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Vegetation Responses to Pinyon–Juniper Treatments in Eastern Nevada

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Abstract

Comparisons of tree-removal treatments to reduce the cover of single-leaf pinyon (*Pinus monophylla* Torr. and Frém.) and Utah juniper (*Juniperus osteosperma* [Torr.] Little), and subsequently increase native herbaceous cover in black sagebrush (*Artemisia nova* A. Nelson), are needed to identify most cost-effective methods. Two adjacent vegetation management experiments were initiated in 2006 and monitored until 2010 in eastern Nevada to compare the costs and efficacy of various tree reduction methods. One Department of Energy (DOE) experiment compared a control to five treatments: bulldozing imitating chaining ($\$205 \cdot ha^{-1}$), lop-pile-burn ($\$2\,309 \cdot ha^{-1}$), lop-and-scatter ($\$1\,297 \cdot ha^{-1}$), feller-buncher and chipper ($\$4\,940 \cdot ha^{-1}$), and mastication ($\$1\,136 \cdot ha^{-1}$), whereas a second Bureau of Land Management (BLM) experiment compared one-way chaining ($\$205 \cdot ha^{-1}$) to a control treatment. Chaining and bulldozing resulted in the least reduction of tree cover among the treatments. In the DOE experiment, forb cover only decreased in the mastication treatment. Litter increased in all methods. Slash cover was lowest in the control and lop-pile-burn treatments, intermediate in the feller-buncher and mastication treatments, and highest in the bulldozing and lop-and-scatter treatments. By 2010, forb cover and the combined cover of dead shrubs and trees were increased and decreased, respectively, by chaining in the BLM experiment. Nonnative annual grass and biotic crust were absent or uncommon before and after treatment implementation. In both experiments, tree removal resulted in a nonsignificant increase in perennial grass cover even 4 yr post-treatment. An ecological return-on-investment (EROI) metric was developed to compare perennial grass cover and tree cover per unit area cost of each active treatment. By 2010, chaining or bulldozing, followed by mastication, showed the highest EROI for improving perennial grass and decreasing tree cover. Mastication is recommended for restoration of smaller tree-encroached areas, whereas land managers should reconsider smooth chaining, despite its negative perceptions, for rapid and cost-efficient restoration of large landscapes obligates.

Key Words: black sagebrush, chaining, feller-buncher, Great Basin, mastication, perennial grass

INTRODUCTION

Vegetation management of Intermountain West rangelands has increased recently to meet the specific needs of various stakeholders (Miller et al. 2005; Wisdom et al. 2005; Hood and Miller 2007). Common reasons for managing vegetation have been to protect homes from wildfires by changing fire behavior (Agee et al. 2000; Stratton 2008) and improve wildlife habitat (Tausch and Tueller 1977; Skousen et al. 1989), livestock forage (Vernon et al. 2001), and habitat for sensitive or listed species (Connelly et al. 2000; Dahlgren et al. 2006). In the Great Basin, recent and century-old challenges that land managers routinely contend with are: encroachment of pinyon and juniper into shrublands, invasion by nonnative plant species, shrublands depleted of native herbaceous cover, and low successional heterogeneity across landscapes (Blackburn and Tueller 1970; Young and Sparks 2002; Wisdom et al. 2005; Kitchen and McArthur 2007; Provencher et al. 2008).

Vegetation treatments are generally expensive, especially for pinyon and juniper control and when the cost of planning mandated by the National Environmental Protection Act (NEPA) and litigation are factored in the management of public lands. Common methods of pinyon–juniper control have varied over the decades: 1) prescribed burning remains a widespread and increasingly economical method at higher elevations when nonnative grasses are at low abundance (Miller et al. 2005); 2) chaining or bulldozing of trees (although limited to few areas today) was frequently deployed to improve livestock forage and big game habitat from the 1950s to 1980s (Tausch and Tueller 1977; Skousen et al. 1989; Miller et al. 2005); 3) chainsaw cutting of western juniper and leaving them intact on the ground is the most commonly used and inexpensive mechanical method in Oregon (Miller et al. 2005); 4) other more expensive forms of chainsaw cutting frequently used in many states include lopping branches and scattering woody material, or piling branches and stems that are subsequently burned, usually when the ground is covered with snow (Miller et al. 2005; Owen et al. 2009; O'Connor et al. 2013); and 5) heavier machines, such as masticators and feller-buncher-chippers grind trees and are increasingly used at the wildland–urban interface, but also in small wildland projects (Miller et al. 2005; Owen et al. 2009; Baughman et al. 2010).

Few pinyon–juniper control projects are monitored before and after treatment implementation with the established quantitative methods required in sagebrush systems (Miller et al. 2005; Baughman et al. 2010). Finally, only a few projects incorporate multiple mechanical treatments with proper control treatments and replication (Miller et al. 2005). Given the high cost of vegetation manipulation, quantitative comparisons of alternative treatments would greatly benefit land managers who are faced with limited resources and who want to achieve the highest ecological return-on-investment (EROI).

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Such results would provide data for future NEPA documentation and possible litigation.

In this study, we examine the short-term (≤ 4 yrs) effects of various single-leaf pinyon (*Pinus monophylla* Torr. & Frém.) and Utah juniper (*Juniperus osteosperma* [Torr.] Little) removal treatments on vegetation and ground cover in black sagebrush (*Artemisia nova* A. Nelson) ecosystems encroached by these tree species on lands managed by the Bureau of Land Management Ely Field Office (hereafter, BLM). Two experiments were performed; however, only one experiment contained true replicates. We hypothesized that removal of pinyon and juniper cover would result in progressively increasing perennial grass cover, forb cover, and nonnative annual grass cover with time after implementation. We also hypothesized that the most expensive pinyon–juniper control methods would not necessarily yield the highest increase in perennial grass and forb cover or the highest EROI. Vegetation and ground cover responses were monitored for 4 yr after treatment implementation, and EROI values were calculated for each treatment.

METHODS

The study was located in Smith Valley (lat 39°26′30″ to 39°25′0″ north to south; long 114°59′0″ to 114°56′15″ west to east), which is a small watershed located about 20 km north-northwest of Ely, Nevada (elevation from 2 042 m to 2 194 m; 250 to 320 mm precipitation; Fig. 1). Black sagebrush is the dominant shrub species in the project area and single-leaf pinyon and Utah juniper are the common trees in the study area. The level of pinyon–juniper encroachment into the project area's shrubland corresponded to any of three definitions: 1) Blackburn and Tueller's (1970) scattered (several old trees, many tree saplings, viable understory with dying sagebrush) to dense (abundant pinyon and juniper with some sagebrush) classification for black sagebrush; 2) the late phase II of Miller and Tausch (2001); or 3) LANDFIRE's late-succession wooded phase of black sagebrush (biophysical setting 1710790; LANDFIRE 2010). Limestone is the dominant bedrock, but the northwest side of the valley contains soil with andesite layers at higher elevations. On most plots, black sagebrush dominates where a calcareous loam soil overlays limestone. Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle & Young) and antelope bitterbrush (*Purshia tridentata* [Pursh] DC.) dominate on gravelly loam soils associated with limestone and andesite on four of nine northwestern pairs of sampling plots on or adjacent to chained plots.

During 2006–2007, the BLM and Eastern Nevada Landscape Coalition (ENLC) implemented two pinyon–juniper reduction experiments. One experiment (funded by the Department of Energy [DOE], referred hereafter as the DOE experiment) compared five pinyon–juniper reduction methods and a no-treatment control with three replications in a complete randomized block design (Steel and Torrie 1980). The second experiment (funded by BLM and referred hereafter as the BLM experiment) used one-way smooth chaining and involved no-treatment control plots. Chaining was a typical one-way operation with a thick 21-m smooth chain dragged over the vegetation between two tractors. In the DOE experiment, replications were stratified in three elevation bands that matched soil types as determined by the BLM's soil scientist (Fig. 1). One replication of each treatment approximately followed contour lines to form one block. Pinyon–juniper reduction methods included bulldozing trees to imitate small-scale chaining, feller-buncher and chipper (hereafter, feller-buncher), chainsaw lopping-pile-burn (hereafter lop-pile-burn), chainsaw lop-and-scatter, and mastication (details in Table 1). For the DOE experiment, a bulldozer's flat shovel was used to push woody vegetation (similar to chaining) because tractors and chain could not be maneuvered within the experimental plot areas. Each replicate plot was 5.4 ha. Piles were burned during the winter with snow on the ground. The feller-buncher treatment was the most expensive at $\$4\,940 \cdot ha^{-1}$, whereas one-way chaining with a smooth chain and bulldozing completed on a total 283-ha area was the least expensive at $\$205 \cdot ha^{-1}$ (Table 1). Costs presented in Table 1 would decrease for application to larger areas than our plots, especially for heavier equipment.

The BLM experiment was not implemented as an experimental design because the BLM's authority under NEPA allowed for treatment of a certain area that did not leave space to set aside randomly placed nonchained (control) paired areas of a similar size and condition. The BLM chaining did, however, create four chained areas (Fig. 1) among a matrix of both open and wooded shrublands, but these areas were not predetermined replicates matched with control plots. Given that BLM could not afford a chaining experiment with dedicated control areas, we compromised by randomly locating pairs of control and chained sampling plots at the interface of three of the four chained and nonchained areas. The pairing of chained and control sampling plots, therefore, became an important source of spatial variation. The current design limited statistical inference, and therefore limited conclusions, because spatial randomization of sampling plots was incomplete; it was entirely possible that the effective number of pairs was < 9 if some pairs were autocorrelated. The effective number of pairs is unknown. We, however, assumed that different pairs of sampling plots were probably statistically independent because the distance between the closest pairs was > 200 m, which was greater than the distance among treatments and blocks in the DOE experiment (Fig. 1). Moreover, Langs (2004) determined that there was no spatial autocorrelation after 40 m in Wyoming big sagebrush cover from the Camp Williams National Guard Training Facility near Bluffdale, Utah, suggesting that there is no spatial autocorrelation in the sampling plots in our BLM experiment.

To characterize vegetation and ground cover, we randomly located one 50×50 m sampling plot within each replicate plot. In each sampling plot, we established four parallel 50-m transects, separated by 10 m. Following the point-intercept method outlined in Forbis et al. (2007), we recorded foliar cover and ground cover by randomly dropping a pin-flag within every meter along each transect, for 50 $points \cdot transect^{-1}$ and 200 $points \cdot sampling\ plot^{-1}$. Data included cover for plant species, ground variables (bare ground, litter, dead shrubs and trees, slash, rock, lichen, moss, and biotic crust), and functional plant group (tree, shrub, perennial grass, native forb, nonnative forb, and cheatgrass [*Bromus tectorum* L.]) in 2006 (pretreatment), 2007 (first yr after

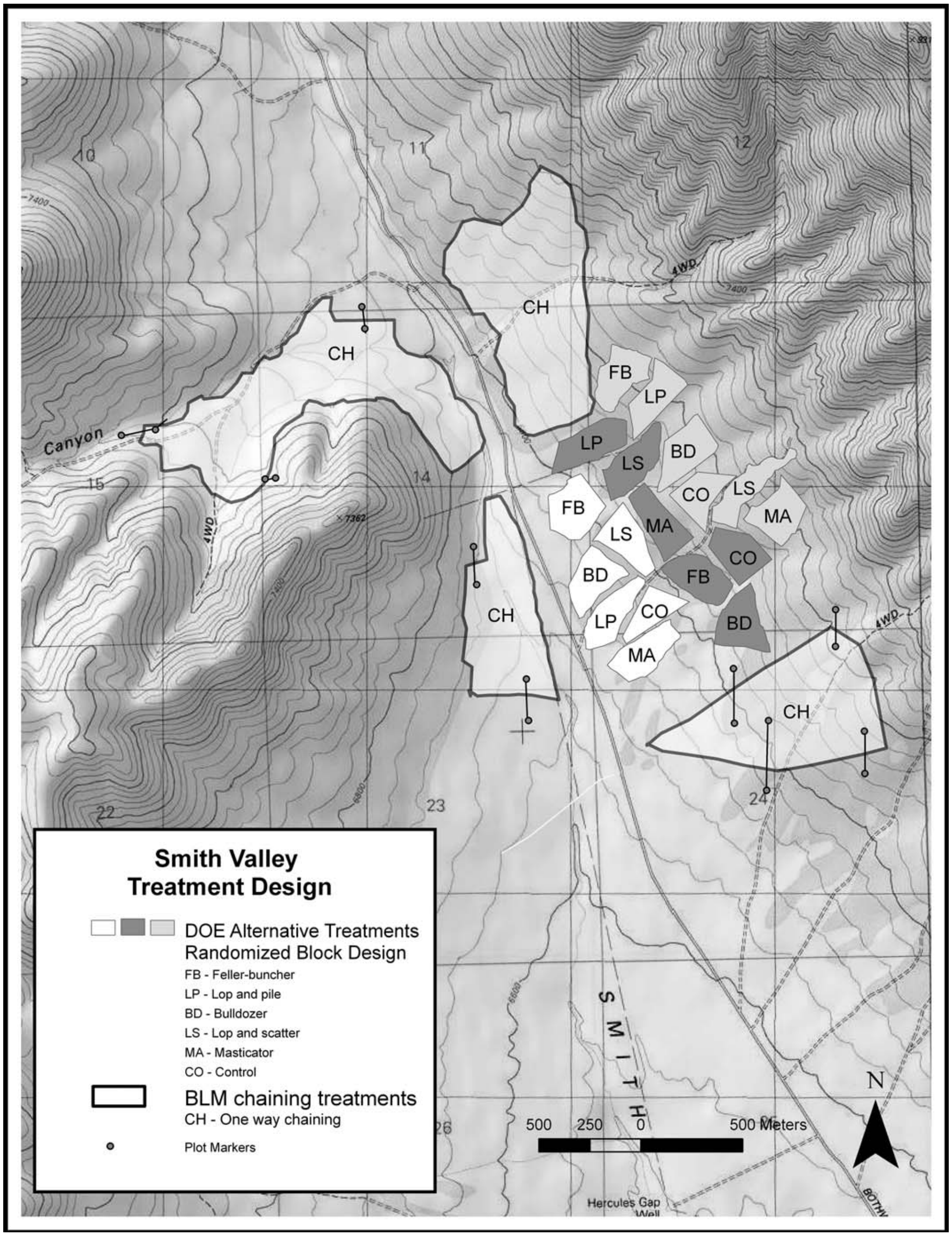

Figure 1. Locations of Department of Energy (DOE) and Bureau of Land Management (BLM) pinyon–juniper reduction experiments in Smith Valley, eastern Nevada. Legend: DOE experiment: BD indicates bulldozing imitating chaining; CO, control; FB, feller-buncher; LP, lop-pile-burn; LS, lop-and-scatter; and Ma, mastication; and BLM experiment: CH indicates Chaining. Green shade at higher elevation represents wooded areas as mapped in the 2006 National Geographic Topo version 4.2 mapping software.

treatment), 2008, and 2010. In our study, a large amount of slash was produced, which was defined as wood pieces > 5 cm in length that were produced by treatment equipment.

The final level of analysis compared treatments in terms of EROI for perennial grass cover and tree cover, although the metric can accommodate any number of response variables. We developed a metric that measured the changes in perennial grass cover and tree cover relative to the control per dollar expenditure for the treatment:

$$\mathrm{EROI} = 1000 \times \left[(\mathrm{Grass}_{t,y} - \mathrm{Grass}_{c,y})/\mathrm{Grass}_{c,y} + (\mathrm{Tree}_{c,y} - \mathrm{Tree}_{t,y})/\mathrm{Tree}_{c,y}\right]/\mathrm{Cost}_t \qquad [1]$$

where $\mathrm{Grass}_{t,y}$ and $\mathrm{Grass}_{c,y}$ (or $\mathrm{Tree}_{t,y}$ and $\mathrm{Tree}_{c,y}$) are the cover of perennial grass (or tree cover) in treatment t and control c in year y in any one replicate, respectively. Cost was calculated as the cost per hectare of treatment t (Table 1). Note that perennial grass cover in a noncontrol treatment plot and tree cover in a control plot were first in the EROI calculation

Table 1. Cost and details of vegetation management treatments during 2006–2007 for the Department of Energy (DOE) and Bureau of Land Management (BLM) experiment, Smith Valley, Nevada. Costs were recorded by BLM and Eastern Nevada Landscape Coalition (ENLC) staff.

Budget item	Lop-and-scatter	Lop-pile-burn	Mastication (Fecon shredder)	Chaining or bulldozer imitation of chaining	Feller-buncher-chipper
$\$ \cdot ha^{-1}$	\$1 297	\$2 309	\$1 136	\$205[1]	\$4 940
Area (ha)	16.2	16.2	16.2	299.6	16.2
Man hours $\cdot ha^{-1}$	86	153	25	1.5	12
Labor $\$ \cdot ha^{-1}$	\$1 297	\$2 309	\$617.50	\$37	n/a[2]
Total labor \$	\$21 000	\$36 500	\$10 000	\$600	n/a
Mechanical equipment	5 chainsaws	5 chainsaws	2 shredders, 2 skid steers	2 D8 Cats, one 21-m smooth chain	feller-buncher and chipper (200 hrs contract)
Equipment rental rate	n/a	n/a	$\geq \$2\,100 \cdot mo^{-1} \cdot shredder^{-1}$ and $\$3\,400 \cdot mo^{-1} \cdot skidsteer^{-1}$	$\$16\,700+ \cdot mo^{-1} \cdot cat^{-1}$, BLM smooth chain	n/a
Equipment rental invoice	Owned	Owned	\$5 500	\$42 869	n/a
Equipment $\$ \cdot ha^{-1}$	n/a	n/a	\$341	\$143	n/a
Equipment fuel	\$180	\$270	\$4 000	\$7 000	n/a
Fuel $\$ \cdot ha^{-1}$	\$11	\$17	\$247	\$24	n/a

[1]This area includes 283.4 ha for the BLM experiment and 16.2 ha for the DOE experiment.
[2]n/a indicates not applicable.

because we hypothesized that EROI became more positive (treatment was more successful) as perennial grass increased and tree cover decreased. The units of EROI were $ha \cdot \$^{-1}$. A negative EROI indicated that the control treatment was better than the comparison treatment. Unlike return-on-investment (ROI) values based on change in dollars invested over time divided by the initial investment, our EROI metric tracked treatment effectiveness, which is similar to the EROI metric used by Low et al. (2010). Perennial grass cover and tree cover were chosen because the BLM and ENLC considered perennial grass cover of fundamental importance for fire behavior (Miller et al. 2005), erosion rates (Buckhouse and Mattison 1980; Pierson et al. 2007), forage quality, and soil water infiltration (Pierson et al. 2007). Tree cover assessed treatment implementation success, including the remnant saplings and trees that would become the source of future tree encroachment in the recently treated shrubland (Tausch and Tueller 1977; Miller et al. 2005).

Cover data and EROI were analyzed using a two-way analysis of covariance with a mixed model (two-way ANCOVA) in both experiments. The DOE experiment was a standard randomized complete block design, where blocks were considered random and treatments fixed with pretreatment data as covariates (Steel and Torrie 1980). The error term was the mean square of the interaction of block and treatment yielding 9 degree of freedom (df) with 1 df lost to the covariate (Steel and Torrie 1980). Preplanned comparisons were performed using four contrasts when the overall treatment effect was significant ($P \leq 0.05$). Contrasts were designed to compare: 1) the control to all other treatments together; 2) the relatively inexpensive bulldozing treatment to three expensive treatments that are more commonly used (feller-buncher, lop-pile-burn, and lop-scatter); 3) the lop-pile-burn to lop-scatter treatments that differed in one action—pile burning, which can favor invasion by nonnative annual plant species; and 4) mastication to all other treatments.

For the BLM experiment, both the pairing effect of sampling plots and the need to account for pretreatment cover values (initial condition effect) limited the choice of statistical tools to a two-way ANCOVA, where the pairing of sampling plots was a random effect blocking factor, treatment was a fixed effect, and the covariate was defined by a random effect (Steel and Torrie 1980). The error term was the mean square of the interaction of pairs and treatment with 7 df with 1 df lost to the covariate (Steel and Torrie 1980). Had covariates not been collected, a paired *t*-test would be mathematically equivalent to (t^2_{paired}=F statistic) and required the same statistical assumptions as two-way analysis of variance (ANOVA; Steel and Torrie 1980). Regardless of the statistical test used, the nature of the BLM design limits our conclusions.

For simplicity, we focused our results on 2010 data in both experiments, although Supplementary Appendices S1 and S2 (http://dx.doi.org/10.2111/REM-D-12-00126.s1) present all years of data. One series of tests was performed for each post-treatment year. For analysis of EROI, the control treatment was nonexistent in the test because cover data from control plots were used to calculate EROI. Moreover, EROI in 2006 was the covariate, as if treatments had been implemented. Data were evaluated for heterogeneous variances among

Table 2. Percent cover of vegetation and ground cover variables by treatment 4 yr after treatment implementation (2010) for the Department of Energy (DOE) experiment with associated 95% confidence interval in parentheses, Smith Valley, Nevada; $n=3$ replications. Cover values for other years are presented in Supplementary Appendix S1 (http://dx.doi.org/10.2111/REM-D-12-00126.s1).

Cover	Control (%)	Bd[1] (%)	FB (%)	LP (%)	LS (%)	Ma (%)
Tree	16.5 (5.7) b[2]	7.3 (16.9)[3]	0.7 (1.9) a	1.0 (<0.1)[3]	0.7 (2.8) a	0.2 (0.7) a
Shrub	10.0 (3.7) a	13.5 (8.6) a	14.5 (16.8) a	14.7 (31.4) a	14.7 (7.6) a	13.7 (5.2) a
Forb	9.0 (8.7) a	11.4 (2.6) a	14.2 (8.9) a	10.9 (7.0) a	11.0 (4.4) a	6.3 (3.1) b
Perennial grass	10.0 (16.2) a	15.3 (20.5) a	23.0 (19.1) a	12.5 (24.8) a	18.3 (8.0) a	22.5 (21.2) a
Annual grass	0.2 (0.7)	1.2 (2.9)[3]	0.2 (0.7)	<0.1 (<0.1)[3]	<0.1 (<0.1)[3]	0.2 (0.7)
Dead shrubs and trees	3.2 (4.0) a	1.2 (3.2) a	3.2 (5.9) a	0.7 (1.9) a	1.5 (2.2) a	0.7 (0.7) a
Bare ground	40.8 (30.0) a	29.2 (21.9) a	19.0 (14.0) a	36.0 (8.7) a	23.7 (14.3) a	25.5 (9.4) a
Litter	43.2 (18.6) a	55.7 (17.1) b	66.7 (25.0) b	51.8 (4.4) b	59.2 (4.4) b	62.8 (6.8) b
Biotic crust	2.3 (5.6)	1.0 (2.5)	1.0 (0)	0.3 (1.4)	1.7 (1.4)	0.3 (1.4)
Slash[4]	4.0 (4.3) a,A	15.5 (6.9) c	7.3 (3.6) b	3.2 (9.4) B	22.8 (16.4) C	13.8 (18.7) B

[1]Bd indicates bulldozing imitating chaining; FB, feller-buncher; LP, lop-pile-burn; LS, lop-and-scatter; and Ma, mastication.

[2]Lowercase letters (a, b) indicate that means with different letters are significantly different at a $P \leq 0.05$. Because two sets of contrasts were conducted for only slash cover due to unequal variances, one additional set of uppercase letters (A to C) were applied. Rows without significance letters (or number for slash cover) are not significantly different (analyses of covariance [ANCOVAs] in Supplementary Appendix S3; http://dx.doi.org/10.2111/REM-D-12-00126.s1). Tests could not be conducted on annual grass and biotic crust cover because of very sparse data and nontransformable or no variances.

[3]Treatments were not included in tests and contrasts because variances were too heterogeneous and nontransformable compared to those of other treatments.

[4]Heterogeneous and nontransformable variances for slash cover only allowed contrasts among the following treatments: control vs. Bd vs. FB; control vs. Ma vs. LP vs. LS; and Ma vs. LP vs. LS.

treatments and transformed when necessary. Transformations were checked to verify that they homogenized variances.

RESULTS

DOE Experiment

For tree cover, only the control, feller-buncher, lop-and-scatter, and mastication treatments had sufficiently homogeneous variances after transformation to allow treatment testing (the variance for bulldozing was highly variable; Table 2). Tree cover at 16.5% was significantly higher in the control treatment than in the feller-buncher (0.7% cover), lop-and-scatter (0.7% cover), and mastication (0.2% cover) treatments ($P < 0.001$; Table 2). Tree cover did not differ among the feller-buncher, lop-and-scatter, and mastication treatments ($P=0.6$). Mean tree cover for the lop-pile-burn treatment, which we could not test, was not different from those of the feller-buncher and lop-and-scatter treatments because the narrow 95% confidence interval for tree cover ($\pm$ 0.01) from the lop-pile-burn treatment was completely contained within those of the feller-buncher and lop-and-scatter treatments (Table 2).

Forb, litter, and slash cover responded significantly to treatments (Tables 2 and 3). The strongest biotic treatment response was detected for forb cover ($P=0.045$; Table 3). Contrasts revealed that forb cover was lowest in the mastication treatment (6.3% cover vs. the next lowest of 9.0% cover in the control treatment, Tables 2 and 3). Litter cover significantly increased in all treatments (52–67% cover) compared to the control (43% cover), but there were no differences among the noncontrol treatments ($P=0.002$; Tables 2 and 3). Predictably, treatments that created coarse woody debris increased slash cover to $> 13\%$ compared to the control ($P=0.002$ with heterogeneous variances; Table 2). Targeted contrasts among homogenous treatment variances showed that the greatest amount of slash was observed in lop-and-scatter and bulldozing plots compared to control plots, whereas the smallest slash cover at $< 5\%$ was found in the lop-pile-burn treatment (Table 2). The control, feller-buncher, and mastication treatments had intermediate levels of slash cover.

Other variables showed no significant effects because of large treatment variances (Table 2; Supplementary Appendix S3 for all ANCOVAs; http://dx.doi.org/10.2111/REM-D-12-00126.s1). Annual grass cover was not tested because it was undetected in most plots in all years (Table 2). Biotic crust cover was especially low, often undetected, in all plots in pretreatment and post-treatment years (Table 2).

BLM Experiment

Significance probabilities from the BLM experiment presented here assumed complete randomization of chained and control areas, which was not the case; therefore, results for the BLM experiment might be less significant than indicated below. As expected, one-way chaining resulted in about a threefold less tree cover (6.2% cover) than that in control plots in 2010

Table 3. Probability of significant differences for mean percent cover (%) showing only variables with at least one significant contrast ($P \leq 0.05$) for the Department of Energy (DOE) experiment in 2010, Smith Valley, Nevada.

	Probability of significant differences[1]			
Cover	Control vs. Bd + FB + LS + LP + Ma	Chaining vs. FB + LP + LS	LP vs. LS	Ma vs. Bd + FB + LS + LP
Forb	0.19	0.96	0.83	0.005
Litter	0.002	0.45	0.19	0.35

[1]Bd indicates bulldozing imitating chaining; FB, Feller-buncher; LP, lop-pile-burn; LS, lop-and-scatter; and Ma, mastication.

Table 4. Mean percent cover and associated 95% confidence intervals for the Bureau of Land Management's (BLM's) chaining experiment from the pretreatment (2006) and fourth post-treatment year (2010), Smith Valley, Nevada. Data for years 2007 and 2008 are shown in Supplementary Appendix S2 (http://dx.doi.org/10.2111/REM-D-12-00126.s1). The test is the treatment effect from analyses of covariance (ANCOVAs; Supplementary Appendix S4; http://dx.doi.org/10.2111/REM-D-12-00126.s1) using the 2006 percent cover as the covariate. P=significance probability; n=9 replications.

	2006		2010		
Treatment	Control (%)	Chaining (%)	Control (%)	Chaining (%)	P test
Tree	23.8 ± 5.7	28.7 ± 6.0	20.1 ± 9.8	6.2 ± 2.9	< 0.001
Shrub	15.2 ± 7.7	13.9 ± 6.6	16.2 ± 7.6	13.6 ± 5.8	0.314
Forb	3.4 ± 1.0	2.8 ± 1.0	5.2 ± 1.8	10.6 ± 3.4	0.015
Perennial grass	11.3 ± 7.3	15.4 ± 8.4	11.8 ± 5.9	18.9 ± 10.9	0.064
Annual grass	1.8 ± 2.4	1.7 ± 3.0	2.1 ± 4.2	2.3 ± 4.3	0.101
Dead shrubs and trees	1.9 ± 1.4	1.7 ± 1.1	3.2 ± 2.5	1.5 ± 0.90	0.038
Bare ground	44.7 ± 9.0	43.0 ± 8.1	33.8 ± 9.8	32.1 ± 8.3	0.712
Litter	48.8 ± 7.7	51.8 ± 7.6	59.0 ± 9.4	57.8 ± 7.2	0.402
Slash	0.0 ± 0.0	0.0 ± 0.0	1.1 ± 1.4	11.2 ± 4.0	nt[1]
Biotic crust	0.7 ± 0.9	0.5 ± 0.6	0.6 ± 0.7	0.9 ± 1.5	nt[1]

[1]nt indicates not testable.

($P < 0.001$; Table 4). Variances were highly variable for tree cover. Only three other cover measurements were significant between chained and control plots in 2010: forb cover doubled, and slash increased by 10 times to 11.22% cover in chained plots (P=0.015, and $P < 0.001$, respectively), whereas dead shrubs and trees decreased by half to 1.5% cover in chained plots compared to the control treatment (P=0.038 in 2010; Table 4). The effect of chaining was nonsignificant for shrub cover (P=0.314), perennial grass cover (P=0.064), nonnative annual grass cover (P=0.101), bare ground cover (P=0.712), and litter cover (P=0.420), and was not testable for biotic soil crust cover because pretreatment and post-treatment cover was nearly undetectable (Table 4). In some cases, transformations to homogenize variances decreased large differences among untransformed data (Supplementary Appendix S4 for transformations and tests; http://dx.doi.org/10.2111/REM-D-12-00126.s1).

Ecological Return-on-Investment (EROI)

In both experiments, average EROI generally increased over time after treatment application (Table 5). The temporal increase of EROI in the DOE experiment was caused by increasing perennial grass cover from 2007 to 2010 (Fig. 2) because tree cover remained relatively unchanged during the same period (Fig. 3). A similar pattern was observed in the BLM experiment (Table 2 and Supplementary Appendix S2; http://dx.doi.org/10.2111/REM-D-12-00126.s1). In 2007, differences were observed between treatments but variances, which differed by two orders of magnitude and were not transformable due to positive and negative EROI values among replicates, prevented use of parametric or nonparametric statistics to detect significant differences (Table 5). Confidence intervals overlapped among all treatments in 2007. In the BLM experiment, EROI for the chaining treatment was –23.2 because of the very low value of one replicate compared to the others. In 2008, the EROI values for the lop-and-scatter and mastication treatments were significantly higher than those for the lop-pile-burn and feller-buncher treatments (P=0.005; Table 5). The bulldozing treatment again could not be included in the statistical test because of a confidence interval that was one to two orders of magnitude higher than those for other treatments. In 2008, the EROI for the chained treatment was 3.4 in the BLM experiment, compared to 4.0 in the bulldozing treatment. In 2010, because of a high perennial grass cover and low cost of expenditure for tree control, the EROI was significantly higher for the bulldozing treatment (8.6) compared to the mastication (2.5) and lop-and-scatter (1.8) treatments (Table 5). The EROI values in these latter two

Table 5. Ecological return-on-investment (EROI) and associated 95% confidence intervals for perennial grass cover among experiments and treatments, Smith Valley, Nevada. The pretreatment covariate is EROI in 2006. For the Department of Energy (DOE) and Bureau of Land Management (BLM) experiments, n=3 and 9 replications, respectively.

	BLM experiment	DOE experiment ($ha \cdot \$^{-1}$)				
Year	Chaining	Bd[1]	LP	LS	FB	Ma
2006	3.5 (2.9)	2.1 (4.8)	< 0.1 (1.0)	0.3 (2.9)	0.2 (0.6)	< 0.1 (2.7)
2007	–23.2 (53.9)	0.8 (5.0)[2,3]	0.2 (0.6)	0.6 (1.2)	0.2 (0.2)	0.3 (0.2)
2008	3.4 (3.1)	4.0 (10.1)[2]	0.4 (0.8) a[4]	1.0 (0.6) b	0.3 (0.2) a	0.8 (0.7) b
2010	5.4 (4.5)	8.6 (15.8) c	0.7 (1.9) a	1.8 (2.7) b	0.6 (1.0) a	2.5 (4.2) b

[1]Bd indicates bulldozing imitating chaining; LP, lop-pile-burn; LS, lop-and-scatter; FB, feller-buncher; and Ma, mastication.
[2]The extremely large variance of bulldozing compared to other treatments prevented the inclusion of bulldozing in statistical tests because variances could not be homogenized.
[3]Variances were too heterogeneous and nontransformable among treatments to allow for any testing.
[4]Means with different letters indicate significant difference at the 0.05 level.

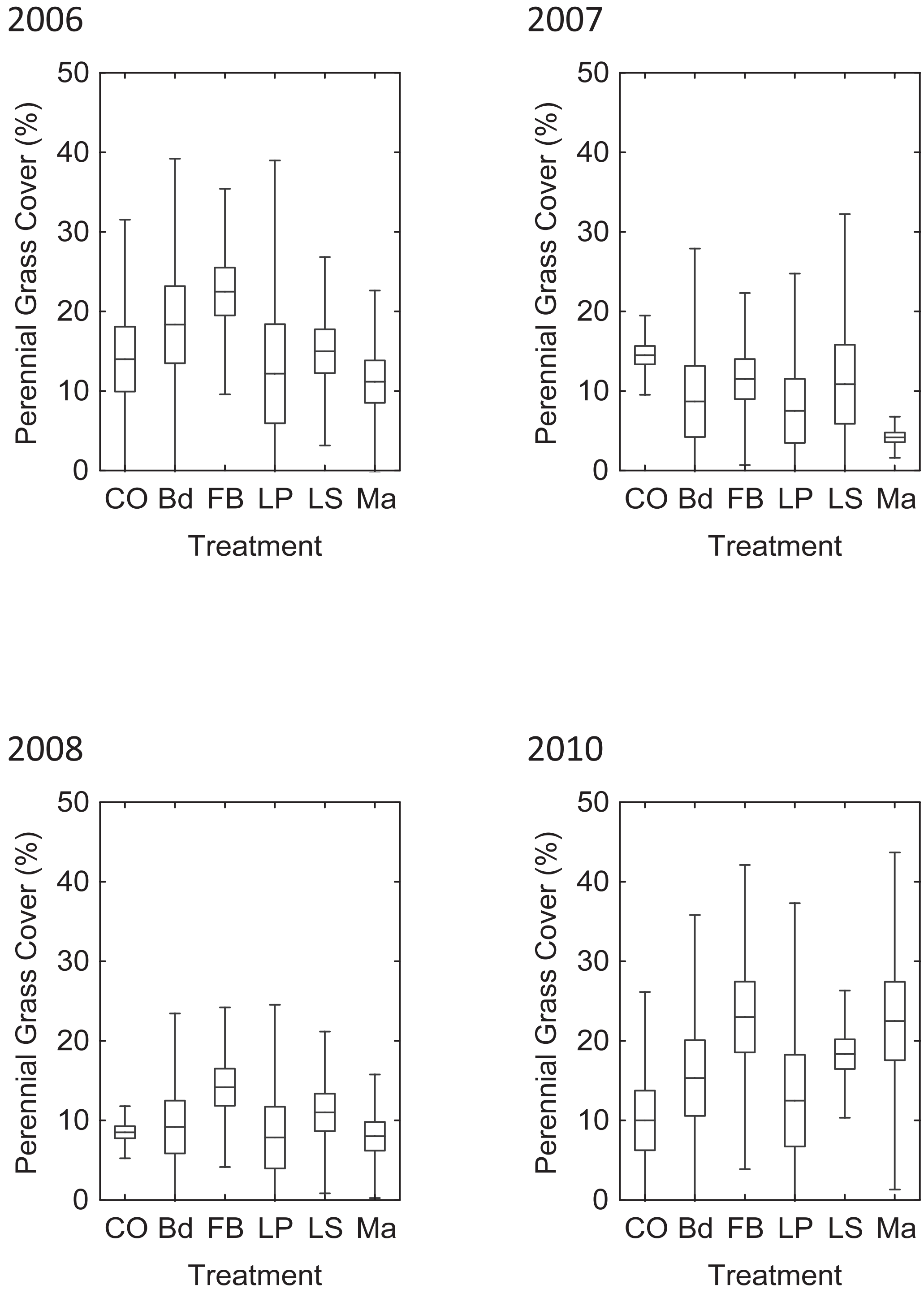

Figure 2. Perennial grass cover for the Department of Energy (DOE) experiment in Smith Valley, Nevada during 2006–2010. The horizontal line in the center of each box plot represents the mean, the edges of the box are one standard error from the mean, and the barred lines indicate the 95% confidence interval of the mean. Legend: CO indicates control; Bd, bulldozing imitating chaining; FB, feller-buncher; LP, lop-pile-burn; LS, lop-and-scatter; and Ma, mastication.

treatments were significantly higher than those in the lop-pile-burn (0.7) and feller-buncher (0.6) treatments (Table 5). An EROI of 5.4 for the chaining treatment in the BLM experiment was intermediate between that of the bulldozing and mastication treatments in the DOE experiment.

Chaining and bulldozing resulted in the least reduction of tree cover among treatments. In both experiments, a) tree removal resulted in a nonsignificant increase in perennial grass cover even 4 yr post-treatment, and b) nonnative annual grass and biotic crust were absent or uncommon before and after treatment implementation. Forb cover only decreased in the DOE mastication treatment and only increased in the BLM chaining treatment. By 2010, chaining or bulldozing, followed by mastication, showed the highest EROI.

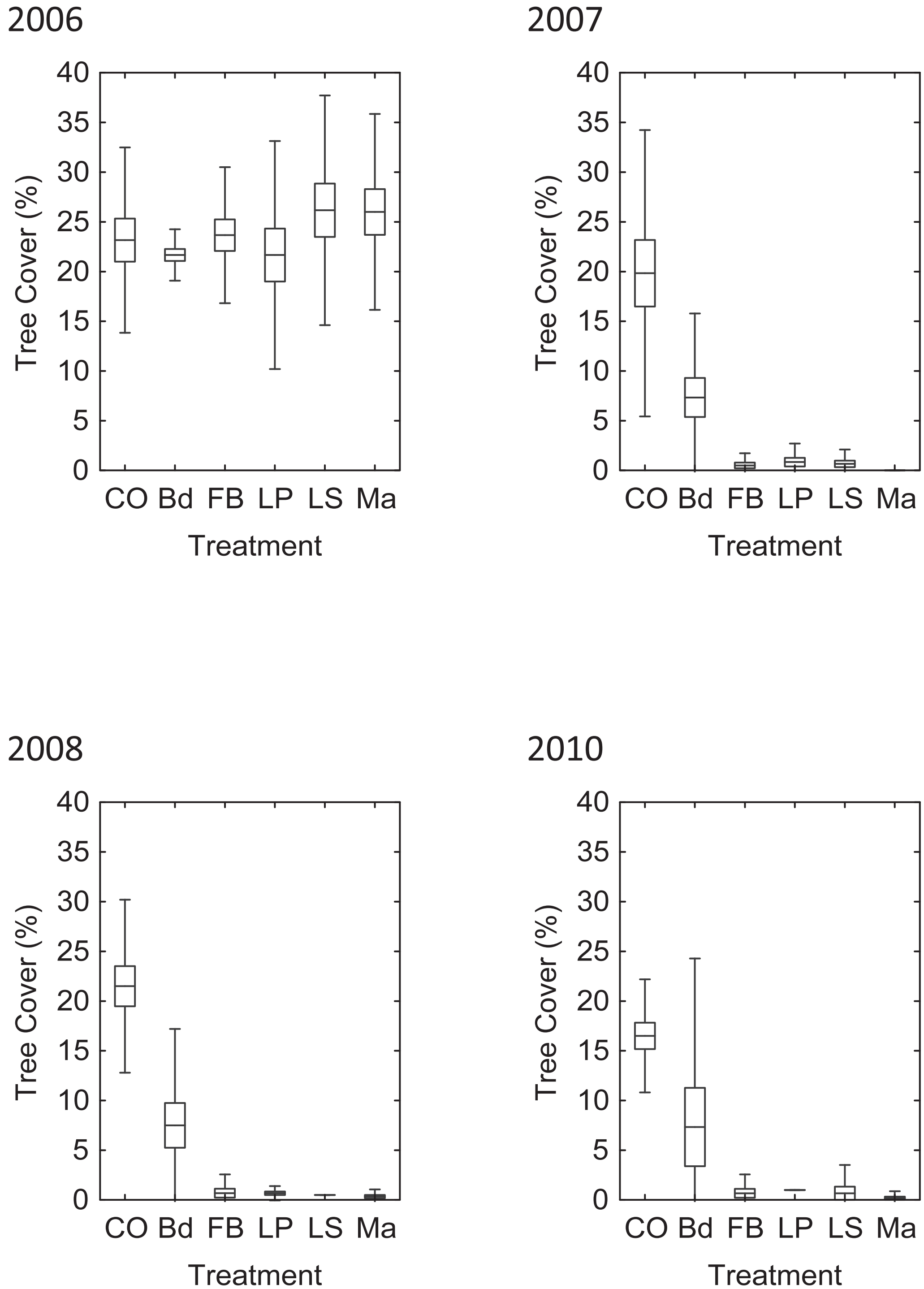

Figure 3. Tree cover for the Department of Energy (DOE) experiment in Smith Valley, Nevada during 2006–2010. The horizontal line in the center of each box plot represents the mean, the edges of the box are one standard error from the mean, and the barred lines indicate the 95% confidence interval of the mean. Legend: CO indicates control; Bd, bulldozing imitating chaining; FB, feller-buncher; LP, lop-pile-burn; LS, lop-and-scatter; and Ma, mastication.

DISCUSSION

Land managers can use various methods to reduce the density of pinyon and juniper in sagebrush shrublands. Cost among methods varies as much as two orders of magnitude. Few replicated studies have been conducted in big sagebrush (*Artemisia tridentata* Nutt.) ecosystems mechanically treated to reduce pinyon or juniper cover (Miller et al. 2005; Owen et al. 2009). As a result, land managers are limited by access to statistically valid, peer-reviewed information to make informed decisions. Even less information concerning land treatment options is available for black sagebrush ecosystems (Baughman et al. 2010).

Overall, one-way chaining and bulldozing (to imitate chaining in smaller areas) reduced tree cover by about half as much as other methods compared to the control treatment, although all our tests of chaining were potentially statistically inaccurate. Previous research suggests that two-way chaining probably would have greatly reduced woody species cover compared to one-way chaining (Tausch and Tueller 1977), but at slightly less than twice the cost per unit area because of small savings on unneeded equipment mobilization during the second chain pass (Natural Resources Conservation Service 2012). Tausch and Tueller (1977) reported a 95% reduction in pinyon cover and 71% reduction in juniper cover with two-way chaining compared to a control treatment in eastern Nevada. In our DOE experiment, lop-pile-burn, lop-and-scatter, mastication, and feller-buncher treatments were very effective at tree removal (Fig. 3).

A critical issue concerning pinyon–juniper treatment is the improvement of perennial grass cover at the lowest possible cost. After 4 yr, perennial grass cover exceeded pretreatment values in some treatments, and an increasing trend in perennial grass cover was evident among noncontrol treatments in 2008 and 2010 (Fig. 2). The number of years it takes for perennial grass cover to increase following tree thinning is variable and can depend on site productivity and levels of tree encroachment. In eastern Nevada, Baughman et al. (2010) found no significant ($P=0.11$) increase in perennial grass cover 3 yr after feller-buncher and chipper operations in black sagebrush; however, perennial grass cover doubled in treated plots compared to pretreatment cover after 4 yr. Perennial grass cover became significantly greater 2 yr after chainsaw cutting of western juniper in a basin big sagebrush (*Artemisia tridentata* Nutt. subsp. *tridentata*) site in southern Oregon and the increase in cover persisted for 7 yr (Bates et al. 2000, 2005). In southwestern Colorado, graminoid cover became significantly greater in mastication than untreated plots after 2.5 yr, but remained significantly lower in the lop-pile-burn treatment (Owen et al. 2009). Vernon et al. (2001) compared paired chained and seeded treatment to unchained treatment in 10 shrubland sites encroached by Utah juniper and pinyon throughout central and southern Utah. Chained sites ranged in age from 10 to 21 yr since treatment. Although native herbaceous understory plant cover, presumably dominated by perennial grass, was significantly greater in chained plots, native herbaceous cover was low because of low cover before chaining. Owen et al. (2009) determined that burning wood piles degraded soil properties and heat probably killed plants and roots, whereas woody debris from mastication increased soil moisture and lowered soil temperature, which would favor perennial grasses, if slash depth and coarseness do not result in smothering perennial grasses (Bates and Svejcar 2009). Any addition of woody debris from the lop-and-scatter, feller-buncher, chaining, and bulldozing treatments probably would have the same effect on soil. In western juniper encroachment areas, the negative effects of burning wood piles on perennial grasses can be lessened by burning during the winter or early spring when soils are frozen or near field capacity (Bates and Svejcar 2009; O'Connor et al. 2013).

In our study, forb cover decreased only with mastication; reasons for this decrease are not clear. Others have measured a variety of responses: 1) forb cover increased in feller-buncher plots during 3 yr in eastern Nevada (Baughman et al. 2010); 2) annual and perennial forb cover rapidly increased for 2–3 yr and then decreased for 3–4 yr in cut western juniper plots (Bates et al. 2005); 3) annual and perennial forb cover dominated plant cover for only 1–2 yr in chained plots (Tausch and Tueller 1977); and 4) no response with mastication compared to a control treatment, but a very reduced forb cover in pile-burned plots in southwestern Colorado (Owen et al. 2009).

Cheatgrass cover changed little after treatment application in our upland black sagebrush sites. This observation is similar to results of Bates et al. (2000, 2005) during the first three growing seasons after juniper cutting in basin big sagebrush of southeastern Oregon. However, cheatgrass cover rapidly increased in cut compared to uncut plots during the fourth and fifth growing seasons in the Oregon study (Bates et al. 2005), but then cheatgrass became a minor component as perennial grass productivity increased 10–13 yr after treatment (Bates and Svejcar 2009). Feller-buncher and chipping treatments significantly increased cheatgrass cover compared to control plots in eastern Nevada black sagebrush (Baughman et al. 2010); however, average cover was $< 1\%$. The site with the greater cover of pinyon and juniper encroachment in their study exhibited the largest increase of cheatgrass after tree removal by feller-buncher. In another Oregon study, mountain big sagebrush (*Artemisia tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle) encroached with western juniper, and cheatgrass production was significantly greater in cut than uncut plots 2 yr after treatment (Vaitkus and Eddleman 1987). In three southwestern Colorado sites, cheatgrass cover increased after mastication of Rocky Mountain pinyon (*Pinus edulis* Engelm.) and Utah juniper compared to the control treatment in only one of two sites 3.5 yr after application, whereas cheatgrass cover and all other plant cover were reduced to nearly undetected levels under burn piles following a lop-pile-burn treatment (Owen et al. 2009). Cheatgrass and medusahead (*Taeniatherum caput-medusae* [L.] Nevski) cover was significantly greater than native grass cover after picloram spraying of western juniper in a California basin big sagebrush site (Young et al. 1985).

An increase in perennial grass cover and decrease in tree cover were chosen as highly desirable characteristics by BLM in our study and, as a result, were used to measure EROI. The cover of cheatgrass would have been another characteristic to consider for calculating EROI, but very low cheatgrass cover in treated plots and no cheatgrass cover in many control plots prevented the use of cheatgrass cover as a characteristic in our study. Although chaining or bulldozing did not cause the greatest reduction in pinyon and juniper cover, the highest EROI values were observed in these treatments by 2010 because they were least expensive. Chaining in the BLM experiment and mastication were comparable in 2010, but mastication, unlike one-way chaining, largely eliminated pinyon and juniper cover. Therefore, one-way chaining would be the first choice if no other criteria are considered; however, mastication, and to a lesser extent the lop-and-scatter treatment, would be good alternatives, assuming a continued recovery of perennial grass (Bates et al. 2005) and if managers want to minimize future repeat cutting of trees as escaped saplings grow to dominate the site (Taush and Tueller 1997; Bates et al. 2005; Miller et al. 2005).

IMPLICATIONS

Chaining, bulldozing, mastication, and lop-scatter treatments yielded the greatest EROI for reducing pinyon–juniper encroachment in black sagebrush shrublands. For large black sagebrush landscapes with extensive pinyon–juniper encroachment, chaining might be the only treatment alternative that managers can afford on large scales. In eastern Nevada or western Utah where black sagebrush is common, it is unlikely that the high cost of feller-buncher-chippers would be offset by the sales of wood chips, because no processing plants are located within 32 km of treatment sites, or in that part of the Intermountain West. In Oregon, cutting and leaving intact dropped western juniper recently was the most commonly used treatment method by land management agencies and is as affordable as chaining (Miller et al. 2005); however, this practice is not commonly employed for felling large trees in Nevada and western Utah, perhaps because of a perceived higher fire danger. More recently in Oregon, the practice of cut-and-leave has become less common, whereas cutting followed by pile burning has become more prevalent (J. D. Bates, personal communication, July 2013).

Because of the past association of chaining with vast seedings of monocultures of crested wheatgrass (*Agropyron cristatum* [L.] Gaertn. and *A. desertorum* [Fisch. ex Link] Schult.) pastures for livestock during 1950 to 1980 (Vernon et al. 2001; Miller et al. 2005), chaining has some negative perceptions (Miller et al. 2005). Although mastication and feller-bunchers are increasingly used by private and public land managers near homes and to avoid litigation associated with chaining, managers should reconsider one- or two-way smooth chaining as a tool to rapidly restore habitat for sagebrush obligates, such as the threatened greater sage-grouse (*Centrocercus urophasianus*) which is declining throughout its range (Connelly et al. 2000; Rowland et al. 2006; Knick et al. 2013), and big game, given the high values of EROI for chaining calculated in our study. Unlike other treatments that require the use of heavy machinery, chaining can be used in areas with moderate slopes, whereas only chainsaw cutting can be employed in areas with steep slopes. As with most mechanical treatment methods, periodic removal of young pinyon and juniper trees that reoccupy sagebrush shrublands, using chainsaws, loppers, or herbicide pellets, probably will be necessary within 15 yr of initial treatment in eastern Nevada (Tausch and Tueller 1977).

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