Long-term trends in restoration and associated land treatments in the southwestern United States: Vegetation...

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RESEARCH ARTICLE

Long-term trends in restoration and associated land treatments in the southwestern United States

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Restoration treatments, such as revegetation with seeding or invasive species removal, have been applied on U.S. public lands for decades. Temporal trends in these management actions have not been extensively summarized previously, particularly in the southwestern United States where invasive plant species, drought, and fire have altered dryland ecosystems. We assessed long-term (1940–2010) trends in restoration using approximately 4,000 vegetation treatments conducted on Bureau of Land Management lands across the southwestern United States. We found that since 1940, the proportions of seeding and vegetation/soil manipulation (e.g. vegetation removal or plowing) treatments have declined, while the proportions of prescribed burn and invasive species treatments have increased. Treatments in pinyon-juniper and big sagebrush communities declined in comparison to treatments in desert scrub, creosote bush, and riparian woodland communities. Restoration-focused treatment objectives increased relative to resource extraction objectives. Species richness and proportion of native species used in seeding treatments also increased. Inflation-adjusted costs per area rose 750% for vegetation/soil manipulation, 600% for seeding, and 400% for prescribed burn treatments in the decades from 1981 to 2010. Seeding treatments were implemented in warmer and drier years when compared to the climate conditions of the entire study period and warmer and wetter years relative to several years before and after the treatment. These results suggest that treatments over a 70-year period on public lands in the southwestern United States are shifting toward restoration practices that are increasingly large, expensive, and related to fire and invasive species control.

Key words: **Bureau of Land Management (BLM), drylands, fire, invasive nonnative species, Land Treatment Digital Library, land-use disturbance, public land, rehabilitation**

Implications for Practice

- Vegetation treatments on southwestern U.S. public lands increasingly align with restoration practices, such as planting native rather than nonnative species, which will likely continue to increase the demand for diverse native seed and plant material resources.
- Planning for future vegetation treatments could benefit from new landscape-level, cost-effective restoration strategies as mean treatment size and cost per area have concurrently increased.
- Land managers may be able to increase seeding success by planting in years when forecasts predict cooler temperatures and higher precipitation.
- A relatively low level of posttreatment monitoring effort may be limiting adaptive management and advancements in restoration practices.

Introduction

Extensive areas of degraded land globally are slated for restoration or rehabilitation treatments that can enhance ecosystem services and native biodiversity at landscape scales (Birch et al. 2010; Menz et al. 2013; Suding et al. 2015). Restoration treatments emphasize reestablishing native communities and increasing resilience from disturbance, while rehabilitation treatments emphasize recovery of ecosystem processes and services (SER International Science & Policy Working Group 2004). Both rehabilitation and restoration treatments vary widely in effectiveness, and costs of ineffective treatments can be high (Lovich & Bainbridge 1999; Kimball et al. 2015), leading to uncertainty regarding "best practices" for restoration in different environmental conditions. Relatively little information on the trends and patterns in land management practices and their relationship to restoration and rehabilitation (hereafter, "restoration") practices at regional or global scales is available

Author contributions: DSP, JLW collected data and compiled database; SMC analyzed data; SMC, JBB, BJB, SMM, DSP, JLW contributed to study design and wrote manuscript.

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(but see LeFevour et al. 2007; Pilliod et al. 2017). For instance, it is unclear whether land management treatments are increasingly aligned with restoration goals and whether trends in treatment practices are associated with increasing costs. Characterizing the change in land treatments related to restoration over broad spatial scales may improve understanding of ecosystem recovery and focus future research to improve restoration effectiveness.

Multiple factors influence treatment effectiveness in achieving restoration goals such as increasing vegetation cover and native diversity, suppressing invasive species, and increasing ecosystem resilience from disturbance. Factors influencing effectiveness include the order and type of treatments (e.g. Ott et al. 2003; Werner et al. 2016), historical and current physical and biological characteristics of the site (Bakker et al. 2003), and disturbance regime (Crouzeilles et al. 2016). For instance, herbicide or mowing treatments combined with optimal timing of sowing seeds or planting seedlings can reduce competition from invasive species and promote desired species (Huddleston & Young 2005; Young et al. 2017). Seeding of native species with characteristics such as high competitiveness or appropriateness for future climate scenarios may increase the likelihood of establishment and persistence of native communities (Leger & Baughman 2015; Broadhurst et al. 2016; Butterfield et al. 2016). Climate conditions in the year of seeding, or extreme climate events during plant establishment, may affect the degree of restoration success (Bakker et al. 2003; Vaughn & Young 2010; Knappova et al. 2013; Young et al. 2015; Stuble et al. 2017).

Drylands, such as the arid and semi-arid ecosystems of the southwestern United States, are particularly vulnerable to degradation, or long-term loss of productivity, due to characteristics such as fragile soils, low perennial vegetation cover, and low and variable precipitation (Reynolds et al. 2007; Ravi et al. 2010; Munson et al. 2011*a*; Bestelmeyer et al. 2015). Restoration treatments in the drylands of the southwestern United States can be time-consuming and expensive with low success (Lovich & Bainbridge 1999). Improving restoration outcomes may require selecting species to match site conditions, ameliorating environmental stressors (Abella et al. 2012; Fick et al. 2016), and avoiding treatments that cause soil disturbance (Duniway et al. 2015). In addition, restoration efforts in drylands of the southwestern United States are affected by the invasion of nonnative grasses and associated increases in wildfire frequency (Brooks & Matchett 2006; Abatzoglou & Kolden 2011; Abella & Berry 2016).

Effective restoration practices are likely to be increasingly important to recovering ecosystem function in drylands impacted by climate change. Restoration outcomes are likely to be affected by increasing climate variability (Dai 2013; Diffenbaugh et al. 2017), greater potential for land-use degradation (Puigdefabregas 1998), and growing threats from invasive species and wildfire associated with climate change (Abatzoglou & Kolden 2011). Given the potential for increasingly dry conditions in the study region and drylands globally (Schlaepfer et al. 2017), targeting favorable climate windows for seeding treatments may become necessary in order to assure successful establishment. Careful timing and sequences of treatments might be able to address the challenges to successful restoration posed by climate change. For instance, cost and ecological effectiveness may be improved by seeding in years with favorable climate conditions (Kimball et al. 2015; Hardegree et al. 2016). Sequences of treatments to control invasive species that consider climate conditions may also promote native species establishment (Munson et al. 2015; Wilson 2015; Young et al. 2017).

We examined trends across 70 years (1940–2010) of vegetation treatments on public lands managed by the Bureau of Land Management (BLM) in dryland ecosystems of the southwestern United States. Our overarching goal was to characterize changes in treatments, particularly in relationship to restoration, as well as effectiveness related to cost and climate conditions. Specifically, we evaluated whether the treatments were associated with restoration practices, including the use of native species in seeding treatments, and restoration objectives, such as improving wildlife habitat. We also assessed trends in the costs and spatial footprint of treatments over time. We evaluated whether seeding treatments were associated with favorable climate conditions by comparing the conditions during and directly after seeding with the historical range of conditions for that site. Finally, we tested whether increasing wildfire frequency in the region is associated with land treatment practices by determining whether treatments designed to encourage wildfire recovery have increased over time.

Methods

Study Area

We examined BLM lands within seven ecoregions (Environmental Protection Agency Level III) in the southwestern United States, which include grasslands, shrublands, and forests (Fig. 1; Appendix S1, Supporting Information; Omernik & Griffith 2014). For BLM-managed lands in the focal ecoregions, mean annual temperatures decrease from south to north and with elevation, ranging from 2.6 to 23.4°C (median: 14.6°C), mean annual precipitation increases with elevation, ranging from 50 to 557 mm (median: 242 mm, WORLDCLIM; Hijmans et al. 2005), and the relative contribution of winter (November–March) versus summer (July–September) precipitation increases from west to east (Sheppard et al. 1999).

Historical land uses on public lands in the region included grazing, forestry, and mining (Schwinning et al. 2008), whereas contemporary land uses also include energy development (oil, gas, wind, and solar) and recreation. A high proportion of the total land base is managed by the federal government, particularly the BLM (26.4% of the area in the focal ecoregions, Fig. 1).

Dataset

We used the Land Treatment Digital Library (LTDL; Pilliod & Welty 2013), a database of land management activities conducted by the BLM from 1940 to 2010 across the study area. The LTDL database includes spatial information and documents

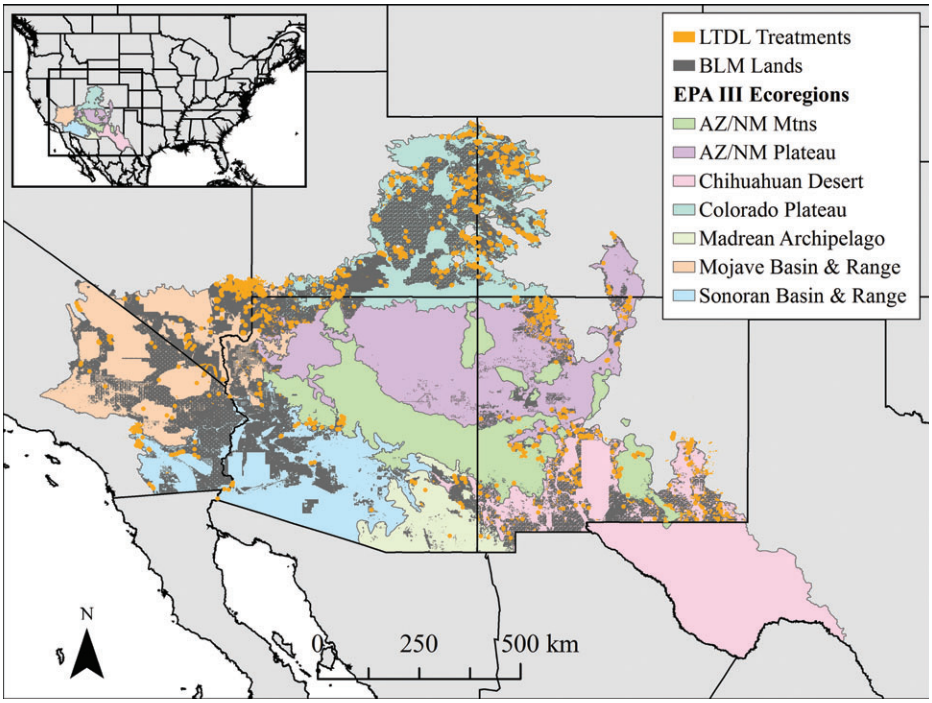

Figure 1. Study area with area of BLM administered lands, LTDL projects, and U.S. Environmental Protection Agency (EPA) Level III ecoregions.

the objectives and details of land management treatments. Categories within the LTDL are based on standardized, nonoverlapping definitions developed to classify treatments based on narrative descriptions (see Appendix S1 for detailed definitions). Multiple treatments may be nested within projects unified by an overarching goal. For example, separate thinning and herbicide treatments may be used in the same project to control juniper encroachment; however, these treatments may not completely overlap spatially and may occur in different years. Treatments are classified into hierarchical categories assigned during the data entry process such as (1) major treatment category (e.g. seedings) and (2) specific treatment type (e.g. aerial seeding). We selected only treatments and corresponding projects with confirmed implementation (as opposed to planned or unconfirmed), which encompassed 4,375 treatments within 2,684 projects covering 17,800 km^2. Spatial polygons, with corresponding area, were available for 3,437 treatments (15,500 km^2). Treatments without polygons either lacked treatment maps (although many reported area treated) or were linear features (e.g. livestock fences).

Analysis

All analyses were conducted in R 3.3.1 (R Core Team 2016). For analyses of the relative amount, or proportion, of treatments in categories over time (major treatment category, potential vegetation type, treatment objectives), we used quasi-binomial models (appropriate due to overdispersion of the response variable compared to a binomial model, deviance/degree of freedom (df) > 2) with time, category, and their interaction as fixed effects in the model.

We tested whether treatments were increasingly associated with wildfire by examining the trends over time for the proportion of treatments mentioning wildfire (quasi-binomial model, $N = 188$ projects, 345 treatments). We analyzed temporal change in the proportion of treatments in the six major treatment categories: closure/exclosure, herbicide/weed control, prescribed burns, seeding, soil stabilization, and vegetation/soil manipulation beginning in 1962 when all categories were present in the dataset (categories described in Appendix S1, $N = 4{,}375$). We excluded 8% of treatments falling into other treatment categories without a clear relationship to restoration.

To characterize whether the dominant vegetation types treated shifted over time, we extracted the area covered by major potential vegetation types for each treatment from the LANDFIRE Environmental Site Potential layer (LANDFIRE 2012), hereafter "potential vegetation" (Appendix S1). We selected the dominant vegetation type(s) for each treatment, defined as the type(s) which covered at least 25% of the treatment area. We analyzed change in the relative proportion of the top five vegetation types based on the number of treatments in which they occurred with dominant cover over the entire study period: pinyon-juniper woodland (2,290 treatments), riparian woodland (334), big sagebrush shrubland (376), creosote bush scrub (250), and desert scrub (297). We analyzed trends beginning in 1961, when all vegetation types were reported until the end of records (2010, $N = 3{,}547$ treatments and vegetation type combinations).

To test for changing management objectives related to restoration over time, we categorized treatments as having: (1) resource extraction, or (2) restoration objectives by searching for keywords within the narrative of the treatment's documented objectives ($N = 2{,}798$). Our analysis of objectives also included two other categories for treatments: (3) both restoration and resource extraction objectives, and (4) uncategorized objectives (neither restoration nor resource extraction). We excluded treatments lacking narrative objectives from the proportion analysis but mention this category in the results. Restoration keywords were based on themes such as invasive species control, native communities, and ecosystem integrity and function (Appendix S1). Resource extraction keywords focused on range improvement for livestock and timber production and excluding cases where livestock removal was indicated, because these treatments were likely designed for vegetation recovery (Appendix S1). We tested for significant trends in the proportions of treatments beginning in 1958 when all categories were present.

We tested the significance of the interaction term in the major treatment category, potential vegetation type, and objective category models with an F test, which detected the difference in deviance between models without and with the interaction ($p < 0.05$). We evaluated whether individual categories should be combined in the final models by testing for (1) significant differences between categories (Tukey test, multcomp package; Hothorn et al. 2008) and (2) model improvement by comparing models with and without combined categories with a deviance F test as above.

We tested whether the species richness and amount of native species in seeding treatments increased over time for the subset of treatments with species names ($N = 1{,}076$, native status and synonyms based on U.S. Department of Agriculture, Natural Resources Conservation Service 2016). We analyzed the change in the proportion of native species with a quasi-binomial model and the change in number of species with a negative binomial model (MASS package; Venables & Ripley 2002). We report significance of terms for all final quasi-binomial and negative binomial models with type III tests and the D^2 statistic (Guisan & Zimmermann 2000), similar to adjusted R^2 (Weisberg 1980), as an overall fit measure (modEvA package; Barbosa et al. 2016). We also calculated the percentage of projects with post-treatment monitoring data for all projects, recent projects (2001–2010), and for projects with seeding treatments.

We tested whether mean area per treatment significantly changed over time with a Mann–Kendall test, a correlation test for temporal trends in nonparametric data, from 1944, after which each year had at least five recorded treatments ($N = 3{,}830$). We tested whether costs per area, adjusted for the rate of inflation (U.S. Bureau of Labor Statistics 2016), decreased or increased over time for all treatments with cost and spatial polygon data using a Mann–Kendall test ($N = 1{,}160$, excluding timber sales which generated revenue, $N = 10$). We also considered whether costs per area changed over time for each of four major treatment categories: herbicide/weed control, prescribed burns, seeding, and vegetation/soil manipulation for recent decades (1981–1990, 1991–2000, and 2001–2010) when we had higher replication at the category level for cost data compared to prior decades (Table S1). We tested for an overall effect of decade on cost per area with nonparametric Kruskal–Wallis rank sum tests (Hollander & Wolfe 1973) and for differences between decades with pairwise Wilcoxon rank sum tests corrected for multiple comparisons with Holm's method (Holm 1979).

We tested how climate conditions during the treatment period (treatment year and the year following the treatment) for seedings compared to general climate conditions for that treatment area over a short-term management period and over the entire study period for treatments with spatial data prior to 2010 ($N = 1{,}174$). We extracted mean annual precipitation and mean annual temperature at a 4 km^2 resolution for the treatment areas from 1935–2015 (PRISM Climate Group OSU 2016). We calculated the percentile for each climate variable for the treatment year (t) and the year after treatment (t + 1) over two different time periods: (1) a short-term management relevant 12-year time period that included the 5 years prior to the treatment year (t − 5) and the 5 years after the year after treatment (t + 6, 10 comparison years; Fig. S1) and (2) a long-term time period spanning the entire 70-year period of record for the dataset (68 comparison years, 1935–2015). The short-term time period allowed us to calculate the percentile of the treatment year and the year posttreatment compared to $N = 10$ years, whereas a shorter series of years would have constrained the result to fewer percentile options. In addition, many of the projects in the database including multiple treatments across a 3–5-year period, which suggested that a 5-year window around the treatment years was relevant to management decisions. We tested whether the median percentile value for the treatment year and the year following treatment differed from the 50% quantile value (the median) with a Wilcoxon signed rank test over both time periods (Bauer 1972; Hollander & Wolfe 1973).

Results

Treatment Practices and Objectives

The area treated and the number of treatments implemented varied across ecoregions in the southwestern United States and over time. The majority of the area treated and number of treatments occurred in the Colorado Plateau ecoregion, followed by the Chihuahuan Desert, with the lowest treatment numbers and areas in the Madrean Archipelago and Sonoran Basin and Range ecoregions (Table 1).

A variety of land management treatments have been implemented in the southwest and their frequency has changed through time. Many projects included treatments in multiple major treatment categories (856), with the majority of these implementing seeding and vegetation/soil manipulation (539). Other treatments included herbicide/weed treatments, prescribed burns, closure/exclosure, and soil stabilization (Fig. S2). Model simplification for the analysis of trends over time led to combined terms for vegetation/soil manipulation and seeding and a term for closure/exclosure with soil stabilization. The proportion of treatments in major categories significantly changed with time ($\chi^2 = 145.2$, $p < 0.001$, $D^2 = 0.67$), with a decline in the vegetation/soil manipulation and seeding

Table 1. Treatment number and area and percent and total area by ecoregion and BLM lands within ecoregion (3,470 total treatments).

Ecoregion III Name	*No. of Treatments*	*Treatment Area (km^2)*	*Ecoregion Area (km^2)*	*Treatment % of Ecoregion*	*BLM Land Area (km^2)*	*Treatment % of BLM Lands*
AZ/NM Mountains	148	1,868	110,910	1.7	6,063	30.8
AZ/NM Plateau	796	4,237	146,859	2.9	19,541	21.7
Chihuahuan Desert	490	5,073	164,060	3.1	29,819	17.0
Colorado Plateau	1,823	6,653	136,575	4.9	71,226	9.3
Madrean Archipelago	34	223	39,650	0.6	5,443	4.1
Mojave Basin and Range	143	1,587	127,690	1.2	53,455	3.0
Sonoran Basin and Range	36	51	118,370	<0.1	37,881	0.1

categories, an increase in the proportion of herbicide/weed and prescribed burns treatments, and no significant change in the closure/exclosure and soil stabilization treatment types (Fig. 2; number of treatments, Fig. S3).

Treatments in pinyon-juniper woodlands were by far the most common over the study period, but the relative proportion of treatments in all five common dominant vegetation types changed over time (interaction term, $\chi^2 = 49.1$, $p < 0.001$, $D^2 = 0.85$; Fig. 3). Model simplification led to combining the creosote bush scrub, desert scrub, and riparian woodland categories into one term in the final model. Treatments in creosote bush scrub, desert scrub, and riparian woodland group increased in proportion over time compared to declines in treatments in big sagebrush shrubland and pinyon-juniper woodland (Fig. 3; number of treatments, Fig. S4). The number of treatments associated with wildfire related objectives have increased over time ($\chi^2 = 14.7$, $p < 0.001$, $D^2 = 0.21$; Fig. S5).

Treatment objectives related to restoration and resource extraction have significantly changed over time ($\chi^2 = 20.9$, $p < 0.001$, $D^2 = 0.33$). Model simplification supported one term combining the restoration category and the category for treatments where both restoration and resource extraction objectives were mentioned. The combined category for restoration and restoration/extraction objectives increased, while the proportion of treatments mentioning only resource extraction objectives or unclear objectives declined (Fig. 4; number of treatments, Fig. S6). While not included as a category in our analysis above, the proportion of treatments with no objectives recorded declined from 64% of the treatments without objectives in 1951–1960 to 17% without objectives for the decade of 2001–2010.

Total species seeded per treatment has increased over time ($\chi^2 = 763.1$, $df = 1$, $p < 0.001$; model fit: $D^2 = 0.42$; Fig. 5A) from a mean of 2.0 species/treatment (±0.12 SE) in the decade 1951–1960 to 8.5 species/treatment (±0.30 SE) in 2001–2010. The proportion of native species seeded per treatment also increased from 16% (±2.4% SE) in 1951–1960 to 75% (±1.8% SE) in 2001–2010 (Fig. 5B; $\chi^2 = 463.8$, $df = 1$, $p < 0.001$, $D^2 = 0.28$).

Only 9.5% of projects included qualitative or quantitative posttreatment monitoring; however, projects with treatments implemented in the decade of 2001–2010 had a higher percentage of monitoring records (14.7%) than the preceding decades. The percentage of projects with seeding treatments with monitoring data was also higher from 2000 to 2010 (30.7%) than for all seeding treatments in the dataset (12.9%).

Treatment Spatial Footprint and Cost

The mean area of each treatment has increased from 1944 to 2010 ($\tau = 0.17$, $z = 1.9$, $p = 0.05$), from an average treatment size of 3.8 km^2 (±0.4 SE) in the decade 1951–1960 to 5.7 km^2 (±0.8 SE) in 2001–2010 (Figs. S7 & S8). Treatment cost has also increased over time ($\tau = 0.29$, $z = 3.4$, $p < 0.001$), outpacing the rate of inflation ($1 in 1940 = $15.58 in 2010). The inflation-adjusted mean cost per area of treatments rose sharply from 1951 to 1960, at 8,559 $/$km^2$ (±$974 SE), to $46,198/$km^2$ (±$4,271 SE) in 2001–2010; median costs on an area basis, adjusted for inflation, also increased—almost tripling from $5,925/$km^2$ in 1951–1960 to $17,695/$km^2$ in 2001–2010. Cost per area from 1981 to 2010 changed by decade for vegetation/soil manipulation ($\chi^2 = 51.2$, $df = 2$, $p < 0.001$), prescribed burns ($\chi^2 = 64.0$, $df = 2$, $p < 0.001$), and seeding treatments ($\chi^2 = 15.9$, $df = 2$, $p < 0.001$), while no significant difference between decades was observed for herbicide/weed treatments ($\chi^2 = 1.06$, $df = 2$, $p = 0.59$). Vegetation/soil manipulation treatments and seeding costs per area significantly increased from the 1980s and 1990s to 2000s (vegetation/soil manipulation: $p < 0.001$, 750%, seedings: $p < 0.05$, 600%). Prescribed burn cost per area increased significantly between the 1980s, 1990s, and 2000s ($p < 0.05$, 400%; Fig. 6).

Climate Conditions of Seeding Treatments

When climate conditions of treatment years and the year after treatment were compared to a long-term climate period (1935–2015), treatments tended to occur in years with warmer annual temperatures (treatment year, $V = 390{,}726$, $p < 0.001$; year after treatment, nonsignificant, $V = 355{,}864$, $p = 0.34$) and lower annual precipitation (treatment year, $V = 288{,}399$, $p < 0.001$; year after treatment, $V = 296{,}842$, $p < 0.001$). When the treatment years were analyzed with respect to the short-term, 12-year time period around the treatment (Fig. S1), treatments tended to occur in years with warmer annual temperatures (treatment year, $V = 341{,}336$, $p < 0.001$; year after treatment, $V = 313{,}447$, $p < 0.001$) and higher annual precipitation (treatment year, $V = 327{,}125$, $p = 0.005$; year after treatment, $V = 327{,}758$, $p < 0.001$; Fig. S9).

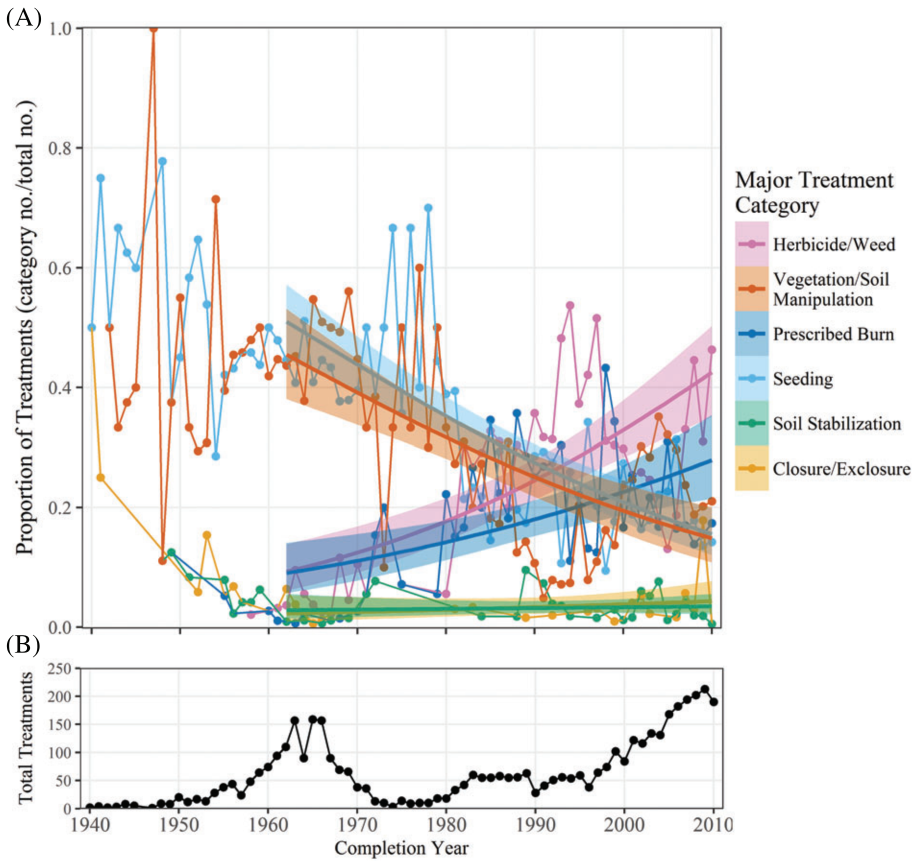

Figure 2. (A) Proportion of treatments by major category over time (fit lines for quasi-binomial model with SE bands for years where all categories are present, 1962–2010). Vegetation/soil manipulation and seeding category trends and soil stabilization and closure/exclosure trends are combined in the final model. (B) Total treatments in this analysis over time.

Discussion

Increasing Restoration Emphasis in Treatments

We found that treatments on public lands administered by BLM across the southwestern United States have changed substantially from 1940 to 2010, with increasing focus on restoration practices. Early treatments tended to be small in size, included a large proportion of nonnative species in seed mixes, and had principal goals of resource extractive uses such as increasing livestock forage availability. Present-day goals are more related to restoration of native communities through the use of native seed, controlling invasive species, and improving wildlife habitat.

Many of the earlier treatments in our study area were within pinyon-juniper and sagebrush vegetation types and focused on improving grass forage for grazing. These management actions may have been a response to woody plant encroachment of open grasslands, perhaps due to decreased fire frequency (Johnsen 1962; Chambers et al. 1999). In contrast, treatments to control nonnative invasive species and prescribed fire treatments are more common in the present day, likely due to the increasing prevalence of invasive species and losses of wildlife habitat due to high severity fire. However, shifts in ecological conditions or management practices may also contribute to the changes in focus on particular vegetation types, such as the increase we observed in the relative abundance of treatments in creosote bush and desert scrub, and riparian woodlands. The observed relative increase in restoration goals among treatments may suggest a changing management focus for the BLM and other U.S. federal land management agencies. These changes may be associated with legislation, such as the Federal Land Policy and Management Act of 1976 (Public Law, 94–579), which mandated multiple use of public lands including their natural resource values. It is possible that these changes were triggered by loss of wildlife habitat (e.g. Esque et al. 2003), increasing invasion by nonnative species and associated wildfire (e.g. Balch et al. 2013), and changes in plant species composition (e.g. Munson et al. 2011*b*). The increasing restoration emphasis may continue to be supported by new policies adopted by the Department of the Interior (of which the BLM is a part) such as agency directives to increase mitigation activities (Improving Mitigation Policies and Practices of the Department of the Interior, Secretarial Order 3330 2013) and restoration after wildfire (Rangeland Fire Prevention, Management and Restoration, Secretarial Order 3336, 2015).

Post-fire-treatment policies, such as the Burned Area Emergency Response (BAER) and Emergency Stabilization and Rehabilitation (ESR) guidelines and practices (e.g. Napper

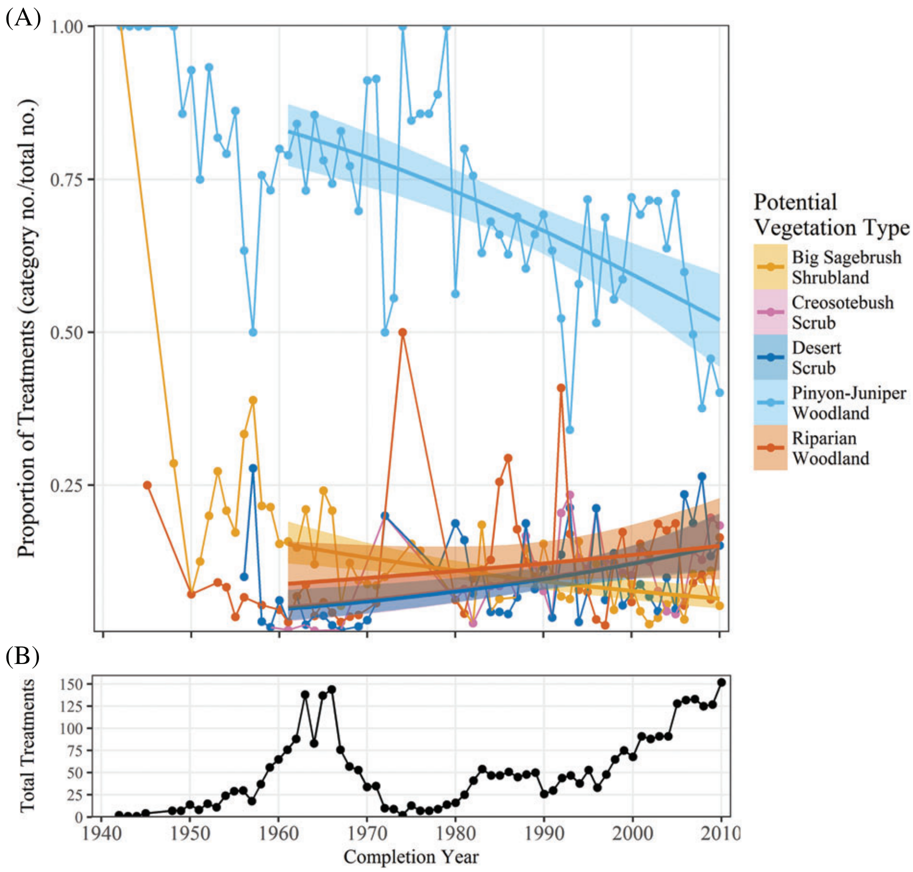

Figure 3. (A) Proportion of treatments by vegetation types over time (fit line for quasi-binomial model with SE bands for years where all categories are present, 1961–2010). Trends for creosote bush, desert scrub, and riparian woodland are combined in the final model. (B) Total treatments in this analysis over time.

2006), likely influence the characteristics of treatments and their effectiveness in relationship to restoration goals. BAER and ESR treatments emphasize the need to minimize soil erosion after wildfire, generally through mulching, erosion barriers, and seeding to improve vegetation cover and reduce erosional soil loss (Napper 2006; Pyke et al. 2013). The urgency of wildfire response and the relatively short-term time frame of post-fire-treatment funding (3–5 years) may prevent managers from staggering treatments over longer time periods to match optimum climate conditions and generally constrain treatment options. Although post-fire treatments are increasingly common, there is little information on their long-term success due to lack of long-term (>5 years) standardized monitoring records (U.S. General Accounting Office 2003; Robichaud et al. 2009). Post-fire-monitoring data may help address this issue (e.g. Knutson et al. 2014) and extensive monitoring of post-fire treatments are now recommended (Rangeland Fire Task Force 2015). We found that the proportion of projects with monitoring records is approximately 50% higher from 2001 to 2010 than for previous decades, perhaps an early indication of increasing emphasis on monitoring within the BLM.

Although the higher proportion of native species and overall number of species in seeding treatments is likely intended to increase the diversity, resistance, resilience, and self-propagation of plant communities among other goals, successful outcomes of restoration efforts are not guaranteed. Including highly competitive nonnative species (e.g. wheatgrasses, *Agropyron* spp.) in seed mixes (Nafus et al. 2015) can negatively impact the establishment of native species and overall restoration outcomes (Knutson et al. 2014; Young et al. 2017). On the other hand, planting nonnative species with high growth rates can impede the spread of invasive species (Davies et al. 2010). Diverse seed mixes may also fail to promote high biodiversity if low establishment occurs due to other factors, such as unfavorable weather conditions (Wainwright et al. 2012; Fick et al. 2016; Stuble et al. 2017), high herbivory, or high competition from invasive species if the seeding treatment is not combined with weed control efforts (Munson et al. 2015).

Despite the trend for seed mixes to include more native species than in the past, many seed mixes used still contain a large proportion of nonnatives, perhaps due to their high germination and growth rates and relatively low cost. This may also be a consequence of the lack of appropriate native seed resources due to the fluctuating demand for seed and short time horizons for some treatments, particularly those associated with wildfires. Increasing the availability of appropriate native

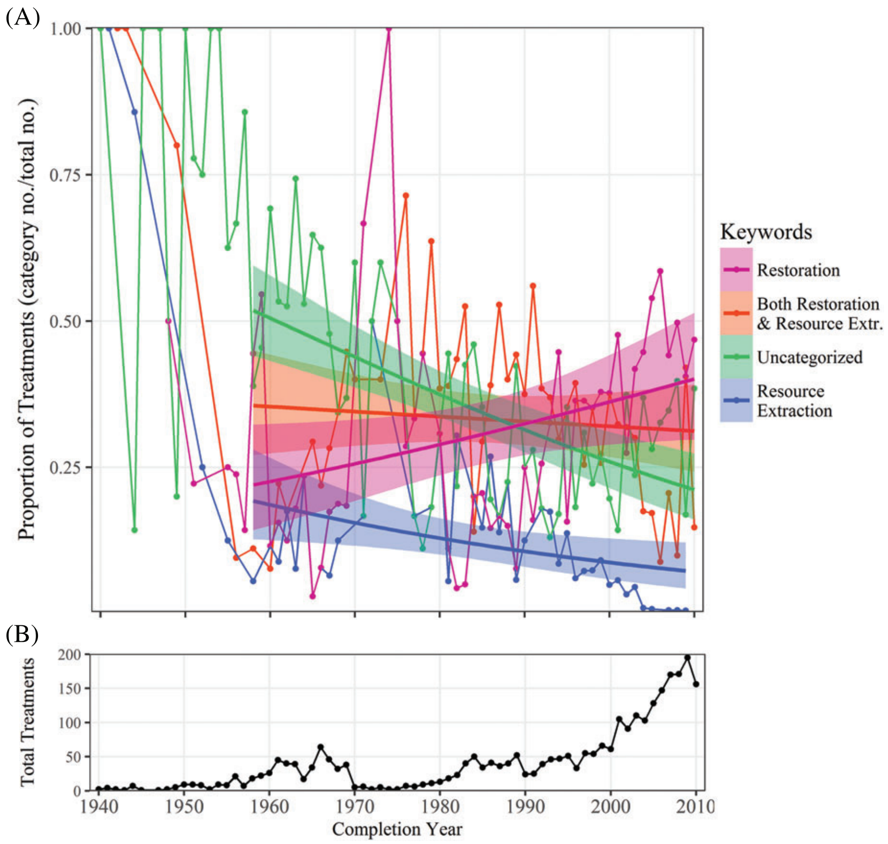

Figure 4. (A) Proportion of treatments by objective category over time (fit line for quasi-binomial models with SE bands for years where all categories are present, 1958–2010). Restoration and both restoration and resource extraction categories are combined in the final model. (B) Total treatments in this analysis over time.

seed resources requires a variety of strategies including selecting species and populations based on their performance and genetic variation and increasing seed storage capacity (Broadhurst et al. 2016); these strategies are already underway in the region (Wood et al. 2015). Ideally greater availability of native seed resources will be paired with increased research on best practices for their use, such as recommendations based on various climate change scenarios (i.e. Gelviz-Gelvez et al. 2015; Butterfield et al. 2016) and tools to select appropriate seed sources (Doherty et al. 2017).

Increasing Spatial Footprint and Cost

The recent focus on wildfire rehabilitation and invasive species control treatments is likely to require treating large areas compared to the local range improvement projects of the past, which may partially explain the increase in mean treatment area we observed. This emphasis is likely to continue due to the projected increase in wildfires and invasion of nonnative species in the region, which positively feed back to each other due to the high flammability and fuel continuity of many nonnative species (Abatzoglou & Kolden 2011). Both increasing wildfire frequency and spread of invasive species may also lead to an increase in restoration efforts to provide habitat for native species of concern, such as the desert tortoise (*Gopherus agassizii*), that are negatively impacted by these factors (Esque et al. 2003). Restoration treatments to increase wildlife populations are more likely to benefit from more diverse native seed mixes to meet habitat requirements than treatments for livestock forage or soil stabilization. The use of native species to support this objective and others related to restoration is likely related to the increase in cost per area of seeding treatments we observed.

Climate Conditions of Seeding Treatments

Our initial analysis suggests that a disproportionally large fraction of seeding treatments occur in years with high temperatures, a potentially adverse climate condition that is less likely to lead to establishment in dry soil. Long-term climate trends for our study area suggest that precipitation is highly variable and temperatures have generally been increasing over the last couple of decades (Fig. S10). This trend probably explains our result that many treatments occurred in warmer and drier climate conditions, which are more common in recent years, than expected compared to the median for the entire period of record. However, we also found that treatments occurred in warmer and wetter conditions at short-term time scales (12 years) that may be more relevant to management decision-making regarding the

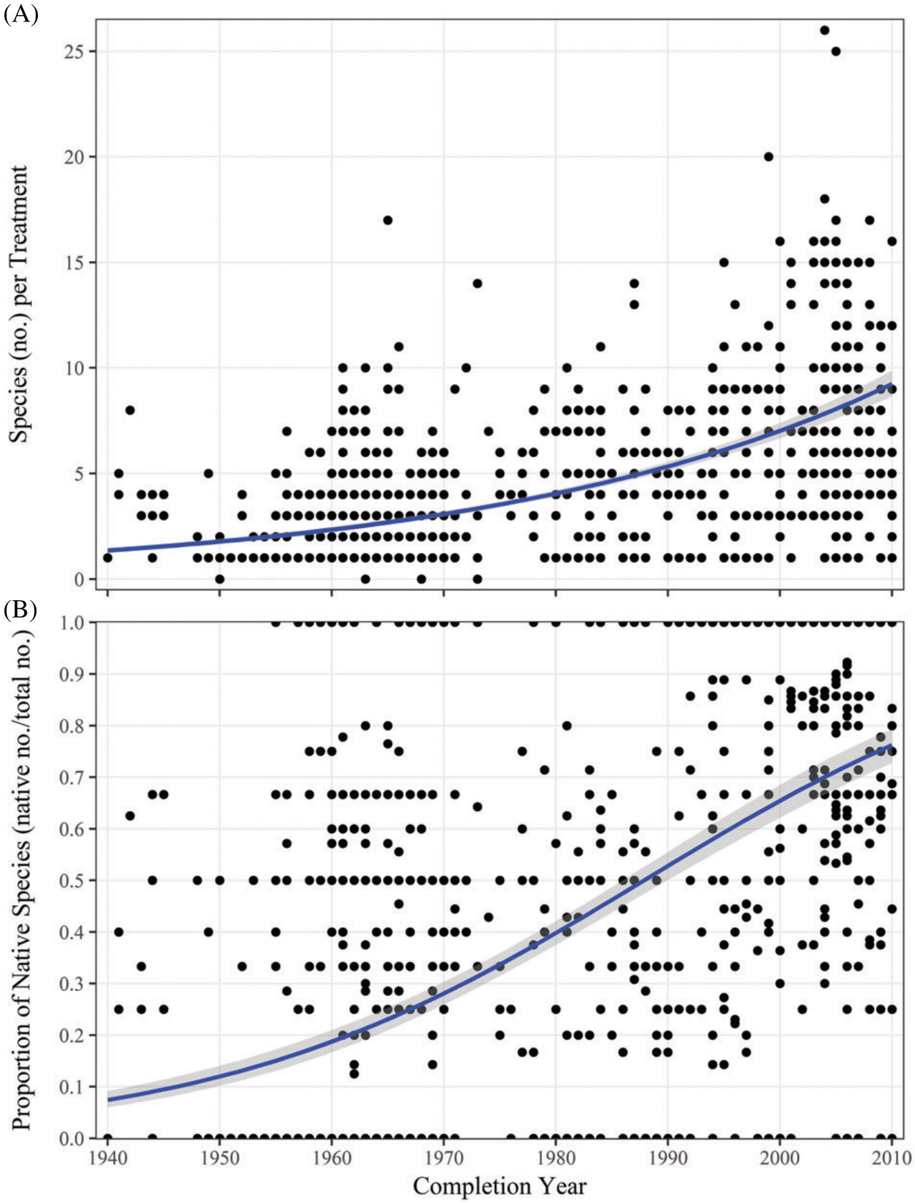

Figure 5. (A) Number of seeded species per treatment over time (fit line for negative binomial model with SE band in gray). (B) Proportion of native species in seeding treatments over time (fit line for quasi-binomial model with SE band in gray).

timing of treatments. Increasing the flexibility of funding available for seeding treatments and improved forecasts of wet and dry years may allow managers to take advantage of ideal climate conditions. While long-term climate predictions tend to be less accurate, some extreme weather patterns are relatively predictable and forecasted well in advance (i.e. El Niño/La Niña years), and seasonal outlooks for extreme temperature and drought are available at coarse spatial scales for the United States for up to 1 year (National Weather Service 2017). Targeting favorable climate conditions for treatments may become increasingly important to restoration success if enhanced aridity and precipitation variability, expected with climate change, lead to lower establishment rates in many years. However, restoration success also depends on site conditions other than climate and competition from invasive species and will likely be difficult to predict (Kimball et al. 2015; Gornish & dos Santos 2016; Stuble et al. 2017).

Insights on Restoration from Large Datasets

The LTDL is the most comprehensive database available that documents treatments conducted by BLM, which manages 1.0 million km^2 of public land in the United States, 16% of the total land area (BLM 2016). However, the extent, cost, and total number of treatments are underestimated in our study. We did not include treatments unless they were clearly documented

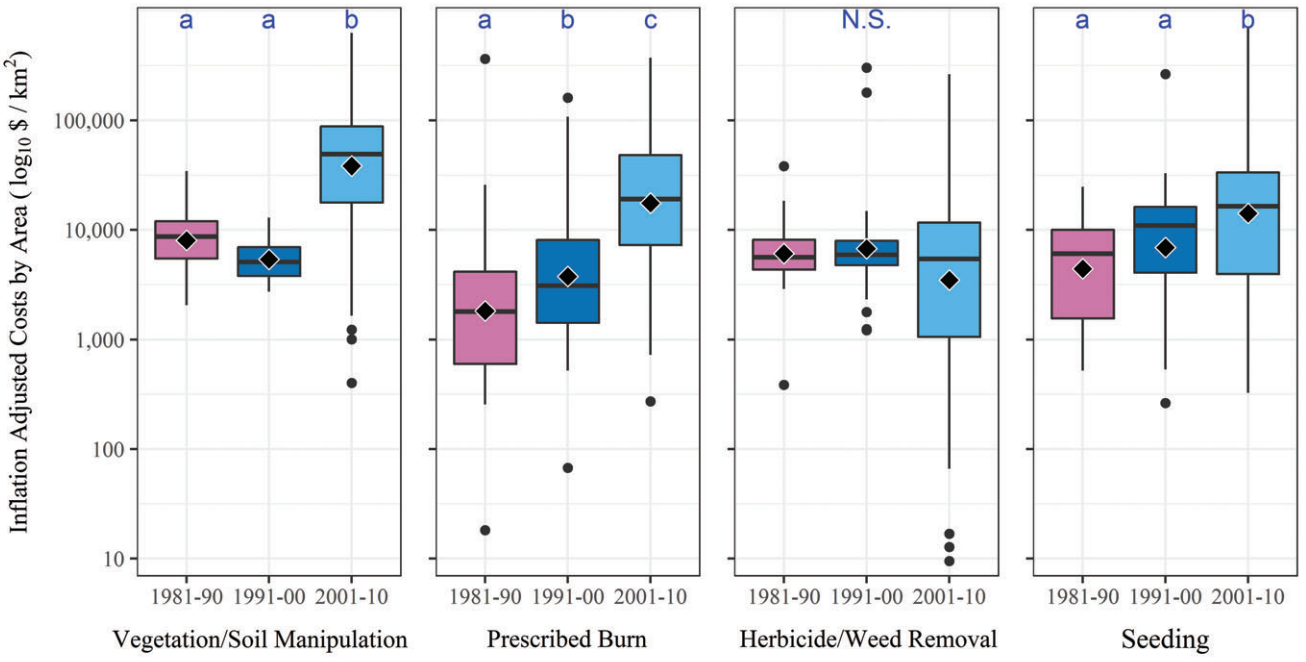

Figure 6. Inflation adjusted costs by area by decade (purple: 1981–1990, dark blue: 1991–2000, light blue: 2001–2010) for four major treatment categories (vegetation/soil manipulation, prescribed burns, herbicide/weed removal, seeding) on a $\log_{10}$ scale with significance of pairwise differences indicated by lowercase letters ($p < 0.05$, pairwise Wilcoxon tests).

as implemented. Older treatments may also be incomplete or missing due to loss of records over time and changing expectations for recording management actions. Spatial variation in treatment information may also exist due to differences in data recording and storage practices between management areas (field offices). Inaccuracies may also have been introduced during the complex task of interpreting handwritten and/or incomplete records for electronic data entry. We increased replication and likely reduced variation across space (e.g. management units) and time by aggregating data at a regional scale and including a long time period in our analysis. In spite of these caveats, our documentation of long-term trends in vegetation treatments for the BLM is significant for the southwestern United States because this agency manages approximately a quarter of the land area in the region.

Myriad questions regarding restoration practices and outcomes can be addressed by synthesizing standardized datasets which cover large spatial scales and long time periods, such as the LTDL. For instance, the LTDL has been used to address questions related to land management practices and outcomes for other ecoregions of the western United States, such as the Great Basin (Knutson et al. 2014; Pilliod et al. 2017). Insights on restoration practices and effectiveness could also result from the use of restoration datasets which focus on specific habitats, such as the National River Restoration Science Synthesis (Bernhardt et al. 2005), or compile large numbers of restoration projects, such as the Global Restoration Network (LeFevour et al. 2007). These syntheses can contribute to international efforts to craft restoration assessment methodologies (IUCN and WRI 2014) and standards (McDonald et al. 2016). These management tools are likely to be increasingly needed to address the growing threats of invasive species, increasing size and frequency of wildfires, loss and fragmentation of dominant vegetation and habitat types, and climate change.

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Supporting Information

The following information may be found in the online version of this article:

Appendix S1. Dataset details.

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