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Practical postfire sagebrush shrub restoration techniques

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ABSTRACT

Wildfire is increasing in frequency and size in the western United States with climate change and invasive species such as cheatgrass. This increase is also causing an increase in the need for restoration techniques, especially in low-elevation, arid shrublands. Sagebrush shrublands are home to the threatened Gunnison sage-grouse and can take decades, if not longer, to recover after fire. We investigated management-friendly restoration techniques aimed at increasing sagebrush cover in a sagebrush system important to Gunnison sage-grouse and impacted by fire in western Colorado. We tested several restoration techniques that could be replicated in management actions to mitigate stressors on sagebrush recruitment, specifically herbivory by large ungulates, water limitation, and competition with other plants. We found that sagebrush grew and survived better when planted as transplanted seedlings versus seeds, when planted in areas where herbicide had been applied versus when vegetation was removed by hand tools, and when caged to prevent herbivory than when not caged. Surprisingly, providing supplementary water did not improve sagebrush transplant growth or survival over use of a microsite (small structure made of wood collected from the burn scar). Constructed microsites were meant to provide protection from wind, retain moisture, and provide shade. Overall, our results indicate that if sagebrush seedlings are provided shelter and structure, then survival can approach natural (not planted) rates and sagebrush can be successfully established in low-elevation sites.

Introduction

Wildfire is increasing in frequency and size across the west, which requires reliable techniques for postfire restoration. Sagebrush systems are prominent in the west and can be negatively affected by frequent wildfire (Baker, 2006). While exact fire return intervals for sagebrush systems are difficult to define, historic fire return intervals for sagebrush can range from 60 yr to 110 yr (Whisenant 1990). Baker (2006) suggests fire rotation, or the time to burn once through a sagebrush landscape, is 100−240 yr for Wyoming big sagebrush (*Artemisia tridentata* Nutt.) (Baker, 2006), although his methods have been questioned (Fulé et al. 2006). Additionally, fire frequency and spatial area are increasing with climate change and increased fuel continuity due to cheatgrass (Pellant 1990; Brown et al. 2004; Dennison et al. 2014). Repeated fires may cause simplification of vegetation communities, limit the ability of communities to recover shrubs (Davies et al. 2012), and reduce cover of shrubs (Mitchell et al. 2017). Sagebrush, specifically, may be eliminated by fire (Perryman et al. 2002). Davies et al. (2012) have suggested that aggressive restoration may be needed, especially in lower-elevation sites, to reestablish sagebrush steppe vegetation after disturbance. While seed mixes often include sagebrush seed (Pillod et al. 2019), establishment of sagebrush from seed has been unreliable (e.g., Meyer 1992; Brabec 2015).

One limitation of sagebrush regeneration in this system may be poorly represented viable sagebrush seed in the seedbank (Meyer 1992). Sagebrush seeds may be limited in spatial distribution from the mother plant (within 1 m of the mother plant) and in longevity in the seedbank when sagebrush is present, but especially after fire when sagebrush is reduced or absent (Young and Evans 1989). Sagebrush seeds in the seedbank typically lose viability within 6 months, although a small proportion of viable seeds may remain longer (Noste and Bushey 1987; Wijayratne and Pyke 2012). Although the addition of sagebrush seed can increase the establishment of sagebrush, both seed germination and seedling establishment can be dependent on many factors (Germino et al. 2018). Competition between sagebrush seeds and herbaceous vegetation may reduce sagebrush seedling survival

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(McAdoo et al. 2013; Brabec et al. 2015). Furthermore, modern-day establishment of sagebrush must contend with non-native species such as crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.), which can limit sagebrush seedling growth (Blaisdell 1949) and recruitment of sagebrush from seed (Davies et al. 2013). Sagebrush establishment can also be limited by invasive species such as cheatgrass (*Bromus tectorum* L.) (Monsen 1994).

Sagebrush recruitment is strongly tied to weather patterns and occurs in pulses when climatic conditions are conducive to recruitment (Perryman et al. 2001; Hourihan et al. 2018). While restoration plantings timed with weather patterns are recommended, practical constraints with funding and weather unpredictability limit effective restoration (Copeland et al. 2018; Hardegree et al. 2018). Additional restoration methods that can be used in low-elevation sites with less precipitation and suboptimal climate conditions are needed for successful and timely sagebrush establishment.

While establishment of sagebrush from seeds can be difficult, establishment of sagebrush from transplanted seedlings may improve sagebrush presence post fire. Although more expensive in cost and labor, transplanting sagebrush seedlings has greater success in sagebrush establishment than planting sagebrush seeds (Davies et al. 2013) and costs per surviving plant may make the use of transplants economically viable (Dettweiler-Robinson et al. 2013). It has been hypothesized that sagebrush planted in patches, or islands, may facilitate additional sagebrush recovery (Davies et al. 2013). The successful establishment of sagebrush islands increases the amount and spatial distribution of seed (Noste and Bushey 1987; Young and Evans 1989). The viability of transplanting sagebrush seedlings continuously across large areas is limited economically and logistically, due to the costs and labor associated with producing and planting transplanted seedlings. The establishment of sagebrush islands across that same area can provide seed sources for further expansion of sagebrush populations, as well as refugia for other plant and animal species (Longland and Bateman 2002). This may increase the area that can be positively affected by restoration efforts.

Restoration in semiarid systems is difficult, and success often depends on factors outside of a land manager's control. Our goal was to determine which factors that management can control would increase positive outcomes in restoration efforts. We sought to determine the best ways to maximize the establishment of sagebrush transplants and establish sagebrush islands in an area mostly devoid of sagebrush due to fire and competition with non-native plants (crested wheatgrass and cheatgrass). Factors known to limit Wyoming big sagebrush seedling (*Artemisia tridentata* Nutt.) establishment were considered in this study including herbivory by large ungulates (deer and elk), water availability, and competition with other plants, especially non-native species. We tested practical management methods of alleviating these stressors to see if this would improve sagebrush survival and growth. We hypothesized that alleviation of these stressors would increase sagebrush survival and growth and that water availability would be especially important. Islands of sagebrush transplants were planted to maximize survival, based on previous published and unpublished work with sagebrush and other transplanted shrub seedlings. We hypothesized that we could achieve > 50% survival of sagebrush transplants, an improvement over reported survival rates of about 20–25% for transplanted seedlings (Dettweiler-Robinson et al. 2013; Davidson et al. 2019).

Site description

The area known as Fish Park is an ≈1 060-ha area important to Gunnison sage-grouse, which were listed as threatened by the US Fish and Wildlife Service in December 2014. Fish Park is located on Bureau of Land Management lands in western Colorado and eastern Utah, straddling the state border, just south of the McInnis Canyons National Conservation Area. The Fish Park area was burned in the Wrigley Complex fire in 1999 and again in the Spring fire in 2006 (Fig. 1), and it still lacks sufficient Wyoming big sagebrush *Artemisia tridentata* Nutt. and forb cover to meet guidelines for Gunnison sage-grouse habitat (BLM Grand Junction Field Office unpublished data, Stiver et al. 2015). Average precipitation for the area is 28.1 cm (11.6 in), and elevation is ≈1 890–1 980 m (6 200–6 500 ft). Average precipitation during our study was 22.5 cm (8.9 in) in 2017, 23.4 cm (9.2 in) in 2018, and 29.9 cm (11.8 in) in 2019 (Western Regional Climate Center 2020, accessed 6 April 2020). The Colorado Plateau generally has a biseasonal cool season, 15 October to 15 April, and a warm season, 15 June to 15 October, precipitation (Hereford et al. 2002). Precipitation during our study was above average to average during the cool- and warm-season periods in 2016 to 2017 and 2018 to 2019, and average to below average during the cool and warm season periods in 2017 to 2018. Soils in the area are mapped as monogram very fine sandy loam and progresso-mellenthin complex. Soil tests performed in the area at 3 points randomly placed across the Fish Park site in 2016 showed soils as silty clay and silty loam, with pH of 7.8, 6.8, and 6.9 and carbon/nitrogen ratios of 11.2, 7.6, and 8.9.

Methods

*Sagebrush (*Artemisia tridentata *Nutt.)*

All sagebrush seed for seed application and transplanted seedlings was collected within a 3-mile (4.8-km) radius of the Fish Park site in November 2015, as local seed sources may perform better than seed or transplant sources from farther away (Brabec et al. 2015). Seed was cleaned and either planted (see details later) or stored in cool storage (10–18°C; 50–65°F) at the Upper Colorado Environmental Plant Center (http://www.coloradoplantcenter.org/). Sagebrush transplants were germinated without stratification on the surface at a temperature of 15–24°C (60–75°F). Seedlings were then grown in potting media in 164 cm^3 (10 cubic in) cones called "cone-tainers" for ≈7 mo. Plants were kept in a greenhouse with temperatures maintained at 4–16°C (40 to 60°F) from January to May. Plants were kept outdoors starting in May where temperatures range from highs in the 20–27°C (upper 70 to mid-80°F) to lows similar to greenhouse temperatures.

Treatments

We set up five 74 × 74 m treatment areas that were fenced to exclude cattle only, not wildlife (exclosures). Treatment areas were chosen on the basis of existing vegetation and topography. We avoided areas where remnant sagebrush existed or areas that were steep. Sagebrush was planted as a transplanted seedling or as seed. Sagebrush seed was planted as part of a seed mix with forb seed (Table 1). Seed was raked into the soil. One Wyoming big sagebrush (*Artemisia tridentata* Nutt.) transplanted seedling was planted in a 0.9 × 0.9 m area. Sagebrush transplants were planted with and without forb seed. Herbivory by elk and deer was prevented by caging transplants with individual chickenwire cages. There was no intent to prevent insect or small herbivore impacts. Cages were circular with a diameter of ≈45 cm (18 in) and open at the top.

We applied supplementary water and used "microsites" to mitigate water limitation. Supplementary water was accomplished by placing two 0.95-L (1 quart) DriWater time-release packs (gel packs of polymer that would release moisture over about 90 d, company no longer in business) with each sagebrush transplant

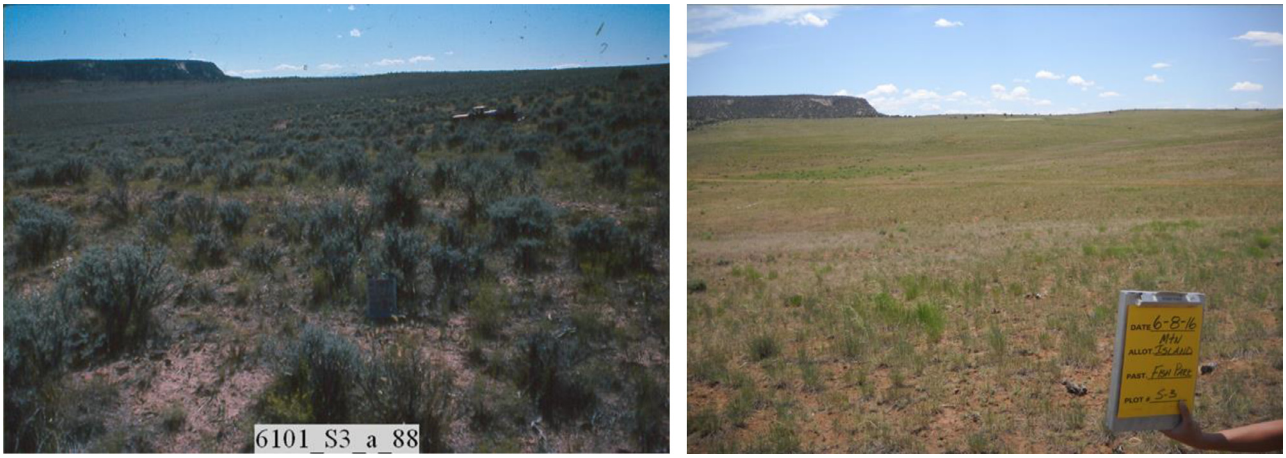

Fig. 1. Photos from 1988 prefires and 2016 postfires in the Fish Park area.

Table 1
Treatments used in treatment areas (exclosures). Transplanted sagebrush seedlings were planted with or without a forb seed mix. Sagebrush seed was always planted as part of a seed mix. Transplanted sagebrush seedlings were either caged or not to deter large ungulate herbivory. Sagebrush was planted as a transplanted sagebrush seedling or as seed, as part of a seed mix. Transplanted sagebrush seedlings were planted with supplementary water versus microsite. Sagebrush seed was planted with microsites versus no alterations for moisture. Treatment areas were either treated with herbicide or vegetation was mechanically removed to reduce competition from existing vegetation.

1	herbicide + sagebrush transplant + microsite + cage
2	herbicide + sagebrush transplant + microsite + no cage
3	herbicide + sagebrush transplant + supplementary water + cage
4	herbicide + sagebrush transplant + supplementary water + no cage
5	herbicide + sagebrush transplant + forb seed + microsite + herbivory
6	herbicide + sagebrush transplant + forb seed + supplementary water + cage
7	herbicide + sagebrush transplant + forb seed + supplementary water + cage
8	herbicide + sagebrush transplant + supplementary water + cage
9	herbicide + sagebrush and forb seed + microsite
10	herbicide + sagebrush and forb seed
11	mechanical + sagebrush transplant + microsite + cage
12	mechanical + sagebrush transplant + microsite + no cage
13	mechanical + sagebrush transplant + supplementary water + cage
14	mechanical + sagebrush transplant + supplementary water + no cage
15	mechanical + sagebrush transplant + forb seed + microsite + cage
16	mechanical + sagebrush transplant + forb seed + supplementary water + cage
17	mechanical + sagebrush transplant + forb seed + supplementary water + cage
18	mechanical + sagebrush transplant + supplementary water + cage
19	mechanical + sagebrush and forb seed + microsite
20	mechanical + sagebrush and forb seed

when they were planted in September 2016. Transplants were "watered" once by refilling 1.9 L (2 qrt) of prewet polymer for each transplant once in June 2017. Microsites were meant to provide shade, protect from wind, and retain moisture for seeds or transplanted seedlings. Microsites were constructed with dead wood collected from within the bur scar area, ≈10 × 10 cm (4 × 4 in) in size, on the southwestern side (where prevailing winds enter the site) of each transplant or seeded plot.

Herbicide or mechanical removal of vegetation was used to limit competition with other plants. Corteva Agriscience Rodeo (53.8% glyphosate) at a rate of 2.3 L per ha (1 ½ qrt per acre) was applied to half of each treatment area. Herbicide was applied with a utility terrain vehicle (UTV)-mounted sprayer with the surfactant Activator 90 made by Loveland products added at a rate of 1.89 L per 454 L (4 pt/100 gal). On the other half of each area we physically removed vegetation with McLeod hand tools in experimental plots, 0.9 × 0.9 m area, with untreated areas (no vegetation removal) surrounding plots. This was meant to mimic management actions that could be performed on a larger scale with machinery (e.g., a chain pulled by a UTV or bulldozer).

We used a factorial experimental design to test factors thought to limit sagebrush recruitment and growth at the site. We considered seeding with or without forb seed ("forb seed"—transplanted seedlings planted with or without forb seeds, sagebrush seed was always planted with forb seed as part of a seed mix); large ungulate herbivory ("herbivory"—transplanted sagebrush seedlings caged versus not caged); "seeding" sagebrush planted as seed or as a transplanted seedling; water limitation ("water"—supplementary water for transplanted seedlings only vs. microsites for seeds and transplanted seedlings vs. no amendment for seeds only); and competition with other plants ("competition"—herbicide vs. mechanical removal of existing vegetation to reduce competition from existing vegetation) (see Table 1). This totaled 20 treatments (see Table 1), each of which was replicated 3 × per treatment area (nested in treatment areas), for a total of 60 plots per treatment area. Treatments were replicated a total of 15 times. Each plot was marked with rebar.

Due to the impracticality of treating very small areas with herbicide at a consistent application rate, one-half of each treatment area was treated with Corteva Agriscience Rodeo (53.8% glyphosate) at a rate of 2.3 L/ha (1 ½ qrt/acre) in June 2016 while vegetation within plots 0.9 × 0.9 m (3 × 3 ft area) were cleared with hand tools in the other half of the treatment area. Treatments were otherwise randomly placed within treatment areas. In seeded plots Wyoming big sagebrush was seeded at a rate of 0.11 kg/0.4 ha (0.25 lb/acre). Forbs included in the mix with sagebrush seed were *Linum lewisii* Pursh, *Achillea millefolium* L., *Penstemon palmeri* A. Gray, and *Lupinus argenteus* Pursh seed at a rate of 0.45 kg/0.4 ha (1 lb/acre). Data on sagebrush transplant survival and growth and density of forb seedlings were collected during the sampling period (2017–2019) in June.

Pretreatment vegetation was sampled using the point intercept method, collecting 50 points per transect along three parallel 25-m transects (Elzinga et al. 1998). These data were collected to give context to results but were not collected to directly explain seed and seedling survival and growth.

Sagebrush islands

We also planted 497 sagebrush transplants grown from collected seed (see earlier). These transplants were planted in five "islands" of ≈100 sagebrush each. Each transplant was marked with rebar, caged, planted with 2 DriWater qrt, and planted with 0.9 × 0.9 m (3 × 3 ft) of weed cloth (10-mm thick) to maximize survival. Survival of transplants was tracked during the sampling period (2017–2018) each fall (October) and spring (May). Due to logistical constraints, data were not collected in 2019. Sagebrush islands were separate from treatment areas.

Natural sagebrush survival

Dog island is a small island in the Ruby-Horsetheif stretch of the Colorado River within the McInnis Canyons National Conservation Area, ≈19 km (12 mi) from the Fish Park site, that burned by a human-caused wildfire in August 2015. Precipitation is similar to the Fish Park site, soils are San Mateo-Escavada, and elevation is ≈1 330 m (4 630 ft). Postfire monitoring found sagebrush (*Artemisia tridentate* Nutt.) recruitment. From 2016 to 2019 all sagebrush seedlings within a 25 × 25-m area were counted and survival rates determined. We compared survival rates of natural regeneration of sagebrush to seeded and planted sagebrush populations.

Statistical analyses

At each sampling date all live sagebrush were counted in islands and treatment areas. Growth of sagebrush was estimated in treatment areas by measuring volume of the plant using height, to the tallest part of the plant not including seed production, and crown size, the area of an ellipse, to calculate volume. This was multiplied by the percent of the plant that was "live," which we classified into one of five categories (trace–20%, 20–40%, 40–60%, 60–80%, 80–100%). Density of forbs was taken in each treatment area.

We analyzed pretreatment vegetation data using cluster analyses to determine how treatment areas compared with each other (Hothorn and Everitt 2014; Complete linkage method, R Core Team 2017). We analyzed growth data (response) in yr 1, 2 (2017, 2018), and a final growth (yr 2019), using analysis of variance with treatments (explanatory variables, see Table 1) nested in treatment areas (AOV in R, R Core Team 2017). Sagebrush survival and forb density were analyzed with a general linear model against a binomial distribution due to count data, using the same explanatory treatment variables (see Table 1; GLM in R, R Core Team 2017).

To determine cost estimates for aerially seeding sagebrush versus planting sagebrush islands, we gathered cost estimates from Bureau of Land Management (BLM) sources. Specifically, we gathered information on prices based on estimates gathered from the BLM Boise Seed Warehouse and from previous contracts and orders in the Grand Junction Field Office. These rates are estimates only and can vary widely on the basis of changing conditions (e.g., fuel prices, seed availability, and demand).

Results

Treatment areas clustered into two groups. One group included two treatment areas that were dominated by crested wheatgrass (treatment areas 1 and 2; 14% and 16% relative cover, with < 1% cover of cheatgrass). The other group included three treatment areas that were dominated by cheatgrass (treatment areas 3, 4, and 5; 22%, 31%, and 22% relative cover), with crested wheatgrass absent (treatment areas 3, 4) or low (treatment area 5 had < 2% relative cover of crested wheatgrass).

Transplanted seedlings grew and survived better in all years, with an average overall survival of 50% for transplanted seedlings in treatment areas by the end of the third growing season, with no surviving seedlings in seeded plots (explanatory variable "seeding," $P < 0.01$, Table 2). Surprisingly, transplanted seedlings did not grow or survive better when provided supplementary water than when they had a microsite wood pile on the windward side of the transplant (explanatory variable "water," $P > 0.8$, see Table 2). Transplants also grew and survived better in areas treated with herbicide than in areas where surface vegetation was removed mechanically with hand tools (explanatory variable "competition," $P \leq 0.03$, see Table 2, Fig. 2a, data for survival by variable "competition" not shown). Transplanted seedlings grew and survived better when caged then when not caged, although this was only marginally significant in the final year for growth (explanatory variable "herbivory" $P = 0.07$ for growth, see Table 2; $P = 0.05$ for survival, explanatory variable "herbivory," see Table 2, Fig. 2b). Few forbs grew, and forb density did not show a significant relationship with any treatment, including the addition of water (see Table 2).

Growth and survival of sagebrush transplants were significantly different in treatment areas, mostly driven by low growth and survival in one treatment area located in an area dominated by cheatgrass (cheatgrass cover 31% compared with 22% and 21% and < 1% for other treatment areas, explanatory variable "seeding" $P < 0.01$, see Table 2). Survival of sagebrush transplants in this treatment area was lower than other areas, 2% overall survival compared with 33%, 77%, 79%, and 81% transplant survival in other treatment areas (Treatment Area 4, see Fig. 2b).

Average survival of transplanted sagebrush in each sagebrush island in the spring of 2017 (yr 1) was 60% with a range of 44% to 70% per island (see Fig. 2c). In the fall of 2018 (yr 2) average survival of transplants from the previous year was 83% with a range of 61–100% per island (see Fig. 2c). The overall average survival of transplanted sagebrush by the end of the study was 40% (not shown in graph). For comparison, survival of sagebrush seedlings in a natural regeneration event (Dog Island) was 55% in the second yr after the fire (2017–2018) and 83% from yr 2 to yr 3 (2018–2019), with an overall average survival of 46% from 2017 to 2019. Recruitment in the natural regeneration event (Dog Island) was noted in 2016, but no baseline population estimate occurred. Therefore, there is no initial survival rate and the survival rate of

Table 2
Statistically significant and important results of statistical analyses including analysis of variance, *F* and *P* values, and general linear models using a binomial distribution, *Z* and *P* values. "Treatment area" refers to fenced treatment areas (exclosures). "Forb seed" refers to sagebrush seedlings being planted with or without a forb seed mix. "Herbivory" refers to seedlings being caged or not to deter large ungulate herbivory. "Seeding" refers to sagebrush planted as seed versus transplanted seedlings. "Water" refers to supplementary water for transplanted seedlings only versus microsites for seeds and transplanted seedlings versus no amendment for seeds only. "Competition" refers to herbicide treatment versus mechanical removal of vegetation to reduce competition from existing vegetation. Results for all treatments (explanatory variables) are included for sagebrush (*Artemisia tridentata* Nutt.) final growth (response variable). Selected significant and interesting results discussed are included for remaining response variables.

Response variable	Explanatory variable	*F* value	*P* value
ARTR Growth Final	Treatment area	31.79	< 0.01
	Forb seed	0.27	0.87
	Herbivory	3.78	0.07
	Seeding	19.31	< 0.01
	Water	0.1	0.9
	Competition	16.01	< 0.01
ARTR Growth Yr1	Seeding	14.72	< 0.01
	Water	0.15	0.86
	Competition	4.62	0.03
ARTR Growth Yr2	Seeding	18.24	< 0.01
	Water	0.15	0.86
	Competition	17.15	< 0.01
Forb Density	Water	0.48	0.62
3 yr ARTR Survival		*Z* Value	*P* value
	Treatment area	3.77	< 0.01
	Seeding	−6.61	< 0.01
	Water	0.97	0.33
	competition	−0.39	0.69
	Herbivory	1.98	0.05

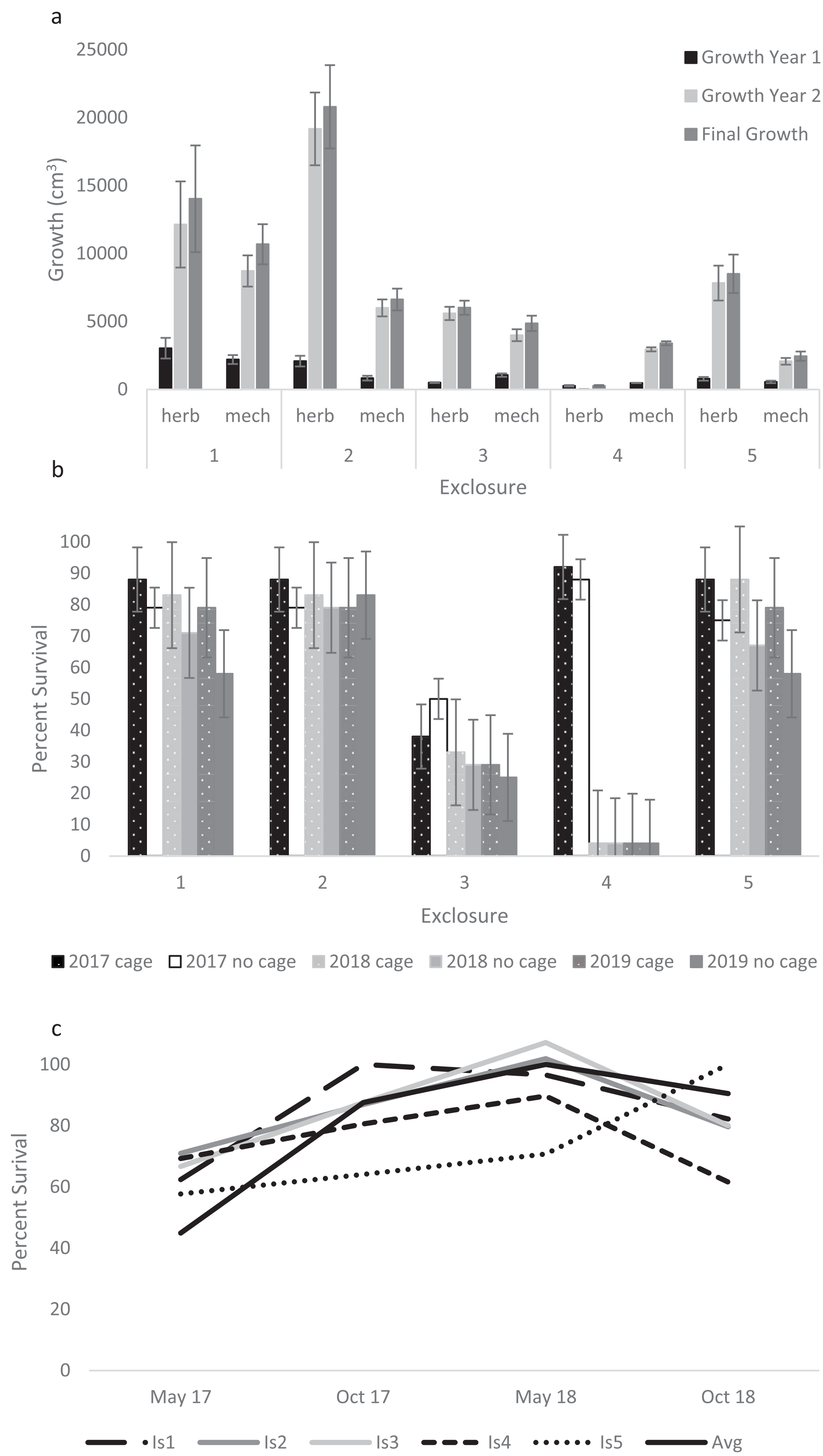

Fig. 2. **a,** Growth from 2017 to 2019 of seedlings in areas treated mechanically and with herbicide (“competition”). Shown are averages of growth of sagebrush seedlings and standard error for all five treatment areas. **b,** Percent survival of caged and uncaged (“herbivory”) seedlings in all treatment areas. Shown are survival counts for each treatment area with standard errors. **c,** Survival, count data, of sagebrush *(Artemisia tridentata)* over 2 yr in each sagebrush island “Is.” Shown are percent survival by sampling date or survival from one sampling date to the next, not overall survival.

46% from 2017 to 2019 is likely higher than the actual overall population survival rate.

Cost of sagebrush seed per pound is ≈$18 for a Pure Live Seed (PLS) rate of 0.16 lb/acre (BLM Seed Warehouse, Boise, ID). Assuming a seeding rate of 0.3 PLS per acre, the cost of sagebrush seed for 100 acres would be ≈$3 375. Flight time for aerially broadcasting seed is estimated at $6 per acre and would be $600 for 100 acres. In our example, the cost of aerially seeding 100 acres with sagebrush seed would be $3 975.

Cost of purchasing sagebrush transplanted seedlings is estimated at $5 per transplant grown out from locally collected seed. In our study we used youth corp crews (Western Colorado Conservation Corp, https://www.wcccpartners.org/) for planting transplanted seedlings at a cost of $8 500 per week. The youth crew was able to plant ~500 transplants in a week with additional amendments (weed cloth, cages, and two driwater containers with each transplant). We did not include estimates of driwater (no longer available), weed cloth, etc., since these may not be used in all situations. If our goal is ~1 sagebrush per m^2, then 4 000 sagebrush are needed per acre. We conservatively estimate that for sagebrush islands, 25% of the area will be planted, which equates to 1 000 sagebrush transplants per acre. Therefore, the cost per acre would be 1 000 sagebrush transplants at $5 each, plus 2 wk of crew work time at $8 500 each for a cost of $22 000 per 100 acres (40.5 ha). The cost of aerial seeding is about 20% that of setting up sagebrush islands, $3 975 for 100 acres versus $22 000 for 100 acres. However, since there was no sagebrush seedling survival from seed, we could not estimate cost per established seedling.

Discussion

As reported in other studies (e.g., Brabec et al. 2015), few sagebrush germinated in seeded plots and there was no survival of sagebrush, 3 yr post planting, from seed in our study. As in other studies, transplanted seedling survival was low in the first yr and high after the initial yr (Dettweiler-Robinson et al. 2013; Boyd and Obradovich 2014). Other studies have found transplanted seedling mortality rates shortly after planting of 46% with mortality rates of 9% of remaining sagebrush the next yr (Davidson et al. 2019). In our study, transplants established and grew over the 3 yr with survival rates quite high, around 90% in later sampling, thus showing that we were able to establish sagebrush islands that should persist. Our overall survival rate in sagebrush islands, 40%, was improved from previous studies, 20−25% survival rate of transplants (Davidson et al. 2019; Dettweiler-Robinson et al. 2013), but did not reach our goal of 50% survival. However, our sagebrush transplants survival rate of 40% approached recorded natural rates from another nearby fire.

Sagebrush seedling emergence can be variable but may be high, up to 500/0.01 m^2 (Young and Evans 1989). Density of established sagebrush has been reported at $1/m^2$ (Young and Evans 1989); for planted stock $0.1/m^2$−$0.7/m^2$ (McAdoo et al. 2013); and for Wyoming big sagebrush and mountain sagebrush $0.5/m^2$−$1/m^2$ (Davies and Bates 2010). High rates of initial mortality are expected in natural regeneration events. Higher initial mortality rates of transplanted sagebrush seedlings may also be expected due to transplant shock; however, this may be minimized through acclimatization and other techniques (Schumar and Anderson 1987), and use of these techniques may be able to increase initial survival rates above what we found in our study.

Other studies have found transplanted seedling survival to be negatively related to exotic annual grass cover (Davidson et al. 2019) or high abundance of perennial grasses (Davidson et al. 2019). One treatment area in this study was located in an area dominated by cheatgrass, and final survival of sagebrush in this treatment area was 2%, much lower than other treatment areas. Further research and other techniques may be needed to ensure adequate survival of transplanted seedlings in areas dominated by exotic annual grasses.

While well-established crested wheatgrass can exclude sagebrush recruitment (Meyer 1992), sagebrush seedlings may be able to establish better in crested wheatgrass stands than seedlings from seed (McAdoo et al. 2013). Other studies have found limited sagebrush establishment from broadcast seedings in areas with crested wheatgrass (Davies et al. 2013). Despite crested wheatgrass being present (16% and 14% relative cover in the two treatment areas clustered together) in the study area, overall sagebrush transplanted seedling survival was adequate in our study area, as has been found in other studies with reported survival of sagebrush seedlings planted in crested wheatgrass (Davies et al. 2013).

Similar to other studies, we found that herbicide application correlated with increased growth and survival of sagebrush transplanted seedlings (McAdoo et al. 2013). However, our results taken together seemed to indicate that providing protection and shelter to transplanted seedlings was the most important factor. We cannot determine how important initial vegetation manipulation (vegetation removal or herbicide application) is compared with no vegetation manipulation in our study. However, other studies have shown that competition with other plants can be important in big sagebrush seedling establishment (see Schlaepfer et al. 2014 and references therein), and vegetation manipulation likely increased transplanted seedling survival in our study.

Providing shelter of some sort seemed to consistently increase survival and growth of transplanted sagebrush seedlings. For example, microsites performed as well as supplementary water (no significant difference in survival of transplanted seedings between microsite and supplementary water treatments), and caged seedlings performed better than seedlings without cages. The first evidence of herbivory by large ungulates, despite signs of presence (e.g., droppings), on any transplanted sagebrush seedlings, caged or uncaged, was not documented until the summer of 2019, suggesting that herbivory on seedlings was not a large concern in the first 2 yr of the study. Therefore, the increased performance of transplanted seedlings that were caged may be because cages provided some environmental protection for seedlings. Additionally, while seedlings in areas treated with herbicide performed better, death of competing plants from herbicide was minimal, likely due to residual vegetation and timing of application (personal observations). Similar to cages and microsites, residual vegetation in areas treated with herbicide may have provided shelter for seedlings, compared with areas mechanically treated, which were exposed. Nurse plants can increase moisture and protect seedlings from extreme temperatures and desiccation from wind (e.g., Holmgren et al. 1997). Nonliving microsites can also provide relief from stressors for seedlings (e.g., Peters et al. 2008) and likely provide some of the same benefits (e.g., protection from wind, temperature extremes, and soil moisture retention). Maier et al. (2001) found that Wyoming big sagebrush recruitment is high in years with above-average winter (December and January) precipitation, likely due to snow cover protecting seedlings from cold temperatures and high winds, and providing soil moisture for seedling growth (Maier et al. 2001).

While the cost of establishing sagebrush islands with transplanted seedlings is significantly more (about 5 × as much from our estimates) as aerially broadcasting seed, the cost may be justified in high-priority, low-elevation sites. In these areas broadcast seeding may have limited success (e.g., Germino et al. 2018), while our study has shown that sagebrush islands can be established in these sites. We could not make comparisons in costs per surviving seedling since no seedlings from seed survived in our study.

However, we did successfully establish sagebrush islands in our study and our research contributes to the growing knowledge of how to successfully restore shrubs in challenging circumstances. Our study did not show any success with forb establishment, and further research is needed to determine how to successfully restore this component of systems.

Implications

Restoration is difficult in arid shrubland systems, and shrub and forb components may be especially difficult to restore. Post-fire recruitment of native plants can be limited by climate and non-native and invasive species, and managers often have only a narrow window of time to perform restoration actions. Our results indicate that initial shrub establishment is possible in semiarid systems with non-native and invasive species present, although success was limited in our study in one treatment area with particularly high cheatgrass cover. Managers may incur high costs associated with intensive management actions on high-priority sights to ensure success. Transplanted sagebrush seedlings that are provided shelter may have increased survival and growth, and costs may be mitigated by using local sources to provide shelter (e.g., locally collected wood or standing vegetation).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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