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The biggest bang for the buck: cost-effective vegetation treatment outcomes across drylands of the western United States

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Abstract. Restoration and rehabilitation are globally implemented to improve ecosystem condition but often without tracking treatment expenditures relative to ecological outcomes. We evaluated the cost-effectiveness of widely conducted woody plant and herbaceous invasive plant removals and seeding treatments in drylands of the western United States from 2004 to 2018 to determine how land managers can optimize efforts. Woody plant cover decreased at a similar rate per dollar spent regardless of vegetation removal type, and the dominant invasive species was reduced by herbicide application. Relatively inexpensive herbicide application also had a large positive effect on seeded perennial grass cover that was enhanced by additional cost; while expensive woody mastication treatments had little effect regardless of additional cost. High seed cost was driven by including a large proportion of native species in seed mixes, and combined with high seeding cost, promoted a short-term (2–3 yr) gain in perennial forb cover and species richness. In contrast, seeding and seed mix cost had no bearing on seeded perennial grass cover, in part, because relatively cheap nonnative seeded species rapidly increased in cover. Our results suggest the differential benefits of commonly implemented treatments aimed at reducing wildfire risk, improving wildlife habitat and forage, and reducing erosion. Given the growing need and cost of restoration and rehabilitation, we raise the importance of specifying treatment budgets and objectives, coupled with effectiveness monitoring, to improve future outcomes.

Key words: ecological economics; ecosystem recovery; invasive species; land management treatments; restoration; wildlife habitat improvement; woody plant encroachment.

Introduction

Cost-effective ecological restoration and rehabilitation depends on achieving treatment objectives to improve ecosystem condition at least cost. Restoration and rehabilitation treatments that manipulate vegetation (hereafter, “treatments”) include invasive species control, wildlife habitat improvements, fuel reduction to mitigate wildfire risk, and seeding to restore degraded ecosystems, cost billions of dollars to implement annually (BenDor et al. 2015). Evaluation of treatment types and costs relative to their outcomes can help land managers weigh the trade-offs of implementing different treatments and guide future investments to enhance land condition. Informed decisions that lead to ecosystem improvements provide large economic, social, and environmental benefits that can outweigh the costs of the treatments and prevent further degradation (De Groot et al. 2013). Achieving cost-effectiveness will become more critical in the future because the size, costs, and complexity of treatments are increasing (Copeland et al. 2018), while the resources available to conduct such treatments remain limited.

Despite the potential for cost-effectiveness analysis to improve treatment approaches, these evaluations are rarely conducted due to two primary limitations. First, cost information is often lacking for treatments due to poor accounting, difficulty in obtaining project or specific treatment costs, or a historical lack of economic perspective in ecological restoration and rehabilitation (IPBES 2018). In a review of over 20,000 ecological restoration and rehabilitation case studies, less than 1% of the studies provided any cost information (Nebhöver et al. 2011). Second, treatment outcomes in the form of ecological benefits are rarely monitored due to time or funding constraints, or a lack of suitable methods, success metrics, or reference conditions (Ruiz-Jaen and Aide

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2005, Kimball et al. 2015). Copeland et al. (2018) found that less than 10% of vegetation treatments conducted on federal lands in the southwestern United States from 1940 to 2010 had any monitoring information, and if monitoring was conducted, it rarely extended over the long term. Accurate accounting of treatment costs and outcomes, and the relationship between them, is needed to optimize land management approaches with limited resources.

One of the most common treatments across drylands (arid and semiarid regions) globally is the removal of woody plants that have increased in density and encroached on grass-dominated communities (Archer et al. 2011). Woody plant expansion can be a form of land degradation because it can reduce plant diversity and production, increase soil erosion, and lead to the spread of invasive species (Archer et al. 2017). Woody plants have been removed since the 1940s throughout drylands of the western United States to meet management objectives to reduce wildfire risk, improve wildlife habitat, enhance forage production for livestock, encourage new growth and rejuvenation of desirable shrubs, and enhance ecosystem processes (Redmond et al. 2014, WRI 2019; Fig. 1). Treatments to remove herbaceous invasive plants can similarly reduce wildfire risk and improve ecosystem condition (D'Antonio and Vitousek 1992). Vegetation is typically removed with mechanical (e.g., chaining, harrowing, and mastication; Fig. 2A), chemical via herbicide, or prescribed burn treatments (Monsen et al. 2004). Vegetation removal treatments range in their effects on the target woody plant overstory, herbaceous understory, and the ability to increase desirable plant species (Ross et al. 2012).

Although vegetation removal treatments can increase understory plant abundance by reducing competition for resources, this compensatory effect is often boosted by seeding perennial grass and forb (herbaceous dicot) species (Pyke et al.2015). Seeding perennial herbaceous species overlaps in the management objectives of vegetation removal to enhance forage production, improve wildlife habitat, and increase species diversity and structural complexity; and can additionally reduce erosion and invasive plant cover via competition (Fig. 1). The number of native species in seed mixes has increased in recent decades to promote community diversity and resistance to disturbance (Copeland et al. 2018). However, many nonnative species are also used, including in our study (Appendix S1), due to their low cost, high establishment rates, and benefits to ecosystem function (Ewel and Putz 2004). The combined effects of vegetation removal and seeding can increase species diversity and vegetation structural complexity, thereby improving habitat for many wildlife species (WRI 2019; Fig. 1). Like woody plant removal, seeding treatments vary widely, and include aerial, ground broadcast, and drill seeding (Monsen et al. 2004; Fig. 2A). Evaluating the differential success of vegetation removal and seeding treatment combinations could identify methods that maximize the rate of perennial grass and forb recovery, inhibit further spread of woody plants and herbaceous invasive plants, and increase plant species richness.

The main goal of our study was to evaluate the cost-effectiveness of combined vegetation removal and seeding treatments to reduce woody plant or herbaceous invasive plant cover and increase perennial grasses, forbs, and species richness (outcomes). We focus on pinyon–juniper and big sagebrush dryland plant communities, which are widely distributed throughout the western United States and have been intensively managed for the last 80 yr (Archer et al. 2011). Our specific

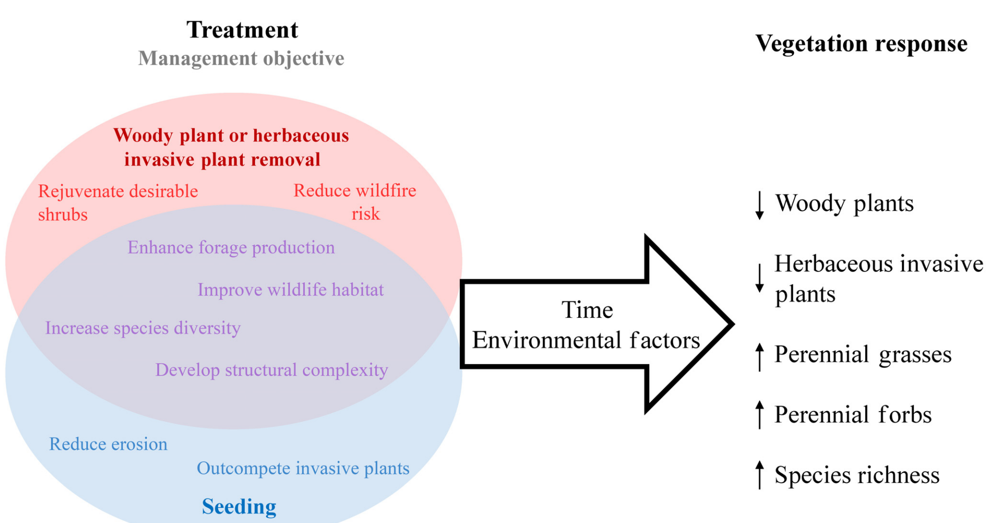

Fig. 1. Woody plant or herbaceous invasive plant removal, coupled with seeding treatments serve multiple management objectives and interact with time and environmental factors to influence vegetation responses.

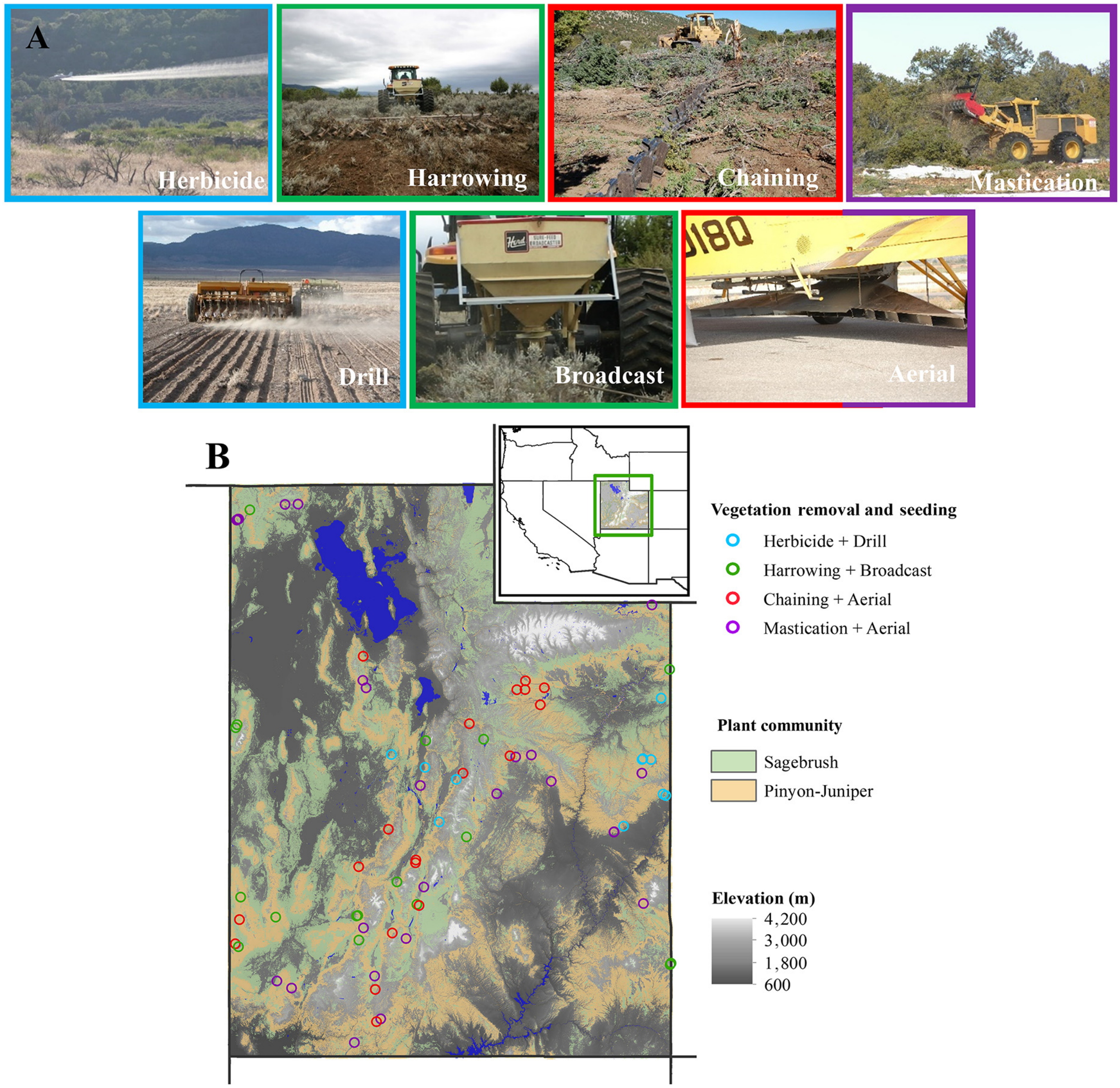

Fig. 2. (A) The combination of vegetation removal and seeding treatments and (B) their locations in Utah big sagebrush and pinyon–juniper communities. The most common treatment combinations evaluated in this study are color coded. Photo credits: Utah Department of Natural Resources.

objectives were to answer the following questions: (1) How do the outcomes of treatment types compare to their relative costs? (2) How do environmental factors and time interact with treatment types to affect outcomes? We expected seeded perennial grasses, forbs, and species richness to increase with rising costs of vegetation removal, seed application, and seed mix due to less overstory and invasive species competition, greater seed-to-soil contact, and a higher quality plant material leading to increased rates of establishment, respectively. We hypothesized that seeded perennial grass and forb cover, and species richness, would increase with time since treatment and environmental factors promoting perennial grass and forb germination and growth, including relatively high precipitation following seeding, high mean annual precipitation, and reduced competition from invasive annual species.

Methods

Monitoring and project databases

We selected 74 sites from the Utah Big Game Range Trend Studies program (Utah Division of Wildlife Resources 2019), hereafter "range trend," which are located within important big game and Sage Grouse habitat throughout Utah. The selected sites span gradients of elevation (1,584–2,578 m) and long-term mean annual precipitation (230–521 mm, 1986–2018; PRISM Climate Group 2019; Fig. 2B). Selected sites were identified as big sagebrush and pinyon–juniper plant communities from the monitoring data, which was confirmed using land cover maps (Lowry et al. 2007). Pinyon–juniper and big sagebrush dominated plant communities are extensive in the western United States, covering 40 million (Knick and Schueck 2002) and 43 million (Romme et al. 2009) hectares, respectively. While pinyon–juniper occupies slightly higher elevation, these two communities overlap in their distributions and experience similar management practices (Bates and Davies 2017, Ott et al. 2019). All selected sites were monitored May–September from 2004 to 2018 on a rotating basis every 3–5 yr. The range trend sites we selected were linked to a subset of vegetation removal and seeding treatments that total 20,000 ha within the multiagency Utah Watershed Restoration Initiative (WRI 2019). WRI aims to improve high priority watersheds throughout Utah by meeting multiple management objectives (Fig. 1). Selected sites were unaffected by recent wildfire (within 10 yr prior to treatments). The range trend sites within WRI projects were measured one to 4 yr preceding treatments and then revisited within three post-treatment years, before falling into the 3–5 year monitoring rotation. Thirty-five of the 74 study sites were monitored only once after the last treatment was applied while 39 study sites had two or more post-treatment monitoring observations. Post-treatment monitoring occurred over a period of 1–12 yr following treatment.

Vegetation removal and seeding treatments

The most common treatments for WRI projects was vegetation removal to decrease woody plant or herbaceous invasive plant abundance with either mechanical or herbicide treatments, respectively, combined with seeding to encourage perennial grass and forb establishment. Vegetation removal was combined with seeding over an average period of 4 months. The four treatment combinations assessed in this study include, herbicide and drill seeding, harrowing and broadcast seeding, chaining and aerial seeding, and mastication and aerial seeding (Fig. 2A). We included these four treatment combinations because they are the most common types for drylands included in the WRI database and allowed for a sufficient sample size for comparison. Other dryland treatments in the WRI database were infrequently used and did not have a large enough sample size to be analyzed. Herbicide and drill seeding consisted of spraying the herbicide imazapic (Plateau,BASF Corporation; Research Park, NC) to reduce the invasive annual cheatgrass (*Bromus tectorum*) with a helicopter or fixed-wing airplane. A rangeland drill pulled by a tractor created a furrow in the soil to a specific depth, dispensed a seed from a seed box, and lightly dragged soil over the seed. Harrowing and broadcast seeding involved pulling an Ely (toothed) chain or pipe harrow (Fig. 2A) behind a tractor to reduce woody plants and scarify the soil surface. Harrowing occurred in one or two passes, depending on the desired density of woody plants. Seed was broadcast behind the tractor pulling the harrow using an open-bottomed hopper with an underlying rotary wheel seed distributer. Chaining and aerial seeding consisted of pulling an anchor chain dragged in a U-shape between two bulldozers moving in parallel. The first pass used an Ely chain (Fig. 2A) to knock over and uproot woody plants and prepare the seed bed. Following the first pass, a helicopter or fixed-wing airplane broadcast grass and forb seed. This was followed by a second chaining pass with either an Ely or a smooth chain in the opposite direction to fully uproot trees and to pull the soil over the seed. Mastication and aerial seeding consisted of broadcast seeding with a helicopter or fixed-wing airplane, followed by shredding woody plants using a mulcher rotor, a toothed rotating drum, attached to an excavator or tractor.

All mechanical woody plant removal treatments primarily targeted decadent (old, densely growing) big sagebrush (*Artemisia tridentata*) and Utah juniper (*Juniperus osteosperma*), though antelope bitterbrush (*Purshia tridentata*), yellow rabbitbrush (*Chrysothamnus viscidiflorus*), black sagebrush (*Artemisia nova*), and broom snakeweed (*Gutierrezia sarothae*) were also removed. Seeded perennial grasses and forbs included both native and nonnative species (Appendix S1) with the proportion of native species ranging from 17% to 100% of total species in the seed mix. Seeding was conducted in the spring (March–May) or fall (September–November) after herbicide, harrowing, and chaining and prior to mastication using rates that averaged 354 $\pm$ 28 (mean $\pm$ SE) pure live seeds (PLS)/m^2. All treated areas were rested from grazing for at least two growing seasons to allow seedlings to establish.

Vegetation data

Range trend monitoring occurred within areas at each site that represented both vegetation removal and seeding effects along five 30.5-m randomly positioned lines set perpendicular to a 152.4-m permanently marked transect. Along each line, ocular cover by plant species was estimated using cover classes within each of 20 equally spaced 50 $\times$ 50 cm plots, for a total of 100 plots per site. The cover of seeded perennial grasses and forbs was calculated across all plots at each monitoring observation using information about which species were included in each WRI project seed mix (Appendix S1: Fig. S1).

Environmental data

We extracted monthly precipitation from 1986 to 2018 for each site using PRISM data (PRISM Climate Group 2019) and calculated long-term (32-yr) mean annual precipitation (October–September). We also calculated four short-term precipitation anomaly variables based on the two seasonal periods of precipitation for the region: cool

(October–March) and warm season (April–September) in both the years directly after treatment and prior to measurement, divided by the long-term standard deviation of annual precipitation (Wilks 2011). We derived elevation, slope, and aspect from a 30-m digital elevation model and then compiled all environmental factors (R raster package; Hijmans et al. 2020; data *available online*).

Vegetation removal and seeding treatment costs

Completed WRI projects included a detailed record of total treatment costs that were representative of treatment effort. Vegetation removal, seeding, and seed costs were specified and weighted by treatment area to estimate real cost per hectare (inflation-adjusted to 2016 US \$). Seeding costs included equipment and operator expenses for sowing seed, while seed cost was the amount spent on the seed mix. Because there are interannual fluctuations in seed costs due to factors such as demand for seed and storage capacity, we calculated the average seed costs (US\$/kg) for each species across all project years. For each perennial grass species, we used the seeding rate (kg/ha) and the average cost per kilogram of seed from the seed mix invoice to calculate the seed mix cost per hectare (US\$/ha). Distance from major roads and urban areas that were unrelated to project success, but could increase cost, were tested by running univariate linear models between the factor and total project cost and found to be nonsignificant ($P < 0.05$).

Statistical analyses

We constructed linear mixed effects models (R lme4 package; Bates et al. 2020) to test how treatment types and their associated costs, time since treatment, and environmental factors influenced changes in woody plant, cheatgrass, seeded perennial grass and forb cover, and seeded species richness. Changes in cover and richness were calculated by differencing post-treatment cover or richness at the time of observation from pre-treatment cover or richness (1–4 yr prior to vegetation and removal treatments).

Time since treatment, vegetation removal and seeding treatment type, and costs for vegetation removal, seeding, and seed mix were included in the model to predict changes in cover and richness. We could not evaluate the individual effects of vegetation removal and seeding treatments because there was a lack of independence in the data set; vegetation removal treatment types were typically combined with distinct seeding types. The environmental factors mean annual precipitation, short-term precipitation anomalies, elevation, slope, and aspect were all considered in initial models. Mean annual precipitation and short-term precipitation anomalies were found to be significant in some of the models, while all other environmental factors were not significant and therefore excluded in the final models. We considered the season (spring or fall) of vegetation removal and seeding in initial models, but it was not significant and dropped in final models. We included a treatment type interaction term with cost and time since treatment to evaluate if the influences of cost or the recovery rates were unique to the treatment performed. Plant community type (pinyon–juniper and big sagebrush) was found to be nonsignificant ($P > 0.05$) in the models, and therefore, we grouped both communities in analyses. This grouping was further warranted because the community types did not significantly differ in elevation (sagebrush 1,927 $\pm$ 45 m, pinyon–juniper 1,959 $\pm$ 29 m) or long-term mean annual precipitation (sagebrush 344 $\pm$ 6 mm, pinyon–juniper 348 $\pm$ 9 mm); and juniper often occurred in the big sagebrush community and big sagebrush in the pinyon–juniper community. We included site as a random effect in the final mixed-effects models.

We evaluated models using conditional (fixed effects only) and marginal (fixed and random effects) R^2 values and estimated the significance of individual factors using a Wald χ^2 (type III) test (R car package; Fox et al. 2020). We conducted linear regressions to test whether costs explained variance in vegetation responses and whether the proportion of native species used in the seed mix influenced cost. When vegetation response was significantly explained by cost, we evaluated cost-effectiveness in terms of the change in cover or number of species per US \$100/ha spent. We used analysis of variance and a Tukey honest significant difference test to identify if there were differences in explanatory factors and vegetation responses among the four combined treatment types. All analyses were performed in R version 3.5.2.

Results

Treatment types and their associated costs, time since treatment, and precipitation (fixed effects) explained 25% of the change (post-treatment − pre-treatment) in woody plant cover, 35% of the change in cheatgrass cover, 41% of the change in seeded perennial grass cover, 47% of the change in seeded perennial forb cover, and 46% of the change in seeded species richness. An additional 7–67% of the variation in these vegetation responses was explained by unmeasured factors at the site-level (conditional R^2 [variance explained by both fixed and random effects]; Table 1).

Mastication and aerial seeding were most effective at reducing woody plant cover, though the cost of mastication was three times greater than the cost of harrowing or chaining (Table 2). Woody plant cover decreased as vegetation removal cost increased across all treatment types, though mastication and aerial seeding was the only single treatment that significantly reduced woody plant cover with increasing cost (Fig. 3A; Table 3). Herbicide and drill seeding were the only treatment effective

TABLE 1. Linear mixed effects model results (degrees of freedom, Wald χ2 [type III], and P values) to predict change (Δ, post-treatment − pre-treatment) in woody plant, cheatgrass, seeded perennial grass, and seeded perennial forb cover, and seeded species richness. Significant (P < 0.05) effects are shown in boldface type.

		Δ Woody plant cover		Δ Cheat-grass cover		Δ Seeded perennial grass cover		Δ Seeded perennial forb cover		Δ Seeded species richness	
Model factors	df	χ^2	P	χ^2	P	χ^2	P	χ^2	P	χ^2	P
Intercept	1	0.2	0.68	0.1	0.72	**4.4**	**<0.05**	0.1	0.47	1.8	0.18
Treatment type	3	2.0	0.57	**9.6**	**< 0.05**	**5.8**	**< 0.05**	0.3	0.96	3.3	0.34
Time since treatment	1	**11.7**	**<0.001**	0.9	0.34	**10.5**	**<0.01**	**6.8**	**<0.01**	**12.9**	**<0.001**
Mean annual precipitation	1	2.1	0.14	0.0	0.99	0.3	0.61	0.0	0.94	0.4	0.55
Warm-season precipitation anomaly before measurement	1	0.5	0.47	**6.5**	**0.01**	0.0	0.99	0.8	0.89	0.7	0.72
Cool-season precipitation anomaly after seeding	1	0.0	0.92	0.0	0.92	2.3	0.13	**5.8**	**0.01**	0.1	0.82
Vegetation removal cost	1	0.0	0.97	0.1	0.71	1.1	0.32	1.3	0.26	0.0	0.91
Seeding cost	1	-	-	1.0	0.07	0.1	0.73	0.3	0.6	1.9	0.17
Adjusted seed mix cost	1	-	-	1.7	0.19	0.1	0.79	1.6	0.21	2.5	0.12
Treatment type × Time since treatment	3	**16.9**	**<0.001**	4.3	0.23	5.4	0.14	3.4	0.34	5.1	0.14
Treatment type × Vegetation removal cost	3	0.4	0.93	1.6	0.67	**7.6**	**<0.05**	1.9	0.59	0.2	0.98
Treatment type × Seeding cost	2	-	-	**8.6**	**<.05**	0.7	0.71	**12.5**	**<0.01**	**6.9**	**0.03**
Treatment type × Adjusted seed mix cost	3	-	-	4.3	0.14	1.7	0.62	6.8	0.07	**9.6**	**0.02**
Marginal R^2		0.25		0.35		0.41		0.47		0.46	
Conditional R^2		0.92		0.42		0.71		0.92		0.85	

Note: A dash indicates factors or interaction terms that were not included in model.

at reducing cheatgrass cover (Table 2). Increasing herbicide cost had no effect on reducing cheatgrass cover for a single application, though here was a tendency for additional herbicide cost to reduce cheatgrass when herbicide was applied twice ($r = -0.55$, $P = 0.15$). Chaining and aerial seeding, and herbicide and drill seeding, had a more positive effect on seeded perennial grass cover than the other treatment types (Table 2). Seeded perennial grass cover was most positively influenced by the cost of herbicide and drill seeding, followed by the cost of harrowing and broadcast seeding (Fig. 3B; Table 3). A second pass of the harrow drove up treatment cost and led to a doubling of seeded perennial grass cover ($r^2 = 0.42$, $P < 0.05$) compared to no cost effect of increasing seeded perennial grass cover for a single pass ($r^2 = 0.08$, $P = 0.76$). Costs for vegetation removal were, on average, at least three times higher than seeding and seed costs (except for herbicide treatment) and were the only expense that had an influence on seeded perennial grass cover (Fig. 4; Table 1).

Spending more on drill seeding treatments following herbicide application was most effective at reducing cheatgrass (Fig. 5A; Table 3). In contrast, increased cost of seeding following chaining increased cheatgrass and had no effect for other treatments. Greater cost associated with aerial seeding increased perennial forb cover following mastication and chaining, with mastication improving this result by the greatest amount (Fig. 5B; Table 3). Spending more on aerial seeding following chaining had the largest effect on increasing seeded species richness (Fig. 5C; Table 3). Increased cost of aerial seeding following mastication also had a positive effect on seeded species richness but spending more on drill seeding after herbicide application had a negative effect.

Higher spending on seed used in the seed mix for chaining and aerial seeding increased seeded perennial forb cover (Fig. 5D) and seeded species richness (Fig. 5E). Higher seed cost for harrowing and broadcast seeding also increased seeded species richness. The percent of native species used in the seed mix increased by 23% for every US$100/ha spent on the seed mix, but this increase had no significant effect on changes in seeded native perennial grass and forb cover (Fig. 6).

Time since treatment influenced vegetation responses. Woody plant cover increased 0.7% per yr (Fig. 7A) and cheatgrass did not significantly change through time across all the different treatment types (Table 1). On average, seeded perennial grass cover increased by 0.3% per yr across all the different treatment types (Fig. 7B), and just chaining and aerial seeding increased seeded perennial grass cover by 0.5% per yr. In contrast, unseeded perennial grass cover did not significantly change through time ($P = 0.15$) and was lower than seeded perennial grass cover across all treatments ($t = 3.92$, $P < 0.001$). Seeded perennial forb cover (Fig. 7C) and species richness (Fig. 7D) decreased 0.2% per yr and one species every 4 yr across all treatments, declines that were primarily driven by aerial seeding with either chaining and mastication. Unseeded perennial forb cover decreased through time at 0.4% per yr and was not significantly different from seeded perennial forb cover across all treatments ($t = 0.90$, $P = 0.37$).

Mean annual precipitation was not significant across all treatments for any of the vegetation responses

Table 2. Vegetation removal and seeding treatment characteristics and their effects on change in woody plants, cheatgrass, seeded perennial grasses, forbs, and species richness.

	Treatment characteristics									Vegetation responses (Δ)				
Treatment	No. sites	No. obs.	Veg. removal cost (US$/ha)	Seeding cost (US$/ha)	Seed cost (US $/ha)	Time since trt. (yr)	Area of trt. (ha)	MAP (mm)	Slope (%)	Woody plant cover	Cheatgrass cover	Seeded per. grass cover	Seeded per. forb cover	Seeded species richness
Mastication + Aerial	25	39	646.90 ± 32.00^{a}	33.60 ± 3.10^{a}	69.40 ± 8.30^{a}	4.0 ± 0.4^{a}	376 ± 43^{a}	341 ± 8^{a}	6.15 ± 1.08^{ab}	-10.16 ± 1.38^{a}	3.68 ± 1.31^{a}	4.1 ± 0.7^{a}	1.79 ± 0.39^{a}	4.38 ± 0.60^{a}
Chaining + Aerial	19	36	234.30 ± 12.10^{b}	29.50 ± 2.50^{a}	43.20 ± 3.50^{b}	5.4 ± 0.5^{ab}	242 ± 25^{b}	348 ± 10^{a}	6.68 ± 0.79^{a}	-4.88 ± 1.03^{b}	1.56 ± 0.63^{a}	6.8 ± 0.7^{b}	1.27 ± 0.28^{a}	5.88 ± 0.44^{a}
Herbicide + Drill	12	22	110.10 ± 11.60^{c}	57.20 ± 3.50^{b}	73.20 ± 3.30^{a}	5.3 ± 0.7^{ab}	197 ± 38^{b}	351 ± 11^{a}	3.38 ± 1.21^{b}	0.15 ± 0.71^{c}	-6.31 ± 2.01^{b}	8.3 ± 1.6^{b}	0.01 ± 0.03^{b}	2.00 ± 0.69^{b}
Harrowing + Broadcast	18	39	198.50 ± 13.90^{b}	0.00*	56.90 ± 3.30^{ab}	6.2 ± 0.5^{b}	247 ± 41^{b}	341 ± 11^{a}	5.94 ± 1.06^{ab}	-7.32 ± 1.24^{ab}	4.83 ± 1.64^{a}	3.1 ± 0.7^{a}	0.26 ± 0.10^{b}	2.88 ± 0.59^{b}

Notes: *Broadcast seeding did not report a separate cost from harrowing and was not assigned a value. Significant differences among treatment types are represented by different letters. Abbreviations are Veg., Vegetation; trt., treatment; per., perennial; MAP, mean annual precipitation.

(Table 1) but seeded perennial grass cover increased with mean annual precipitation at sites receiving herbicide and drill seeding ($r^2 = 0.37$, $P < 0.05$) and mastication and aerial seeding ($r^2 = 0.14$, $P < 0.01$) treatments. Changes in cheatgrass cover were related to the warm-season (April–September) precipitation anomaly the year before measurements, whereas seeded perennial forb cover increased when the cool-season precipitation anomaly was high the year after seeding (Table 1).

Discussion

We found that widely implemented treatments to remove woody plants and herbaceous invasive plants, and seed perennial grasses and forbs (native and non-native), responded differently to the types and costs of treatments, precipitation, and time since treatments. Our study provides new insight on the cost-effectiveness of treatments spanning 14 yr. As expected, spending more on mechanical treatments reduced a greater amount of woody plant cover, while multiple and more costly herbicide applications suppressed the cover of the widespread invasive annual, cheatgrass. Bolstering perennial grasses was driven to a greater degree by the type and costs of removing vegetation rather than seeding methods and their associated costs, which enhanced perennial forbs and associated species richness in the recovering plant community.

Mastication removed the highest amount of woody plant cover over the largest treatment areas in our study, but at much greater cost than harrowing and chaining. Mastication treatments typically have a higher cost per area because they selectively remove individual woody plants, whereas harrowing and chaining are indiscriminate in the removal process (Pyke et al. 2015). High mastication costs may lead to large reductions in wildfire risk and improvements for wildlife that require an open overstory, but we did not detect differences among mechanical treatments in the rates at which they reduced woody plant cover per dollar spent. Despite a lack of differences in cost-effectiveness, mastication is growing in usage, while harrowing and chaining are declining because mastication generally allows for more control in the woody plant species and size classes removed, creates lower soil disturbance and erosion, and leads to greater reduction in surface fuel loads (Redmond et al. 2014). Based on previous results (Coop et al. 2017), we expected mastication to have a longer duration of treatment effectiveness because it more completely destroys woody plants relative to other treatments. However, we found a similar 0.7% per yr increase of woody plant cover across all treatments, which indicates a similar regrowth potential regardless of the removal method. We found some

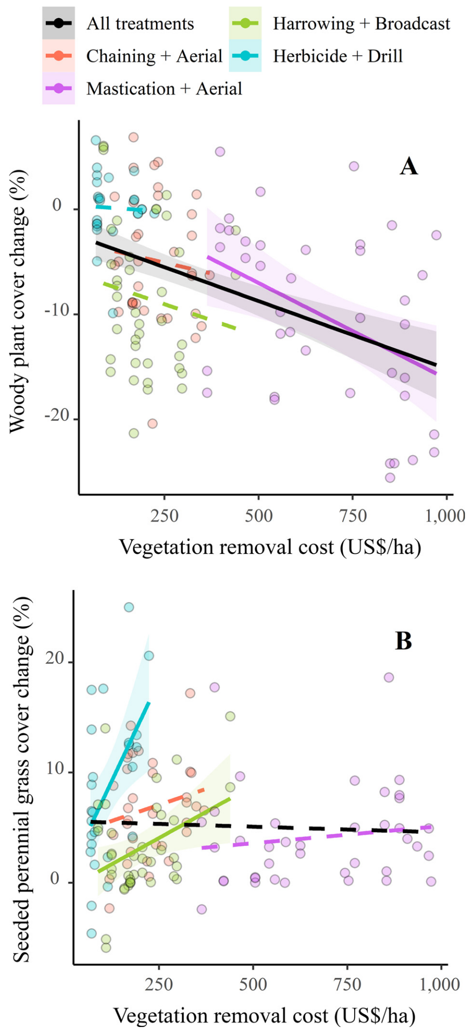

FIG. 3. Changes in woody cover and seeded perennial grass cover in relation to vegetation removal costs for each combination of vegetation removal and seeding treatment type. Significant regressions are shown by solid lines, non-significant trends are shown by dashed lines. Shaded regions along regression lines are 95% confidence intervals.

TABLE 3. Relationships between vegetation responses and costs of treatment types as indicated by slopes ± standard errors of slopes, coefficients of determination, and P values.

Treatment	Slope (Δ cover or no. species per US $100 per ha)	r^2	P
Vegetation removal cost			
Δ woody plantcover			
Mastication + Aerial	−1.8 ± 0.6	0.19	0.01
All treatments	−1.3 ± 0.2	0.17	<0.0001
Δ seeded perennial grass cover			
Herbicide + Drill	7.2 ± 2.5	0.27	0.01
Harrowing + Broadcast	2.4 ± 0.9	0.15	0.01
Seeding cost			
Δ cheatgrass cover			
Herbicide + Drill	−27.5 ± 11.0	0.21	0.02
Chaining + Aerial	12.7 ± 3.5	0.32	<0.01
All treatments	−11.5 ± 3.0	0.11	<0.001
Δ seeded perennial forb cover			
Chaining + Aerial	5.1 ± 1.8	0.20	0.01
Mastication + Aerial	8.0 ± 1.6	0.40	<0.0001
All treatments	1.9 ± 0.5	0.08	<0.001
Δ seeded richness			
Chaining + Aerial	6.5 ± 2.6	0.16	0.02
Mastication + Aerial	3.7 ± 2.1	0.08	0.05
Herbicide + Drill	−7.1 ± 2.1	0.33	<0.01
Seed cost			
Δ seeded perennial forb cover			
Chaining + Aerial	3.9 ± 1.6	0.16	0.02
Δ seeded richness			
Chaining + Aerial	5.8 ± 2.2	0.18	0.01
Harrowing + Broadcast	4.0 ± 1.9	0.1	0.04

Note: Only significant relationships are shown.

evidence that spending more led to prolonged woody plant reduction, as cover remained low for more costly double- but not single-harrowed treatments ($F_{1,37} = 4.1$, $P < 0.05$).

There was a tendency for a higher cost of applying a second dose of herbicide to further reduce the invasive annual cheatgrass. Increasing cost and effectiveness was likely due to a higher concentration of imazapic, the only herbicide used in our study treatments. Other studies have found cheatgrass reductions with increasing rate of application (Morris et al. 2009), though there may be no effect of a second application if the dosages are longer than 3 yr apart (Munson et al. 2015). In contrast, all mechanical treatments increased cheatgrass cover, indicating a clear negative effect of removing vegetation and disturbing soils with heavy machinery (Coop et al. 2017). We found no evidence that cheatgrass cover changed through time in the areas treated with herbicide and mechanical vegetation removal, although site revisits were likely spaced too far apart to detect changes in the cover of an annual species.

The increase in seeded perennial grasses compared to unseeded perennial grasses through time suggests that seeding efforts encouraged perennial grass recovery over the long term. In contrast, seeded perennial forb cover was initially high and decreased through time, and never exceeded unseeded perennial forb cover. Similar changes in species richness suggest a short-term benefit of seeding that has been found in other studies (Copeland et al. 2019). Forbs compose a large proportion of species richness and were likely suppressed through time by recovering perennial grasses (Munson and Lauenroth 2012) or woody plants. Herbicide and drill seeding doubled-seeded perennial grass cover at half the cost relative to other treatments. The cost-effectiveness of this treatment was driven by the low cost of vegetation removal through herbicide application, and multiple applications leading to high effectiveness despite relatively low added cost. The effectiveness of herbicide on increasing seeded perennial

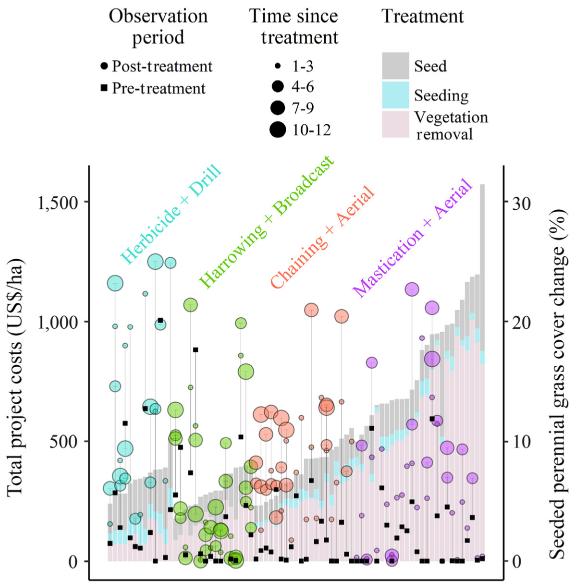

FIG. 4. Vegetation removal, seeding, and seed material costs per hectare for each site, ordered by total cost of the project. Each small black square represents seeded perennial grass cover pre-vegetation removal and pre-seeding. Each circle represents post-treatment cover color-coded by treatment type, while the size of each circle represents the time since treatment (yr), and the line between square and circle represents the change in cover. Seeding costs could not be distinguished in the harrowing + broadcast treatment because no explicit cost was reported.

grass cover may vary by plant community and whether detrimental effects on emerging seedlings are minimized (Munson et al. 2015). The lack of herbicide effect, and no benefit of additional herbicide cost, on increasing seeded perennial forbs and species richness may be reflective of the low average number of forb species (3.6) used in drill seed mixes compared to other treatments (4.3–6.1). We are uncertain why cheatgrass and species richness declined with increasing drill seeding cost, but it was not tied to higher establishment of perennial grasses.

Chaining and aerial seeding had a relatively large effect on increasing perennial grass cover, though spending more on vegetation removal did not improve outcome. Harrowing and broadcast seeding did not increase seeded perennial grass cover as much as chaining and aerial seeding, but spending more on removal improved outcome. These contrasting results suggest that certain treatments are effective at a baseline cost, and additional provisioning of resources is only worthwhile for cost-effective treatment types. In our study, a second pass of the harrow is what drove up treatment cost and led to a doubling of seeded perennial grass cover compared to no cost effect for a single pass. This positive effect on perennial grasses was likely because the target woody plant species were not as effectively reduced (3.0% cover reduction) and compete with herbaceous vegetation if only single harrowed, but there was higher woody plant reduction (11.3% cover) if double harrowed (Greenwood 2004). However, a common goal for single-harrowed treatments is to maintain some woody plant cover for suitable wildlife habitat.

Both harrowing and chaining break up the soil surface, which can loosen and smooth the surface soil, and increase seed-to-soil contact, to promote plant germination and establishment (Pyke 2015). However, only seeded perennial grass cover was enhanced by spending more on harrowing, and there was no effect on seeded perennial forb cover for spending more on either vegetation removal treatment. Increased cost of aerial seeding following chaining drove up seeded perennial forb cover and associated species richness due to a higher seeding rate. While we were not able to separate the broadcast seeding cost from harrowing, there was a clear benefit of spending more on the seed mix to increase seeded species richness following harrowing and chaining, and to increase seeded perennial forb cover following chaining. We did not find that increased richness in our study was due to a higher seeding rate, which has been previously shown (Barr et al. 2017). However, increased seed mix cost was associated with a higher number of species in the seed mix across treatments in our study. More costly diverse seed mixes likely led to high forb cover and richness by ensuring that some species could establish and compensate for those that failed to germinate. Indeed, Barr et al. (2017) experimentally showed that optimal seed mixture diversity and seeding rates were well above those used in the treatments in our study, though this added cost is often not feasible given the resource limitations of reclamation and restoration projects. Our average seeding rate of 354 PLS/m^2 was within the recommended guidelines of 249–405 PLS/m^2 for the region (Shaw and Pellant 2013).

Mastication and aerial seeding cost two to three times as much as the other treatments and produced relatively low increases in perennial grass cover, which were not related to removal cost. Seeded perennial forb cover increased with higher cost of seeding, but not vegetation removal cost. These results contrast with previous studies that demonstrate how mastication coupled with seeding treatments in pinyon–juniper woodlands can increase herbaceous cover by up to three times as much relative to controls (Young et al. 2013, Redmond et al. 2014). Enhancements of perennial grasses and forbs in these other studies were associated with wetter conditions compared to the sites in our study, though relatively high changes in seeded perennial grass cover occurred at our wettest sites. In addition to low water availability, residual woody debris or herbaceous understory left over from mastication may have inhibited grass and forb establishment from seed (Young et al. 2013). Interestingly, higher aerial seeding costs following mastication or chaining were successful in enhancing seeded perennial forb cover and species richness. This suggests that the additional cost associated with high-quality

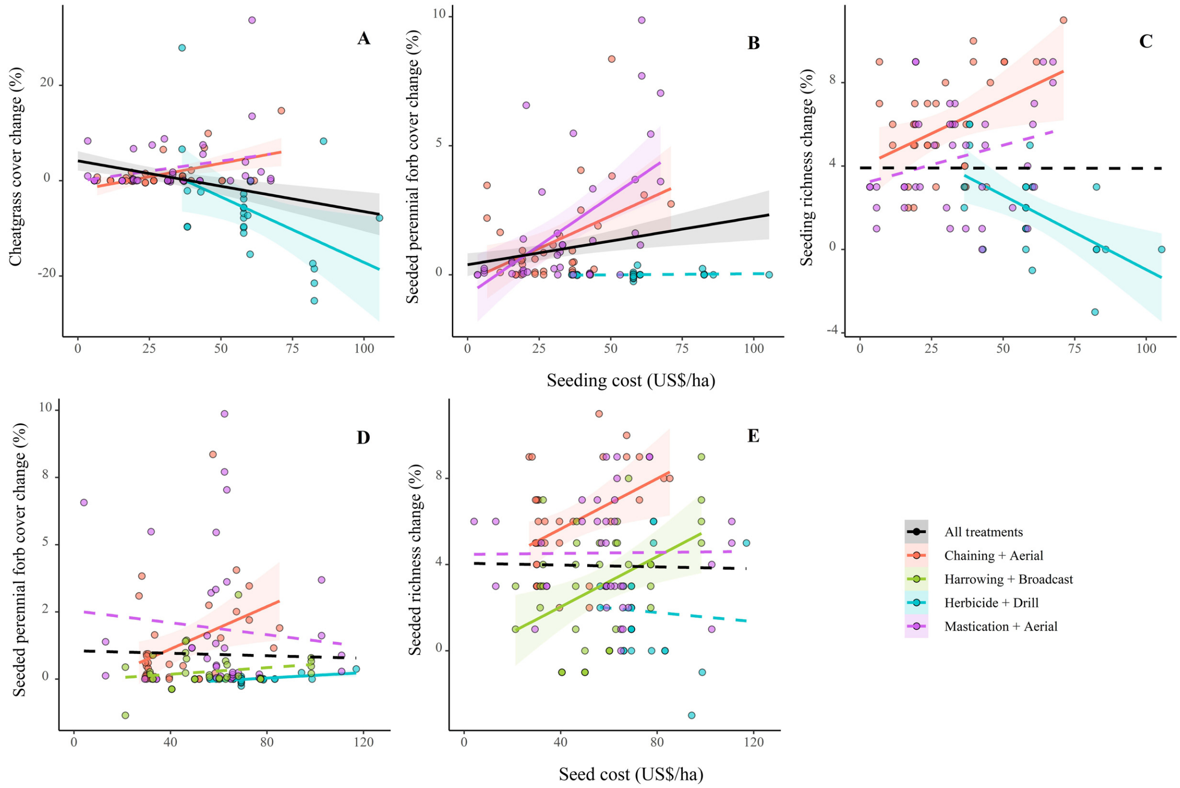

FIG. 5. Changes in (A) cheatgrass, (B) seeded perennial forb cover, and (C) species richness in relation to seeding costs, and (D) changes in seeded perennial forb cover and (E) species richness in relation to seed (seed mix) costs, for each combination of vegetation removal and seeding treatment type. Significant regressions shown by solid line, not significant trends shown by dashed lines. Shaded regions along regression lines are 95% confidence intervals.

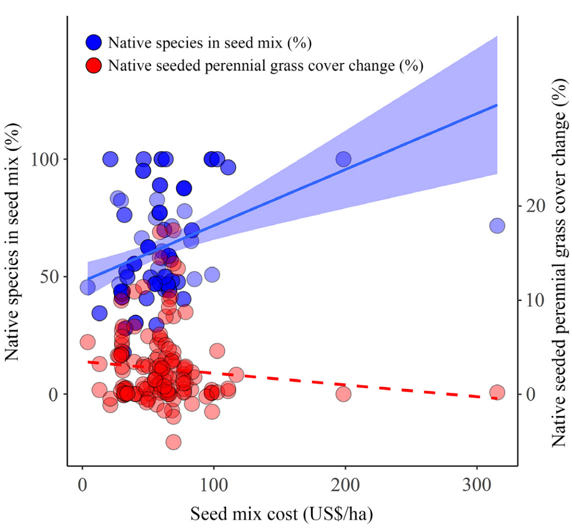

FIG. 6. The relationship between seed mix cost and the percentage of native seed in the mix (blue points and line) and change in native seeded perennial grass cover (red points and line). Native species in seed mix = 0.25(cost) + 47.00, $r^2 = 0.14$, $P < 0.01$. Shaded color region along regression line is the 95% confidence interval. Change in native species is not significant.

seeding equipment or more aerial seeding passes can promote non-grass elements of the plant community.

The positive effect of increasing vegetation removal cost on perennial grass cover relative to seeding and seed mix costs in our study suggests the importance of the indirect effect of competitive release on promoting grass establishment. Higher cost resulted in more woody plants or herbaceous invasive plants removed, which likely reduced competition for water, light, and nutrients. In a recent review, Archer et al. (2011) found that 80% of woody plant removal treatments increased herbaceous vegetation, but this positive effect reached an upper-limit 5–7 yr following removal. We found a prolonged removal effect to 12 yr in our study for grasses, but seeded perennial forbs began to decline after 2–3 yr, which indicates divergent trajectories reinforced by a trade-off to spend more on vegetation removal or seeding to increase these two herbaceous plant functional types, respectively. Future studies that address the cost-effectiveness of promoting a specific balance among woody plants, grasses, and forbs, and even target species compositions, can help refine future treatments.

The use of native species in seed mixes has increased through time (Copeland et al. 2018), in part due to their enhancement of ecosystem properties (Munson and

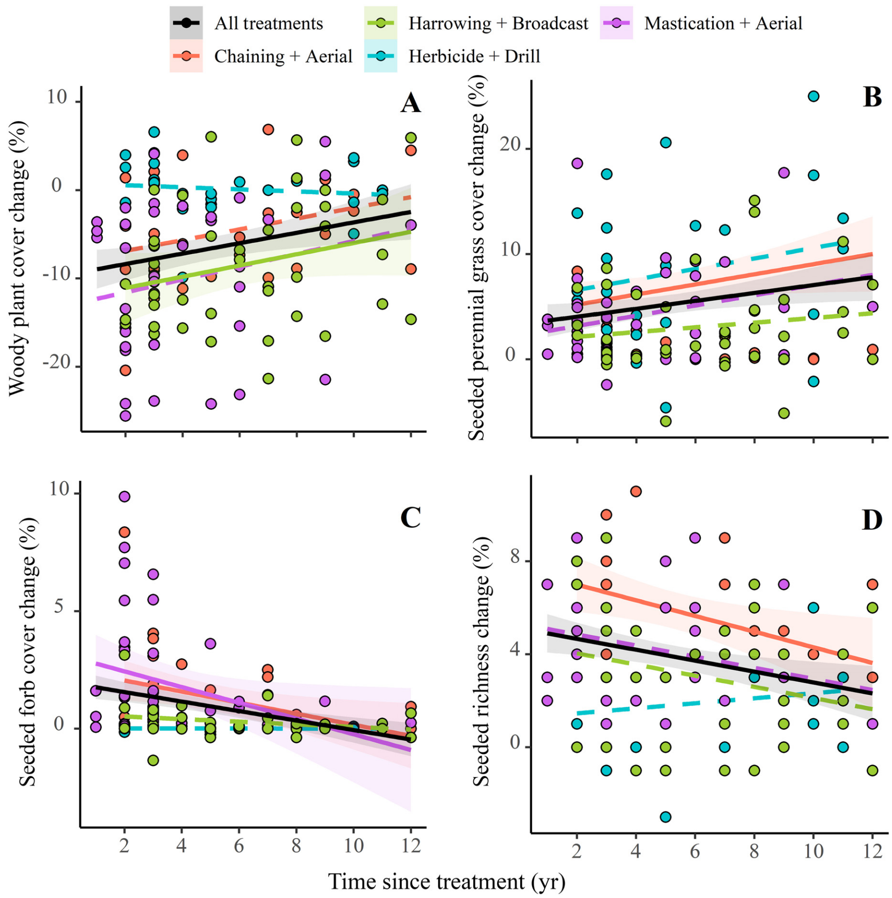

FIG. 7. Change in (A) woody plant, (B) seeded perennial grass, and (C) forb cover and (D) species richness in relation to time since treatment. Significant regressions shown by solid line, not significant trends shown by dashed lines. Shaded regions along regression lines are 95% confidence intervals.

Lauenroth 2012) and ability to tolerate low-resource availability (Daehler 2003) compared to nonnative species. In our study, both native and nonnative species were seeded. Adding native species to the seed mixes incurred additional cost, but we found no evidence that seed mixes with a higher proportion of native species led to greater increases in cover. Instead, more costly seed mixes led to a short-term increase in richness that did not persist beyond the initial 2–3 yr following treatments. Nonnative wheatgrass species used in the seed mixes in our study (*Agropyron cristatum*, *A. fragile*) have high germination, growth, and reproductive rates (Ambrose and Wilson 2003), which resulted in large increases in cover following treatments. High growth potential and other advantages explains why nonnative species are used to promote ecosystem recovery (Ewel and Putz 2004), though long-term persistence and population growth of introduced species can lead to low establishment of native species and associated diversity (Gunnell et al. 2010, Copeland et al. 2019, Ott et al. 2019). Native perennial species can be slower to increase in cover compared to nonnative perennial species, a long-term effect that was not captured by our analysis.

An average increase in seeded perennial grass cover of 0.3% per yr is low, even compared to rates at other water-limited (mean annual precipitation < 500 mm) sites (0.7–1.4% per yr; Abella 2009, Munson and Lauenroth 2012). We found some evidence that low water availability limited recovery at treated sites because seeded perennial forb cover increased with higher than average cool-season precipitation the year following treatments and seeded perennial grasses increased with higher mean annual precipitation for certain treatment types. Low precipitation across our study area can strongly influence the effectiveness of seeding treatments by limiting seed germination and seedling growth (Copeland et al. 2019). While wetter than average years benefited seeded species, they also promoted high cheatgrass cover, which can increase competition for soil water. Consideration of weather and other environmental variation is critical for deciding when to use limited funds on restoration and reclamation treatments.

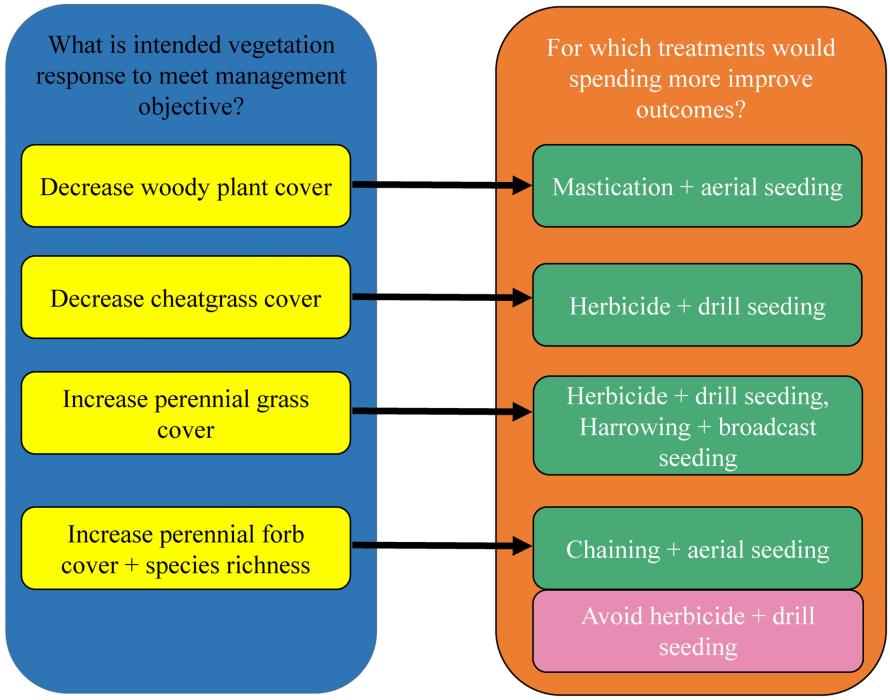

Fig. 8. Framework to decide for which treatments would spending more improve outcomes to meet management objectives. Spending more on herbicide and drill seeding has a negative effect on increasing perennial forb cover and species richness and can be avoided.

Although the monitoring results employed in our study provided useful information, we were not able to fully determine whether post-treatment changes in perennial grass cover were due to the seeding or from regrowth and colonization, if the seeded species occurred at a site pre-treatment. At 9% of sites, seeded perennial grass and forb cover decreased between pre- and post-treatment monitoring, which was likely due to seeding not leading to sufficient cover to overcome the reduction of perennial herbaceous cover associated with vegetation removal. There was also no information on the reduction of perennial grass and forb cover immediately following woody plant removal and seeding, which would have increased our certainty of seeding treatment effectiveness. Tracking individual plants germinating and establishing from seed, and monitoring after each individual treatment, can improve the evaluation of future treatment outcomes. At 91% of sites, there was low or no cover of the seeded species before treatment, and seeding efforts had high cost relative to other studies (SageSTEP Project; SageSTEP 2013), which increases our confidence that our analysis captured the seeding effort.

Conclusions

While tracking treatment budgets and outcomes take additional resources, these efforts are generally a small percentage of the overall costs of treatments and allow for the adaptation of future treatments. Our study monitored 12 yr of treatment outcomes, but only a small fraction of vegetation treatments in the United States and globally are monitored. Long-term monitoring is necessary to increase our knowledge of treatment effectiveness, especially in ecosystems with slow recovery rates. Cost tracking and long-term vegetation monitoring in our study revealed different cost-effectiveness of vegetation removal and seeding treatments to meet multiple management objectives. While spending more on removing woody plants and herbaceous invasive plants resulted in a reduction of undesirable species, there was a clear trade-off between spending more on vegetation removal to increase perennial grasses and on seeding and seed mixes to promote perennial forb cover and species richness. Taken together, results from our study provide a framework to prioritize for which treatments spending more improve outcomes to meet multiple management objectives ("the biggest bang for the buck"; Fig. 8). For example, spending more on herbicide and drill seeding can increase perennial grass cover and suppress the invasive annual cheatgrass, but decreases perennial forb cover and species richness. The utility of this decision-making support for treatments commonly used across drylands globally underscores the strong need for well-designed studies that keep track of costs and recovery (Kimball et al. 2015). The need for cost-effective treatments is widespread and will continue to grow in the future, as more of the global land surface becomes degraded and negatively affects ecosystem condition (IPBES 2018).

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.2151/full