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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 elevations less than ~ 2100m (7000 ft.), 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 elevation near 2100m, 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 and ecological conditions 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, rolling, disking with rolling, and vibratory drum rolling. The tillage treatments were of interest because cheatgrass has been shown to be sensitive to seed burial and soil compaction. Vegetation response was quantified by assessing seedling density in 2009 and percent cover in 2010 and 2011. Three years post-application, Plateau plots had 7-fold higher shrub cover, over 2-fold lower cheatgrass cover, with similar perennial grass and forb cover to no-Plateau plots. Disking reduced initial cheatgrass density, but by the end of the experiment had little effect on cheatgrass cover. Disking slightly improved perennial grass cover, however other tillage treatments were ineffective. Initial cheatgrass density was greatly impacted by the pipeline disturbances, regardless of treatment, and this is attributed to the timing of the disturbance, which maximized cheatgrass seed burial.

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-absorbent polymer called Luquasorb® (BASF Corporation), addition of a soil binding agent called DirtGlue® (DirtGlue® Enterprises), and rolling with a heavy lawn roller. In 2011, vegetation response was quantified by percent cover. Both super-absorbent polymer and binding agent reduced cheatgrass cover by almost half, although neither treatment was effective in the presence of the other. The super-absorbent polymer was effective where applied at 31 g/m^2 but ineffective where applied at 7 g/m^2. No treatments impacted 2011 perennial grass density.

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), and surrounding plots with seed dispersal barriers composed of aluminum window screen secured to oak stakes. Unfallowed plots were seeded in 2009 and fallowed plots were seeded in 2010. In 2011 vegetation was assessed by percent cover. Fallowed plots had drastically lower perennial grass, shrub, and cheatgrass cover, 60% lower forb cover, and higher annual forb cover than unfallowed plots. Some of these differences can be attributed to the 1-year lag in seeding time between fallowed and unfallowed plots, an effect which is expected to lessen in future years. Plateau application reduced perennial grass cover at 1 of 4 sites, increased shrub cover at 3 of 4 sites, reduced perennial forb cover at 2 of 4 sites, and successfully controlled cheatgrass. Barriers increased perennial grass cover by 20% across sites, and reduced annual forb cover by about half in fallowed plots without Plateau at one site.

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 degree to which current seeding practices help or hinder this outcome. Plots left unseeded are compared to plots seeded with a mixture containing a typical density of rhizomatous grass seeds, and these treatments are crossed with treatments designed to create favorable microsites for germination: a rough soil surface treatment consisting of mounds and holes, and a brush mulch treatment. In 2011 vegetation response was quantified by percent cover. Seeding increased perennial grass cover up to 10-fold, increased perennial forb cover up to 4-fold, reduced annual forb cover up to 4-fold, and reduced shrub cover by 50%. The rough surface treatment increased perennial forb cover by 50% across sites when seeded, and controlled annual grasses at the 1 site with sufficient annual grass to permit analysis. The brush treatment increased perennial grass cover at 2 of 4 sites when seeded, and increased shrub cover by 70% across sites in flat surface plots.

The Strategy Choice experiment was implemented in 2009 on simulated well pad disturbances at 4 middle elevation sites with surrounding plant communities that 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 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 brush mulch versus a flat soil surface with straw mulch, and a high competition seed mix, including a typical density of rhizomatous grass seed, versus a low competition seed mix focused on forbs. Vegetation response in 2011 was assessed by percent cover. Plateau treatment successfully controlled annual grasses, but at a high price: perennial grass cover was 4 times lower, perennial forb cover was lower at 1 of 2 sites, shrub cover was almost 3 times lower, and annual forbs were 2 times higher in Plateau plots versus no-Plateau plots. The rough surface treatment increased perennial grass cover at 2 of 4 sites, and brought about an over 7-fold decrease in annual grass cover in plots without Plateau at one site. The rough surface treatment also slightly reduced shrub cover. The seed mix focused on forbs produced 60% higher forb cover than the typical seed mix, with similar cover of weeds between seed mixes.

Results of Plateau application are mixed, generating beneficial results in one experiment, mixed results in another experiment, and largely detrimental results a third experiment. Successful use of this herbicide requires accurately applying a light rate, and focusing on areas with cheatgrass cover prior to disturbance. In areas where cheatgrass is a threat, but is not evident prior to disturbance, using a roughened soil surface may provide adequate cheatgrass control, as was shown at 2 sites in 2 different experiments in this study. The rough soil surface may be effective because when cheatgrass seeds are few in number, they may be trapped within holes, where they experience a wetter microclimate in which they are less competitive. Both the super-absorbent polymer and the binding agent provided some cheatgrass control in 2011, although the super-absorbent polymer has performed more consistently and is less expensive to apply. The seed mix lacking rhizomatous grass seed performed well, producing high forb cover without allowing weed infestation. In the experiment where unseeded and seeded plots were compared, the expected initial result of higher annual forbs and lower perennial grasses and forbs in unseeded plots was found. However, unseeded plots had higher shrub cover than seeded plots, which may ultimately produce a more desirable plant community for wildlife.

Throughout the elevation range of this suite of experiments, treatments were found which improved post-reclamation wildlife habitat. Excellent recovery of wildlife habitat value should be the goal for oil and gas disturbances. The Competition, Gulley, Mountaintop, and Strategy Choice experiments will continue to be monitored in 2012.

RESTORING ENERGY FIELDS FOR WILDLIFE
Annual Progress Report, January 16, 2011- January 15, 2012
Danielle B. Johnston

PROJECT OBJECTIVES

- Develop reclamation techniques for big sagebrush (*Artemisia tridentata*) 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:* Assess vegetation response 3 years following herbicide and tillage treatments by measuring plant cover in 10 plots at each of 6 research sites. Synthesize results over 3 years, and prepare final report for publication.

- *Competition Experiment:* Assess vegetation 2 years following soil additive and compaction treatments by measuring plant cover in 60 plots at each of 2 research sites. Assess soil moisture once in all plots.

- *Gulley Experiment:* Assess vegetation 1 year post-implementation of a fallowing treatment, and two years post-treatment in non-fallowed plots. Measure plant cover in 24 plots at each of 4 research sites.

- *Mountain Top Experiment:* Assess vegetation 2 years following seeding, soil surface roughening, and brush mulch treatments by measuring plant cover in 24 plots at each of 4 research sites.

- *Strategy Choice Experiment:* Assess vegetation 2 years following herbicide, soil surface roughening, and seed mix treatments by measuring plant cover in 12-24 plots at each of 4 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 which cause large-scale disturbances, such as coal mining companies. In oil and gas fields, however, local reclamation trials are difficult to implement due to the spatial pattern of disturbance.

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

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

The Piceance Basin in northwestern Colorado provides an ideal laboratory for conducting a large-scale study of restoration techniques. The area is 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.

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, and some treatments are tested in multiple experiments. Overlap of treatments allows the experiments to relate to one another in a way that will permit broad-scale conclusions, if appropriate, while the differences in the experiments permit tailoring of particular treatments to those portions of the landscape where they are potentially useful.

The 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 purported ability to bind soil particles while increasing water infiltration. The combination of soil binding agent with rolling was of interest because of the potential for creating a crust that might hinder cheatgrass emergence.

The 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 CPW study demonstrated that a sufficient number of cheatgrass seeds may disperse from the edges of disturbance to compromise reclamation efforts (Johnston 2011a).

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, creates microsites of higher moisture availability, and traps dispersing seeds (Chambers 2000). Similarly, brush mulch creates favorable germination conditions by causing snow to drift, creating shade, entraping seeds (Kelrick 1991), and perhaps also providing a source of 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 order to establish a diverse plant community?

The Strategy Choice experiment was conducted at middle-elevation sites where the degree of threat from invasive weeds is ambiguous. Such situations raise the question: should one take a conservative strategy by seeding a highly competitive seed mix, using aggressive weed control measures, and avoiding contaminating the site with seed from the surrounding area? Such measures often come at a price of reduced plant diversity and forb establishment (Marlette and Anderson 1986, Chambers 2000, Krzic et al. 2000, Baker et al. 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 the use of herbicide, and entrapping seeds via brush mulch, holes, or other mechanisms. An optimistic strategy is the obvious choice when the surrounding plant community is desirable, and the risks of soil erosion and weed invasion are low. This study compares the results of these 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.

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

STUDY AREA

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

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

METHODS: DISTURBANCE CREATION

Two types of disturbances, simulated pipelines and simulated well pads, were created in order to provide templates for the experiments. Pipeline disturbances measured 11 m X 52 m and were simulated using a bulldozer and a backhoe. Vegetation was scraped and discarded, the top 20 cm of topsoil was scraped and stockpiled, and then a 1 m wide X 1 m deep trench was dug. Trenches were left open 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 to which subsoil disturbance occurs. Well pad disturbances measured 31 m X 52 m and were simulated using a bulldozer. Vegetation was cleared, the top 20 cm of topsoil was scraped and stockpiled in windrows less than 2 m in height, and then the subsoil was cut and filled to create a level surface. The initial work was completed in July and August of 2008, and the surface was kept weed-free for one year by repeated hand-spraying of emerging plants with 2% (v/v) glyphosate. In August of 2009, the subsoil was recontoured to approximate the original contour, and the stockpiled topsoil spread evenly across the surface of the site. Simulated well pads were created in 12 locations, each with slopes of 5% or less. The Gulley, Strategy Choice, Competition, and Mountain Top experiments were implemented on the well pad disturbances in 2009 and 2010.

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 and promoting perennial plants.
- 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
- Responses measured: seedling density (2009) and plant cover (2010 and 2011). As this experiment is now mature, all 3 years of post-treatment data are synthesized in this report.

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, and 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 due to access contraints.

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).

Soil bulk density samples were used to compare sites and to compare on-disturbance vs. off-disturbance locations. Jornada cone penetrometer measurements (Herrick and Jones 2002) were used to quantify within-site differences between the tillage plots. Penetrometer measurements are much more easily obtained, but because penetration resistance depends on soil moisture, penetration resistance is poor choice for comparing differences between sites (Miller et al. 2001). Bulk density samples were taken in September of 2008 using a 30.5 cm drop-hammer double cylinder core sampler fitted with 6 abutting 5.1 cm-long inner cylinders. Five cores were taken in undisturbed areas near each site, and 6 cores, 3 in each C soil treatment subplot, were taken within pipeline disturbances. A piece of metal flashing was inserted between adjoining cylinders to separate each core into 6 depth fractions. The dry weight of each fraction was divided by its volume to find bulk density. Five penetrometer measurements were taken in each subplot in May of 2009. The number of hammer drops required to move the penetrometer through the soil was recorded for each 5 cm depth increment from 4 cm to 29 cm, and the force required to penetrate the soil was calculated for each depth fraction.

Seedling counts were conducted in May and July of 2009 for 9 miniplots within each subplot, with one miniplot in the center of the subplot, and the remaining miniplots equidistant from the center miniplot and either a subplot corner or the midpoint of a subplot edge. Because seedling density varied widely from site to site, the size of the sampled miniplot was allowed to vary from 300 to 3000 cm^2 so that an area sufficient for sampling was obtained. In May, only cheatgrass seedlings were counted. In July, all seedlings were counted. Cheatgrass seedlings were also counted in 9 miniplots in undisturbed vegetation near the study sites in May and July of 2009.

Percent cover by species was quantified in July of 2010 and 2011. In 2010, nine $1m^2$ miniplots were arrayed systematically per subplot as described above. In 2011, five $1m^2$ miniplots were sampled per subplot, one in the center of the subplot, and the remaining miniplots equidistant from the center miniplot and a subplot corner. A grid containing thirty-six intersections was held over each miniplot, and point-intercept hits were measured at each grid intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT). All layers of vegetation were identified to species at each hit. When calculating percent cover of a given functional group (perennial grasses, perennial forbs, annual forbs, cheatgrass, or shrubs), overlapping hits of different species within a functional group (for instance, western wheatgrass overlying Sandberg bluegrass) were counted as a single instance of the functional group.

Cheatgrass propagule pressure was quantified using techniques outlined in Appendix 1. Seeds caught per square meter per Julian date was calculated and then averaged over years for each site.

Analysis of variance (ANOVA) in SAS PROC MIXED (SAS Institute Inc., Cary, NC) was used to analyze differences in responses to treatments. Site was considered a random effect. For bulk density, separate analyses were done for each depth fraction, and the fixed effect was a location variable (on or off pipeline). For penetration resistance, separate analyses were done for each depth fraction, and the fixed effects were the soil tillage treatments. Density and cover data were analyzed separately by functional group (cheatgrass, annual forbs, perennial grasses, perennial forbs, and shrubs), and a site*Plateau random effect was used to account for the split-plot design. Biennial forbs were lumped with annual forbs. Cover data was transformed by an arcsine [square root (x)] transformation to improve normality. For cover data, fixed effects were treatments and up to 3-way interactions among them. For cheatgrass seedling density and cover, a repeated measures ANOVA was performed, with season or year as a fixed effect, and up to 3-way interactions involving season or year included in the initial model. The final model was determined using a backwards selection process with a cutoff value of $\alpha = 0.05$ for means and $\alpha = 0.10$ for interactions. Effect sizes are presented with 95% confidence intervals. Linear regression was used to examine the effect of soil penetration resistance on cheatgrass seedling density and cover, using only non-disked plots without the Plateau treatment.

Results

The creation of the simulated pipeline disturbances increased soil bulk density by 0.13 ± 0.05 g/cm^3. The increase in bulk density was evident at all depth fractions except the 5-10 cm depth fraction ($p < 0.01$, Figure 3). Bulk density also varied across study sites with the discrepancy between the two most disparate sites, RYG and SKH, being 0.29 ± 0.08 g/cm^3. Off-pipeline, bulk density in the uppermost depth fraction varied from 0.64 g/cm^3 to 1.41 g/cm^3 with a mean of 1.06 g/cm^3. On-pipeline, bulk density in the uppermost depth fraction varied from 0.77 g/cm^3 to 1.52 g/cm^3 with a mean of 1.21 g/cm^3(Figure 3).

The soil tillage treatments significantly affected soil penetration resistance (Figure 4). For the 4-9 cm depth fraction, the soil had 99 ± 34 N greater resistance in the V treatment than in the control, 134 ± 29 N less resistance in the D treatment than in the control, and 74 ± 29 N less resistance in the DR treatment than in the control (Figure 4a). For the 9-14 cm depth fraction, the V treatment had 163 ± 64 N more resistance than the control, and the D treatment had 171 ± 56 N less resistance than the control (Figure 4b). For the 14-19 cm depth fraction, penetration resistance was 230 ± 107 N greater in the V treatment than in the control (Figure 4c). Differences were not evident for any treatment at depths greater than 19 cm, and the R treatment was not significantly different from the control at any depth.

In undisturbed, off-plot locations, 2009 cheatgrass seedling density was 506 ± 216 plants/m^2 in May and 139 ± 75 plants/m^2 in July. In treatment plots, 2009 cheatgrass seedling density was influenced by interactions between Plateau and season ($p < 0.0001$) and between Plateau and disking treatment ($p = 0.03$). Cheatgrass seedling density increased from 41 ± 20 in May to 201 ± 82 plants/m^2 in July in plots without Plateau ($p < 0.0001$), but there was no seasonal difference in plots with Plateau ($p = 0.12$; Figure 5). In May, Plateau reduced cheatgrass density from 53.3 plants/m^2 to 11.1 plants/m^2 in non-disked plots ($p = 0.03$), but had no detectable effect in disked plots ($p = 0.62$). In May, disking reduced cheatgrass seedling density from 53.3 to 23.3 plants/m^2 in the absence of Plateau ($p = 0.008$), but made no significant difference when applied with Plateau ($p = 0.83$; Figure 5). In July, Plateau reduced cheatgrass density from 242.5 to 44.0 plants/m^2 in undisked plots ($p = 0.03$), but had no detectable effect in disked plots ($p = 0.32$). In July, disking reduced cheatgrass seedling density from 242.5 to 138.6 plants/m^2 in plots without Plateau ($p = 0.002$), but had no detectable effect in plots with Plateau ($p = 0.87$; Figure 5). There were no detectable effects of any treatments on July seedling density of perennial grasses, perennial forbs, annual forbs, shrubs, or sagebrush. There was no significant relationship between soil penetration resistance and cheatgrass seedling density in May ($R^2 = 0.08$; $p = 0.27$) or July ($R^2 = 0.05$; $p = 0.43$).

Cheatgrass cover was influenced by year ($p = 0.03$), a strong main effect of Plateau ($p = 0.003$), and an interaction between disking and Plateau ($p = 0.02$). Cheatgrass cover increased from 32.9% in 2010 to 40.0% in 2011. Averaged across years and other treatments, cheatgrass cover was 52.1% in plots without Plateau and 21.6% in plots with Plateau. Disking tended to produce opposite effects depending on whether or not Plateau was applied, although individual contrasts of means were not significant. With Plateau, disking may have increased cheatgrass cover, from a mean of 17.6% to 25.7% ($p = 0.06$). In the absence of Plateau, disking may have decreased cheatgrass cover, from 54.6% to 47.8% ($p = 0.10$; Figure 6). There was no significant relationship between soil penetration resistance and cheatgrass cover in 2010 ($R^2 = 0.03$; $p = 0.37$) or 2011 ($R^2 = 0.02$; $p = 0.43$).

Perennial grass cover was influenced by disking ($p = 0.01$) and by year ($p = 0.002$). Perennial grass cover increased from 21.5% in 2010 to 27.5% in 2011. Averaged over years, perennial grass cover was 26.1% in disked plots and 22.9% in non-disked plots.

Perennial forb cover was not influenced by any factors ($p > 0.20$). Annual forb cover was not influenced by any treatments, but dropped from 26.0% in 2010 to 16.6% in 2011 (year effect $p = 0.0006$).

Shrub cover was influenced by an interaction between Plateau and year ($p = 0.001$) and a likely interaction between Plateau and rolling treatment ($p = 0.06$). In 2010, no Plateau effect was evident ($p = 0.24$), and shrub cover averaged 1.5%. In 2011, shrub cover depended on Plateau treatment ($p = 0.002$) with 9.1% shrub cover in Plateau plots and 1.2% shrub cover in no-Plateau plots (Figures 7 and 8). Rolling had no apparent effect in the absence of Plateau ($p = 0.75$) but with Plateau, shrub cover dropped from 7.7% in not-rolled plots to 4.0% in rolled plots ($p = 0.02$; Figure 7).

Ambient cheatgrass propagule pressure in the study areas peaked between early June and mid-July, and then taperd off by early September (Figure 9). Peak values varied from 160 seeds/m^2·day at SKH to 1 seed/m^2·day at WRR (Figure 9).

Discussion

The Plateau treatment reduced cheatgrass seedling density and cover, and effects were still evident 3 years post-treatment. The Plateau treatment also greatly increased shrub cover 3 years post-treatment, and had no effect on forb or grass cover. These results contrast with some other studies in Wyoming big sagebrush plant communities, in which cheatgrass cover in plots where Plateau was applied rebounded to levels as high (Owen et al. 2011) or higher (Morris et al. 2009) than that of control plots in 2-3 years, or in which Plateau negatively affected forbs (Baker et al. 2009, Owen et al. 2011) or grasses (Strategy Choice Experiment in this document, *see below*). Several factors likely contributed to the positive effect of Plateau in the Pipeline Experiment, including the timing of the pipeline disturbances, the application method and rate, and the timing of herbicide application relative to sagebrush seeding.

The timing of the pipeline disturbances may have reduced cheatgrass propagule pressure, acting additively with the herbicide to provide enough cheatgrass control for desirable perennial plants to establish. Prior work has shown that Plateau is more effective on annual grasses when applied after disturbances such as burning (Sheley et al. 2007, Davies and Sheley 2011). In a rate trial study, 70 g/ha of Plateau, when applied to bare soil, was as effective as 210 g/ha when applied without disturbance (Kyser et al. 2007). The reason commonly cited for the disturbance effect is that the herbicide reaches the soil surface more easily in the absence of thatch (DiTomaso 2000, Kyser et al. 2007, Sheley et al. 2007, Davies and Sheley 2011). However, the effect of disturbance at reducing propagule pressure is probably also an important factor, as burns can reduce cheatgrass seed density by 97% (Humphrey and Schupp 2001). In the spring following the pipeline disturbances, in the absence of Plateau, cheatgrass seedling density was 5-fold lower in disturbed versus undisturbed locations. This may have been due to the timing of the disturbances the prior year. Cheatgrass seed distribution in the study areas peaks in June and continues until September (Figure 9), and the pipeline disturbances were completed in September. Topsoil removal, stockpiling, and replacement likely buried the majority of cheatgrass seeds which had fallen on the soil surface during the 2008 growing season. The Plateau application may have been sufficient to provide continuing control for the portion of seeds that remained viable.

The Plateau rate used in this study, 105 g ai/ha (6 oz./acre), avoided substantial effects on forbs, which has been seen with rates of 132 g ai/ha (8 oz./acre) or higher (Baker et al. 2009, Owen et al. 2011), and was neutral with respect to grasses. Forbs, grasses, shadscale saltbush (*Atriplex confertifolia*), and fourwing saltbush (*Atriplex canescens*) were planted 2-20 days after herbicide application in this study. Another study has shown that the amount of time between Plateau application and seeding is important for western wheatgrass biomass, with a 90-day interval resulting in a positive impact of Plateau, and shorter intervals resulting in inconsistent or negative impacts (Sbatella et al. 2011). It is possible that a positive effect on grasses might have been realized in this study had the plant-back interval been longer. As big sagebrush was broadcast over snow, sagebrush plant-back interval was 75-90 days. This may explain why the Plateau treatment improved shrub cover to a greater degree than grass cover, as 77% of shrub cover was big sagebrush cover.

The effects of Plateau on shrub and cheatgrass cover are likely intertwined. In a study of competitive dynamics between cheatgrass and big sagebrush, sagebrush and cheatgrass competed for soil water, and cheatgrass cover increased when sagebrush was removed (Prevey et al. 2010). In plots where Plateau was applied, sagebrush appears to have established well enough to limit cheatgrass cover, resulting in a long-term effect of Plateau on the composition of the plant community.

The disking treatment was moderately effective at reducing cheatgrass seedling density and improving perennial grass cover. This was probably in part due to directly killing germinating cheatgrass plants, as disking was applied near the time of cheatgrass emergence. Disking may have also helped improve perennial grass cover by relieving compaction of the rooting zone, which can restrict root growth and compromise establishment of deeply-rooted perennial plants (Thompson et al. 1987). Disking may also have buried a few cheatgrass seeds which distributed over the disturbance in the 3- 4 weeks between when the pipelines were reclaimed and the disking treatment was applied. However, the creation of the pipeline disturbances themselves likely achieved the majority of the benefit to be gained by this strategy. A recent study demonstrated that cheatgrass seeds distribute themselves very readily over bare soils (Johnston 2011a). The longer bare soil is exposed, the more important it may be to apply an additional disturbance to bury cheatgrass seeds, particularly if bare soil is exposed during the summer.

The goal of the rolling treatments was to increase soil bulk density to 1.2 -1.3 g/cm^3, as bulk densities in this range may reduce cheatgrass emergence by 52-60% (Thill et al. 1979). The pipeline disturbances increased bulk density from 1.1 to 1.2 g/cm^3, and the vibratory drum treatment further increased soil density. However, there was no effect of the vibratory drum treatment on cheatgrass, and no correlation between soil penetration resistance and cheatgrass seedling density or cover. In the field, whenever the soils presented a dense upper layer, cheatgrass was noted growing through cracks. Creating a layer of uniformly dense soil that would impede cheatgrass emergence may require the use of a soil binding agent, or may not be possible with soil types which shrink and swell, such as those found at the majority of sites in this study. Rolling also had a negative effect on shrub cover, therefore rolling is not recommended.

In summary, a moderate rate of Plateau can be successful in limiting cheatgrass and promoting perennial plant establishment in pipeline restoration in Wyoming big sagebrush plant communities. The success of restoration may depend on using the disturbance itself to bury some cheatgrass seeds, and then applying herbicide for continuing control. If a reclaimed surface is left exposed during the time when cheatgrass seeds are distributing, it may also be helpful to disk the surface prior to planting. Rolling the surface to discourage cheatgrass emergence is not recommended. The initial, intensively monitored phase of the Pipeline Experiment is now considered to be complete. Monitoring of the Pipeline Experiment in the future will limited to every 3rd year.

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 10).
- Plot size: 2.4 m X 2.4 m
- 5 replicates per site
- Responses measured: Cover of perennial grasses and cheatgrass

Methods

Cheatgrass seed was collected using a lawnmower with a bagging attachment from monocultures or near-monocultures in 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 then immediately lightly raked to incorporate seed into the soil. The 300 seeds/m^2 seeding rate is about 25% of the 2009 cheatgrass seed production at heavily cheatgrass-infested sites quantified for the Pipeline experiment, and therefore thought to be a reasonable seed density for a Piceance Basin site in the initial phases of invasion.

A mixture of native wheatgrasses (Table 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 agricultural purposes.

Next, whole plots receiving the rolling treatment were rolled 10 times with a static roller supplying a linear load of 36.5 N/cm (20.8 lbs/in). Binding agent 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, percent cover by species was quantified in late July and early August, 2011 in a 1 m X 1 m subplot centered within each plot. A grid containing thirty-six intersections was held over the subplot, and point-intercept hits were measured at each grid intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT). All layers of vegetation were identified to species at each hit. When calculating percent cover of perennial grasses, overlapping hits of different species within that functional group (for instance, western wheatgrass overlying Sandberg bluegrass) were counted as a single instance of the functional group.

Three soil moisture readings were made in random locations within each plot on 6 June, 16 June, and 19 July 2011. Readings were taken to 12 cm using a Hydro Sense® Soil Water Measurement System (Campbell Scientific, Inc, Logan, Utah) and were averaged for each plot on each date. At SGE on 16 June, only 15 of 60 plots were sampled due to equipment failure.

The cover of perennial grasses, cover 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 completely randomized whole plots. For cover data, site was included as a fixed effect, and interactions between treatments and site were also considered. Cover data was transformed by an arcsine [square root (x)] transformation to achieve normality. Soil moisture data was not transformed, and sites were analyzed separately. Due to the high proportion of missing data points at SGE on 16 June, the June 16 date was not analyzed at SGE.

Main effects and all possible interactions were included as fixed effects in the initial model, and a backwards model selection process was used to determine the final model. A significance level of $\alpha =$

0.05 was used to determine significantly different means, and a level of α = 0.10 for interactions was used to determine which means to compare. For volumetric soil moisture, a repeated measures analysis with a compound symmetry autocorrelation coefficient was incorporated within the split-split plot design, and interactions between treatment effects and measurement date were included as fixed effects.

Results

Perennial grass cover was influenced by site (p = 0.0004). Perennial grass cover averaged 45.7% at SGE and 58.5% at WRR. No treatments or interactions significantly affected perennial grass cover (p > 0.15).

Cheatgrass cover was influenced by site (p = 0.0005), a probable interaction between site and SAP, and an interaction between SAP and binding agent (p = 0.05). At SGE, cheatgrass cover averaged 11.2%, and no difference in SAP versus no SAP plots was evident (p = 0.93). At WRR, SAP reduced cheatgrass cover (p = 0.02) from a mean of 33.8% in plots without SAP to 22.4% in plots with SAP. Averaged across sites, in the absence of binding agent, SAP reduced cheatgrass cover (p = 0.006), but had no apparent effect with moderate or high levels of binding agent (p > 0.26). In the absence of SAP, the high binding agent treatment reduced cheatgrass cover from 26.8% to 16.9% relative to no binding agent treatment (p = 0.01). There was no significant difference between the moderate binding agent treatment and the no binding agent treatment, and there were no differences between any binding agent treatment levels in the presence of SAP (p > .20; Figure 11).

Volumetric soil moisture at WRR was influenced by many interacting effects, including 3 different 3-way interactions: rolling with SAP and binding agent (p = 0.04), date with rolling with SAP (p = 0.04), and date with rolling and binding agent (p = 0.02); 2 different 2-way interactions: rolling treatment with SAP (p = 0.01), and binding agent with date (p = 0.005), and two main effects: date (p < 0.0001) and binding agent (p = 0.0009). Soil moisture averaged 24.0% on June 3, 9.5% on June 16, and 11.4% on July 19 (Figure 12). On June 3, plots with low or high binding agent had 3.2 ± 2.1 % higher soil moisture than plots with no binding agent (Figure 12). On June 16 there was no difference due to binding agent (p > 0.36), and on July 19, there were no differences at the α = 0.05 level (p > 0.06, Figure 12). The nature of the rolling by SAP interaction was such that SAP tended to increase soil moisture in the absence of rolling, but decrease soil moisture when applied with rolling (Figure 13). This 2-way interaction was influenced by date and binding agent. On June 3, there was a probable 3-way interaction between binding agent, SAP, and rolling (p = 0.07). With no or low binding agent, there were no clear effects of rolling, SAP, or their interaction (p > 0.07). With high binding agent, rolling and SAP interacted (p = 0.008) such that SAP increased soil moisture by 5.3 ± 4.7 % in the absence of rolling, but reduced soil moisture by 4.8 ± 4.6 % when applied with rolling (Figure 13). On June 16, there were no clear treatment effects (p > 0.08). On July 19, a 3-way interaction occurred between rolling, SAP and binding agent (p = 0.05). With no binding agent, rolling and SAP interacted (p = 0.05) such that SAP may have increased soil moisture in the absence of rolling, but reduced soil moisture in the presence of rolling (although individual contrasts were non-significant). With low binding agent, there were no clear treatment effects (p > 0.41). With high binding agent, rolling and SAP interacted (p = 0.05) such that SAP may have increased soil moisture in the absence of rolling, but reduced soil moisture in the presence of rolling (although individual contrasts were non-significant; Figure 13).

At SGE, soil moisture was higher on June 3 than July 19, but there were no treatment effects (p > 0.20).

Discussion

Under certain conditions, both binding agent and SAP reduced cheatgrass cover. Where SAP was not applied, the high binding agent treatment reduced cheatgrass cover, and where the binding agent treatment was not applied, the SAP treatment reduced cheatgrass cover. Averaged over binding agent treatments, SAP reduced cheatgrass cover from 34% to 22% at WRR, where it was applied at 30.8 g/m^2, but not at SGE, where SAP was applied at 6.7 g/m^2. In the absence of binding agent, SAP reduced cheatgrass cover from 37.5% to 19.7% at WRR.

Binding agent, SAP, and rolling interacted in complex ways to influence soil moisture. Binding agent increased soil moisture at WRR on 1 of 3 measurement dates in 2011, and increased soil moisture at both SGE and WRR on 1 of 2 measurement dates in 2010. These results confirm the manufacturer's claim that the product tested increases water infiltration, resulting in increased soil water at some points in time. At WRR in 2011, on certain dates and at certain levels of binding agent, there was an interaction by which SAP increased soil moisture in plots that were not rolled, but decreased soil moisture in plots that were rolled. This may be related to a pattern of perennial grass density which was evident in the 2010 data. In rolled plots at WRR, SAP promoted 2010 perennial grass density. Higher grass density would likely result in quicker utilization of soil moisture, resulting in the observed pattern in the soil moisture data.

It is unclear why neither SAP nor binding agent affected 2011 perennial grass cover, while effects of both of these products on cheatgrass cover are evident. It is possible that perennial grasses benefit from these products, but that the benefits are yet only realized belowground. The aboveground response of cheatgrass may be more sensitive to these treatments because cheatgrass fluctuates more widely in response to resource variability than do perennial plants (Bradley 2009). Another possibility is that there is some direct negative influence of SAP and binding agent on cheatgrass.

It is interesting to note that the effect of binding agent and SAP on cheatgrass cover seem to cancel one another. While both of these products reduced cheatgrass cover in 2011, neither was effective the presence of the other. The effect of each of these additives on soil moisture and competitive dynamics is complex. For management purposes, the most important task is to determine which application or combination of applications may aid in cheatgrass control.

The effect of binding agent on cheatgrass has been inconsistent. In 2010, cheatgrass cover increased with the low level of binding agent at SGE. In 2011, lower cheatgrass cover was apparent in plots with the high binding agent treatment. This could be due to the stage of the experiment, and/or to different precipitation in different years. In 2010, early June soil moisture averaged 25%, while in 2011, it averaged 35%. The binding agent might have helped cheatgrass overcome a spring moisture limitation in 2010, while in 2011 the overriding factor may have been amplification of rain events critical for perennials.

Cheatgrass has adapted to complete its life cycle before the dry period of the summer in the intermountain west (Rice et al. 1992), making it an effective competitor in arid ecosystems with variable soil moisture (Chambers et al. 2007). By absorbing water and then gradually releasing it into the soil, SAPs can reduce the variability in soil moisture over time. With respect to cheatgrass control and perennial grass establishment, SAP addition had only beneficial or neutral effects. In addition to more reliably producing desirable results than the binding agent treatment, SAP addition is less expensive and requires less mobilization of machinery. In order to apply the binding agent in the manner tested in this study, 3200 gal/ac of water is needed, requiring a water truck. In contrast, granulated SAP can easily be applied through a drill seeder or fertilizer spreader.

If results from 2012 corroborate those already observed, then addition of super-absorbent polymer at 30 g/m^2 may be a useful tool for promoting perennial grasses under competition from cheatgrass. Future work may involve investigating the best application method and rate of SAP, and testing SAP addition in combination with other treatments that alter soil moisture.

GULLEY EXPERIMENT

Overview

- Goal*:* identify which potential sources of weeds are important to control: those that originate from within the soil seed bank of the reclamation area, those that enter from the surrounding landscape, or both.
- Conducted at 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 whole plot factor was fallowing, the subplot factor was seed barriers, and the sub-subplot factor was Plateau (Figure 14). Whole plots were completely randomized.
- 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 them individually. Seed was mixed 1:1 by volume with rice hulls to aid in even distribution of species. Seed was lightly raked to incorporate it into the soil after broadcasting. The same day as seeding, Plateau was applied at 140 g ai/ha (8 oz/ac) with 655 li/ha (70 gal/ac) of water using a backpack sprayer to Unfallowed, Plateau plots. Dye indicator was used to ensure even application.

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

During the 2010 growing season, Fallowed plots were maintained in a nearly unvegetated condition by applying glyphosate at 560 g/ac (8 oz./ac) in early June, and hand-pulling any plants nearing seed production in late June. In early September, 2010, soil compaction was relieved in Fallowed plots by ripping to 30 cm with a Plotmaster™ 400 (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 that had been caught in the dispersal barriers in 2009 germinated and grew through the barrier In order to fortify the barriers, we applied Plateau at 140 g ai/ha (8 oz/ac) in a 0.1 m strip between 9/14/10 and 9/28/10 at the base of the barrier.

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

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

The cover of perennial grasses, perennial forbs, annual forbs, annual grasses, and shrubs in response to site, fallow treatment, Plateau treatment, and barrier treatment was analyzed using ANOVA in

SAS PROC MIXED. All factors were considered fixed. Site and fallowing were considered between-subject effects for whole plots, and Barriers and Plateau treatment (nested within Barriers) were considered within-subject effects. Biennial forbs were lumped with annual forbs. Cover data was transformed by an arcsine [square root (x)] transformation to achieve normality. A full model including all possible interactions was first considered, and a backwards model selection process was used to determine the final model. A significance level of $\alpha = 0.05$ was used to determine significantly different means, and a level of $\alpha = 0.10$ for interactions was used to determine which means to compare. The percentage of native versus non-native species was calculated for all functional groups.

Results

Perennial grass cover was influenced by site, fallowing treatment, and their interaction ($p < 0.0001$), barrier treatment ($p = 0.05$), and an interaction between site and Plateau treatment ($p = 0.03$). Fallowing reduced perennial grass cover from 19.6 to 3.8% at RYG, 45.7 to 3.1% at SKH, 63.5 to 7.6% at YC1, and 26.7 to 2.6% at YC2 ($p < 0.0008$; Figure 15a-d). Barriers increased perennial grass cover from an average of 19.5% in No Barrier subplots to 23.7% in Barrier subplots (Figure 16a). Plateau reduced perennial grass cover from 27.6 to 21.3% at SKH ($p = 0.01$), while Plateau effects at other sites were non-significant ($p > 0.06$). 94% of perennial grass cover was native.

Perennial forb cover was influenced by site, fallowing treatment, plateau treatment, and an interaction between site and Plateau treatment ($p < 0.0008$). Across sites, perennial forb cover averaged 8.1% in unfallowed plots and 5.4% in fallowed plots. Plateau treatment had an effect at YC1 and YC2 ($p < 0.0001$), but no apparent effect at SKH or RYG ($p > 0.39$). At YC1, perennial forb cover averaged 5.4% in Plateau plots and 23.3% in no Plateau plots. At YC2, perennial forb cover averaged 3.1% in Plateau plots and 10.5% in no Plateau plots (Figure 15e-h). 99% of perennial forb cover was native.

Annual forb cover was influenced by many interacting effects, including a 4-way interaction between site, fallowing treatment, barrier treatment, and Plateau treatment ($p = 0.004$). The analysis will be presented site-by-site. At RYG, Plateau treatment and fallowing treatment likely interacted ($p = 0.06$). Unfallowed, no-Plateau plots averaged 37.0% annual forb cover, fallowed-only plots averaged 58.1%, Plateau-only plots averaged 6.9%, and plots both fallowed and treated with Plateau averaged 5.6% (Figure 15i). At SKH, Plateau and fallow treatment interacted ($p = 0.007$). Unfallowed, no-Plateau plots averaged 48.0% annual forb cover, fallowed plots averaged 54.6%, Plateau plots averaged 4.9%, and plots both fallowed and treated with Plateau averaged 24.5% (Figure 15j). At YC1, only the fallowing treatment had an effect ($p = 0.02$). Fallowed plots averaged 24.4% annual forb cover, while unfallowed plots averaged 0.9% annual forb cover (Figure 15k). At YC2, a 3-way interaction occurred between fallowing, Plateau, and barrier treatments ($p = 0.01$). Without fallowing, no other effects were significant ($p > 0.11$). With fallowing, Plateau and barrier treatment interacted ($p = 0.06$). Barriers were effective in the absence of Plateau ($p = 0.03$) but not in the presence of Plateau ($p = 0.75$). Annual forb cover averaged 72.4% in plots with neither Plateau nor barriers, 39.6% in plots with only barriers, 9.3% in plots with only Plateau, and 11.1% in plots with both Plateau and barriers (Figures 13l and 14b). 87% of annual forb cover was non-native.

Annual grass cover was influenced by Plateau treatment, fallow treatment, and their interaction ($p < 0.0001$). Annual grass cover averaged 35.5% in unfallowed, no-Plateau plots, 1.7% in plots with only the fallow treatment, 3.8% in plots with only the Plateau treatment, and 1.0% in plots with both the fallow and Plateau treatments (Figure 15m-p). 100% of annual grass cover was non-native.

Shrub cover was influenced by Plateau treatment, fallowing treatment, site, and all interactions between these 3 variables ($p < 0.0016$; Figure 15q-t). At RYG, SKH, and YC1, shrub cover was influenced by Plateau, fallowing and their interaction ($p < 0.003$). At RYG, shrub cover averaged 12.8%

in unfallowed, no-Plateau plots, 0.8% in plots with only the fallow treatment, 38.9% in plots with only the Plateau treatment, and 0.9% in plots with both the fallow and Plateau treatments (Figure 15q). At SKH, shrub cover averaged 4.3% in unfallowed, no-Plateau plots, 0.1% in plots with only the fallow treatment, 12.0% in plots with only the Plateau treatment, and 0.1% in plots with both the fallow and Plateau treatments (Figure 15r). At YC1, shrub cover averaged 8.4% in unfallowed, no-Plateau plots, 0.3% in plots with only the fallow treatment, 26.9% in plots with only the Plateau treatment, and 0.2% in plots with both the fallow and Plateau treatments (Figure 15s). At YC2, only the fallowing treatment had an effect ($p = 0.02$). Shrub cover was 0.4% in fallowed plots and 4.5% in unfallowed plots (Figure 15t). 100% of shrub cover was native.

Discussion

One year after completion of treatments, the fallowing treatment had mostly undesirable results. Perennial grass, forb, and shrub cover were reduced, and annual forb cover was increased by the fallow treatment. In examining the effects of fallowing, it is important to recall that fallowed plots were seeded in fall 2010, while unfallowed plots were seeded in fall 2009. Cover of perennial grasses, perennial forbs, and shrubs can be expected to increase with time since seeding, and cover of annual forbs can be expected to decrease with time since seeding. A fair test of the fallowing treatment will only be realized after sufficient time has passed to moderate the effect of the 1-year time lag between fallowed and unfallowed plots. The fallowing treatment did provide good control of annual grasses.

In combination with the fallow treatment, effects of the Plateau were usually not evident, but in unfallowed plots, the Plateau treatment resulted in lower cover of annual grasses, lower annual forbs at 2 of 4 sites, lower perennial forb cover at 2 of 4 sites, and lower perennial grass cover at 1 of 4 sites. Plateau also increased shrub cover at 3 of 4 sites. These results are similar to those shown in the pipeline experiment, which showed little effect of Plateau on perennial grasses, but a positive effect on shrubs. In this experiment, however, a negative effect on forbs was found, which corroborates earlier studies (Baker et al. 2007, Owen et al. 2011). The combination of Plateau and fallowing appears to be too heavy-handed, with very little cover of any functional groups in plots where both treatments were applied.

The barrier treatment improved perennial grass cover, and in one instance (fallowed, no-Plateau plots at YC2), reduced cover of annual forbs. Unlike the Plateau and fallowing treatments, which controlled the seed bank within plots, the Barrier treatment controlled seed input from without the plots. The application of the barriers, however, was far from perfect. Wind and cow trampling compromised the barriers at RYG and SKH during a critical time of cheatgrass dispersal in 2009, and design modifications improved the barriers over time, as we learned how to prevent weeds from passing beneath the barriers or growing through them. In spite of these imperfections, benefits of the technique were shown, and unlike herbicide application, the barriers have no undesirable effects on seeded species. Future work should focus on improving the design of barriers to increase their effectiveness.

The Gulley experiment will continue to be monitored for at least 3 additional growing seasons.

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 17)
- 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 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.

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

Vegetation was assessed in 2011 by percent cover using five 1m^2 miniplots per plot. One miniplot was located in the center of the plot, and the remaining miniplots were equidistant from the center miniplot and a plot corner. A grid containing thirty-six intersections was held over each miniplot, and point-intercept hits were measured at each grid intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT). All layers of vegetation were identified to species at each hit. When calculating percent cover of a given functional group, such as perennial grasses, overlapping hits of different species within a functional group (for instance, western wheatgrass overlying Sandberg bluegrass) were counted as a single instance of the functional group.

Analysis of variance in SAS PROC MIXED was used to analyze differences in responses to treatments. Site was included as a fixed effect. Cover data was analyzed separately by the following functional groups: perennial grasses, perennial forbs, annual grasses, annual forbs, and shrubs. Biennial forbs were lumped with annual forbs. Cover data was transformed by an arcsine [square root (x)] transformation to achieve normality. A full model including all possible interactions was first considered, and a backwards model selection process was used to determine the final model. A significance level of $\alpha = 0.05$ was used to determine significantly different means, and a level of $\alpha = 0.10$ for interactions was used to determine which means to compare. The percentage of native versus non-native species was calculated for all functional groups.

Results

Perennial grass cover was influenced by site, the seeding treatment, and their interaction ($p < 0.0001$), as well as by a 3-way interaction involving site, seeding treatment, and brush treatment ($p = 0.02$). Seeding increased perennial grass cover from 14.3% to 44.8% at SCD, from 3.9% to 36.2% at SPG, from 6.8% to 20.2% at SQS, and from 5.6% to 37.8% at TGC. The 3-way interaction occurred because there was an interaction between seeding and brush treatment at SQS ($p = 0.01$) and possibly at SPG ($p = 0.06$), but not at other sites ($p > 0.36$). At SQS, brush increased perennial grass cover from 14.7% to 26.7% when seeded ($p = 0.006$) but had no effect in the absence of seed ($p = 0.39$; Figure 18). At SPG, brush had a nearly significant effect in seeded plots ($p = 0.06$), but had no effect in unseeded plots ($p = 0.42$; Figure 18). 99.6% of perennial grass cover was native.

Perennial forb cover was influenced by site, seeding treatment, a surface treatment by seeding interaction, a site by seeding treatment interaction, and a site by surface treatment interaction ($p < 0.033$). Across sites, surface treatment had an effect in seeded plots ($p = 0.01$) but not in unseeded plots ($p = 0.20$); forb cover averaged 7.2% in flat plots with seed and 10.8% in rough plots with seed. The seeding treatment had an effect at SCD, SPG, and SQS ($p < 0.05$), but not at TGC ($p = 0.78$). Seeding increased perennial forb cover from 2.4% to 8.9% at SCD, from 2.5% to 9.1% at SPG, and from 2.4% to 4.8% at SQS. A main effect of surface treatment was evident at SCD and TGC ($p < 0.006$) but not at other sites ($p > 0.22$). At SCD, the rough surface treatment increased forb cover from 2.7% to 8.6%, while at TGC, the rough surface treatment reduced forb cover from 18.2% to 9.3% (Figure 19). 97.4% of perennial forb cover was native.

Annual forb cover was influenced by site, seeding treatment, and their interaction ($p < 0.0001$). Seeding reduced annual forb cover from 49.0% to 14.35% at SCD, 58.6 to 21.1% at SPG, from 68.0% to 54.7% at SQS, and from 47.0 to 25.5% at TGC. 41.8% of annual forb cover was native.

Annual grass cover only occurred in sufficient levels for analysis at SCD, and even at this site, annual grass cover averaged only 0.4%. The seeding treatment ($p = 0.02$) and the surface treatment ($p = 0.03$) affected annual grass cover at SCD. Seeding reduced annual grass cover from 0.8% to 0.05%. The rough surface treatment reduced annual grass cover from 0.8% to 0.01% (Figure 20). All annual grass cover was non-native.

Shrub cover was influenced by site ($p < 0.0001$), brush treatment ($p = 0.04$), seeding ($p = 0.02$), and an interaction between brush treatment and surface treatment ($p = 0.05$). Shrub cover averaged 1.1% at MTN, 1.5% at SPG, 3.7% at SQS, and 1.3% at TGC. Across sites, seeding reduced shrub cover from

2.2% to 1.5%. The brush treatment increased shrub cover from 1.3% to 2.3% in flat surface plots ($p = 0.005$), but had no apparent effect in rough surface plots ($p = 0.97$). All shrub cover was native.

Discussion

Seeding increased perennial grass and perennial forb cover, while reducing annual forb and annual grass, and shrub cover two years post-treatment. Higher annual cover in unseeded plots was expected, as annual plants are typically prolific seed producers and tend to dominate following disturbances. The annual species most prevalent in the plots were the native Douglas' knotweed (*Polygonum douglasii*) and the non-native prostrate knotweed (*Polygonum aviculare*). Prostrate knotweed typically persists in highly compacted soils, which are not present at the study sites, and it is expected that prostrate knotweed cover will decline with time. Seeding also decreased shrub cover, even though shrubs were seeded. Higher shrub cover in unseeded plots was due to establishment of snowberry and green rabbitbrush (*Chrysothamnus vicidiflorus*), which were not included in the seed mix. Apparently, even at this early stage of the experiment, the lessened competition in unseeded plots is promoting establishment of shrubs from naturally occurring seed.

The rough soil surface treatment improved perennial forb cover, especially when applied with seed. The pattern of results TGC, however, differed from that of other sites. At TGC, forb cover was higher in flat surface plots when unseeded. This may be due to an imperfection in how the well pad disturbance was simulated. TGC was flatter than other sites, and required very little cut-and-fill to create a level surface. The topsoil layer was deep and was not completely disturbed. The year after disturbance, mature silvery lupine (*Lupinus argentus*) and white locoweed (*Oxytropis sericea*) plants were noted at the site. In rough surface treatment plots, these plants were disrupted, but in flat surface plots, these deeply-rooted species may have survived treatment implementation, leading to very high forb cover in flat surface plots at TGC. Excluding this site from interpretation, we find a large positive effect of the rough surface treatment on forbs (Figure 19).

The rough soil surface treatment also reduced the prevalence of annual grasses, namely cheatgrass, at the one site with sufficient cheatgrass to permit analysis (Figure 20). This pattern is similar to that observed in the Strategy Choice Experiment at the MTN site. As is explained in the following section, this may be due to reduced dispersal of cheatgrass seeds in rough surface treatment plots.

The brush treatment appears to improve shrub cover, and also improved perennial grass cover when seeded. The addition of brush may have added shrub seed to the plots, and the brush may also improve the establishment of shrub seedlings.

The Mountain Top experiment contrasts extreme treatments: seeding with a high density of perennial grasses, shrubs, and forbs, versus not seeding at all, in order to gauge the ecological resiliency of higher-elevation sites. The results occurring in unseeded plots, over time, will provide a baseline of expectations for these sites when topsoil is managed well, microcatchments providing higher moisture availability are provided, and when mulched with native brush.

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).
    - Herbicide (2 levels): Plateau applied (Plateau) or no Plateau applied (No Plateau)
- Completely randomized factorial (Figure 21)
- 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 that 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.

Ambient cheatgrass propagule pressure was quantified at all 4 sites in 2011 using techniques outlined in Appendix 1. The seeds caught per square meter for the entire growing season were calculated for each site.

Vegetation was assessed in 2011 by percent cover using five $1m^2$ miniplots per plot. One miniplot was located in the center of the plot, and the remaining miniplots were equidistant from the center miniplot and a plot corner. A grid containing thirty-six intersections was held over each miniplot, and point-intercept hits were measured at each grid intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT). All layers of vegetation were identified to species at each hit. When calculating percent cover of a given functional group, such as perennial grasses, overlapping hits of different species within a functional group (for instance, western wheatgrass overlying Sandberg bluegrass) were counted as a single instance of the functional group.

The cover of perennial grasses, perennial forbs, annual forbs, annual grasses, and shrubs in response to site, seed mix, surface/mulch type, and Plateau treatment was analyzed using ANOVA in SAS PROC MIXED. All factors were considered fixed. Biennial forbs were lumped with annual forbs. Cover data was transformed by an arcsine [square root (x)] transformation to achieve normality. A full model including all possible interactions was first considered, and a backwards model selection process was used to determine the final model. A significance level of $\alpha = 0.05$ was used to determine significantly different means, and a level of $\alpha = 0.10$ for interactions was used to determine which means to compare. Because the Plateau treatment was only conducted at 2 of the 4 sites (GVM and MTN), separate backwards model selection processes were conducted for models with the Plateau treatment versus those without. The SGE and WRR sites were excluded from models containing the Plateau treatment parameter (the "complete experiment" results, denoted hereafter as *CE*). Results for the surface and seed mix treatments include all 4 sites, but plots where Plateau was applied at GVM and MTN were excluded (the "all sites" results, denoted hereafter as *AS*). The percentage of native versus non-native species was calculated for all functional groups.

Results

Ambient cheatgrass propagule pressure at the four study sites for the 2011 season were as follows: GVM, 1256 seeds/m^2; MTN, 1.3 seeds/m^2; SGE, 4.0 seeds/m^2; and WRR, 4.0 seeds/m^2.

Perennial grass cover was influenced site, Plateau treatment, and their interaction ($p < 0.0017$ *CE*) as well as by surface treatment ($p = 0.02$ *AS*), seed mix treatment ($p < 0.0001$ *AS*), and an interaction between site and surface treatment ($p = 0.003$ *AS*). At GVM, Plateau treatment reduced perennial grass cover from 28.3% in no-Plateau plots to 16.9% in Plateau plots (Figure 22a). At MTN, Plateau reduced perennial grass cover from 32.6% in no-Plateau plots to 7.0% in Plateau plots (Figure 22b). The seed mix treatment was consistent across sites, with perennial grass cover averaging 41.9% in High Competition plots and 29.9% in Low Competition plots (Figure 23). The surface treatment had significant effects at MTN ($p = 0.0005$) and SGE ($p = 0.05$) but not at other sites ($p > 0.09$). At MTN, perennial grass cover averaged 41.3% in rough surface plots and 23.8% in flat surface plots (Figure 24a). At SGE, perennial grass cover was 41.5% in rough surface plots and 31.8% in flat surface plots. 100% of perennial grass cover was native.

Perennial forb cover was influenced by Plateau, site, and their interaction ($p < 0.05$ *CE*) as well as by seed mix treatment ($p < 0.0001$ *AS*). At MTN, perennial forb cover dropped from 28.6% in no-Plateau plots to 17.7% in Plateau plots ($p = 0.003$; Figure 22b). At GVM, there was no apparent effect of Plateau on perennial forb cover ($p = 0.69$; Figure 22a). Across sites, perennial forb cover averaged 25.7% in LC plots and 15.8% in HC plots (Figure 23). Perennial forb cover was 99% native.

Annual forb cover was influenced by a strong main effect of Plateau ($p = 0.0004$ *CE*) as well as by a probable 3-way interaction involving Plateau, surface treatment, and seed mix treatment ($p = 0.07$ *CE*). Averaged across other treatments, annual forb cover was 20.8% in Plateau plots and 9.2% in no-Plateau plots (Figure 22). With the High Competition mix, Plateau and surface treatment interacted ($p = 0.02$). Where Plateau was applied, annual forb cover was 31.7% with the flat surface treatment, and 13.1% with the rough surface treatment ($p = 0.02$ for comparison of means). Where Plateau was not applied, there was no apparent effect of surface treatment ($p = 0.29$). With the Low Competition mix, there was no interaction between Plateau and surface treatment ($p = 0.96$) and no significant difference between the flat and rough surface when applied either with or without Plateau ($p > 0.34$). Annual forb cover was 97% non-native.

Annual grass cover was influenced by a highly significant 3-way interaction between site, surface treatment, and Plateau ($p=0.0003$ *CE*). At GVM, no interaction between surface treatment and Plateau was evident ($p = 0.16$), but Plateau had an effect ($p = 0.001$), with 29.1% annual grass cover in no-Plateau plots, and 7.1% annual grass cover in Plateau plots (Figure 22a). At MTN, the surface treatment and the Plateau treatment interacted ($p < 0.0001$). In plots with Plateau, the surface treatment had no effect ($p = 0.56$), but in plots without Plateau, annual grass cover was 44.1% in flat surface plots and 5.9% in rough surface plots ($p < 0.0001$ for comparison of means; Figure 24b). Annual grass cover was 100% non-native and 97.6% cheatgrass.

Perennial shrub cover was influenced by a strong main effect of Plateau ($p < 0.0001$ *CE*) a 3-way interaction between site, surface treatment, and Plateau treatment ($p = 0.02$ *CE*) as well as by a main effect of the surface treatment ($p = 0.05$ *AS*). Averaged across other factors, perennial shrub cover was 2.9% in Plateau plots and 7.9% in no-Plateau plots (Figure 22). At GVM, no interaction between Plateau treatment and surface treatment was evident ($p = 0.74$). At MTN, the surface treatment and the Plateau treatment interacted ($p = 0.006$). In plots with Plateau, the surface treatment had an effect ($p = 0.01$), with 1.7% cover of perennial shrubs in flat surface plots, and 8.0% cover of perennial shrubs in rough surface plots. In plots without Plateau, no significant effect of the surface treatment at MTN was evident ($p = 0.14$; Figure 24c). In the cross-site analysis, however, surface treatment did have an effect, with 5.8% shrub cover in rough surface plots, and 8.5% shrub cover in flat surface plots. Perennial shrub cover was 100% native.

Discussion

The Plateau treatment had mostly undesirable consequences in this experiment. Although Plateau did have the positive effect of reducing annual grass cover, it also reduced perennial grass cover, reduced perennial forb cover at 1 of 2 sites, reduced shrub cover, and increased annual forb cover. The detrimental effects of Plateau were more evident at the MTN site, where perennial grass cover was over 4 times lower in Plateau plots than in no-Plateau plots. Reduced competition with perennial grasses is a likely explanation for higher annual forb cover in Plateau plots. Although some detrimental effect of

Plateau on non-target species is expected, especially in the first year post-application, the degree of injury seen in this experiment 2-years post-application is likely unacceptable to managers. More favorable results might result from a lighter application rate than the 8 oz./acre used here. Also, the method of application used, backpack spraying, is not recommended because the rate is difficult to control precisely. Finally, allowing 3 months or more between applying Plateau and seeding has been shown to reduce injury to some desirable rangeland species (Sbatella et al. 2011) and may promote more favorable results.

The Low Competition seed mix had favorable results for improving reclamation areas as wildlife habitat, because very forb cover, 25.7%, was achieved. Annual forb and annual grass cover were similar between the High Competition and Low Competition mixes, therefore higher forb cover did not come at the expense of increased weeds. The Low Competition seed mix differed from the High Competition mix in having a much lower density of rhizomatous grass (Figure 25) and by including 3 additional species of perennial forbs: hairy golden aster (*Heterotheca villosa*), multi-lobed groundsel (*Packera multilobata*) and showy fleabane (*Erigeron speciosus*). Hairy golden aster and multi-lobed groundsel established successfully where seeded, with hairy golden aster comprising 1.2% cover and multi-lobed groundsel comprising 3.5% cover in Low Competition plots. The difference in perennial forb cover between the two mixes was 9.9%. Therefore, a little less than half of the difference in forb cover between the two mixes is attributable to the forb species unique to the Low Competition mix. The rest of the difference is due to better establishment of species such as sulfur-flower buckwheat (*Eriogonum umbellatum*), Western yarrow (*Achillia millefolium*), Lewis flax (*Linum Lewisii*), and Utah sweetvetch (*Hedysarum boreale*), which were seeded at the same rate in both mixes (Table 6). Higher cover of these species is likely due to lessened competition with rhizomatous grasses. This highlights the increase in cost-effectiveness of seeding forbs when the density of rhizomatous grasses is greatly reduced. The density of rhizomatous grasses included in the High Competition mix was similar to a commonly-used mix recommended by the White River BLM office for the pinyon-juniper habitat type (Figure 25). This study suggests that a lower density of rhizomatous grass may result in more valuable wildlife habitat following disturbances.

The rough surface with brush treatment had many favorable results. Rough/Brush plots had higher perennial grass cover at 2 of 4 sites, lower annual forb cover when Plateau and the High Competition mix were also applied, higher shrub cover at MTN when Plateau was also applied, and lower annual grass cover at MTN when Plateau was not applied. One negative result of the rough surface treatment was lower shrub cover when averaged across sites in the absence of Plateau. Perhaps the most interesting result is the dramatic reduction in annual grass cover- from 44.1% to 5.9%- at MTN in the absence of Plateau. The MTN site was one of the 3 sites that had low ambient cheatgrass propagule pressure. At two other such sites, SGE and WRR, very little cheatgrass established regardless of treatment. At MTN, nearby disturbances with thick stands of cheatgrass indicated that the site was vulnerable to cheatgrass invasion. How did the rough surface treatment prevent cheatgrass from invading? Perennial grass cover was somewhat higher in Rough/Brush plots at MTN, so increased competition from grasses is one explanation. However, shrub cover was lower with the rough surface treatment, and shrubs such as sagebrush are known to compete with cheatgrass (Prevey et al. 2010), so the end result of competitive dynamics on cheatgrass is unclear. Another explanation is that the rough surface treatment impeded cheatgrass dispersal. Recent work has shown that cheatgrass seeds disperse much farther in the absence of obstructions than they do in intact ecosystems, leading to enhanced dispersal following disturbances such as well pad construction or fires (Johnston 2011a, Monty et al. in review). Cheatgrass seeds may have been trapped in the holes in the rough surface treatment, preventing them from dominating the Rough/Brush plots.

The benefit of the rough surface treatment when used in conjunction with Plateau indicates that this treatment may have broad applicability. Two of the detrimental effects of Plateau shown in this study, reduced shrub cover and increased annual forb cover, were ameliorated when the rough surface treatment was also applied. Furthermore, visual comparisons between flat and rough surface plots suggest that the rough surface treatment increases plant stature (Figure 26), which was not captured by the cover data. Plans for the 2012 season include assessing biomass in this experiment in order to better quantify treatment responses.

The Strategy Choice experiment focuses on situations where a wide range of outcomes of reclamation are possible. The data from this experiment indicates that excellent restoration of wildlife habitat should be the goal in these cases. Elements of an optimistic strategy, including a seed mix focused on forbs, broadcasting seed over a roughened soil surface, and using brush mulch, resulted in a better outcome than the more common strategy of drill seeding grasses heavily over a flat surface with straw mulch. This is especially striking given that broadcast and drill seeded plots were seeded at the same rate, whereas the seeding rate for broadcast application is usually doubled. It should be noted that moisture in the 2010 and 2011 growing seasons was normal or above normal. Additional years of data including drought years will be assessed before a final recommendation is made.

CONCLUSION

Although the 5 experiments comprising this project vary in their degree of maturation (e.g. 1 year of post-treatment data for the Gulley Experiment, vs. 3 for the Pipeline Experiment), some broad-scale synthesis of results can be made at this time. Treatments which appear promising in improving the quality of reclaimed wildlife habitat include applying Plateau herbicide (with extreme caution), timing disturbances to maximize weed seed burial, creating a rough soil surface composed of mounds and holes, utilizing obstructions to prevent weed seed dispersal, treating soil with granulated super-absorbent polymer, and using a seed mix focused on perennial forbs.

This report contains results of 3 experiments in which Plateau herbicide was applied. Of these, one experiment demonstrated only positive effects of the herbicide, one demonstrated both positive and negative effects, and one demonstrated mainly negative effects. In all 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) to low and mid-elevation sites, and results after 3 years are very favorable. The herbicide was neutral with respect to grasses and forbs, but greatly improved shrub cover and reduced annual grass cover. In the Gulley experiment, Plateau was applied with a backpack sprayer at 140 g ai/ha (8 oz/ac) to low-elevation, weedy sites, and results after 2 years are mixed: Plateau effectively controlled both annual grasses and forbs and positively affected shrubs, but negatively affected perennial forbs and grasses. In the Strategy Choice Experiment, Plateau was applied with a backpack sprayer at 140 g ai/ha (8 oz/ac) to mid-elevation sites, and results after 2 years are unfavorable: perennial grass and shrub cover are greatly reduced, and annual forb cover is increased where Plateau was applied. The differences cannot be entirely attributable to time since treatment, because the Pipeline Experiment showed favorable responses to Plateau application after only 2 years (Johnston 2011b). The lower rate used in the Pipeline Experiment partially explains these results. The difference between the Gulley experiment and the Strategy Choice experiment may be due to the difference in initial weediness of the treated sites. At the Gulley sites, cheatgrass was a major component of the plant community prior to disturbance, and the positive effects of cheatgrass control counteracted the direct negative effect of the herbicide. At the Strategy Choice sites, the rate was too high for the conditions. Using lower rates, matching the rate to the site, and increasing time between application and seeding are recommended. A rate of 6 oz./acre may be a good maximum for very weedy sites, with lower rates to be used at less weedy sites. Note that the 6 oz./ acre rate has been shown to provide only fleeting and ultimately insufficient cheatgrass control in Wyoming sagebrush communities in a prior study (Morris et al. 2009). It appears that while a light rate of Plateau application may be beneficial in restoration, it cases of severe infestation, it should be coupled with other measures to control cheatgrass.

One such other measure is the judiciously-timed application of disturbance. Auxiliary data taken for the Pipeline and Gulley experiments shows the time course of cheatgrass seed dispersal in northwestern Colorado, with a peak in late June, and continued dispersal until mid-September (Figure X). At the weediest site measured, cheatgrass seed production peaks at 160 seeds/m^2·day. Since 40 cheatgrass seeds/m^2 is sufficient to hinder the growth of even the most competitive perennial grasses (Evans 1961), many times more cheatgrass seed is produced *in a single day* than is acceptable for establishing native plants on restoration sites. Furthermore, these will readily spread from the edge of disturbances into bare soil areas (Johnston 2011a). Given the timing of cheatgrass seed dispersal, the worst possible scenario is if a disturbance occurs before spring, and is left bare over the summer. If the disturbance occurs in the fall, however, and is planted immediately, then there is little opportunity for cheatgrass seeds to disperse before seeded species germinate. Because cheatgrass seeds are sensitive to burial (Wicks 1997), then a fall disturbance will partially control cheatgrass. This was the case in the Pipeline Experiment, where cheatgrass density was 5 times lower in the disturbed area than in the adjacent undisturbed area the spring following disturbance. If a disturbance must occur early in the year, then applying an additional disturbance such as disking prior to fall planting may limit the number of viable cheatgrass seeds on the soil surface. For very weedy areas, some strategy such as this is recommended to augment chemical control. Dense cheatgrass stands may produce 20,000 seeds/m^2, therefore even a 99% effective herbicide would leave 200 viable seeds/m^2, which is more than enough to compromise a seeding.

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 both experiments the rough soil surface outperformed the flat soil surface in most respects. The rough soil surface produced higher perennial forb cover in the Mountain Top experiment, higher perennial grass cover at 2 of the Strategy Choice sites, and lower annual grass cover at one site in each experiment. For the Strategy Choice Experiment, the results differ from those reported for 2010. In 2010, density of most desirable functional groups was lower with the rough soil surface treatment. Apparently, improved growth of plants with the rough soil surface offset the effect of lower initial density. In both experiments, the seed was applied at the same rate in the rough surface plots, which were broadcast, as the flat surface plots, which were drill seeded. These results bring into question the common practice of doubling the seeding rate for broadcast seeding. If the seedbed is well-prepared, doubling the seeding rate may be wasteful. The machinery and mobilization costs for the two methods are comparable, therefore broadcast seeding over a rough soil surface appears to be a cost-effective alternative. These results confirm and extend those of Eldridge (2011) who found that a rough soil surface treatment improved the cover of native plants at low elevation sites in the Colorado River Valley (Eldridge et al. 2011).

The reduction in annual grass shown at two sites with a rough soil surface treatment, the SCD site in the Mountain Top experiment, and the MTN site in the Strategy Choice experiment, suggests that a rough soil surface may aid in cheatgrass control under certain conditions. Altered competitive dynamics is one explanation for these results, but altered seed dispersal is probably also important. In a study of many kinds of seeds, Chambers (2000) found that large holes capture more seeds than flat surfaces (Chambers 2000). Recent work done as part of this project has shown that cheatgrass seeds move farther in the absence of obstructions that they do in intact ecosystems (Johnston 2011a). At both the SCD and MTN sites, cheatgrass was not prevalent prior to disturbance. The rough soil surface probably prevented a few cheatgrass seeds introduced during disturbance from spreading, concentrating them in a higher-moisture microclimate, where they may have been less competitive. Another experiment, the Gulley experiment, looked explicitly at creating obstructions to seed dispersal, in the form of windowscreen barriers placed around plots. Although there were imperfections in the implementation of these barriers, there were still some benefits from the treatment- an increase in perennial grass cover, and a decrease in annual forb cover in fallowed, no-Plateau plots at YC2. Creating barriers to seed dispersal, either though aboveground structures or large holes to act as seed traps, may improve reclamation of disturbed areas by limiting the movement of weed seeds. In less weedy areas, it is possible that this would alleviate the need for herbicide and associated injury to desirable species.

In the Competition experiment, we tested the effect of granulated super-absorbent polymer (SAP) on the competitive balance between perennial wheatgrasses and cheatgrass. In the absence of other treatments, SAP cut cheatgrass cover in half 2 years post-treatment when applied at 31 g/m^2 and concentrated in drill-seeded rows. Further studies should investigate the optimal application rate and application method. Although it might be desirable to treat the entire soil volume for a broadcast seeding, such application would probably be prohibitively expensive. For instance, a 0.2% v/v application rate (Agaba et al.) to a depth of 10 cm would require 225 g/m^2 (2013 lbs/acre), at a current cost of $5,450/acre. Concentrating the product in either drill-seeded rows or the holes of a rough soil surface treatment are likely the only cost-effective application methods.

Two experiments examined the consequences of seed mix choices. In the Strategy Choice experiment, we compared a seed mix with almost 75% forbs by seed number and virtually no rhizomatous grass (the Low Competition mix) to a seed mix with fewer forbs and a typical, 4.4 kg/ha (3.9 PLS/acre) rate of rhizomatous grass (the High Competition mix). In the Mountain Top experiment, we compared a seed mix with 4.4 kg/ha rhizomatous grass to the extreme of not seeding at all. The Low Competition mix produced higher forb cover with similar weed cover to the High Competition mix. The unseeded plots in the Mountain Top experiment had more weeds than the seeded plots, but the weeds were not species thought to persist over time, and they also had higher shrub cover. Collectively, these studies suggest that post-reclamation wildlife habitat could be improved by altering the composition of seed mixes to focus on forbs, bunchgrasses, and shrubs. The idea that seed mixes should limit the proportion of rhizomatous grasses in order to promote a mixed plant stand was proposed nearly 30 years ago (Redente et al. 1984). However, most seed mixes continue to be dominated by competitive grasses, probably out of a fear of weed invasion, a lack of availability of appropriate forb seeds, and/or a need for an inexpensive seed mix. This study made use of several forb species provided by the Uncompagre Partnership (http://www.upartnership.org/) that 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, hairy golden aster, sulfur flower buckwheat, bluestem penstemon (*Penstemon cyanocaulis*), and Western yarrow. The results of this study highlight the importance of making species such as these available at a reasonable cost.

Treatments which do not appear promising include surface compaction, fallowing with Pendulum herbicide, and addition of a soil binding agent to the soil. Rolling to create 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. In no case was cheatgrass emergence affected, and a negative effect on shrubs was found in the Pipeline experiment. Fallowing with Pendulum herbicide was attempted in the Gulley experiment, and although the 2011 data is only one year post-treatment, the results were so detrimental to perennial grasses and forbs that it appears unlikely that fallowing will be recommended. Soil binding agent was tested in the Competition experiment, and had mixed results, at times causing increased cheatgrass cover, and at times limiting it. Because of these inconsistencies and the cost of the treatment, it is unlikely to be recommended.

In summary, excellent restoration of wildlife habitat following oil and gas disturbances is possible over a wide range of elevations in northwestern Colorado. At lower elevations and in places with some cheatgrass cover prior to disturbance, then a combination of approaches to control cheatgrass and promote native plants should be used. This may include a light herbicide application, fall disking prior to planting, using a roughened soil surface, and amending soil with a super-absorbent polymer. At middle and higher elevations, using a roughened soil surface and using a seed mix primarily of forbs is recommended. Note that these results apply to slopes of less that 5% and areas protected from grazing. Steeper slopes and grazed areas may require using rhizomatous grasses to protect soil resources.

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Table 1. Study site information. Pie charts are baseline relative cover from undisturbed areas.

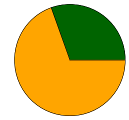
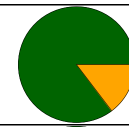
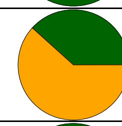
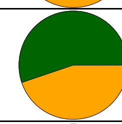
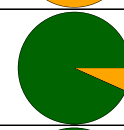
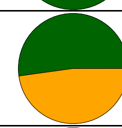
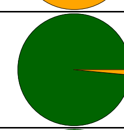
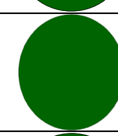
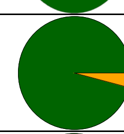
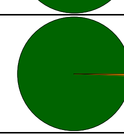
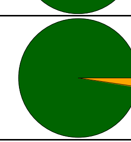
Code	Name	Landowner	Elev. m (ft)	Experiment(s) Conducted	Native / NonNative
SKH	SK Holdings	Williams	1561 (5120)	Pipeline Gulley	
GVM	Grand Valley Mesa	Williams	1662 (5451)	Pipeline Strategy Choice	
YC2	Yellow Creek 2	DOW	1829 (5999)	Pipeline Gulley	
YC1	Yellow Creek 1	DOW	1905 (6248)	Pipeline Gulley	
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 millifolium	western yarrow	0.10	67
Erigonum umbellatum	sulfur flower buckwheat	1.03	53
Hedysarum boreale	Utah sweetvetch	0.44	11
Heterotheca villose	hairy golden aster	1.11	137
Linum lewisii	Lewis flax	0.38	28
Packera multilobata	multi-lobed groundsel	0.10	67
Penstemon strictus	Rocky Mountain penstemon	0.33	23
grasses			
Achnatherum lymenoides	Indian ricegrass (Nezpar)	0.83	33
Pascopyrum smithii	western wheatgrass	0.40	11
Pseudoroegneria spicata	bearded bluebunch wheatgrass P-7	0.38	11
Pseudoroegneria spicata	bearded bluebunch wheatgrass Secar	0.36	10
Elymus trachycaulus	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			
Artemisia 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						
Artemisia 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.

				high comp.mix		low comp.mix	
	Scientific Name	**Common Name**	**Variety**	**seeds/ m^2**	**PLS (kg/ha)**	**seeds / m^2**	**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						
	Kraschenìnnikovia lanata	winterfat	VNS	22	0.8	22	0.8
	Artemisia 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**

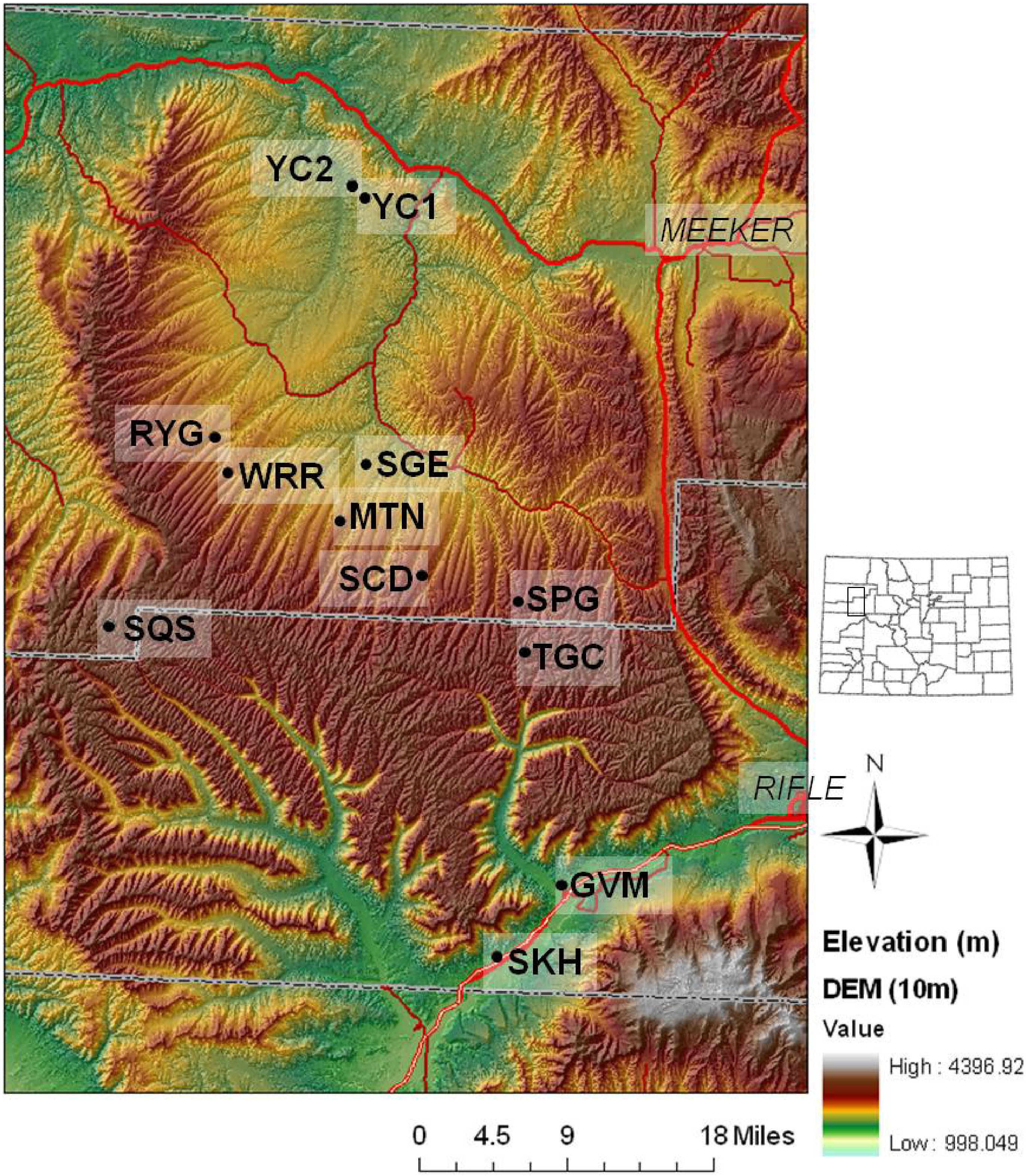


Figure 1. Locations of the 12 research sites in Rio Blanco and Garfield counties, Colorado.

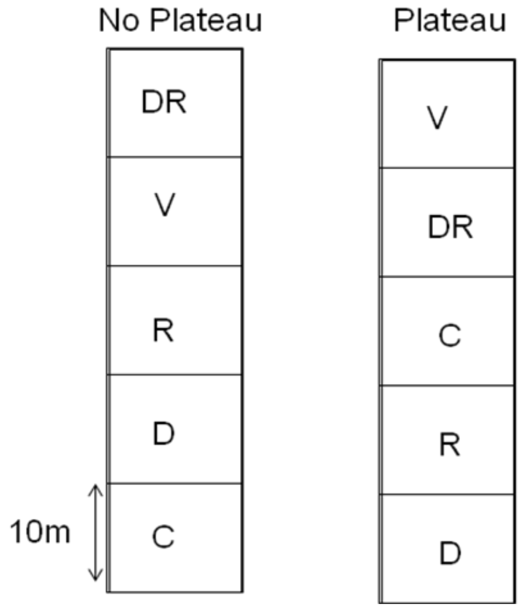


Figure 2. Layout of the Pipeline experiment at one of 6 sites. D = disked, R = rolled, DR = disked and rolled, V = rolled with a vibratory drum compactor, C = control.

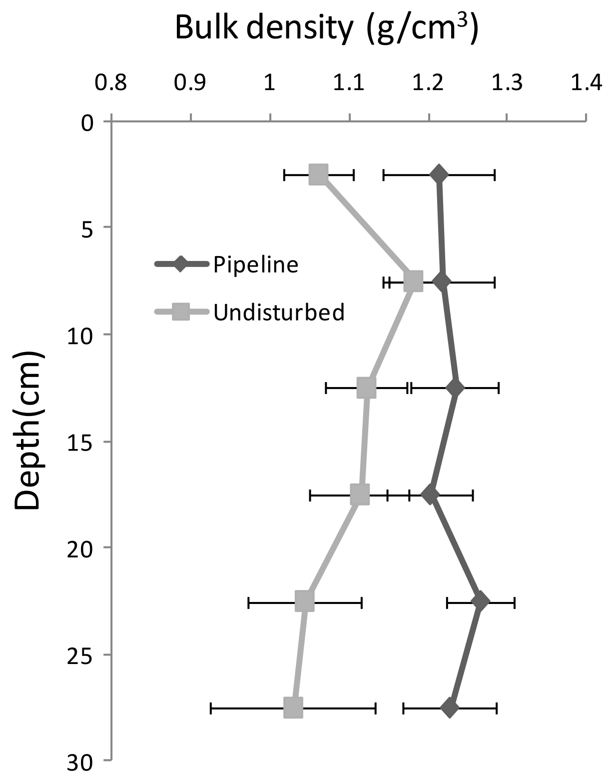


Figure 3. Bulk density of disturbed and undisturbed areas in the Pipeline experiment. Error bars = SE.

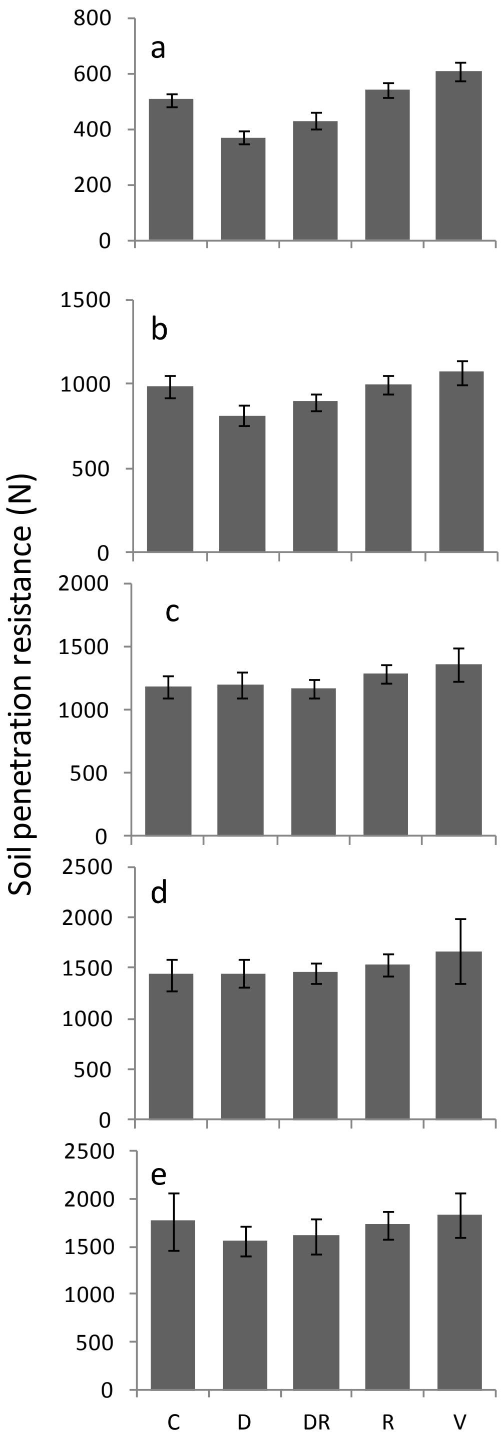


Figure 4. Pipeline experiment soil penetration resistance by soil tillage treatment at depths of: (a) 4- 9 cm; (b) 10- 14 cm; (c) 15- 19 cm; (d) 20- 24 cm and (e) 25-29 cm. C= control, D= disked, DR= disked and rolled, R= rolled, and V= rolled with vibratory drum compactor. Error bars= SE for 12 plots, 2 at each of 6 sites. Note differing y-axis scales.

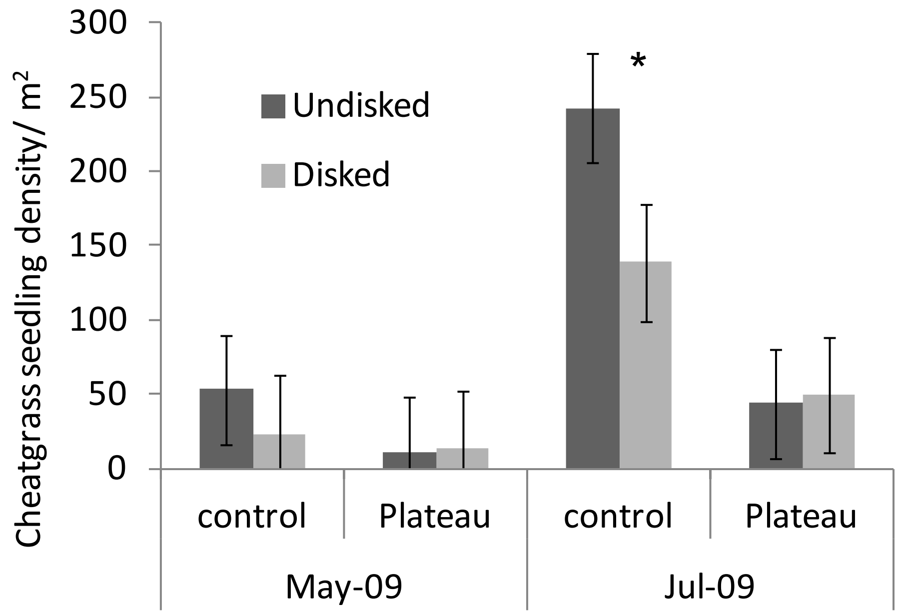


Figure 5. Density of cheatgrass seedlings in May and July of 2009 by disking and Plateau treatment in the Pipeline experiment. Bars represent least square means over sites and non-significant treatments. Error bars = SE.

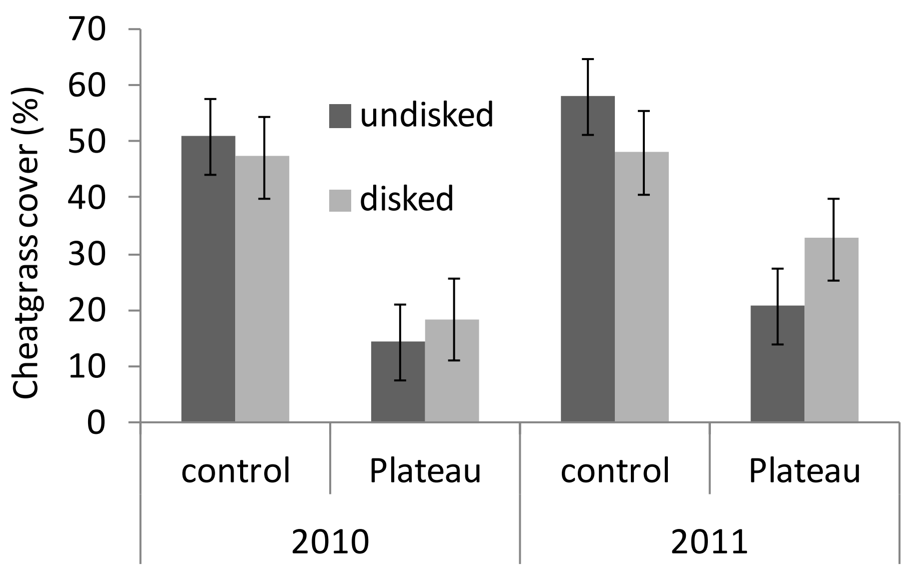


Figure 6. Cover of cheatgrass in 2010 and 2011 in response to disking and Plateau treatment in the Pipeline experiment. Bars represent least square means over sites and non-significant treatments. Error bars= SE.

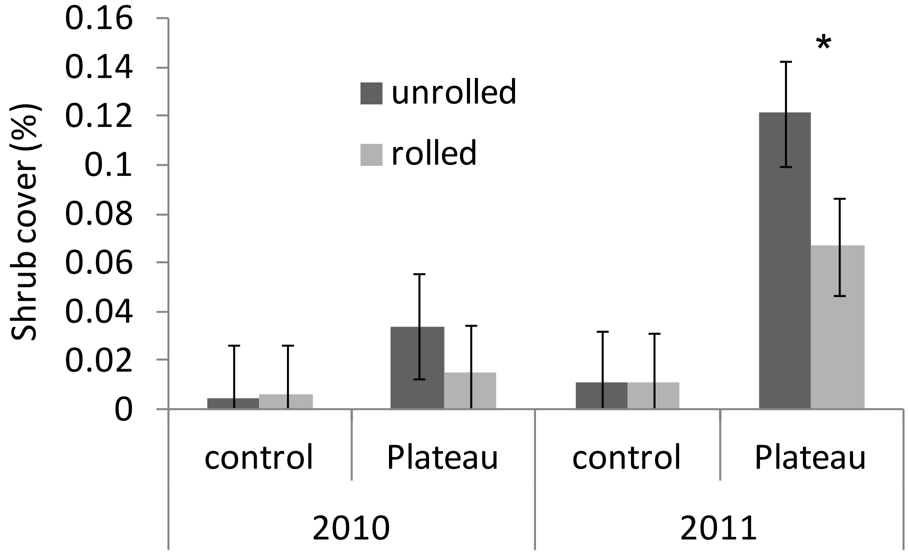


Figure 7. Cover of shrubs in 2010 and 2011 by rolling and Plateau treatment in the Pipeline experiment. Bars represent least square means over sites and non-significant treatments. Error bars= SE.

No Plateau

Plateau

Figure 8. Visual comparison of plots where Plateau was applied vs. no Plateau applied at the RYG site in the Pipeline experiment, three years post-application.

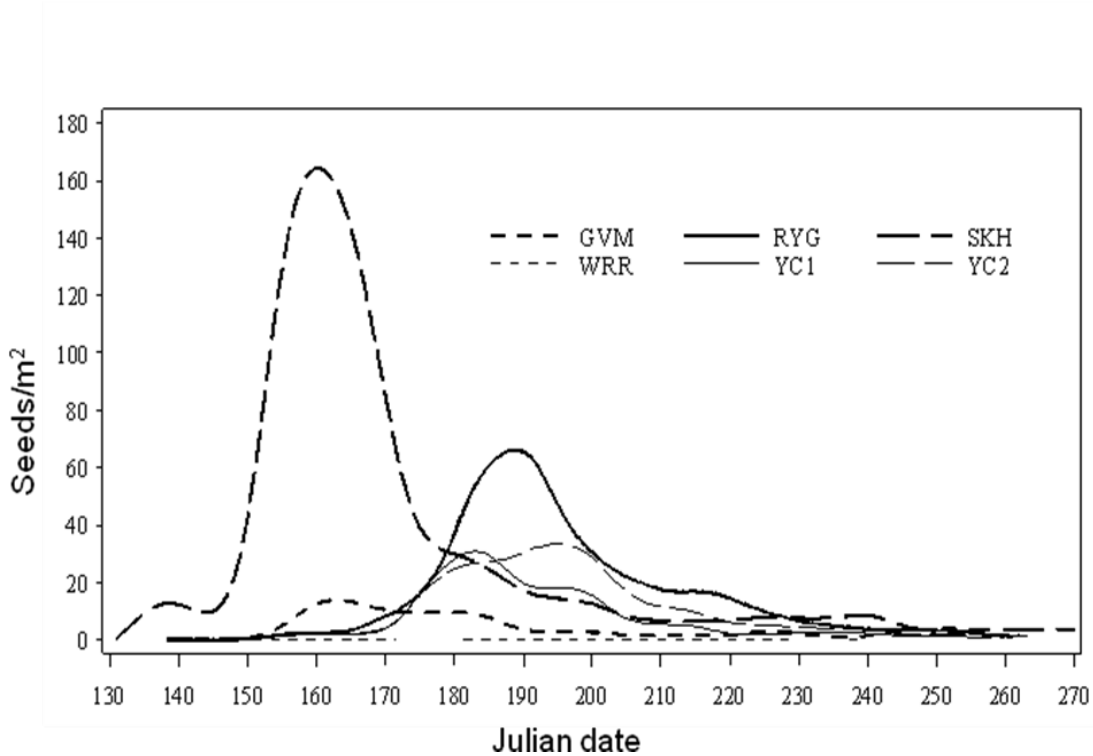


Figure 9. Prevalence of cheatgrass seeds between May and September in undisturbed locations near the 6 study sites of the Pipeline experiment. Data are averages over 3 years, 2009-11. The data was smoothed using a cubic spline with an nn value of 15 (Reinsch 1967).

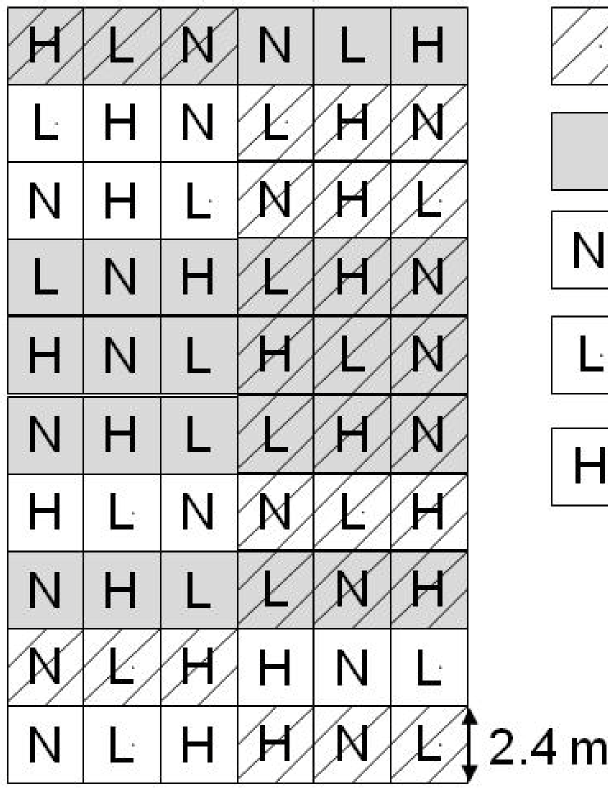


Figure 10. Layout of the Competition experiment at one of 2 research sites. SAP = super-absorbent polymer. BA = soil binding agent.

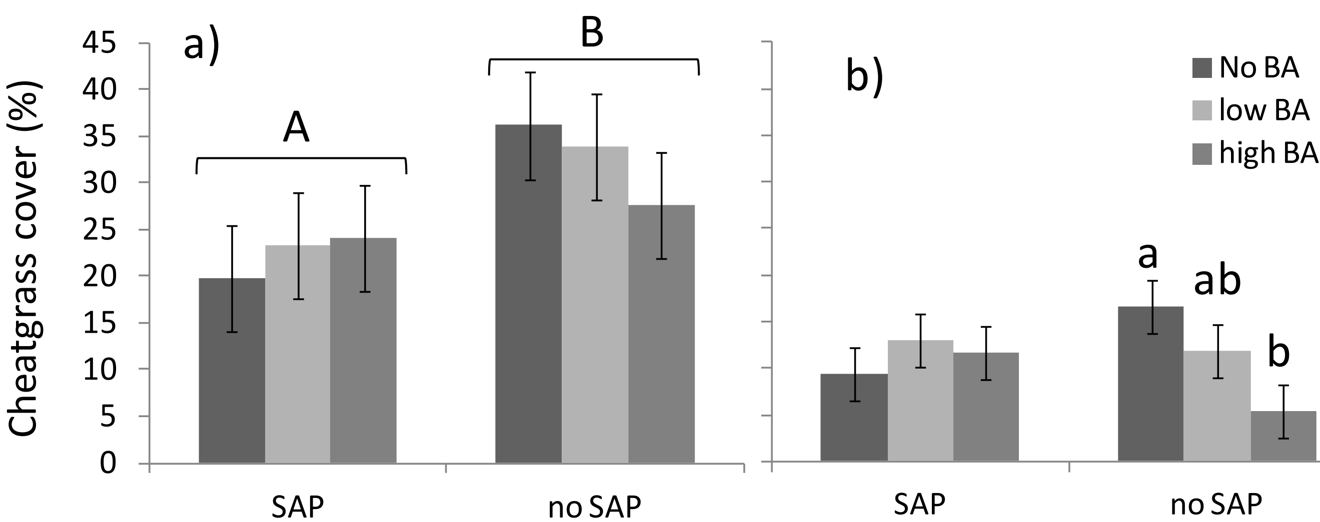


Figure 11. Cheatgrass cover in 2011 in response to 2009 addition of super-absorbent polymer (SAP) and binding agent (BA) at a) Wagon Road Ridge and b) Sagebrush 69 Road in the Competition experiment. Error bars = SE. Bars not sharing a letter denote significant differences within a site at α = 0.05.

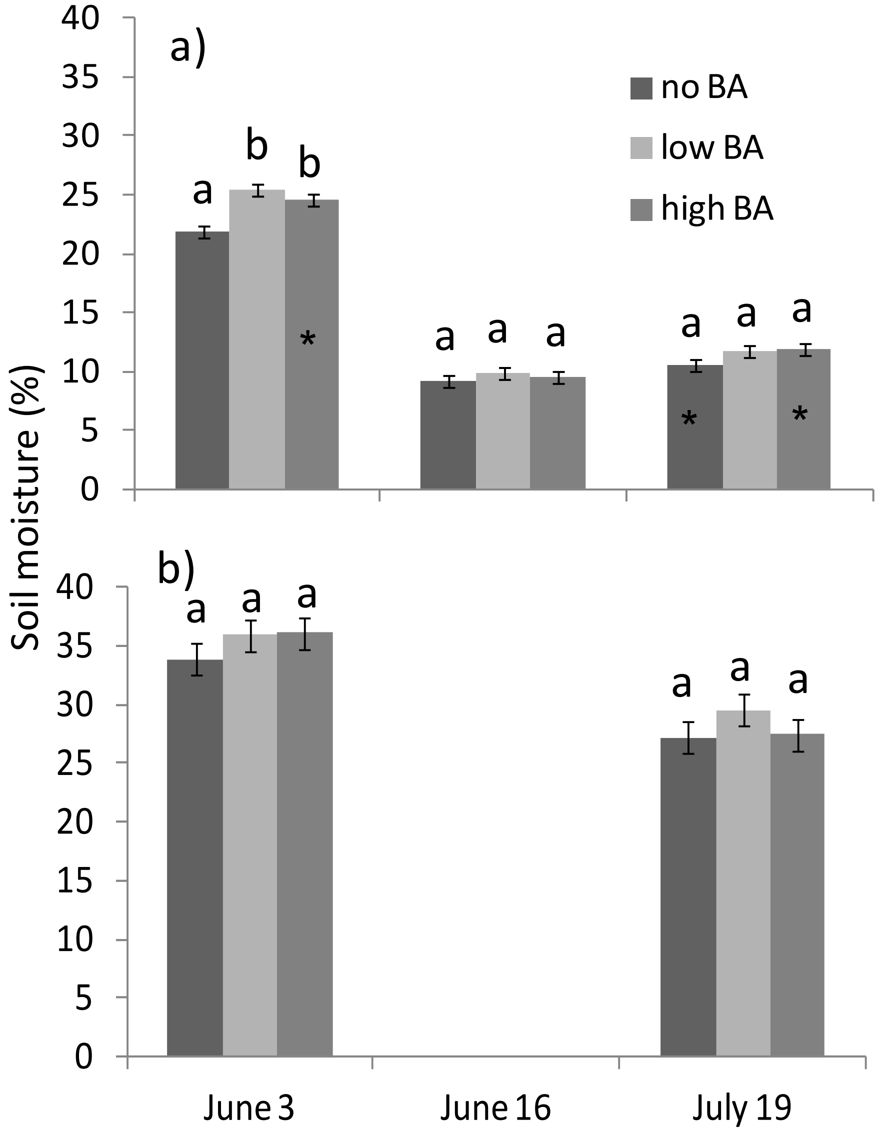


Figure 12. Effect of 3 levels of soil binding agent (none, low, high) on volumetric soil moisture at a) WRR and b) SGE study sites in 2011 in the Competition experiment. Bars not sharing a letter denote significant differences within a site and date at α = 0.05. Error bars = SE. Stars within bars indicate dates and BA levels for which an interaction between SAP and Rolling treatment occurred for soil moisture (Figure 11)

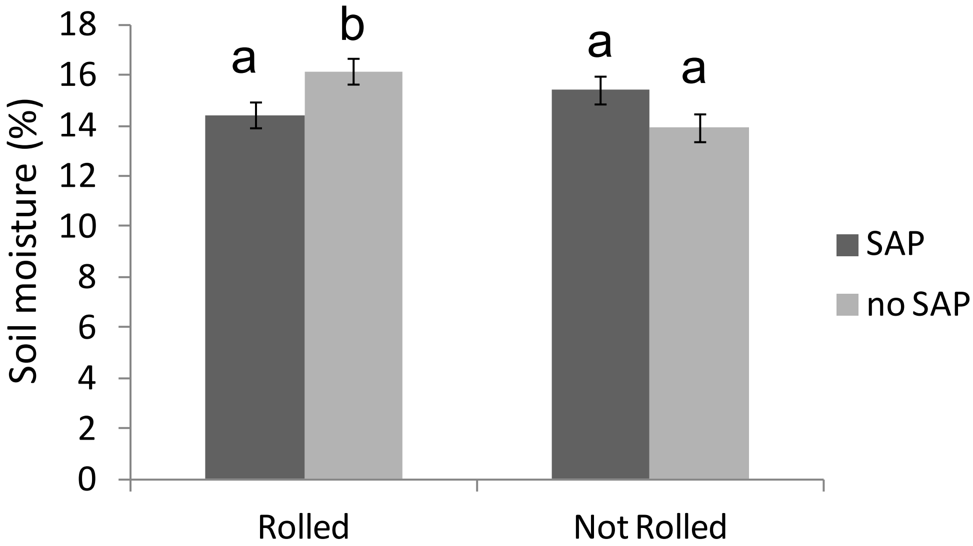


Figure 13. Effect of Rolling and super-absorbent polymer (SAP) addition on soil moisture at WRR, averaged over dates and binding agent treatments in the Competition experiment. Bars not sharing a letter denote significant differences within a site and date at α = 0.05. Error bars = SE.

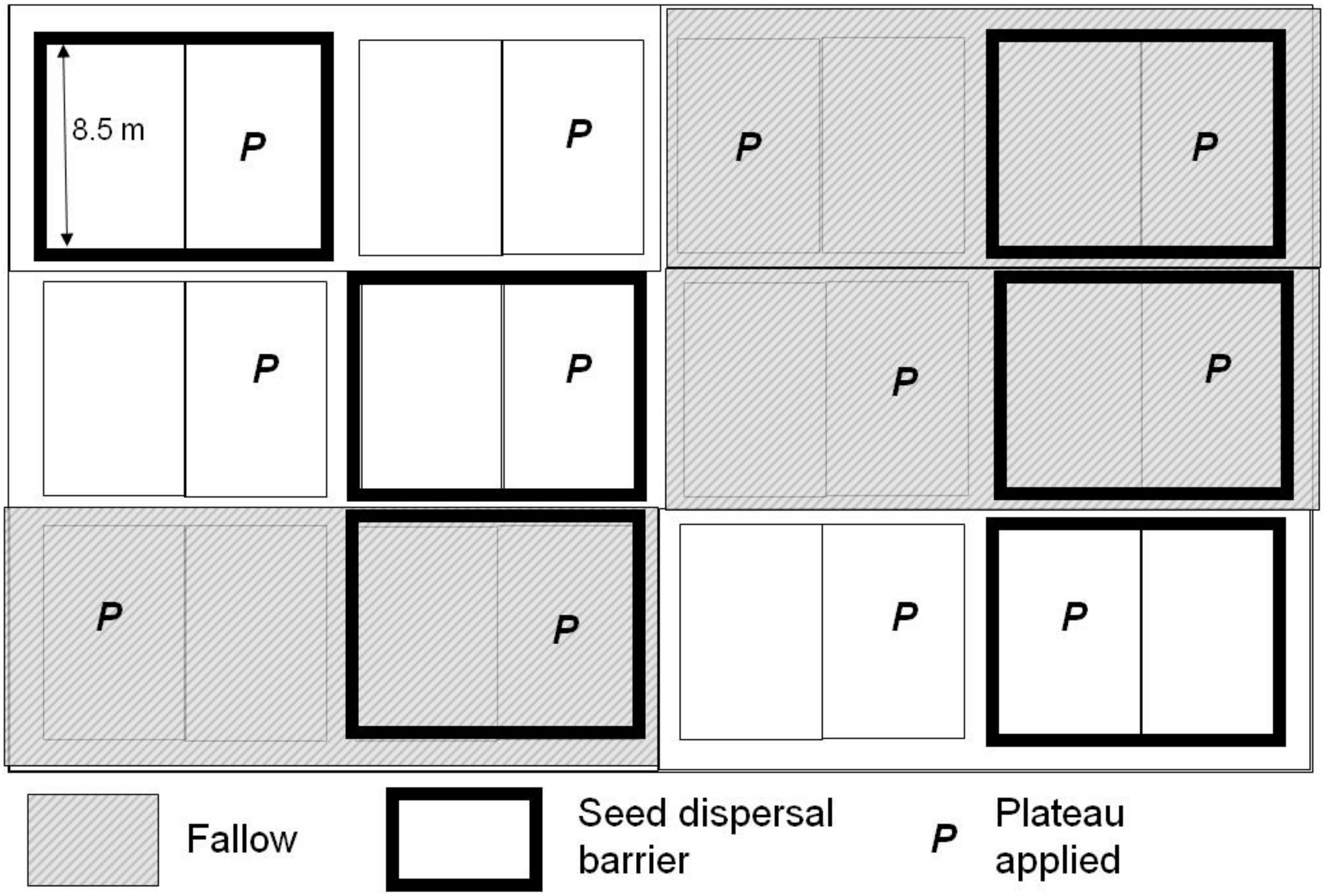


Figure 14. Layout of the Gulley experiment at one of 4 research sites.

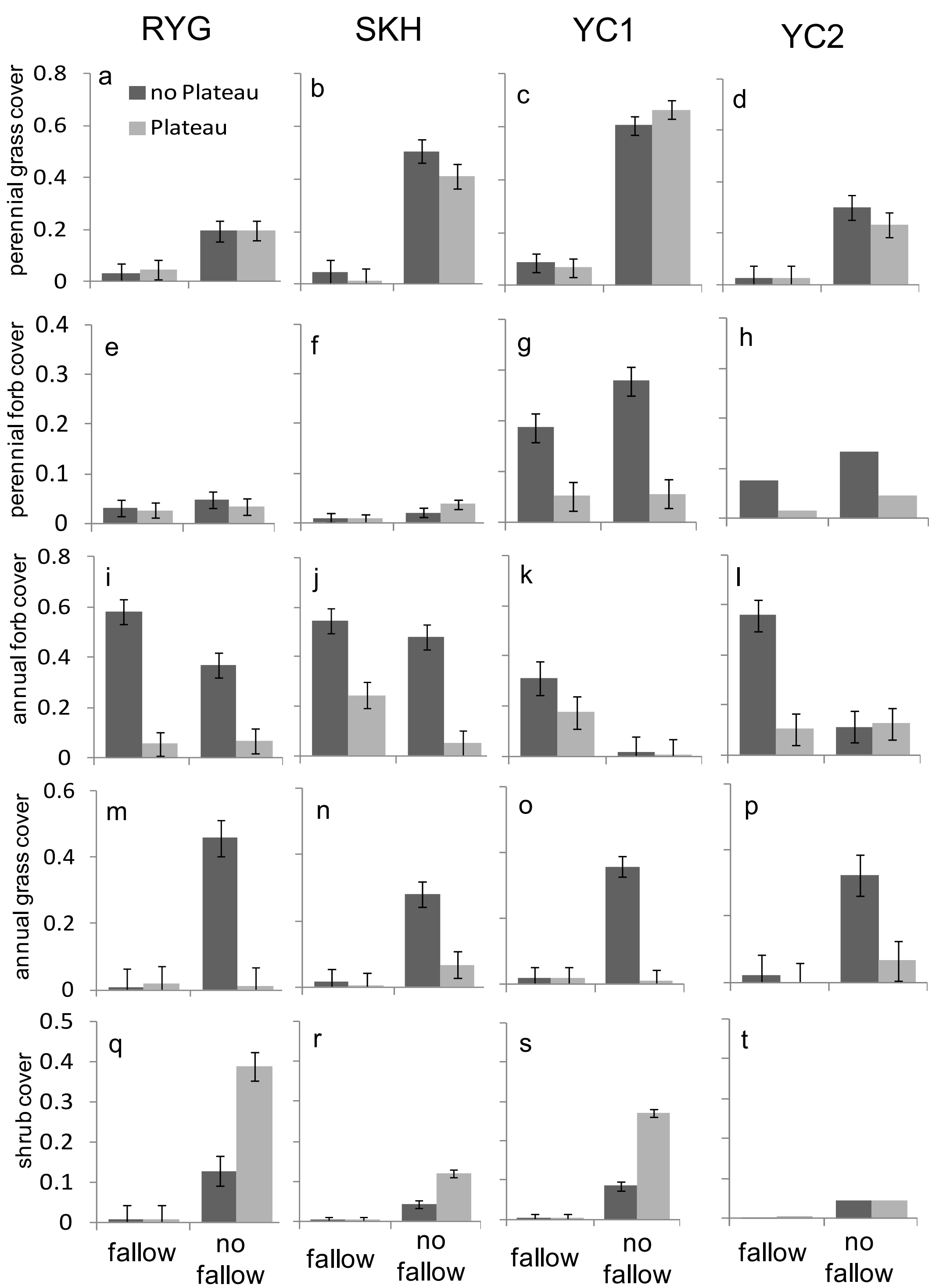


Figure 15. Effect of fallowing and Plateau treatment on cover of perennial grasses (a-d), perennial forbs (e-h), annual forbs (i-l), annual grasses (m-p), and shrubs (q-t) at four sites: RYG (a, i, m, and q), SKH (b, j, n, r), YC1 (c, k, o, s) and YC2 (q, r, s, t) in the Gulley experiment. In l, the effect of Plateau on annual forbs depended on barrier treatment; see Figure 16b. Error bars = SE of least square means taken over brush treatment.

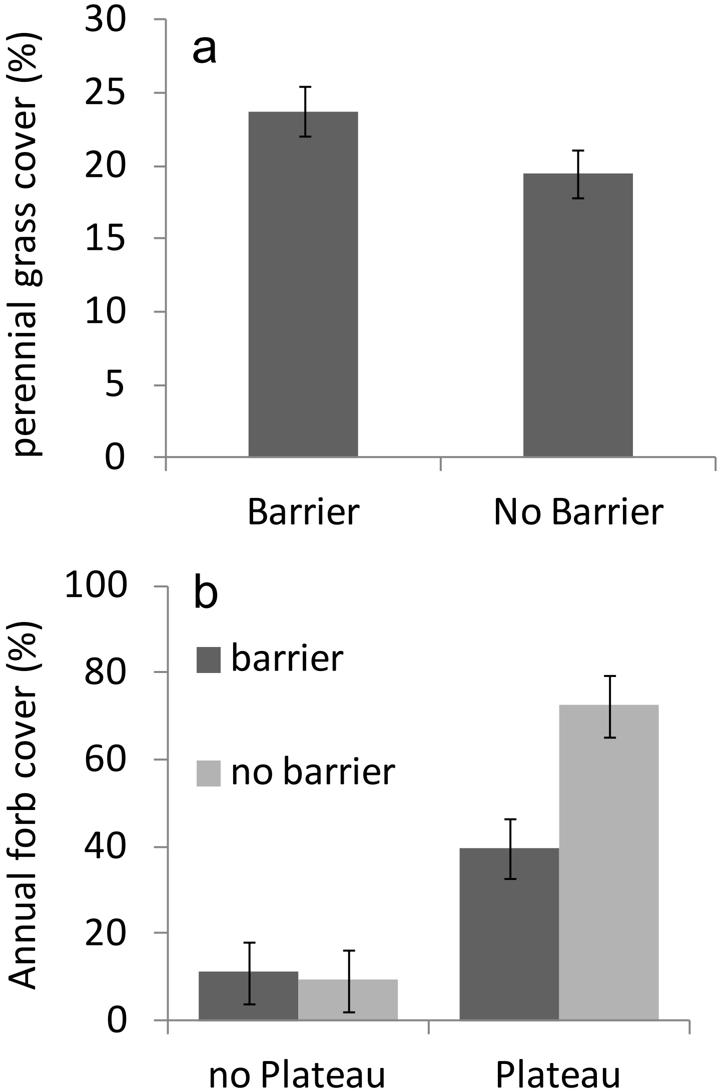


Figure 16. Effect of barrier treatment in the Gulley experiment on a) perennial grasses, across sites and other treatments and b) annual forbs in fallowed plots at the YC2 site. Error bars = SE of least square means.

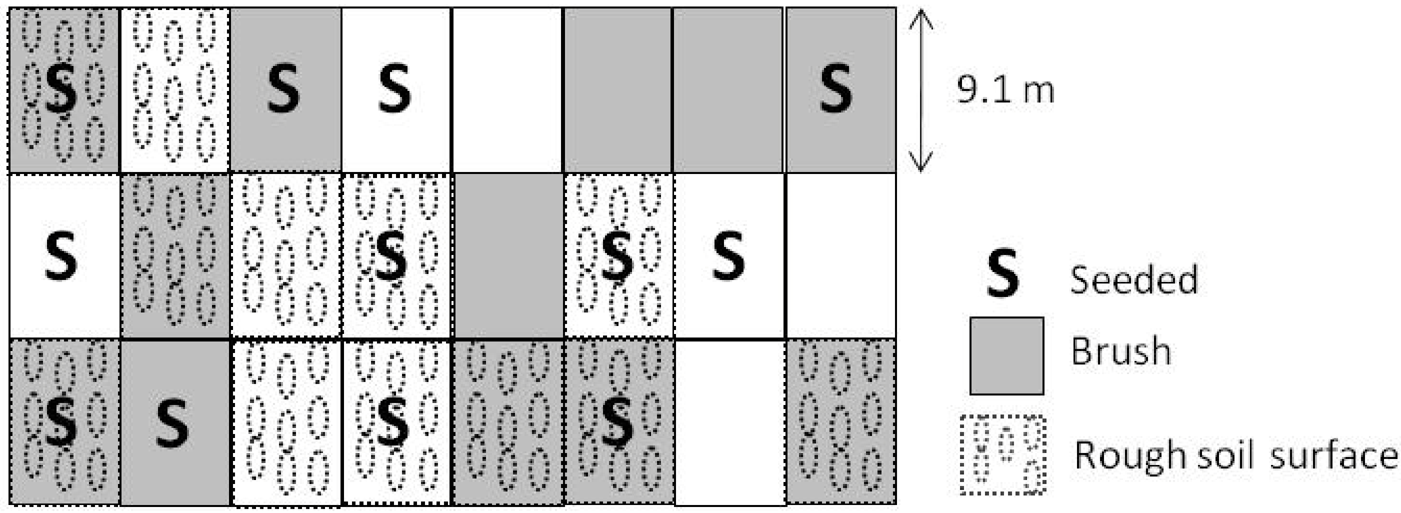


Figure 17. Layout of the Mountain Top experiment at one of 4 research sites.

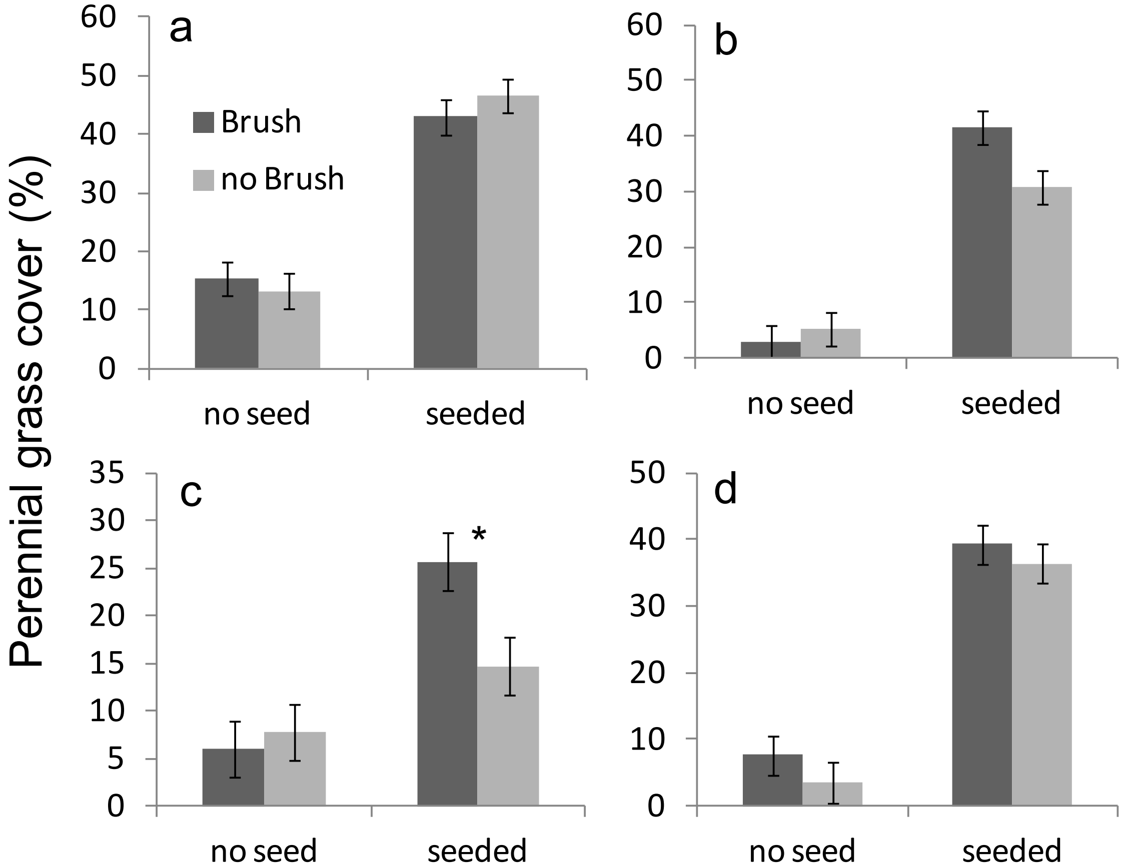


Figure 18. Effect of brush mulch and seeding on cover of perennial grasses in the Mountain Top experiment at 4 study sites: a) SCD, b) SPG, c) SQS, and d) TGC. Error bars = SE for least square means taken over soil surface treatment.

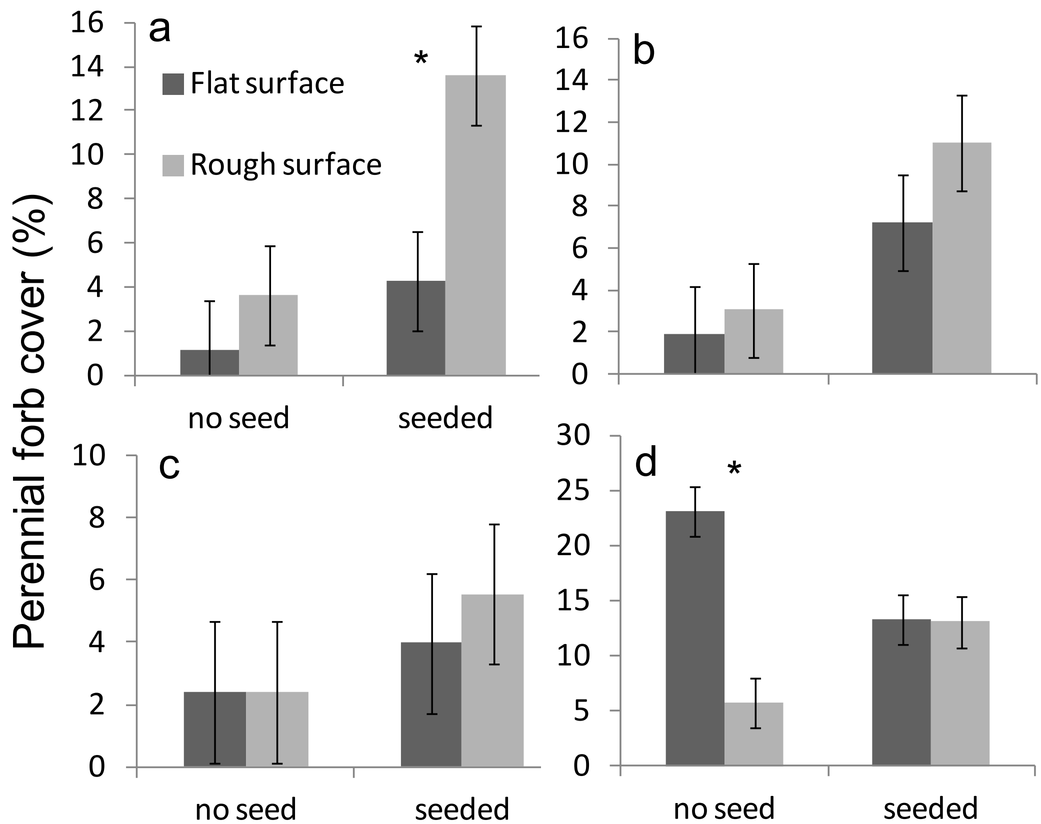


Figure 19. Effect of seeding and soil surface treatment on perennial forb cover in the Mountain Top experiment at four study sites: a) SCD, b) SPG, c) SQS, and d) TGC. Error bars = SE for least square means taken over brush treatment.

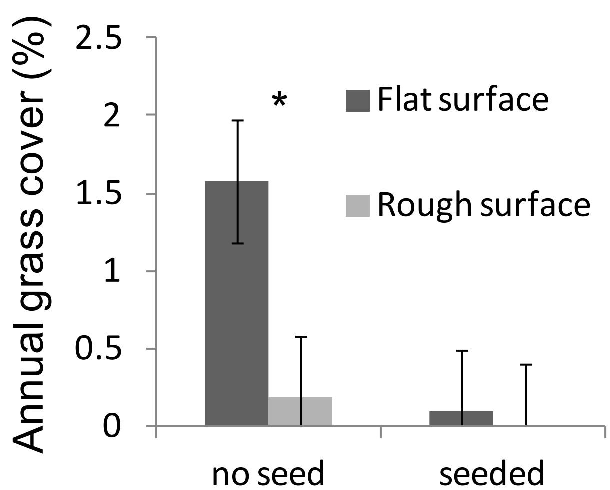


Figure 20. Effect of seeding and soil surface treatment on annual grass cover in the Mountain Top experiment at the SCD site. Error bars = SE for least square means taken over the brush treatment.

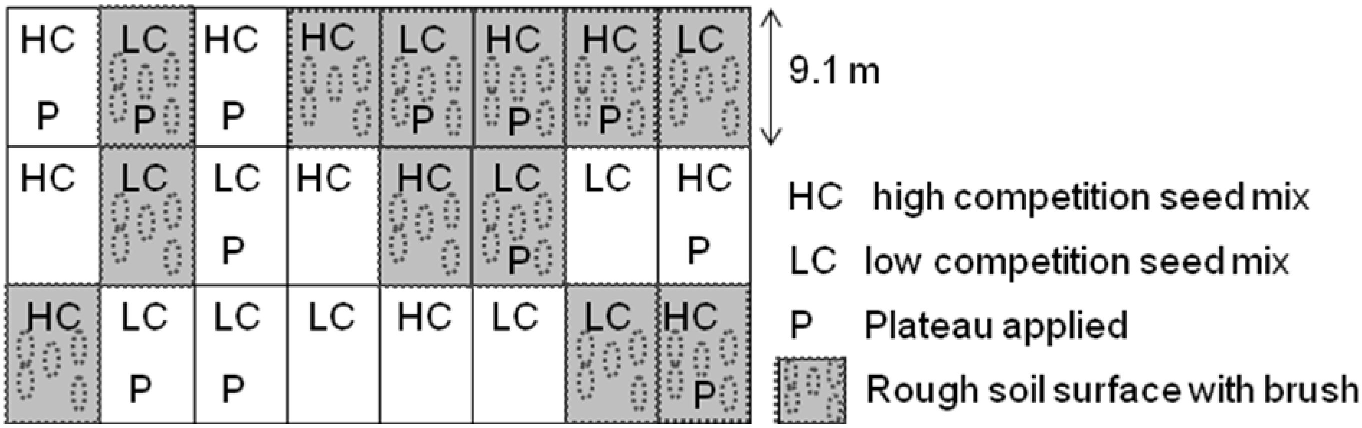


Figure 21. Layout of the Strategy Choice experiments at one of 2 sites where the full experiment was implemented. At 2 additional sites, a reduced form of the experiment lacking the Plateau treatment was implemented.

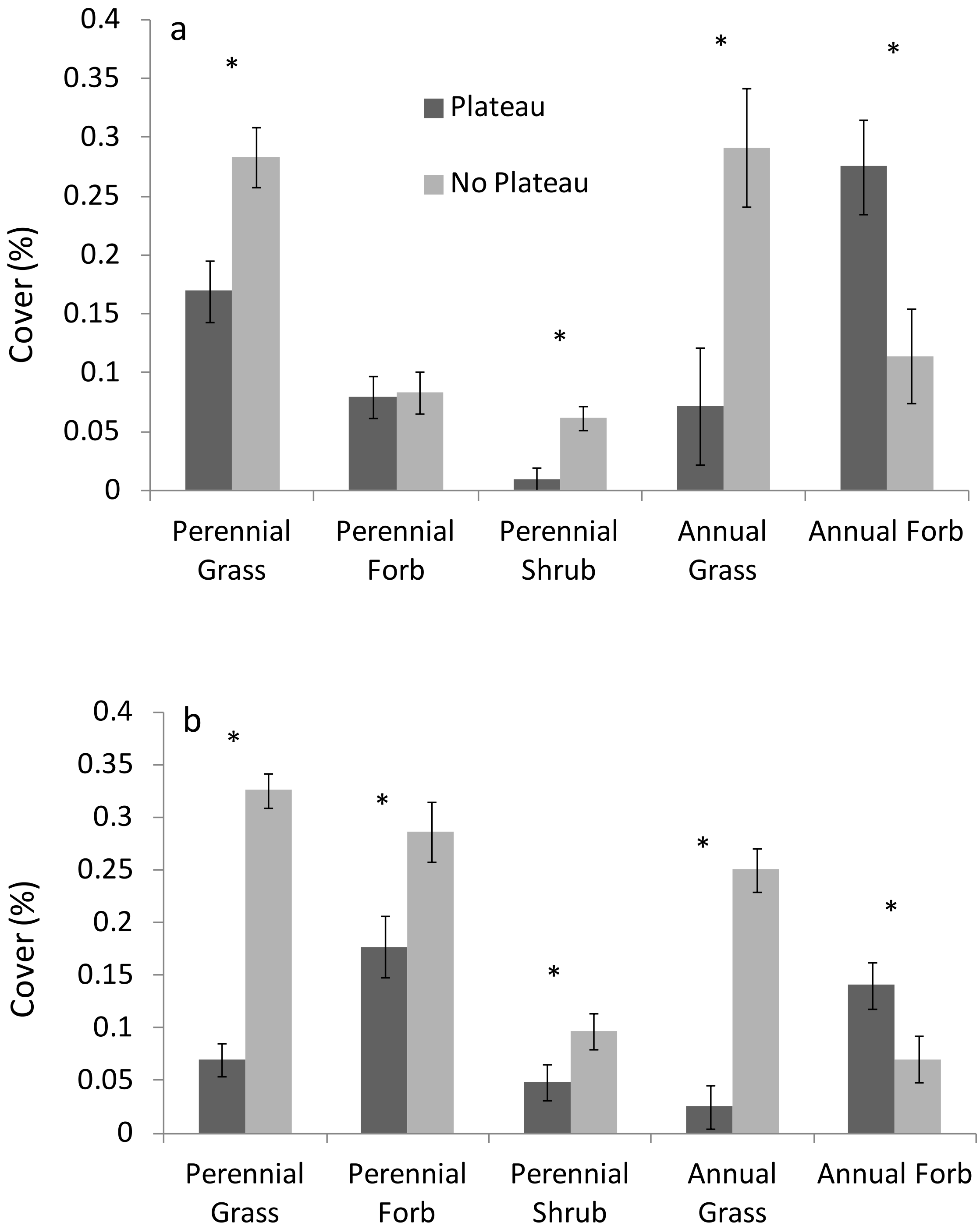


Figure 22. Effect of Plateau treatment on cover of functional groups at a) GVM and b) MTN in the Strategy Choice experiment. Error bars = SE of least square means taken over seed mix and soil surface treatments. Stars represent significantly different means at the α = 0.05 level.

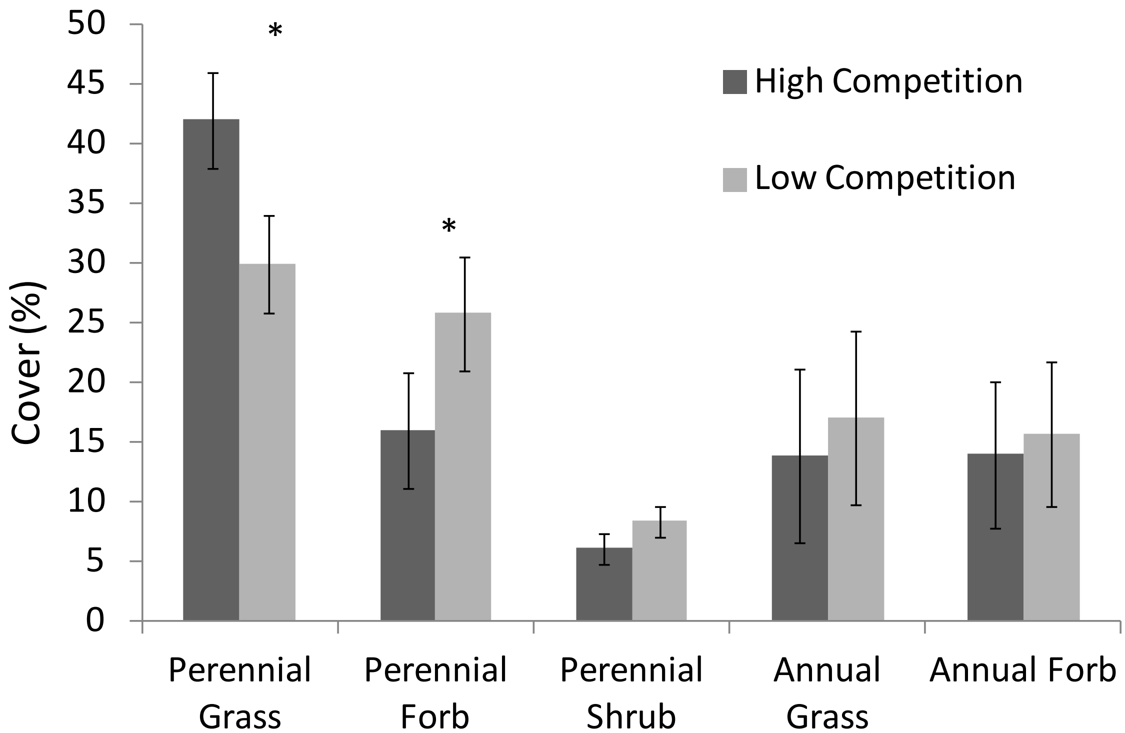


Figure 23. Effect of seed mix treatment on cover of functional groups in the Strategy Choice experiment (sites combined). Error bars = SE of least square means taken over soil surface treatments, with Plateau plots excluded. Stars represent significantly different means at the α = 0.05 level.

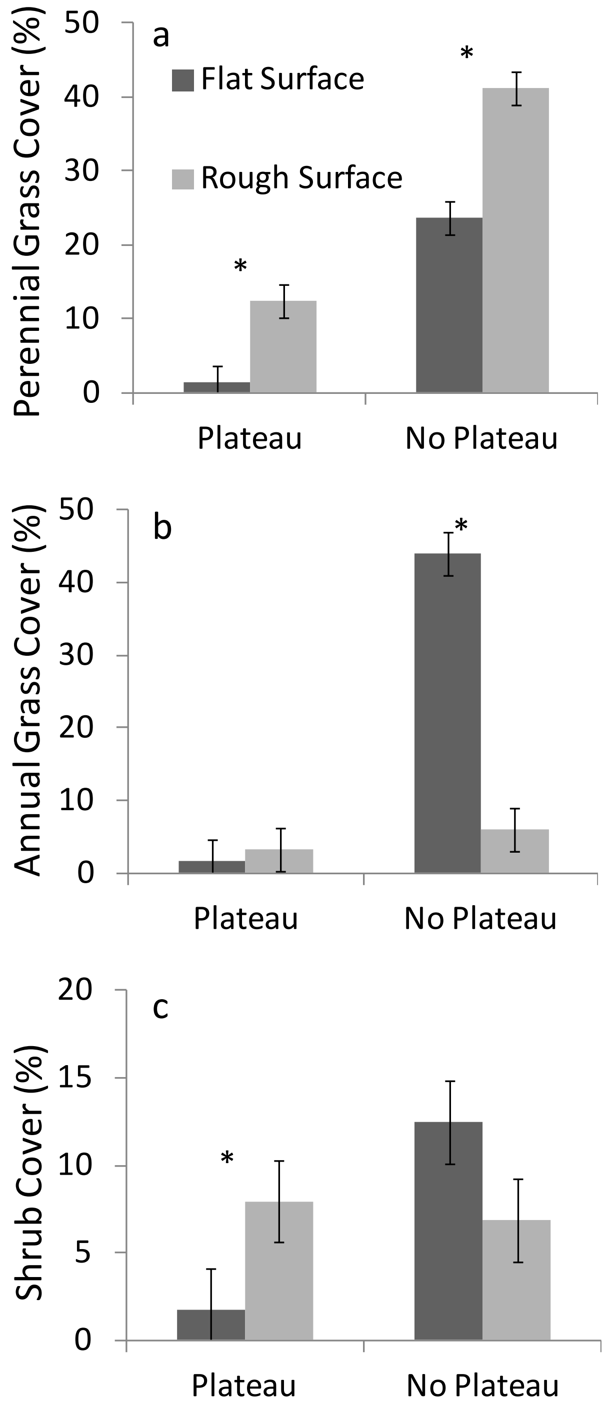


Figure 24. Effect of Plateau and soil surface treatment at the MTN site in the Strategy Choice experiment on a) perennial grass cover, b) annual grass cover, and c) shrub cover. Error bars = SE of least square means taken over seed mix treatment. Stars represent significantly different means at the α = 0.05 level. For annual grass and shrub cover, an interaction between Plateau and surface treatment was significant. For perennial grass cover, only main effects of Plateau and surface treatment were significant.

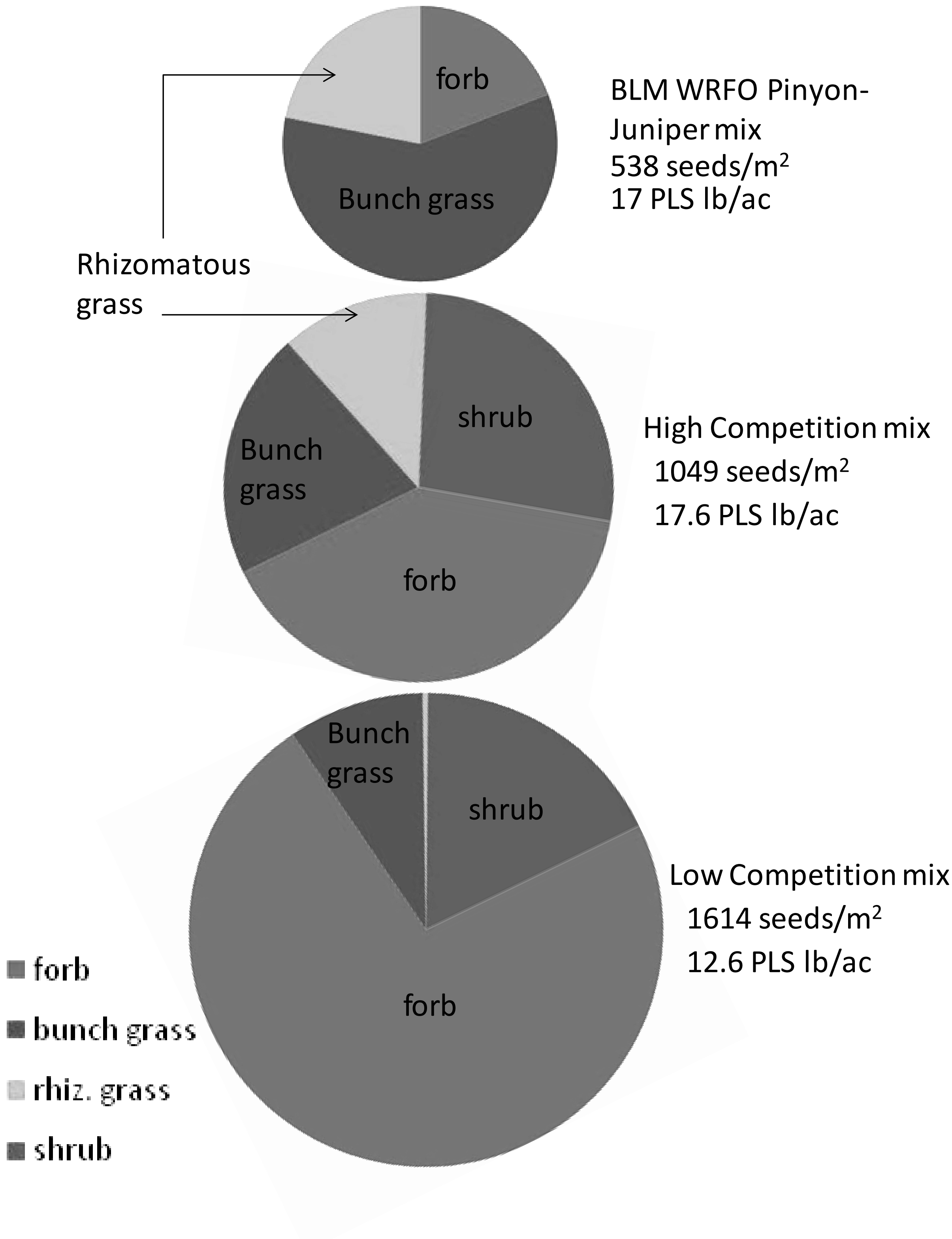


Figure 25. Comparison of the seed mixes used in the Strategy Choice experiment, with a commonly used Bureau of Land Management (BLM) mix for reference. The size of the pie charts is proportional to the number of seeds in the mix.

Flat

Rough

Figure 26. Visual comparison of flat surface versus rough surface plots in the Strategy Choice experiment at the MTN site. Both plots received the Low Competition seed mix and did not receive Plateau herbicide.

APPENDIX 1: CHEATGRASS PROPAGULE PRESSURE METHODS

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

We quantified cheatgrass propagule pressure at each study site using 0.1 m^2 seed rain traps constructed of posterboard covered with Tree Tanglefoot (The Tanglefoot Company, Grand Rapids, MI), a sticky resin (Figure A1-1). Eight traps were set in systematically chosen locations in undisturbed vegetation surrounding each site. Cheatgrass seeds were counted and removed from traps a mean of every 12 days from mid-May to late September, 2009- 2011. Tanglefoot was reapplied as necessary to ensure a sticky surface. Total growing season cheatgrass propagule pressure (seeds/m^2) was calculated by summing the seeds on each trap, and then taking an average for the site.

Figure A1-1. A seed trap.