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Challenges of Establishing Big Sagebrush *(Artemisia tridentata)* in Rangeland Restoration: Effects of Herbicide, Mowing, Whole-Community Seeding, and Sagebrush Seed Sources☆,☆☆

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ABSTRACT

The loss of big sagebrush (*Artemisia tridentata* Nutt.) on sites disturbed by fire has motivated restoration seeding and planting efforts. However, the resulting sagebrush establishment is often lower than desired, especially in dry areas. Sagebrush establishment may be increased by addressing factors such as seed source and condition or management of the plant community. We assessed initial establishment of seeded sagebrush and four populations of small outplants (from different geographies, climates, and cytotypes) and small sagebrush outplants in an early seral community where mowing, herbicide, and seeding of other native plants had been experimentally applied. No emergence of seeded sagebrush was detected. Mowing the site before planting seedlings led to greater initial survival probabilities for sagebrush outplants, except where seeding also occurred, and these effects were related to corresponding changes in bare soil exposure. Initial survival probabilities were > 30% greater for the local population of big sagebrush relative to populations imported to the site from typical seed transfer distances of ~320–800 km. Overcoming the high first-year mortality of outplanted or seeded sagebrush is one of the most challenging aspects of postfire restoration and rehabilitation, and further evaluation of the impacts of herb treatments and sagebrush seed sources across different site types and years is needed.

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Introduction

Wildfires burn hundreds of thousands of hectares per year on average in the Great Basin, some of which leave vast areas devoid of big sagebrush for decades and susceptible to permanent conversion to invasive annual grasslands (Miller et al., 2011). Big sagebrush (*Artemisia tridentata* Nutt.) is not fire adapted, and postfire recovery is complicated by its limited seed dispersal capabilities and short-term seed viability (Young and Evans, 1989; Wijayratne and Pyke, 2012). The rapid loss of sagebrush habitat across the Great Basin and corresponding impacts to imperiled species such as Greater sage-grouse *(Centrocercus urophasianus)* have motivated efforts to restore sagebrush through seeding and planting (e.g., Dettweiler-Robinson et al., 2013), especially on recently burned sites susceptible to postfire invasion or dominance by cheatgrass (*Bromus tectorum* L.).

Planting and especially seeding of big sagebrush have had mixed success, particularly in sagebrush steppe communities with low and variable mean-annual precipitation, frequent fire, and invasive annual plants (Knutson et al., 2014). Difficulties in establishing sagebrush may be amplified by competition with the herbaceous community (Boyd and Svejcar, 2011; McAdoo et al., 2013). Big sagebrush seeding or planting is often accompanied by management treatments, including herbicides to reduce competition from exotic annual grasses, drill or broadcast seeding to increase native herbs, and mowing to reduce herbaceous wildfire fuel continuity (e.g., Pyke et al., 2014). These treatments can alter soil resource availability (Rau et al., 2014) and potentially affect sagebrush seedling survival and establishment. Negative interactions (e.g., competition) between native herbs and sagebrush have been documented at plot scales in intensely managed mine reclamation sites and high elevations (e.g., Williams et al., 2002; DiCristina and Germino, 2006). However, interactions of sagebrush seedlings and herbs have not been evaluated at landscape-scales in drier, less productive big sagebrush communities after management treatments, despite the prevalence of such treatments.

Selection of seed source may also affect establishment and long-term persistence of sagebrush. Sagebrush is a genetically diverse species in which subspecies, cytotypes that differ in ploidy, and populations can have different responses to the surrounding environment (McArthur and Sanderson, 1999). Genetic variation is evident in growth rate, stress

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and climate responses, water-use efficiency, depth of rooting, phenology, and other related variables (e.g., Welch and Jacobson, 1988; Maier et al., 2001) that enable sagebrush to occupy diverse abiotic environments and likely influence interaction with herbs. For example, big sagebrush populations with rapid growth rates may evade competitive exclusion by attaining large stature and deeper roots before herbaceous competitors exhaust soil resources.

The objective of this study was to evaluate how initial establishment of big sagebrush seedlings is influenced by management treatments of the herbaceous community and to determine how these effects vary among four populations of big sagebrush (including a polyploid) originating from different climates. We predicted that treatments resulting in lower abundances of competing herbs would increase survival of sagebrush outplants. We also expected sagebrush seedlings from local seed would have greater survival compared with seedlings from seed collected from 320–800 km away, although populations from drier/warmer climates or polyploids might have advantages under drought conditions.

Materials and Methods

The experiment was conducted in a large, fenced area with loam soils where livestock had been excluded since 2012 in Birds of Prey National Conservation Area (BOP NCA) in southwestern Idaho (lat 43°13'50"N, long 116°19'20"W). The historical plant community was dominated by *A. tridentata* subsp. *wyomingensis* and secondarily by *A. tridentata* subsp. *tridentata*, but multiple fires and past land use eliminated them from the study area and much of the surrounding landscape. The area last burned in 1987. Before the experimental treatments, the plant community was dominated by cheatgrass, a non-native tumble-mustard (*Sisymbrium altissimum* L), and Sandberg's bluegrass (*Poa secunda* J Presl, an early seral perennial).

Twenty-four 1-ha plots separated by untreated, 1-ha areas were arranged in three replicate blocks using a full-factorial, completely randomized combination of four management practices (no treatment, herbicide application, mowing, and mowing plus herbicide) and two seeding treatments (seeded and unseeded). A minimum-till drill (7512 OTG Drill, Truax Company, New Hope, MN, USA) simultaneously drilled certain seeds (e.g., grasses and forbs) and imprinted others (e.g., sagebrush and other shrubs) in alternating strips aligned with separate seed boxes, in November 2012 (Table A2). Multiple sagebrush populations were outplanted into each plot. Control plots were untreated and unseeded. Following wetter than average growing conditions in 2011, cheatgrass and exotic forbs had created tall (> ~0.5 m), dense standing litter by spring 2012. Herbicide plots were prep-mowed in April 2012 (customarily used to reduce interception by standing/senesced vegetation). Mow-only and mow + herbicide plots were mowed in May 2012, after appreciable grass growth. Mowing was to 10 cm stubble height using a tractor-pulled rotomower. Herbicide plots received 280 g · ha^{-1} of glyphosate with a boomless sprayer without surfactant in April 2012 following mowing and then 280 g · ha^{-1} of imazapic with Hasten surfactant via a calibrated boom sprayer in October 2012.

We obtained seedlings from four populations of *A. tridentata* subsp. *tridentata*, from different ecoregions, mean annual temperature and annual precipitation (MAT/MAP) ranges, and cytotypes, including:

1) Idaho, BOP NCA, 10.8°C/297 mm · yr^{-1}, diploid,
2) New Mexico, San Luis Mesa, 9.9°C/265 mm · yr^{-1}, tetraploid,
3) California, near Benton, 8.9°C/250 mm · yr^{-1}, diploid, and
4) Oregon, near Echo, 11.5°C/239 mm · yr^{-1}, diploid.

The Oregon and California sources appeared to have the fastest and slowest growing strategies, respectively, based on growth of adults in other common gardens (MJ Germino, unpublished data). Seedlings were propagated outdoors by sowing seeds into 10 cm^3 cone-tainers filled with native soils (silty loam) on 10 August 2012. Germination occurred within a week. Cone-tainers were rearranged periodically to limit the influence of microsite and watered one to two times daily depending on climate conditions. Plants overwintered (January to March 2013) in a nursery cold-storage facility. Seedlings were shifted to full sun and cold-hardened with exposure to < 0°C surface temperatures before outplanting in March 2013, when shoot heights were 4–5 cm. Outplants were approximately the size of young seedlings that undergo the most culling and selection (based on other observations we have made, e.g., DiCristina and Germino, 2006), about 1/10 size of stock that agencies usually plant (21–24 months old, ~30 cm shoot height, roots densely filling cone-tainer) and ~5–10× larger than ~1- to 3-week-old germinants.

Seedling outplanting occurred from 16 March to 10 April 2013. Seedlings were bare-root transplanted into small holes created with pickaxes and received 1 L of supplemental water two times in the first month after outplanting (watering is customary in the BOP NCA). Soils were hand-packed around seedling roots, resulting in an ~2 cm deep and ~20 cm diameter basin-like depression of bare soil around each seedling. Nine seedlings from each of the four populations were outplanted in a completely stratified and intermixed pattern into each of the 24 plots (36 seedlings · $plot^{-1}$, 864 total), with 12–15 m distance between each seedling.

Survival of seedling outplants was measured in April, May, July, and September 2013 and in March 2014. Mortality was assumed when a plant was gone or all foliage was missing and no re-greening occurred after rain. Percent ground cover of functional group or key species (e.g., annual grasses) was measured using digital, grid-point intercept sampling of nine aerial photographs of 1 m^2 areas per plot in July 2013 (SamplePoint software, Pilliod and Arkle, 2013).

Data Analysis

Semiparametric proportional-hazard regression was used to estimate the effects of mowing, herbicide, herb seeding, and sagebrush seed source on seedling hazards of death (coxph function in survival library of R, version 3.0.2). The "exact" marginal likelihood method in this function was used to separate dates of mortality that were otherwise not detected on a particular sampling date ("tied" data). The regression model could not accommodate the entire observation period because of high seedling mortality up to July 2013 and little thereafter. We used survival analysis to examine seedling survival only during April, May, and June 2013, when the most significant die-off occurred. Significance of differences in cover were determined with full-factorial generalized linear model in JMP (version 11, SAS Institute, Cary, NC, USA) with $\alpha = 0.05$.

Results

The study coincided with warmer and drier-than-normal conditions: for the 2013 water year, MAT = 11.9°C and MAP = 237 mm · yr^{-1}, compared with the mean values of 10.8°C and 297 mm · yr^{-1}. Only 60 mm of precipitation was received in March to June of 2013, compared with a 70-year average of 120 mm. Grand means for cover were 22% soil, 27% litter, 22% cheatgrass, 22% Sandberg's bluegrass, and < 5% each of tumble mustard and Russian thistle (*Salsola kali* L). Across all treatments, few to no shrubs or forbs that were seeded in 2012 were evident in 2013, probably as a result of the drought. Cover classes differed in the seeded and mowing + herbicide + seeding plots in the bare soil category only. Seeding led to a reduction in bare soil cover (22.6 ± 6%, $\chi^2 = 6.0$, $P = 0.01$) across all treatment types, and combination of mowing + herbicide + seeding further reduced bare soil (19 ± 4%, $\chi^2 = 7.8$, $P < 0.01$). Also, mowed plots had considerably more bare soil than control plots (32 ± 5% vs. 18 ± 4% soil, respectively, although marginally significant in spite of the large effect size, $\chi^2 = 2.5$, $P = 0.1$), but seeding mowed plots reduced bare soil back to 21 ± 7%. Cheatgrass covered 16.4 ± 15% of unseeded plots and 21 ± 12% of seeded plots (n.s.). No seeded sagebrush germinated, or at least survived to be counted, in seeded plots.

Management treatments and seed source influenced sagebrush seedling survival times, according to Cox "hazards of death" ($\chi^2 = 39.4$, $P < 0.0001$, Table 1). The risk of seedling mortality decreased > 50% with mowing but increased 2.2-fold where seeding followed mowing (Fig. 1, Table 1, the hazard ratio of 0.53 indicated that rate or "hazard" of death was 0.53 per seedling in mowed plots relative to seedlings in control plots, compared with 2.2 seedlings dying in mowed + seeded plots per seedling in control plots). The combination of mowing + herbicide + seeding increased the hazard of death for sagebrush 2-fold (57 seedlings died compared with 26 with herbicide + mowing, Table 1).

Distant seed sources for outplanting had lower initial survival than the local population: For every one local that died, 1.3–1.6 of the seedlings from California, New Mexico, or Oregon perished in spite of their either being from warmer or drier climates or being polyploid (Table 1, Fig. 2). By July 2013, 23 local seedlings remained overall, whereas < 14 seedlings from each of the other populations remained. Thus, the local population had at least 64% more surviving individuals than other populations at that point in the study.

Discussion

The greater initial survival of sagebrush seedlings with diminished herbaceous cover as a result of mowing and, to a lesser extent, herbicide, is consistent with other studies that found relatively rapid growth, recovery, and establishment of sagebrush under conditions of reduced competition from herbaceous vegetation (Boyd and Svejcar, 2011; Davies et al., 2013; McAdoo et al., 2013). The negative effect of drill seeding on initial seedling survival was likely due to increased ground disturbance, leading to more cheatgrass competition in seeded plots, given that seeded native species did not establish.

Our ability to make generalizable inferences on the importance of factors such as climate of origin, growth strategy, and polyploidy is limited without multiple populations of each condition, but our results do indicate that in general terms, seed source can play an important role in seedling survival. Our inferential power was also weakened by the substantial mortality among all seedlings, which appeared related to drought, and may have been lessened if larger stock was used and planted in fall. Considering these limitations, support for our predictions was mixed. Populations that were either tetraploid or fast growing and from warmer/drier climates did not have greater initial survival under any treatment condition. However, initial survival probability was greater for the local relative to other populations, regardless of treatment, which is consistent with the concept of local adaptation. Local sagebrush populations may have undergone past selection for survival with invasive annual plants that now dominate large areas of southwest Idaho.

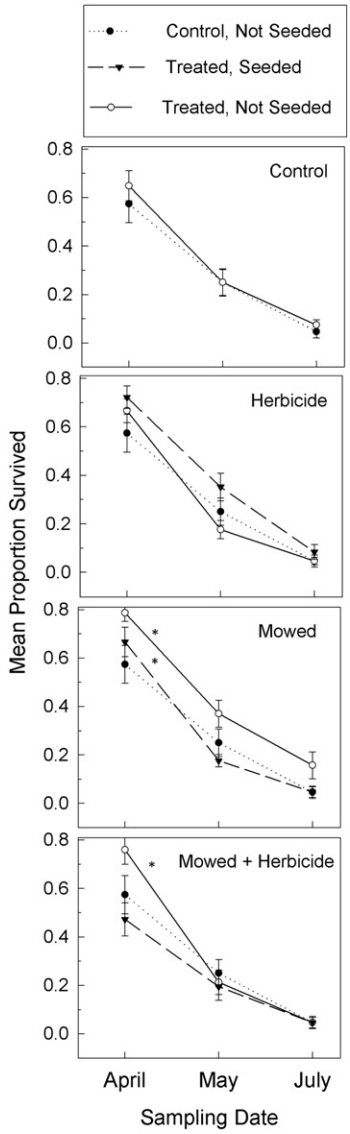

Fig. 1. Differences in sagebrush seedling survivorship among treatments in the Birds of Prey National Conservation Area by month, for four populations of sagebrush outplants combined. Outplanting occurred from 16 March to 10 April. Asterisks denote significant differences from controls, which are shown by dotted lines in all three panels (unseeded, the base level for comparison for supporting statistics, repeated in lower panels to allow comparison, see Table 1 for statistics). Mortality did not occur from September to March, so those data are not shown.

Table 1
Coefficients of sagebrush seedling survival model results from outplantings into treatment plots (averaged across treatments) at the Birds of Prey National Conservation Area. Hazard ratios > 1 indicate increased hazards of death relative to the base level of the explanatory variable (i.e., similar to a relative death rate). The base level is unseeded control for the treatment factor and the local Idaho seed source for the population factor.

Variable	Parameter estimate	Hazard ratio	Mean (SE)	z	*P* value
Population: California	0.487	1.628	0.156	3.120	0.002
Population: New Mexico	0.276	1.318	0.153	1.800	0.072
Population: Oregon	0.260	1.298	0.154	1.690	0.090
Seeded	−0.160	0.852	0.220	−0.730	0.467
Mowed	−0.634	0.530	0.218	−2.920	0.004
Mowed × Seeded	0.797	2.219	0.309	2.580	0.010
Herbicide	0.066	1.068	0.221	0.300	0.765
Herbicide × Seeded	−0.430	0.650	0.311	−1.380	0.166
Mowed + Herbicide	−0.200	0.819	0.219	−0.910	0.361
Mowed + Herbicide × Seeded	0.708	2.029	0.314	2.250	0.024

Implications

Initial establishment (first growing season) is an important demographic milestone in the life history of big sagebrush, and factors that increase longevity, and especially establishment to adulthood, could increase seeding or planting outcomes (Boyd and Obradovich, 2014). Large numbers of seeds and seedlings are used in restoration projects, and even small percentage increases in initial survival are worthwhile, particularly in relatively warm, dry, and invaded sites like our study site. These site types often require multiple and often repeated restoration actions, and consideration of how one treatment affects subsequent treatments may improve restoration outcomes. Further testing conducted across different years and sites, without supplemental watering and with different seedling stock types and planting approaches (i.e., season of planting), will help guide large sagebrush seeding and planting investments in rangelands across the western United States.

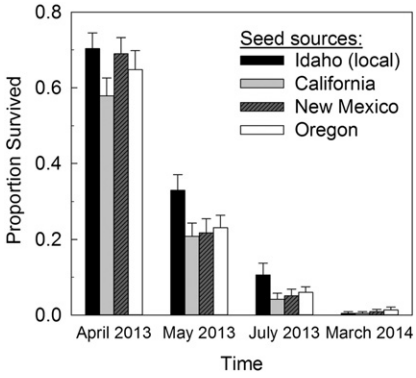

Fig. 2. Differences in sagebrush seedling survivorship of *Artemisia tridentata* subsp. *tridentata* from four states in the United States, planted from 16 March to 10 April into treatment plots (averaged across treatments) in the Birds of Prey National Conservation Area. See Table 1 for statistics.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rama.2015.07.001.

References

Boyd, C.S., Obradovich, M., 2014. Is pile seeding Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*) an effective alternative to broadcast seeding? Rangeland Ecology & Management 67, 292–297.

Boyd, C.S., Svejcar, T.J., 2011. The influence of plant removal on succession in Wyoming big sagebrush. Journal of Arid Environments 75, 734–741.

Davies, K.W., Boyd, C.S., Nafus, A.M., 2013. Restoring the sagebrush component in crested wheatgrass-dominated communities. Rangeland Ecology & Management 66, 472–478.

Dettweiler-Robinson, E., Bakker, J.D., Evans, J.R., Newsome, H., Davies, G.M., Wirth, T.A., Pyke, D.A., Easterly, R.T., Salstrom, D., Dunwiddie, P.W., 2013. Outplanting Wyoming big sagebrush following wildfire: stock performance and economics. Rangeland Ecology & Management 66, 657–666.

DiCristina, K., Germino, M.J., 2006. Correlation of neighborhood relationships, carbon assimilation, and water status of sagebrush seedlings establishing after fire. Western North American Naturalist 64, 441–449.

Knutson, K.C., Pyke, D.A., Wirth, T.A., Arkle, R.S., Pilliod, D.S., Brooks, M.L., Chambers, J.C., Grace, J.B., 2014. Long-term effects of seeding after wildfire on vegetation in Great Basin shrubland ecosystems. Journal of Applied Ecology 51, 1414–1424.

Maier, A.M., Perryman, B.L., Olson, R.A., Hild, A.L., 2001. Climatic influences on recruitment of 3 subspecies of *Artemisia tridentata*. Journal of Rangeland Management 54, 699–703.

McAdoo, J.K., Boyd, C.S., Sheley, R.L., 2013. Site, competition, and plant stock influence transplant success of Wyoming big sagebrush. Rangeland Ecology & Management 66, 305–312.

McArthur, E.D., Sanderson, S.C., 1999. Cytogeography and chromosome evolution of subgenus Tridentatae of Artemisia (Asteraceace). American Journal of Botany 86, 1754–1775.

Miller, R.F., Knick, S.T., Pyke, D.A., Meinke, C.W., Hanser, S.E., Wisdom, M.J., Hild, A.L., 2011. Characteristics of sagebrush habitats and limitation to long-term conservation. In: Knick, S., Connelly, J.W. (Eds.), Greater sage-grouse ecology and conservation of a landscape species and its habitats. University of California Press, Oakland, CA, USA, pp. 145–185.

Pilliod, D.S., Arkle, R.S., 2013. Performance of quantitative vegetation sampling methods across gradients of cover in great basin plant communities. Rangeland Ecology & Management 66, 634–647.

Pyke, D.A., Shaff, S.E., Lindgren, A.I., Schupp, E.W., Doescher, P.S., Chambers, J.C., Burnham, J.S., Huso, M.M., 2014. Region-wide ecological responses of arid Wyoming big sagebrush communities to fuel treatments. Rangeland Ecology & Management 67, 455–467.

Rau, B.M., Chambers, J.C., Pyke, D.A., Roundy, B.A., Schupp, E.W., Doescher, P., Caldwell, T.G., 2014. Soil resources influence vegetation and response to fire and fire-surrogate treatments in sagebrush-steppe ecosystems. Rangeland Ecology & Management 67, 506–521.

Welch, B.L., Jacobson, T.L.C., 1988. Root growth of *Artemisia tridentata*. Journal of Range Management 41, 332–334.

Wijayratne, U.C., Pyke, D.A., 2012. Burial increases seed longevity of two *Artemisia tridentata* (Asteraceae) subspecies. American Journal of Botany 99, 438–447.

Williams, M.I., Schuman, G.E., Hild, A.L., Wicklund, L.E., 2002. Wyoming big sagebrush density: effects of seedlings rates and grass competition. Restoration Ecology 10, 385–391.

Young, J.A., Evans, R.A., 1989. Dispersal and germination of big sagebrush (*Artemisia tridentata*) seeds. Weed Science 37, 201–206.