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EXTENDED ABSTRACT

The pinyon-juniper (PJ) habitat type has been expanding in the western United States, and understory forage for big game may become reduced in areas where PJ has outcompeted more palatable species. Because prescribed fire is often difficult to implement, managers often rely on mechanical tree removal methods such as ship anchor chaining, roller chopping, and mastication. These methods differ in cost, type of woody debris produced, and soil disturbance. We made head-to-head comparisons of understory vegetation changes due to chaining, rollerchopping, and mastication (Figure 1), and also examined how each treatment impacted the success of seeding desirable understory forage species. Half of each treated plot was seeded with a shrub-heavy seed mix including chokecherry (*Prunus virginiana*), Saskatoon serviceberry (*Amelanchier alnifolia*), Utah serviceberry (*Amelanchier utahensis*), mountain mahogany (*Cercocarpus montanus*), bitterbrush (*Purshia tridentata*), and winterfat (*Kraschenninnikovia lanata*). The study was conducted at two sites in the Magnolia region of the Piceance Basin, Rio Blanco County, Colorado. The North Magnolia site (n=4) had higher control plot tree density, lower tree basal area, and higher shrub cover than the South Magnolia site (n=3).

Treatments were implemented in fall 2011, and understory vegetation data (cover, biomass, and shrub density) was collected in 2012 and 2013 through collaboration with Colorado State University. Site visits in 2014 and 2015 indicated significant changes from this initial assessment period, particularly in the cover of cheatgrass (*Bromus tectorum*), an invasive annual grass that reduces wildlife habitat quality. Understory vegetation cover was assessed in July 2016-17 using about 300 point-intercept hits (arrayed over 13 transects) in each plot. Density, summer utilization, and winter-available forage were assessed

for four palatable focal species: bitterbrush, serviceberry, mountain mahogany, and big sagebrush (*Artemisia tridentata*) in September 2017 using 4 belt transects per subplot.

Five and six years post-treatment, differences in perennial grasses and forbs due to type of mechanical treatment were minimal, but all treated plots differed greatly from controls. Treated plots had 3-5 times higher perennial grass cover than control plots, with bottlebrush squirreltail (*Elymus elymoides*), Indian ricegrass (*Achnatherum hymenoides*), and western wheatgrass (*Pascopyrum smithii*) dominating (Figure 5). In 2016, seeded subplots had approximately double the cover of perennial forbs as unseeded subplots, due largely to Utah sweetvetch (*Hedysarum boreale*) and Lewis flax (*Linum lewisii*).

In addition, treatment plots had about 10 times higher cheatgrass cover than control plots (Figure 9). Cheatgrass had been present at only 1-3% cover in the 2013 data (Stephens et al. 2016), and was practically undetectable at the South Magnolia site. By 2016, cheatgrass cover in treated plots was about 27% at North Magnolia and about 7% at South Magnolia. In 2017, we detected a slight difference in cheatgrass cover due to mechanical treatment type, with rollerchopped plots having higher cheatgrass cover than chained plots. Although some studies have found that seeding helps to control cheatgrass, we found the opposite: at the South Magnolia site in 2016, cheatgrass cover was 2-3 times higher in seeded subplots within chained ($p < 0.01$) and rollerchopped ($p < 0.008$) plots. We suspect cheatgrass contamination in the seed that was used.

Shrub cover was higher in all mechanically treated plots than in control in 2016. In 2017, shrub cover in chained plots exceeded that of control or rollerchopped plots ($p < 0.06$). Most of the increase in shrub cover was due to snowberry (*Symphoricarpos rotundifolius*). Seeding did not affect total shrub cover, but it did increase cover of bitterbrush in 2016 and 2017. Seeding had an effect across sites and mechanical treatments, increasing bitterbrush cover from 3.3% to 5.0% in 2017 ($p = 0.01$).

We saw no significant effects of mechanical treatment on 2017 total shrub density. However, seeding in conjunction with rollerchopping approximately doubled total desirable shrub, bitterbrush, and mountain mahogany density. 2017 summer utilization differed by mechanical treatment, with masticated plots having greater utilization than chained or roller chopped plots, which were in turn greater than control plots (Figure 13). Total winter forage of desirable shrubs was lower in masticated plots than in chained ($p = 0.01$) or control plots ($p = 0.04$ Figure 14). The winter forage estimates accounted for losses due to summer browsing; therefore the most obvious explanation for lower winter forage in masticated plots is that much forage had already been consumed.

Increased grass production is the most reliable outcome that can be expected with PJ removal. Increasing winter shrub forage is more difficult, both because less desirable shrubs such as snowberry can respond vigorously to treatment, and because increased shrub production may be consumed in summer rather than in winter. A previous CPW study found a similar result following mastication, with lower winter-available shrub forage and big game pellet density in treatment versus control areas (Johnston 2013). In that study, cattle had utilized the treatments heavily in summer. In this study, many browsers are present in summer, and it is not clear which ones had utilized the plots.

Increases in cheatgrass are common after PJ removal, as shade tends to suppress cheatgrass. Some studies have found that seeding can help, but other studies, such as this one, have found a negative effect of seeding. We urge practitioners to be cautious when applying seed, especially in areas previously free of cheatgrass. To avoid problems of seed contamination and to control costs, we suggest limiting seeded species to those plant types lacking in the restoration area, to proven performers, and to those with seed morphologies that make cheatgrass contamination easier to detect. Bitterbrush, Utah sweetvetch, and Lewis flax are three species that fit those criteria in this study. The Hansen seed dribbler was an effective way to plant bitterbrush and Utah sweetvetch.

A notable difference among the mechanical treatment types included better shrub establishment, but somewhat worse cheatgrass issues, with rollerchopping than with other treatment types. Rollerchopping produced the most bare ground in year after treatment, a condition which may have both allowed better shrub establishment and also fostered more cheatgrass. Other notable differences were in how treatments impacted utilization; rollerchopped and chained plots were less utilized in summer than masticated plots. This may be because shrubs were specifically targeted for biomass removal in masticated plots, but any rejuvenation of shrubs in rollerchopped and chained plots was incidental. Greater rejuvenation of shrubs in masticated plots may have attracted more use.

We suggest that the choice of mechanical treatment should depend on cost, desired level of shrub rejuvenation, and desired spatial arrangement of treatment patches. More detailed mosaics are possible with mastication than with rollerchopping, and chaining is the least flexible. We used a shorter-than-typical 50-foot smooth chain in our study, which could be a viable and cost-effective option for creating small treatment patches. However, it is not possible to leave isolated trees with chaining. Chaining costs are one-third to one-sixth that of mastication, with rollerchopping having intermediate costs.

Presence of cheatgrass, even at very low levels, should influence the choice of treatment locations. Recent research has shown that cheatgrass is adapting to higher elevation sites (Merrill et al. 2012), therefore problems with cheatgrass can be expected to worsen. Nevertheless, the substantial amount of perennial grass cover at the sites in this study should prevent cheatgrass from dominating. Wildlife benefits are still possible with PJ removal if enough understory vegetation is present to respond (Miller et al. 2005), but practitioners should consider potential risks as well as benefits when selecting projects.

WILDLIFE RESEARCH REPORT

EXAMINING THE EFFECTIVENESS OF MECHANICAL TREATMENTS AS A RESTORATION TECHNIQUE FOR MULE DEER HABITAT

DANIELLE B. JOHNSTON

INTRODUCTION

Pinyon-juniper (PJ) woodlands play an important role in mule deer ecology. Pinyon pine (*Pinus edulis*), Utah juniper (*Juniperus osteosperma*) and the associated understory shrub species such as mountain mahogany (*Cercocarpus montanus*), antelope bitterbrush (*Purshia tridentata*) and big sagebrush (*Artemisia tridentata*) are key to winter survival (Hansen and Dearden 1975). Deer strongly select for this habitat type because of the escape and thermal cover provided by pinyon and juniper trees (Anderson et al. 2013). However, PJ habitats occasionally lack understory and may provide very little forage (Bender et al. 2007). It has been shown that increasing nutrition in poor quality PJ winter range can increase deer populations in western Colorado (Bishop 2007). Therefore, creating patches of habitat types with higher nutritional value within PJ stands is a desirable management objective for mule deer.

The PJ habitat type has increased in many parts of western North America over the past 100 years (Miller and Rose 1999, Schaffer et al. 2003, Bradley and Fleishman 2008). Disruption of natural fire regimes, overgrazing, and invasion by weedy species have led to a wide array of management problems. Of particular concern are overgrown stands of PJ that have allowed the overstory to shade out understory plant species. Fire is a natural remedy, however prescribed fire is often impractical because of the proximity to infrastructure and human activity, as well as the lack of continuous understory fuels. Alternatives to fire include mechanical treatments, which can open up the canopy and reduce competition (Young et al. 2013). Mechanical treatments may also increase mule deer fawn survival in western Colorado (Bergman et al. 2014). Several different types of mechanical removal methods exist, and little information is available to determine which method is most desirable and cost-effective.

Mechanical treatments in PJ forests differ in the size of woody litter produced, in the degree of soil disturbance created, and in cost. Chaining is an inexpensive technique by which trees are removed by dragging a ship anchor chain between two bulldozers (Figure 1a). Trees are uprooted and left intact and the action of uprooting may create a great degree of soil disturbance (Cain 1972; Figure 1b). Roller chopping is a more expensive technique in which a heavy rotating drum with protruding steel plates is pulled behind a bulldozer (Figure 1c). The bulldozer knocks the trees over and the drum chops them into large pieces (Figure 1d). The action of the roller chopper creates soil disturbance, though to a lesser depth than does chaining. Mastication is a technique by which entire trees are mulched, typically using a rubber-tired industrial tractor (e.g. Hydro-ax© or Barko©) with front-end mounted rotary cutter or a drum-style mulcher (e.g. Fecon© or FAE©; Figure 1e). Fine woody debris is produced (Figure 1f), there is little ground disturbance, and the cost per area may be 5 to 10 times higher than that of chaining. Mastication is a relatively new method which has gained favor because of the lower degree of ground disturbance, but only recently has any research been done to understand the effect of mastication on plant communities (Ross et al. 2012, Young et al. 2013, Provencher and Thompson 2014). Only one study (Provencher and Thompson 2014), and none on the Colorado Plateau, has made head-to-head comparisons of older mechanical removal methods with mastication.

Differences in the size of woody litter produced and the degree of soil disturbance may influence the germination and establishment of desirable understory species. For instance, the mulch layer produced by a mastication treatment may have positive or negative effects on germination; germination may be inhibited by lower light availability at the soil surface, or it may be enhanced by higher soil moisture. In chaining and roller chopping, the higher degree of soil disturbance may provide an opportunity for seeded species to establish, or it may become a liability by allowing invasion by weedy species. Finally, in a chaining treatment, the tree skeletons may offer a few years of protection from herbivory, which could play an important role in allowing shrubs to establish. These differences may affect the success of seeding attempts following mechanical tree removal, but such differences have yet to be examined. Finally, characteristics of the PJ forest stand, such as density, basal area, and understory seed bank, may influence which treatment produces the most desirable results.

Our study has three goals: to compare the desirability of vegetation produced by three types of mechanical treatment (ship anchor chaining, roller chopping, and mastication), to determine the usefulness of seeding within each of these three treatments, and to determine if these results differ between two PJ stands with differing basal areas and densities. Desirable vegetation in this context is native vegetation with a high proportion of ground cover consisting of broadleaf forbs and palatable shrubs. Undesirable vegetation includes cheatgrass (*Bromus tectorum*) and non-native annual forbs such as Russian thistle (*Salsola tragus*).

STUDY AREA

The Piceance Creek Basin, located in Rio Blanco and Garfield Counties of northwestern Colorado, serves as winter range for one of North America's largest migratory mule deer (*Odocoileus hemionus*) populations (White and Lubow 2002). The basin ranges in elevation from 1706 meters to 2743 meters with the highest points near the edges (Tiedeman 1978). This basin encompasses nearly 4143 square kilometers and is bordered from the north by the White River, from the south by the Roan Plateau, from the east by the Grand Hogback and from the west by the Cathedral Bluffs. Terrain varies from rugged badlands, abrupt cliffs and sharp ridges to open valleys, parks and basins. Its semiarid climate receives between 27 and 63 centimeters of annual precipitation, half coming in the form of snow during winter months (Tiedeman 1978). The basin is part of the Green River Geologic Formation, consisting of primarily sandstone, siltstone, mudstone, limestone, and shale. Sagebrush and desert shrub dominate lower elevations, and middle elevations are dominated by upland sagebrush, mixed mountain shrub, and PJ woodlands (Tiedeman 1978). Grasslands, aspen (*Populus tremuloides*) and douglas-fir (*Pseudotsuga menziesii*) forests can be found at the highest elevations (Tiedeman 1978).

Historically, the land was sparsely populated and used primarily for agricultural and recreational purposes (Tiedeman 1978). In recent decades, natural resource extraction of rich oil shale and natural gas reserves has dramatically altered the landscape. As of April 2013, the 1.8 by 10^6 ha Piceance Basin area contained about 24,000 gas wells (Colorado Oil and Gas Conservation Commission 2013). Through the construction of well pads, roads and compressor stations, development of this infrastructure has and continues to fragment suitable mule deer habitat (Anderson 2011). Traffic, noise and increased human presence also contribute to adversely affect this important winter range (Anderson 2011).

The Magnolia area of Piceance occupies the northeastern corner of the basin, and is bounded by Piceance Creek on the south and west, the White River on the north, and the Grand Hogback on the east. It is dominated by PJ woodlands.

METHODS

Site Selection

Study area selection was done in conjunction with Dr. Charles Anderson's larger-scale project to examine deer responses to PJ removal (Anderson 2011). First, several hundred PJ stands were delineated within the Magnolia area of Piceance Basin using aerial photography, excluding areas with slopes greater than 30%. Next, stands were visited and scored for suitability of treatment based on a scale of 1 to 3:

Score 1 – most suitable acreage. These parcels contained abundant younger trees growing in dense stands. Simultaneously, the understory of desired shrubs, grasses, and forbs appeared to be robust. Treatment of these areas should yield a strong growth response from that desired understory.

Score 2 – highly suitable acreage. These parcels contained a mix of younger and older trees that grew in less dense patches. The understory of desired shrubs was also less robust than a Score 1 site. Score 2 parcels were highly suitable for treatment, but will likely yield a lesser initial growth response from the desired understory than a Score 1 site.

Score 3 – suitable acreage. These parcels contained more mature PJ,that possessed larger individual tree canopies, growing in less dense stands. Diameter of tree trunks was larger than trees in Score 1 or 2 sites. The understory of desired shrubs, grasses, and forbs was often lacking, and more bare ground was found here than Score 1 or 2 tracts.

Delineations and suitability scores were assigned by Todd Graham of Ranch Advisory Partners. A total of 203 tracts comprising 585 ha (1, 445 ac) were deemed suitable for treatment. Next, two focal areas were selected based on the following criteria: at least 40 acres with the same suitability score were available, access routes for ground-disturbing equipment were available, and the cover of PJ trees within each area was as uniform as possible. These two focal areas are called North Magnolia (elevation 2194 m, score of 1 on suitability scale, Figure 2a) and South Magnolia (elevation 1828 m, score of 3 on suitability scale, Figure 2b). At the North Magnolia site, a contiguous parcel met the needed criteria. At South Magnolia, the study area was fragmented by gullies which were unsuitable for treatment (Figure 3).

Experimental Design and Setup

We implemented a split-plot design with four blocks at the North Magnolia location, and three blocks at the South Magnolia location (Figure 3). Block divisions were designed to minimize variation within each block in PJ density, based on visual inspection of the aerial photography. Mechanical treatments were randomly assigned to whole plots within blocks. Each treated plot was further subdivided into two subplots, with seeding treatments (seeded or unseeded) randomly assigned to subplots within plots. Control plots were not seeded. Subplots were 0.40 ha (1 acre) in size and about three times as long as wide. The long axis of each subplot was arranged perpendicular to the slope. This is because mechanical treatments are typically applied across slopes, rather than up and down them, because it is safer and saves fuel to drive heavy machinery across the slope.

Mechanical Treatments

Mechanical treatments were applied between Oct. 23, 2011 and Nov. 28, 2011. The chaining treatment was done using two D8 bulldozers (Caterpiller, Inc., USA), each attached to one end of an 18 m (60-ft.) ship anchor chain with links weighing 40.8 kg (90 lbs.) each. Trees were pulled over by running the chain in one direction, and then killed more completely by running the chain back over the plots in the opposite direction (2-way chaining; Figure 1a-b). The roller chopping treatment was accomplished by attaching a 3.7 m (12-ft.) long, 0.6 m (1.9-ft.) diameter roller chopper to a D8 dozer (Figure 1c). The drum weighed approximately 1100 kg (2,500 lbs.) when empty and held 8338 li (2,200 gal) of water. The drum was filled during operation for a total weight of approximately 9100 kg (20,000 lbs.). Roller chopper plates acted as blades to chop downed trees into pieces approximately 30 cm long (Figure 1c-d). The mastication treatment was accomplished used a 930 Barko© industrial tractor with a FAE© mulching head, which produced fine masticated material ranging in size from 2 – 20 cm and a few larger sections of tree boles (Figure 1e-f). All vegetation was masticated to ground level (or as close as the equipment would allow; less than 30 cm). In the vicinity of former trees, masticated material was up to 40 cm deep. Equipment operators used handheld GPS units to ensure the correct areas were being treated. Every plot was completely treated and no “leave” areas, or refugia, strips were left in the plots. Although the area of the seeded and unseeded subplots was only 0.4 ha, an area larger than this was mechanically treated in some cases. The estimated total area treated across all 21 thinned plots was 16.8 ha.

Seeding

All seeded plots received the same diverse native seed mix comprised of 10 shrub species, 14 forb species and 10 grass species (Table 1). The mix emphasizes shrubs while incorporating light rates of forbs and grasses in order to fill resource niches and thereby reduce the likelihood of weed invasion. Most species were broadcast seeded prior to mechanical treatment using EarthWay® hand crank spreaders. Because the seed mix contained seeds of varying sizes, seeds were broadcast in groups based on size (Table 1) in order for uniform seed dispersal to occur using the spreaders. Five evenly spaced passes, parallel to the long axis of the plot, were made through each seeded subplot using the hand spreaders. Two seeders followed one navigator using a handheld GPS unit to ensure dispersal occurred in the seeded subplot only. Seeds of Group 5 (Table 1) were large-seeded shrubs and forbs which benefit from deep planting. Seeding method for these species differed by treatment. In the treatments using tracked machinery, chaining and rollerchopping, Group 5 species were seeded using Hansen seed dribblers mounted to the tracks of the bulldozer (Figure 4). The linear seeding rate for dribbled seed was 3.5 g/m. In masticated plots, these species were broadcast in a similar manner to Groups 1-4.

Plant Cover

In July of 2016-17, percent cover was assessed using 13 systematically placed transects per subplot. These ran perpendicular to the long axis of the plot, and were the transects numbered 1, 3, 5, 6, 7, 9, 10, 11, 13, 14, 15, 17, and 19, of the 20 original transects marked out in 2012. A 5m buffer around the perimeter of the subplot was excluded from measurement. Transects were usually 23 m long, unless an usually shaped plot mandated that the transect be shortened. Point-intercept hits were gathered at 1m intervals using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT), and roughly 300 point-intercept hits were measured per subplot. All canopy layers of vegetation were characterized to species, if possible. When calculating percent cover of a given functional group, such as perennial grasses, overlapping hits of different species within a functional group were counted as a single instance of the functional group.

Desirable shrub density, summer utilization and winter-available forage

In September 2017, we estimated shrub density, summer utilization, and winter-available forage using four of the transects on which cover data had been collected: 5, 9, 13, and 17. We measured all sagebrush, serviceberry, bitterbrush, and mountain mahogany plants that were 50% or more within a 4-m wide belt centered on the transect line. Transects were typically 15 m long for a total area of 240m^2 sampled per subplot. All of the species of interest grow multiple stems, requiring some judgment in determining what constituted a plant. Often it was helpful to shake stems to determine if they rooted back to a central location.

We made trained ocular estimates of summer utilization for each plant. We examined each plant to look for fresh bite marks, distinguishable from older bite marks because the color of the wood was pinkish or tan rather than grey. We considered how prevalent they were as well as how deep the bites were- was the diameter at the bite mark small, so that just the tip of the current year shoot was removed, or was the diameter bigger and occurring in wood older than one year, so that a current year shoot, plus some older wood and possibly some smaller side shoots were all removed in one bite? We used these benchmarks to help maintain consistency: 5%- only one to a few nibbles of shoot tips; 10% several nibbles of shoot tips; 30% many nibbles plus a few bites into older wood; 50% many nibbles, several bites into older wood, most branches having some browsing evident; 70% many bites into older wood, the only intact shoots occurring deep within the plant where they had protection from herbivory by woody braches above. We checked our training by having 3 observers make estimates for the same plant, and verifying that estimates were within 10% of each other.

We estimated winter-available forage by canopy measurements of shrubs. For serviceberry, bitterbrush, and mountain mahogany, we developed regressions predicting winter forage from canopy measurements within the study area (average R^2= 0.73; Table 2). There regressions were developed over the years 2013-2016 by measuring and clipping plants in September from off-plot locations. We included plants whether or not they had experienced summer browsing. We measured plant height, height of the tallest 2-year-old wood on the plant, length of the longest leader, longest canopy axis when viewed from above, and length of the canopy axis perpendicular to the longest axis. Next we clipped all current year shoots longer than 1cm and stripped leaves from shoots. For serviceberry and mountain mahogany, we had noted that shoots shorter than 3cm were often shed along with leaves prior to winter. Therefore, we separated out these 'puny shoots' for serviceberry and mountain mahogany. We dried all biomass fractions (long shoot leaves, long shoot stems, and puny shoots, if applicable) at 105°C for 35-48h and weighed them to the nearest 0.1g. We considered summer-available biomass to be the sum of all of the biomass fractions, and winter-available biomass to be long shoot stems only. We used linear regression of transformed data to create equations predicting winter-available biomass from plant measurements (Table 2). For big sagebrush, a regression was available in the literature (Cleary et al. 2008). This equation includes non-ephemeral sagebrush leaves (M. Cleary, *pers. comm*.). We measured the necessary canopy dimensions, which varied by species according to Table 2, on all plants within the belt transects. We used the equations to estimate winter-available forage per plant, summed these by subplot, and then converted these values to g/m^2.

Statistical Analysis

Because the design of the experiment was not fully factorial (there were no plots which were seeded, but not mechanically treated), two types of analyses were used to examine cover, density, summer utilization, and winter-available forage: the *Mechanical treatment analysis*, and the *Seeding effect analysis* (Stephens et al. 2016).

The *Mechanical treatment analysis* used only unseeded subplots to examine effects of mechanical treatments relative to one another and also to untreated controls with a nested randomized complete block mixed effects model where mechanical treatment (chained, rollerchopped, masticated, or control) and site (North Magnolia or South Magnolia) were fixed effects, and block within site was a random effect; the Kenward-Rogers denominator degrees of freedom method was used to account for unequal variances. Results from these analyses will be designated *MEA.*

The *Seeding effect analysis* excluded plots without mechanical treatment to allow analysis of the seeding treatment, and interactions involving the seeding treatment. These analyses were conducted using a nested randomized complete block split-plot mixed effects model where site, mechanical treatment type (chained, rollerchopped, or masticated), seeding treatment (Seeded or Unseeded), and site (North Magnolia or South Magnolia) were fixed effects and block within site and mechanical treatment within block were random effects; the Kenward-Rogers denominator degrees of freedom method was used to account for unequal variances. Results from these analyses will be designated *SEA.*

For significant interactions involving site (cutoff of $\alpha = 0.1$), further analyses to test for mechanical and/or seeding treatment effects were conducted separately for each site.

Cover data was split into the following six groups: native annual forb, exotic annual forb, perennial forb, cheatgrass, perennial grass, and shrub. We also analyzed bitterbrush as an individual species, as an effect of seeding had been noted for this species in prior work (Johnston 2014). Species with biennial life cycles were lumped in with annuals. Because both native and exotic annual forbs were present, they were analyzed as two separate groups. Perennial forbs were all native with trace amounts of exotics. Cheatgrass, an invasive non-native, was the only annual grass present. Perennial grasses and shrubs were all native. Cover data was arcsin (sqrt (X)) transformed to improve normality prior to parametric analyses, and residual plots were examined to ensure proper adherence to normality assumptions. Years were analyzed separately.

Density and winter-available forage of bitterbrush, serviceberry, mountain mahogany, and sagebrush were analyzed for individual species as well as for the average response of these four focal species. Summer utilization was analyzed as an average response only. Data were log + constant transformed to improve normality prior to parametric analyses, and residual plots were examined to ensure proper adherence to normality assumptions.

All analyses were conducted in SAS 9.3 (SAS Institute, Cary, NC, USA).

RESULTS

Plant cover

In 2016, all treated plots had three to four times higher perennial grass cover than controls ($p < 0.0001$ *MEA*), but no differences were apparent between types of mechanical treatment ($p > 0.34$ *MEA*; Figure 5). In 2017, results were similar, with treated plots having 2-4 times higher grass cover than controls ($p < 0.009$ *MEA*; Figure 5), and no differences by treatment type ($p > 0.57$ *MEA*). Bottlebrush squirreltail (*Elymus elymoides*), Indian ricegrass (*Achnatherum hymenoides*), and western wheatgrass (*Pascopyrum smithii*) were the dominant grass species (Figure 6). We detected no effects of seeding on perennial grass cover.

Perennial forb cover did not differ by mechanical treatment in either 2016 or 2017 ($p > 0.17$, *MEA*; Figure 7). However, an effect of seeding was apparent in 2016, when seeding increased forb cover from 2.4% to 5.4% at South Magnolia and from 3.5% to 7.9% at North Magnolia ($p < 0.006$). Utah sweetvetch (*Hedysarum boreale*) accounted for most of the difference, followed by Lewis flax (*Linum lewisii*). Results were similar among each of the three mechanical treatment types. By 2017, the effect had been reduced to a trend for a slight increase in forb cover with seeding ($p = 0.06$ *SEA*).

There were no effects of mechanical treatment or seeding on native annual forb cover in 2016 ($p > 0.06$, *MEA* and *SEA*). In 2017, there was insufficient native annual forb cover for analysis. In 2016, exotic annual forb cover differed by mechanical treatment at South Magnolia only (site*mechanical treatment interaction $p = 0.04$). At South Magnolia, all treated plots had about 4 times higher exotic annual forb cover than control plots ($p < 0.04$ *MEA*), but treated plots did not differ by treatment type ($p > 0.82$ *MEA*). Similarly, in 2017 there was a possible interaction between mechanical treatment and site for ($p = 0.09$), and there were trends for higher exotic annual forb cover for all treated plots versus control at South Magnolia only ($0.06 < p < 0.09$ *MEA*). There were no effects of seeding on exotic annual forbs. Exotic annual forbs have had low cover over the course of the study (Figure 8).

Cheatgrass cover in 2016 was about 10 times higher in treated plots than in control plots ($p < 0.0003$ *MEA*; Figure 9) but there were no detected differences by mechanical treatment type ($p > 0.19$). In 2017, cheatgrass cover was 2-4 times higher in treated plots than in controls ($p < 0.02$ *MEA;* Figure 9), and rollerchopped plots had almost double the cheatgrass cover of chained plots ($p = 0.05$ *MEA*). In 2016, the effect of seeding on cheatgrass depended on a 3-way interaction with site and mechanical treatment ($p = 0.003$ *SEA*). Seeding had no effect on cheatgrass at North Magnolia, but at South Magnolia, cheatgrass cover was 2-3 times higher in seeded subplots within chained ($p < 0.01$) and rollerchopped ($p < 0.008$) plots (*SEA*). In 2017, no effects of seeding were apparent for cheatgrass cover ($p > 0.13$ *SEA*).

In 2016, shrub cover was higher in chained ($p = 0.0045$) and masticated ($p = 0.05$) than control, and there was a trend for higher shrub cover in rollerchopped plots than in control ($p = 0.06$ *MEA;* Figure 10). In 2017, shrub cover in chained plots was significantly higher than in masticated or rollerchopped plots ($p < 0.02$ *MEA* Figure 10). There was also a trend for higher shrub cover in chained plots than in control ($p = 0.06$ *MEA* Figure 10). Much of this increase was due to a strong snowberry response at North Magnolia (*Symphoricarpos rotundifolius*; Figure 11). In 2016, there was no effect of seeding on total shrub cover, but there was a slight effect of seeding for bitterbrush as an individual species ($p = 0.04$ *SEA*), whereby seeding increased bitterbrush cover from 2.9% to 3.8% across mechanical treatment types. In 2017, the difference was 3.3% vs. 5.0% ($p = 0.01$ *SEA*).

2017 Desirable shrub density, utilization, and winter-available forage

2017 shrub density was not affected by mechanical treatment, either for species lumped or for bitterbrush, serviceberry, mountain mahogany, or sagebrush individually ($p > 0.08$ *MEA*). The effect of seeding on shrub density depended on mechanical treatment type (mechanical treatment*seeding interaction $p = 0.01$ *SEA*). Seeding increased total shrub density from 0.23 ± 0.05 plants/m^2 to 0.46 ± 0.10 plants/m^2 only within roller chopped plots ($p = 0.0015$ *SEA;* Figure 12). Bitterbrush and mountain mahogany density followed the same pattern, with effects of seeding evident within roller chopped plots only ($p < 0.02$ *SEA*). There was no effect of seeding on serviceberry or sagebrush density as individual species.

Summer utilization of desirable shrubs differed by mechanical treatment type ($p < 0.0001$), with masticated plots having greater utilization than chained or roller chopped plots ($p < 0.01$), which were in turn greater than control plots ($p < 0.001$ *MEA*; Figure 13). The effect of seeding on summer utilization depended on site (interaction $p = 0.03$ *SEA*), with effects evident at North Magnolia only. At North Magnolia, summer utilization was higher in seeded subplots ($14.5 \pm 1.4\%$) than in unseeded subplots ($12.0 \pm 1.4\%$; $p= 0.04$ *SEA*).

Total winter forage of desirable shrubs was lower in masticated plots than in chained ($p = 0.01$) or control plots ($p = 0.04$ *MEA*; Figure 14). Mountain mahogany winter forage followed the same pattern ($p < 0.02$ *MEA;* Figure 14). Other species had no significant effects for winter forage. Seeding effects on winter forage differed by site (site*treatment*seeding interaction $p = 0.01$ *SEA*). At North Magnolia, there were no significant effects.. At South Magnolia, there was lower winter forage with seeding in chained plots ($p = 0.01$ *SEA*), and trends for higher winter forage with seeding in masticated and roller chopped plots ($p < 0.07$ *SEA*).

Treatment costs

A summary of the costs incurred by the 3 treatment types in setting up this experiment is summarized in Table 3. Rollerchopping had the highest cost of mobilization due to the need for a crane to remove the roller chopping drum from the trailer, and the need for a water truck to fill the drum. Chaining had the next highest mobilization cost, because it required two bulldozers plus the chain. Mastication had the lowest mobilization cost, but required more than double the cost per acre of the other two treatments. The times per acre reported here were for times actually spent implementing the treatments, excluding time spent traveling from one plot to another. The costs per acre are inclusive of inter-plot travel to achieve the research design, and are therefore about two times higher than normal. Costs per acre also depend on terrain, tree density, and local markets.

DISCUSSION

In general, perennial grasses and forbs responded similarly to tree removal, regardless of removal method. Starting at 2 years post-treatment and persisting through 6 years post-treatment, mechanically treated plots had 3-5 times higher grass cover than control plots. Perennial forbs did not respond to mechanical treatment alone, but seeding in combination with mechanical treatment did increase forb cover, largely due to Utah sweetvetch and Lewis flax. We observed twice as much forb cover in seeded versus unseeded subplots in 2016, regardless of mechanical treatment type.

The type of mechanical treatment had some interesting effects on shrubs. Six years post-treatment, we observed higher summer utilization of shrubs in masticated plots than in chained or roller chopped plots, which in turn had higher utilization rates than control plots. Unlike in chained and roller chopped plots, shrubs within masticated plots were specifically targeted for biomass removal. These species are vigorous root-sprouters, and the palatable regrowth appears to have been attractive for summer browsers. Winter-available forage was lower in masticated plots than in control or chained plots. Our estimates of winter-available forage accounted for biomass removal by summer browsing; therefore the most obvious explanation for lower winter-available forage in masticated plots is the higher summer utilization we observed. Lower winter-available forage with mastication was also observed in a prior CPW study (Johnston 2013). In that study, heavy summer utilization by cattle was suspected, and big game use (as indicated by pellet density) actually declined within treatment areas. The Magnolia area is utilized by elk, deer, cattle, and wild horses, although deer are by far the most numerous. Whether the summer utilization in this study was primarily due to deer or another browser is not clear.

In a 10-year study of effects of biomass removal on productivity of mountain mahogany, serviceberry, and bitterbrush, Shepard (1971) found that heavy clipping causes these species to have an initial spike in productivity. However, continued heavy removal in subsequent years causes drought sensitivity and lower productivity (Shepard 1971). The masticated shrubs in this study experienced initial heavy biomass removal followed by increased utilization, conditions somewhat similar to the plants in Shepard's study. Although the level of removal does not appear to be enough to jeopardize plant survival, repeated rejuvenation of these shrubs is not advised. The trend for lessened winter forage with mastication differs from a 2014 analysis of nearby two-year-old mastication treatments which were a part of a more extensive study on mitigation treatments for mule deer impacted by oil and gas development. In that study, masticated plots had about double the winter forage of control areas. It is possible that in the first years following rejuvenation, shrub productivity may be high enough to satisfy summer browsers and also provide higher winter forage.

Rollerchopping, and especially chaining, had different effects on shrubs than mastication. In rollerchopped plots, most shrubs were rejuvenated, but some were missed by the rollerchopper. In chained plots, most shrubs were flexible enough to retain their aboveground biomass through the treatment. We observed upright shrubs with mature wood the year after treatment in chained plots. We also noted higher shrub cover in chained plots than in masticated or rollerchopped plots six years post treatment. However, this was primarily due to snowberry, which is not considered to be a desirable forage species in this area. Summer utilization of desirable shrubs in chained plots was higher than control, but winter-available forage was similar to control. Shrubs in chained plots are providing some summer as well as winter forage, even though the species-level response to this treatment was less than ideal.

Chaining has often been thought to cause a great degree of soil disturbance (Miller et al. 2005). We noted that chaining had a much more variable impact to the soil surface than the other treatments. Bulldozer attachment points for the chain were elevated from the ground about a meter, which prevented some of the chain from contacting the soil surface. In addition, when the chain was being dragged it occasionally rode above the ground entirely if it was caught in a pile of slash. Therefore, although the depth of soil disturbance was great where trees were uprooted, large portions of plots had no disturbance at all. Interestingly, grass biomass was higher in chained than in rollerchopped or masticated plots in the first post-treatment year, indicating that more of the understory survived chaining than the other treatment types. This result may have been influenced by the type and length of chain used in this experiment. We used a 60 ft chain, smooth chain, which is shorter than typical, and causes less disturbance than an Ely chain. We found that the short chain was helpful in creating the small-patch-size disturbances desired for deer habitat improvement. While the short chain is more expensive per acre than a longer chain would be, we still found chaining to be less expensive than the other treatments tested in this study. We concur with Provencher (2014) who found chaining to be a cost-effective way to create desired ecological changes (Provencher and Thompson 2014).

The mechanical treatments differed slightly in the growth of cheatgrass and in the response of seeded shrubs. Rollerchopped plots had higher exotic cover in the early years of the study (Figures 8-9), and this effect has persisted. Six years post-treatment, rollerchopped plots had notably higher cheatgrass cover than chained plots. Some effects of rollerchopping were positive, however; bitterbrush, mountain mahogany, and total desirable shrub density were higher with seeding within rollerchopped plots, but there was no effect of seeding on shrub density within other mechanical treatment types. Rollerchopping produced the most extensive soil disturbance of the three types, and had the highest amount of bare ground in the early years of the study (Johnston 2014). Reduced competition and a higher degree of disturbance may have allowed both desirable shrubs and cheatgrass a window of opportunity for establishment.

All three mechanical treatments have resulted in higher cheatgrass than in control plots. It is well understood that mechanical removal of PJ can increase exotics relative to untreated areas. Many similar studies have observed dramatic increases in cheatgrass following a variety of treatment types including chaining (Skousen et al. 1989), mastication (Owen et al. 2009, Ross et al. 2012), and hand-thinning with chain saws (Huffman et al. 2013). Cheatgrass had been present at only 1-3% cover in 2013, and was practically undetectable at the South Magnolia site. By 2016, cheatgrass cover in treated plots was about 27% at North Magnolia (Figure 15) and about 7% at South Magnolia. Shade suppresses cheatgrass (Pierson et al. 1990), therefore an increase in cheatgrass should be expected with tree removal if cheatgrass is present at a site. If cheatgrass is initially present at very low levels, the increase may not become evident until 2-3 years after treatment. We first noted a flush of cheatgrass in 2014, three years post-treatment.

The increase in cheatgrass at South Magnolia could have been aided by seed contamination. In chained and rollerchopped plots in 2016, cheatgrass cover was higher in seeded than unseeded subplots. In 2017, we could not detect an effect of seeding. Depending on the amount of vegetation or other dispersal obstructions, cheatgrass can spread either slowly- a few feet a year- or quickly- closer to a hundred feet a year (Johnston 2011, Johnston and Chapman 2014). It is possible that seed introduced as a contaminant is now affecting unseeded subplots as well as the surrounding area. While some prior studies have found that seeding after loss of PJ helps control weedy annuals (Floyd et al. 2006, Thompson et al. 2006), we found no such effect. Our study concurs with those studies which have found seeding to have a negligible or even negative effect (Getz and Baker 2008, Shinneman and Baker 2009).

In the earlier analysis, we also noted an effect of seeding at increasing exotic annual forbs at South Magnolia, but not at North Magnolia. We initially suspected that South Magnolia would be more vulnerable to weed invasion than North Magnolia, because of differences in initial conditions between sites: South Magnolia had larger, fewer trees and less understory biomass than North Magnolia (Figure 2; (Stephens et al. 2016). We did not find South Magnolia to be more vulnerable to cheatgrass or other weed invasion due to tree removal alone. However, tree removal in combination with seeding does seem to have caused a greater problem at South Magnolia than at North Magnolia. We urge managers to be cautious when applying seed, especially in areas previously free of cheatgrass.

Six years post-treatment, the effect of seeding on cheatgrass is the only notable difference in how the sites responded to treatments. In earlier analysis, many effects depended on site. For instance, the seeding effect for shrub density was not evident at North Magnolia, and a seeding effect for native annual forb cover had a larger effect size at South than at North (Johnston 2014). By 2017, we noted few instances where the effects of treatments depended on site. Although South Magnolia continues to be more grass-dominated, and North Magnolia continues to be more shrub-dominated, the direction of treatment effects was similar for both sites (Figure 17).

The seed mix used was very expensive, about $714/ac, and included 34 species. The best performer was bitterbrush, which had higher cover in seeded subplots across all mechanical treatment types five and six years post-treatment. Utah sweetvetch performed well in this study as well as at many other research sites in northwest Colorado (Johnston 2016). Lewis flax is also a consistent performer. The price for those three species would have been only $173/ac. As managers know, it is important to choose species judiciously for cost considerations. Limiting the number of species also limits the chances of seed contamination. It may be worthwhile to consider the morphology of the seeds to be planted. Bitterbrush, Utah sweetvetch, and Lewis flax are all small, round seeds which are dissimilar from the awned grass cheatgrass. It’s likely more difficult to detect seed contamination within lots of grasses such as western wheatgrass or bluebunch wheatgrass, which are colored and shaped similarly to cheatgrass.

Bitterbrush established successfully in spite of high browsing pressure on seedlings. In the early years of the experiment, we noted higher bitterbrush density within grazing cages placed within seeded subplots than outside of grazing cages (Johnston 2014). Although we did not remeasure the grazing cages in 2017, they had a visible effect on bitterbrush (Figure 17). Even so, bitterbrush established effectively enough that a difference in cover due to seeding was evident by five years post-treatment. It is not clear why other shrubs were not successful, but browsing may have played a role. In 2017, field crews noted a few Skunkbush Sumac (*Rhus trilobata*) plants, and these were always heavily browsed. Both plants are desirable forage, but bitterbrush was present in the surrounding landscape, while sumac was novel. Perhaps this novelty made it so attractive to browsers that few seedlings survived. Alternatively, germination or resource limitations may have played a role.

In the treatments which used bulldozers, chaining and rollerchopping, we planted large-seeded species with a Hansen dribbler (Johnston 2014). This tool dribbles the seed onto the track and facilitates deep planting. Bitterbrush and Utah sweetvetch were both planted this way, and it is interesting to note that both species established as well in the chaining treatment as it did in the mastication treatment. In the mastication treatment, all species were broadcast-seeding prior to treatment, which required more effort. The dribbler seems to be a useful tool to plant large-seeded species efficiently.

In summary, the response of grasses and forbs was similar to the three treatment types, cheatgrass response was slightly worse with rollerchopping, and shrub utilization and winter-available forage differed greatly by mechanical treatment. The decision of which tool to use should depend largely on the desired manipulation of shrubs, the size and complexity of area to be treated, and cost. Rejuvenation of shrubs is an option when using mastication. With rollerchopping, most shrubs will be treated, as it is not possible to drive the rollerchopper to selectively avoid them. With chaining, only the oldest and most brittle shrubs will be rejuvenated. More detailed mosaics are possible with mastication than with rollerchopping, and chaining is the least flexible. We used a shorter-than-typical 50-foot smooth chain in our study, which could be a viable and cost-effective option for creating small treatment patches. However, it is not possible to leave isolated trees with chaining. Chaining costs are one-third to one-sixth that of mastication, but mobilization costs are high, making it more appropriate for larger treatments. Rollerchopping has intermediate per-acre cost but the highest mobilization costs.

Managers have a good understanding of the difficulty of producing effective winter range habitat treatments. The most reliable benefit of tree removal is an increase in grass production, which certainly can benefit wildlife. However, increasing winter shrub forage is more difficult, because increased production can be consumed before it benefits animals in winter. The increase in cheatgrass with all three treatment types, at both study sites, is somewhat alarming. Recent research has shown that cheatgrass is adapting to higher elevation sites (Merrill et al. 2012), therefore problems with cheatgrass can be expected to worsen. Nevertheless, the substantial amount of perennial grass cover at these sites should prevent cheatgrass from dominating. Wildlife benefits are still possible with PJ removal if enough understory vegetation is present to respond (Miller et al. 2005), but practitioners should consider potential risks as well as benefits when selecting projects.

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Table 1. Native seed mix. Functional Group: G - grass, F - forb, S - shrub. Lifespan: P - perennial, A - annual. Seed groups 1 - 4 were hand broadcast while group 5 was seeded using bulldozer mounted seed dribblers in the chain and rollerchop plots. Group 5 was hand broadcast in masticated plots.

Functional Group	Type	Seed Group	Latin Name	Common Name	Pure Live Seeds/m^2	PLS lbs/ ac
G	P	1	*Achnatherum hymenoides* (Roem. & Schult.) Barkworth	Indian Ricegrass	18	0.45
F	A	2	*Amaranthus retroflexus* L.	Redroot Amaranth	12	0.04
S	P	5	*Amelanchier alnifolia* (Nutt.) Nutt. ex M. Roem.	Saskatoon Serviceberry	30	2.02
S	P	5	*Amelanchier utahensis* Koehne	Utah Serviceberry	12	1.88
F	P	2	*Artemisia frigida* Willd.	Fringed Sagebrush	36	0.02
F	P	2	*Artemisia ludoviciana* Nutt.	White Sagebrush	24	0.02
S	P	2	*Artemisia tridentata* Nutt.	Wyoming Sagebrush	24	0.09
F	P	1	*Balsamorhiza sagittata* (Pursh) Nutt.	Arrowleaf Balsamroot	12	0.83
S	P	5	*Cercocarpus montanus* Raf.	Mountain Mahogany	24	2.05
S	P	2	*Ericameria nauseosa* (Pall. ex Pursh) G.L. Nesom & Baird	Rubber Rabbitbrush	18	0.18
S	P	2	*Chrysothamnus viscidiflorus* (Hook.) Nutt.	Yellow Rabbitbrush	18	0.10
F	A	1	*Cleome serrulata* Pursh	Rocky Mountain Beeplant	24	1.47
F	P	2	*Crepis acuminata* Nutt.	Tufted Hawksbeard	1	0.01
G	P	1	*Elymus elymoides* (Raf.) Swezey	Bottlebrush Squirreltail	18	0.38
G	P	1	*Elymus trachycaulus* (Link) Gould ex Shinners	Slender Wheatgrass	12	0.36
F	P	3	*Eriogonum umbellatum* Torr.	Sulfur Buckwheat	10	0.17
F	P	5	*Hedysarum boreale* Nutt.	Utah Sweetvetch	12	1.05
F	A	1	*Helianthus annuus* L.	Common Sunflower	30	2.08
G	P	1	*Hesperostipa comata* (Trin. & Rupr.) Barkworth	Needle And Thread	12	0.35
G	P	2	*Koeleria macrantha* (Ledeb.) Schult.	Prairie Junegrass	24	0.04
S	P	3	*Krascheninnikovia lanata* (Pursh) A. Meeuse & Smit	Winterfat	18	0.66
F	P	1	*Linum lewisii* Pursh	Lewis Flax	24	0.33
F	P	5	*Lupinus argenteus* Pursh	Silvery Lupine	12	0.39
F	P	1	*Oenothera caespitosa* Nutt.	Tufted Evening Primrose	12	0.04
F	P	1	*Oenothera pallida* Lindl.	Pale Evening Primrose	24	0.15
G	P	1	*Pascopyrum smithii* (Rydb.) Á. Löve	Western Wheatgrass	6	0.17
F	P	1	*Penstemon strictus* Benth.	Rocky Mountain Penstemon	36	0.30
G	P	2	*Poa fendleriana* (Steud.) Vasey	Muttongrass		0.02
G	P	2	*Poa secunda* J. Presl	Sandberg Bluegrass	12	0.05
S	P	4	*Prunus virginiana* L.	Chokecherry	6	4.88
S	P	5	*Purshia tridentata* (Pursh) DC.	Bitterbrush	30	7.06
S	P	5	*Rhus trilobata* Nutt.	Skunkbush Sumac	6	0.94
G	A	4	*Triticum aestivum* L. x *Secale cereale* L.	Quick Guard	12	3.74
G	A	2	*Vulpia octoflora* (Walter) Rydb.	Six-Weeks Fescue	18	0.08

Table 2. Regressions used in predicting winter-available forage from shrub dimensions of serviceberry (AMAL), mountain mahogany (CEMO), bitterbrush (PUTR) and big sagebrush (ARTR). All measurements were taken in cm. Height gain was calculated as total plant height minus height at tallest bud scar. Canopy area was calculated from the formula for an ellipse from shrub longest diameter (when viewed from above), and the diameter perpendicular to the longest diameter. For ARTR, crown volume was calculated from the formula for an ellipsoid from crown depth (total plant height minus height of the bottom of the canopy), longest diameter when viewed from above, and perpendicular diameter (Cleary et al. 2008). ARTR winter forage was considered as the sum of estimates for leaves and new stems, since the leaf estimate included only persistent leaves. For other species, winter forage included only stems.

species	observed Variable 1	Variable 1 Transfor-mation	observed Variable 2	Variable 2 Transfor-mation	predicted Variable	Intercept	Slope Variable 1	Slope Variable 2	Slope Interaction Term	Y_Back Transformation	n	Variable 2 Max Value	Variable 1 Max Value	R^2
AMAL	Height Gain	ln(Height Gain+10)	Canopy Area	ln(Canopy Area)	winter forage	0.3962	-0.8534	-0.2046	0.2769	exp(y)	64	111236.1	57	0.69
CEMO	Longest Leader	none	Canopy Area	ln(Canopy Area+100000)	winter forage	272.05	-227.75	-25.65	19.876	none	47	72543.42	67	0.74
PUTR	Longest Leader	none	Canopy Area	ln(Canopy Area+2000)	winter forage	-19.80	0.4417	2.3387	-0.04197	exp(y)	35	91491.75	50	0.77
ARTR	Crown Volume	ln(Crown Volume)			leaves	5.129	0.6144			exp(y)	37			0.87
ARTR	Crown Volume	ln(Crown Volume)			new Stems	3.668	0.5679			exp(y)	37			0.76

Table 3. Costs incurred in this experiment to implement 3 pinyon-juniper removal treatments: ship anchor chaining (CHAIN), roller chopping (ROLLER), and mastication (MAST). Mobilization costs were for a site in the Piceance Basin a 1-hr drive from the nearest town of Meeker, CO. Costs per unit area were higher than typical, because the replicated, small plots for this experiment were difficult to create. More normal rates on a per-area basis are about half of the costs incurred here.

	CHAIN	**ROLLER**	**MAST**
Mobilization/ demobilization	$5,600	$8,000	$2,050
Time per area	49 min/ha (20 min/ac)	1.9 hr/ha (45 min/ac)	6.2 hr/ha (2.5 hr/ac)
Cost per area	$329/ha ($133/ac)	$368/ha ($149/ac)	$1230/ha ($498/ac)

Figure 1. Types of machinery used and woody debris produced: Ship anchor chaining (a) and tree skeletons left behind by chaining (b); roller chopper (c) and coarse debris left by roller chopping (d); industrial tractor with masticating head (e) with fine debris left behind by mastication (f).

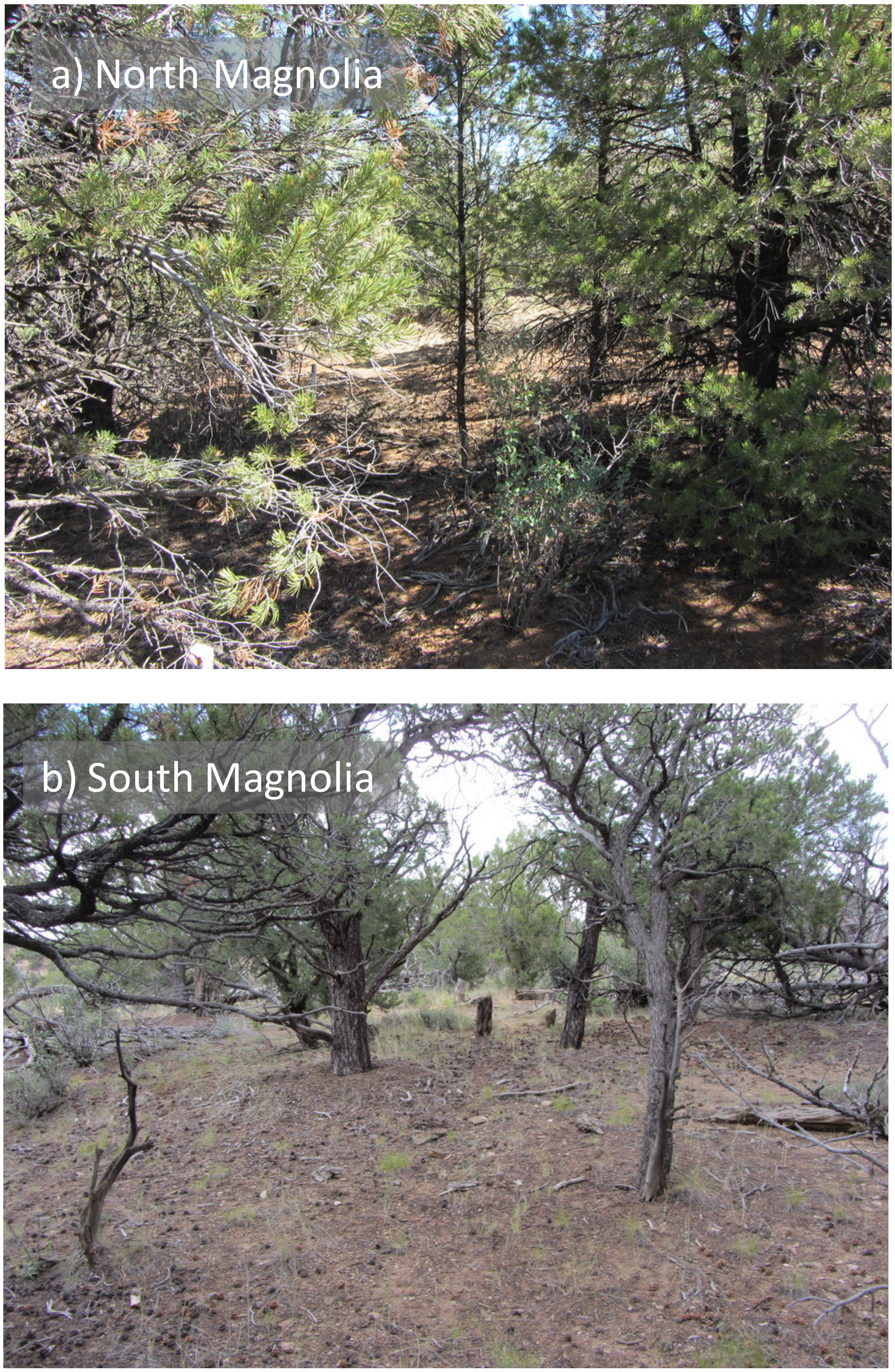

Figure 2. Control plots photos from the early years of the experiment at a) North Magnolia and b) South Magnolia.

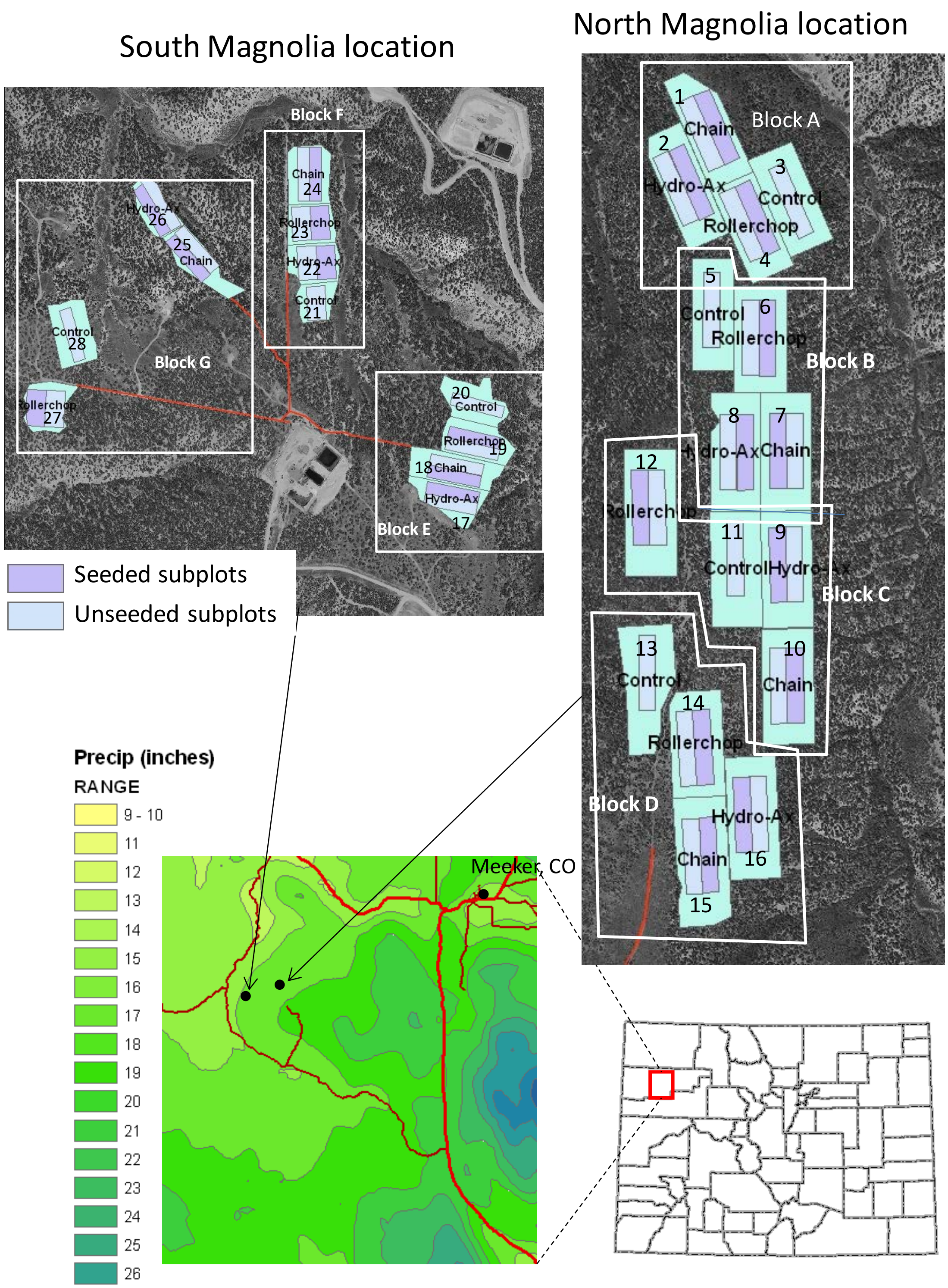

Figure 3. Layout of experiment within North and South Magnolia locations, Rio Blanco County, Colorado.

Figure 4. Hansen-style seed dribbler mounted to the track of bulldozer. Two such dribblers were mounted on each bulldozer used in the chaining and roller chopping treatments.

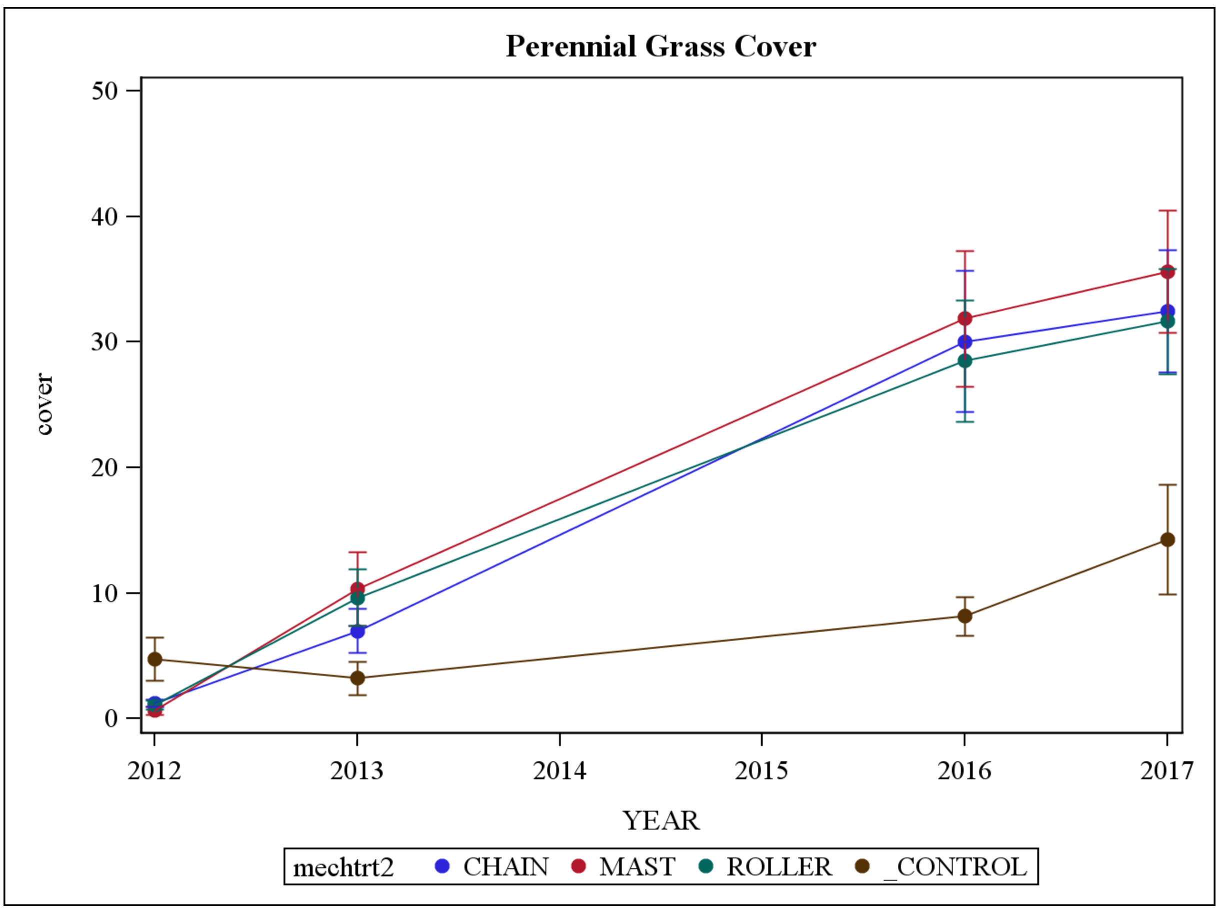

Figure 5. Perennial grass cover in response to tree removal treatments imposed in the fall of 2011: chaining (CHAIN), mastication (MAST), rollerchopping (ROLLER) or control. Data are from unseeded subplots. Error bars = SE.

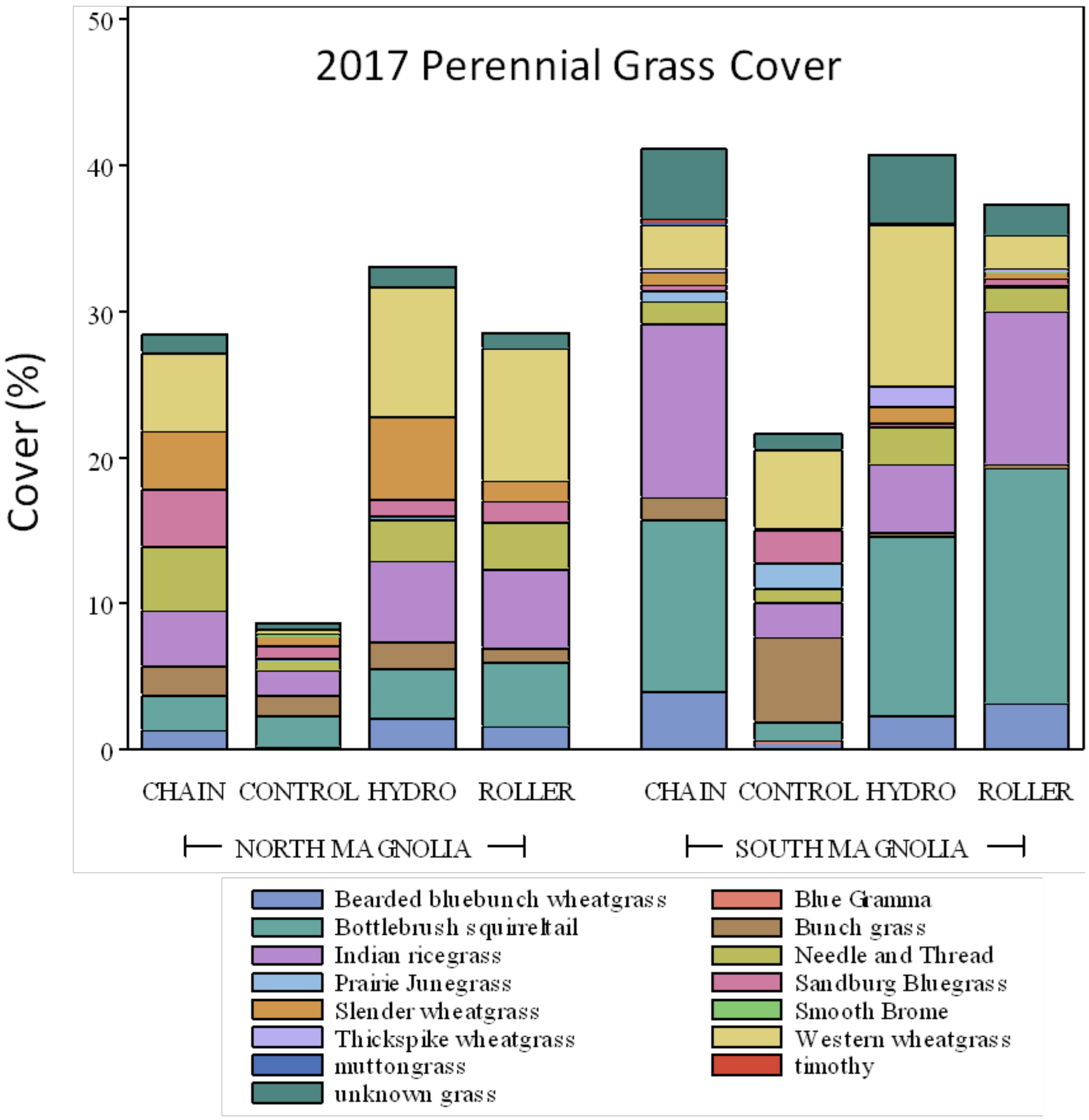

Figure 6. Perennial grass cover six years post-treatment at two sites, North Magnolia and South Magnolia, in response to tree removal treatments: chaining (CHAIN), mastication (MAST), rollerchopping (ROLLER) or control. Data are averaged over seeded and unseeded subplots.

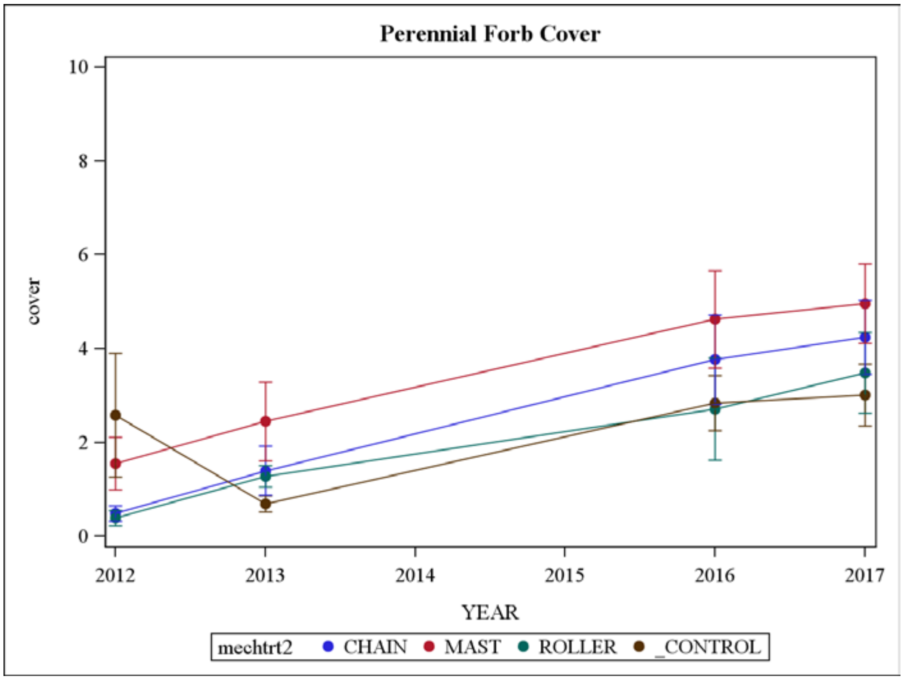

Figure 7. Perennial forb cover in response to tree removal treatments imposed in the fall of 2011: chaining (CHAIN), mastication (MAST), rollerchopping (ROLLER) or control. Data are from unseeded subplots. Error bars = SE.

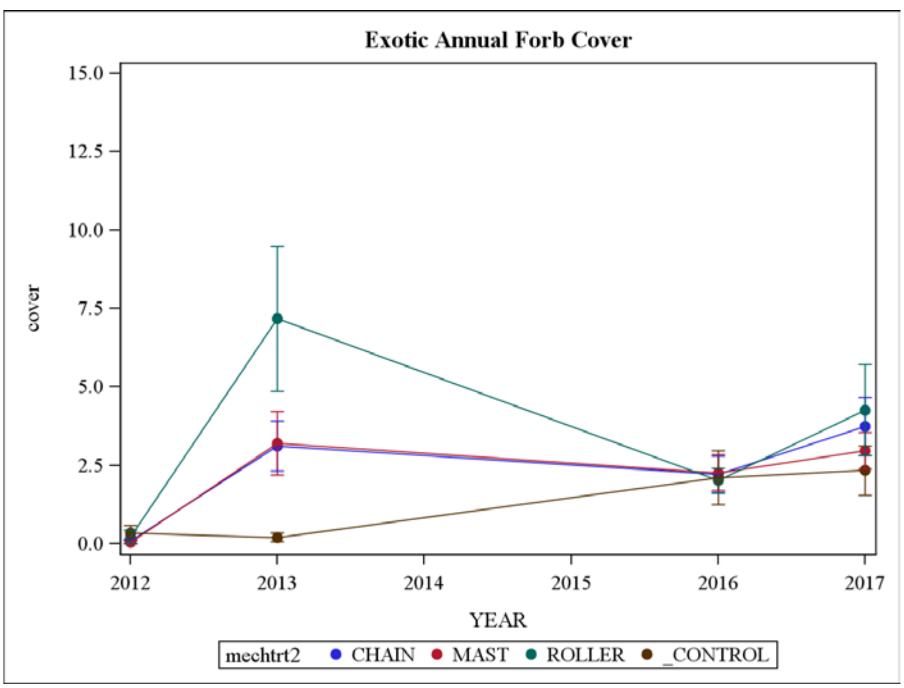

Figure 8. Exotic annual forb cover in response to tree removal treatments imposed in the fall of 2011: chaining (CHAIN), mastication (MAST), rollerchopping (ROLLER) or control. Data are from unseeded subplots. Error bars = SE.

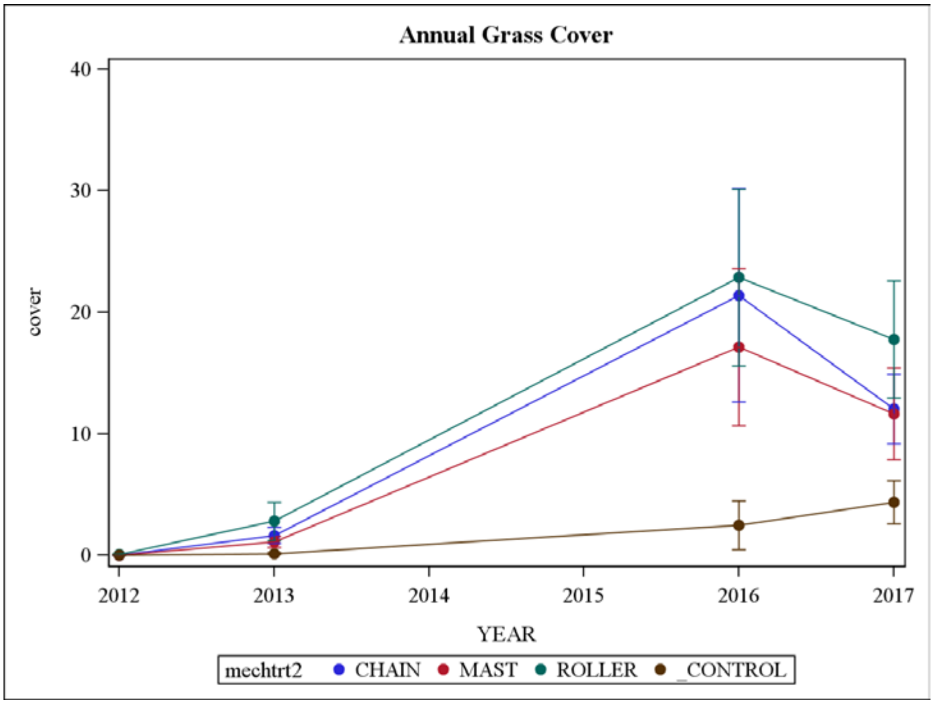

Figure 9. Annual grass cover in response to tree removal treatments imposed in the fall of 2011: chaining (CHAIN), mastication (MAST), rollerchopping (ROLLER) or control. Cheatgrass was 95% or more of annual grass cover each year. Data are from unseeded subplots. Error bars = SE.

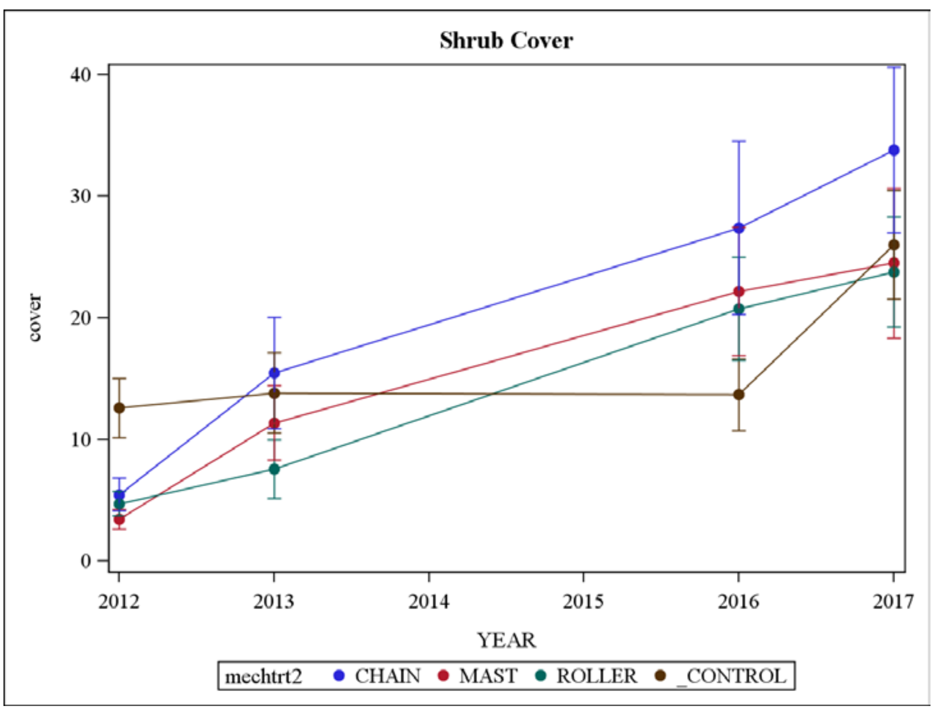

Figure 10. Shrub cover in response to tree removal treatments imposed in the fall of 2011: chaining (CHAIN), mastication (MAST), rollerchopping (ROLLER) or control. Data are from unseeded subplots. Error bars = SE.

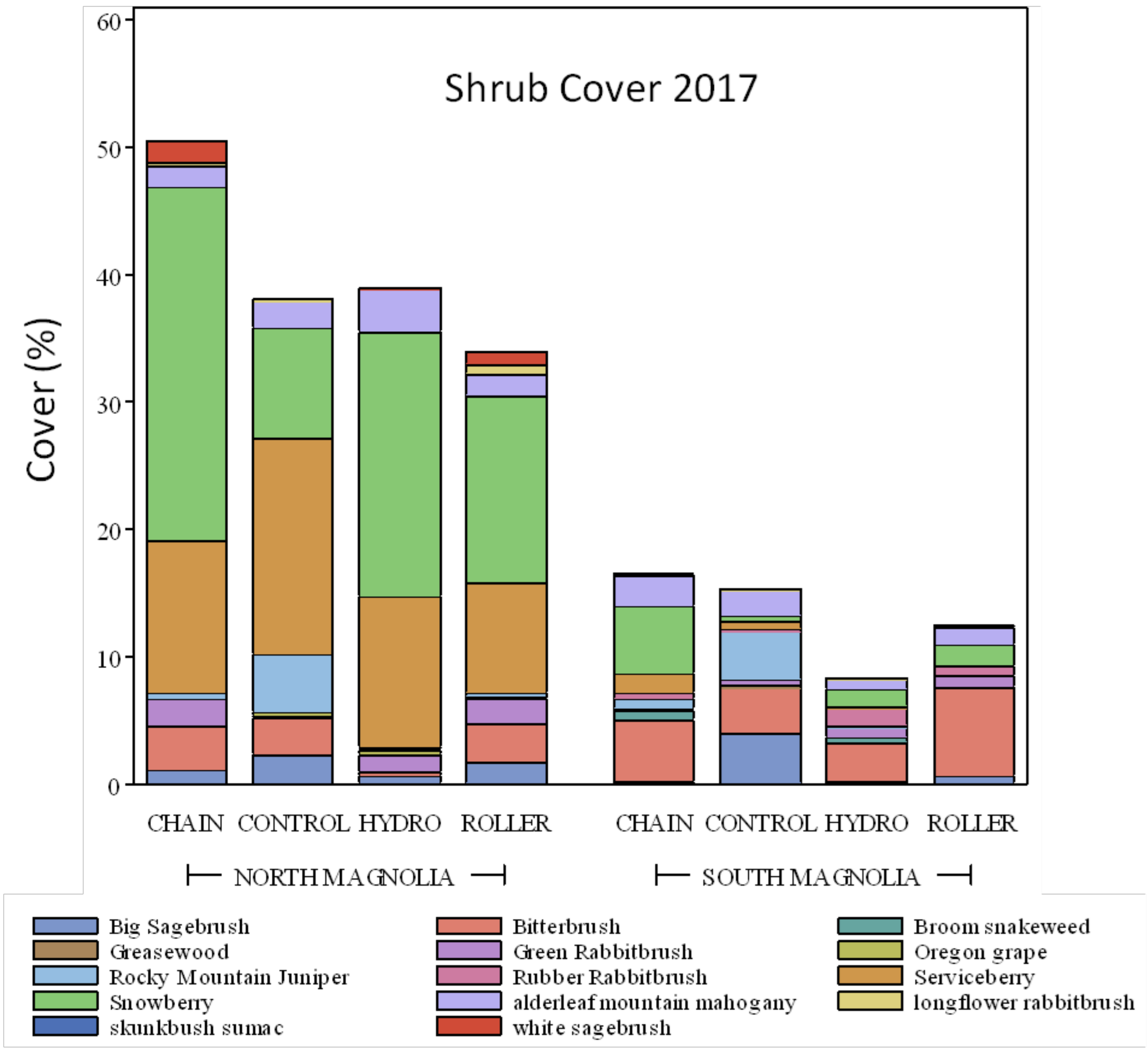

Figure 11. Shrub cover six years post-treatment at two sites, North Magnolia and South Magnolia, in response to tree removal treatments: chaining (CHAIN), mastication (MAST), rollerchopping (ROLLER) or control. Data are averaged over seeded and unseeded subplots.

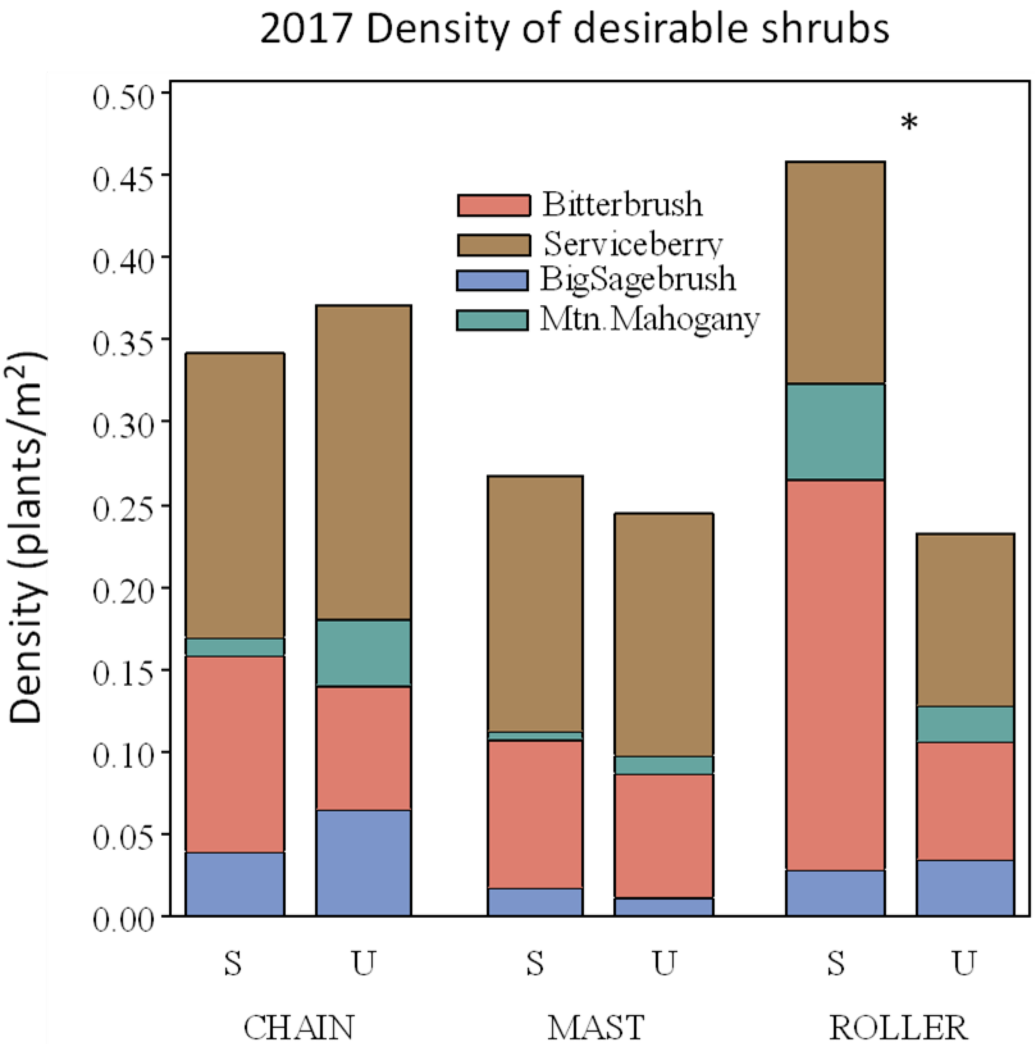

Figure 12. Density of four desirable shrub species within seeded (S) or unseeded (U) subplots subjected to three different mechanical treatments: chaining (CHAIN), mastication (MAST), or rollerchopping (ROLLER). Star denotes a significant difference at alpha = 0.05 for all shrubs. In addition, in analysis of individual species, bitterbrush and mountain mahogany were significantly denser within seeded subplots of the rollerchopped treatment.

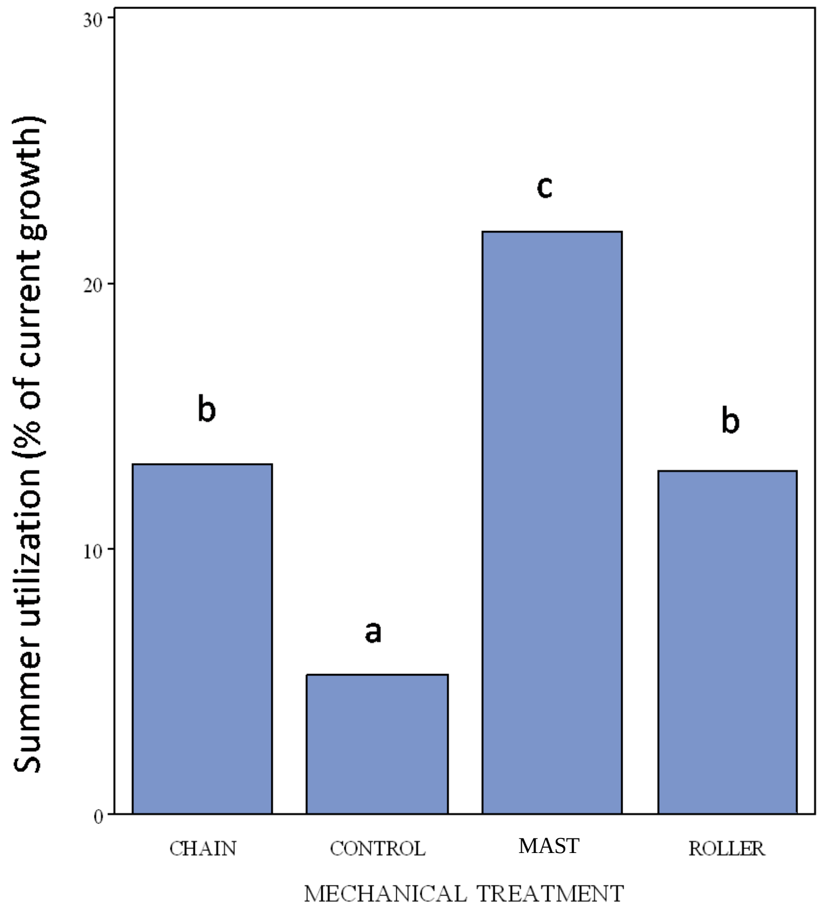

Figure 13. Percent removal of current-year growth assessed in September 2017, six years following tree removal by chaining (CHAIN), mastication (MAST), or rollerchopping (ROLLER). Bars not sharing letters have significantly different means at alpha = 0.05.

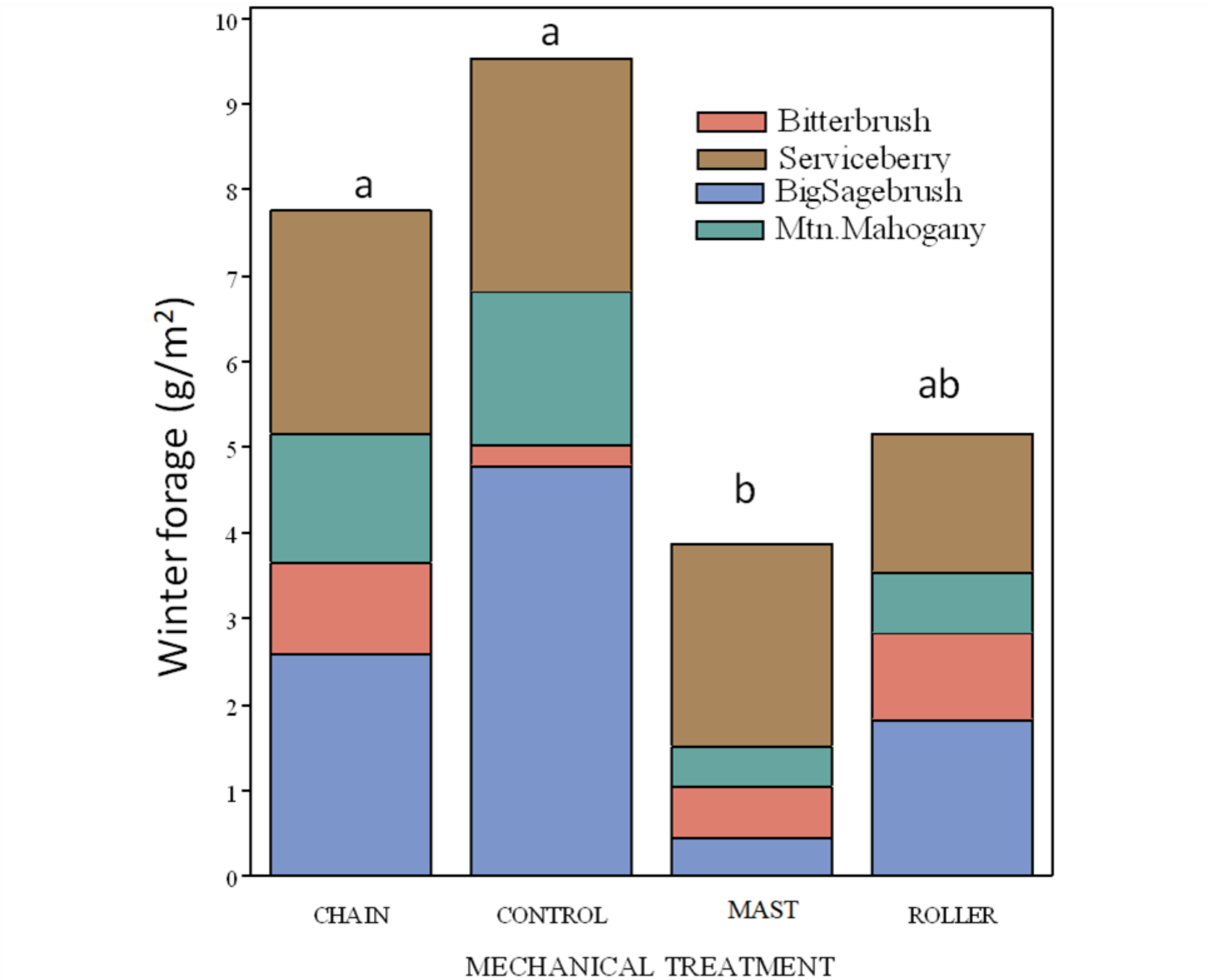

Figure 14. Winter-available forage (long shoot stems remaining on the plant) assessed in September 2017, six years following tree removal by chaining (CHAIN), mastication (MAST), or rollerchopping (ROLLER). Bars not sharing letters have significantly different means at alpha = 0.05.

Figure 15. A 2016 photo collage of North Magnolia plots where pinyon and juniper trees were removed in 2011 shows good perennial grass and shrub cover, but also reveals some undesirable cheatgrass patches.

Figure 16. August six years following treatment in masticated, unseeded subplots at a) North Magnolia and b) South Magnolia

Figure 17. A grazing cage within a seeded subplot at North Magnolia, and a hedged bitterbrush seedling from outside the cage (inset). Bitterbrush has clearly experienced heavy use. Even so, bitterbrush seedings established successfully.