage treatments (Tables A1- A6, A9).

Discussion

Plateau herbicide increased perennial grass cover in reclamation areas 2 years after herbicide application and seeding. There was no discernable effect of Plateau on species diversity or on native forb cover. This is in contrast to in an earlier study which found forb cover to be greatly reduced one year after applying Plateau to mature plants (Baker et al. 2009). The difference may be due to the longer period of time between herbicide application and sampling which occurred in this study, or it may have been due to the rate or timing of application.

Plateau dramatically reduced cover of annuals. This was beneficial in this study, as 98.5% of annual cover was non-native. Reduced competition with annuals is a likely explanation for the increase in perennial grass cover. In this study, 85.1% of perennial cover was native. Plateau therefore improved the outcome of reclamation by promoting perennial, primarily native grasses, at the expense of non-native annuals.

While Plateau was effective on annuals when considered as a whole, there was no significant effect of Plateau on annual grasses, annual forbs, or cheatgrass when considered separately. This may be due to the fact that different species of annuals were dominant at different sites; the particular suite of species present may influence how Plateau affects a given species. For instance, cheatgrass cover was lower in Plateau plots at most sites, but was higher in Plateau plots at GVM. At GVM, Russian thistle (*Salsola tragus* L.), a non-native annual forb, heavily dominated No Plateau plots. In Plateau plots, reduced competition with Russian thistle could have allowed cheatgrass to grow more effectively in spite of the presence of the herbicide.

The Plateau treatment effects were more pronounced in the 2010 measurements of plant cover than they were in the 2009 assessment of seedling density. In 2009, there was no effect of Plateau on the density of native seedlings, and effects on cheatgrass seedlings were only evident at 2 of 6 sites. Plateau herbicide remains effective in the soil for 2 years post-application. It appears that the herbicide benefits maturing native plants through time as annuals continue to be suppressed.

The tillage treatments were ineffective except for a slight negative effect of rolling on shrub cover and big sagebrush cover. The rolling treatment in this study increased soil bulk density throughout the rooting zone. This likely made root penetration difficult. The lack of beneficial effect of rolling at controlling cheatgrass may mean that slight soil compaction is not a useful tool to control cheatgrass, or it may mean that a different method of implementation is needed in order to compact upper soil layers without influencing deeper parts of the rooting zone.

Disking did not affect annuals, perennials, or any of the functional groups studied. These results are in contrast to the seedling counts from 2009, which showed increased native seedling density and decreased cheatgrass seedling density with disking. It is likely that under the conditions studied, the effect of disking was too slight to persist through time.

COMPETITION EXPERIMENT

Overview:

- Goal: Test novel techniques for minimizing the competitive advantage of cheatgrass under a condition of controlled cheatgrass propagule pressure.
- Conducted at 2 sites: WRR and SGE (Figure 1, Table 1)
- Treatments:
    - Binding agent (3 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 (2 levels): super-absorbent polymer applied (SAP) or no polymer applied (No SAP)
    - Rolling (2 levels): rolled with a static heavy roller (Rolled) or not rolled (Not rolled)
- Design: Factorial split-split plot, with completely randomized whole plots. The subplot factor was binding agent, the split plot factor was super-absorbent polymer, and the whole plot factor was rolling (Figure 4).
- Plot size: 2.4 m X 2.4 m
- 5 replicates per site

Methods

Cheatgrass seed was collected using a lawnmower with a bagging attachment from monocultures or near-monocultures in 4 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 3 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 subplot. Seed was hand-broadcast in early October, 2009, and immediately lightly raked to incorporate seed into the soil. The 300 seeds/m^2 seeding rate is about 25% of the 2009 cheatgrass seed rain 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 3) 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, granulated super-absorbent polymer 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 different agricultural purposes.

Next, whole plots receiving the rolling treatment were rolled 10 times with a static roller supplying a linear load of 20.8 lbs/in (36.5 N/cm). Binding agent 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.

To assess vegetation response, seedlings were counted by species in late July and early August, 2010 in a 1 m X 1 m area centered within each plot. Three soil moisture readings were made in random locations within each plot on 21 May and 7 June, 2010 to evaluate treatment effects on soil moisture. 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.

The density of perennial grasses, density of cheatgrass, and volumetric soil moisture in response to rolling, super-absorbent polymer, and binding agent treatments was analyzed in SAS PROC MIXED for a split-split plot structure, with main effects and 2-way interactions among them included as fixed effects. A backwards model selection process ($\alpha = 0.05$) was used to determine the final model. Sites were analyzed separately because the amount of super-absorbent polymer applied differed between sites. The magnitude of significant treatments was determined using ESTIMATE statements. Effect sizes are given ± 95% confidence intervals.

Results

The super-absorbent polymer treatment was effective at WRR, where perennial grass density was 17.3 ± 11.8 plants/m^2 higher in SAP plots than in No SAP plots ($p = 0.012$). The effect was more pronounced (30.4 ± 15.9 perennial grasses /m^2) in No SAP plots also receiving the rolling treatment (treatment interaction $p = 0.036$; Figure 5). Cheatgrass density did not discernibly differ between SAP and No SAP plots at WRR ($p = 0.29$). At SGE, neither perennial grass nor cheatgrass density differed between SAP and No SAP plots ($p > 0.21$), although the pattern of the averages for perennial grasses was similar to that at WRR (Figure 5). We did not detect a difference in soil moisture between SAP and No SAP plots on either measurement date at WRR ($p > 0.46$) or at SGE ($p > 0.69$).

The binding agent treatment increased soil moisture on 5/21/10 at both SGE and WRR ($p < 0.006$). At SGE, soil moisture was 3.6 ± 2.2 % higher in Low BA or High BA plots versus the No BA plots (Figure 6). At WRR this difference was 4.0 ± 2.0 %. There was no significant difference at either site on 6/7/10 ($p > 0.09$). At WRR, neither perennial grass nor cheatgrass density differed among the binding agent treatments ($p > 0.67$). At SGE, cheatgrass density differed by binding agent treatment, with

5.0 ± 3.4 plants/m^2 higher cheatgrass density in Low BA plots than in No BA plots ($p = 0.004$; Figure 7). Perennial grass density did not differ by binding agent treatment at SGE ($p = 0.49$).

Aside from the aforementioned interaction between the rolling and super-absorbent polymer treatment at WRR, there were no differences in perennial grass density, cheatgrass density, or soil moisture between Rolled and Not rolled plots at WRR or at SGE ($p > 0.11$).

Discussion

The treatment increased the density of perennial grasses at WRR, where it was applied at 30.8 g/m^2, but not at the SGE site, where it was applied at 6.7 g/m^2. The effect of super-absorbent polymer was more pronounced when applied with the rolling treatment. If these trends continue, then addition of super-absorbent polymer at 30 g/m^2 may be a useful tool for promoting perennial grasses under competition from cheatgrass, especially in compacted soils. Although we did not detect an effect of the super-absorbent polymer treatment on soil moisture, this may have been a result of the pattern of application. Polymer was applied only in drill seeded rows, where growing plants may have removed any extra moisture that was made available. Also, the soil moisture readings were taken from throughout the plot, where the action of the polymer may not have been detectable.

The binding agent treatment increased soil moisture in late May, supporting the manufacturer's claim that the product studied, DirtGlue, increases water infiltration. In contrast to super-absorbent polymer, binding agent was applied throughout each plot, where it might impact cheatgrass seed as well as the drill-seeded grasses. Cheatgrass density was higher when binding agent was applied at the moderate rate than when no binding agent was applied at the SGE site. This may mean that under certain conditions, the increased early season soil moisture resulting from binding agent application may promote cheatgrass establishment.

The rolling treatment had little or no effect on perennial grass density, cheatgrass density, or soil moisture. The combination of rolling with other treatments used in this experiment was an effort to improve the effectiveness of surface compaction as compared to the way rolling was applied in the Pipeline experiment. In the Pipeline experiment, rolling was not applied in concert with a soil binding agent, and it was hypothesized that using rolling with a binding agent might create a surface crust useful in preventing cheatgrass germination. If the trends seen in 2010 persist, then it will seem as though rolling is not a useful tool for controlling cheatgrass, whether used alone or with the particular binding agent tested here.

Perennial grasses and cheatgrass have different water use patterns through the growing season. Cheatgrass performs well in ecosystems where soil moisture is plentiful only in the early season, while perennial grasses perform best when soil moisture is available throughout the growing season. The soil additives used in the study manipulate the amount and timing of soil moisture availability by either improving the depth to which rainfall penetrates, or by slowly releasing rainfall at times when soils would otherwise be dry. In either case, the action of the additives depends on rainfall. Therefore, the usefulness of the additives will depend on rainfall patterns in a particular location. In 2010, late growing season rain was higher than the prior year, resulting in favorable conditions for perennial seedling survival (Appendix 3). If either additive improves the competitive advantage of perennial grasses in this study, then a broader scale study, encompassing areas with different rainfall patterns, would be warranted.

In 2011 and 2012, vegetation responses will be assessed using percent cover of perennial grasses and cheatgrass. Soil moisture will continue to be monitored in May and June. Costs and recommended application procedures will be discussed for any treatments promoting dominance of desirable vegetation under competition from cheatgrass.

GULLEY EXPERIMENT

Overview

- Goal*:* identify 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.
- Conducted at 4 sites: RYG, SKH, YC1, and YC2 (Figure 1, Table 1)
- Treatments:
    - Fallowing (2 levels): fallowed with Pendulum herbicide for one year prior to seeding (Fallowed) or seeded immediately (Unfallowed)
    - Plateau application (2 levels): Plateau applied (Plateau) or no Plateau applied (No Plateau)
    - Seed Barriers (2 levels): surrounded by a seed dispersal barrier (Barrier) or not surrounded (No Barrier)
- Design: Factorial split-split plot, with completely randomized whole plots. The subplot factor was Plateau, the split plot factor was seed barriers, and the whole plot factor was fallowing (Figure 8).
- Plot size: 9 m X 6 m
- 3 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 plots 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, soil binding agent (DirtGlue®, DirtGlue® Enterprises, Amesbury, MA) 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 (Figure 8). 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 (Tecomate Wildlife Systems, San Antonio, TX). 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 which had been caught in the dispersal barriers the prior year germinated and grew through the barrier (Figure 9). 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 Tanglefoot seed rain traps (Appendix 2). 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 for each subsample.

A photo of Unfallowed plots in the 2010 season is included as Figure 10.

At 2 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 assessments in the Gulley experiment will begin in 2011, and will continue for at least 3 growing seasons. The performance of the treatments will be assessed by quantifying cover and diversity of vegetation in the study plots. Data will be analyzed using a repeated measures analysis with treatments and their interactions as fixed effects. If the effectiveness of treatments differs across study sites, a site-by-site analysis will be done. The costs and benefits of the 3 weed control measures tested will be compared and discussed.

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 4 sites: SCD, SPG, TGC and SQS (Figure 1, Table 1)
- Locations had predominately native and desirable surrounding plant communities, and varied in elevation from 2342 m (7681 ft) to 2676m (8777 ft; Table 1).
- Treatments:
    - Seeding (2 levels): Seeded or Unseeded
    - Soil surface (2 levels): roughened with holes and mounds (Rough) or left flat (Flat)
    - Brush mulch (2 levels): mulched with brush (Brush) or not mulched with brush (No Brush)
- Design: Completely randomized factorial (Figure 11)

- Plot size: 9 m X 6 m
- 3 replications per site

Methods

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 5) 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 hunter grain 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 4 liters of topsoil from brush stockpiles was scattered over each Brush plot.

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.

Vegetation response was quantified in 2010 by assessing density of seedlings by species. Where species identification could not be made, the functional group (shrub, forb, or grass) and lifespan (annual or perennial) of the seedling was noted. Counts were made for five 0.5 m X 1 m subplots arrayed systematically within each plot. One subplot was placed in the center of each plot, and the remaining 4 subplots were placed equidistant from this plot and the plot corners. Subplot density values were averaged to determine plot-level density.

The density of annuals, perennial forbs, perennial grasses, and shrubs in response to the seeding treatment, the soil surface treatment, and the brush treatment were analyzed in SAS PROC MIXED with main effects and 2-way interactions among them included as fixed effects, and site as a random effect. Biennial forbs were lumped with annual forbs. Backwards model selection with $\alpha = 0.05$ was used to determine the final model. The magnitude of significant treatments was determined using ESTIMATE statements in this model. Effect sizes are given ± 95% confidence intervals. Annual forbs and annual grasses were not analyzed separately in this experiment because 99% of annuals were forbs.

Results

The density of annuals was 12.7 ± 4.6 plants/m^2 lower in Rough plots than in the Flat plots (Figure 12). For perennial grass and perennial forbs, the effect of the soil surface treatment depended upon the seeding treatment (treatment interaction $p < 0.005$). Without seeding, there was no difference between Rough and Flat plots, but with seeding, perennial grass density was 6.4 ± 3.5 plants/m^2 higher in Rough plots than in Flat plots (Figure 13). For perennial forbs, this difference was 12.8 ± 6.7 plants/m^2 (Figure 14). There was no significant effect of the soil surface treatment on shrubs ($p = 0.07$).

The seeding treatment had no significant effect on the density of annuals ($p = 0.08$). Averaged across the surface treatments, seeding increased the density of perennial grasses by 22.2 ± 2.5 plants/m^2 and the density of perennial forbs by 12.4 ± 4.7 plants/m^2. Seeding had no significant effect on the density of shrubs ($p = 0.25$).

There was no significant difference in annual, perennial grass, perennial forb, or shrub density in Brush versus No Brush plots.

Discussion

In the first year post-treatment, the rough surface treatment promoted several responses which may result in a more diverse, perennial plant community. The density of annuals was lower, the density of perennial grasses was slightly higher, and the density of perennial forbs, when combined with seeding, was more than twice as high as that in Flat surface plots. The reduction in annuals is a beneficial response because approximately 85% of annuals in this experiment were non-native. The overall increase in perennial plant density is beneficial, and the more dramatic response of forbs versus that of grasses is also likely beneficial to the long-term goal of promoting a mixed plant community.

The effect of the rough surface treatment on perennials was constrained to plots that were seeded. This implies that the action of the treatment was due to increased germination and/or survival of seeds, rather than to capture of dispersing seed. The rough surface treatment was applied in the fall of 2009, after most plants had finished dispersing seed for that year. It is possible that that an effect of the rough surface treatment may be realized in unseeded plots once natural dispersal has had more time to take place.

Perennial grass and forb density was much higher in plots that were seeded. This is unsurprising, as all of the seeded species were perennials. There was no effect of seeding on the density of annuals. Annual plant density and cover may increase in unseeded plots if natural dispersal provides insufficient seed to compete with annuals. Alternately, the naturally recruited plants in unseeded plots may provide sufficient competition to control annuals.

The brush treatment did not affect any of the response variables. The effect of brush at creating microsites and capturing seed may be negligible under the conditions studied, or an effect may become evident through time.

The Mountain Top experiment will be monitored for at least 3 additional growing seasons. In future years the performance of the treatments will be assessed by quantifying cover of desirable vegetation in the study plots. If the effectiveness of treatments differs across study sites, a site-by-site analysis will be done. The cost and value of large holes, brush mulching, and seeding in areas with desirable surrounding habitat will be compared and discussed.

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 4 sites: WRR, SGE, GVM, MTN (Figure 1, Table 1)
- Treatments include:
    - Seed mix (2 levels): seeded with a high competition seed mix (HC) or a low competition mix (LC)
    - Soil surface/mulch type (2 levels): flat with straw mulch (Flat/Straw) or rough surface with brush mulch (Rough/Brush; Figure 15).
    - Herbicide (2 levels): Plateau applied (Plateau) or no Plateau applied (No Plateau)
- Completely randomized factorial (Figure 16)
- Plot size: 9 m X 6 m

- 3 replications per site
- The 4 locations had 0-15% non-native cover prior to the start of the experiment

Methods

At GVM and MTN, the full experiment with all 3 treatments was implemented. At WRR and SGE, space constraints mandated implementing an abbreviated form of the experiment, and the herbicide treatment was omitted. Treatments were implemented in October of 2009.

Seed mixes for the HC and LC plots are shown in Table 6. A key difference between the mixes is in the number and type of grass seeds used. In the high competition mix, 344 grass seeds/m^2 (32 seeds/ft^2) were used, and these were mostly rhizomatous wheatgrasses. In the low competition mix, 156 grass seeds/m^2 (15 seeds/ft^2) were used, and 90% of these were less competitive bunchgrass species.

In Rough/Brush plots, all species were hand-broadcast and raked, after creation of the holes but before the application of brush. On Flat/Straw plots, some seed was hand broadcast and then lightly raked, and the remainder was drill seeded approximately 1 cm deep using a Plotmaster™ 400 with a hunter grain drill attachment (Table 6). Seed was mixed 1:1 by volume with rice hulls to aid in an even distribution of species.

Certified weed-free straw was applied by hand at a rate of 4.0 Mg/ha (1.8 tons/ac) to Flat/Straw plots. Straw was crimped in place using a custom-built mini crimper pulled behind an ATV. Rough/Brush plots were treated using a 331 Bobcat® compact excavator to dig holes approximately 130 cm X 80 cm X 50 cm deep. Material removed was mounded next to each hole, and 18 holes were dug per plot. This resulted in approximately 1/3 of the ground being allocated to each of holes, mounds, and interspaces.

Plateau plots were sprayed with 140 g ai/ha of Plateau (8 oz /ac) applied with 655 li/ha of water (70 gal /ac) with a backpack sprayer. To hit the target rate, a quantity of liquid sufficient to treat 2 plots was mixed, and then that quantity was applied to the 2 plots with a dye indicator to ensure even application. In Plateau, Flat/Straw plots, the amount of water used in herbicide application was tripled to aid the Plateau in penetrating the straw mulch.

After Plateau application, brush which had been cleared and stockpiled next to each site was applied to Rough/Brush plots. Approximately 5 m^3 of brush was applied evenly to each plot.

Big sagebrush was hand-broadcast on top of snow in all plots in December of 2009.

Vegetation response was quantified in 2010 by assessing density of seedlings by species. Counts were made for five 0.5 m X 1 m subplots arrayed systematically within each plot. One subplot was placed in the center of each plot, and the remaining 4 subplots were placed equidistant from this plot and the plot corners. Subplot density values were averaged to determine plot-level density.

The density of perennial grasses, perennial forbs, shrubs, annual grasses, and annual forbs in response to the seeding treatment, the soil surface/mulch type treatment, and the Plateau treatment were analyzed in SAS PROC MIXED with main effects and 2-way interactions among them included as fixed effects, and site as a random effect. Biennial forbs were lumped with annual forbs. Because the Plateau treatment was only conducted at 2 of the 4 sites, separate backwards model selection processes ($\alpha = 0.05$) were conducted for models with the Plateau treatment versus those without. Plots receiving Plateau were excluded from models not containing the Plateau treatment parameter, and sites where Plateau was not applied were excluded from models containing the Plateau treatment paramter. The magnitude of significant treatments was determined using ESTIMATE statements in final models. Effect sizes are given ± 95% confidence intervals.

Results

The Plateau treatment affected the density of perennial grasses, perennial forbs, shrubs, annual grasses, and annual forbs ($p < 0.01$). In Plateau plots, perennial grass density was 13.1 ± 7.8 plants/m^2 lower, perennial forb density was 21.4 ± 4.7 plants/m^2 lower, shrub density was 5.6 ± 1.5 plants/m^2 lower, annual grass density was 3.7 ± 2.8 plants/m^2 lower, and annual forb density was 4.2 ± 1.5 plants/m^2 lower than No Plateau plots (Figure 17).

In No Plateau plots, the seed mix treatment affected the density of perennial grasses and perennial forbs ($p < 0.0001$), but did not detectably affect shrubs, annual grasses, or annual forbs ($p > 0.13$; Figure 19). Perennial grasses were 19.2 ± 7.2 plants/m^2 less dense in LC plots than in HC plots. Perennial forbs were 14.8 ± 6.4 plants/m^2 more dense in LC plots than in HC plots. The seed mix and Plateau treatments interacted for perennial forbs ($p = 0.04$); where Plateau was applied, the density of perennial forbs did not differ between LC plots and HC plots ($p=0.44$). There was no evident interaction between seed mix and Plateau application for perennial grasses, shrubs, annual forbs, or annual grasses ($p > 0.60$). There was no interaction between the seed mix treatment and the soil surface/mulch treatment for any functional group ($p > 0.36$).

In the absence of Plateau, the soil surface/mulch treatment affected the density of perennial grasses, perennial forbs, shrubs, and annual forbs ($p < 0.04$), but did not detectably affect the density of annual grasses ($p = 0.73$; Figure 20). In Rough/Brush plots, perennial grass density was 7.6 ± 7.2 plants/m^2 lower, perennial forb density was 19.6 ± 6.4 plants/m^2 lower, shrub density was 6.2 ± 3.8 plants/m^2 lower, and annual forb density was 5.5 ± 2.6 plants/m^2 lower than in Flat/Straw plots. At sites where Plateau was applied, the Plateau treatment interacted with the surface treatment for annual forbs, perennial forbs, and shrubs ($p < 0.03$) but did not interact with the surface treatment for annual grasses or perennial grasses ($p > 0.48$). For annual forbs, perennial forbs, and shrubs, there was no effect of the soil surface treatment in plots treated with Plateau ($p > 0.36$), but plots without Plateau had soil surface effects similar to those quoted above. An unexpected result in Flat/Straw plots was germination of wheat from seed included in the straw mulch. Wheat plants were present at 14.7 ± 7.5 plants/m^2 in Flat/Straw plots.

A photo indicating some of the treatment differences is included as Figure 18.

Discussion

The 2 seed mixes differed in the relative densities of perennial grasses versus perennial forbs one year post-treatment: the low competition mix resulted in a higher density of perennial forbs, while the high competition mix resulted in a higher density of perennial grasses. There was no difference in the density of annual forbs or annual grasses due to the seed mix treatment. If these trends continue, the higher proportion of forbs produced by the low competition mix may result in a more favorable mixture of plant types. Also, one may conclude that the composition of plants in the low competition mix, while less competitive than that in the high competition mix, is sufficient to suppress annuals. This is a benefit because 94.5% of annual cover was non-native in this study.

The Rough/Brush plots had lower densities of most plant groups than the Flat/Straw plots. Because both desirable and undesirable plant density was lessened in the Rough/Brush plots, it is difficult to determine which treatment will ultimately result in a more desirable plant community. The Rough/Brush plots averaged 41.0 ± 7.7 perennial plants/m^2. Values as low as 5 perennial plants/m^2 have been used as the lower limit of success for rangeland seedings (Vallentine 1989). Therefore survival rates as low as 12% in the Rough/Brush plots may still result in a desirable plant community, if that plant community is diverse and palatable to wildlife.

The Plateau treatment lessened the density of all plant groups. Plots with Plateau averaged 20.3 ± 9.0 perennial plants/m^2, while plots without Plateau averaged 60.4 ± 9.8 perennial plants/m^2. Perennial forbs were especially reduced in Plateau plots; perennial forb density was 79% lower in plots with Plateau than in plots without Plateau, while perennial grass density was 48% lower in plots with Plateau. Like the soil surface/mulch treatments, it is difficult to determine which herbicide treatment will ultimately result in a more desirable plant community. If survival of desirable plants in plots with Plateau is high, and the herbicide continues to suppress undesirable plants, then a more favorable plant community could result from the Plateau treatment. If survival is poor in plots treated with Plateau, or the relatively higher grass density reduces forb productivity, then plots without Plateau may result in a more favorable community.

The Strategy Choice experiment will be monitored for at least 3 additional growing seasons. In future years the performance of the treatments will be assessed by quantifying cover and diversity of vegetation in the study plots. If the effectiveness of treatments differs across study sites, a site-by-site analysis will be done. The cost and value of highly competitive versus less competitive seed mixes, flat versus rough soil surface preparation, and Plateau herbicide will be discussed in the context of weed prevalence in the surrounding plant community.

SUMMARY

Two years after the initiation of this suite of experiments, several treatments appear promising in improving the quality of reclaimed wildlife habitat by promoting mixed, perennial plant communities in reclamation areas: applying Plateau herbicide, creating a rough soil surface composed of mounds and holes, using a seed mix with a small fraction of rhizomotous grasses, and including granulated super-absorbent polymer when drill seeding.

This report contains results of 2 experiments in which Plateau herbicide was applied. In both cases, the herbicide was applied in the fall just prior to seeding. In the Pipeline experiment, Plateau was applied with a boom sprayer at 105 g ai/ha (6 oz/ac), while in the Strategy Choice experiment, Plateau was applied with a backpack sprayer at 140 g ai/ha (8 oz/ac). Results of percent cover assessments 2 years following treatment in the Pipeline experiment are favorable: annuals are reduced, perennial grasses are increased, and perennial forbs are unaffected by treatment with Plateau. Results of plant density assessments one year following treatment in the Strategy Choice experiment are not apparently favorable: the density of perennial grasses, shrubs, and perennial forbs, as well as that of annuals, are reduced by treatment with Plateau. The length of time since treatment is probably the largest factor in the differences between the 2 experiments. In the Pipeline experiment, the apparent vigor of all plants was lower one year post-treatment in plots treated with Plateau, but that result had changed by 2 years post-treatment. It appears that while Plateau herbicide does incur a cost in terms of reduced density and vigor of desirable plants, the reduced competition with annuals allows those perennials which do survive to eventually outperform (in the case of perennial grasses) or at least perform comparably (in the case of perennial forbs) to those which were never treated with herbicide. While this is a beneficial result, the potential of Plateau to favor grasses over forbs should be carefully weighed against the benefits. When applying Plateau, the 105 g ai/ha (6 oz/ac) seems sufficient for areas where the ground has been disturbed, and may reduce the effect on forbs to an acceptable level. In undisturbed areas, where the density of viable weed seeds is likely to be higher, a higher rate of herbicide might be needed. In those cases, a cost-effective seed mix might be limited to those few forbs which appear more resistant to the herbicide. One such forb which established well in Plateau plots in this study is Utah sweetvetch (*Hedysarum boreale*).

There were 2 experiments where a roughed soil surface of mounds and holes, coupled with broadcast seeding, was compared to a flat soil surface coupled with drill seeding. In the Mountain Top experiment, the rough soil surface treatment was crossed with a brush mulch treatment, while in the

Strategy Choice experiment, the rough soil surface treatment was always applied with brush mulch, and the flat soil surface treatment was always applied with straw mulch. In the Mountain Top experiment, the rough soil surface performed well: the density of annuals was lower, the density of perennial grasses was higher, and the density of perennial forbs was higher as compared to the Flat plots. In the Strategy Choice experiment, the results were different: perennial grasses, perennial forbs, shrubs, and annuals all had lower density in the Rough plots than in the Flat plots. The difference is likely to be due to the addition of straw mulch in the Strategy Choice experiment Flat plots, which probably improved water infiltration and retention. Even so, Strategy Choice Rough plot perennial grass and forb densities were still quite high; the treatment producing the most desirable outcome will depend on the survival rates of plants of different types. In the Mountain Top experiment, the higher perennial grass and forb density in Rough plots was surprising because Rough plots were broadcast seeded at the same rate as drill-seeded Flat plots. In both experiments, a benefit of the rough soil surface was a reduction in annuals. If these trends continue, the rough soil surface may be a cost effective alternative, because the lack of need for a drill seeder, mulch, and mulch crimper would offset the cost of creating the holes and mounds. This result confirms and extends those of Eldridge et al. (2011), who found that a rough soil surface treatment improved the cover of native plants at low elevation sites in the Colorado River Valley.

One year after treatment implementation, the low competition seed mix tested in the Strategy Choice experiment seems to perform well. There was no difference in the density of annuals between the low competition mix and the high competition mix, and the low competition mix resulted in a higher proportion of perennial forbs. The idea that seed mixes should limit the proportion of competitive 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 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. Also, the degree to which rhizomatous grass seed should be reduced had not been determined. This study made use of several forb species provided by the Uncompagre Partnership (http://www.upartnership.org/) which are either not yet commercially available or have no Colorado-specific variety available. Several of these species established well, including local cultivars of many-lobed groundsel (*Packera multilobata*), hairy golden aster (*Heterotheca villosa*), sulfur flower buckwheat (*Eriogonum umbellatum*), bluestem penstemon (*Penstemon cyanocaulis*), and western yarrow (*Achillia millefolium*). The amount of rhizomatous grass seed (western wheatgrass and slender wheatgrass) included in the mix was only 16 seeds/m^2 (1.5 seeds/ft^2 or 0.5 PLS pounds/ac), and the cost of the mix, aside from the species which have no commercially available variety, was \$384/ha (\$159/ac). If the trends shown in 2010 continue, then a seed mix similar to the low competition mix (perhaps more appropriately called a high diversity mix) may successfully and cost-effectively prevent weed invasion and promote mixed plant communities.

One year post-implementation, the use of granulated super-absorbent polymer, tested in the Competition experiment, shows some promise. Where applied at 30 g/m^2 to compacted soils, super-absorbent polymer increased the density of seeded perennial grasses, but did not increase the density of cheatgrass. The cost of this treatment is approximately \$210/ha (\$85/ac). If these trends continue, then the addition of super-absorbent polymer to soils in reclamation areas should be studied in additional soil types and with more complex seed mixes. A limitation of super-absorbent polymer is that it must be incorporated into soil to avoid breakdown due to ultraviolet light. It could be added when redistributing topsoil or when drill seeding, but would be difficult to use with broadcast seeding.

Treatments which do not appear beneficial at this time include surface compaction and addition of a soil binding agent to the soil. Slight soil surface compaction was attempted in 2 studies: the Pipeline experiment and the Competition experiment. The goal of this treatment in these experiments was to determine if creating a crust of compacted soil would benefit reclamation by preventing the emergence of cheatgrass. In the Pipeline experiment, compaction with both a static and vibratory roller was tested, and in the Competition experiment, the combination of a static roller with a soil binding agent was tested. An ideal treatment would have created a denser surface crust without affecting the rooting zone, but this was not achieved. Where a surface crust was created, cheatgrass was noted emerging through inevitable cracks in the crust. In none of the cases was cheatgrass emergence affected, and a slight negative effect on shrubs was found in the Pipeline experiment, probably due to restricted root development. Although cheatgrass has been shown to have reduced emergence in slightly compacted soil in the laboratory (Thill et al. 1979), it remains to be shown that compacting soil is a practical approach for discouraging cheatgrass growth in a field setting. The soil binding agent tested, DirtGlue, was promoted by the manufacturer as increasing water infiltration, and we found that it was successful at increasing soil moisture in late May, but not later in the growing season. A slight effect of increased cheatgrass density with DirtGlue addition was found at one of 2 study sites, and no effect was found on perennial grass density. If these trends continue, then use of this soil binding agent is not likely to positively affect the competitive ability of perennial plants under competition from cheatgrass.

Re-creating wildlife habitat in areas disturbed by oil and gas development implies challenges greater than those typically met in reclamation. Not only must soil be stabilized and weeds controlled, but plant diversity and plant functional group diversity must be maintained or improved. While perfection in reaching this goal will always be elusive, opportunities exist to maximize the outcome of reclaimed areas as wildlife habitat. Capitalizing on these opportunities requires assessing reclamation difficulties in particular locations and then making judicious use of herbicides, seed mixes, and soil preparations. In the Piceance Basin, much of the variability in reclamation difficulty is associated with elevation and aspect. As additional time allows the outcome of these experiments become more finalized, specific information about which treatments are recommended in which elevation zones will be compiled and disseminated.

LITERATURE CITED

AVIS, L. 1997. COGCC Piceance basin well site reclamation survey. Colorado Department of Natural Resources.

BAKER, W. L., J. GARNER, AND P. LYON. 2007. Effect Imazapic on Downy Brome (*Bromus tectorum*) and Native Plants in Wyoming Big Sagebrush. Colorado Division of Wildlife.

_____. 2009. Effect of Imazapic on Cheatgrass and Native Plants in Wyoming Big Sagebrush Restoration for Gunnison Sage-grouse. Natural Areas Journal 29:204-209.

BEKEDAM, S. 2004. Establishment tolerance of six native sagebursh steppe species to imazapic (PLATEAU) herbicide: implications for restoration and recovery. Oregon State University, Corvallis, OR.

BERGQUIST, E., P. EVANGELISTA, T. J. STOHLGREN, AND N. ALLEY. 2007. Invasive species and coal bed methane development in the Powder River Basin, Wyoming. Environmental Monitoring and Assessment 128:381-394.

CHAMBERS, J. C. 2000. Seed movements and seedling fates in disturbed sagebrush steppe ecosystems: implications for restoration. Ecological Applications 10:1400-1413.

CHAMBERS, J. C., B. A. ROUNDY, R. R. BLANK, S. E. MEYER, AND A. WHITTAKER. 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? Ecological Monographs 77:117-145.

DITOMASO, J. M. 2000. Invasive weeds in rangelands: Species, impacts, and management. Weed Science 48:255-265.

DIVITTORIO, C. T., J. D. CORBIN, AND C. M. D'ANTONIO. 2007. Spatial and temporal patterns of seed dispersal: An important determinant of grassland invasion. Ecological Applications 17:311-316.

ELDRIDGE, J. D., E. F. REDENTE, AND M. W. PASCHKE. 2011. The use of seedbed modifications and wood chips to accelerate restoration of well pad sites in western Colorado, U.S.A. Restoration Ecology doi: 10.1111/j.1526-100X.2011.00783.x.

HUTTERMANN, A., L. J. B. ORIKIRIZA, AND H. AGABA. 2009. Application of Superabsorbent Polymers for Improving the Ecological Chemistry of Degraded or Polluted Lands. Clean-Soil Air Water 37:517-526.

JOHNSTON, D. B. 2011. Movement of weed seeds in reclamation areas. Restoration Ecology 19:446-449.

KELRICK, M. 1991. Factors affecting seeds in a sagebrush-steppe ecosystem and implications for the dispersion of an annual plant species, cheatgrass (*Bromus tectorum* L.). Utah State University, Logan, UT.

KRZIC, M., K. BROERSMA, D. J. THOMPSON, AND A. A. BOMKE. 2000. Soil properties and species diversity of grazed crested wheatgrass and native rangelands. Journal of Range Management 53:353-358.

KYLE, G. P., K. H. BEARD, AND A. KULMATISKI. 2007. Reduced soil compaction enhances establishment of non-native plant species. Plant Ecology 193:223-232.

KYSER, G. B., J. M. DITOMASO, M. P. DORAN, S. B. ORLOFF, R. G. WILSON, D. L. LANCASTER, D. F. LILE, AND M. L. PORATH. 2007. Control of medusahead (*Taeniatherum caput-medusae*) and other annual grasses with imazapic. Weed Technology 21:66-75.

LYSNE, C. R. 2005. Restoring Wyoming Big Sagebrush. Pages 93-98 *in* Proceedings of Sage-grouse habitat restoration symposium.93-98.

MARLETTE, G. M., AND J. E. ANDERSON. 1986. Seed banks and propagule dispersal in crested wheatgrass stands Journal of Applied Ecology 23:161-175.

MOHLER, C. L., J. C. FRISCH, AND C. E. MCCULLOCH. 2006. Vertical movement of weed seed surrogates by tillage implements and natural processes. Soil & Tillage Research 86:110-122.

MULUGETA, D., AND D. E. STOLTENBERG. 1997. Weed and seedbank management with integrated methods as influenced by tillage. Weed Science 45:706-715.

NEWMAN, G. J., AND E. F. REDENTE. 2001. Long-term plant community development as influenced by revegetation techniques. Journal of Range Management 54:717-724.

PILKINGTON, L., AND E. F. REDENTE. 2006. Evaluation of reclamation success of Williams Production RMT Company natural gas well pad sites near Parachute, Colorado. Colorado State University, Department of Forest, Rangeland, and Watershed Stewardship, Fort Collins, CO.

REDENTE, E. F., T. B. DOERR, C. E. GRYGIEL, AND M. E. BIONDINI. 1984. Vegetation establishment and succession on disturbed soils in northwest Colorado. Reclamation & Revegetation Research 3:153-165.

SAWYER, H., R. M. NIELSON, F. LINDZEY, AND L. L. MCDONALD. 2006. Winter habitat selection of mule deer before and during development of a natural gas field. Journal of Wildlife Management 70:396-403.

SMITH, D. C., S. E. MEYER, AND V. J. ANDERSON. 2008. Factors affecting *Bromus tectorum* seed bank carryover in western Utah. Rangeland Ecology & Management 61:430-436.

ST. JOHN, L., D. OGLE, D. TILLEY, M. MAJERUS, AND L. HOLZWORTH. 2005. Technical note: Mixing seed with rice hulls. USDA-Natural Resources Conservation Service, Boise, Idaho.

THILL, D. C., R. D. SCHIRMAN, AND A. P. APPLEBY. 1979. Influence of soil-moisture, temperature, and compaction on the germination and emergence of downy brome (*Bromus tectorum*). Weed Science 27:625-630.

THOMPSON, P. J., I. L. JANSEN, AND C. L. HOOKS. 1987. Penetrometer resistance and bulk density as parameters for predicting root system performance in mine soils. Soil Science Society of America Journal 51:1288-1293.

THOMSEN, M. A., C. M. D'ANTONIO, K. B. SUTTLE, AND W. P. SOUSA. 2006. Ecological resistance, seed density and their interactions determine patterns of invasion in a California coastal grassland. Ecology Letters 9:160-170.

TRAMMELL, M. A., AND J. L. BUTLER. 1995. Effects of exotic plants on native ungulate use of habitat. Journal of Wildlife Management 59:808-816.

VALLENTINE, J. F. 1989. Range developments and improvements, 3rd Edition. Academic Press, San Diego, CA.

WALKER, B. L., D. E. NAUGLE, AND K. E. DOHERTY. 2007. Greater sage-grouse population response to energy development and habitat loss. Journal of Wildlife Management 71:2644-2654.
WICKS, G. A. 1997. Survival of downy brome (*Bromus tectorum*) seed in four environments. Weed Science 45:225-228.

Table 1. Basic information about study locations. Relative cover is for undisturbed ground near each study location in the growing season of 2009.

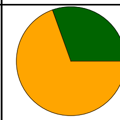
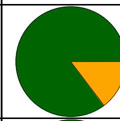
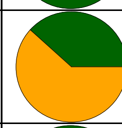
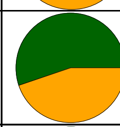
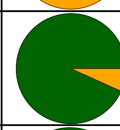
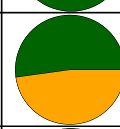
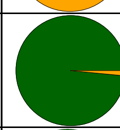
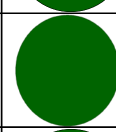
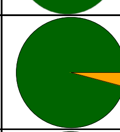
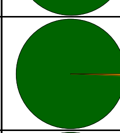
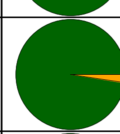
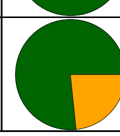
Code	Name	Landowner	Elev. m (ft)	Experiment(s) Conducted	RelativeCover Native NonNative
SKH	SK Holdings	Williams	1561 (5120)	Pipeline Gulley	
GVM	Grand Valley Mesa	Williams	1662 (5451)	Pipeline Strategy Choice	
YC2	Yellow Creek 2	DOW	1829 (5999)	Pipeline Gulley	
YC1	Yellow Creek 1	DOW	1905 (6248)	Pipeline Gulley	
SGE	Sagebrush	BLM	2004 (6573)	Strategy Choice Competition	
RYG	Ryan Gulch	Williams	2084 (6835)	Pipeline Gulley	
MTN	Mountain Shrub	BLM	2183 (7160)	Strategy Choice	
WRR	Wagon Road Ridge	Williams	2216 (7268)	Pipeline Strategy Choice Competition	
SCD	Scandard	BLM	2342 (7681)	Mountain Top	
SPG	Sprague	Conoco	2445 (8019)	Mountain Top	
TGC	The Girls' Claims	Encana	2527 (8288)	Mountain Top	
SQS	Square S	DOW	2676 (8777)	Mountain Top	

Table 2. Seed mix used in the Pipeline experiment

Scientific Name	Common Name	PLS (lbs/ ac)	Live seeds/m^2
forbs			
Achillea lanulosa	western yarrow	0.10	67
Erigonum umbellatum	sulfur flower buckwheat	1.03	53
Hedsarum boreale	Utah sweetvetch	0.44	11
Heterotheca villose	hairy golden aster	1.11	137
Linum lewisii	Lewis flax	0.38	28
Packera multilobata	lobeleaf groundsel	0.10	67
Penstemon strictus	Rocky Mountain penstemon	0.33	23
grasses			
Achnatherum lymenoides	Indian ricegrass (Nezpar)	0.83	33
Agropyron smithii	western wheatgrass	0.40	11
Agropyron spicatum	bearded bluebunch wheatgrass P-7	0.38	11
Agropyron spicatum	bearded bluebunch wheatgrass Secar	0.36	10
Agropyron trachycaulum	slender wheatgrass	0.24	10
Elymus elymoides	bottlebrush squirreltail	0.45	21
Koeleria macrantha	prarie junegrass	0.18	105
Poa secunda	sandberg bluegrass	0.26	68
Stipa viridula	green needlegrass	0.68	22
shrubs			
Artemesia tridentata ssp. *Wyomingensis*	Wyoming big sagebrush	0.33	246
Atriplex canescens	fourwing saltbush	0.54	7
Atriplex confertifolia	shadscale saltbush	0.47	7
	TOTAL	**8.60**	

Table 3. 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 4. Seed mix used in the Gulley experiment.

Scientific name	Common Name	Variety	Seeds/ m2	PLS (kg/ha)	Seeds/ ft2	PLS (lbs/ac)
forbs						
Achillia 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						
Artemesia tridentat 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**

Table 5. Seed mix used in the Mountain Top experiment.

Scientific Name	Common Name	Variety	Seeds/ m^2	PLS (kg/ha)	Seeds/ ft^2	PLS (lbs/ac)
forbs						
Achillia millefolium	western yarrow	Eagle Mtn.	161	0.3	15	0.2
Hedysarum boreale	Utah sweetvetch	Timp	15	1.5	1	1.3
Penstemon palmeri	palmer penstemon	Cedar	215	1.7	20	1.5
Penstemon strictus	Rocky Mtn. penstemon	Bandera	108	1.7	10	1.5
grasses						
Bromus marginatus	mountain brome	Garnet	54	3.8	5	3.4
Elymus lanceolatus spp. lanceolatus	thickspike wheatgrass	Critana	22	0.6	2	0.6
Elymus trachycaulus spp. trachycaulus	slender wheatgrass	San Luis	65	2.2	6	1.9
Nassella viridula	green needlegrass	Lowdorm	43	1.2	4	1.0
Poa fendleriana	muttongrass	VNS	215	0.5	20	0.4
Pseudoroegneria spicata spp. spicata	bluebunch wheatgrass	Anatone	65	2.3	6	2.1
shrubs						
Artemisia cana	silver sage	VNS	323	1.3	30	1.2
*Artemisia tridentata spp. vaseyana**	mtn. big sagebrush	VNS	250	0.6	23	0.5
Ericameria nauseosa	rubber rabbitbrush	VNS	22	0.2	2	0.2
		TOTAL	**1556**	**17.8**	**145**	**15.9**

Table 6. Seed mixes used in the Strategy Choice experiment. Species noted as "drill seeded" were drill seeded in plots with a flat surface. In plots with a rough surface, all seed was broadcast.

	Scientific Name	Common Name	Variety	high competition mix seeds/ m^2	high competition mix PLS (kg/ha)	low competition mix seeds/ m^2	low competition mix PLS (kg/ha)
drill seeded	***forbs***						
	Hedysarum boreale	Utah sweetvetch	Timp	22	2.1	22	2.1
	grasses						
	Achnatherum hymenoides	Indian ricegrass	Rimrock	65	1.8	11	0.3
	Elymus lanceolatus spp. lanceolatus	thickspike wheatgrass	Critana	65	1.9		
	Elymus trachycaulus spp. trachycaulus	slender wheatgrass	San Luis	75	2.5	11	0.4
	Pascopyrum smithii	western wheatgrass	Rosana	65	2.5	5	0.2
	Pleuraphis jamesii	galleta grass	Viva	75	2.2		
	Poa fendleriana	muttongrass	VNS			54	0.1
	Pseudoroegneria spicata spp. spicata	bluebunch wheatgrass	Anatone			22	0.8
	shrubs						
	Atriplex canescens	fourwing saltbush	VNS CO	11	1.1	11	1.1
broadcast seeded	***forbs***						
	Achillia millefolium	western yarrow	VNS	129	0.2	129	0.2
	Erigeron speciosis	oregon daisy	VNS			323	0.9
	Eriogonum umbellatum	sulphur flower buckwheat	VNS	108	2.3	108	2.3
	Heterotheca villosa	hairy golden aster	VNS			215	1.3
	Linum lewisii	lewis flax	Maple Gr.	54	0.8	54	0.8
	Packera multilobata	many-lobed grounsel	VNS			215	1.3
	Penstemon cyanocaulis	bluestem penstemon	VNS	108	0.7	108	0.7
	grasses						
	Koeleria macrantha	prairie junegrass	VNS			54	0.1
	shrubs						
	Krascheninnikovia lanata	winterfat	VNS	22	0.8	22	0.8
	Artemesia tridentat spp. Wyomingensis	Wyoming big sagebrush	VNS	253	0.6	253	0.6
			GRASS TOTAL	***344***	***9.8***	***156***	***1.7***
			FORB TOTAL	420	5.6	1173	8.7
			SHRUB TOTAL	285	2.2	285	2.2
			OVERALL TOTAL	**1049**	**17.6**	**1614**	**12.6**

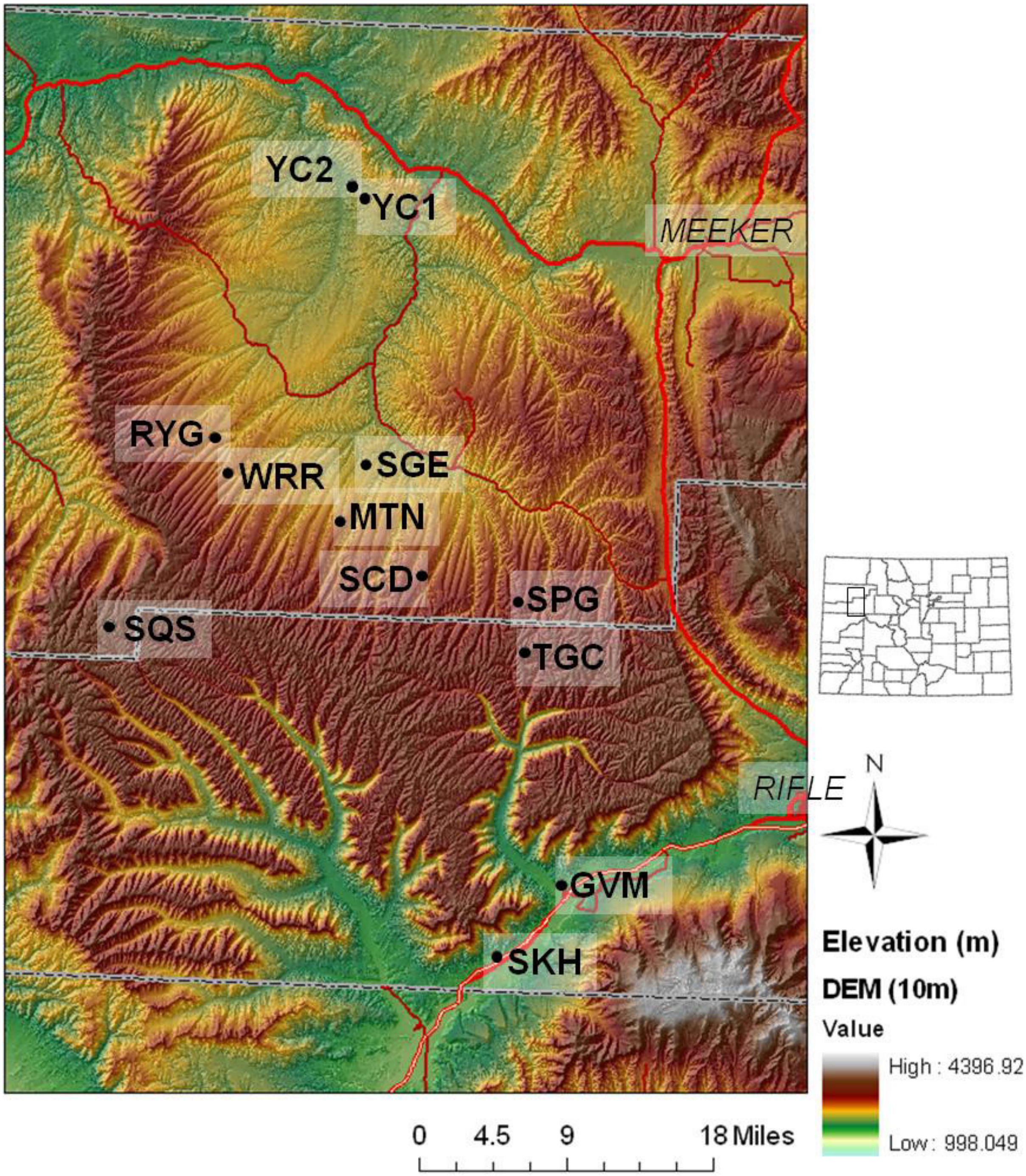


Figure 1. Locations of the 12 research sites in Rio Blanco and Garfield counties, Colorado.

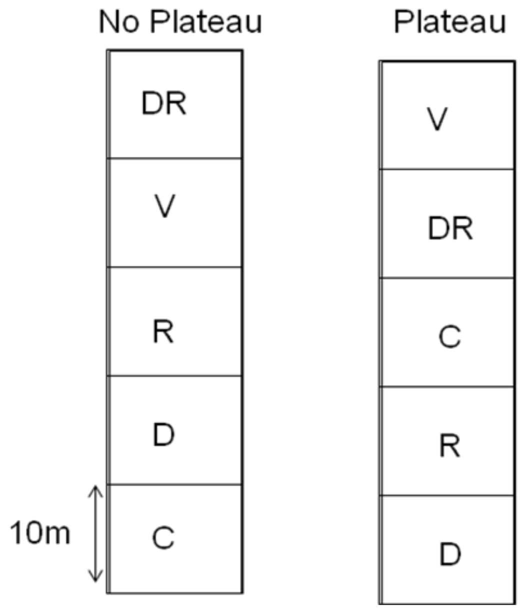


Figure 2. Layout of the Pipeline experiment at one of 6 sites. D = disked, R = rolled, DR = disked and rolled, V = rolled with a vibratory drum compactor, C = control.

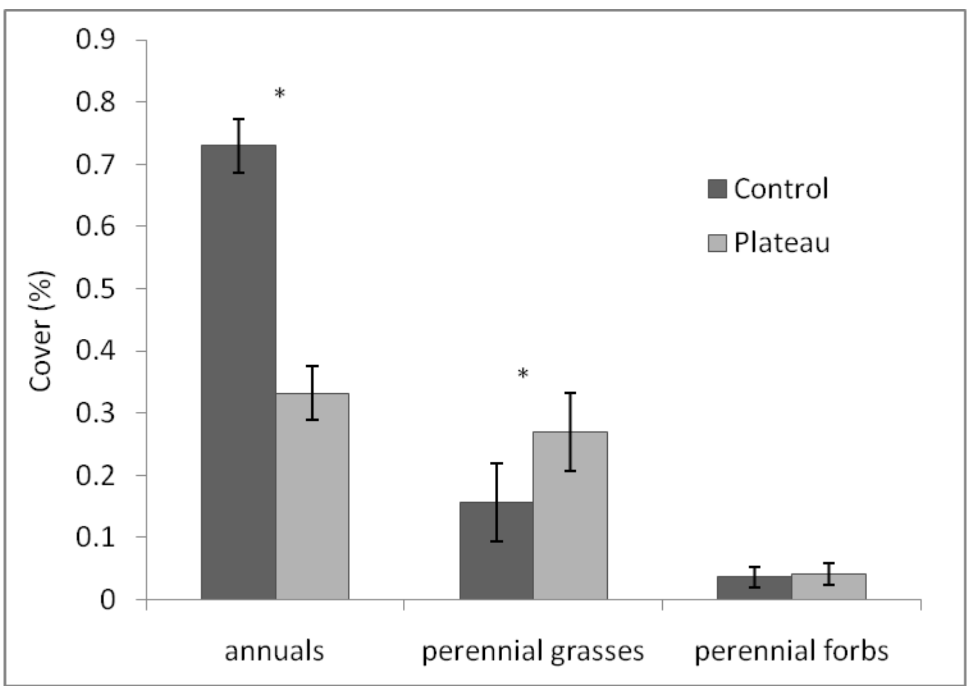


Figure 3. Cover of annuals, perennial grasses, and perennial forbs in plots with versus without Plateau herbicide 2 years after herbicide application and seeding in the Pipeline experiment. Stars denote significant differences at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

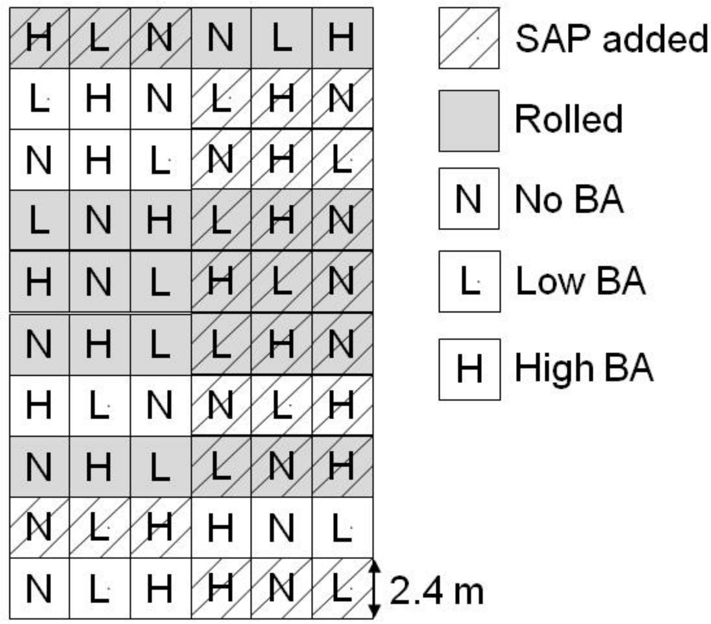


Figure 4. Layout of the Competition experiment at one of 2 research sites. SAP = super- absorbent polymer. BA = soil binding agent.

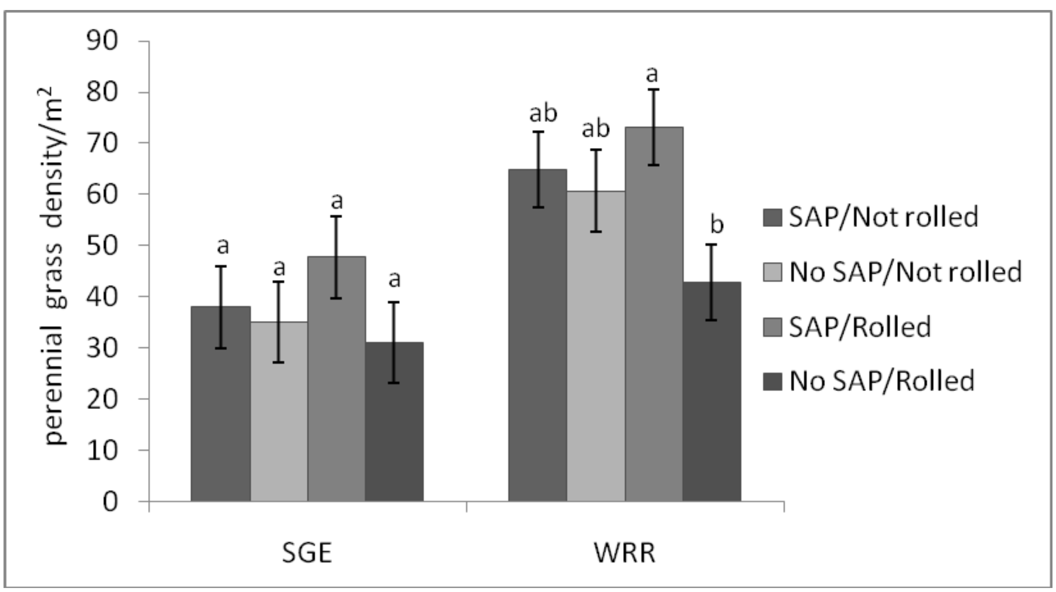


Figure 5. Effect of super-absorbent polymer (SAP) and compaction by a static roller on density of perennial grasses at 2 study sites, SGE and WRR. Bars not sharing a letter denote significant differences within a site at $\alpha = 0.05$. Error bars = SE. SE's include random site effects which cancel when means are compared.

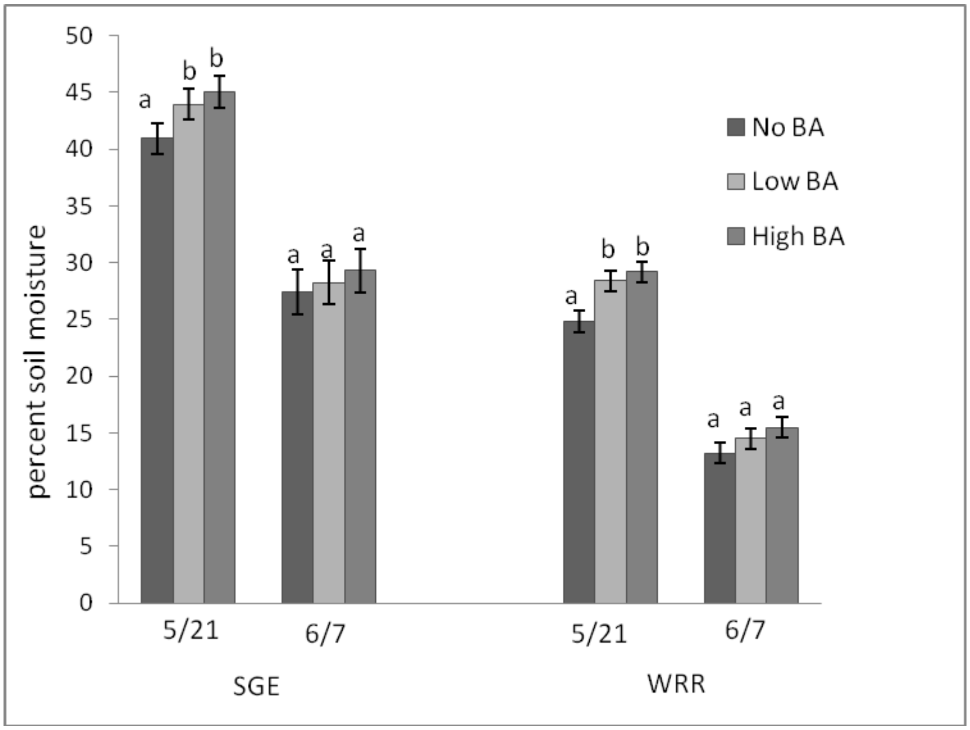


Figure 6. Effect of 3 levels of soil binding agent (BA) on percent soil moisture at 2 study sites, SGE and WRR, on May 21 and June 7, 2010. Bars not sharing a letter denote significant differences within a site and measurement date at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

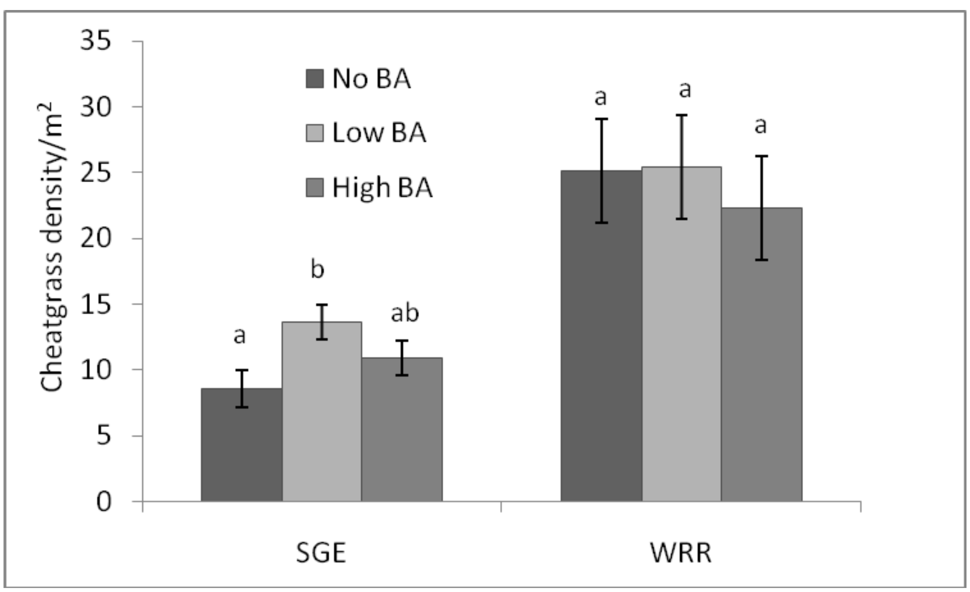


Figure 7. Effect of 3 levels of soil binding agent (none, low, high) on density of cheatgrass at the SGE and WRR study sites. Bars not sharing a letter denote significant differences within a site at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

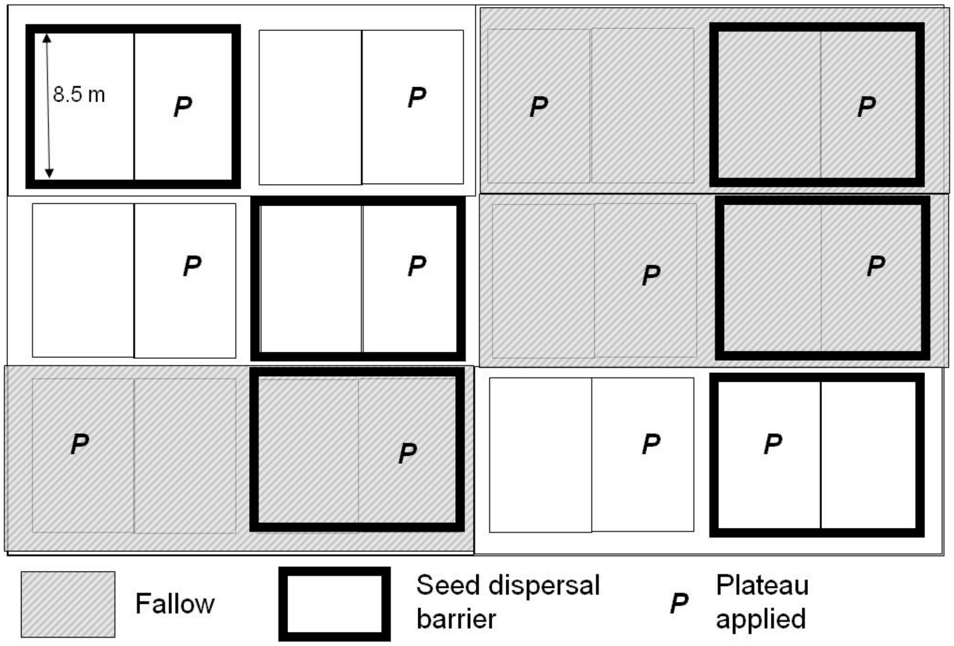


Figure 8. Layout of the Gulley experiment at one of 4 research sites.

Figure 9. Cheatgrass seed caught in barrier in 2009 (left) and cheatgrass seedlings growing through barrier in 2010 (right).


Figure 10. Gulley experiment Unfallowed plots at RYG in 2010. In foreground, plot treated with Plateau is on the left, untreated plot is on the right. The majority of plants on the right are the non-native annual Blue Mustard (*Chorospora tenella*).

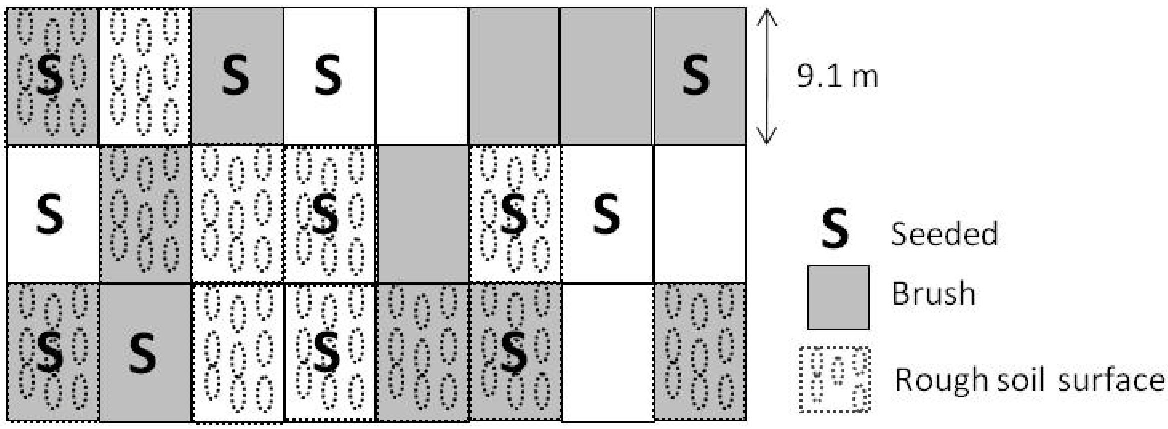


Figure 11. Layout of the Mountain Top experiment at one of 4 research sites.

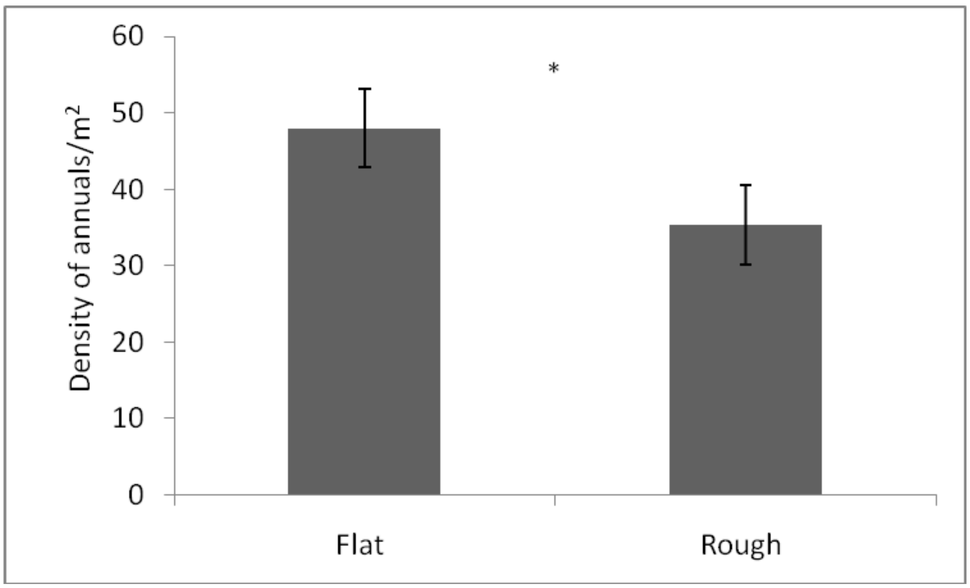


Figure 12. Density of annuals in the Mountain Top experiment in plots with a flat surface versus plots with a rough surface of mounds and holes. Star denotes a significant difference at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

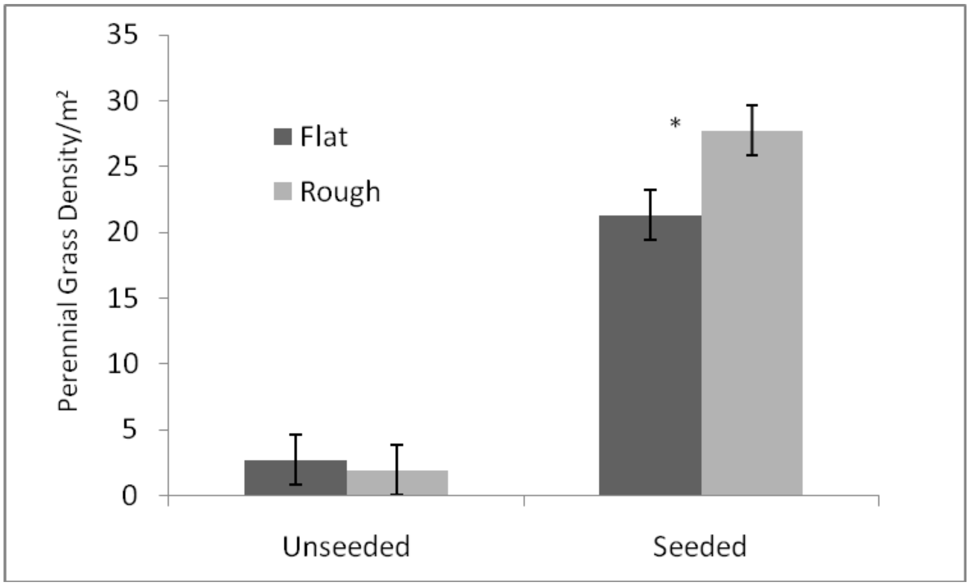


Figure 13. Density of perennial grasses in response to the seeding and soil surface treatments in the Mountain Top experiment. Star denotes a significant difference at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

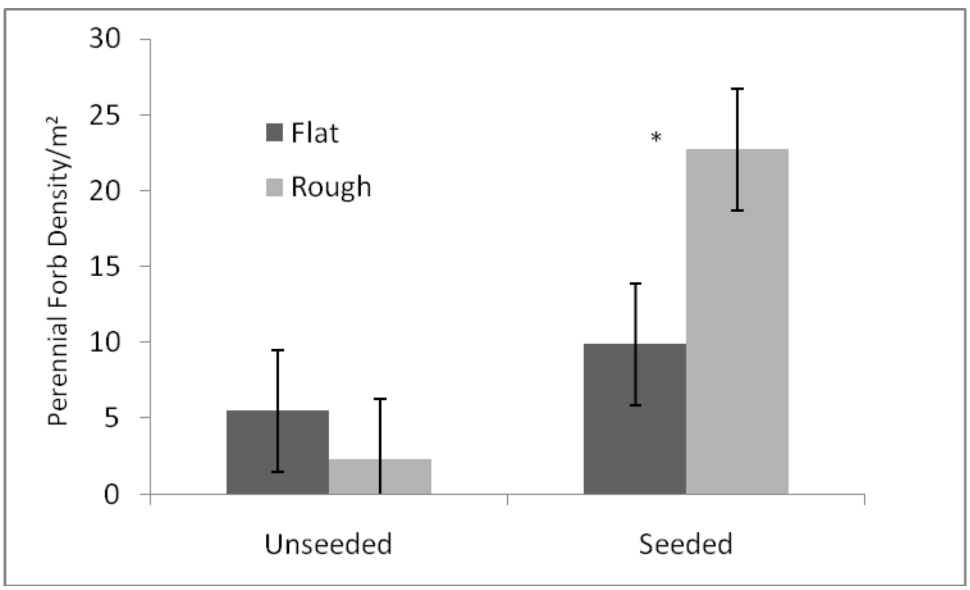


Figure 14. Density of perennial forbs in response to the seeding and soil surface treatments in the Mountain Top experiment. Star denotes a significant difference at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

Figure 15. The rough soil surface/brush treatment in the Strategy Choice experiment.

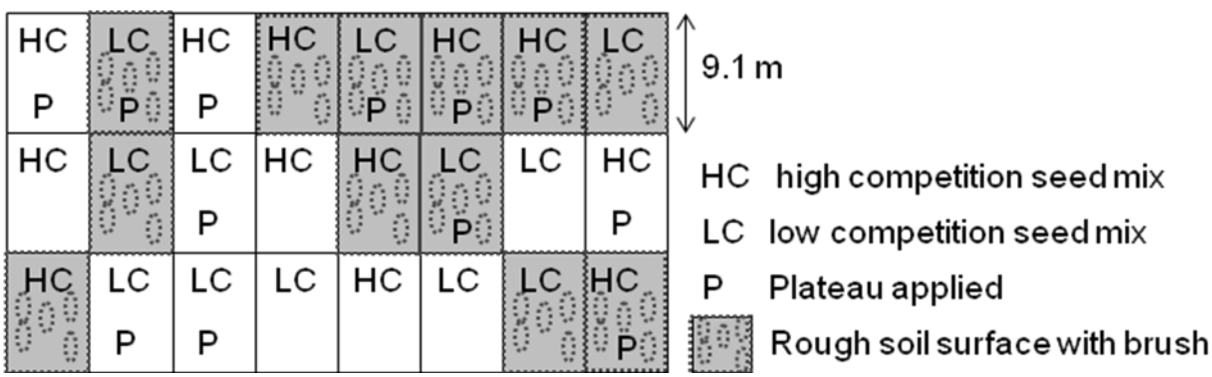


Figure 16. Layout of the Strategy Choice experiments at one of 2 sites where the full experiment was implemented. At 2 additional sites, a reduced form of the experiment lacking the Plateau treatment was implemented.

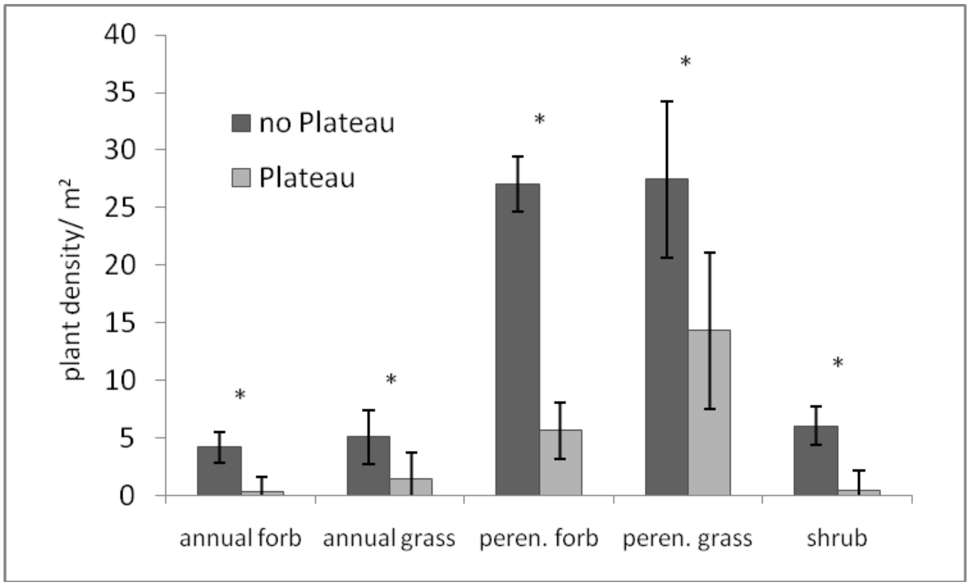


Figure 17. Effect of Plateau herbicide in the Strategy Choice experiment one year after herbicide application and seeding. Stars denote significant differences at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

Figure 18. The Strategy Choice experiment at the MTN site on 10/19/2010. In the foreground, the plot on the left received the high competition seed mix, the flat surface with straw mulch treatment, and no Plateau. The plot on the right received the low competition seed mix, the rough soil surface with brush mulch treatment, and Plateau.

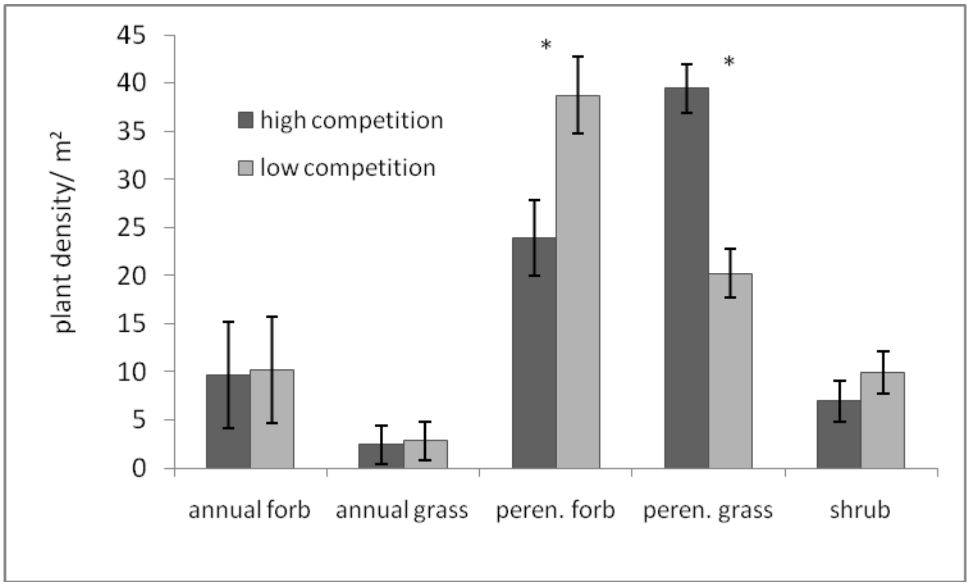


Figure 19. Effect of the seed mix treatment in the Stategy Choice experiment one year after seeding. The high competition mix contained a higher concentration of rhizomatous grasses than the low competition mix. Stars denote significant differences at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

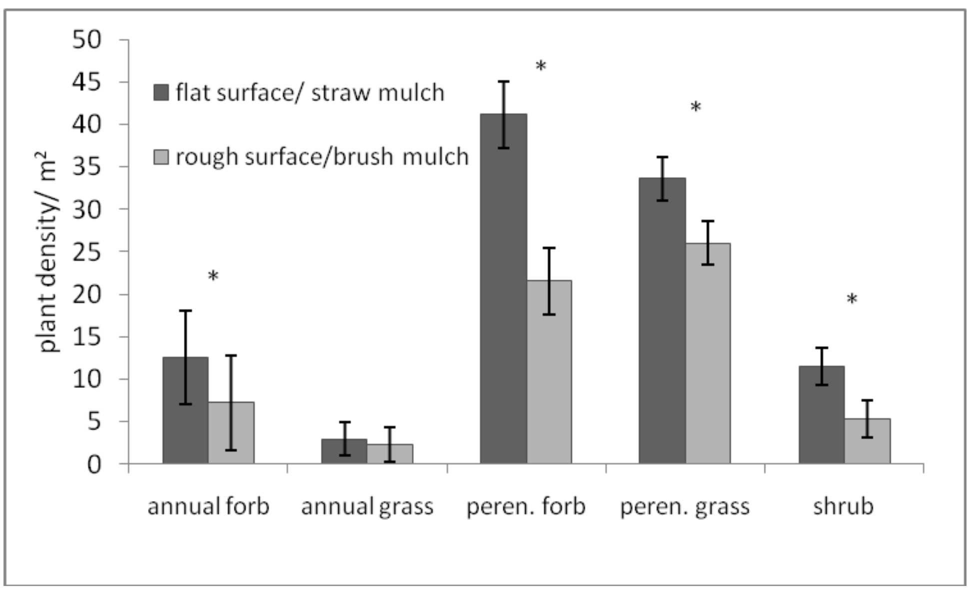


Figure 20. Effect of the soil surface/mulch type treatment in the Strategy Choice experiment one year after implementation. Stars denote significant differences at α = 0.05. Error bars = SE. SE's include random site effects which cancel when means are compared.

APPENDIX 1: MODEL SELECTION RESULTS FOR PIPELINE EXPERIMENT

Table A1. Models of percent cover of perennial grasses. P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	AIC_c	ΔR	Likelihood	W_r
P	-107.7	0.00	1.00	0.295
P, D	-106.8	0.89	0.64	0.188
P, D, R	-105.4	2.34	0.31	0.091
P, R, P*R	-104.4	3.31	0.19	0.056
P, D, P*D	-104.3	3.46	0.18	0.052
P, V, P*V	-104.1	3.63	0.16	0.048
null	-104.0	3.72	0.16	0.046
D	-103.2	4.50	0.11	0.031
R	-103.2	4.54	0.10	0.030
V	-103.0	4.71	0.09	0.028
P, D, R, V	-103.0	4.74	0.09	0.027
P, D, R,P*R	-102.9	4.80	0.09	0.027
P, D, R, P*D	-102.7	5.01	0.08	0.024
P, D, V, P*V	-102.3	5.43	0.07	0.020
D, R	-101.9	5.85	0.05	0.016
P, D, R, P*R, R*D	-100.2	7.50	0.02	0.007
P, D, R, P*D, R*D	-100.0	7.71	0.02	0.006
D, R, D*R	-99.4	8.34	0.02	0.005
P, D, R, P*V, R*D	-97.4	10.33	0.01	0.002

Table A2. Models of percent cover of total annuals. P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	AIC_c	ΔR	Likelihood	W_r
P	-56.7	0.00	1.00	0.45
P, D	-54.5	2.13	0.35	0.16
P, D, P*D	-54.0	2.61	0.27	0.12
P, R, P*R	-52.7	3.92	0.14	0.06
P, V, P*V	-52.4	4.24	0.12	0.05
P, D, R	-52.1	4.52	0.10	0.05
P, D, R, P*D	-51.6	5.10	0.08	0.04
P, D, R,P*R	-50.5	6.18	0.05	0.02
P, D, V, P*V	-50.0	6.61	0.04	0.02
P, D, R, V	-49.6	7.06	0.03	0.01
P, D, R, P*D, R*D	-49.2	7.41	0.02	0.01
P, D, R, P*R, R*D	-48.2	8.50	0.01	0.01
null	-46.2	10.45	0.01	0.00
P, D, R, P*V, R*D	-45.0	11.63	0.00	0.00
D	-44.2	12.49	0.00	0.00
V	-44.0	12.70	0.00	0.00
R	-43.9	12.72	0.00	0.00
D, R	-41.9	14.80	0.00	0.00
D, R, D*R	-39.7	16.93	0.00	0.00

Table A3. Models of percent cover of cheatgrass. P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	**AIC$_c$**	**ΔR**	**Likelihood**	**W$_r$**
P	-39.58	0.00	1.00	0.23
V	-38.74	0.85	0.65	0.15
R	-38.65	0.93	0.63	0.15
D	-38.64	0.94	0.62	0.15
P, D	-37.11	2.47	0.29	0.07
P, R, P*R	-37.05	2.53	0.28	0.07
D, R	-36.27	3.31	0.19	0.04
P, V, P*V	-35.82	3.77	0.15	0.04
P, D, P*D	-35.41	4.17	0.12	0.03
P, D, R	-34.56	5.02	0.08	0.02
P, D, R,P*R	-34.39	5.20	0.07	0.02
D, R, D*R	-33.97	5.61	0.06	0.01
P, D, V, P*V	-33.15	6.43	0.04	0.01
P, D, R, P*D	-32.75	6.83	0.03	0.01
P, D, R, V	-31.98	7.60	0.02	0.01
P, D, R, P*R, R*D	-31.80	7.79	0.02	0.00
P, D, R, P*D, R*D	-30.16	9.42	0.01	0.00
P, D, R, P*V, R*D	-27.77	11.82	0.00	0.00
			4.29	

Table A4. Models of percent cover of perennial forbs. P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	**AIC$_c$**	**ΔR**	**Likelihood**	**W$_r$**
null	-206.7	0.00	1.00	0.355
D	-204.7	2.01	0.37	0.130
P	-204.5	2.22	0.33	0.117
V	-204.4	2.27	0.32	0.114
R	-204.3	2.37	0.31	0.109
P, D	-202.4	4.34	0.11	0.040
D, R	-202.2	4.47	0.11	0.038
D, R, D*R	-201.8	4.94	0.08	0.030
P, D, P*D	-200.4	6.31	0.04	0.015
P, R, P*R	-199.9	6.85	0.03	0.012
P, D, R	-199.8	6.90	0.03	0.011
P, V, P*V	-199.5	7.17	0.03	0.010
P, D, R, P*D	-197.7	8.97	0.01	0.004
P, D, R,P*R	-197.6	9.14	0.01	0.004
P, D, R, V	-197.2	9.54	0.01	0.003
P, D, V, P*V	-197.1	9.56	0.01	0.003
P, D, R, P*D, R*D	-197.1	9.62	0.01	0.003
P, D, R, P*R, R*D	-196.9	9.81	0.01	0.003
P, D, R, P*V, R*D	-193.9	12.79	0.00	0.001

Table A5. Models of percent cover of annual forbs. P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	**AIC_c**	**ΔR**	**Likelihood**	**W_r**
null	-84.0	0.00	1.00	0.248
P	-83.3	0.73	0.69	0.172
D	-82.2	1.75	0.42	0.103
R	-82.1	1.85	0.40	0.098
V	-81.7	2.34	0.31	0.077
P, D	-81.4	2.62	0.27	0.067
P, D, P*D	-80.7	3.29	0.19	0.048
D, R	-80.6	3.43	0.18	0.045
D, R, D*R	-79.5	4.47	0.11	0.027
P, D, R	-79.5	4.47	0.11	0.026
P, R, P*R	-79.0	4.96	0.08	0.021
P, D, R, P*D	-78.8	5.22	0.07	0.018
P, V, P*V	-78.4	5.57	0.06	0.015
P, D, R, P*D, R*D	-77.5	6.51	0.04	0.010
P, D, R,P*R	-77.2	6.81	0.03	0.008
P, D, R, V	-76.9	7.14	0.03	0.007
P, D, V, P*V	-76.4	7.60	0.02	0.006
P, D, R, P*R, R*D	-75.9	8.15	0.02	0.004
P, D, R, P*V, R*D	-72.9	11.07	0.00	0.001

Table A6. Models of percent cover of annual grasses. P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	**AIC_c**	**ΔR**	**Likelihood**	**W_r**
null	-41.5	0.00	1.00	0.317
P	-40.1	1.38	0.50	0.159
V	-39.3	2.24	0.33	0.104
R	-39.2	2.33	0.31	0.099
D	-39.2	2.34	0.31	0.098
P, D	-37.7	3.85	0.15	0.046
P, R, P*R	-37.6	3.86	0.15	0.046
D, R	-36.8	4.71	0.09	0.030
P, V, P*V	-36.4	5.14	0.08	0.024
P, D, P*D	-36.0	5.50	0.06	0.020
P, D, R	-35.1	6.40	0.04	0.013
P, D, R,P*R	-35.0	6.52	0.04	0.012
D, R, D*R	-34.5	7.00	0.03	0.010
P, D, V, P*V	-33.7	7.81	0.02	0.006
P, D, R, P*D	-33.3	8.16	0.02	0.005
P, D, R, V	-32.5	8.97	0.01	0.004
P, D, R, P*R, R*D	-32.4	9.10	0.01	0.003
P, D, R, P*D, R*D	-30.8	10.74	0.00	0.001
P, D, R, P*V, R*D	-28.3	13.17	0.00	0.000

Table A7. Models of percent cover of shrubs. P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	**AIC_c**	**ΔR**	**Likelihood**	**W_r**
R	-264.08	0.00	1.00	0.23
null	-264.00	0.08	0.96	0.22
P, R, P*R	-263.21	0.86	0.65	0.15
D, R	-261.75	2.32	0.31	0.07
V	-261.73	2.35	0.31	0.07
D	-261.73	2.35	0.31	0.07
P	-261.18	2.90	0.23	0.05
P, D, R,P*R	-260.61	3.47	0.18	0.04
D, R, D*R	-260.30	3.78	0.15	0.03
P, D, R, P*R, R*D	-258.96	5.11	0.08	0.02
P, D	-258.70	5.38	0.07	0.02
P, D, R	-258.55	5.53	0.06	0.01
P, V, P*V	-257.37	6.70	0.04	0.01
P, D, P*D	-256.15	7.93	0.02	0.00
P, D, R, V	-256.05	8.03	0.02	0.00
P, D, R, P*D	-255.89	8.19	0.02	0.00
P, D, V, P*V	-254.70	9.37	0.01	0.00
P, D, R, P*D, R*D	-254.13	9.94	0.01	0.00
P, D, R, P*V, R*D	-252.60	11.48	0.00	0.00

Table A8. Models of percent cover of big sagebrush (*Artimesia tridentata*). P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	**AIC_c**	**ΔR**	**Likelihood**	**W_r**
R	-272.5	0.00	1.00	0.271
null	-272.2	0.24	0.89	0.240
D, R	-270.3	2.16	0.34	0.092
V	-270.1	2.33	0.31	0.084
D	-270.0	2.50	0.29	0.078
P, R, P*R	-269.5	2.96	0.23	0.062
P	-269.4	3.02	0.22	0.060
D, R, D*R	-267.9	4.53	0.10	0.028
P, D, R	-267.2	5.30	0.07	0.019
P, D, R,P*R	-267.1	5.39	0.07	0.018
P, D	-267.0	5.46	0.07	0.018
P, V, P*V	-264.7	7.73	0.02	0.006
P, D, R, P*D	-264.6	7.87	0.02	0.005
P, D, P*D	-264.5	7.93	0.02	0.005
P, D, R, V	-264.5	7.97	0.02	0.005
P, D, R, P*R, R*D	-264.4	8.06	0.02	0.005
P, D, V, P*V	-262.2	10.27	0.01	0.002
P, D, R, P*D, R*D	-261.9	10.55	0.01	0.001
P, D, R, P*V, R*D	-259.1	13.36	0.00	0.000

Table A9. Models of Diversity (Shannon Index). P = Plateau treatment, D = disking treatment, R = rolling treatment, V = vibratory drum roller treatment.

Parameter(s) in Model	**AIC_c**	**ΔR**	**Likelihood**	**W_r**
null	35.1	0.00	1.00	0.301
V	36.3	1.16	0.56	0.169
P	36.8	1.64	0.44	0.133
R	37.2	2.04	0.36	0.108
D	37.4	2.30	0.32	0.095
P, D	39.2	4.11	0.13	0.039
D, R	39.5	4.42	0.11	0.033
P, D, P*D	40.1	4.95	0.08	0.025
D, R, D*R	40.3	5.21	0.07	0.022
P, V, P*V	40.6	5.52	0.06	0.019
P, R, P*R	41.5	6.34	0.04	0.013
P, D, R	41.5	6.42	0.04	0.012
P, D, R, P*D	42.5	7.34	0.03	0.008
P, D, R, V	43.2	8.03	0.02	0.005
P, D, V, P*V	43.2	8.05	0.02	0.005
P, D, R, P*D, R*D	43.5	8.38	0.02	0.005
P, D, R,P*R	44.1	9.00	0.01	0.003
P, D, R, P*R, R*D	45.2	10.09	0.01	0.002
P, D, R, P*V, R*D	46.0	10.91	0.00	0.001

Appendix 2: Cheatgrass propagule pressure

Background

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 (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.

Methods

We quantified cheatgrass propagule pressure at each study site using 0.1 m^2 seed rain traps constructed of posterboard covered with Tree Tanglefoot (The Tanglefoot Company, Grand Rapids, MI), a sticky resin (Figure A2-1). Eight traps were set in systematically chosen locations in undisturbed vegetation surrounding each site. Cheatgrass seeds were counted and removed from traps biweekly from 5/11/2010 until 9/28/2010. 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.

Figure A2-1. A seed trap.

Results

Cheatgrass propagule pressure varied widely by site (Figure A2-2).

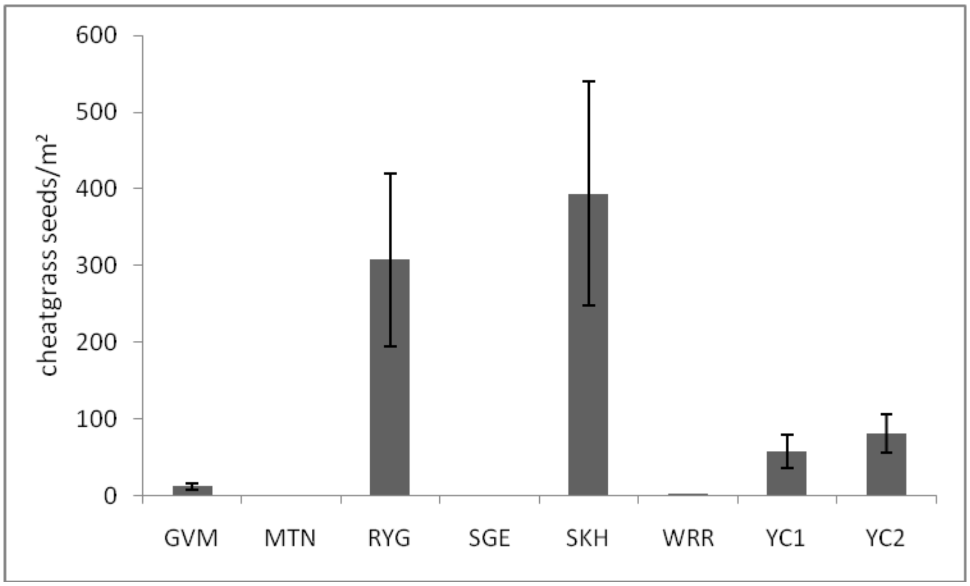


Figure A2-2. Cheatgrass propagule pressure in undisturbed areas surrounding each of 8 study sites, GVM, MTN, RYG, SGE, SKH, WRR, YC1, and YC2. Error bars = SE for 8 traps at each site.

APPENDIX 3: RAIN DATA

Precipitation data were collected at each study site using RG3 datalogging rain gauges (Onset® Computer Corporation) mounted 1.2 m from the ground surface. Rain events were recorded in 0.2mm increments, and then summed over seasons of interest. Gauges at GVM, RYG, SKH, WRR, YC1, and YC2 were installed about May 20, 2009. Gauges at MTN, SGE, SPG, SQS, TGC, and SCD were installed about May 20, 2010. Logger failure resulted in lost data at TGC (all data), SCD (all data), and WRR (winter 09-10 data). Results are shown in Table A3-1.

Table A3-1. Precipitation totals for the study sites. "early growing season" is May 20- July 15; "late growing season" is July 16- September 30"; "prior winter" is the remainder of the year.

	2009		2010		
SITE	**early growing season (mm)**	**late growing season (mm)**	**prior winter (mm)**	**early growing season (mm)**	**late growing season (mm)**
GVM	99	28	169	31	61
MTN				28	75
RYG	111	63	215	29	94
SGE				36	86
SKH	107	33	148	23	55
SPG				54	100
SQS				8	92
WRR	94	45		27	90
YC1	94	41	156	36	112
YC2	82	42	178	41	155