THESIS

UNDERSTORY RESPONSES TO MECHANICAL REMOVAL OF PINYON-JUNIPER OVERSTORY

Submitted by

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Graduate Degree Program in Ecology

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2014

Master's Committee

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ABSTRACT

UNDERSTORY RESPONSES TO MECHANICAL REMOVAL OF PINYON-JUNIPER OVERSTORY

Declining Colorado mule deer (*Odocoileus hemionus*) populations have necessitated improved habitat management techniques. In particular, oil and gas development in the Piceance Basin of western Colorado has impacted critical winter range, creating a need for treatments that will increase forage, and especially palatable shrub species. Pinyon-juniper (*Pinus spp* – *Juniperus spp*) tree removal is one technique, however it is unclear which method of tree removal will most effectively promote forage species. This experiment quantified understory responses to pinyon-juniper canopy removal and seed additions using three different methods: anchor chain, rollerchopper, and hydro-ax. Twenty-one 0.8-ha plots were mechanically treated during the fall of 2011 (7 replicates of each treatment). Half of each plot was seeded prior to mechanical treatment with a mix of native grasses, shrubs, and forbs. After two growing seasons, productivity of forbs, grasses, and shrubs combined was roughly three times greater in hydro-ax, rollerchop, and chain plots relative to control plots (where tree removal did not occur). Comparisons of vegetation productivity among treated plots showed that the response of early seral species, some of which were included in the seed mix, was dependent upon the interaction of seeding and mechanical treatments. Specifically, the productivity of annual species was greater in seeded versus unseeded plots for chain and hydro-ax but not for rollerchop. Rollerchop plots, however, had greater productivity of non-native species than chain or hydro-ax (such as *Salsola tragus, Descurainia sophia*, and *Bromus tectorum*). Also, the abundance of shrubs, which are an important source of winter forage, was greater in seeded than unseeded subplots. Results after two growing seasons suggest that all three mechanical treatments increase forage productivity and of the three techniques, rollerchop may promote non-native establishment (primarily forbs). At this early stage in plant community development, differences in the effect of mechanical treatments on shrub forage are not yet apparent, but may emerge with future monitoring.

ACKNOWLEDGEMENTS

There are many individuals to acknowledge upon the completion of this project. I would first like to thank my advisor Dr. Mark Paschke for providing me the opportunity to participate in field-based research conducted in the Restoration Ecology Lab (REL). I have enjoyed working in such a well-organized lab alongside faculty, research associates, and other students. Among the invaluable members of the REL from whom I have learned so much and to whom I am entirely grateful are Dr. Jayne Jonas-Bratten and Brett Wolk. Thank you to Jayne for your tireless help with data management and analysis and for helping me to become a better scientific writer and presenter. Thanks also to Brett for helping me organize and implement a fun field research experiment with lots of great people (REL undergrads 2011-2013), lots of seed, and lots of big machines. Finally, my fellow REL grad students have been great lab mates and I enjoyed the chance to struggle and succeed alongside them; Cassie Kieffer Stube, Catherine Cumberland, Stephanie Barr, and Sasha Victor.

I also appreciate the support of my other committee members, Drs. Paul Meiman, Ken Wilson, and Danielle Bilyeu-Johnston, in helping me conduct sound research and produce a well-constructed thesis. Thanks especially to Danielle for bringing this project to the REL and for helping me implement this collaborative large-scale experiment. Thank you also to XTO Energy Inc. for providing funding for this research.

Lastly I would like to thank those nearest to me, first and foremost my wife Lindsey. She has shown unwavering love and support during this graduate school journey and for that I am eternally grateful. Thank you also to my parents, Kendell and Andrea Stephens, who since the very beginning have encouraged me to excel academically and have supported me in endless ways. Lastly I would like to thank my grandfather, W. Richard Stephens, who has been a tremendous source of guidance and wisdom and who is largely to blame for my interest in the Rocky Mountains.

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Introduction

The pinyon-juniper (*Pinus spp.* L. – *Juniperus spp.* L.) vegetation type is one of the most widespread plant associations in the western United States. Various species of pinyon and juniper trees occupy nearly 40 million ha, which are administered largely by federal land-management agencies (Romme et al. 2009). Because of their vast occurrence and critical role within many ecosystems, significant attention has been given to research and management of pinyon-juniper throughout the West. One reason for this focus is the extreme change that pinyon-juniper communities have undergone over the last 150 years. Specifically, pinyon-juniper woodlands in many areas have become more dense and trees have also expanded their range into former grasslands and shrublands (Christensen and Johnson 1964, Tausch et al. 1981, Miller 1999, Miller et al. 2008).

The causes of this phenomenon vary and are not consistent in all stands. In some cases, historic human land uses (*e.g.*, heavy livestock grazing and fire suppression) that have disrupted fire cycles may be driving pinyon-juniper encroachment, but other causes outside of anthropogenic influence are also possible (Romme et al. 2009). Romme et al. (2009) suggest alternatives such climate-driven range expansion and habitat reoccupation (that may look like shrubland and grassland invasion but could really be occurring as a response to historic disturbance or logging). In addition, fire regimes in pinyon-juniper are highly variable in terms of frequency and severity (Baker and Shinneman 2004), which further complicates our understanding of fire as a forest thinning agent. Nevertheless, efforts to halt expansion, improve forage conditions, and restore pinyon-juniper to pre-European conditions have taken place (Romme et al. 2009).

Managers have utilized various methods, including prescribed fire and mechanical thinning, to reduce tree canopy coverage and increase understory vegetation. Effectiveness of prescribed fire for increasing understory vegetation varies and invasion by non-native species is not uncommon (Ott et al. 2003, Bates et al. 2011, Huffman et al. 2013). Additionally, fuel structures may not be appropriate to carry fire and the risk of fire escape is also of concern. Mechanical treatments provide an alternative to burning, which can be implemented more widely in terms of season and vegetation structure. Effectiveness of mechanical treatments can also vary, however, due to differences between technique types and interrelated environmental characteristics of each site. Because mechanical methods of pinyon-juniper removal continue to be used to meet resource objectives, understanding their impacts to vegetation is important. The purpose of this chapter is to summarize how various mechanical treatments influence pinyon-juniper communities.

Pinyon-Juniper Communities

Pinyon-juniper woodlands, known also as piñon-juniper or pygmy conifer, are characterized by short stature species (8-15 m average maximum height) of pinyon and juniper trees. They are found in almost every western state, from California, Oregon and Washington east to the Great Plains and are dominant across the Great Basin and Colorado Plateau. Pinyon-juniper extend well into Mexico while the range of junipers include parts of Canada and the eastern US (West 1999).

As a result of this wide geographic occurrence, pinyon-juniper communities are found on a variety of landforms, from ridges, mesa tops and mountain slopes to alluvial fans and valley floors (Romme et al. 2009, Vankat 2013). Soils across their habitat are quite variable, ranging from deep clays or sand to shallow rocky soils and even rock outcrops (Romme et al. 2009). They typically grow at elevations just above deserts or semi-desert grasslands and shrublands and just below more mesic pine forests (Romme et al. 2009). Pinyon dominate middle elevations while juniper can be found at the upper and lower limits due their tolerance of moisture and temperature extremes (West 1999).

Species composition of pinyon-juniper communities changes along a northwest-to-southeast climate gradient across the western states. Precipitation in the northern Great Basin (25-30 cm annually) arrives primarily during winter and spring; the timing of precipitation transitions to winter and summer peaks near the Colorado Plateau (20-40 cm annually) and then changes to summer monsoons in southern Arizona and New Mexico (25-43 cm annually) (Mitchell 1976, Romme et al. 2009, NOAA 2013). *Juniperus occidentalis* Hook and *Pinus monophylla* Torr. & Frem. are common at the northern extent of pinyon-juniper range, along with cool-season bunch grasses and *Artemisia spp.* in the understory (Romme et al. 2009). *Pinus monophylla* Torr. & Frem. and *Juniperus osteosperma* (Torr.) Little occupy the Great Basin while *Pinus edulis* Engelm. and *J. osteosperma* dominate the Colorado Plateau; understory in these regions are comprised of warm-season bunch grasses and mountain shrub species (*Quercus* L. *spp.*, *Ericameria* Nutt. *spp.*, *Amelanchier* Medik. *spp.*, *Purshia tridentata* (Pursh) DC., and *Cercocarpus* Kunth *spp.*,(Romme et al. 2009). *Juniperus scopulorum* Sarg. inhabits higher elevations on the Colorado Plateau and southern Rockies and *Juniperus deppeana* Steud. occupies southern regions of Arizona and New Mexico (Romme et al. 2009). This habitat also supports a variety of birds, small mammals, and big game such as bighorn sheep (*Ovis Canadensis*) and mule deer (*Odocoileus hemionus*) (Bowns 1999).

Pinyon-juniper forest types can be broken into three broad groupings based on understory characteristics, canopy structure, and historic disturbance regime; Romme et al. (2009) distinguishes these groups as wooded shrublands, persistent woodlands, and savannas. This general framework, explained in greater detail in Romme et al. (2009), highlights the importance of recognizing natural variability of pinyon-juniper, which can be helpful for making appropriate management decisions in response to the structural changes that have been observed since Euro-American settlement (Romme et al. 2009).

Mechanical Treatments

Government agencies have been mechanically manipulating pinyon-juniper woodlands in efforts to meet management goals in the western U.S. for nearly 70 years (Aro 1971). Anchor chaining, which is one of the oldest methods, was a common technique during the 1960s (Fig. 1.1); between 1960 and 1972 it was prescribed to treat over 200,000 ha across the Great Basin and Colorado Plateau (Aro 1975). This technique utilizes a heavy anchor chain (20-40 kg per link) pulled between two crawler tractors or bulldozers to uproot woody vegetation. The degree of vegetation mortality is influenced by: length of chain, size and type of individual link, and pattern of drag, which is determined by the positioning of bulldozers in relation to each other (Stevens 1997). Modifications to individual chain links, such as addition of cross-welded rail sections (known as an Ely chain, as opposed to the unmodified smooth chain), have been used to increase soil disturbance and remove small trees and shrubs while also uprooting mature trees. Heavy duty cables have also been used in much the same manner as chain (Skousen et al. 1989).

Rollerchopping is a technique that uses a crawler tractor or bulldozer to pull a heavy rolling drum lined with blades (Fig. 1.1). The drum, which can be filled with water to increase weight and therefore soil disturbance, crushes and chops vegetation as it rolls over the ground. Bulldozing alone, without any additional implements, has also been used to push over vegetation and reduce pinyon-juniper density (Springfield 1976).

Other methods include hand thinning (with chainsaws) and mastication. Hand thinning allows for very selective prescriptions in terms of which trees are removed and how slash (woody debris) is organized. Mastication, or tree shredding, is a relatively new method of thinning, which involves a large tracked or rubber-tired machine mounted with a hydraulic rotating drum (lined with teeth) or rotating blade that grinds down individual standing vegetation (Figure 1.1).

Figure 1.1. Heavy equipment used for pinyon-juniper removal. From left to right: anchor chain, rollerchopper, and mastication (or hydro-ax).

Impacts to Vegetation

Physical Impacts

The primary function of each piece of equipment used in pinyon-juniper control is to reduce density of trees. However, each method is different in the way it impacts vegetation, which further varies its effectiveness across the broad spectrum of pinyon-juniper forests (Table 1.1). For example, although chaining and cabling appear to have the same strategy in removing vegetation, closer examination reveals many differences. Cables are light, relative to an anchor chain, which prevents them from uprooting shrubs and small flexible trees that may simply bend over as the cable is dragged over top (Plummer et al. 1968, Skousen et al. 1989). In a stand of mature trees with low understory establishment, cabling may be sufficient for removing woody vegetation, but in mixed-age stands with vegetation of various sizes, an Ely chain, or other methods such as rollerchopping and mastication, may be more effective. Rollerchoppers are much heavier and are more likely to damage all size classes of vegetation relative to cabling and chaining. The same is true for mastication in that it can effectively remove both small and large woody vegetation. Table 1.1broadly summarizes the physical impacts of some common methods.

Table 1.1 Some of the physical impacts on vegetation by common mechanical treatments used in pinyon-juniper control.

	Anchor Chain (or cable)	Bulldozer	Rollerchop	Mastication	Chainsaw
Soil Disturbance	Moderate	Moderate	High	Low to high	Low
Ability to target individual plants	Low	Low to moderate	Low to moderate	High	High
Size and arrangement of woody debris left on site	Small to large pieces piled or dispersed	Small to large pieces piled or dispersed	Medium wood chunks piled or dispersed	Small to medium wood chunks in scattered piles	Size and dispersal is up to discretion of operator
Effective at large tree removal	Moderate to high	Moderate to high	Moderate to high	High	High
Effective at removal of shrubs and small trees	Low	Moderate	Moderate	Moderate to High	High
Impact to grasses and forbs	Low	Low to moderate	Moderate	Low	Low

Understory Responses

Understory vegetation may be impacted directly and indirectly by mechanical treatments. Direct impacts to the physical structure of plants may cause mortality or vigorous growth depending on the species. Some perennial shrubs occurring within pinyon-juniper communities, such as *C. montanus, P. tridentata,* and *Amelanchier alnifolia* Nutt., exhibit compensatory growth following stem removal (Wandera et al. 1992). These findings suggest that physical damage caused by mechanical treatments that cut, chop, or tear away above-ground plant material may stimulate growth for some shrub species. Furthermore, *C. montanus* and *A. alnifolia* exhibit the ability to stump sprout even after severe bud loss (Wandera et al. 1992). However, *Artemisia tridentata*, despite its high growth rate, is not able to compensate for high tissue loss (Wandera et al. 1992, Bilbrough and Richards 1993) and thus may not benefit from certain mechanical treatments.

Indirect effects of mechanical treatments are related to availability of resources that change after canopy removal. The reduction in canopy trees, which consume substantial soil and water resources and intercept sunlight and precipitation, can release lower vegetation from competition allowing vigorous growth in the post-treatment environment (Jacobs and Gatewood 1999). In certain stands where treatments failed to remove small trees, seedlings and saplings take advantage of resource-rich growing conditions. In these situations, treated areas may unintentionally return to undesirable levels of tree density and basal area sooner than expected (Tausch and Tueller 1977, Rippel et al. 1983, Skousen et al. 1989). On a 24-year old cable-treated site in Utah, Skousen et al. (1989) found that 68% of junipers were older than 24 years, which means they survived treatment. Skousen et al. (1989) recommend completing a stand analysis on all pinyon-juniper sites to be mechanically treated in order to understand the structure of the stand and form realistic expectations of how much tree mortality can be achieved for the given treatment type. Where tree removal is more complete, reduced tree abundance can be expected for several decades after treatment. In a 40-year old chaining in southern Utah, Redmond et al. (2013) reported tree density to be twice as high in untreated areas compared to treated areas (approximately 200 trees/ha and 100 trees/ha respectively) and of the trees in chained plots, only 16% recruited prior to treatment. The implications for tree responses are important not only for estimating how quickly trees may return to dominance, but also for understanding their competitive effect on herbaceous species and shrubs.

Increased resource availability also benefits herbaceous species and shrubs. Studies throughout the range of pinyon-juniper have documented a variety of herbaceous understory and shrub responses when comparing mechanically treated areas with pre-treatment conditions or untreated control plots. In general, canopy removal appears to increase understory establishment and productivity (Table 1.2). However, understory responses often lack robust native communities due to invasion of introduced species, which are discussed below in the Undesirable Species section.

Table 1.2. A sample of studies that have assessed understory responses to mechanical pinyon-juniper canopy removal. Time since treatment is the amount of time between treatment implementation and sampling; some studies were sampled over several years (*e.g.*, 1-8) while others were sampled at one point in time. In addition, multi-year sampling may have occurred on the same site or different sites of varying ages. Only results from mechanical treatments are shown in major findings (although some studies included burn treatments as well). Major findings include timing of seeding in relation to mechanical treatments.

Study	Location	Mechanical treatment and time since treatment	Major Findings
Tausch and Tueller, 1977	Nevada	Chain 1-8 years Cable 12 years	Seeded before: Treatments of varying ages (at different locations) showed a progression of understory dominance starting with forbs (youngest sites), then perennial grasses, shrubs and eventually trees. Tree dominance may return sooner than desired where treatments do not remove all trees.
O'meara et al., 1981	Colorado	Chain 1-15 years	No seeding: Shrub and grass cover was greater in treated versus untreated areas on a 15-year-old chaining, but neither was greater than 7%. Tree cover was less in treated areas.
Rippel et al., 1983	New Mexico	Cable > 20 years	No seeding: Tree density was higher on cabled areas relative to untreated areas. Some shrub species increased in response to treatment while others did not. Cabling appeared to reduce grasses and forbs (possibly due to competition from shrubs).
Skousen et al., 1986	Utah	Chain 16 years Bulldozer 24 years	Seeded before: Native grass and shrub cover were greater in treated versus untreated areas but mechanical treatments were not different. Bulldozing was more effective at removing trees. Shrub density was higher in chained plots, which was driven by *Gutierrezia sarothrae* (Pursh) Britton & Rusby (broom snakeweed). *Agropyron cristatum* (L.) Gaertn. (crested wheatgrass) was seeded and may suppress native grasses.
Skousen et al., 1989	Utah	Chain 2-24 years Cable 24 years	Seeded during: Understory plant cover was different among different-aged sites. Those most recently treated were dominated by forbs, followed by perennial grasses and shrubs for middle-aged sites, and finally shrubs and trees at the oldest site. Seeded shrubs appeared most successful where shrubs were naturally occurring. Cabling spared some shrubs but also allowed for the survival of young trees.
Jacobs and Gatewood 1997	New Mexico	Chainsaw 2-3 years	Seeded after: Overstory removal and slash additions increased total herbaceous cover relative to controls and pre-treatment conditions. Secondary soil surface and seeding treatments had no additional effects. Variable precipitation during sampling years and seed herbivory may have impacted results.
Brockway et al., 2002	New Mexico	Chainsaw 1-2 years	No seeding: Mechanical thinning, which involved different slash treatments, increased herbaceous plants and broom snakeweed relative to untreated areas, but there were no differences between the treatments. Scattering slash, as opposed to leaving it piled at the base of cut stumps, increased soil disturbance and may have contributed to greater species diversity and richness in those plots.

Table 1.2. Continued

Study	**Location**	**Mechanical treatment and time since treatment**	**Major Findings**
Ott et al., 2003	Utah	Chain 1-3 years	Seeded before, none: Understory cover on previously burned (and subsequently chained) sites increased between first and second years, due largely to above average precipitation. Seeded grass (non-native wheatgrasses) establishment was greater on chained versus non-chained, which was dominated by cheatgrass. Competition from seeded grasses may have contributed to declines in native species diversity.
Bates et al., 2005	Oregon	Chainsaw 1-14 years	No seeding: Herbaceous cover increased relative to uncut areas, but did not change after year 5. Pre-treatment vegetation was sufficient drive understory recovery with no artificial seeding. Junipers rapidly established from seed and from seedlings not initially cut. Shrub and juniper cover were equivalent suggesting the need to repeat juniper control in order to create a shrub steppe community.
Owen et al., 2009	Colorado	Mastication 6 months – 3.5 years	No seeding: Over time, plant cover and cheatgrass cover was greater in treated versus untreated plots. Plant community composition was weakly different between treated and untreated plots, due possibly to the increase in exotic species.
Ross et al., 2012	Utah	Mastication Chainsaw 1-2 years	No seeding: Both mastication and chainsaw treatments led to increases in understory plant cover but much of this was driven by cheatgrass and other undesirable species as a result of soil disturbance.
Huffman et al., 2013	Arizona	Chainsaw 1-5 years	No seeding: Total understory plant cover was higher in thinned versus control plots 5 years after treatment (but it was < 6%). Sampling years had below average precipitation.
O’Connor et al., 2013	Oregon	Chainsaw 1-4 years	No seeding: Cutting juniper increased perennial grass and mountain mahogany cover relative to treatments that burned the cut slash. Burning treatments had greater cover of cheatgrass.
Redmond et al., 2013	Utah	Chain 25-40 years	Seeded during, after: Herbaceous understory cover, averaged across 17 sites, was higher in treated versus untreated areas, although in a few sites the opposite was true. Cover of individual herbaceous functional groups was not different between treated and untreated areas except for perennial graminoids. Crested wheatgrass, a heavily seeded species, contributed to high perennial grass cover and high non-native cover in treated areas; it may have suppressed native grasses. Cover of *Bromus tectorum* L. (cheatgrass) was low across all sites. Tree cover and density was significantly reduced in treated areas.

Individual site conditions that influence understory responses add further complexity to understanding the effect of specific treatments. Characteristics such as site history, topography, soils, climate (especially precipitation), and pre-treatment plant community composition and structure have tremendous impacts on vegetation. Despite these variables, some patterns have emerged in the results of studies that assess mechanical treatment effects on understory species.

First, an awareness of the amount of time that has passed since treatments were implemented is important for interpreting any study. Plant communities change over time and understanding the effect of mechanical thinning on understory communities is a long-term process (Bates et al. 2000). Often the goal of pinyon-juniper control is to increase establishment of perennial grasses and shrubs that provide forage for livestock and/or wildlife. Early assessments of a treatment may reveal abundant weedy annuals (Owen et al. 2009, Ross et al. 2012, Huffman et al. 2013), whereas long-term monitoring might reveal vigorous establishment of native perennials (Tausch and Tueller 1977, Skousen et al. 1989). Leaf litter decomposition and nutrient dynamics, which impact soil communities and thus plant productivity, also require several years to fully react to canopy removal (Bates et al. 2007). The rate and trajectory of succession in pinyon-juniper is contingent upon species present from the beginning and also those that disperse into the site. Though many species from the entire sere may exist initially, they will come to dominate at different times (Tausch and Tueller 1977). This has also been observed in areas of burned pinyon-juniper (Everett and Ward 1984, Vaitkus and Eddleman 1987).

Considerations for Different Mechanical Techniques

Seeding Treatments

Artificial seeding is a common component of mechanical thinning strategies where understory communities are severely diminished or where seed banks are likely deficient. In order to achieve desired understory composition, seeding treatments must be carefully selected for site adaptability and compatibility with mechanical treatment (Plummer et al. 1968). *Agropyron cristatum* (crested wheatgrass) is a species with a long history of use after pinyon-juniper removal that is well adapted to arid western climates and is compatible with livestock grazing (Smoliak and Dormaar 1985, Walker et al. 1995). However, this non-native species has been shown to persist several decades after initial treatment (Skousen et al. 1989, Ott et al. 2003, Redmond et al. 2013) and it may suppress establishment of desirable native species (Skousen et al. 1986, Ott et al. 2003).

Successful seeding is also dependent on proper timing and amount of precipitation (Vallentine 1989). Jacobs and Gatewood (1997) observed no significant impact of seeding on grass cover in thinned pinyon-juniper despite seeding and soil surface preparation. They concluded that inadequate precipitation along with seed herbivory (from insects) and seed mortality contributed to lack of response. Rodents are also seed predators, especially in the arid West, and they can have detrimental impacts on artificial seeding (Archer and Pyke 1991).

Seeds must also have good contact with the soil, which has implications for the timing of seeding in relation to mechanical treatments. Seeding may be unsuccessful when it occurs after or in the absence of mechanical treatments (Ott et al. 2003, Baughman et al. 2010). Baughman et al. (2010) found no effect of seeding where pinyon-juniper had been logged by a feller-buncher and subsequently aerially seeded (a feller-buncher cuts and stacks trees in a seamless manner eliminating the disturbance associated with falling trees). They suggested that poor seed-soil contact may have reduced seeded species establishment due to seeding after mechanical treatment as opposed to before. Seeding prior to surface disturbance, whether by heavy equipment (Skousen et al. 1989, Ott et al. 2003) or by hand (Jacobs and Gatewood 1999, Stoddard et al. 2008), may benefit seeded species establishment.

Impact of Slash

Pinyon-juniper canopy removal adds slash to the landscape, which may vary in size, amount, and distribution depending on the structure of the stand and type of treatment used. In some cases, slash may inhibit seed germination or growth. Where wood is simply too large, plants may not be able to grow out from underneath until sufficient decay occurs. Shredded wood or wood chips (created by mastication or wood chippers) may also suppress understory vegetation when the depth of woody material becomes too great (Wolk and Rocca 2009).

Studies comparing understory establishment in the presence of slash (versus no-slash) have generally found higher plant abundance in plots with slash (Jacobs and Gatewood 1999, Hastings et al. 2003). Slash can ameliorate harsh environmental conditions, reduce erosion, and help conserve water, all of which improve growing conditions for remnant and newly germinating plants (Farmer et al. 1999, Jacobs and Gatewood 1999, Brockway et al. 2002, Owen et al. 2009). Decomposition of woody debris over time can also provide a source of soil nutrients (Bates et al. 2007). Slash, depending on its size and arrangement may further benefit establishment of herbaceous species by impeding travel of browsing ungulates, (Potts and Stephens 2009).

Undesirable Species

Surface disturbances, while beneficial for seeding, may also promote exotic or undesirable species. Many studies have shown increased understory plant cover after mechanical pinyon-juniper removal, but often non-natives, such as cheatgrass, are a significant part of that plant community (Owen et al. 2009, Ross et al. 2012, Huffman et al. 2013). The degree of surface disturbance may differ for various mechanical treatments and thereby have varying effects on exotic establishment. For example, Ross et al. (2012) observed greater cover of cheatgrass in areas thinned by mastication versus chainsaw.

Resource availability, which is impacted by surrounding competitors, is also important to cheatgrass invasion (Beckstead and Augspurger 2004) and the presence of understory competitors after pinyon-juniper removal may depend on the successional stage of the stand (Baughman et al. 2010). Baughman et al. (2010) examined the same mechanical method of pinyon-juniper removal at two sites (feller-buncher) and reported greater cheatgrass cover at a site that initially had lower native herbaceous cover and higher tree cover relative to the second site. Their results suggest that older denser stands of pinyon-juniper lacking native understory species or seed banks may be more susceptible to cheatgrass invasion.

Summary

The use of mechanical methods for the control of pinyon-juniper in the western US has occurred over many decades and continues to be employed for wildlife habitat management, ecological restoration, and hazardous fuels reduction. Variation among methods and plant community responses has been noted and the extensive geographic range of pinyon-juniper is partly responsible for this observation. However, some conclusions about vegetation impacts from this management strategy can be drawn.

1. Mastication and hand thinning (with chainsaws) are more effective at removing all size classes of trees compared with chaining or cabling. In treatments where all trees are not removed, tree dominance may return sooner than expected and increases understory vegetation abundance will be short-lived.
2. Some mechanical methods are more destructive to understory vegetation than others and therefore a method may be chosen for its ability to remove or preserve a particular plant functional group (or size class).
3. Seeding prior to mechanical treatments may result in better seed-soil contact and therefore better establishment of seeded species.
4. Invasion of exotic species is possible with all types of mechanical treatments and may be more likely where soil disturbance is increased and native understory species are lacking.
5. The time at which treatment outcomes are assessed will influence interpretation of treatment effectiveness. Plant communities change over time; generally short-lived plants (annual and biennial grasses and forbs) that are abundant during the first few years are replaced by longer-lived plants (perennials) that are the desired outcome of mechanical canopy removal.
6. Indirect responses of understory species to mechanical treatments are highly conditional and therefore it is difficult to separate the impact of a particular technique from other factors including climate, soils, topography, and pretreatment vegetation. Furthermore, comparisons between mechanical treatments in the same location are lacking. My literature research suggests that it is difficult to draw conclusions about the relative effectiveness of different mechanical treatments for improving understory vegetation.

Thus, there is a clear need for multiple-treatment evaluations that compare different mechanical methods of pinyon-juniper removal in the same area.

LITERATURE CITED

Archer, S. and D. A. Pyke. 1991. Plant-Animal Interactions Affecting Plant Establishment and Persistence on Revegetated Rangeland. Journal of Range Management 44:558-565.

Aro, R. S. 1971. Evaluation of pinyon-juniper conversion to grassland. Journal of Range Management 24:188-197.

Aro, R. S. 1975. Pinyon-Juniper Woodland Manipulation with Mechanical Methods. Pages 67-75 *in* The pinyon-juniper ecosystem: A symposium. Utah State University, Logan, UT.

Baker, W. L. and D. J. Shinneman. 2004. Fire and restoration of pinon–juniper woodlands in the western United States: a review. Forest Ecology and Management 189:1-21.

Bates, J., K. Davies, and R. Sharp. 2011. Shrub-Steppe Early Succession Following Juniper Cutting and Prescribed Fire. Environmental Management 47:468-481.

Bates, J., T. Svejcar, and R. Miller. 2007. Litter decomposition in cut and uncut western juniper woodlands. Journal of arid environments 70:222-236.

Bates, J. D., R. F. Miller, and T. J. Svejcar. 2000. Understory dynamics in cut and uncut western juniper woodlands. Journal of Range Management:119-126.

Baughman, C., T. A. Forbis, and L. Provencher. 2010. Response of two sagebrush sites to low-disturbance, mechanical removal of piñyon and juniper. Invasive Plant Science and Management 3:122-129.

Beckstead, J. and C. K. Augspurger. 2004. An experimental test of resistance to cheatgrass invasion: limiting resources at different life stages. Biological Invasions 6:417-432.

Bilbrough, C. J. and J. H. Richards. 1993. Growth of Sagebrush and Bitterbrush Following Simulated Winter Browsing: Mechanisms of Tolerance. Ecology 74:481-492.

Bowns, J. E. 1999. Ecology and Management of Pinyon-Juniper Communities within the Interior West: Overview of The" Resource Values Session" Of the Symposium. Pages 157-163 *in* Ecology and management of pinyon-juniper communities within the Interior West. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-P-9, Provo, UT.

Brockway, D. G., R. G. Gatewood, and R. B. Paris. 2002. Restoring grassland savannas from degraded pinyon-juniper woodlands: effects of mechanical overstory reduction and slash treatment alternatives. Journal of Environmental Management 64:179-197.

Christensen, E. M. and H. B. Johnson. 1964. Presettlement vegetation and vegetational change in three valleys in central Utah. Brigham Young University Science Bulletin-Biological Series 4:1-16.

Everett, R. L. and K. Ward. 1984. Early plant succession on pinyon-juniper controlled burns. Northwest Science 58:57-68.

Farmer, M. E., K. T. Harper, and J. N. Davis. 1999. The influence of anchor-chaining on watershed health in a juniper-pinyon woodland in central Utah. Pages 299-301 *in* Ecology and Management of Pinyon-Juniper Communities within the Interior West: Overview of The" Resource Values Session" Of the Symposium. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-P-9, Provo, UT.

Hastings, B. K., F. M. Smith, and B. F. Jacobs. 2003. Rapidly Eroding Piñon–Juniper Woodlands in New Mexico. Journal of Environmental Quality 32:1290-1298.

Huffman, D. W., M. T. Stoddard, J. D. Springer, J. E. Crouse, and W. W. Chancellor. 2013. Understory plant community responses to hazardous fuels reduction treatments in pinyon-juniper woodlands of Arizona, USA. Forest Ecology and Management 289:478-488.

Jacobs, B. F. and R. G. Gatewood. 1999. Restoration Studies in Degraded Pinyon-Juniper Woodlands of North-Central New Mexico. Pages 294-298 *in* Ecology and management of pinyon-juniper communities within the Interior West. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-P-9, Provo, UT.

Miller, M. E. 1999. Use of historic aerial photography to study vegetation change in the Negrito Creek watershed, southwestern New Mexico. The Southwestern Naturalist:121-137.

Miller, R. F., R. J. Tausch, E. D. McArthur, D. D. Johnson, and S. C. Sanderson. 2008. Age structure and expansion of piñon-juniper woodlands: a regional perspective in the Intermountain West. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-69. 15p.

Mitchell, V. L. 1976. The Regionalization of Climate in the Western United States. Journal of Applied Meteorology 15:920-927.

NOAA. 2013. Climate at a Glance. National Oceanic and Atmospheric Administration. http://www.ncdc.noaa.gov/cag/time-series/us 2013).

Ott, J. E., E. D. McArthur, and B. A. Roundy. 2003. Vegetation of chained and non-chained seedings after wildfire in Utah. Journal of Range Management 56:81-91.

Owen, S. M., C. H. Sieg, C. A. Gehring, and M. A. Bowker. 2009. Above-and belowground responses to tree thinning depend on the treatment of tree debris. Forest Ecology and Management 259:71-80.

Plummer, A. P., D. R. Christensen, and S. B. Monsen. 1968. Restoring big-game range in Utah. Page 183. Utah Division of Fish and Game. Publication No. 68-3. 183p.

Redmond, M. D., N. S. Cobb, M. E. Miller, and N. N. Barger. 2013. Long-term effects of chaining treatments on vegetation structure in piñon–juniper woodlands of the Colorado Plateau. Forest Ecology and Management 305:120-128.

Rippel, P., R. D. Pieper, and A. L. Gordon. 1983. Vegetational Evaluation of Pinyon-Juniper Cabling in South-Central New Mexico. Journal of Range Management 36:13-15.

Romme, W. H., C. D. Allen, J. D. Balley, W. L. Baker, B. T. Bestelmeyer, P. M. Brown, K. S. Eisenhart, M. L. Floyd, D. W. Huffman, B. F. Jacobs, R. F. Miller, E. H. Muldavin, T. W. Swetnam, R. J. Tausch, and P. J. Weisberg. 2009. Historical and Modern Disturbance Regimes, Stand Structures, and Landscape Dynamics in Pinon-Juniper Vegetation of the Western United States. Rangeland Ecology & Management 62:203-222.

Ross, M., S. Castle, and N. Barger. 2012. Effects of fuels reductions on plant communities and soils in a Piñon-juniper woodland. Journal of arid environments 79:84-92.

Skousen, J., J. N. Davis, and J. D. Brotherson. 1986. Comparison of vegetation patterns resulting from bulldozing and 2-way chaining on a Utah pinyon-juniper big game range. Great Basin Naturalist 46:508-512.

Skousen, J. G., J. N. Davis, and J. D. Brotherson. 1989. Pinyon-juniper chaining and seeding for big game in central utah. Journal of Range Management 42:98-104.

Smoliak, S. and J. Dormaar. 1985. Productivity of Russian wildrye and crested wheatgrass and their effect on prairie soils. Journal of Range Management:403-405.

Springfield, H. W. 1976. Characteristics and management of southwestern Pinyon-Juniper ranges: the status of our knowledge. US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Paper RM-160. 32p.

Stevens, R. 1999. Mechanical Chaining and Seeding. Pages 281-284 *in* Ecology and management of pinyon-juniper communities within the Interior West. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-P-9, Provo, UT.

Stoddard, M. T., D. W. Huffman, T. M. Alcoze, and P. Z. Fule. 2008. Effects of slash on herbaceous communities in pinyon-juniper woodlands of northern Arizona. Rangeland Ecology & Management 61:485-495.

Tausch, R. J. and P. T. Tueller. 1977. Plant succession following chaining of pinyon-juniper woodlands in eastern Nevada. Journal of Range Management 30:44-49.

Tausch, R. J., N. E. West, and A. A. Nabi. 1981. Tree Age and Dominance Patterns in Great Basin Pinyon-Juniper Woodlands. Journal of Range Management 34:259-264.

Vaitkus, M. R. and L. E. Eddleman. 1987. Composition and productivity of western juniper understory and its response to canopy removal. Pages 456-460 *in* Pinyon-Juniper Conference. US Department of Agriculture Forest Service General Technical Report INT-215, Ogden, UT.

Vallentine, J. F. 1989. Range development and improvements. Academic Press, San Diego, CA, USA.

Vankat, J. 2013. Vegetation Dynamics on the Mountains and Plateaus of the American Southwest. Pages 268-324 *in* M. J. A. Weger, editor. Plant and Vegetation. Springer, New York, NY, USA.

Walker, S. C., R. Stevens, S. B. Monsen, and K. R. Jorgensen. 1995. Interaction between native and seeded introduced grasses for 23 years following chaining of juniper-pinyon woodlands. Pages 372-380 *in* Wild Land Shrub and Arid Land Restoration Symposium. US Department of Agriculture, Forest Serice, Intermountain Research Station, INT-GTR-315, Las Vegas, NV.

Wandera, J., J. Richards, and R. Mueller. 1992. The relationships between relative growth rate, meristematic potential and compensatory growth of semiarid-land shrubs. Oecologia 90:391-398.

West, N. E. 1999. Distribution, Composition, and Classification of Current Juniper-Pinyon Woodlands and Savannas Across Western North America. Pages 20-23 *in* Ecology and management of pinyon-juniper communities within the Interior West. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-P-9, Provo, UT.

UNDERSTORY RESPONSES TO MECHANICAL REMOVAL OF PI01NYON JUNIPER IN NORTHWEST COLORADO

Introduction

Pinyon-juniper (*Pinus spp.* L. – *Juniperus spp.* L.) communities are one of the most widespread vegetation types in the western United States covering nearly 40 million ha (Romme et al. 2009). Species of pinyon (*e.g.*, *Pinus edulis* Engelm. and *Pinus monophylla* Torr. & Frém.) and juniper (*e.g.*, *Juniperus monosperma* (Engelm.) Sarg., *Juniperus occidentalis* Hook. and *Juniperus osteosperma* (Torr.) Little) may co-dominate or occur as single species depending on climate and other physical site characteristics. While often described as woodlands, the structure of pinyon-juniper communities, varies along a continuum that includes these broad groupings: dense woodland, wooded shrubland, or savanna (Romme et al. 2009). These diverse communities provide a variety of ecosystem services and are home to a wide array of plants and animals including many big game mammals (Bowns 1999).

Mule deer (*Odocoileus hemionus*) are one such species that utilize pinyon-juniper as a source of forage and cover. While some regions of the western US provide year-round mule deer habitat, others serve primarily as winter range for migratory herds seeking resources that are no longer available in their high elevation summer range. Forage quality in particular is critically important to mule deer winter survival and therefore the long-term sustainability of populations (Bishop et al. 2009). A mix of shrubs, grasses, and forbs with diverse phenological characteristics reside in the understory and if available provide nutrition throughout the winter (Bartmann 1983). Browse such as antelope bitterbrush (*Purshia tridentata* (Pursh) DC.), mountain mahogany (*Cercocarpus montanus* Raf.), and Utah serviceberry

(*Amelanchier utahensis* Koehne) are highly palatable to mule deer and are also accessible in deep winter snows.

Winter range in some areas of pinyon-juniper, however, does not support productive understory (Bender et al. 2007, Romme et al. 2009), which can lead to malnutrition and mortality, especially among fawns during harsh winters. One reason that understory communities may be depleted is due to resource competition with pinyon and juniper trees in the overstory (Jameson 1967, Clary 1971, Miller et al. 2008). Diminished understory productivity in many regions of the western US has raised questions about the condition of pinyon-juniper and studies have concluded that over the last 150 years, range expansion and density increases of pinyon-juniper have been occurring (Christensen and Johnson 1964, Tausch et al. 1981, Miller et al. 2008). Suspected causes of this phenomenon, which are evidenced by comparisons of historical photographs and tree age-structure analyses (Vankat 2013), have largely been related to land uses that began during European settlement in the mid-1800s (Tausch et al. 1981, Romme et al. 2009). Anthropogenic disruptions to ecological processes brought about by logging, livestock grazing, and fire suppression are potential explanations for modern pinyon-juniper conditions, however climate driven expansion has also occurred (Romme et al. 2009). More specifically, warm and wet periods during the 1800s promoted tree establishment throughout the West, which, coupled with the onset of livestock grazing, has contributed to stand conditions observed today (Miller et al. 2008, Shinneman and Baker 2009).

Energy development also influences the ability of mule deer to access forage in pinyon-juniper communities. Oil and gas extraction, which occurs in many western states, has brought about the construction of roads, well pads, and other infrastructure to areas that previously were largely devoid of human presence. Consequently, habitat loss has occurred reducing the availability of forage and cover both directly and indirectly, as mule deer select areas farther away from oil and gas activity (Sawyer et al. 2006, Sawyer et al. 2009). Habitat fragmentation also disrupts migration routes of some herds, which can impact the rate and distance mule deer must travel to find suitable habitat; these factors influence nutrition and body condition of females that typically birth young near the end of spring migration (Lendrum et al. 2013). Poor adult female nutrition in turn can reduce fawn survival (Parker et al. 2009, Tollefson et al. 2011) and thus fragmented and unsuitable habitat has important implications for mule deer population dynamics (Bishop et al. 2009).

To improve understory productivity and mitigate impacts of energy development, managers have used different methods to reduce pinyon-juniper density and canopy coverage. Prescribed fire is one tool that has been utilized for many decades in the management of western rangelands (Vallentine 1989). Fire is a natural ecosystem process in pinyon-juniper woodlands, however its frequency and severity are highly variable and therefore its role in maintaining low tree densities and productive understories is not well known (Baker and Shinneman 2004). In addition, wildfire risk and fuel conditions that may not support a spreading fire mean that prescribed fire is not always a feasible option.

Mechanical removal of pinyon-juniper is an alternative method that has been used since the 1950s to increase forage production for livestock and big game (Aro 1975). These methods are also used, in more recent times, as fire surrogates to achieve pinyon-juniper restoration and fuels reduction (Stephens et al. 2012). Typically, heavy machinery like bulldozers have been used to cut, uproot, and crush vegetation to reduce tree density and canopy coverage (Vallentine 1989). Anchor chaining, one of the oldest forms of large-scale mechanical pinyon-juniper removal, involves a heavy ship anchor chain attached to crawler tractors or bulldozers, with one at each end of the chain. As the tractors move forward with the chain between them, trees and shrubs are uprooted or broken off leaving piled and scattered slash (woody debris) in their wake. More recent technology includes various machines that shred or chip trees (aka mastication), which allows for the removal of individual trees and results in smaller debris relative to chaining.

In general, studies have reported increased understory vegetation after canopy removal using methods such as chainsaw thinning (Sheley and Bates 2008, Huffman et al. 2013), anchor chaining (Omeara et al. 1981, Ott et al. 2003), and mastication (Owen et al. 2009, Ross et al. 2012). However, the composition of those communities has often included exotic or undesirable species that suppress native plant establishment (Skousen et al. 1989, Owen et al. 2009, Ross et al. 2012, Huffman et al. 2013). Understory responses have also been variable due to site conditions such as pretreatment vegetation and climate (Bates et al. 2005), which can vary widely across the geographic range of pinyon-juniper. In addition, most studies have measured the effects of one particular method. For these reasons, there is uncertainty about how vegetation may respond to different mechanical techniques in a particular location. Because of the ecological importance of pinyon-juniper and the role it plays in providing mule deer habitat, there is a need to test the impacts of different mechanical techniques in the same area to gain a better understanding of how different methods affect understory communities.

In this study, I measured understory vegetation during the first two years after mechanical removal of pinyon-juniper overstory using three methods: anchor chaining, rollerchopping, and hydro-axing (mastication) in a northwest Colorado pinyon-juniper ecosystem (plots treated by each method will hereafter be referred to as chain, rollerchop, and hydro-ax). Artificial seeding was conducted in conjunction with mechanical treatments. I wanted to determine how different mechanical and seeding treatments in the same area influence understory vegetation. Based on the current knowledge of the use of mechanical treatments in pinyon-juniper communities, I constructed the following hypotheses:

1) Biomass and cover of understory vegetation would be greater in mechanically treated plots relative to control plots.

2) Of the three mechanical treatments, rollerchop would have greater biomass and cover of understory vegetation relative to chain or hydro-ax.

3) Seeded subplots would have greater biomass and cover of understory vegetation than unseeded subplots and of the seeded subplots, rollerchop plots would have greater biomass and cover of understory vegetation compared with chain or hydro-ax plots.

4) Seeded subplots would have greater seeded shrub density than unseeded subplots, and of the seeded subplots, rollerchop plots would have greater seeded shrub density than chain or hydro-ax.

Methods

Site Description

The study area was located on property managed by the Bureau of Land Management in the Piceance Creek Basin of Rio Blanco County, Colorado, USA. It consisted of two sites, North Magnolia (12S 738327 E 4423141 N) and South Magnolia (12S 733958E, 4420956N). Elevations at the two sites range from 2000 to 2100 m. Soils at North Magnolia are composed primarily of Rentsac channery loam and Rentsac-Piceance complex while South Magnolia is composed of the Redcreek-Rentsac complex and Forelle loam (NRCS 2012). This semi-arid region receives 33 – 40 cm of precipitation annually (Tiedeman and Terwilliger 1978).

Vegetation is dominated by an overstory of *P. edulis* and *J. osteosperma*. The understory is a mix of mountain shrubs (primarily *Purshia tridentata* (Pursh) DC., *Amelanchier spp.* Medik., *Cercocarpus montanus* Raf., *Symphoricarpos spp.* Duham., *Artemisia tridentata* Nutt.), forbs (*Opuntia polyacantha* Haw., *Phlox* L.*spp.*, *Machaeranthera* Nees *spp.*, *Linum lewisii* Pursh), and graminoids (*Carex* L. *spp.*, *Elymus* L. *spp.*, *Pascopyrum smithii* (Rydb.) Á. Löve, *Poa* L. *spp.*, *Achnatherum hymenoides* (Roem. & Schult.) Barkworth). South Magnolia had larger and fewer trees and sparser understory vegetation relative to North Magnolia (see Appendix C). Oil and gas industry infrastructure occurred within a kilometer of each site.

Experimental Design and Site Preparation

Each site contained multiple treatment blocks, four at North Magnolia and three at South Magnolia. A block consisted of a chain plot, rollerchop plot, hydro-ax plot, and untreated control (for a total of 28 plots). Every mechanically treated plot was further divided into a seeded and unseeded subplot. Controls were not mechanically treated or seeded. One of the main assumptions for the experiment was that the presence of pinyon-juniper overstory was contributing to reduced understory (Jameson 1967, Schott and Pieper 1985, Naillon et al. 1997) and therefore, adding seed to plots with intact overstory would not increase understory vegetation. Thus we did not include a non-mechanically treated plus seeded treatment in the experiment. All plots within a block were adjacent to one another except in one block at South Magnolia where chain and hydro-ax plots were located 0.75 km away from the rollerchop and control plots. Mechanical treatment plots were 137 m x 60 m (0.8 ha), but in some instances treated areas were slightly smaller or larger due to difficulty of operating heavy equipment in this field setting.

Seeding occurred 1 to 14 days prior to mechanical treatments between 24 October and 23 November 2011. All seeded subplots received the same native seed mix at a rate of 600 pure live seeds m^{-2}, which was comprised of 10 shrub species, 14 forb species and 10 grass species (Table 2.1). Species were chosen to fill ecological niches at all stages of succession and to increase palatable shrub production. Native early seral species in particular were included to provide quick cover and compete with non-native annuals. All species were native to the continental United States (USDA 2013) except QuickGuard™, which is a sterile wheat hybrid. Method of seeding differed for each mechanical treatment. In hydro-ax subplots all seed was broadcast using Earthway® hand-crank spreaders along five evenly spaced transects parallel to the long axis of the subplot. Because the seed mix contained seeds of varying sizes and shapes, species were grouped by size and morphology into seeding groups (Table 2.1) to aid in uniform seed distribution. In rollerchop and chain plots, the majority of species was broadcast, but several large-seeded species that benefit from deeper planting were seeded using a seed dribbler (Figure 2.1) mounted on the tracks of the bulldozers (Plummer 1968). This device dropped seeds onto the bulldozer track as it moved forward; seeds were then pressed into the soil by the track. Because the hydro-ax was not a tracked machine and had no mounted seed dribbler, all species were hand-broadcast.

Figure 2.1. Seed dribbler mounted on bulldozer tracks. Species in seeding group 5 (Table 2.1) were seeded with the dribbler. Seeds were applied to half of each plot at two sites in northwest Colorado where pinyon-juniper canopy was removed using one of three mechanical treatments: anchor chain, rollerchopper, or hydro-ax (seed dribbler was used for chain and rollerchop treatments).

Table 2.1. Plant species used in a seed mix that was applied to half of each plot in northwest Colorado where pinyon-juniper canopy was removed using one of three mechanical treatments: anchor chain, rollerchopper, or hydro-ax. Treatments were applied in a randomized complete block design. Seeded species were separated into seeding groups by seed size and morphology to aid in uniform seed distribution. All groups were broadcast seeded for hydro-ax plots; in chain and rollerchopper plots, groups 1-4 were broadcast seeded and group 5 was seeded using a seed dribbler mounted on the bulldozers. Lifespan: annual (A) or perennial (P). Seeding rate (pure live seeds m^{-2}) is found in the far right column. Plant taxonomy – Natural Resource Conservation Service (USDA 2013).

***Genus species* authority**	**Common Name**	**Lifespan**	**Seeding Group**	**Pure Live Seeds m^{-2}**
Forb				
Amaranthus retroflexus L.	Redroot Amaranth	A	2	12
Artemisia frigida Willd.	Fringed Sagebrush	P	2	36
Artemisia ludoviciana Nutt.	White Sagebrush	P	2	24
Balsamorhiza sagittata (Pursh) Nutt.	Arrowleaf Balsamroot	P	1	12
Cleome serrulata Pursh	Rocky Mountain Beeplant	A	1	24
Crepis acuminata Nutt.	Tufted Hawksbeard	P	2	1
Eriogonum umbellatum Torr.	Sulfur-Flower Buckwheat	P	3	10
Hedysarum boreale Nutt.	Utah Sweetvetch	P	5	12
Helianthus annuus L.	Common Sunflower	A	1	30
Linum lewisii Pursh	Lewis Flax	P	1	24
Lupinus argenteus Pursh	Silvery Lupine	P	5	12
Oenothera caespitosa Nutt.	Tufted Evening Primrose	P	1	12
Oenothera pallida Lindl.	Pale Evening Primrose	P	1	24
Penstemon strictus Benth.	Rocky Mountain Penstemon	P	1	36
Graminoid				
Achnatherum hymenoides (Roem. & Schult.) Barkworth	Indian Ricegrass	P	1	18
Elymus elymoides (Raf.) Swezey	Bottlebrush Squirreltail	P	1	18
Elymus trachycaulus (Link) Gould ex Shinners	Slender Wheatgrass	P	1	12
Hesperostipa comata (Trin. & Rupr.) Barkworth	Needle And Thread	P	1	12
Koeleria macrantha (Ledeb.) Schult.	Prairie Junegrass	P	2	24
Pascopyrum smithii (Rydb.) Á. Löve	Western Wheatgrass	P	1	6
Poa fendleriana (Steud.) Vasey	Muttongrass	P	2	12
Poa secunda J. Presl	Sandberg Bluegrass	P	2	12
Triticum aestivum L. x *Secale cereale* L.	QuickGuard	A	4	12
Vulpia octoflora (Walter) Rydb.	Six-Weeks Fescue	A	2	18

Table 2.1. Continued

***Genus species* authority**	**Common Name**	**Lifespan**	**Seeding Group**	**Pure Live Seeds m^{-2}**
Shrub				
Amelanchier alnifolia (Nutt.) Nutt. ex M. Roem.	Saskatoon Serviceberry	P	5	30
Amelanchier utahensis Koehne	Utah Serviceberry	P	5	12
Artemisia tridentata Nutt.	Wyoming Sagebrush	P	2	24
Cercocarpus montanus Raf.	Mountain Mahogany	P	5	24
Ericameria nauseosa (Pall. ex Pursh) G.L. Nesom & Baird	Rubber Rabbitbrush	P	2	18
Chrysothamnus viscidiflorus (Hook.) Nutt.	Yellow Rabbitbrush	P	2	18
Krascheninnikovia lanata (Pursh) A. Meeuse & Smit	Winterfat	P	3	18
Prunus virginiana L.	Chokecherry	P	4	6
Purshia tridentata (Pursh) DC.	Bitterbrush	P	5	30
Rhus trilobata Nutt.	Skunkbush Sumac	P	5	6

Mechanical Treatments

Mechanical treatments were applied during October and November of 2011. Chain plots were treated by an 18-m long Ely chain (40.8 kg per link with added sections of rail welded to the individual links) that was dragged between two bulldozers, a Caterpillar D8R (Caterpillar Inc., USA) and Komatsu D65EX (Komatsu Ltd., Japan), in such a manner that vegetation was either pushed over by the bulldozers or uprooted by the chain. The chain was dragged over the same area twice, with the second pass in the opposite direction of the first pass. Chaining generated slash and uprooted trees that were scattered and piled across the plot. In rollerchop plots, pinyon-juniper vegetation was knocked down by a Komatsu D65EX bulldozer towing a heavy cylindrical drum that crushed and chopped vegetation as it rolled over the ground. The drum was 3.6 m long and 1.5 m in diameter with 25-cm long blades spanning the length of the drum; it weighed approximately 1100 kg empty and held 8338 L of water for an operational weight of 9100 kg. The size of debris left by this treatment varied depending on the size of the tree, but in most cases slash was chopped into approximately 0.5-m sections or smaller. Slash was scattered across the plot with less vertical structure relative to chaining. For hydro-ax plots, standing trees and shrubs were masticated (or shredded) to ground level by a Barko 930 tractor (Barko Hydraulics, LLC, USA) mounted with a Fecon Bull Hog mulcher (Fecon Inc., USA). Although measurements were not taken, most of the shredded material was less than approximately 20 cm in length; woody material scattered across the plot varied in depth between 0 and 25 cm. No strips or patches of un-cut vegetation were left in mechanically treated plots.

Vegetation Sampling

To measure understory vegetation, percent cover, biomass, and shrub density data were gathered along transects in all 49 subplots (20 transects per subplot in 2012 and 10 transects per subplot in 2013). Percent cover by species was estimated using first-hit point-intercept method at 1-m intervals along each transect (first hit ≤ 1.4 m in height). Biomass was collected using one sampling frame (0.25-m x 0.75-m) randomly placed along each transect; all current-year's aboveground plant growth was clipped and bagged by species. Herbaceous species were clipped only if rooted inside the frame. For woody species, current-year's growth hanging inside the frame, up to 1.4 m in height, was clipped whether or not it was rooted inside the frame (1.4 m is approximately breast height in standard forest measurements and was used as the height cutoff for understory vegetation). All biomass was composited by species for each subplot. Plant biomass was oven-dried to constant mass at 65°C and subsequently weighed to estimate total aboveground production per subplot. Individual shrubs rooted within biomass frames were counted and identified by species prior to being clipped.

Statistical Analysis

Analysis of variance was performed using SAS 9.3 (SAS Institute, Cary, NC, USA) to examine mechanical treatment and seeding treatment effects on understory vegetation biomass and percent cover and seeded shrub density. Parametric analyses were conducted using a nested randomized complete block split-plot mixed effects model where site (North Magnolia and South Magnolia), mechanical treatment (Chain, Rollerchop, Hydro-Ax) and seeding treatment (Seeded or Unseeded) were fixed effects and block (A-G) 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. The first analysis examined effects of mechanical treatments by comparing all unseeded subplots including control where mechanical treatment was a fixed effect, block was a random effect, and Tukey's adjustment was used to assess the effect of mechanical treatment relative to each other and to control. A separate analysis excluding control plots was used for comparisons among mechanical and seeding treatments. For significant effects, pairwise comparisons were made using Tukey's adjustment. Response variables were grouped by lifeform (graminoid, forb, shrub), duration (annual, perennial) and nativity (native or exotic) Due to differences in precipitation between years (Figure 2.2), analyses for year 1 and 2 were done separately. Data were transformed as necessary to achieve normality prior to parametric analyses. Significance was determined at $\alpha = 0.05$.

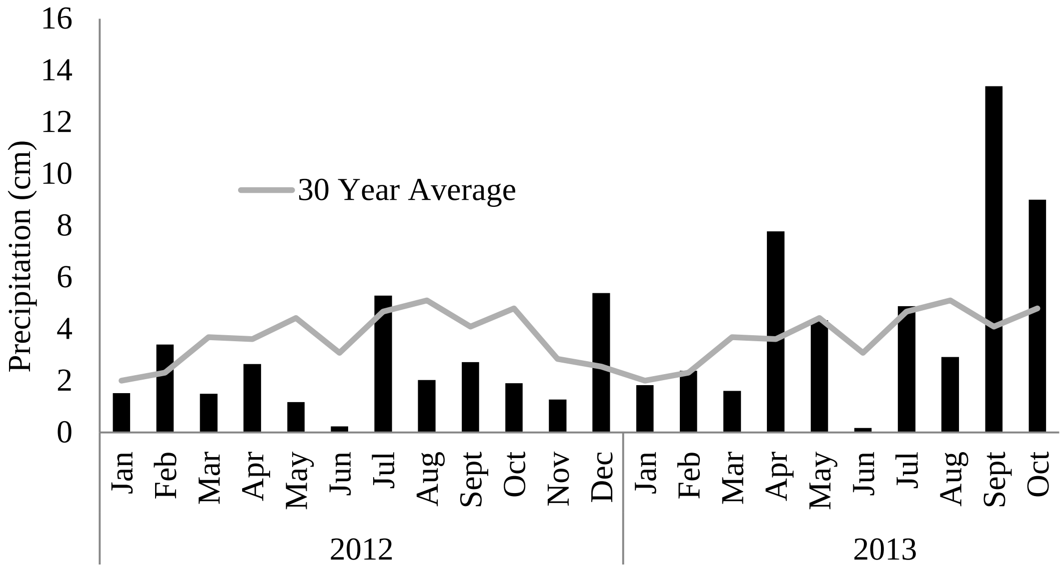

Figure 2.2. Monthly precipitation data (Station: Rifle 23 NW, 12S 253890E 4405179N, www.ncdc.noaa.gov) and the 30 year average (1981-2010, Station: Little Hills, 12S 254146E 4431731N, http://www.raws.dri.edu/wraws/coF.html). Data were taken from two stations because neither had both monthly precipitation and 30 year average. Rifle 23 NW is approximately 16 km south of the study site and Little Hills is approximately 11 km north of the study sites.

Results

The first analysis comparing mechanical treatment plots (unseeded subplots) and control plots revealed no statistical differences in mean biomass for all plant functional groups in 2012 (Table 2.2). Understory vegetation in 2013 was much more productive than the previous year and several functional groups had higher biomass in mechanically treated plots relative to control including forbs (in rollerchop only, $p = 0.0089$), graminoids (all three treatment types: chain $p = 0.0015$, rollerchop $p < 0.0001$, hydro-ax $p = 0.0001$), and total exotics combined (in rollerchop only, $p = 0.0001$). Perennial graminoids responded particularly strongly, with 10-15 times greater biomass in treated plots than in controls. Exotic biomass was 6-10 times greater in rollerchop compared to chain ($p = 0.0035$) and hydro-ax ($p = 0.0014$). Mean shrub biomass, while 2-3 times higher in all three treatment types relative to control, had too much variability to detect statistically significant differences.

Percent cover of perennial graminoids, shrubs, and all natives combined was significantly lower for all treatment types relative to control in 2012 (maximum observed $p < 0.02$; Table 2.3). Cover of perennial graminoids and shrubs in treated plots was less than half that of controls. Cover increased dramatically in 2013 and followed the same general trend as biomass with greater coverage of forbs and grasses in treated plots over control and high exotic cover in rollerchop relative to chain, hydro-ax, or control (for all comparisons, highest observed $p < 0.03$). Exotics were 10% of total ground cover in rollerchop unseeded (using first-hit point-intercept method), but in chain and hydro-ax they were only 4-5% (and exotics were <1% in control). The most common exotic species, in both biomass and cover data, were *Salsola tragus* L., *Descurainia sophia* (L.) Webb ex Prantl, *Bromus tectorum* L., and *Alyssum alyssoides* (L.) L.

Table 2.2. Mean biomass (g m^{-2}) by plant functional group from 2 sites in northwest Colorado where 3 mechanical treatments were used to remove pinyon-juniper overstory: anchor chain, rollerchopper, or hydro-ax. Half of each mechanically treated plot was seeded and control plots received no mechanical or seeding treatment. Two analyses (both ANOVAs using Tukey's adjustment) were performed comparing means in the same row (n = 7). The first analysis compared means in all unseeded subplots within the same row (*p-values* shown in column "with Control; means with different letters are different at α = 0.05). The second analysis examining mechanical and seeding treatment interactions compared means across all subplots excluding control (*p-values* shown in column "without Control").

	Control	**Chain**		**Rollerchop**		**Hydro-Ax**		***p-value* with Control**	***p-value* without Control**
	Unseeded Subplots	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**		
2012				**Biomass (SE)**					
Forb	1.20 (0.51)	1.26 (0.30)	1.44 (0.36)	0.87 (0.10)	1.33 (0.48)	1.28 (0.45)	1.23 (0.38)	0.9248	0.9936
Annual[1]	0	0.07 (0.04)	0.02 (0.01)	0.23 (0.10)	0.27 (0.26)	0.28 (0.19)	0.13 (0.13)	*	*
Perennial[2]	1.20 (0.51)	1.17 (0.31)	1.39 (0.37)	0.63 (0.12)	1.06 (0.47)	1.00 (0.44)	1.10 (0.35)	0.6599	0.9085
Graminoid	2.56 (1.15)	3.95 (2.07)	2.68 (1.28)	1.27 (0.52)	1.89 (0.57)	1.72 (1.14)	2.19 (0.39)	0.7366	0.1112
Annual[3]	<0.01 (<0.01)	0.02 (0.01)	0.01 (0.01)	<0.01 (<0.01)	0.02 (0.02)	<0.01 (<0.01)	0.01 (0.01)	*	*
Perennial[4]	2.56 (1.16)	3.93 (2.07)	2.67 (1.28)	1.27 (0.52)	1.86 (0.58)	1.71 (1.14)	2.19 (0.39)	0.7116	0.1262
Shrub	8.88 (2.51)	4.41 (1.62)	6.39 (1.81)	8.75 (4.1)	6.24 (2.04)	5.64 (1.58)	4.51 (2.25)	0.1093	0.0313
Total Native	12.64 (2.65)	9.62 (2.19)	10.49 (1.96)	10.88 (4.03)	9.16 (2.33)	8.64 (1.9)	7.98 (2.38)	0.2192	0.5299
Total Exotic	<0.01 (<0.01)	0.01 (0.01)	0.01 (0.01)	<0.01 (<0.01)	0.29 (0.26)	0.01 (0.01)	0.01 (0.01)	*	*
2013									
Forb	1.95 (0.76)A	11.28 (2.43)	4.73 (1.4)AB	36.46 (11.98)	27.58 (13.63)B	28.19 (7.11)	8.04 (2.89)AB	0.0152	0.2945
Annual[5]	0.07 (0.04)A	4.04 (1.99)	1.73 (0.57)AB	29.65 (12.45)	22.6 (13.89)B	21.67 (8.47)	3.02 (2.45)AB	0.0015	0.1093
Perennial[6]	1.73 (0.74)	7.23 (2.14)	3 (1.19)	6.8 (3.20)	4.98 (1.58)	6.51 (1.64)	5.02 (2.39)	0.5286	0.4343
Graminoid	1.38 (0.62)A	10.08 (4.31)	14.09 (7.94)B	12.45 (4.09)	19.99 (4.48)B	14.86 (5.86)	15.67 (5.31)B	<0.0001	0.4638
Annual[7]	0.06 (0.06)	0.72 (0.43)	0.58 (0.34)	1.19 (0.40)	3.42 (2.22)	1.66 (1.08)	0.51 (0.50)	*	*
Perennial[8]	1.32 (0.63)A	9.36 (4.39)	13.51 (8.03)B	11.26 (4.18)	16.56 (5.23)B	13.2 (6.29)	15.15 (5.42)B	0.0001	0.6719
Shrub	15.77 (4.44)	40.25 (14.66)	54.45 (32.10)	22.18 (7.48)	30.26 (16.57)	41.17 (19.12)	55.37 (26.86)	0.3126	0.8495
Total Native	19.03 (4.64)	59.64 (15.30)	71.36 (31.10)	49.47 (8.57)	58.97 (20.32)	81.16 (16.10)	75.90 (23.70)	0.2826	0.5192
Total Exotic	0.08 (0.06)A	1.97 (0.75)	1.91 (0.92)A	21.61 (10.83)	18.85 (13.2)B	3.06 (1.39)	3.17 (2.99)A	<0.0001	0.4419

*Data were not normally distributed due to zero inflation.

[1] Primarily native with trace amounts of exotics (except for Rollerchop unseeded - 99% exotic); [2] Trace amounts of exotics ; [3] Primarily exotic; [4] Primarily native with trace amounts of exotics; [5] Both native and exotic; [6] Primarily native with trace amounts of exotics; [7] All exotic; [8] All native

Table 2.3. Percent cover by plant functional group from 2 sites in northwest Colorado where 3 mechanical treatments were used to remove pinyon-juniper overstory: anchor chain, rollerchopper, or hydro-ax. Half of each mechanically treated plot was seeded and control plots received no mechanical or seeding treatment. Two analyses (both ANOVAs using Tukey's adjustment) were performed comparing means in the same row (n = 7). The first analysis compared means in all unseeded subplots within the same row (*p-values* shown in column "with Control; means with different letters are different at α = 0.05). The second analysis examining mechanical and seeding treatment interactions compared means across all subplots excluding control (*p-values* shown in column "without Control"). Table includes percent cover of bare soil in addition to vegetation groups.

	Control	**Chain**		**Rollerchop**		**Hydro-Ax**		***p-value* with Control**	***p-value* without Control**
	Unseeded Subplots	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**		
2012	**Percent Cover (SE)**								
Forb	0.84 (0.23)	0.38 (0.07)	0.14 (0.05)	0.41 (0.2)	0.31 (0.17)	1.07 (0.31)	0.47 (0.19)	0.0934	0.6053
Annual	0.03 (0.03)	0.10 (0.07)	0	0.22 (0.14)	0.03 (0.03)	0.45 (0.19)	0.07 (0.05)	*	*
Perennial	0.80 (0.22)	0.27 (0.06)	0.10 (0.05)	0.19 (0.1)	0.27 (0.17)	0.59 (0.23)	0.40 (0.21)	0.0633	0.4396
Graminoid	4.07 (1.4)A	2.16 (0.75)	1.89 (0.39)AB	1.31 (0.31)	1.76 (0.55)B	1.86 (0.8)	1.75 (0.57)B	0.0166	0.7612
Annual	0	0	0	0.07 (0.07)	0.07 (0.05)	0	0.03 (0.03)	*	*
Perennial	4.07 (1.4)A	2.16 (0.75)	1.89 (0.39)AB	1.24 (0.3)	1.69 (0.55)B	1.86 (0.8)	1.72 (0.58)B	0.0093	0.7562
Shrub	12.57 (2.5)A	4.97 (1.6)	5.13 (1.54)B	4.32 (1.39)	4.25 (1.16)B	3.40 (1)	3.49 (0.89)B	<0.0001	0.9855
Total Native	17.44 (2.11)A	7.50 (1.42)	7.13 (1.28)B	6.04 (1.47)	6.25 (1.32)B	6.23 (1.14)	5.64 (0.72)B	<0.0001	0.7432
Total Exotic	0.03 (0.03)	0	0	0.07 (0.05)	0.04 (0.04)	0.07 (0.05)	0.03 (0.03)	*	*
Bare Soil	18.97 (2.09)AB	17.74 (2.82)	13.83 (1.56)AC	19.01 (2.33)	22.33 (2.32)B	13.62 (2.55)	11.37 (1.48)C	0.0012	0.0722
2013									
Forb	0.97 (0.26)A	9.02 (0.82)	5.09 (1.16)B	10.89 (2.26)	9.80 (2.2)B	8.71 (1.47)	6.37 (1.77)B	0.0001	0.0725
Annual	0.28 (0.14)A	6.68 (0.96)	3.71 (0.82)B	8.95 (2.02)	8.54 (2.22)B	4.86 (1.02)	4.00 (1.13)B	<0.0001	0.1545
Perennial	0.69 (0.18)	2.35 (0.53)	1.38 (0.52)	1.94 (0.77)	1.26 (0.23)	3.85 (0.7)	2.36 (0.79)	0.0927	0.5934
Graminoid	3.35 (1.26)A	10.12 (2.2)	8.71 (1.66)B	10.61 (1.35)	12.52 (1.96)B	11.2 (2.24)	11.37 (2.82)B	0.0005	0.3655
Annual	0.14 (0.09)	1.86 (1.16)	1.63 (0.67)	2.80 (1.87)	2.99 (1.75)	1.57 (0.99)	1.09 (0.42)	*	*
Perennial	3.21 (1.31)A	8.27 (2.09)	7.08 (1.88)	7.81 (1.53)	9.53 (2.24)B	9.63 (2.6)	10.27 (2.86)B	0.0043	0.4061
Shrub	13.79 (3.3)	10.13 (3.54)	15.35 (4.59)	13.87 (3.55)	7.52 (2.47)	11.25 (3)	11.63 (3.1)	0.0678	0.0136
Total Native	17.77 (2.88)	24.24 (2.45)	24.38 (3.93)	27.84 (2.78)	19.79 (2.69)	27.62 (2.44)	25.13 (2.71)	0.1792	0.2388
Total Exotic	0.34 (0.2)A	5.33 (1.59)	4.78 (1.36)B	7.61 (3.2)	10.05 (3.57)C	3.61 (1.33)	4.23 (1.37)B	<0.0001	0.2798
Bare Soil	17.27 (1.49)A	14.28 (1.73)	15.99 (3.14)A	17.07 (2.38)	17.49 (1.93)A	10.25 (1.9)	9.77 (1.95)B	0.0025	0.6791

*Data were not normally distributed due to zero inflation.

The second analysis examining mechanical and seeding treatment interactions (without control plots) revealed no significant effects due to high variability within most biomass functional groups in 2012 and 2013 (Table 2.2). Shrub biomass in 2012 had a significant mechanical by seeding treatment interaction (*p* = 0.0313) in the overall test and subsequent analyses looking at the effect of seeding within each mechanical treatment individually revealed a significant impact of seeding within hydro-ax (*p* = 0.0425) but not chain (*p* = 0.0668) or rollerchop (*p* = 0.9846). Mean understory productivity in 2013 was again much greater than 2012 for all levels of mechanical and seeding treatments (5 – 9 times as much; see totals for natives and exotics in Table 2.2).

Percent cover in the second analysis followed closely with biomass and most functional groups were not different between treatments for both years (Table 2.3). There was a significant mechanical by seeding treatment interaction in the overall test for shrub cover in 2013 and further analyses looking at the effect of seeding within each mechanical treatment individually revealed a significant impact of seeding within rollerchop (*p* = 0.0144) but not chain (*p* = 0.0637) or hydro-ax (*p* = 0.8364).

Of the functional groups listed in Table 2.2, only annual forbs were comprised of both native and exotic species (see Table 2.2 footnotes). Annual forb biomass in 2013 had varying proportions of native and exotic species depending on treatment type (Figure 2.3). There was a significant mechanical by seeding treatment interaction (*p* = 0.0409) for native annual forbs (seeded and unseeded species combined) and they were greater in seeded versus unseeded subplots for hydro-ax (*p* = <0.0001) but there was not effect of seeding within chain or rollerchop. Exotic annual forbs were greater in rollerchop than in hydro-ax or chain (*p* = 0.0114 for the effect of mechanical treatment averaging over seeded and unseeded subplot; exotics were not significantly impacted by seeding treatments). Contributions of seeded species to native annual forb biomass are shown (Figure 2.3) but due to zero inflation they could not be analyzed using ANOVA.

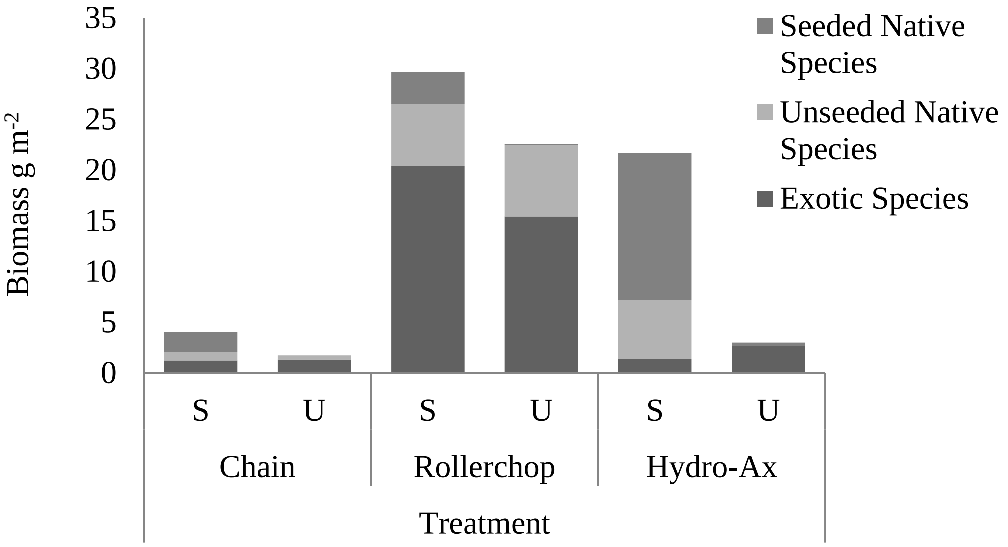

Figure 2.3. Mean annual forb biomass organized by mechanical treatment and seeding treatment (S – seeded subplot, U – unseeded subplot). Mechanical treatments (anchor chain, rollerchopper, and hydro-ax) were used to remove pinyon-juniper overstory at two sites in northwest Colorado and half of each plot was seeded. n = 7

Shrub density was measured in 2013 to assess establishment of seeded shrub species (Figure 2.4) and results showed increased establishment in seeded subplots (1.02±0.14 plants m^{-2}) relative to unseeded subplots (0.79±0.19 plants m^{-2}) when averaged over mechanical treatment (p = 0.0429). The impact of herbivory on this variable was also measured through the use of grazing exclosures within seeded subplots (Appendix A) and no significant difference was detected between the density of shrubs inside and outside the cages.

Mean biomass of seeded subplots and unseeded subplots, averaged over mechanical treatment, is shown in Table 2.4 and forb biomass, driven largely by annuals, was significantly greater in seeded subplots in 2013. The occurrence of all seeded species in seeded subplots in

2013 is shown in Table 2.5 (individual species were not consistently present in enough subplots to analyze with ANOVA).

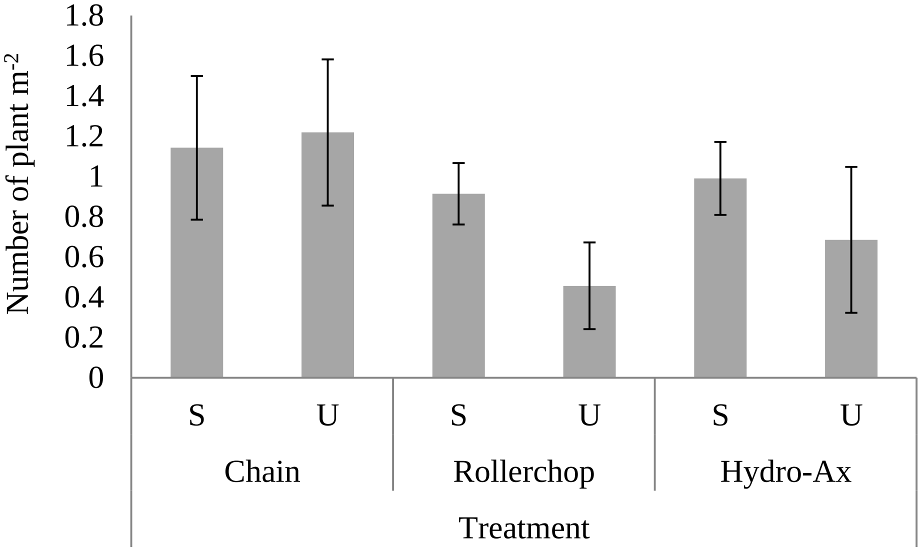

Figure 2.4. Mean seeded shrub density (n=7) organized by mechanical treatment and seeding treatment (S – seeded subplot, U – unseeded subplot). Mechanical treatments (anchor chain, rollerchopper, and hydro-ax) were used to remove pinyon-juniper overstory at two sites in northwest Colorado and half of each plot was seeded. *Symphoricarpos rotundifolius* A. Gray was the only unseeded shrub species encountered; including this species, total shrub density for each treatment was as follows (plants m^{-2} ± SE): Chain/seeded = 2.67 (0.72), Chain/unseeded = 3.28 (1.36), Rollerchop/seeded = 2.36 (0.75), Rollerchop/unseeded = 1.45 (0.8), Hydro-Ax/seeded = 2.51 (0.8), Hydro-Ax/unseeded = 1.75 (0.73).

Table 2.4. Mean biomass (g m^{-2}) of all seeded subplots combined and unseeded subplots combined (averaged over mechanical treatment). Mechanical treatments (anchor chain, rollerchopper, and hydro-ax) were used to remove pinyon-juniper overstory at two sites in northwest Colorado and half of each plot was seeded. Means with different letters in the same row are different at $\alpha = 0.05$ (n = 21).

	Seeded Subplots	**Unseeded Subplots**	***p-values***
2012	**Biomass (SE)**		
Forb	1.13 (0.18)	1.33 (0.23)	0.4047
Annual	0.20 (0.07)	0.14 (0.10)	*
Perennial	0.93 (0.18)	1.18 (0.22)	0.1285
Graminoid	2.31 (0.81)	2.25 (0.47)	0.2677
Annual	0.01 (<0.01)	0.01 (0.01)	*
Perennial	2.30 (0.81)	2.24 (0.45	0.2962
Shrub	6.28 (1.53)	5.74 (1.13)	0.9006
Total Native	10.21 (1.62)	9.83 (1.35)	0.6883
Total Exotic	0.01(<0.01)	0.10 (0.09)	*
2013			
Forb	25.31 (5.05)a	13.45 (4.97)b	0.0005
Annual	18.46 (5.38)a	9.15 (4.95)b	0.0002
Perennial	6.85 (1.33)	4.33 (1.00)	0.2162
Graminoid	12.46 (2.68)	16.58 (3.38)	0.1470
Annual	1.19 (0.40)	1.51 (0.79)	*
Perennial	11.27 (2.78)	15.07 (3.49)	0.1284
Shrub	34.53 (8.21)	46.69 (14.47)	0.5505
Total Native	63.73 (8.06)	70.13 (13.94)	0.5676
Total Exotic	8.88 (4.00)	7.98 (4.62)	0.0969

*Data were not normally distributed due to zero inflation.

Table 2.5. Seed mix species and the number of seeded subplots in which they occurred during 2013 biomass sampling. Seed mix was applied to half of each plot across 2 sites in northwest Colorado where pinyon-juniper canopy was removed using one of three mechanical treatments: anchor chain, rollerchopper, or hydro-ax.

	Seeded Subplot Occurrence			
Genus species	**Chain** n = 7	**Rollerchop** n = 7	**Hydro-Ax** n = 7	**Total** n = 21
Forb				
Amaranthus retroflexus	0	0	0	0
Artemisia frigida	0	0	0	0
Artemisia ludoviciana	2	2	0	4
Balsamorhiza sagittata	1	0	1	2
Cleome serrulata	4	4	7	15
Crepis acuminata	0	0	4	4
Eriogonum umbellatum	1	0	0	1
Hedysarum boreale	2	3	4	9
Helianthus annuus	4	1	5	10
Linum lewisii	4	1	5	10
Lupinus argenteus	5	0	1	6
Oenothera caespitosa	0	0	1	1
Oenothera pallida	0	0	0	0
Penstemon strictus	3	2	2	7
Graminoid				
Achnatherum hymenoides	2	3	3	8
Elymus elymoides	5	6	7	18
Elymus trachycaulus	1	1	3	5
Hesperostipa comata	3	3	2	8
Koeleria macrantha	3	3	6	12
Pascopyrum smithii	6	4	4	14
Poa fendleriana	3	2	4	9
Poa secunda	3	3	2	8
Triticum aestivum x *Secale cereale*[1]	0	0	0	0

[1] Trace amounts of this sterile annual found in 5 different seeded subplots in 2012 (between biomass and cover data)

Table 2.5 Continued

	Seeded Subplot Occurrence			
Genus species	**Chain** n = 7	**Rollerchop** n = 7	**Hydro-Ax** n = 7	**Total** n = 21
Shrub				
**Amelanchier spp.*	3	6	5	14
Artemisia tridentata	4	2	2	8
Cercocarpus montanus	2	1	0	3
Ericameria nauseosa	1	0	1	2
Chrysothamnus viscidiflorus	2	0	0	2
Krascheninnikovia lanata	0	0	1	1
Prunus virginiana	0	0	0	0
Purshia tridentata	2	4	1	7
Rhus trilobata	0	1	0	0

* Combines *A. alnifolia* and *A. utahensis* which were indistinguishable

Discussion

In this study, all three types of mechanical pinyon-juniper removal had an effect on understory vegetation relative to untreated areas. Cover data from 2012 indicated that all mechanical treatments significantly reduced shrub cover initially but not shrub biomass, relative to control. Shrub biomass was assessed as current annual growth. This suggests that while each mechanical treatment may reduce the size of shrubs initially, the biomass of palatable, current-year growth may not be significantly reduced, which is interesting in the context of big game habitat management where maintaining forage productivity is important. By 2013, shrub cover was not statistically different from controls.

Perennial graminoid and forb cover was initially reduced by rollerchop and hydro-ax relative to control in 2012 (and statistically significant for graminoids only), however, as with shrubs, productivity was not significantly different. Biomass and cover of graminoids and forbs was greater in some treatments relative to control in 2013, which follows the expectation of community development after pinyon-juniper removal where forbs and grasses establish initially and perennials and woody species dominate in subsequent years (Barney and Frischknecht 1974, Tausch and Tueller 1977, Skousen et al. 1989, Redmond et al. 2013); based on this theory and the marked increased in shrub productivity between 2012 and 2013, I anticipate all mechanically treated plots to have significantly greater shrub productivity relative to controls in future growing seasons.

Another important difference to note between treated and untreated plots in 2013 was the significantly higher biomass of exotic forbs in all treatments relative to control. The percentage of understory biomass that was exotic was relatively low for chain (3%) and hydro-ax (4%), but nearly one quarter of the biomass in rollerchop was exotic. In control, non-natives were less than 1%. These results are confirmed by other studies that report increased non-native establishment compared to pre-treatment or untreated areas (Ott et al. 2003, Owen et al. 2009, Ross et al. 2012). The large proportion of exotic biomass in rollerchop, which occurred in the seeded subplots as well (Figure 2.3), suggests that this treatment may promote exotic species to a greater extent than hydro-ax or chain. This result could be driven by soil disturbance, a known driver of exotic invasion (D'Antonio and Meyerson 2002), which was likely greatest in rollerchop as evidenced by the high percent cover of bare ground in this treatment (Table 2.3).

In the second analysis, among mechanically treated subplots only, mechanical and seeding treatment interactions were apparent for biomass of native annual forbs. Early seral species like annual forbs are adapted to the variety of physical conditions found in post-disturbance environments (Pickett 1976) and thus it is not surprising that treatment interactions were detected among those species. The effect of seeding on native annual forbs was significant within the chain and hydro-ax treatments. For hydro-ax it was especially pronounced and one potential explanation for this response may be related to the size and distribution of woody debris created by this treatment. The chipped and shredded wood in hydro-ax plots was smaller than the larger branches and boles left after chaining or rollerchopping. In addition, the percent cover of wood on the ground was much greater in hydro-ax relative to chain and rollerchop. It is well known that mulch can enhance germination and growing conditions, especially in arid lands, by reducing erosion, retaining moisture, and reducing soil surface temperatures (Vallentine 1989, Bainbridge 2007). The mulching effect of the hydro-ax may be of greater benefit to native annuals than that of chain or rollerchop.

The effect of seeding, when averaged over mechanical treatment (n = 21), was significant for seeded shrub density and although the seeding effect *within* individual treatments was not significant (n=7), this result is still meaningful for understanding the interaction of seeding and mechanical pinyon-juniper removal. This result was depended on site (Appendix C), a result which may be important for managers. Shrub seed can vastly increase the cost of seed mixes and knowing that seeded species can indeed establish in pinyon-juniper ecosystems may improve managers' ability to efficiently spend money on seed.

Plant community responses in this experiment are characteristic of early successional systems. Early seral forbs were a major component of the seed mix and thus their response during the second year was expected. It was also in the second year that increased establishment of seeded shrubs began to emerge within seeded subplots, which indicates that a transition to perennial establishment may be occurring. Of course more time is needed to see if this trend persists amid herbivory and fluctuating environmental conditions, but data after two growing seasons suggest that differing treatment effects on shrubs and other perennials may arise through time.

A final discussion point of this study's results that is worth noting concerns community responses within each site individually. This blocked experiment (n = 7) was designed to test the effect of mechanical and seeding treatments; however, the 7 blocks were split between two sites, North Magnolia and South Magnolia, in order to compliment a separate mule deer habitat use study occurring in the area. When site was included as a fixed effect in the overall mixed model, several plant functional groups had a significant effect of site, meaning that average productivity differed between the sites. Shrub biomass, for instance, was much greater at North Magnolia. At South Magnolia, the effect of seeding on seeded shrub density was apparent in all mechanical treatments and was not evident within North Magnolia. The differences in community responses between the sites and within the sites are discussed in greater detail in Appendix C.

The impact of the mechanical removal of pinyon-juniper canopy on mule deer forage conditions appears to be positive. Removing trees, even without seeding, can increase understory productivity compared to no treatment at all. However, forage quality is important for maintaining nutritional requirements of mule deer under all winter conditions (Bartmann 1983), and in order to achieve a diverse community of forbs, grasses, and shrubs, artificial seeding may be necessary. This method has proven effective based on results from this study.

Management Implications

This study confirms that mechanical removal of pinyon-juniper canopy by chaining, rollerchopping, or hydro-axing in northwest Colorado can result in increased understory vegetation relative to untreated areas two years after treatment. This can occur with or without the addition of seed, although seeding in conjunction with mechanical treatments may be necessary in certain circumstances where understory productivity is low or desired species are lacking. Shrub abundance, for instance, can increase in response to seeding by the second year.

Findings also reveal each mechanical treatment to have a unique impact on early seral species driven in part by the degree of surface disturbance and arrangement of woody debris left on the landscape, which are different for each method. This provides a basis for on-going monitoring of these treatments, because differential responses of perennial grasses and shrubs will not be noticed during the first few years. Lastly, exotic species may be promoted to a greater extent by rollerchopping. Alternative methods should be considered where exotics are already present and where understory communities lack native competitors.

LITERATURE CITED

Aro, R. S. 1975. Pinyon-Juniper Woodland Manipulation with Mechanical Methods. Pages 67-75 *in* The pinyon-juniper ecosystem: A symposium. Utah State University, Logan, UT.

Bainbridge, D. A. 2007. A guide for desert and dryland restoration: new hope for arid lands. Island Press, Washington DC, USA.

Baker, W. L. and D. J. Shinneman. 2004. Fire and restoration of pinon–juniper woodlands in the western United States: a review. Forest Ecology and Management 189:1-21.

Barney, M. A. and N. C. Frischknecht. 1974. Vegetation changes following fire in the pinyon-juniper type of west-central Utah. Journal of Range Management 27:91-96.

Bartmann, R. M. 1983. Composition and Quality of Mule Deer Diets on Pinyon-Juniper Winter Range, Colorado. Journal of Range Management 36:534-541.

Bates, J. D., R. F. Miller, and T. Svejcar. 2005. Long-term successional trends following western juniper cutting. Rangeland Ecology & Management 58:533-541.

Bender, L. C., L. A. Lomas, and T. Kamienski. 2007. Habitat effects on condition of doe mule deer in arid mixed woodland-grassland. Rangeland Ecology & Management 60:277-284.

Bishop, C. J., G. C. White, D. J. Freddy, B. E. Watkins, and T. R. Stephenson. 2009. Effect of Enhanced Nutrition on Mule Deer Population Rate of Change. Wildlife Monographs 172:1-28.

Bowns, J. E. 1999. Ecology and Management of Pinyon-Juniper Communities within the Interior West: Overview of The" Resource Values Session" Of the Symposium. Pages 157-163 *in* Ecology and management of pinyon-juniper communities within the Interior West. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-P-9, Provo, UT.

Christensen, E. M. and H. B. Johnson. 1964. Presettlement vegetation and vegetational change in three valleys in central Utah. Brigham Young University Science Bulletin-Biological Series 4:1-16.

Clary, W. P. 1971. Effects of Utah Juniper Removal on Herbage Yields from Springerville Soils. Journal of Range Management 24:373-378.

D'Antonio, C. and L. A. Meyerson. 2002. Exotic Plant Species as Problems and Solutions in Ecological Restoration: A Synthesis. Restoration Ecology 10:703-713.

Huffman, D. W., M. T. Stoddard, J. D. Springer, J. E. Crouse, and W. W. Chancellor. 2013. Understory plant community responses to hazardous fuels reduction treatments in pinyon-juniper woodlands of Arizona, USA. Forest Ecology and Management 289:478-488.

Jameson, D. A. 1967. Relationship of tree overstory and herbaceous understory vegetation. Journal of Range Management 20:247-249.

Lendrum, P. E., C. R. Anderson Jr, K. L. Monteith, J. A. Jenks, and R. T. Bowyer. 2013. Migrating Mule Deer: Effects of Anthropogenically Altered Landscapes. PloS one 8:e64548.

Miller, R. F., R. J. Tausch, E. D. McArthur, D. D. Johnson, and S. C. Sanderson. 2008. Age structure and expansion of piñon-juniper woodlands: a regional perspective in the Intermountain West. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-69. 15p.

Naillon, D., K. Memmott, and S. B. Monsen. 1997. A Comparison of Understory Species at Three Densities in a Pinyon-Juniper Woodland. Pages 72-75 *in* Ecology and Management of Pinyon-Juniper Communities Within the Interior West. USDA Forest Service, Provo, Utah.

NRCS. 2012. Web Soil Survey, Rio Blanco County, Colorado. http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx accessed June 19, 2013. Natural Resource Conservation Service.

Omeara, T. E., J. B. Haufler, L. H. Stelter, and J. G. Nagy. 1981. Non-game wildlife responses to chaining of pinyon-juniper woodlands. Journal of Wildlife Management 45:381-389.

Ott, J. E., E. D. McArthur, and B. A. Roundy. 2003. Vegetation of chained and non-chained seedings after wildfire in Utah. Journal of Range Management 56:81-91.

Owen, S. M., C. H. Sieg, C. A. Gehring, and M. A. Bowker. 2009. Above-and belowground responses to tree thinning depend on the treatment of tree debris. Forest Ecology and Management 259:71-80.

Parker, K. L., P. S. Barboza, and M. P. Gillingham. 2009. Nutrition integrates environmental responses of ungulates. Functional Ecology 23:57-69.

Pickett, S. T. A. 1976. Succession: An Evolutionary Interpretation. The American Naturalist 110:107-119.

Redmond, M. D., N. S. Cobb, M. E. Miller, and N. N. Barger. 2013. Long-term effects of chaining treatments on vegetation structure in piñon–juniper woodlands of the Colorado Plateau. Forest Ecology and Management 305:120-128.

Romme, W. H., C. D. Allen, J. D. Balley, W. L. Baker, B. T. Bestelmeyer, P. M. Brown, K. S. Eisenhart, M. L. Floyd, D. W. Huffman, B. F. Jacobs, R. F. Miller, E. H. Muldavin, T. W. Swetnam, R. J. Tausch, and P. J. Weisberg. 2009. Historical and Modern Disturbance Regimes, Stand Structures, and Landscape Dynamics in Pinon-Juniper Vegetation of the Western United States. Rangeland Ecology & Management 62:203-222.

Ross, M., S. Castle, and N. Barger. 2012. Effects of fuels reductions on plant communities and soils in a Piñon-juniper woodland. Journal of arid environments 79:84-92.

Sawyer, H., M. J. Kauffman, and R. M. Nielson. 2009. Influence of well pad activity on winter habitat selection patterns of mule deer. Journal of Wildlife Management 73:1052-1061.

Sawyer, H., R. M. Nielson, F. Lindzey, and L. L. McDonald. 2006. Winter habitat selection of mule deer before and during development of a natural gas field. Journal of Wildlife Management 70:396-403.

Schott, M. R. and R. D. Pieper. 1985. Influence of canopy characteristics of one-seed juniper on understory characteristics. Journal of Range Management 38:328-331.

Sheley, R. L. and J. D. Bates. 2008. Restoring western juniper-(Juniperus occidentalis) infested rangeland after prescribed fire. Weed Science 56:469-476.

Shinneman, D. J. and W. L. Baker. 2009. Historical fire and multidecadal drought as context for pinon-juniper woodland restoration in western Colorado. Ecological Applications 19:1231-1245.

Skousen, J. G., J. N. Davis, and J. D. Brotherson. 1989. Pinyon-juniper chaining and seeding for big game in central utah. Journal of Range Management 42:98-104.

Stephens, S. L., J. D. McIver, R. E. J. Boerner, C. J. Fettig, J. B. Fontaine, B. R. Hartsough, P. L. Kennedy, and D. W. Schwilk. 2012. The Effects of Forest Fuel-Reduction Treatments in the United States. BioScience 62:549-560.

Tausch, R. J. and P. T. Tueller. 1977. Plant Succession following Chaining of Pinyon-Juniper Woodlands in Eastern Nevada. Journal of Range Management 30:44-49.

Tausch, R. J., N. E. West, and A. A. Nabi. 1981. Tree Age and Dominance Patterns in Great Basin Pinyon-Juniper Woodlands. Journal of Range Management 34:259-264.

Tiedeman, J. A. and C. Terwilliger. 1978. Phyto-edaphic classification of the Piceance Basin, Range Science Department Series No. 31. Colorado State University, Fort Collins, CO, USA.

Tollefson, T. N., L. A. Shipley, W. L. Myers, and N. Dasgupta. 2011. Forage quality's influence on mule deer fawns. The Journal of Wildlife Management 75:919-928.

USDA. 2013. The PLANTS Database. http://plants.usda.gov/ accessed January 5, 2013. National Plant Data Team, Greensboro, NC, USA.

Vallentine, J. F. 1989. Range development and improvements. Academic Press, San Diego, CA, USA.

APPENDIX A

Effect of Grazing Cages on Shrub Establishment

Livestock and wildlife can have an effect on shrub establishment. Because experimental plots were not fenced to exclude livestock or wildlife and were subject to herbivory, grazing cages were used to measure the effect of grazing and browsing on shrub density. In May 2012, three pyramid-shaped woven-wire grazing cages (1 m^2 at the base and 1 m tall) were distributed along a center transect running parallel to the long axis of the plot (one cage near each end and the remaining cage in the middle). Due to the heterogeneity of ground cover (e.g., downed trees, slash, shrubs, rock, bare soil, etc), predetermined points were often unsuitable for cage placement; in those cases, the nearest suitable point was chosen. Cage locations contained space for the cage and an adjacent point of visually comparable cover to serve as a reference point. Cage location, between the two adjacent points, was randomly chosen by coin flip. A nail that was 3 m away from the nearest edge of the grazing cage marked the reference point, which represented the southwest corner of the 1-m^2 reference area.

Shrub density within grazing cages was collected in August 2013 by counting the number of individual shrubs rooted within the cage and identifying them to species. The same method was used to sample the grazing cage reference area; after locating the reference nail and laying down the 1-m^2 sampling frame, rooted shrubs were counted and identified to species. Shrub stems greater than 60 cm away (linear) from any other shrub stem of the same species was considered an individual shrub.

Analysis of these data, described in Table A.1, revealed no differences in mean seeded shrub density between the mechanical and cage treatments. These results indicated that seeded shrub establishment during the second year after mechanical removal of pinyon-juniper overstory was not affected by the presence of grazing cages. In addition, I did not notice any visual evidence of browsing on shrubs. Results also suggest that livestock and wildlife may not have an effect on shrub density two years after treatment at these sites.

Table A.1. Mean seeded shrub density (plants m^{-2} ± SE) at 2 sites in northwest Colorado where 3 mechanical treatments were used to remove pinyon-juniper overstory: anchor chain, rollerchopper, or hydro-ax. Each mechanically treated plot was divided into 2 subplots; one subplot was seeded with a native species mix and the other left unseeded. Grazing cages were placed in all seeded subplots to measure effects of ungulate herbivory on seeded shrub establishment. Analysis of variance was performed on total shrub density in a nested randomized complete block split-plot mixed effects model. Mean comparisons among mechanical/cage treatments (Table A.1a, Tukey adjustment, n = 7) showed no difference at α = 0.05. Species were not present where values are missing.

	Chain		**Rollerchop**		**Hydro-Ax**	
Species	**Cage**	**No Cage**	**Cage**	**No Cage**	**Cage**	**No Cage**
*Amelanchier spp**	0.14 (0.07)	0.24 (0.10)		0.05 (0.05)	0.24 (0.19)	0.43 (0.16)
Artemisia tridentata	0.05 (0.05)	0.10 (0.06)	0.05 (0.05)		0.05 (0.05)	
Cercocarpus montanus		0.05 (0.05)	0.10 (0.06)	0.05 (0.05)		
Chrysothamnus viscidiflorus	0.10 (0.06)	0.05 (0.05)	0.05 (0.05)	0.05 (0.05)	0.10 (0.1)	
Ericameria nauseosa		0.05 (0.05)				
Prunus virginiana			0.05 (0.05)			
Purshia tridentata	0.24 (0.1)	0.14 (0.1)	0.62 (0.27)	0.10 (0.06)	0.33 (0.18)	0.05 (0.05)
Rhus trilobata			0.05 (0.05)			
Total	0.52 (0.12)	0.62 (0.17)	0.90 (0.34)	0.24 (0.1)	0.71 (0.34)	0.48 (0.14)

*Lumping *A. utahensis* and *A. alnifolia* together

APPENDIX B

Soil Seed Bank Study

A soil seed bank study was performed to determine the presence of seeds one year after mechanical and seeding treatments were implemented. In May 2012, 3.7 L of soil were collected from each of the 49 subplots. Eight 400-mL soil cores were taken every 2.5 m along four equally spaced transects running parallel to the short axis of the plot; bulb planters were used to extract soil (bulb planters were inserted 10 cm deep to extract the full 400-mL sample). Soil samples for each subplot were pooled, mixed and sieved (5.6-mm wire mesh) to remove rocks and debris. Sieved soil was then layered 1 cm deep atop PRO-MIX® Biofungicide™ growth medium in 20-cm diameter growth pots. Field soil samples for each subplot were distributed between ten growth pots and soaked (with water) in a greenhouse 2-3 times per week (or when soil surfaces appeared dry). Germinated plants were identified to species, counted and removed from pots. Unidentifiable species were lumped into a separate category (which is called "Unidentified" at the bottom of Table B.1). The soil seed bank growth period continued until mid-February 2013.

Analysis of variance (on transformed data, $\alpha = 0.05$) was used in a nested randomized complete block split-plot mixed effects model test for the effect of mechanical treatment (among all unseeded subplots including control) and the interaction between seeding and mechanical treatment (among all mechanically treated subplots); response variables were mean count data per subplot using functional group totals found in Table B.1. See chapter 2 for a complete description of these analyses.

There was no significant difference between means for all functional groups for both analyses except for total perennial graminoids, which were greater in seeded subplots (2.57

plants ± 0.52) versus unseeded subplots (1 plant ± 0.36) when averaged over mechanical treatment ($p = 0.0054$). Results suggest several conclusions. First, seeding in conjunction with mechanical treatments appears to improve perennial graminoid establishment. Within each mechanical treatment, the statistical power to detect the seeding effect is lost, however, it is important to highlight the impact of seeding, which can be effective when done prior to mechanical tree removal. For all other functional groups, mechanical and seeding treatments may not have an impact on the number of individuals present in the soil seed bank, although, there are many reasons why seeds that were present may not have germinated. First, soil moisture and temperature cues are factors that affect seed germination (Vallentine 1989) and growth conditions in the greenhouse may not have been appropriate to promote germination of certain species. Secondly, soil sampling techniques may also have influenced germination outcomes. Volume of soil collected might have diluted the seed content, since most of the seeds in the seed bank reside in the top few centimeters (Guo et al. 1998). Finally, it is possible that abundance of unidentified species might have diluted treatment effects.

Table B.1. Mean occurrence (number of plants ± SE) of species germinated from soil seed bank from 2 sites in northwest Colorado where 3 mechanical treatments were used to remove pinyon-juniper overstory: anchor chain, rollerchopper, or hydro-ax. Treatments were applied in a randomized complete block design. Each mechanically treated plot was divided into a seeded and unseeded subplot. Each block contained an untreated and unseeded control plot. Unidentified species are totaled at the bottom of Table B.1. Species were not present where values are missing.

	Control	**Chain**		**Rollerchop**		**Hydro-Ax**	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Annual Forb							
Alyssum alyssoides[I]		0.29 (0.29)			0.29 (0.29)		
Alyssum desertorum[I]	0.86 (0.46)	1.57 (1.09)	1.00 (0.85)	0.86 (0.7)	0.86 (0.55)	0.57 (0.3)	0.14 (0.14)
Ceratocephala testiculata[I]		0.14 (0.14)			0.14 (0.14)		
Collinsia parviflora	6.57 (3.6)	8 (4.31)	6.71 (4.68)	7.43 (3.23)	7.43 (3.72)	3.29 (1.96)	1.14 (0.67)
Collomia grandiflora		0.43 (0.43)				0.14 (0.14)	
Descurainia pinnata	4.00 (3.18)	2.57 (1.45)	1.14 (0.4)	3.29 (1.87)	1.86 (0.74)	0.57 (0.57)	0.86 (0.59)
Draba reptans	1.29 (0.84)	0.86 (0.55)	1.71 (0.97)	1.29 (0.75)	0.57 (0.3)	1.57 (1.25)	1.71 (0.57)
Lactuca serriola[I]	0.29 (0.29)						
Lappula occidentalis		0.29 (0.18)			0.14 (0.14)		
Machaeranthera canescens					0.29 (0.18)	0.14 (0.14)	
Sonchus asper[I]					0.14 (0.14)		0.14 (0.14)
Streptanthella longirostris					0.29 (0.29)		
Total Annual Forb	13.00 (5.09)	14.14 (4.87)	10.57 (5.03)	12.86 (4.38)	12.00 (4.2)	6.29 (2.2)	4.00 (1.15)

[I] Introduced species

Table B.1. continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Perennial Forb							
Androsace septentrionalis				0.14 (0.14)			0.14 (0.14)
Artemisia ludoviciana^{S}				0.14 (0.14)		0.43 (0.30)	
Boechera retrofracta	0.14 (0.14)	0.43 (0.43)	0.14 (0.14)	0.14 (0.14)	0.29 (0.18)	0.57 (0.30)	0.14 (0.14)
Boechera Spp	0.43 (0.30)	0.43 (0.2)	1.00 (0.44)		0.29 (0.18)	0.43 (0.20)	0.43 (0.30)
Erysimum capitatum							0.14 (0.14)
Hedeoma drummondii	0.43 (0.43)		0.14 (0.14)		0.29 (0.18)	3.43 (3.43)	0.43 (0.30)
Juncus balticus	0.14 (0.14)			0.14 (0.14)	0.14 (0.14)		
Oenothera pallida^{S}		0.14 (0.14)		0.29 (0.29)			
Packera multilobata	0.14 (0.14)	1.43 (1.13)	0.71 (0.47)	1.00 (0.69)	0.43 (0.43)		0.14 (0.14)
Penstemon strictus				0.14 (0.14)		0.14 (0.14)	
Salsola tragus^{I}							0.14 (0.14)
Solidago missouriensis	0.14 (0.14)	0.14 (0.14)			0.14 (0.14)	0.14 (0.14)	0.57 (0.30)
Taraxacum officinale^{I}	0.14 (0.14)				0.14 (0.14)		
Tragopogon dubius^{I}				0.29 (0.29)			
Trifolium gymnocarpum				0.14 (0.14)			
Total Perennial Forb	1.57 (0.53)	2.57 (1.13)	2.00 (0.76)	2.43 (1.17)	1.71 (0.84)	5.14 (3.32)	2.14 (0.59)

^{S} Seeded species
^{I} Introduced species

Table B.1. continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	Unseeded Subplots	Seeded Subplots	Unseeded Subplots	Seeded Subplots	Unseeded Subplots
Annual Graminoid							
Bromus tectorum^{I}	0.14 (0.14)	1.43 (1.02)	1.14 (0.77)	0.71 (0.36)	1.43 (0.81)	0.43 (0.43)	
Perennial Graminoid							
Carex spp	0.14 (0.14)	1.29 (0.97)	0.29 (0.29)	0.57 (0.3)	0.86 (0.59)	0.43 (0.43)	0.14 (0.14)
Elymus elymoides^{S}		0.14 (0.14)			0.14 (0.14)	0.71 (0.57)	0.14 (0.14)
Elymus trachycaulus^{S}				0.29 (0.18)		0.43 (0.43)	
Festuca idahoensis	1.00 (0.65)	0.57 (0.37)	0.57 (0.3)	0.43 (0.20)	0.57 (0.3)	1.86 (0.59)	0.29 (0.18)
Hordeum jubatum						0.29 (0.29)	
Koeleria macrantha^{S}				0.71 (0.42)			
Total Perennial Graminoid	1.14 (0.63)	2.00 (0.93)	0.86 (0.55)	2.00 (0.65)	1.57 (0.84)	3.71 (1.06)	0.57 (0.3)
Shrub							
Artemisia tridentata^{S}	0.14 (0.14)	0.29 (0.29)					
Rhus trilobata^{S}							0.14 (0.14)
Total Shrub	0.14 (0.14)	0.29 (0.29)					0.14 (0.14)
Unidentified Total	6.71 (1.48)	4.00 (1.2)	8.57 (2.48)	6.71 (2.49)	7.14 (1.83)	5.57 (1.74)	6.86 (2.44)

^{S} Seeded species

^{I} Introduced species

LITERATURE CITED

Guo, Q., P. W. Rundel, and D. W. Goodall. 1998. Horizontal and vertical distribution of desert seed banks: patterns, causes, and implications. Journal of arid environments 38:465-478.

Vallentine, J. F. 1989. Range development and improvements. Academic Press, San Diego, CA, USA.

APPENDIX C

SITE DIFFERENCES BETWEEN NORTH MAGNOLIA AND SOUTH MAGNOLIA

Understory productivity was different between North Magnolia and South Magnolia both in mechanically treated plots and in control plots. Biomass of annual graminoids, perennial forbs, shrubs, and total understory combined was generally greater at North Magnolia relative to South Magnolia while perennial graminoids and annual forbs were greatest at South Magnolia (Table C.1). Percent cover showed similar patterns (Table C.2). Because plant communities were different between sites, an ANOVA was used within each site individually to first test for the effect of mechanical treatments in all unseeded subplots (including control plots) and second to test for the effect of seeding in conjunction with mechanical treatments (excluding control plots; for complete description of statistics see Methods in chapter 2).

In the first analysis comparing all unseeded subplots, biomass data revealed significant mechanical treatment effects among both annual forbs and perennial graminoids at North Magnolia and among perennial graminoids at South Magnolia (Table C.1). For native annual forbs at North Magnolia, biomass was much greater in rollerchop than in control ($p = 0.0296$) and hydro-ax ($p = 0.0166$) and these differences were driven by a large amount of *Chenopodium fremontii* in one unseeded rollerchop plot. Perennial graminoids at North Magnolia were 8 times higher in rollerchop ($p = 0.0025$) and hydro-ax ($p = 0.0019$) relative to control.

At South Magnolia, perennial graminoids were greater in rollerchop than control ($p = 0.0417$). Mean biomass of exotic annual forbs (Figure C.1) was particularly high in rollerchop at South Magnolia, but due to high variability (driven by one plot with a large amount of *Salsola tragus*), significant differences between mechanical treatments or control were not detected.

For percent cover, differences were observed between treated plots and control for annual forbs and annual graminoids (Table C.2). Exotic annual forbs were 4-6 times greater in chain ($p = 0.0313$) and rollerchop ($p = 0.0195$) than in control. Annual graminoids, which were comprised of only *Bromus tectorum*, were also greater in chain ($p = 0.0278$) and rollerchop ($p = 0.00052$) than in control, and rollerchop was also greater than hydro-ax ($p = 0.0342$).

At South Magnolia, native annual forb cover was greater in rollerchop than control ($p = 0.0459$) and the same relationship was true for exotic annual forbs as well ($p = 0.0034$). Exotic annual forbs were also greater in rollerchop relative to chain ($p = 0.0274$). Annual graminoids were rare at South Magnolia and no differences were detected between treatments.

Table C.1. Mean 2013 biomass (g m^{-2}) from 2 sites in northwest Colorado (North Magnolia, n = 4 and South Magnolia, n = 3) where pinyon-juniper overstory was removed using 3 mechanical treatments: anchor chain, rollerchopper, or hydro-ax. Column "*p-value* with Control" shows p-values for analysis comparing all unseeded subplots (means with no letters in common at different at $\alpha = 0.05$). Column "*p-value* without Control" shows p-values for analysis comparing all mechanically subplots (native annual forbs had the only significant mechanical by seeding treatment interaction, which is explained below and in figure C.1). 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. Annual graminoids were comprised of one exotic species, *Bromus tectorum*. Perennial graminoids and shrubs were all native.

	Control	**Chain**		**Rollerchop**		**Hydro**		***p-value* with Control**	***p-value* without Control**
	Unseeded Subplots	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**		
North Magnolia				**Biomass (SE)**					
Native Annual Forb	0.10 (0.06)A	1.00 (0.16)	0.41 (0.32)AB	1.48 (0.62)	11.38 (9.31)B	13.86 (11.49)	0.04 (0.04)A	0.0145	0.0169
Exotic Annual Forb	0.02 (0.01)A	0.57 (0.19)	2.33 (0.68)B	14.16 (7.30)	1.96 (1.27) AB	0.77 (0.54)	4.54 (4.35)AB	0.0270	0.1915
Perennial Forb	2.85 (1.05)	10.19 (2.88)	3.44 (2.04)	11.33 (4.45)	6.92 (2.14)	7.31 (2.48)	4.83 (3.74)	0.4202	0.6253
Annual Graminoid	0.11 (0.11)	1.27 (0.65)	1.02 (0.5)	1.35 (0.59)	5.00 (3.8)	2.91 (1.7)	0.89 (0.88)	*	*
Perennial Graminoid	0.43 (0.13)A	4.92 (0.76)	3.76 (1.56)AB	5.69 (1.59)	8.46 (2.81)B	3.96 (1.44)	8.19 (1.72)B	0.0013	0.1794
Shrub	21.27 (4)	61.92 (18.51)	91.22 (50.53)	30.14 (9.96)	52.28 (24.15)	66.38 (28.01)	91.34 (38.86)	0.4681	0.9234
South Magnolia									
Native Annual Forb	0.01 (0.01)	5.19 (4.83)	0.38 (0.24)	19.58 (4.51)	1.56 (1.11)	28.83 (12.1)	0.81 (0.77)	0.4332	0.3203
Exotic Annual Forb	0 (0)	2.15 (1.75)	0 (0)	28.75 (25.28)	33.39 (31.49)	2.23 (1.8)	0.13 (0.1)	0.0749	0.5776
Perennial Forb	0.58 (0.27)	3.28 (1.39)	2.42 (1.12)	0.77 (0.67)	2.38 (1.58)	5.45 (2.36)	5.28 (3.48)	0.4967	0.6447
Annual Graminoid	0	0	0	0.98 (0.59)	1.32 (1.32)	0	0.01 (0.01)	*	*
Perennial Graminoid	2.51 (1.23)A	15.27 (10.16)	26.5 (17.29)AB	18.68 (8.3)	27.37 (8.58)B	25.52 (11.84)	24.43 (11.17)AB	0.0359	0.7231
Shrub	8.42 (7.65)	11.37 (9.42)	5.43 (1.99)	11.56 (9.74)	0.89 (0.89)	7.56 (0.55)	7.41 (4.15)	0.5691	0.6227

*Data were not normally distributed due to zero inflation.

Table C.2. Percent cover (in 2013) from 2 sites in northwest Colorado (North Magnolia, n = 4 and South Magnolia, n = 3) where pinyon-juniper overstory was removed using 3 mechanical treatments: anchor chain, rollerchopper, or hydro-ax. Column "*p-value* with Control" shows p-values for analysis comparing all unseeded subplots (means with no letters in common at different at $\alpha = 0.05$). Column "*p-value* without Control" shows p-values for analysis comparing all mechanically subplots. 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. Annual graminoids were comprised of one exotic species, *Bromus tectorum*. Perennial graminoids and shrubs were all native.

	Control	**Chain**		**Rollerchop**		**Hydro**		***p-value* with Control**	***p-value* without Control**
	Unseeded Subplots	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**		
North Magnolia	**Percent Cover (SE)**								
Native Annual Forb	0	1.38 (0.57)	0.63 (0.47)	2.84 (0.87)	1.03 (0.35)	1.8 (1.08)	0.63 (0.25)	0.0583	0.8881
Exotic Annual Forb	0.36 (0.23)A	3.91 (0.41)	4.78 (0.36)B	5.89 (2.76)	6.76 (3.78)B	2.15 (0.79)	3.35 (1.31)AB	0.0174	0.9858
Perennial Forb	0.97 (0.21)	2.93 (0.62)	2.07 (0.75)	2.47 (1.17)	1.55 (0.31)	4.42 (0.73)	2.22 (0.25)	0.2002	0.6195
Annual Graminoid	0.24 (0.14)A	3.13 (1.85)	2.73 (0.79)BC	4.77 (3.03)	4.98 (2.76)B	2.63 (1.60)	1.07 (0.76)AC	0.0046	0.3996
Perennial Graminoid	1.45 (0.6)	4.94 (1.22)	4.06 (1.01)	5.70 (1.59)	5.58 (1.92)	5.85 (1.47)	4.8 (1.80)	0.1349	0.9279
Shrub	20.27 (1.94)	16.29 (3.77)	23.71 (4.35)	20.23 (3.51)	11.48 (2.94)	16.75 (2.41)	16.93 (3.17)	0.0909	0.0732
South Magnolia									
Native Annual Forb	0.17 (0.17)A	6.33 (0.89)	0.48 (0.27)AB	6.09 (1.98)	2.08 (0.83)B	4.49 (0.66)	1.18 (0.13)AB	0.0455	0.1519
Exotic Annual Forb	0 A	2.19 (1.1)	0.97 (0.26)A	3.16 (0.83)	7.46 (1.28)B	1.57 (0.95)	2.85 (2.09)AB	0.0047	0.2481
Perennial Forb	0.33 (0.16)	1.57 (0.83)	0.47 (0.28)	1.23 (0.98)	0.86 (0.2)	3.10 (1.38)	2.55 (2.06)	0.3919	0.8050
Annual Graminoid	0	0.15 (0.15)	0.16 (0.16)	0.17 (0.17)	0.33 (0.33)	0.17 (0.17)	1.12 (0.25)	*	*
Perennial Graminoid	5.57 (2.54)	12.7 (3.23)	11.10 (2.91)	10.62 (2.09)	14.79 (1.85)	14.67 (4.55)	17.57 (2.08)	0.0665	0.5247
Shrub	5.15 (1.79)	1.92 (0.28)	4.21 (1.14)	5.38 (0.78)	2.25 (1.04)	3.93 (2.11)	4.57 (1.89)	0.5342	0.1571

*Data were not normally distributed due to zero inflation.

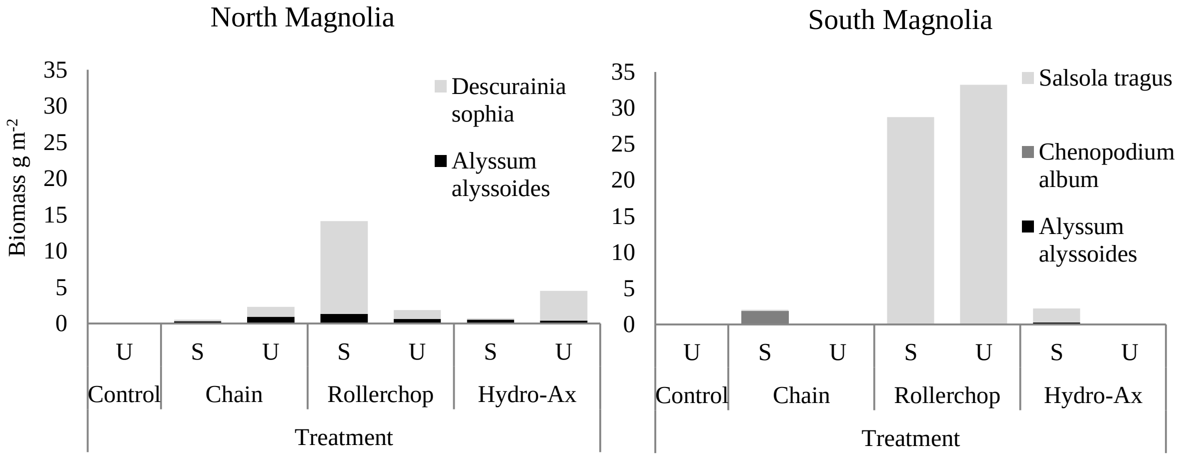

Figure C.1. Biomass of exotic annual forbs from 2 sites in northwest Colorado (North Magnolia, n = 4 and South Magnolia, n = 3) where pinyon-juniper overstory was removed using 3 mechanical treatments: anchor chain, rollerchopper, or hydro-ax. Half of each mechanically treated plot was seeded (S) and control plots were not seeded (U). Other species were present but only in trace amounts that were not visible in these figures.

In the second analysis, which explored effects of the seeding treatment and interactions between mechanical and seeding treatments, significant effects were only observed for native annual forb biomass. At North Magnolia, there was a significant interaction between mechanical and seeding treatments ($p = 0.0169$). Seeded subplots had greater native annual forb biomass than unseeded subplots in hydro-ax ($p = 0.0024$) but not rollerchop ($p = 0.3242$) or chain ($p = 0.2146$). At South Magnolia, there was no interaction between seeding treatment and mechanical treatment, but an overall effect of seeding was significant for native annual forbs (seeded subplots = 17.87 ± 5.26 g m^{-2} and unseeded subplots = 0.92 ± 0.43 g m^{-2}, $p = 0.0018$). Figure C.2 shows the proportion of seeded and unseeded native annual forbs in each treatment at both sites. Seeded native annual forbs were a substantial proportion of native annual forbs in seeded subplots for hydro-ax at North Magnolia and in all mechanical treatments at South Magnolia (although due to zero inflation seeded species alone could not be analyzed with ANOVA).

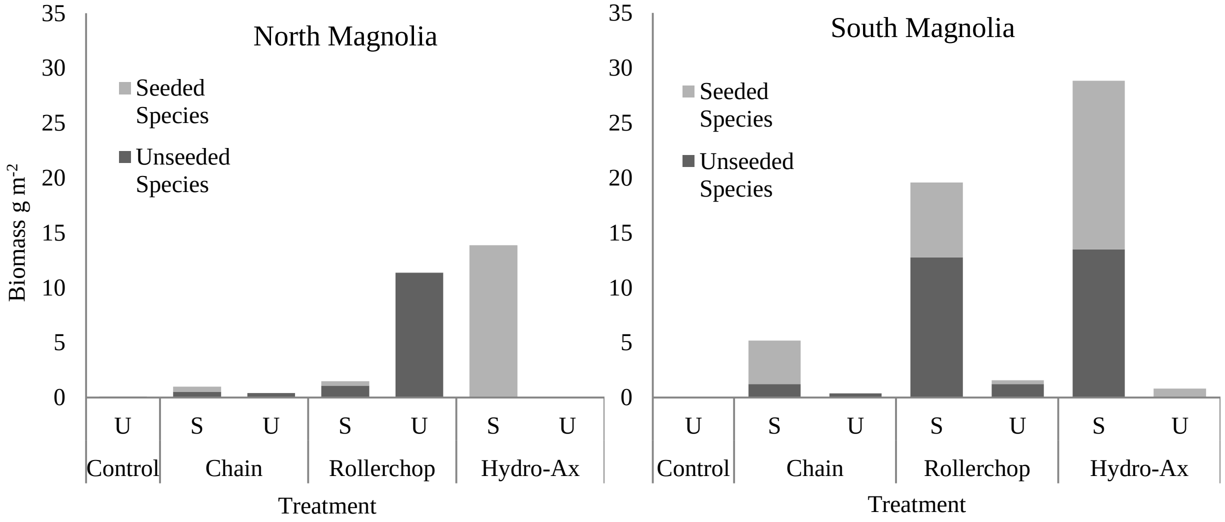

Figure C.2. Biomass of native annual forbs from 2 sites in northwest Colorado (North Magnolia, n = 4 and South Magnolia, n = 3) where pinyon-juniper overstory was removed using 3 mechanical treatments: anchor chain, rollerchopper, or hydro-ax. Half of each mechanically treated plot was seeded (S) and control plots were not seeded (U). Bars show proportion of native annual forbs that were seeded and those that were unseeded.

Density of seeded shrubs also responded differently within each site. At North Magnolia means were not different between mechanical and seeding treatments, but at South Magnolia, an overall effect of seeding was significant (*p* = 0.0031, shrub density was 3 times greater in seeded subplots) indicating that seeding shrubs can increase shrub establishment at this site (Figure C.3). There was no interaction between seeding and mechanical treatments at either site.

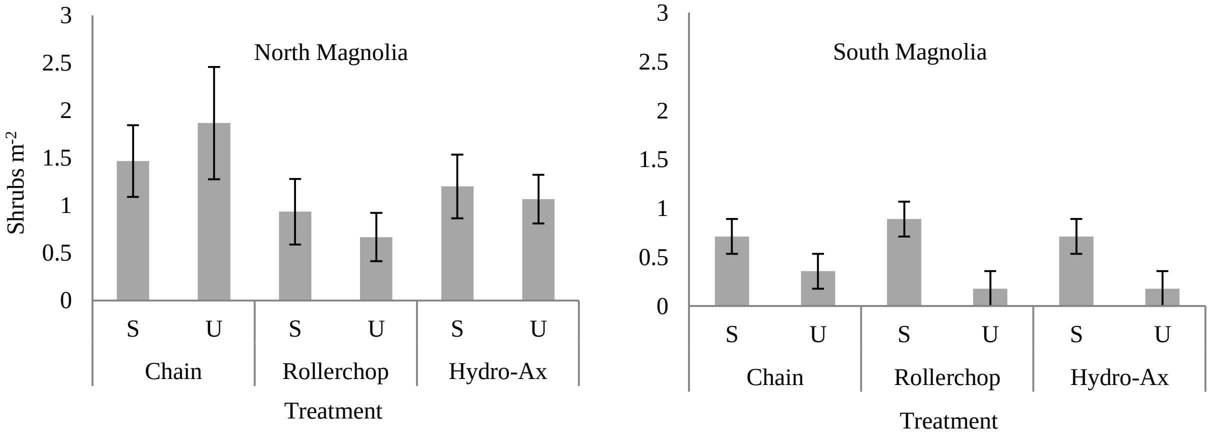

Figure C.3. Mean seeded shrub density from 2 sites in northwest Colorado (North Magnolia, n = 4 and South Magnolia, n = 3) where pinyon-juniper overstory was removed using 3 mechanicaltreatments: anchor chain, rollerchopper, or hydro-ax. Half of each mechanically treated plot was seeded (seeded subplot – S, unseeded subplot – U).

To further understand site differences, and because pinyon-juniper stand structure impacts understory characteristics, tree basal area and density in control plots was measured during spring of 2013. Belt transects were used to record density counts and basal diameter measurements of live trees ≥ 2m tall along five evenly spaced transects within each control plot. Single juniper trees were often multi-stemmed or elliptical in shape at the base; multi-stemmed trees at the ground level were measured separately for diameter and added together to determine basal area for that single tree. Junipers that were elliptical at the base were measured for diameter along the widest axis and the narrowest axis and the average of those to numbers was used for diameter. Originally designated control plots in block E and G could not be used for these measurements due to logistical issues; visually similar areas adjacent to the original controls served as the alternative. Results of the stand analysis (Table C.3) confirm site differences in stand structure. Basal area was greater at South Magnolia but there were fewer trees. At North Magnolia, there were more trees, but they were smaller.

Table C.3. Mean tree basal area ($m^2 ha^{-1}$) and density (trees ha^{-1}) of control plots at North Magnolia and South Magnolia, which are 2 sites in northwest Colorado where pinyon-juniper overstory was removed using 3 mechanical treatments: anchor chain, rollerchopper, or hydro-ax. Tree data is from control plots that received no mechanical tree removal.

	North Magnolia	**South Magnolia**
Basal Area		
Juniperus osteosperma	6.20 (2.66)	24.85 (2.54)
Pinus edulis	10.53 (1.21)	16.7 (2.79)
Total	16.73 (2.30)	41.54 (3.95)
Density		
Juniperus osteosperma	181.11 (71.66)	296.52 (48.07)
Pinus edulis	970.56 (89.92)	370.84 (114.63)
Total	1151.67 (158.32)	667.36 (159.81)

Results of the analyses within each site individually clearly indicate that understory responses were different between North Magnolia and South Magnolia. Seeding in particular was effective for native annual forbs and shrubs at South Magnolia, but not at North Magnolia (although seeding increased native annual forbs in hydro-ax). It is likely that pre-treatment vegetation, both in the understory and overstory, contributed to these effects. Control plots, which served as a proxy for pre-treatment conditions, had a high density of small trees with greater understory biomass at North Magnolia (6.03 g m^{-2} ± 0.63 of tree biomass in the understory) while controls in South Magnolia had fewer and larger trees with higher crowns (1.67 g m^{-2} ± 1.67 of tree biomass in the understory). North Magnolia controls also had more shrubs and perennial forbs in the understory while South Magnolia had more perennial graminoids. It is possible that similar understory responses could be seen at other sites with comparable characteristics to North or South Magnolia, but further testing is needed that can replicate similar site conditions.

APPENDIX D

BIOMASS SPECIES LISTS

Table D.1. Mean understory biomass (g m^{-2} ± SE) of each species collected in 2012. Pinyon-juniper overstory was removed at 2 sites in northwest Colorado using 3 mechanical treatments: anchor chain, rollerchopper, or hydro-ax. Treatments were applied in a randomized complete block design with 3 blocks at the south site and 4 blocks at the north site. Each mechanically treated plot was divided into 2 subplots; one subplot was seeded with a native species mix and the other left unseeded. Each block contained an untreated and unseeded control plot. Unidentified species are totaled at the bottom. Species were not present where values are absent.

	Control	**Chain**		**Rollerchop**		**Hydro-Ax**	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Annual Forb							
Alyssum spp[I]			<0.01 (<0.01)		<0.01 (<0.01)	0.01 (0.01)	<0.01 (<0.01)
Chenopodium fremontii							0.13 (0.13)
Cleome serrulata[S]		0.05 (0.05)	<0.01 (<0.01)	0.08 (0.07)		0.09 (0.09)	
Helianthus annuus[S]		0.02 (0.01)	<0.01 (<0.01)	0.14 (0.07)		0.12 (0.1)	
Machaeranthera canescens		0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	<0.01 (<0.01)	0.06 (0.06)	<0.01 (<0.01)
Melilotus officinalis[I]					<0.01 (<0.01)		
Salsola tragus[I]					0.26 (0.26)		<0.01 (<0.01)
Total Seeded		0.07 (0.04)	<0.01 (<0.01)	0.22 (0.1)		0.22 (0.19)	
Total Introduced			<0.01 (<0.01)	0.27 (0.26)	0.01 (0.01)	<0.01 (<0.01)	
Total Annual Forb		0.07 (0.04)	0.02 (0.01)	0.23 (0.1)	0.27 (0.26)	0.28 (0.19)	0.13 (0.13)

[S] Seeded species

[I] Introduced species

Table D.1 Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Perennial Forb							
Achillea millefolium			0.01 (0.01)				
Antennaria parvifolia	0.02 (0.01)	0.04 (0.03)	0.13 (0.05)	<0.01 (<0.01)		<0.01 (<0.01)	0.08 (0.08)
Arenaria eastwoodiae					0.06 (0.06)		
Artemisia ludoviciana^S		0.02 (0.02)	0.06 (0.05)			0.13 (0.13)	<0.01 (<0.01)
Astragalus convallarius		0.01 (<0.01)	<0.01 (<0.01)		<0.01 (<0.01)	0.01 (0.01)	
Astragalus purshii	0.01 (<0.01)	0.08 (0.07)	0.03 (0.03)	0.03 (0.02)	0.01 (0.01)		0.01 (0.01)
Astragalus spp			0.01 (0.01)			0.01 (0.01)	0.21 (0.21)
Calylophus lavandulifolius		0.02 (0.02)	0.02 (0.02)	0.04 (0.04)			
Comandra umbellata	0.14 (0.09)	0.08 (0.06)	0.04 (0.04)	0.04 (0.03)		0.23 (0.17)	0.11 (0.11)
Crepis acuminata^S		0.04 (0.04)				0.02 (0.02)	0.01 (0.01)
Cryptantha flavoculata	<0.01 (<0.01)				0.05 (0.05)		0.14 (0.14)
Cryptantha sericea				0.05 (0.05)			0.01 (0.01)
Erigeron eatonii							0.01 (0.01)
Erigeron pumilus						0.01 (0.01)	
Eriogonum umbellatum^S		<0.01 (<0.01)	0.19 (0.19)	0.06 (0.06)			
Erysimum spp	<0.01 (<0.01)	0.02 (0.01)	0.03 (0.02)	<0.01 (<0.01)	0.03 (0.02)	<0.01 (<0.01)	<0.01 (<0.01)
Euphorbia esula		0.01 (0.01)					
Galium trifidum						<0.01 (<0.01)	
Gutierrezia sarothrae	0.02 (0.02)			<0.01 (<0.01)	0.05 (0.05)		<0.01 (<0.01)
Hedysarum boreale^S					<0.01 (<0.01)	0.12 (0.12)	
Hymenopappus filifolius		<0.01 (<0.01)	<0.01 (<0.01)				
Ipomopsis aggregata			0.01 (0.01)	0.01 (<0.01)	0.02 (0.02)		
Lesquerella spp					0.01 (0.01)		

^{S} Seeded species
^{I} Introduced species

Table D.1 Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Perennial Forb Continued							
Linum lewisii^S		<0.01 (<0.01)		<0.01 (<0.01)		<0.01 (<0.01)	
Lithospermum incisum			0.03 (0.03)				
Lithospermum ruderale						0.04 (0.04)	
Lupinus argenteus^S		0.19 (0.15)	0.01 (0.01)		0.08 (0.08)	0.01 (0.01)	0.19 (0.17)
Machaeranthera grindelioides			0.03 (0.02)		0.01 (0.01)	<0.01 (<0.01)	0.07 (0.06)
Mahonia repens					0.01 (0.01)		
Oenothera pallida^S				0.01 (0.01)	<0.01 (<0.01)		
Opuntia polyacantha		0.13 (0.13)	0.16 (0.13)		0.19 (0.19)	0.06 (0.06)	
Packera multilobata	0.56 (0.56)	<0.01 (<0.01)	<0.01 (<0.01)		<0.01 (<0.01)	<0.01 (<0.01)	0.03 (0.02)
Penstemon secundiflorus	<0.01 (<0.01)	0.08 (0.06)	0.07 (0.06)			0.09 (0.09)	0.14 (0.09)

^{S} Seeded species
^{I} Introduced species

Table D.1 Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Perennial forb continued							
Penstemon spp			0.02 (0.02)				
Penstemon strictus[S]		<0.01 (<0.01)				<0.01 (<0.01)	
Phlox hoodii	0.17 (0.08)	0.07 (0.06)	0.43 (0.19)	0.14 (0.07)		0.05 (0.03)	0.01 (0.01)
Phlox longifolia	0.08 (0.07)	0.01 (0.01)	0.02 (0.01)	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (0.01)	0.01 (<0.01)
Physaria acutifolia		0.01 (0.01)	<0.01 (<0.01)	0.01 (0.01)	<0.01 (<0.01)		
Schoenocrambe linifolia			0.01 (0.01)		0.02 (0.02)		0.03 (0.03)
Sphaeralcea coccinea	<0.01 (<0.01)	0.1 (0.08)	0.04 (0.04)		0.1 (0.1)	0.02 (0.02)	0.01 (<0.01)
Stenotus acaulis	0.18 (0.14)	0.06 (0.06)		0.13 (0.13)	0.42 (0.42)	0.15 (0.15)	0.01 (0.01)
Taraxacum officinale[I]						<0.01 (<0.01)	
Tetraneuris ivesiana	0.02 (0.02)	0.03 (0.03)	<0.01 (<0.01)	0.09 (0.07)		0.02 (0.01)	0.01 (0.01)
Trifolium gymnocarpon		<0.01 (<0.01)				0.01 (<0.01)	0.01 (0.01)
Wyethia amplexicaulis		0.16 (0.16)	0.04 (0.04)				<0.01 (<0.01)
Total Seeded		0.26 (0.15)	0.26 (0.2)	0.07 (0.06)	0.08 (0.08)	0.28 (0.25)	0.2 (0.17)
Total Introduced		0.01 (0.01)				<0.01 (<0.01)	
Total Perennial Forb	1.2 (0.51)	1.17 (0.31)	1.39 (0.37)	0.63 (0.12)	1.06 (0.47)	1 (0.44)	1.1 (0.35)

[S] Seeded species

[I] Introduced species

Table D.1 Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**
Annual Graminoid							
Bromus tectorum^{I}	<0.01 (<0.01)	<0.01 (<0.01)	0.01 (0.01)	<0.01 (<0.01)	0.02 (0.02)	<0.01 (<0.01)	0.01 (0.01)
Triticum aestivum		0.01 (0.01)				<0.01 (<0.01)	
Total Annual Graminoid	<0.01 (<0.01)	0.02 (0.01)	0.01 (0.01)	<0.01 (<0.01)	0.02 (0.02)	<0.01 (<0.01)	0.01 (0.01)
Perennial Graminoid							
Achnatherum hymenoides^{S}	0.74 (0.53)	0.58 (0.4)	0.38 (0.2)	0.05 (0.04)	0.05 (0.05)	0.03 (0.02)	0.44 (0.33)
Carex spp	0.33 (0.17)	1.23 (0.71)	1.11 (0.62)	0.29 (0.1)	0.59 (0.28)	0.57 (0.52)	0.72 (0.25)
Elymus elymoides^{S}	0.15 (0.08)	0.1 (0.07)		0.03 (0.02)	0.03 (0.02)	0.11 (0.07)	0.1 (0.04)
Elymus lanceolatus	0.32 (0.22)	0.6 (0.55)	0.15 (0.1)	0.49 (0.41)	0.1 (0.1)	0.19 (0.18)	0.27 (0.2)
Elymus trachycaulus^{S}		0.07 (0.06)	0.29 (0.24)	0.13 (0.08)	0.35 (0.31)	0.01 (0.01)	0.13 (0.08)
Hesperostipa comata^{S}		0.03 (0.02)	0.03 (0.02)		0.14 (0.14)		0.08 (0.08)
Koeleria macrantha^{S}	0.17 (0.15)	0.18 (0.07)	0.11 (0.08)	0.02 (0.01)	0.04 (0.03)	0.04 (0.02)	0.05 (0.03)
Pascopyrum smithii^{S}	0.07 (0.05)	0.6 (0.27)	0.25 (0.15)	0.07 (0.04)	0.29 (0.14)	0.61 (0.43)	0.1 (0.05)
Poa fendleriana^{S}	0.77 (0.32)	0.5 (0.2)	0.32 (0.15)	0.2 (0.07)	0.17 (0.08)	0.12 (0.06)	0.29 (0.12)
Poa secunda^{S}	<0.01 (<0.01)	<0.01 (<0.01)			0.01 (0.01)	<0.01 (<0.01)	<0.01 (<0.01)
Pseudoroegneria spicata		0.04 (0.04)	0.02 (0.02)		0.1 (0.1)	0.01 (0.01)	
Total Seeded	1.91 (0.82)	2.07 (0.84)	1.38 (0.58)	0.49 (0.1)	1.08 (0.4)	0.94 (0.47)	1.2 (0.32)
Total Perennial Graminoid	2.56 (1.16)	3.93 (2.07)	2.67 (1.28)	1.27 (0.52)	1.86 (0.58)	1.71 (1.14)	2.19 (0.39)

^{S} Seeded species
^{I} Introduced species

Table D.1 Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Shrub							
Amelanchier spp[S]	3.48 (1.58)	0.56 (0.29)	3.02 (1.23)	5.77 (2.97)	3.57 (1.72)	2.66 (1.42)	3.33 (2.08)
Artemisia tridentata[S]	0.82 (0.57)	0.97 (0.68)	0.75 (0.5)	0.46 (0.36)	0.5 (0.3)	0.07 (0.07)	0.09 (0.07)
Cercocarpus montanus[S]	1.33 (0.83)	0.01 (0.01)	0.14 (0.14)	0.56 (0.37)	0.1 (0.1)		0.01 (0.01)
Chrysothamnus depressus	0.06 (0.05)	0.2 (0.2)	0.27 (0.27)	0.01 (0.01)	0.31 (0.27)	0.16 (0.08)	0.05 (0.04)
Chrysothamnus viscidiflorus[S]	0.2 (0.2)		0.07 (0.06)	0.03 (0.03)		0.01 (0.01)	0.03 (0.03)
Ericameria nauseosa[S]	0.68 (0.68)						
Prunus virginiana[S]						0.01 (0.01)	
Purshia tridentata[S]	1.34 (0.69)	0.64 (0.57)	1.04 (0.49)	0.71 (0.5)	1.39 (0.82)	0.62 (0.41)	0.03 (0.03)
Rhus trilobata[S]			<0.01 (<0.01)				
Symphoricarpos rotundifolius	0.96 (0.48)	2.03 (0.73)	1.1 (0.58)	1.22 (0.51)	0.36 (0.2)	2.12 (0.74)	0.96 (0.32)
Total Seeded Shrub	7.87 (2.05)	2.18 (0.95)	5.02 (1.36)	8.61 (3.58)	5.77 (1.73)	3.56 (1.43)	2.34 (1.85)
Total Shrub	8.88 (2.51)	4.41 (1.62)	6.39 (1.81)	8.75 (4.1)	6.24 (2.04)	5.64 (1.58)	4.51 (2.25)
Tree							
Juniperus osteosperma	2.13 (1.52)	0.7 (0.6)	1.12 (1.12)			0.05 (0.05)	
Pinus edulis	5.41 (2.3)	0.15 (0.12)	0.03 (0.03)	0.57 (0.54)	0.35 (0.35)	0.01 (0.01)	0.36 (0.36)
Total Tree	7.54 (3.61)	0.85 (0.63)	1.15 (1.12)	0.57 (0.54)	0.35 (0.35)	0.06 (0.05)	0.36 (0.36)
Total Unidentified Species	<0.01 (<0.01)	0.05 (0.03)	0.06 (0.04)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)	0.07 (0.06)

[S] Seeded species

[I] Introduced species

Table D.2. Mean understory biomass (g m^{-2} ± SE) of each species collected in 2013. Pinyon-juniper overstory was removed at 2 sites in northwest Colorado using 3 mechanical treatments: anchor chain, rollerchopper, or hydro-ax. Treatments were applied in a randomized complete block design with 3 blocks at the south site and 4 blocks at the north site. Each mechanically treated plot was divided into 2 subplots; one subplot was seeded with a native species mix and the other left unseeded. Each block contained an untreated and unseeded control plot. Unidentified species are totaled at the bottom. Species were not present where values are absent.

		Chain		**Rollerchop**		**Hydro-Ax**	
	Control	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Annual Forb							
Alyssum alyssoides^{I}	<0.01 (<0.01)	0.2 (0.13)	0.54 (0.34)	0.77 (0.38)	0.36 (0.26)	0.44 (0.29)	0.25 (0.23)
Centaurium pulchellum^{I}				0.01 (0.01)	0.05 (0.05)	0.03 (0.02)	0.01 (0.01)
Ceratocephala testiculata^{I}	<0.01 (<0.01)	<0.01 (<0.01)					
Chenopodium album^{I}		0.81 (0.81)					<0.01 (<0.01)
Chenopodium fremontii		0.25 (0.19)		2.61 (2.61)	4.95 (4.95)	5.65 (5.65)	<0.01 (<0.01)
Chenopodium leptophyllum		<0.01 (<0.01)			0.5 (0.5)		
Cleome serrulata^{S}		1.67 (1.66)		3.13 (2.68)	0.14 (0.14)	13.16 (7.77)	0.14 (0.14)
Collinsia parviflora	0.02 (0.02)	0.3 (0.12)	0.2 (0.16)	0.14 (0.11)	0.33 (0.21)	0.03 (0.02)	0.01 (0.01)
Collomia grandiflora	0.04 (0.04)	0.06 (0.06)	0.01 (0.01)			0.01 (0.01)	
Descurainia pinnata			0.16 (0.12)	1.2 (1.16)		0.03 (0.03)	
Descurainia sophia^{I}	0.01 (0.01)	0.13 (0.07)	0.78 (0.57)	7.32 (4.64)	0.79 (0.54)	0.1 (0.06)	2.34 (2.26)
Draba reptans			0.01 (0.01)	0.11 (0.1)	0.03 (0.03)		
Gayophytum diffusum				0.02 (0.02)			

^{S} Seeded species

^{I} Introduced species

Table D.2. Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**	**Seeded Subplots**	**Unseeded Subplots**
Annual Forb							
Helianthus annuus[S]		0.3 (0.18)		0.02 (0.02)	0.01 (0.01)	1.3 (0.61)	0.2 (0.2)
Lactuca serriola[I]					<0.01 (<0.01)		
Lappula occidentalis		0.16 (0.16)	<0.01 (<0.01)	0.02 (0.02)	0.04 (0.03)		
Machaeranthera canescens				1.97 (1.64)	1.09 (0.7)	0.09 (0.09)	
Malva neglecta		0.04 (0.04)					
Polygonum douglasii	<0.01 (<0.01)	0.07 (0.05)	0.02 (0.01)	0.01 (0.01)	0.09 (0.06)	0.01 (0.01)	0.02 (0.02)
Salsola tragus[I]		0.07 (0.07)	<0.01 (<0.01)	12.31 (11.18)	14.24 (13.69)	0.83 (0.83)	0.05 (0.05)
Sisymbrium altissimum[I]				<0.01 (<0.01)			
Total Seeded		1.97 (1.62)		3.15 (2.67)	0.14 (0.14)	14.46 (7.81)	0.33 (0.33)
Total Introduced	0.01 (0.01)	1.25 (0.74)	1.33 (0.6)	20.42 (10.73)	15.43 (13.51)	1.4 (0.8)	2.65 (2.49)
Total Annual Forb	0.07 (0.04)	4.04 (1.99)	1.73 (0.57)	29.65 (12.45)	22.6 (13.89)	21.67 (8.47)	3.02 (2.45)

[S] Seeded species
[I] Introduced species

Table D.2. Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	Unseeded Subplots	Seeded Subplots	Unseeded Subplots	Seeded Subplots	Unseeded Subplots
Perennial Forb							
Androsace septentrionalis							0.02 (0.02)
Antennaria parvifolia	0.08 (0.08)	0.51 (0.46)	0.1 (0.1)	0.2 (0.14)	<0.01 (<0.01)	0.1 (0.1)	0.45 (0.36)
Arenaria eastwoodiae					0.18 (0.18)		
Artemisia ludoviciana[S]		0.47 (0.46)	0.07 (0.07)	2.21 (2.2)			
Astragalus convallarius	0.01 (0.01)		0.02 (0.02)			0.01 (0.01)	0.08 (0.07)
Astragalus lentiginosus			0.26 (0.26)	0.3 (0.21)		<0.01 (<0.01)	
Astragalus purshii				<0.01 (<0.01)	0.05 (0.05)	0.22 (0.15)	0.07 (0.05)
Balsamorhiza sagittata[S]	0.09 (0.09)	0.62 (0.62)	0.89 (0.89)			0.58 (0.58)	
Boechera Spp	0.09 (0.09)		0.19 (0.19)	0.23 (0.16)	0.16 (0.16)	0.39 (0.39)	0.03 (0.02)
Calochortus nuttallii					0.01 (0.01)		
Calochortus spp	0.01 (0.01)						0.02 (0.02)
Calylophus lavandulifolius	0.02 (0.02)						0.06 (0.06)
Carduus nutans[I]							0.01 (0.01)
Chamaesyce fendleri						0.05 (0.05)	
Comandra umbellata	0.12 (0.11)	0.38 (0.38)		0.21 (0.16)	0.73 (0.73)	0.28 (0.28)	0.46 (0.45)
Crepis acuminata[S]	0.01 (0.01)				0.04 (0.04)	0.19 (0.15)	0.17 (0.15)
Erigeron eatonii		0.13 (0.07)	0.03 (0.02)		0.22 (0.22)	0.02 (0.02)	0.02 (0.02)
Eriogonum elatum						<0.01 (<0.01)	
Erysimum spp	<0.01 (<0.01)	0.03 (0.03)	0.17 (0.15)	0.05 (0.05)	0.24 (0.19)	0.04 (0.04)	0.03 (0.03)
Galium trifidum		<0.01 (<0.01)					
Hedysarum boreale[S]		0.01 (0.01)	0.01 (0.01)	0.68 (0.66)		0.47 (0.35)	
Ipomopsis aggregata		<0.01 (<0.01)	0.09 (0.08)			<0.01 (<0.01)	
Ipomopsis spp		0.17 (0.15)				0.01 (0.01)	

[S] Seeded species
[I] Introduced species

Table D.2. Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded	Unseeded	Seeded	Unseeded	Seeded	Unseeded

		Subplots	**Subplots**	**Subplots**	**Subplots**	**Subplots**	**Subplots**
Perennial Forb Continued							
Ipomopsis aggregata		<0.01 (<0.01)	0.09 (0.08)			<0.01 (<0.01)	
Ipomopsis spp		0.17 (0.15)				0.01 (0.01)	
Linum lewisii^S		0.27 (0.25)		<0.01 (<0.01)		1.75 (0.85)	
Lupinus argenteus^S		1.49 (1.06)	0.03 (0.03)		0.31 (0.2)	0.04 (0.04)	1.63 (1.63)
Lygodesmia juncea						0.04 (0.04)	0.02 (0.02)
Machaeranthera grindelioides	0.27 (0.27)			0.11 (0.11)			0.33 (0.3)
Oenothera caespitosa^S					1.38 (1.38)	0.03 (0.03)	
Opuntia polyacantha		0.88 (0.59)		1.15 (0.87)	0.12 (0.12)		0.02 (0.02)
Oxytropis lambertii				<0.01 (<0.01)		0.01 (<0.01)	
Packera multilobata				0.11 (0.09)		0.49 (0.32)	0.19 (0.16)
Penstemon secundiflorus		0.77 (0.77)	0.07 (0.07)	0.01 (0.01)		0.41 (0.41)	0.02 (0.02)
Penstemon strictus^S		0.35 (0.33)		0.02 (0.02)		<0.01 (<0.01)	
Phacelia sericea							0.12 (0.12)
Phlox hoodii	0.29 (0.14)	0.09 (0.09)	0.51 (0.39)	0.05 (0.05)		0.09 (0.07)	0.32 (0.31)
Phlox longifolia	0.02 (0.02)	0.1 (0.09)	0.01 (0.01)	0.01 (0.01)	0.06 (0.05)	0.05 (0.02)	0.06 (0.04)
Physaria acutifolia		0.64 (0.57)	0.29 (0.26)	0.05 (0.04)	0.59 (0.59)	0.45 (0.41)	0.08 (0.07)
Scabrethia scabra					0.39 (0.39)		
Schoenocrambe linifolia			0.11 (0.11)	0.37 (0.37)			
Senecio spp		0.05 (0.05)				0.03 (0.03)	
Sphaeralcea coccinea		0.26 (0.17)	0.16 (0.16)	0.07 (0.07)	0.2 (0.14)	0.06 (0.06)	0.22 (0.13)
Stenotus acaulis				0.94 (0.94)	0.32 (0.32)	0.69 (0.54)	0.56 (0.56)

^{S} Seeded species

^{I} Introduced species

Table D.2. Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplots	Unseeded Subplots	Seeded Subplots	Seeded Subplots	Seeded Subplots	Unseeded Subplots
Perennial Forb Continued							
Symphotrichum spp				0.02 (0.02)			
Trifolium gymnocarpon	0.72 (0.72)		<0.01 (<0.01)	0.01 (0.01)		0.01 (0.01)	0.02 (0.02)
Total Seeded	0.24 (0.16)	3.22 (1.16)	1 (0.88)	2.91 (2.21)	1.73 (1.49)	3.07 (1.02)	1.81 (1.62)
Total Introduced							0.01 (0.01)
Total Perennial Forb	1.73 (0.74)	7.23 (2.14)	3 (1.19)	6.8 (3.2)	4.98 (1.58)	6.51 (1.64)	5.02 (2.39)
Annual Graminoid							
Bromus tectorum^{I}	0.06 (0.06)	0.72 (0.43)	0.58 (0.34)	1.19 (0.4)	3.42 (2.22)	1.66 (1.08)	0.51 (0.5)
Perennial Graminoid							
Achnatherum hymenoides^{S}	0.02 (0.02)	0.03 (0.02)	0.59 (0.42)	0.26 (0.24)	4.31 (3.74)	1.91 (1.77)	2.48 (1.16)
Bouteloua gracilis		0.11 (0.11)	<0.01 (<0.01)				
Carex spp	0.26 (0.15)	1.52 (0.82)	2.81 (1.76)	2.03 (0.87)	1.82 (0.85)	1.78 (1.54)	2.34 (0.98)
Elymus elymoides^{S}	0.03 (0.02)	0.81 (0.48)	1.17 (0.76)	2.67 (1.22)	3.68 (1.8)	3.75 (2.13)	1.5 (0.62)
Elymus lanceolatus	0.02 (0.02)					1.41 (1.41)	
Elymus trachycaulus^{S}	0.01 (0.01)	0.47 (0.47)		0.22 (0.22)	0.08 (0.08)	1.57 (0.85)	1.5 (1.5)
Hesperostipa comata^{S}	0.19 (0.18)	2.16 (1.49)	1.34 (1.04)	0.14 (0.08)	0.31 (0.21)	0.23 (0.21)	0.78 (0.53)
Koeleria macrantha^{S}	0.06 (0.06)	0.08 (0.06)	0.91 (0.71)	0.12 (0.09)	0.84 (0.54)	0.64 (0.17)	0.98 (0.74)
Pascopyrum smithii^{S}	0.5 (0.33)	3.18 (1.67)	5.81 (4.37)	4.7 (3.96)	4.74 (2.75)	1.15 (0.45)	4.58 (1.62)
Poa fendleriana	0.15 (0.08)	0.65 (0.51)	0.71 (0.57)	0.38 (0.33)	0.35 (0.32)	0.28 (0.16)	0.45 (0.38)
Poa pratensis				0.63 (0.63)		0.02 (0.02)	
Poa secunda^{S}	0.07 (0.04)	0.32 (0.22)	0.16 (0.11)	0.1 (0.06)	0.03 (0.03)	0.44 (0.42)	0.54 (0.33)
Pseudoroegneria spicata					0.41 (0.41)		
Total Seeded	1.04 (0.5)	7.72 (3.99)	10.69 (7.21)	8.6 (4.08)	14.33 (4.9)	9.98 (3.75)	12.81 (4.8)
Total Perennial Graminoid	1.32 (0.63)	9.36 (4.39)	13.51 (8.03)	11.26 (4.18)	16.56 (5.23)	13.2 (6.29)	15.15 (5.42)

^{S} Seeded species

^{I} Introduced species

Table D.2. Continued

	Control	Chain		Rollerchop		Hydro-Ax	
		Seeded Subplot	Unseeded Subplot	Seeded Subplot	Unseeded Subplot	Seeded Subplot	Unseeded Subplot
Shrub							
Amelanchier spp^S	8.96 (3.79)	17.35 (11.01)	37.94 (28.25)	7.29 (4.1)	22.05 (14.4)	24.89 (16.94)	42.61 (25.67)
Artemisia tridentata^S		4.32 (2.3)	3.24 (3.24)	0.07 (0.05)	0.37 (0.37)	1.19 (1.14)	
Cercocarpus montanus^S	1.9 (1.9)	2.17 (2.12)	0.19 (0.19)	0.23 (0.23)	0.38 (0.38)		0.41 (0.41)
Chrysothamnus depressus	0.3 (0.22)	0.27 (0.27)	0.58 (0.58)	0.26 (0.26)	1.3 (1.3)	0.39 (0.33)	1.63 (1.15)
Chrysothamnus viscidiflorus^S		1.4 (1.4)	1.4 (1.4)			0.27 (0.27)	
Ericameria nauseosa^S		0.04 (0.04)	<0.01 (<0.01)				
Eriogonum umbellatum^S	0.15 (0.15)	0.01 (0.01)					
Krascheninnikovia lanata^S						0.08 (0.08)	
Purshia tridentata^S	0.69 (0.45)	2.06 (1.69)	1.42 (1.1)	4.94 (4.36)	0.27 (0.23)	0.99 (0.99)	2.05 (2.05)
Rhus trilobata^S				<0.01 (<0.01)			
Symphoricarpos rotundifolius	3.92 (2.15)	12.65 (5.22)	9.69 (5.19)	9.38 (5.21)	5.89 (3.09)	13.36 (5.14)	8.68 (3.46)
Total Seeded Shrub	11.54 (3.96)	27.34 (10.26)	44.19 (30.87)	12.54 (4.84)	23.07 (14.43)	27.42 (16.37)	45.06 (25.46)
Total Shrub	15.91 (4.51)	40.26 (14.66)	54.45 (32.1)	22.18 (7.48)	30.26 (16.57)	41.17 (19.12)	55.37 (26.86)
Tree							
Juniperus osteosperma	1.18 (0.76)	<0.01 (<0.01)	0.2 (0.2)	0.8 (0.56)	1.13 (1.13)	0.04 (0.03)	
Pinus edulis	2.98 (1.15)		0.01 (0.01)	0.08 (0.06)	2.84 (2.03)	<0.01 (<0.01)	
Total Tree	4.16 (1.13)	<0.01 (<0.01)	0.21 (0.2)	0.89 (0.58)	3.96 (2.1)	0.04 (0.02)	

^{S} Seeded species

^{I} Introduced species

APPENDIX E

Plot Location

There are 28 total plots, 16 at North Magnolia and 12 at South Magnolia. Mechanically treated plots were further divided into adjoining subplots (seeded subplot and unseeded subplot). Control plots received no mechanical treatment and are the same size as one mechanically treated subplot. Subplots 21-23 and 27 are 85m long and 45m wide; remaining subplots are all 137 m long and 30 m wide. The UTM coordinates listed below (Table F.1) represent the ends of the shared boundary line (long axis) between seeded and unseeded subplots for mechanically treated plots (Figure F.1). For control plots, coordinates represent corners. Most plots are oriented north-south on the long axis, but a few are oriented east-west. The location of control plots 20 and 28 were different in 2012 and 2013 (after 2012 data collection, these plots were mistakenly treated and different areas had to be used in 2013; areas were chosen for 2013 that visually approximated the overstory and understory structure of the areas used in 2012). For all other plots, the same plots were sampled in both years.

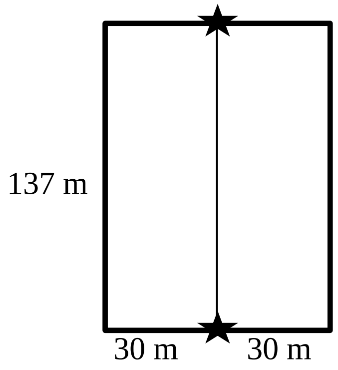

Figure E.1 Mechanical treatment plot layout, with a boundary down the middle dividing the seeded subplot and unseeded subplot. Stars represent the location of UTM coordinates listed in Table E.1. At 2 sites in northwest Colorado, 3 mechanical treatments were used to remove pinyon-juniper overstory: anchor chain, rollerchopper, or hydro-ax. Half of each mechanically treated plot was seeded.

Table E.1 Plot number with UTM coordinates for two points on the plot. Plots occur at 2 sites in northwest Colorado where 3 mechanical treatments were used to remove pinyon-juniper overstory: anchor chain, rollerchopper, or hydro-ax.

Plot Number	UTM Coordinates
1	738288 4423846 North End; 738341 4423722 South End
2	738241 4423748 North End; 738296 4423624 South End
3	738420 4423714 Northwest Corner; 738475 4423591 Southwest Corner
4	738360 4423683 North End; 738415 4423559 South End
5	738305 4423531 Northwest Corner; 738303 4423395 Southwest Corner
6	738403 4423478 North End; 738404 4423346 South End
7	738452 4423276 North End; 738454 4423142 South End
8	738364 4423275 North End; 738364 4423139 South End
9	738451 4423073 North End; 738453 4422939 South End
10	738452 4422856 North End; 738456 4422720 South End
11	738346 4423084 North End; 738347 4422948 South End
12	738205 4423175 North End; 738208 44230395 South End
13	738188 4422879 Northwest Corner; 738188 4422742 Southwest Corner
14	738248 4422743 North End; 738293 4422610 South End
15	738297 4422550 North End; 738303 4422415 South End
16	738386 4422625 North End; 738392 4422489 South End
17	734391 4420783 West End; 734522 4420758 East End
18	734400 4220853 West End; 734533 4420827 East End
19	734446 4420922 West End; 734577 4220894 East End
20	734452 4421006 Southwest Corner (2012); 734583 4420972 Southeast Corner (2012)
	734452 4421006 Northwest Corner (2013); 734583 4420972 Northeast Corner (2013)
21	734089 4421302 Northwest Corner; 734095 4421219 Southwest Corner
22	734115 4421405 North End; 734119 4421321 South End
23	734101 4221505 North End; 734106 4421419 South End
24	734098 4421652 North End; 734100 4421519 South End
25	733763 4421434 North End; 733851 4421434 South End
26	733679 4421561 North End; 733749 4421443 South End
27	733437 4221040 North End; 733433 4421040 South End
28	733470 4421243 Northwest Corner (2012); 733507 4421113 Southwest Corner (2012).
	733486 4421020 Northwest Corner (2013); 733480 4420884 (2013)