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# Rangeland Ecology & Management

journal homepage: <http://www.elsevier.com/locate/rama>

## Understory Responses to Mechanical Treatment of Pinyon-Juniper in Northwestern Colorado<sup>☆</sup>

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### ARTICLE INFO

#### Article history:

Received 10 September 2015

Received in revised form 9 June 2016

Accepted 14 June 2016

#### Keywords:

chain  
habitat  
mastication  
mule deer  
woody encroachment

### ABSTRACT

Pinyon-juniper (*Pinus* spp.–*Juniperus* spp.) encroachment and declining mule deer (*Odocoileus hemionus*) populations in western Colorado have necessitated management for increased forage. Pinyon-juniper removal is one such technique; however, it is unclear which method of tree removal most effectively promotes forage species. We conducted an experiment to quantify understory responses to mechanical pinyon-juniper removal and seed additions in a blocked design using three different methods: anchor-chaining, rollerchopping, and mastication. Blocks contained each mechanical and seeding treatment along with an untreated control. Seven blocks across two sites, North Magnolia (NM, 4 blocks) and South Magnolia (SM, 3 blocks), were treated during the fall of 2011. Half of each plot was seeded before or during mechanical treatment with a mix of grasses, shrubs, and forbs. After two growing seasons, biomass of perennial grasses was 90–160 kg · ha<sup>-1</sup> in mechanically treated plots compared with 10 kg · ha<sup>-1</sup> in untreated controls. There were no differences, however, between mechanical treatments for any perennial plant species. Response of annual plant species depended on mechanical treatment type and site. Rollerchopping had higher exotic annual grass cover than mastication or control at NM and higher exotic annual forb cover than chaining or control at SM. Rollerchopping was the only treatment to have higher native annual forb cover than control in the absence of seeding. Seeding increased native annual forb biomass in mastication compared with control. Seeding also increased shrub density at SM, which had fewer shrubs pretreatment relative to NM. Results suggest any type of mechanical removal of pinyon-juniper can increase understory plant biomass and cover. Seeding in conjunction with mechanical treatments, particularly mastication, can initially increase annual forb biomass and shrub density. Finally, different understory responses between sites suggests that pretreatment conditions are important for determining outcomes of pinyon-juniper removal treatments.

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### Introduction

The phenomenon of woody plant encroachment into semiarid grasslands, shrublands, and savanna has been observed throughout the world, including places such as Africa, Australia, and western North America (House et al. 2003; Asner et al. 2004; Eldridge et al. 2011). Transitions to shrub- or tree-dominated systems are driven by a variety of causes involving climate-induced shifts that have promoted woody plant establishment and human land use such as livestock grazing and fire suppression (House et al. 2003; Sankaran et al. 2005; Romme et al. 2009). Concerns over woody plant encroachment are driving

resource managers to explore different methods of control to improve forage for wildlife and livestock.

Pinyon-juniper (*Pinus* spp. L.–*Juniperus* spp. L.) communities of the western United States are one example where rangeland and wildlife managers have battled the expansion and infill of trees, which reduces understory cover over time (Baker and Shinneman 2004; Miller et al. 2008; Vankat 2013). From the 1950s through the 1970s, thousands of hectares of pinyon-juniper trees were removed to improve grass production for sheep and cattle (Aro 1975). In more recent years increased attention has been given to managing specifically for mule deer (*Odocoileus hemionus*) populations, which have declined throughout many western states (Unsworth et al. 1999; Gill 2001; Wasley 2004).

Multiple interacting factors influence mule deer population dynamics, but survival, as it relates to forage quality, has been identified as a significant driver (Unsworth et al. 1999; Bishop et al. 2009; Tollefson et al. 2011). Nutritious forbs and shrubs are especially important for overwinter survival of mule deer (Bartmann 1983), but availability within and between stands of pinyon-juniper can vary greatly.

<sup>☆</sup> This research was funded by XTO Energy, Inc.

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For decades, land managers have tried various methods for increasing forage quantity and quality in areas where trees and/or shrubs have become dominant. Prescribed fire is one tool that has been used for many decades in the management of western rangelands (Vallentine 1989). However, because fire histories within pinyon-juniper are not well understood on a site-by-site basis (Romme et al. 2009; Shinneman and Baker 2009) and because fuel conditions may not support controlled burns (Tausch et al. 2009), this treatment method may not be appropriate. Mechanical removal of pinyon-juniper is an alternative that involves the use of small tools, such as chainsaws, or heavy machinery, like bulldozers or crawler tractors, that cut, uproot, or crush vegetation in order to achieve reductions in tree density and canopy coverage. Anchor chaining, one of the oldest forms of large-scale mechanical pinyon-juniper removal, involves a heavy ship anchor chain towed between two bulldozers; the dragged chain uproots and breaks off trees and shrubs while also creating variable soil disturbance depending on the type of chain (Stevens 1999). Rollerchopping, a less common technique, involves a bulldozer towing a heavy rotating drum with protruding steel plates. The bulldozer knocks the trees over and the drum rolling behind crushes them into large pieces (Rummer 2010). More recent technology includes various tracked or rubber-tired machines mounted with rotating blades or drums that shred or grind individual trees and shrubs (aka mastication), which allows for more selective treatments that result in smaller woody debris relative to chaining and rollerchopping.

In many instances, artificial seeding has been done alongside these treatments, with varying degrees of success, in order to improve forage establishment for livestock or wildlife (Aro 1975; Vallentine 1989). Seed application may occur before, during, or after tree removal and varies by technique; options include hand-broadcast, aerial seeding, rangeland drills, and tractor-mounted seed dribblers, which operate while the tractor is in motion.

Differences in the size of woody material produced and in the degree of soil disturbance may influence establishment of native and exotic understory species. For instance, the woody debris layer produced by mastication may physically impede herbaceous seedling emergence, but for seedlings that survive, their production may increase (Young et al. 2013a), possibly due to increased moisture infiltration (Cline et al. 2010). Soil disturbance produced by chaining and rollerchopping may provide an opportunity for seeded species to establish, but it may also become a liability by allowing invasion of weedy species (Stevens 1999). Chaining also leaves tree skeletons that may offer a few years of protection from herbivory (Matney et al. 2005), which could play an important role in allowing shrubs to establish. These differences may affect the success of seeding attempts following mechanical tree removal, but such differences have yet to be examined. Finally, condition of the biophysical site such as degree of tree encroachment and the abundance and composition of understory species are important drivers of post-treatment understory dynamics (Young et al. 2013a; Miller et al. 2014; Roundy et al. 2014a).

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 (O'Meara et al. 1981; Ott et al. 2003), and mastication (Owen et al. 2009; Ross et al. 2012). However, the composition of those plant communities has often included exotic or undesirable species that may suppress native plant establishment (Skousen et al. 1989; Owen et al. 2009; Ross et al. 2012; Huffman et al. 2013). Understory responses in pinyon-juniper 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. Because of inconsistent responses and the fact that most studies have measured the effects of only one particular treatment type, there is uncertainty about how different treatment types influence vegetation responses.

The goal of this study was to understand vegetation responses to three different mechanical treatments (anchor chaining, rollerchopping, and

mastication) in conjunction with seeding treatments at two sites with different levels of pinyon-juniper encroachment. Seeding was performed in conjunction with mechanical treatments to determine if seeding would, as expected, inhibit establishment of exotic understory species and promote native forage establishment. Early-seral species were expected to respond most positively to chaining because it is typically associated with a high degree of soil disturbance (Vallentine 1989; Stevens 1999; Bates et al. 2005), creating conditions to which early-seral species are adapted (Pickett 1976). Because chaining can result in variable mortality of woody plants (Skousen et al. 1989), our final expectation was greater shrub abundance in chaining versus mastication and rollerchopping treatments due to greater shrub survival after chaining.

## Methods

### Site Description

The study area was located on federal lands (Bureau of Land Management) in the Piceance Creek Basin of Rio Blanco County in northwestern Colorado, United States. The Piceance Creek Basin serves as winter range for one of North America's largest migratory mule deer populations (White and Lubow 2002). In recent decades, construction of well pads, roads, and compressor stations for natural gas extraction has fragmented important wildlife habitat (Anderson 2011). As mitigation for these impacts to wildlife, extensive removal of pinyon and juniper trees has occurred in efforts to increase forage quality and quantity.

Piceance Creek Basin is a semiarid region with 30-year average annual precipitation of 40 cm (NOAA, 2013). Total precipitation in the study area from January through July during 2012 and 2013 was 34% and 3% below average, respectively. Within the Piceance Creek Basin, our study was conducted at two sites that were approximately 4.5 km apart, North Magnolia (NM; UTM 738327 E, 4423141 N; 12S) and South Magnolia (SM; UTM 733958 E, 4420956 N; 12S). Elevations at the two sites range from 2000 to 2100 m. NM plots are clustered together in a long rectangle encompassing 50 ha; plots generally face northeast with slopes of 5–15%. SM plots are arranged within a 70-ha triangle with each block clustered at each corner of the triangle; aspects vary and slopes range from 0–20%. Soils at both sites are shallow and well drained, derived from sandstone and shale bedrock (Tiedeman and Terwilliger 1978). We estimate the average condition of NM to fit within late phase II stage of woodland development and SM to fit in late phase III stage of woodland development (Miller et al. 2008). At NM, shrubs and trees dominate and grasses and forbs are low in abundance. Tree crowns generally reach the ground, and space between trees/shrubs is minimal (i.e., walking through this site is difficult). At SM, tree density is much lower ( $667.36 \pm 159.81$  trees  $\cdot$  ha $^{-1}$  in control plots) and trees are larger (control plot basal area:  $41.45 \pm 3.95$  m $^2$   $\cdot$  ha $^{-1}$ ) than at NM (control plot density:  $1151.67 \pm 158.32$  trees  $\cdot$  ha $^{-1}$  and basal area:  $16.73 \pm 2.3$  m $^2$   $\cdot$  ha $^{-1}$ ); crowns are raised at SM (site is easier to walk through), and some trees exhibit characteristics of being several hundred years old (W. H. Romme 2013, personal communication). Shrub and perennial grass biomass also differed between NM and SM, with grasses being more dominant at SM and shrubs being more dominant at NM. Dominant shrub species also differed by site. At NM, 67% of all biomass was serviceberry (*Amelanchier Medik.* sp.) and 26% was snowberry (*Symphoricarpos rotundifolius* A. Gray). At SM, bitterbrush (*Purshia tridentata* [Pursh] DC.) was most prevalent, comprising 43% of shrub biomass, while big sagebrush (*Artemisia tridentata* Nutt.) and mountain mahogany (*Cercocarpus montanus* Raf.) comprised about 17% each. Common forbs at both sites included plains pricklypear cactus (*Opuntia polyacantha* Haw.), phlox (*Phlox* L. spp.), tansyaster (*Machaeranthera* Nees. spp.), and Lewis flax (*Linum lewisii* Pursh). Common grasslike plants were sedges (*Carex* L. spp.), wildrye (*Elymus* L. spp.), western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), bluegrass (*Poa* L. spp.), and Indian ricegrass (*Achnatherum hymenoides* [Roem. & Schult.] Barkworth).

### Experimental Design and Site Preparation.

Each site contained multiple treatment blocks, four at NM and three at SM. Blocks consisted of a randomly assigned chain plot, rollerchop plot, mastication plot, and untreated control for a total of 28 plots. Mechanically treated plots were further divided into randomly assigned seeded and unseeded subplots. Controls were not seeded because 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. All subplots were 137 m × 30 m (0.4 ha), but in some instances treated areas were slightly smaller or larger due to difficulty of operating heavy equipment within a precise area.

Seeding occurred 1–14 days before mechanical treatments between 24 October and 23 November 2011. All seeded subplots received the same seed mix at a rate of 600 pure live seeds · m<sup>-2</sup>, which was composed of 10 shrub species, 14 forb species, and 10 grass species (Table 1). Species were chosen to fill ecological niches at various stages of succession and to increase palatable shrub production. Native early seral species in particular were included to provide quick cover and compete with exotic annuals. All species were native to western Colorado except QuickGuard (Granite Seed Company, Lehi, UT), which is a sterile wheat hybrid.

Species were separated into five groups by seed size and morphology (see Table 1) to aid in uniform seed distribution during seeding. Seed

groups 1–4, generally smaller and lighter seeds, were all hand broadcast using Earthway chest-mounted, hand-crank spreaders (Earthway Products, Inc., Bristol, IN). All hand broadcast seeding occurred along five evenly spaced transects parallel to the long axis of the subplot for all three of the mechanical treatments (chaining, rollerchopping, mastication). Relatively heavy and large seeds that benefit from deeper planting, mostly shrubs and forbs (Group 5 in Table 1), were applied with a seed dribbler mounted on the tracks of the bulldozers used for chaining and rollerchopping (Plummer et al. 1968). This device dropped seeds onto the bulldozer track as it moved forward; seeds were then pressed into the soil by the track. The tractor used in mastication plots was rubber-tired, not tracked, and thus seed dribblers could not be used. Instead, heavy Group 5 seeds (see Table 1) were hand broadcast in seeded mastication subplots as described for seed groups 1–4 earlier.

### Mechanical Treatments

Mechanical treatments were applied during October and November of 2011. Chained plots were treated by an 18-m-long Ely chain (40.8 kg per link). The Ely chain is distinguished from a smooth chain by the presence of cross-welded sections of rail on every other link that are intended to increase weight and surface disturbance. The chain was dragged between two bulldozers, a Caterpillar D8R (Caterpillar Inc., Peoria, IL) and Komatsu D65EX (Komatsu Ltd., Tokyo, Japan). Here, trees and shrubs were either pushed over, broken off at the soil surface, or

**Table 1**

Plant species used in a seed mix that was applied to half of each plot in northwestern Colorado where pinyon-juniper canopy was removed using one of three mechanical treatments: anchor chain, rollerchop, or mastication. Seeded species were separated into seeding groups by seed size and morphology to aid in uniform seed distribution. All groups were broadcast seeded for mastication plots; in chain and rollerchop plots, groups 1–4 were broadcast seeded and group 5 was seeded using a Hansen seed dribbler mounted on the bulldozers. Lifespan: annual (A) or perennial (P). Seeding rate (pure live seeds · m<sup>-2</sup>) is found in the far right column. Plant taxonomy—USDA Plants Database 2013

Genus species authority	Common name	Lifespan	Seeding group	Pure live seeds m <sup>-2</sup>
<b>Forb</b>				
<i>Amaranthus retroflexus</i> L.	Redroot amaranth	A	2	12
<i>Artemisia frigida</i> Willd.	Fringed sagebrush	P	2	36
<i>Artemisia ludoviciana</i> Nutt.	White sagebrush	P	2	24
<i>Balsamorhiza sagittata</i> (Pursh) Nutt.	Arrowleaf balsamroot	P	1	12
<i>Cleome serrulata</i> Pursh	Rocky Mountain beeplant	A	1	24
<i>Crepis acuminata</i> Nutt.	Tufted hawkbeard	P	2	1
<i>Eriogonum umbellatum</i> Torr.	Sulfur-flower buckwheat	P	3	10
<i>Hedysarum boreale</i> Nutt.	Utah sweetvetch	P	5	12
<i>Helianthus annuus</i> L.	Common sunflower	A	1	30
<i>Linum lewisii</i> Pursh	Lewis flax	P	1	24
<i>Lupinus argenteus</i> Pursh	Silvery lupine	P	5	12
<i>Oenothera caespitosa</i> Nutt.	Tufted evening primrose	P	1	12
<i>Oenothera pallida</i> Lindl.	Pale evening primrose	P	1	24
<i>Penstemon strictus</i> Benth.	Rocky Mountain penstemon	P	1	36
<b>Graminoid</b>				
<i>Achnatherum hymenoides</i> (Roem. & Schult.) Barkworth	Indian ricegrass	P	1	18
<i>Elymus elymoides</i> (Raf.) Swezey	Bottlebrush squirreltail	P	1	18
<i>Elymus trachycaulus</i> (Link) Gould ex Shinners	Slender wheatgrass	P	1	12
<i>Hesperostipa comata</i> (Trin. & Rupr.) Barkworth	Needle and thread	P	1	12
<i>Koeleria macrantha</i> (Ledeb.) Schult.	Prairie Junegrass	P	2	24
<i>Pascopyrum smithii</i> (Rydb.) Á. Löve	Western wheatgrass	P	1	6
<i>Poa fendleriana</i> (Steud.) Vasey	Muttongrass	P	2	12
<i>Poa secunda</i> J. Presl	Sandberg bluegrass	P	2	12
<i>Triticum aestivum</i> L.				
× <i>Secale cereale</i> L.	QuickGuard	A	4	12
<i>Vulpia octoflora</i> (Walter) Rydb.	6-weeks fescue	A	2	18
<b>Shrub</b>				
<i>Amelanchier alnifolia</i> (Nutt.) Nutt. ex M. Roem.	Saskatoon serviceberry	P	5	30
<i>Amelanchier utahensis</i> Koehne	Utah serviceberry	P	5	12
<i>Artemisia tridentata</i> Nutt. ssp. <i>wyomingensis</i>	Wyoming sagebrush	P	2	24
<i>Cercocarpus montanus</i> Raf.	Mountain mahogany	P	5	24
<i>Ericameria nauseosa</i> (Pall. ex Pursh) G.L. Nesom & Baird	Rubber rabbitbrush	P	2	18
<i>Chrysothamnus viscidiflorus</i> (Hook.) Nutt.	Yellow rabbitbrush	P	2	18
<i>Krascheninnikovia lanata</i> (Pursh) A. Meeuse & Smit	Winterfat	P	3	18
<i>Prunus virginiana</i> L.	Chokecherry	P	4	6
<i>Purshia tridentata</i> (Pursh) DC.	Bitterbrush	P	5	30
<i>Rhus trilobata</i> Nutt.	Skunkbush sumac	P	5	6



uprooted by the bulldozers driving over top or by force of the chain being dragged between them. The chain was dragged over the same area twice, with the second pass in the opposite direction of the first pass. Bulldozer attachment points for the chain were approximately 1 m above the ground, which meant that the chain did not come into contact with the ground until it was a few meters away from the attachment point. Chaining generated slash and uprooted trees that were scattered and piled across the plot. In rollerchopped plots, 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 blades 25 cm tall 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 woody material 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 mastication plots, all standing trees and shrubs were masticated to ground level by a Barko 930 tractor (Barko Hydraulics, LLC, Duluth, MN) mounted with a Fecon Bull Hog mulcher (Fecon Inc., Lebanon, OH). Although measurements were not taken, most of the masticated material was < approximately 20 cm in length; woody material scattered across the plot varied in depth between 0 and 25 cm. Untreated areas or reserves were not left in mechanically treated plots; all areas within the plot boundary experienced mechanical treatment. While no trees remained standing after chaining and rollerchopping, some younger, more flexible trees were discovered to be leaning severely but still alive with green leaves 2 years posttreatment (however, trees were not encountered in our sampling). In addition, some shrubs also survived treatment even though significant aboveground biomass was damaged or removed.

#### Vegetation Sampling

To measure understory vegetation, cover, biomass (current year's growth), and shrub density data were gathered in all 49 subplots during the first and second growing seasons after treatment. Data were collected along 20 transects per subplot in July 2012 and 10 transects per subplot in August 2013. Following analysis of 2012 biomass data, it was determined that the same level of within-plot variability could be captured by sampling 10 transects per subplot, requiring less field effort without compromising robustness of data collected in 2013. Plant cover by species was estimated using the point-intercept method at 1-m intervals along each transect with bare ground recorded for points not intercepted by vegetation, rock, or other organic material. Biomass was collected using one sampling frame (0.25 × 0.75 m) randomly placed along each transect. Plots were large and heterogeneous due to the nature of the equipment used to implement treatments, and we sampled as randomly as possible to try to capture that heterogeneity without bias. For herbaceous species, all current-year biomass rooted within the frame was clipped and bagged by species. For woody species, current-year growth hanging inside the frame, up to 1.4 m in height, was clipped whether or not it was rooted inside the frame. All biomass was composited by species for each seeded and unseeded subplot (i.e., for a given subplot, all biomass across all transects for a given species was collected together in one bag). Plant biomass was oven-dried to constant mass at 65°C and subsequently weighed to estimate total aboveground production per subplot. In addition to collecting biomass, individual shrubs rooted within biomass frames were counted by species before clipping the current-year growth.

#### Statistical Analysis

Because the design of the experiment was not fully factorial (there were no seeded control plots), two types of analyses were used to

examine cover, biomass, and shrub density data: mechanical treatment effects analysis (MEA) and seeding effect analysis (SEA).

The MEA used only unseeded subplots to examine effects of mechanical treatments relative to one another and also to untreated controls with a nested, randomized, complete-block, mixed-effects model in which mechanical treatment (chain, rollerchop, mastication, control) and site (NM and SM) were fixed effects, and block within site was a random effect. The Kenward-Rogers denominator degrees of freedom method was used to account for unequal variances. Where covariance associated with a random factor was zero, the factor was dropped from the model, resulting in an increase in denominator degrees of freedom. Each year (2012, 2013) was analyzed separately because of expected rapid changes during the early phase of plant community development following disturbance and treatment.

The SEA excluded control plots, which had no mechanical treatment, to allow analysis of the seeding treatment, and interactions involving the seeding treatment. These analyses were conducted for each year separately using a nested, randomized, complete-block, split-plot, mixed-effects model in which mechanical treatment type (chain, rollerchop, mastication), seeding treatment (seeded or unseeded), and site (NM or SM) were fixed effects and block within site and mechanical treatment within block were random effects. The Kenward-Rogers denominator degrees of freedom method was used to account for unequal variances. Where covariance associated with a random factor was zero, the factor was dropped from the model, resulting in an increase in denominator degrees of freedom.

For significant main effects in all analyses, pairwise comparisons were made using Tukey's adjustment ( $\alpha = 0.05$ ). For significant interactions involving site (cutoff of  $\alpha = 0.1$ ), further analyses to test for mechanical and/or seeding treatment effects were conducted separately for each site.

Biomass response variables were split into the following six groups: native annual forb, exotic annual forb, perennial forb, annual grass, perennial grass, and shrub. Species with biennial life cycles were grouped with annuals. Because both native and exotic annual forbs were present, they were analyzed as two separate groups. Perennial forbs were all native with trace amounts of exotics. Annual grasses were composed of only exotic species, cheatgrass (*Bromus tectorum* L.), and the seeded sterile wheat (only in 2012; see Table 1). Perennial grasses and shrubs were all native. Data were transformed to improve normality before parametric analyses: perennials:  $\log(\text{biomass} + 1)$  or  $\arcsin(\sqrt{[\text{cover}]})$ ; annuals:  $\log(\text{biomass} + 0.01)$  or  $\arcsin(\sqrt{[\text{cover}]})$ ; and shrub density:  $\log(\text{density} + 1)$ . Residual plots were examined to ensure proper adherence to normality assumptions. All analyses were conducted with PROC GLIMMIX in SAS 9.3 (SAS Institute, Cary, NC).

#### Results

Total understory plant biomass (current year's production) was much lower in 2012 than in 2013 due to the severe 2012 drought. Mean understory biomass in 2012 was  $127 \pm 12 \text{ kg} \cdot \text{ha}^{-1}$  at NM and  $64 \pm 12 \text{ kg} \cdot \text{ha}^{-1}$  at SM. In 2013, understory biomass averaged  $803 \pm 111 \text{ kg} \cdot \text{ha}^{-1}$  at NM and  $483 \pm 96 \text{ kg} \cdot \text{ha}^{-1}$  at SM.

#### Perennial Plant Responses

In 2012, there was a significant treatment × site interaction ( $F_{3,15} = 3.30, P = 0.0493$ ) for perennial grass biomass; however, when each site was analyzed separately, there were no significant effects of mechanical treatment at either NM or SM. In 2013, perennial grass biomass was not different among mechanical treatments, but mechanically treated, unseeded subplots had 10–15 times greater grass biomass than control plots ( $P < 0.0052$ , MEA; Table 2). Although perennial grass biomass at SM was higher on average than NM ( $P = 0.0224$ , MEA; Table 2), response to treatments was similar at both sites (site × mechanical

**Table 2**

Mean biomass ( $\pm$  SE kg  $\cdot$  ha<sup>-1</sup>) by plant functional group collected in 2013 from 2 sites in northwestern Colorado where 3 mechanical treatments were used to remove pinyon-juniper overstory: anchor chain, rollerchopper, or mastication. Half of each mechanically treated plot was seeded, and control plots received no mechanical or seeding treatment. **A**, Mean biomass across both sites. **B**, Mean biomass at North Magnolia. **C**, Mean biomass at South Magnolia

	Control		Chain		Rollerchop		Mastication	
	Unseeded	Seeded	Unseeded	Seeded	Unseeded	Seeded	Unseeded	Seeded
<b>A) Both sites pooled (N = 7)</b>								
Native annual forb	0.6 (0.4)	27.9 (20.2)	4.0 (1.9)	92.4 (40.5)	71.7 (53.8)	202.8 (82.3)	3.7 (3.3)	
Exotic annual forb	0.1 (0.1)	12.5 (7.4)	13.3 (6.0)	204.2 (107.3)	154.3 (135.1)	14.0 (8.0)	26.5 (24.9)	
Perennial forb	18.8 (7.3)	72.3 (21.4)	30.0 (11.9)	68.0 (32.0)	49.8 (15.8)	65.1 (16.4)	50.2 (23.9)	
Annual grass	0.6 (0.6)	7.2 (4.3)	5.8 (3.4)	11.9 (4.0)	34.2 (22.2)	16.6 (10.8)	5.1 (5.0)	
Perennial grass	13.2 (6.3)	93.6 (43.9)	135.1 (80.3)	112.6 (41.8)	165.6 (52.3)	132.0 (62.9)	151.5 (54.2)	
Shrub	157.7 (44.4)	402.5 (146.6)	544.5 (321.0)	221.8 (74.8)	302.6 (165.7)	411.7 (191.2)	553.7 (268.6)	
<b>B) North Magnolia (N = 4)</b>								
Native annual forb	1.0 (0.6)	10 (1.6)	4.1 (3.2)	14.8 (6.2)	113.8 (93.1)	138.6 (114.9)	0.4 (0.4)	
Exotic annual forb	0.2 (0.1)	5.7 (1.9)	23.3 (6.8)	141.6 (73.0)	19.6 (12.7)	7.7 (5.4)	45.4 (43.5)	
Perennial forb	28.5 (10.5)	101.9 (28.8)	34.4 (20.4)	113.3 (44.5)	69.2 (21.4)	73.1 (24.8)	48.3 (37.4)	
Annual grass	1.1 (1.1)	12.7 (6.5)	10.2 (5.0)	13.5 (5.9)	50.0 (38.0)	29.1 (17)	8.9 (8.8)	
Perennial grass	4.3 (1.3)	49.2 (7.6)	37.6 (15.6)	56.9 (15.9)	84.6 (28.1)	39.6 (14.4)	81.9 (17.2)	
Shrub	212.7 (40.0)	619.2 (185.1)	912.2 (505.3)	301.4 (99.6)	301.4 (99.6)	663.8 (280.1)	913.4 (388.6)	
<b>C) South Magnolia (N = 3)</b>								
Native annual forb	0.1 (0.1)	51.9 (48.3)	3.8 (2.4)	195.8 (45.1)	15.6 (11.1)	288.3 (121)	8.1 (7.7)	
Exotic annual forb	0	21.5 (17.5)	0	287.5 (252.8)	333.9 (314.9)	22.3 (18)	1.3 (1)	
Perennial forb	5.8 (2.7)	32.8 (13.9)	24.2 (11.2)	7.7 (6.7)	23.8 (15.8)	54.5 (23.6)	52.8 (34.8)	
Annual grass	0	0	0	9.8 (5.9)	13.2 (13.2)	0	0.1 (0.1)	
Perennial grass	25.1 (12.3)	152.7 (101.6)	265.0 (172.9)	186.8 (83.0)	273.7 (85.8)	255.2 (118.4)	244.3 (111.7)	
Shrub	84.2 (76.5)	113.7 (94.2)	54.3 (19.9)	115.6 (97.4)	115.6 (97.4)	75.6 (5.5)	74.1 (41.5)	

treatment  $P > 0.10$ , MEA, Table 1S). Patterns of perennial grass cover in 2013 were also similar between NM and SM (site  $\times$  mechanical treatment  $P > 0.10$ , MEA; Table 1S). Cover differed with mechanical treatment ( $P < 0.05$ , MEA; Table 1S). Cover in mastication and rollerchop plots was significantly higher than in controls ( $P < 0.0091$ ); chained plots did not differ from control, mastication, or rollerchop plots (Table 3). We did not detect any effect of seeding or interactions involving the seeding treatment for perennial grass biomass or cover in either year ( $P > 0.05$ , SEA; Table 2S).

For perennial forbs (mostly native with trace exotics), we detected no differences in response to mechanical and seeding treatments ( $P > 0.05$ ) or treatment by site interactions ( $P > 0.10$ ) in either year, for either cover or biomass (see Tables 1S and 2S).

Shrub biomass, cover, and density were higher at SM than at NM in 2012 (biomass:  $F_{1,5} = 32.34$ ,  $P = 0.0023$ , MEA and  $F_{1,15} = 51.81$ ,  $P < 0.0001$ , SEA; cover:  $F_{1,20} = 48.07$ ,  $P < 0.0001$ , MEA and  $F_{1,15} = 36.15$ ,  $P < 0.0001$ , SEA; density:  $F_{1,5} = 7.82$ ,  $P = 0.0382$ , MEA and  $F_{1,5} = 13.48$ ,  $P = 0.0144$ , SEA). Despite a significant mechanical by seeding interaction for 2012 shrub biomass ( $F_{2,15} = 4.40$ ,  $P = 0.0313$ , SEA), all pairwise comparisons were nonsignificant after Tukey's adjustment. Shrub cover was higher in control plots than all mechanically treated plots in 2012 ( $F_{3,20} = 13.30$ ,  $P < 0.0001$ , MEA), but there were no detectable differences in shrub biomass (Tables 2, 1S, 2S) and cover (Tables 3, 1S, 2S) in response to treatments in 2013. Effect of seeding on seeded

shrub density depended on site (site  $\times$  seeding interaction  $F_{1,15} = 3.03$ ,  $P = 0.1022$ , SEA). Seeding did not have a detectable effect at NM ( $P > 0.18$ , SEA), but seeding increased average-seeded shrub density more than threefold at SM ( $F_{2,6} = 16.13$ ,  $P = 0.0070$ , SEA) (Fig. 1). Seeded shrub density was not influenced by mechanical treatment or by a seed  $\times$  mechanical treatment interaction ( $P > 0.59$  SEA).

#### Annual Plant Responses

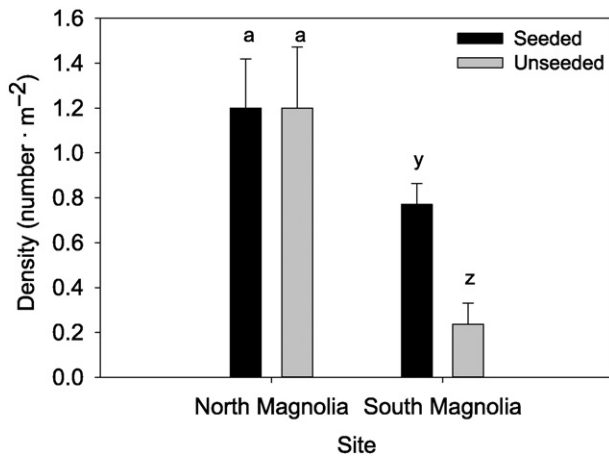
Annual plant growth was extremely limited in 2012. Across sites and treatments, biomass of exotic annual forbs was  $0.4 \pm 0.4$  kg  $\cdot$  ha<sup>-1</sup>, that of native annual forbs was  $1.0 \pm 0.4$  kg  $\cdot$  ha<sup>-1</sup>, and exotic annual grass biomass was  $< 0.1$  kg  $\cdot$  ha<sup>-1</sup>. In contrast, the corresponding biomass values in 2013 were roughly 150 times higher (see Table 2).

Native annual forb biomass in 2013 responded similarly at both sites (site  $\times$  mechanical treatment  $P > 0.10$ , MEA, see Table 1S) and was influenced by mechanical treatment ( $P < 0.05$ , MEA, see Table 1S). Native annual forb biomass in rollerchop plots was significantly higher than controls ( $P = 0.0176$ ), while mastication and chain treatments were intermediate and did not differ from one another, rollerchop, or control plots (see Table 2). Native annual forb cover in 2013 also differed by mechanical treatment ( $P < 0.05$ , MEA; see Table 1S), with rollerchop and mastication treatments having significantly higher native annual forb

**Table 3**

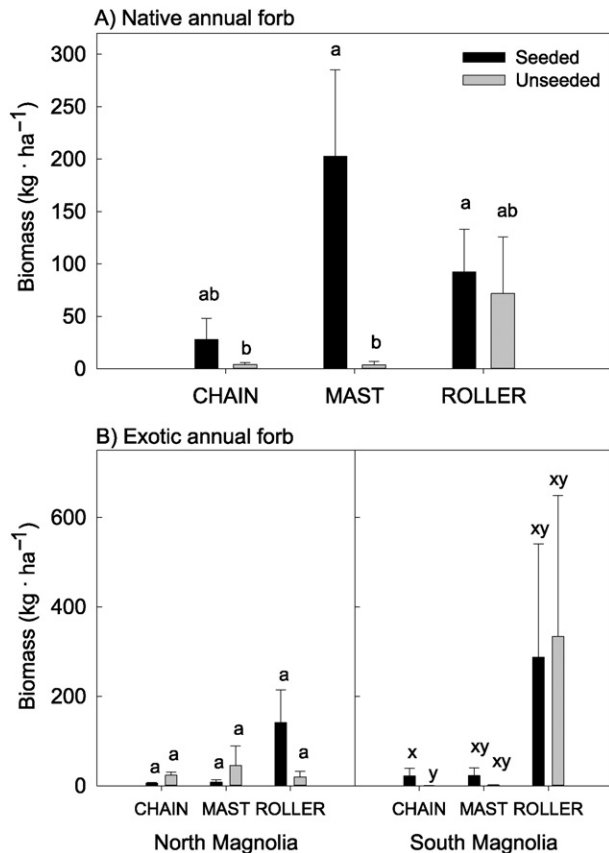
Mean cover ( $\pm$  SE %) by plant functional group collected in 2013 from 2 sites in northwest Colorado where 3 mechanical treatments were used to remove pinyon-juniper overstory: anchor chain, rollerchopper, or mastication. Half of each mechanically treated plot was seeded, and control plots received no mechanical or seeding treatment

	Control		Chain		Rollerchop		Mastication	
	Unseeded	Seeded	Unseeded	Seeded	Unseeded	Seeded	Unseeded	Seeded
<b>Cover (SE)</b>								
Native annual forb	0.07 (0.07)	3.50 (1.09)	0.56 (0.27)	4.22 (1.09)	1.47 (0.42)	2.95 (0.83)	0.86 (0.17)	
Exotic annual forb	0.20 (0.14)	3.17 (0.58)	3.14 (0.80)	4.72 (1.60)	7.06 (2.08)	1.90 (0.56)	3.13 (1.05)	
Perennial forb	0.69 (0.18)	2.34 (0.53)	1.38 (0.52)	1.93 (0.76)	1.25 (0.22)	3.85 (0.70)	2.36 (0.79)	
Annual grass	0.13 (0.08)	1.85 (1.16)	1.63 (0.67)	2.79 (1.87)	2.98 (1.75)	1.57 (0.99)	1.09 (0.41)	
Perennial grass	3.21 (1.30)	8.26 (2.09)	7.08 (1.87)	7.80 (1.52)	9.52 (2.23)	9.62 (2.59)	10.2 (2.86)	
Shrub	13.79 (3.29)	10.12 (3.53)	15.35 (4.59)	13.86 (3.55)	7.52 (2.46)	11.25 (2.99)	11.63 (3.10)	



**Fig. 1.** Density (numbers · m<sup>-2</sup>) of seeded shrub species occurring in seeded and unseeded plots at North Magnolia and South Magnolia. Because there was a significant site × seeding interaction, seeded shrub density was analyzed separately for each site; different letters above bars for a given site indicate significant difference at  $P = 0.05$ . Error bars represent  $\pm 1$  standard error.

cover than controls ( $P < 0.0190$ ; see Table 3). There was a significant seeding × mechanical treatment interaction for biomass ( $P < 0.05$ , SEA; Fig. 2A, see Table 2S) but no interactions involving site ( $P > 0.10$ ,



**Fig. 2.** Average biomass (g · m<sup>-2</sup>) of **A**, native annual forb biomass in seeded and unseeded subplots associated with each mechanical treatment and **B**, exotic annual forb biomass in seeded and unseeded subplots associated with each mechanical treatment at each site (North Magnolia, South Magnolia). There was no effect of site (main effect or interactions) on native annual forb biomass. Because there was a significant site-wise interaction, exotic annual forb biomass was analyzed separately for each site. Treatment abbreviations are as follows: CHAIN = chaining, MAST = mastication, ROLLER = rollerchopping). Different letters above bars indicate significant difference at  $P = 0.05$ . Error bars represent  $\pm 1$  standard error.

SEA; see Table 2S). Seeding increased native annual forb biomass more than 50-fold in mastication plots, while seeding effects for other mechanical treatments were not significant (see Fig. 2A, Table 2). For cover, the magnitude of the seeding effect depended on site (site × seeding  $P < 0.05$ , SEA; see Tables 3 and 2S). Seeding increased native annual forb cover from  $0.76 \pm 0.20\%$  to  $2.0 \pm 0.49\%$  at NM ( $F_{1,9} = 5.17$ ,  $P = 0.0096$ , SEA) and increased native annual forb cover from  $1.24 \pm 0.35\%$  to  $5.63 \pm 0.72\%$  at SM ( $F_{1,6} = 52.29$ ,  $P = 0.0004$ , SEA). At both sites, there were no interactions involving mechanical treatment for native annual forb cover ( $P > 0.05$ , SEA; see Table 2S). Common native annual forbs were Rocky Mountain bee plant (*Cleome serrulata* Pursh) (seeded species), Hoary tansyaster (*Machaeranthera canescens* [Pursh] A. Gray), Western tansymustard (*Descurainia pinnata* [Walter] Britton), sunflower (*Helianthus annuus* L.) (seeded species), and Fremont's goosefoot (*Chenopodium fremontii* S. Watson).

In 2013, exotic annual forb biomass responded differently to mechanical treatments at NM and SM (site × mechanical treatment  $P < 0.10$ , MEA, see Table 1S). At NM, exotic annual forb biomass was higher in all three mechanical treatments than controls ( $F_{3,9} = 9.19$ ,  $P = 0.0042$ , MEA,  $P < 0.0384$ ; see Table 2). At SM, exotic annual forb biomass depended on mechanical treatment ( $F_{3,6} = 7.16$ ,  $P = 0.0208$ , MEA), with rollerchop higher than chain and control plots ( $P < 0.0285$ ; see Table 2). Exotic annual forb cover in 2013 responded similarly at NM and SM (site × mechanical treatment  $P > 0.10$ , MEA). Exotic annual forb cover in rollerchop, chain, and mastication treatments was significantly higher than in controls ( $P < 0.0108$ ), and rollerchop was also higher than mastication ( $P = 0.0519$ ; see Table 3). There was a significant three-way interaction among seeding, site, and mechanical treatment for biomass ( $P < 0.10$ , SEA; see Fig. 2B, Table 3). At NM, there were no significant effects involving seeding ( $P > 0.36$ ). The effect of seeding at SM depended on mechanical treatment (seeding × mechanical treatment  $F_{2,6} = 5.10$ ,  $P = 0.0508$ ). There were no exotic annual forbs in unseeded chained subplots but over  $20 \text{ kg} \cdot \text{ha}^{-1}$  in seeded subplots (see Fig. 2B). In mastication and rollerchop treatments, no effect of seeding was detected. High exotic annual forb cover means for rollerchop plots at SM were due to a dense patch of Russian thistle (*Salsola tragus* L.) in a single plot (see Fig. 2B). There were no significant effects of seeding or interactions involving seeding on exotic annual forb cover ( $P > 0.05$ , SEA; see Table 3). Common exotic annual forbs were Russian thistle, lambsquarters (*Chenopodium album* L.), and pale madwort (*Alyssum alyssoides* L.).

In 2013, the only annual grass detected was cheatgrass. Cheatgrass biomass did not differ by site or mechanical treatment ( $P > 0.05$ , MEA; see Table 2S), but cover responded differently depending on site and mechanical treatment ( $P < 0.10$ , MEA; see Table 2S). At NM, rollerchop plots had  $4.98 \pm 2.76\%$  annual grass cover, which was significantly higher than mastication ( $1.07 \pm 0.76\%$ ) and control plots ( $0.24 \pm 0.14\%$ ;  $P < 0.033$  MEA). Chained plots had  $2.73 \pm 0.79\%$  annual grass cover, which was statistically similar to rollerchop and mastication but higher than control plots ( $P = 0.0278$ , MEA). Mastication plots were statistically similar to controls. At SM, mastication ( $1.12 \pm 0.25\%$ ) had significantly higher cheatgrass cover than control ( $0\%$ ;  $P = 0.0341$ ). All other treatments were intermediate between and not significantly different from mastication and control ( $F_{3,8} = 4.50$ ,  $P = 0.0395$ , MEA). For both biomass and cover, there were no effects of seeding ( $P > 0.05$ , SEA) or interactions involving seeding with site ( $P > 0.10$ , SEA). The seeded native annual grass, 6-weeks fescue (*Vulpia octoflora* [Walter] Rydb.), was not detected in either year. Seeded sterile wheat was present at very low levels in 2012 ( $0.02 \pm 0.01\%$  cover across sites) and not found in 2013.

#### Bare Ground

Mechanical treatments differed in the amount of resulting bare ground in 2012 ( $F_{3,20} = 7.81$ ,  $P = 0.0012$ ), and sites responded similarly (site × mechanical treatment  $F_{3,15} = 0.73$ ,  $P = 0.5482$ , MEA). Across



sites, there was a higher percentage of bare ground in rollerchop ( $22 \pm 0.02\%$ ) versus chain ( $14 \pm 0.02\%$ ) and mastication treatments ( $11 \pm 0.01\%$ ;  $P < 0.0152$ ). Bare ground coverage in control plots ( $19 \pm 0.02\%$ ) did not differ from rollerchop or chain but was greater than in mastication ( $P = 0.0275$ , MEA).

## Discussion

Differential impacts of mechanical pinyon-juniper removal and seeding treatments on understory vegetation were observed in this study. Each method of mechanical treatment was successful in removing trees and generally benefited understory species. Plant community composition after two growing seasons appears to be consistent with other studies that have reported establishment of annuals initially, as well as presence of perennial understory species that survived mechanical treatment (Barney and Frischknecht 1974; Tausch and Tueller 1977; Skousen et al. 1989; Redmond et al. 2013).

Early-seral species are adapted to postdisturbance environments (Pickett 1976) and rely on regeneration from seed (Bazzaz 1996), so it is not surprising that annuals tended to respond to mechanical treatments, seeding, or both. All annual groups (native forb, exotic forb, exotic grass) were promoted by rollerchopping, mastication, and/or chaining relative to controls. Roundy et al. (2014b) found that pinyon-juniper tree removal increased soil water during spring and summer across a variety of western US sites. Fast-growing annuals in newly disturbed sites are likely able to take advantage of such increased availability of water early in the growing season (Cline et al. 1977; Bazzaz 1996; Bates et al. 2006). Tree removal may also promote germination and establishment of annual plants by reducing competition with trees, improving the light, nutrient, and thermal environment following canopy removal and creating roughened patches of bareground (Evans and Young 1972; McConnaughay and Bazzaz 1987; Hobbs and Huenneke 1992; Bazzaz 1996; Chambers 2000; Bates et al. 2002; D'Antonio and Meyerson 2002). Although we did not track changes in light, temperature, or soil nutrients, annuals tended to have the most consistent positive response to rollerchopping, which was associated with 8% or 10% more bare ground than chaining or mastication, respectively. That annuals were often similar between chaining and mastication is somewhat surprising given that chaining has often been thought to cause a greater degree of soil disturbance (Vallentine 1989; Stevens 1999; Bates et al. 2005) relative to mastication, which uses rubber-tired machines rather than tracked vehicles (Cline et al. 2010). In this study, however, chaining tended to have a much more patchy impact on the soil surface due to decreased chain-soil contact with proximity to bulldozer attachment points and the chain occasionally snagging on slash. Therefore, although the depth of soil disturbance was great where trees were uprooted, portions of chained plots had no surface disturbance at all.

Despite our expectation that seeding in conjunction with mechanical treatments may inhibit establishment of exotic annual species, we did not detect negative seeding effects on exotic annual forbs or grasses in the first 2 years posttreatment. However, seeding was effective for promoting native annual forbs; cover was 2.5 and 4.5 times higher in seeded than unseeded plots across all mechanical treatments at NM and SM, respectively, while biomass in mastication plots increased more than 50-fold when seeded. Mastication may have been particularly effective at enhancing germination and growth of seeds because the smaller chunks of wood produced by this method can reduce erosion, retain moisture, and reduce soil surface temperatures (Owen et al. 2009; Battaglia et al. 2010; Ross et al. 2012; Young et al. 2013a, 2013b; Pierson et al. 2014). It should be noted, however, that masticated material can inhibit seedling emergence if debris depth becomes too great (Wolk and Rocca 2009; Young et al. 2013a). It is also important to emphasize that broadcast seeding was done before treatment in this study to facilitate seed-soil contact. Seeding posttreatment would be easier and cheaper, but establishment of seed broadcast after

treatments may be less successful (Ott et al. 2003; Baughman et al. 2010). Our results illustrate that including native annual species in seed mixes and applying them before treatment can improve native plant establishment early in recovery.

Rapid changes in the early years of plant community development following treatment were expected (Tausch and Tueller 1977; Bates et al. 2002; Bates et al. 2011) and were confirmed in this study. Exotic annual abundance was negligible in 2012 and remained so in control plots in 2013. However, in mechanically treated plots, exotic annuals rose substantially in 2013. Recent anecdotal reports indicate further increases, particularly of cheatgrass, across all mechanically treated plots, especially rollerchopped plots. Delayed responses of exotics to mechanical treatments have also been observed in other pinyon-juniper removal studies where exotics were not abundant before treatment (Bates et al. 2005; Owen et al. 2009; Miller et al. 2014). Machinery may act as a vector for non-native annual seed (Vitalos and Karrer 2009), and this may have been a factor in this study, as machinery was not washed before treatment implementation. However, exotic species abundance may increase following tree removal regardless of whether there is an obvious propagule source in the surrounding landscape (Roundy et al. 2014a). Further study is necessary to understand the relative importance of seed dispersal versus altered abiotic conditions in promoting undesirable annuals. Continued monitoring is essential for determining if exotic species or desirable perennials will eventually gain site dominance after mechanical treatments (Roundy et al. 2014a).

While responses of annual plants differed to some degree among mechanical treatments, those of perennials generally did not. Shrubs and perennial forbs were similar across mechanical treatments and controls. Although similar results were found for perennial forbs in some pinyon-juniper removal studies (Owen et al. 2009; Provencher and Thompson 2014), others observed that perennial forbs significantly increased by 2–3 yr posttreatment (Tausch and Tueller 1977; Skousen et al. 1989; O'Connor et al. 2013). Although perennial grass biomass did not differ among mechanical treatment types, it was 10–15 times higher in mechanically treated plots than in untreated controls. Contrary to our expectation concerning shrubs, mechanical treatments likely encouraged growth of surviving grasses (Miller et al. 2014) because the response was not related to seeding. Such a stimulatory effect may also explain greater response of perennial grasses at SM, relative to NM, where controls suggest higher pretreatment abundance of grasses. The lack of perennial grass response to seeding treatments may be due to seedling competition with existing grasses (Fowler 1986) or because 2 yr posttreatment is too soon to detect significant establishment and growth of perennials (Bates et al. 2005; Bates et al. 2007).

Seeding was effective for increasing shrub density, but the effect was limited to SM. At SM, shrub cover in control plots was only 5% (compared with 20% at NM). Shrubs may have been too dominant at NM for seeding to matter, which supports the results of Roundy et al. (2014a) in suggesting that seeding may be necessary for achieving desirable understory establishment in areas where pretreatment tree dominance is high and perennial forbs and shrubs are sparse.

Understanding site conditions is at least as important as the choice of equipment in creating a desirable outcome. Pretreatment tree dominance is important because the degree of woody encroachment influences understory abundance and hence the trajectory of response posttreatment (Bates et al. 2005; Miller et al. 2014; Roundy et al. 2014a). In this study, there was higher tree basal area and understory forbs and shrubs were more compromised in control plots at SM (late phase III sensu Miller et al. 2008) compared with NM (late phase II). All instances in which biomass or cover responses to mechanical or seeding treatments differed between sites occurred with annual plant functional groups (native forb, exotic forb, exotic grass; see Tables 1S and 2S in the online version at <http://dx.doi.org/10.1016/j.rama.2016.06.003>), and in most cases differences due to site effects were equal to or greater than those due to treatment type.

Initial results suggest mechanical removal of pinyon-juniper canopy will increase mule deer forage at these sites. Removing trees, even without seeding, increased understory abundance compared with no tree removal as was also shown by Roundy et al. (2014a). However, forage quality is also important for maintaining nutritional requirements of mule deer under winter conditions (Bartmann 1983). In order to achieve a nutritionally adequate and diverse understory plant community, artificial seeding may be necessary (Young et al. 2013a). This study highlights the effectiveness of seeding shrubs before mechanical tree removal, particularly in areas with low pre-existing shrub abundance. Our results also suggest that the choice of mechanical equipment may impact annual plant responses. Further monitoring is necessary to understand long-term responses of desirable perennial species to mechanical and seeding treatments.

## Implications

This study indicates that mechanical removal of pinyon-juniper canopy by chaining, rollerchopping, or mastication in northwestern Colorado can result in increased understory vegetation relative to untreated areas 2 yr after treatment. In particular, grass biomass increased 10- to 15-fold with treatment. Perennial plant responses were similar among tree removal methods; therefore, logistical factors or cost may dictate which method is most appropriate. In this study, mobilization costs were highest for rollerchopping (\$8 000), which required a bulldozer, a crane to remove the rollerchopper drum from the trailer, and a water truck to fill the drum. Per-area cost was intermediate ( $\$400 \cdot \text{ha}^{-1}$ ) for rollerchopping. Rollerchopping produced the most bareground, which may lead to a higher risk of invasion by exotic species. Therefore, rollerchopping may be most appropriate for large project areas where exotic species invasion is not a concern. Mastication had the lowest mobilization cost (\$2 050) but the highest per-area cost ( $\$1\,230 \cdot \text{ha}^{-1}$ ). Mastication allowed the most operator selectivity in tree removal, making it an attractive choice where the operator may retain desirable shrubs or create a mosaic of tree-covered and treeless areas in order to provide a combination of hiding cover and foraging opportunities for mule deer. Mastication was also the most effective in conjunction with pretreatment seeding. We conclude that mastication is a useful technique, especially for smaller areas, where lower mobilization costs are a benefit. Chaining had intermediate mobilization costs (\$5 600) and the lowest per-acre cost ( $\$300 \cdot \text{ha}^{-1}$ ). Although precise tree removal is not possible with chaining, the shorter chain used in this study permits application of small-patch-size treatments that may benefit mule deer in a cost-effective manner. We concur with Provencher and Thompson (2014), who found chaining to be a cost-effective way to reduce tree cover across the landscape.

We observed differences between our two study sites highlighting the need for careful attention to pretreatment understory conditions. For example, we found that seeding can increase shrub density by the second year, but this may only be realized where pretreatment shrub abundance is low. The seed mix used in this experiment cost  $\$2\,000 \cdot \text{ha}^{-1}$  ( $\$810 \cdot \text{ac}^{-1}$ ), and about half of that cost was for just four species of desirable shrubs: Utah serviceberry, Saskatoon serviceberry, bitterbrush, and mountain mahogany. Therefore, we recommend targeting seeding efforts on those sites where it is most likely to be effective. Careful selection of species is also critical. In our study, bitterbrush was the most abundant species detected in shrub density counts. Where seeding is deemed appropriate and treatments involve tracked machinery, use of a seed dribbler (Stevens and Monson 2004) seems to be a viable option for species that require deeper planting (e.g., bitterbrush, serviceberry) because seeded shrub density was similar whether broadcast before treatment (mastication) or applied with the seed dribbler during treatment (rollerchopping and chaining). Where shrubs and other desirable understory species are abundant, mechanical treatments alone may be sufficient to increase forage.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.rama.2016.06.003>.

## Acknowledgments

We thank Brett Wolk and laboratory assistants from the Restoration Ecology Laboratory at Colorado State University for their assistance with field work and data processing, Lisa Belmonte and Ed Hollowed for Bureau of Land Management access, Todd Graham of Ranch Advisory Partners and Charles Anderson of Colorado Parks and Wildlife for help with site selection, Jim Gammonley and Sandra Billings for administrative support, and Mike Wille of T&M Contracting for treatment implementation.

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