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Response of Planted Sagebrush Seedlings to Cattle Grazing Applied to Decrease Fire Probability☆,☆☆

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ABSTRACT

Restoration of non-sprouting shrubs after wildfire is increasingly becoming a management priority. In the western U.S., Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) restoration is a high priority, but sagebrush establishment from seed is sporadic. In contrast, planting seedlings often successfully restores sagebrush, but is expensive and time consuming. After planting, hence, there is a need to protect the investment from disturbances such as fire that will erase gains in sagebrush recovery. Grazing is likely the only tool that can be applied feasibly across the landscape to decrease wildfire probability, but there are concerns that grazing and associated activities (e.g. trampling) may negatively impact sagebrush seedlings. We investigated effects of grazing by cattle, applied as a fine fuel management strategy, on planted sagebrush seedlings at five blocks for five years. Grazing substantial reduced exotic annual grasses, large perennial bunchgrasses, and total herbaceous cover, thus achieving fuel management goals. Sagebrush cover and reproductive efforts were almost 2-fold greater in grazed compared to non-grazed areas in the final year of the study. This suggests that grazing favored sagebrush, a generally unpalatable shrub, recovery, likely by reducing competition from highly palatable herbaceous vegetation. Density of sagebrush, however, was similar between grazed and non-grazed areas. This research demonstrates that grazing can be strategically applied to reduce the probability of wildfire in areas with planted sagebrush seedlings; thereby, protecting the investment in sagebrush recovery. With more refinement, it also appears that grazing can be utilized to accelerate the recovery of sagebrush and potentially other woody vegetation habitat by modifying the competitive relationship between herbaceous and woody vegetation.

Introduction

Restoration of shrubs is becoming increasingly recognized as a management need in ecosystems around the world (Wong et al., 2007; Medina-Roldán et al., 2012; Miao et al., 2015). Shrubs can provide critical ecosystem services, including increased soil organic carbon, fertility islands, and increased diversity (Zhao et al., 2007; Fonseca et al., 2012; Gang et al., 2012; van Zonneveld et al., 2012). Shrub restoration can also be a management priority because many shrubs are key habitat components for wildlife of conservation concern (Shaw and Monsen, 1986; Chandler et al., 2009; Fulbright et al., 2018). Shrub restoration, particularly in water-limited ecosystems, can be challenging because establishment is often limited by water stress (Porensky et al., 2014).

Big sagebrush (*Artemisia tridentata* Nutt.) restoration is a management objective in many western United States rangelands because of its importance and wide-spread loss (Davies et al., 2011). By the early 2000s, sagebrush occupied only approximately half of its historic range (Knick et al., 2003; Schroeder et al., 2004). Recent large wildfires (mega-fires) have resulted in large landscapes devoid of sagebrush (Davies et al., 2018) and an uncertainty when and even if they will naturally recover. This

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loss of sagebrush habitat has further challenged the conservation of sagebrush-associated organisms, especially sagebrush-obligate wildlife (Crawford et al., 2004; Suring et al., 2005; Shipley et al., 2006). Sagebrush restoration is needed because it is a foundation species that provides ecosystem services and functions (Prevéy et al., 2010), including microhabitats for seed germination and establishment, and habitat for wildlife of conservation concern.

Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) is particularly difficult to restore because it occupies more water-limited and hotter rangelands. Similar to many other perennial species in arid ecosystems, Wyoming big sagebrush establishment from seed is sporadic. Most efforts to restore Wyoming big sagebrush by seeding have failed (Lysne and Pellant, 2004; Davies et al., 2013; Knutson et al., 2014), though there are exceptions (Davies et al., 2018). Planting seedlings has proven to be a more reliable method to restore Wyoming big sagebrush (Davies et al., 2013, 2020; McAdoo et al., 2013; Davidson et al., 2019); probably because this method bypasses the smallest size classes that are the most likely to suffer mortality (Shriver et al., 2019). This method is logistically challenging, labor intensive, and expensive (McAdoo et al., 2017). Therefore, after investing in this method, avoiding disturbance-induced mortality of planted sagebrush seedlings is a high priority.

Wildfire is a common disturbance in this ecosystem and a persistent threat to efforts to restore big sagebrush as this species is fire intolerant. In post-fire landscapes, the most common scenario where sagebrush restoration is needed, fine fuels are often greatly increase in the following years. This poses an elevated risk of re-burning. Herbaceous vegetation biomass often doubles after fire in sagebrush communities (Harniss and Murray, 1973; Uresk et al., 1976; Davies et al., 2007). Exotic annual grasses often also increase after fire in Wyoming big sagebrush communities (Chambers et al., 2007). Increases in exotic annual grasses substantially increase the probability of wildfire because they produce more fine fuels that dry out earlier than native-dominated communities (Davies and Nafus, 2013). Thus, there is significant concern that areas planted with sagebrush seedlings will burn and erase all gains in sagebrush recovery. For example, wildfire burned several areas on the Hanford Reach National Monument where sagebrush seedling had been planted, removing most of the sagebrush transplants (Dettweiler-Robinson et al., 2013).

Successful recovery of sagebrush by planting sagebrush seedlings is, to some degree, dependent upon fire management, which includes fine fuel management. Livestock grazing is likely the only treatment that can be applied feasibly to reduce fine fuel loads across large sagebrush landscapes. Grazing by cattle can reduce fine fuel amounts (Diamond et al., 2009; Davies et al., 2010) and increase fuel moisture by removing dead materials (Davies et al., 2015), subsequently decreasing the probability of wildfire ignition and spread (Diamond et al., 2009; Davies et al., 2017). However, land and wildlife managers are hesitant to apply cattle grazing to areas planted with sagebrush seedlings because of concerns that cattle use will increase sagebrush mortality through trampling and potentially inadvertent grazing. Non-planted, just emerged seedling survival of basin big sagebrush (*A. t. tridentata*) was lower on livestock-grazed compared to non-grazed plots in a short-term study in Utah; however, mortality was high (>95%) in both grazed and non-grazed areas (Owen and Norton, 1992). The susceptibility of planted sagebrush seedlings to livestock use may be different than just emerged seedlings.

Grazing may also influence the competitive relationships between sagebrush, which is generally non-palatable to cattle, and highly palatable herbaceous vegetation, thereby, potentially mediating any negative effects or even promoting sagebrush growth. Diet of cattle in the spring and summer are 97% or more herbaceous vegetation, with the majority being graminoids, and 0–1% sagebrush (Torstenson et al., 2006). Selective grazing can place grazed plants at a competitive disadvantage with ungrazed plants, often leading to increases in ungrazed plants, but other factors also determine the plant community response (Wan et al., 2015). A long term evaluation would likely be needed to evaluate if grazing by cattle favors planted sagebrush seedling growth.

The objective of this study was to evaluate long term (5 yrs) effects of grazing by cattle on survival and growth of planted Wyoming big sagebrush seedlings. We expected that sagebrush survival would be lower in grazed compared to non-grazed areas, but that growth of sagebrush seedlings would be greater in grazed areas.

Methods

Study area

The study was located on the Northern Great Basin Experimental Range 50–56 km west of Burns, OR, USA (43°29′N, 119°43′W). Climate is hot and dry in the summer and cool and wet during the winter. Study sites were located in areas that were lacking sagebrush as a result of prior fires. Elevation was approximately 1400–1425 m above sea level, aspects were south, southwest, and west and slopes ranged from 6 to 14°. Long-term (1981–2010) average annual precipitation was 266 mm (PRISM, 2019). Annual precipitation was 62, 104, 104, 78, 88, and 57% of the long-term average in 2013, 2014, 2015, 2016, 2017, and 2018, respectively (PRISM, 2019). Soils across the study area were loamy and well-drained. Study sites were formerly Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle and A. Young)-bunchgrass steppe. The dominant native perennial bunchgrass was bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursch) A. Löve) or Thurber needlegrass (*Achnatherum thurberianum* (Piper) Blackworth), depending on site. Other common perennial grasses included prairie Junegrass (*Koeleria macrantha* (Ledeb.) J.A. Schultes), Sandberg bluegrass (*Poa secunda* J. Presl), and squirreltail (*Elymus elymoides* (Raf.) Swezey). The exotic annual grass cheatgrass (*Bromus tectorum* L.) was common across the study sites. Common perennial forbs across the study area included *Phlox longifolia* Nutt., *Erigeron* L. sp., *Crepis* L. sp., *Astragalus* L. sp., *Lomatium* Raf. sp., *Eriogonum* Michx. sp., and *Achillea millefolium* L.. Native ungulates were excluded from study sites for the duration of the study with cattle panel fencing. Small herbivores were not excluded from study sites, but we did not detect herbivore-induced mortality of sagebrush seedlings.

Experimental design and measurements

A randomized block design was used to investigate the effects of grazing with cattle on planted sagebrush seedlings. Treatments (grazed and non-grazed) were applied to five blocks with varying site and vegetation characteristics. Each block consisted of one grazed and one non-grazed 66 m^2 (6×11 m) treatment replicate with a two meter buffer between them. Treatment replicates were planted with one sagebrush$\bullet m^{-2}$ in November 2013 (66 sagebrush seedlings per treatment replicate, 132 seedlings per block, and 660 seedlings in total). Sagebrush seedlings were grown by sowing five sagebrush seeds in seedling cone containers (3.8 cm diameter X 21 cm tall) in April, 2013. Sagebrush seed was locally collected seed. Seedlings were thinned to one plant per cone container three weeks after emergence and were 7–10 cm tall at time of planting. Sagebrush seedlings were planted by digging a hole ~21 cm deep, placing the seedling in the hole, and pressing soil formerly around the roots of the seedling. Grazing was applied in mid- to late May of each year in each grazed treatment. One to two cows were place in each grazed treatment replicate until perennial bunchgrass height was 7–10 cm, resulting in 35 to 50% utilization. Cattle were

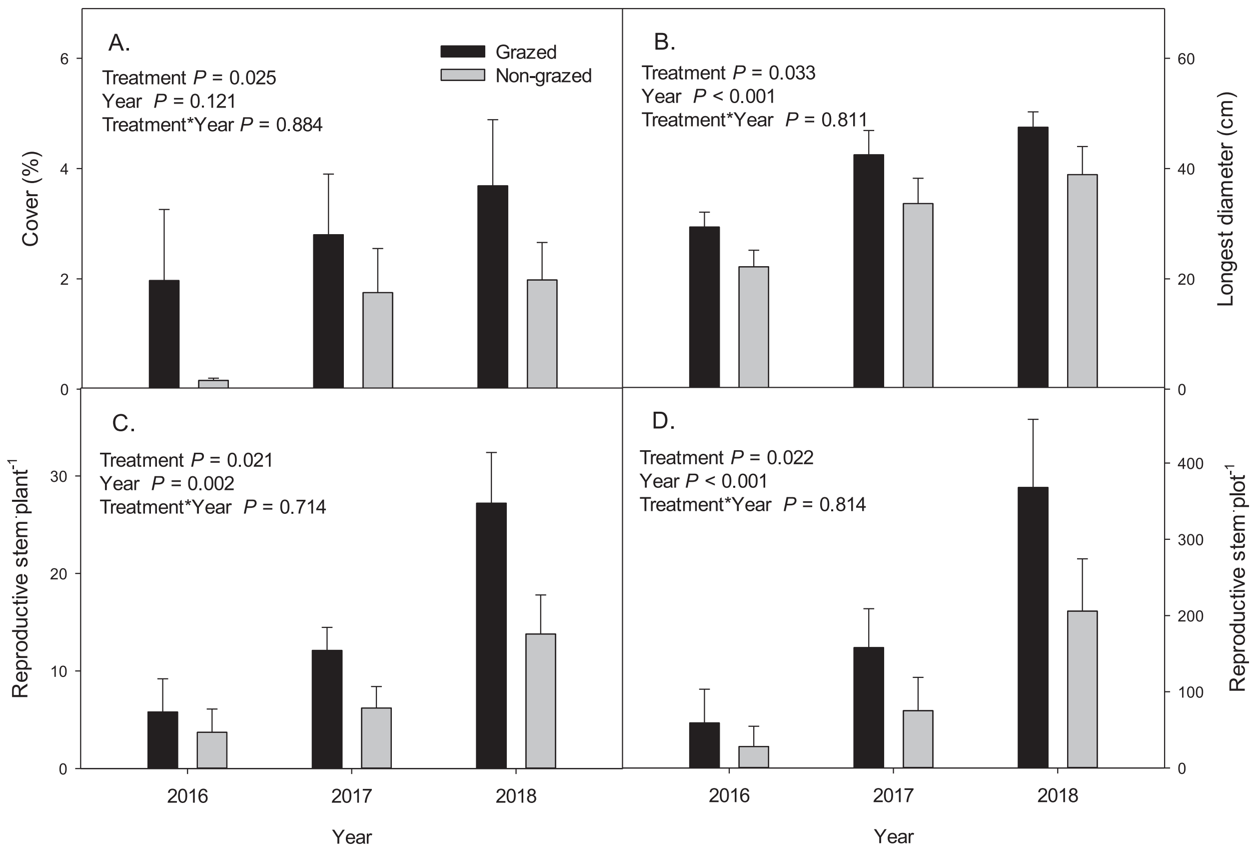

Fig. 1. Sagebrush cover (A), longest canopy diameter (B), reproductive effort per plant (C), and reproductive effort per plot (D) (Mean + S.E.) in grazed and non-grazed areas in 2016, 2017, and 2018 where sagebrush seedlings were planted in the fall of 2013.

confined to each treatment replicated using fencing consisting of t-post and cattle panels. Grazing duration varied between one and two days depending on annual production in each treatment replicate.

Vegetation measurements were conducted in June of 2016, 2017, and 2018 (3rd, 4th, and 5th year post-planting). Sagebrush cover was measured using the line intercept method along three, 10-m transects placed at 1, 3, and 5 m mark on the 6 m-side of each treatment replicate. Sagebrush density was measured by counting all sagebrush plants rooted in three, 2 × 10-m belt transects in each treatment replicate. Sagebrush seedling survival (%) was calculated by dividing the final density by the starting density and multiplying by 100. Sagebrush height and longest canopy diameter was measured on every sagebrush in the treatment replicate. Number of reproductive stems was counted on every sagebrush in each treatment replicate. Herbaceous vegetation cover and density were measured in five 0.2 m^{-2} quadrats placed every 2 m along the three 10-m transects in each treatment replicate. Herbaceous cover was estimated visually to the nearest 1% in the quadrats. Herbaceous density was measured by counting all individuals rooted inside 0.2 m^{-2} quadrats.

Statistical analyses

Repeated measures analysis of variance (RM-ANOVA) using a mixed model in SAS 9.4 (SAS Institute, Inc., Cary, NC, USA) was used to investigate grazing effects on sagebrush seedlings and vegetation characteristics. Year was the repeated variable and treatment was considered a fixed variable. Block and block by treatment interactions were treated as random variables in models. The appropriate covariance structure was selected using Akaike's Information Criterion (Littell et al., 1996). Herbaceous vegetation was separated into the following groups for analyses: Sandberg bluegrass, large perennial bunchgrasses, perennial forbs, exotic annual grasses, and annual forbs. Sandberg bluegrass was separated from other native perennial bunchgrasses because it is smaller in stature, develops earlier, and responds differently to grazing pressure and fire (McLean and Tisdale, 1972; Yensen et al., 1992). The exotic annual grasses group was largely comprised of cheatgrass. Data that violated ANOVA assumptions were either log or square-root transformed prior to analyses. Data presented in the manuscript are in their original dimensions. Means were considered different at $P \leq 0.05$ and reported with standard errors.

Results

Sagebrush cover was greater in the grazed compared to the non-grazed treatment (Fig. 1A; $P = 0.025$). Five years after planting, sagebrush cover was 1.9-fold greater in the grazed than the non-grazed treatment. Density (0.39 ± 0.05 and 0.38 ± 0.04 individual•m^{-2}) and height (44.4 ± 2.6 and 42.8 ± 2.7 cm) of sagebrush was similar between grazed and non-grazed treatments ($P = 0.737$ and 0.572). Average longest canopy diameter was greater in the grazed compared to the non-grazed treatment (Fig. 1B; $P = 0.033$). Height and longest canopy diameter increased with time ($P < 0.001$). Number of reproductive stems per plant and per plot were greater in the grazed compared to the non-grazed treatment (Fig. 1C and D; $P = 0.021$ and 0.022) and both increased with time ($P = 0.002$ and < 0.001). By the fifth year after planting, reproductive stems per plot was 1.8-fold greater in grazed compared to non-grazed areas. The interaction between treatment and

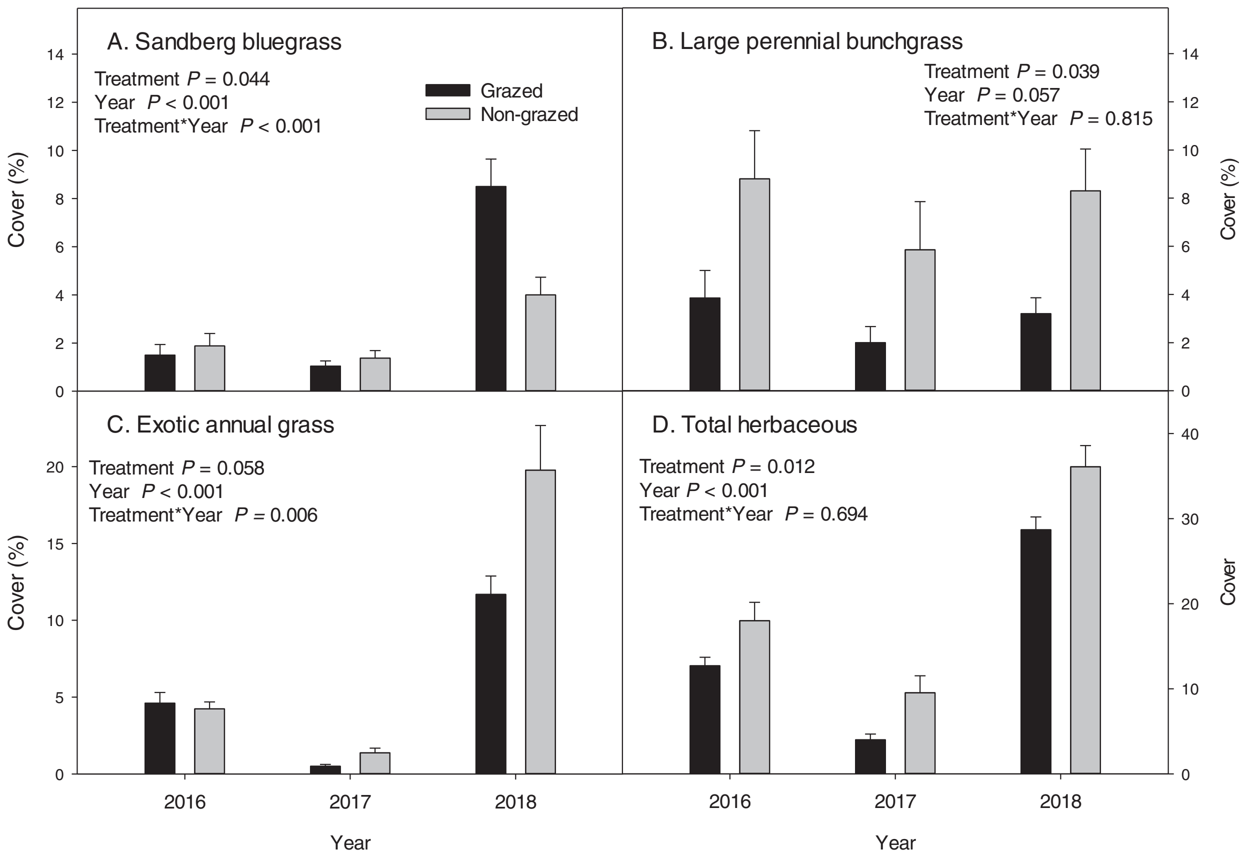

Fig. 2. Sandberg bluegrass (A), large perennial bunchgrass (B), exotic annual grass (C), and total herbaceous (D) cover (Mean + S.E.) in grazed and non-grazed areas in 2016, 2017, and 2018 where sagebrush seedlings were planted in the fall of 2013.

year was not significant for any measured sagebrush characteristics ($P > 0.05$).

The interaction between treatment and year was significant for Sandberg bluegrass cover (Fig. 2A; $P < 0.001$). Sandberg bluegrass cover was similar between treatments in 2016 and 2017, but was 2-fold greater in the grazed compared to the non-grazed treatment in 2018. Large perennial bunchgrass cover was >2-fold greater in the non-grazed compared to grazed treatment (Fig. 2B; $P = 0.039$). Perennial forb cover was similar between treatments ($P = 0.156$) and generally low (<1%; Data not shown). Exotic annual grass cover varied by the treatment by year interaction (Fig. 2C; $P = 0.006$). In 2016, exotic annual grass cover was similar between treatments, but it 2017 and 2018 it 2.9- and 1.7-fold greater in the non-grazed compared to the grazed treatment, respectively. There was no evidence that annual forb cover differed between treatments ($P = 0.078$; Data not shown). Total herbaceous cover was 1.3- to 2.4-fold greater in the non-grazed compared to the grazed treatment (Fig. 2D; $P = 0.012$).

Sandberg bluegrass density was influenced by the interaction between treatment and year (Fig. 3A; $P < 0.001$). Sandberg bluegrass density increased in both treatments across time and became greater in the grazed than the non-grazed treatment in the fifth year of the study. Large perennial bunchgrass density was similar between treatments (Fig. 3B; $P = 0.907$). Perennial forb density did not differ between treatments ($P = 0.537$; Data not shown). Exotic annual grass density was influenced by the interaction between treatment and year (Fig. 3C; $P = 0.046$). Exotic annual grass density was similar in 2016 and 2017, but it was 2-fold greater in the non-grazed compared to the grazed treatment in 2018. Annual forb density did not differ between the grazed and non-grazed treatment (Fig. 3D; $P = 0.332$).

Discussion

Cattle use did not negatively impact planted sagebrush seedlings and favored their growth and reproductive effort. These results are counter to results from a study in Utah that reported greater mortality of just emerged, non-planted sagebrush seedlings in grazed areas (Owen and Norton, 1992). Our seedlings were much larger than just emerged seedlings and a different subspecies of big sagebrush and these differences may explain why we did not find similar effects. Also dissimilar to our study, Owen and Norton (1992) study site had a mature overstory of sagebrush that may have concentrated trampling in the areas between mature sagebrush where many just emerged sagebrush seedlings were found. Our results demonstrated that grazing by cattle can be applied to areas where sagebrush seedlings were planted without negatively impacting sagebrush seedling survival. The probability of a cow stepping on a sagebrush seedling under normal stocking rates for sagebrush communities is unknown; however, this may be inconsequential as young sagebrush plants are often flexible and decreased herbaceous vegetation competition may mediate any adverse impacts. Regardless of the mechanism, cattle use did not decrease the density of planted sagebrush seedlings compared to non-grazed areas, even when applied consecutively for five years.

This result is important because it provides evidence for allowing the application of grazing to reduce fine fuels to decrease fire probability in conjunction with planting sagebrush seedlings. Grazing in the current study substantially decreased exotic annual grass, large perennial grass, and total herbaceous cover, thereby, likely decreasing wildfire probability and increasing fire suppression effectiveness. Fine fuel reductions with strategically applied grazing greatly decreases the likelihood of fire propaga-

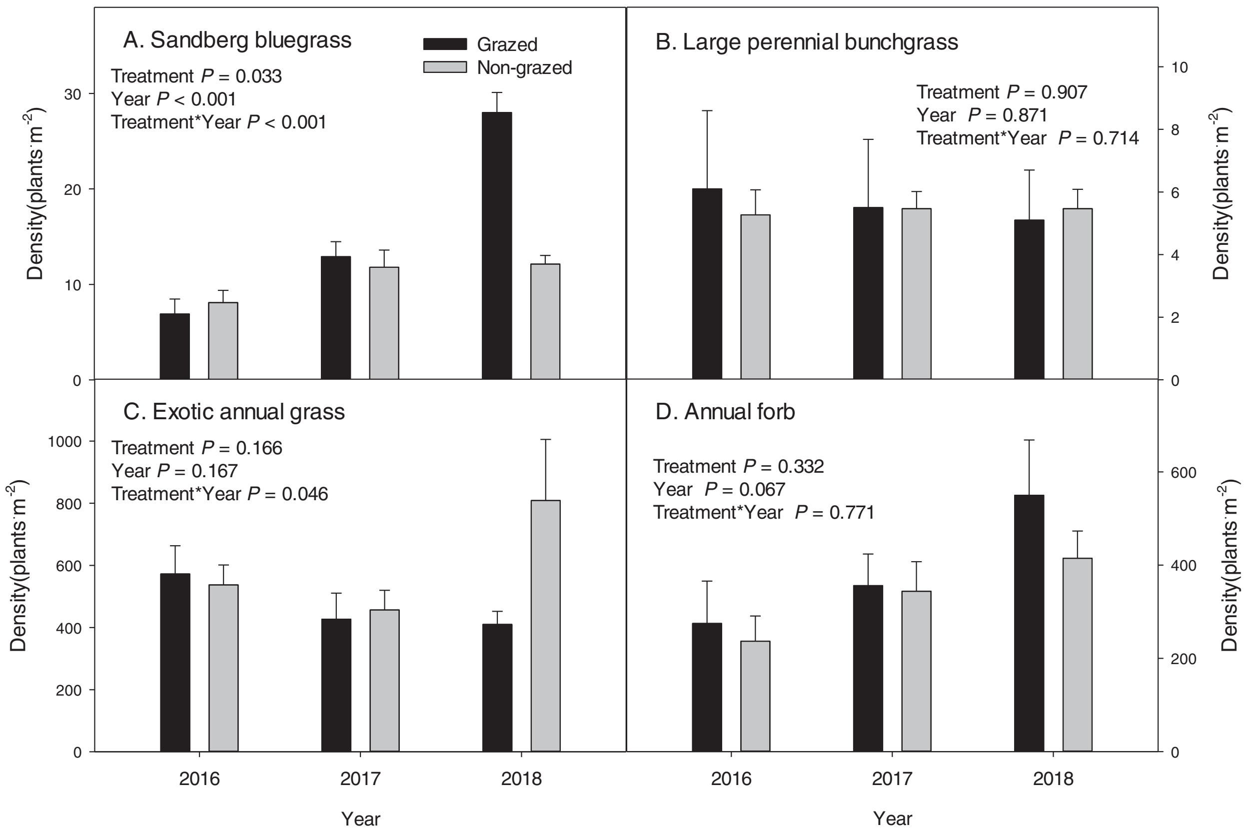

Fig. 3. Sandberg bluegrass (A), large perennial bunchgrass (B), exotic annual grass (C), and annual forb (D) density (Mean + S.E.) in grazed and non-grazed areas in 2016, 2017, and 2018 where sagebrush seedlings were planted in the fall of 2013.

tion and modifies fire behavior to improve suppression effectiveness (Diamond et al., 2009; Davies et al., 2016, 2017). Decreasing the probability of wildfire in areas where sagebrush seedling were planted is important, because fire eliminates sagebrush recovery in this ecosystem. Once Wyoming big sagebrush plants are established, fire is undoubtedly the primary threat to their survival. Restoration success across the sagebrush biome may, in many instances, depend upon effective fire prevention (Brooks et al., 2004; Monsen et al., 2004; Dettweiler-Robinson et al., 2013). Another important aspect, is that this study demonstrated that planting sagebrush seedlings does not hinder normal use of the resource. In other words, grazing by cattle does not need to be altered (i.e. ceased or greatly reduced) because sagebrush seedlings were planted.

Grazing was associated with greater growth and reproductive effort of planted sagebrush seedlings. Cattle grazing in our study likely provided sagebrush, a generally unpalatable species to cattle, a competitive advantage over highly palatable herbaceous vegetation. The loss of photosynthetic tissue places grazed plant species at a competitive disadvantage with non-grazed species (Caldwell et al., 1987; Briske and Richards, 1995; Wan et al., 2015). Similar to our results, heavy spring grazing increased sagebrush by decreasing native herbaceous vegetation (Laycock, 1967). Heavy horse grazing in the spring also increased sagebrush seedling recruitment (Austin and Urness, 1995). Further suggesting that cattle grazing can promote sagebrush, grazed compared to non-grazed introduced grasslands had greater cover of Wyoming big sagebrush in southeastern Oregon (Nafus et al., 2016). It is also well established in the literature that herbaceous vegetation competes with shrubs and can limit their recovery (e.g. Mikoko et al., 2005; DeFalco et al., 2007; Rinella et al., 2015).

Sandberg bluegrass increased in the final year of our study suggesting that grazing potentially increased resources to plants less impacted by grazing. Exotic annual grasses, however, were much greater in the non-grazed compared to the grazed treatment in the final year. Spring grazing may be negatively impacting annual grasses and thus favoring Sandberg bluegrass. Sandberg bluegrass, because of its smaller stature, often is not negatively impacted by heavy grazing that decreases larger perennial bunchgrasses (McLean and Tisdale, 1972). Increased Sandberg bluegrass is not generally a desirable outcome, but may be in this situation if it is a response to decreased exotic annual grasses. We, however, argue caution in interpreting this result as it was only observed in the final year of the study. Furthermore, we would not recommend repeatedly applying spring grazing, because of the risk of negatively impacting large perennial grasses (Davies et al., 2014). Instead, we recommend strategically applying grazing to minimize fine fuel accumulations when most needed. This would probably be after high fine fuel production years as big wildfire years are often preceded by a year or two of above average plant production (Knapp, 1998; Westerling et al., 2003; Littell et al., 2009).

Survival of transplanted Wyoming big sagebrush seedlings in both grazed and non-grazed treatments was similar to results from other studies. Five years after planting, survival was approximately 40% for both treatments. This was greater than 3 yr survival reported for similar container-grown sagebrush seedlings (30%) at Hanford Reach National Monument in Washington (Dettweiler-Robinson et al., 2013), but less than 9 yr survival (60%) in southeastern Oregon (Davies et al., 2020). The first year after planting is the greatest barrier to sagebrush survival (Dettweiler-Robinson et al., 2013), thus differences in sagebrush survival may large be due to post-planting moisture availability in the first year. Our study reaffirms that planting Wyoming big sagebrush seedlings is generally successful.

Sagebrush density of approximately 0.4 plants•m^{-2} suggests that sagebrush density is nearly fully recovered at our study sites, regardless of whether they were grazed or not. Intact Wyoming big sagebrush communities in this region average 0.5 plants•m^{-2} (Davies and Bates, 2010). In contrast, sagebrush cover at the final sampling in the non-grazed and grazed treatments was only 16–20% and 30–38%, respectively, of what would be expected in relatively intact Wyoming big sagebrush communities (Davies et al., 2006; Davies and Bates, 2010). Wyoming big sagebrush is slow growing and recovery of its cover may take decades. For example, Wyoming big sagebrush cover was $<$3% nine years after being planted in non-grazed crested wheatgrass stands (Davies et al., 2020). Cattle grazing, besides decreasing the fire threat to sagebrush seedlings, can promote recovery of sagebrush cover.

Management implications

Our results suggest that cattle can moderately graze areas that have been planted with sagebrush seedlings without negatively impacting sagebrush recovery. Thus, concerns about grazing decreasing survival of planted sagebrush seedlings were not supported by our results and post-planting grazing restrictions appear unnecessary for sagebrush recovery, but may be needed for other reasons such as allowing seeded herbaceous vegetation to establish. Clearly, additional studies in other locations are needed to investigate if the findings of this study can be broadly applied. The lack of negative consequences to planted sagebrush seedlings and the increased need for fine fuel management to reduce the threat of wildfire suggests grazing can, and possible should, be utilized to protect sagebrush seedlings. This is important because planting sagebrush seedlings is expensive, logistically challenging, and time-consuming (McAdoo et al., 2017) and, therefore, often restricted to areas where sagebrush restoration is a priority. Grazing can also be prescribed to accelerate the recovery of sagebrush cover and increase sagebrush growth and reproductive efforts by reducing competing herbaceous vegetation. We are not suggesting that grazing needs to be applied every year, especially in the spring, as was conducted in this study. This prescription was applied to investigate if grazing negatively impacted sagebrush seedlings, not to determine the optimum grazing strategy for rangelands with sagebrush plantings. Spring grazing is more effective at decreasing fire probability, but dormant season grazing also significantly reduces it, thus there is flexibility in how grazing is applied (Davies et al., 2017). Additional research evaluating different timings and intensities of grazing on planted sagebrush seedlings as well as on seeded sagebrush and associated vegetation could improve sagebrush restoration efforts. Grazing can likely also be used to promote the recovery of other woody vegetation by altering the competitive relationship between woody and herbaceous 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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References

Austin, D.D., Urness, P.J., 1995. Effects of horse grazing in spring on survival, recruitment, and winter injury damage of shrubs. Great Basin Nat. 55, 267–270.

Briske, D.D., Richards, J.H., 1995. Plant responses to defoliation: a physiological, morpho-logical and demographic evaluation. In: Bedunah, D.J., Sosebee, R.E. (Eds.), Wildland Plants: Physiological Ecology and Developmental Morphology. Society for Range Management, Denver, CO, USA, pp. 635–710.

Brooks, M.L., D'Antonio, C.M., Richardson, D.M., Grace, J.B., Kelley, J.E., DiTomaso, J.M., Hobbs, R.J., Pellant, M., Pyke, D., 2004. Effects of invasive alien plants on fire regimes. Bioscience 54, 677–688.

Caldwell, M.M., Richards, J.H., Manwaring, J.H., Eissenstat, D.M., 1987. Rapid shifts in phosphate acquisition show direct competition between neighboring plants. Nature 327, 615–616.

Chambers, J.C., Roundy, B.A., Blank, R.R., Meyer, S.E., Whittaker, A., 2007. What makes Great Basin sagebrush ecosystems invasible by Bromus tectorum. Ecol. Monogr. 77, 117–145.

Chandler, R.B., King, D.I., Chandler, C.C., 2009. Effects of management regime on the abundance and nest survival of shrubland birds in wildlife openings in northern New England, USA. For. Ecol. Manag. 258, 1669–1676.

Crawford, J.A., Olson, R.A., West, N.E., Mosley, J.C., Schroeder, M.A., Whitson, T.D., Miller, R.F., Gregg, M.A., Boyd, C.S., 2004. Ecology and management of sage–grouse and sage-grouse habitat. J. Range Manag. 57, 2–19.

Davidson, B.E., Germino, M.J., Richardson, B., Bardnard, D., 2019. Landscape and organismal factors affecting sagebrush-seedling transplant survival after megafire restoration. Restor. Ecol. 27, 1008–1020.

Davies, K.W., Bates, J.D., 2010. Vegetation characteristics of mountain and Wyoming big sagebrush plant communities in the northern Great Basin. Rangel. Ecol. Manag. 63, 461–466.

Davies, K.W., Bates, J.D., Miller, R.F., 2006. Vegetation characteristics across part of the Wyoming big sagebrush alliance. Rangel. Ecol. Manag. 59, 567–575.

Davies, K.W., Bates, J.D., Miller, R.F., 2007. Short-term effects of burning Wyoming big sagebrush steppe in southeast Oregon. Rangel. Ecol. Manag. 60, 515–522.

Davies, K.W., Bates, J.D., Svejcar, T.J., Boyd, C.S., 2010. Effects of long-term livestock grazing on fuel characteristics in rangelands: an example from the sagebrush steppe. Rangel. Ecol. Manag. 63, 662–669.

Davies, K.W., Boyd, C.S., Bates, J.D., Hamerlynck, E.P., Copeland, S.M., 2020. Restoration of sagebrush in crested wheatgrass communities: a longer-term evaluation in the northern Great Basin. Rangel. Ecol. Manag. 73, 1–8.

Davies, K.W., Boyd, C.S., Bates, J.D., Hulet, A., 2015. Dormant-season grazing may decrease wildfire probability by increasing fuel moisture and reducing fuel amount and continuity. Int. J. Wildland Fire 24, 849–856.

Davies, K.W., Boyd, C.S., Bates, J.D., Hulet, A., 2016. Winter grazing can reduce wildfire size, intensity, and behavior in a shrub-grassland. Int. J. Wildland Fire 25, 191–199.

Davies, K.W., Boyd, C.S., Beck, J.L., Bates, J.D., Svejcar, T.J., Gregg, M.A., 2011. Saving the sagebrush sea: an ecosystem conservation plan for big sagebrush plant communities. Biol. Conserv. 144, 2573–2584.

Davies, K.W., Boyd, C.S., Madsen, M.D., Kerby, J., Hulet, A., 2018. Evaluating a seed technology for sagebrush restoration efforts across an elevation gradient: support for bet hedging. Rangel. Ecol. Manag. 71, 19–24.

Davies, K.W., Boyd, C.S., Nafus, A.M., 2013. Restoring the sagebrush component in crested wheatgrass-dominated communities. Rangel. Ecol. Manag. 66, 472–478.

Davies, K.W., Gearhart, A., Boyd, C.S., Bates, J.D., 2017. Fall and spring grazing influence fire ignitability and initial spread in shrub steppe communities. Int. J. Wildland Fire 26, 485–490.

Davies, K.W., Nafus, A.M., 2013. Exotic annual grass invasion alters fuel amounts, continuity and moisture content. Int. J. Wildland Fire 22, 353–358.

Davies, K.W., Vavra, M., Schultz, B., Rimbey, N., 2014. Implications of longer term rest from grazing in the sagebrush steppe. J. Rangel. Appl. 1, 14–34.

DeFalco, L.A., Fernandez, G.C.J., Nowak, R.S., 2007. Variation in the establishment of a non-native annual grass influences competitive interactions with Mojave Desert perennials. Biol. Invasions 9, 293–307.

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. Rangel. Ecol. Manag. 66, 657–666.

Diamond, J.M., Call, C.A., Devoe, N., 2009. Effects of targeted cattle grazing on fire behavior of cheatgrass-dominated rangeland in the northern Great Basin, USA. Int. J. Wildland Fire 18, 944–950.

Fonseca, F., de Figueiredo, T., Famos, M.A.B., 2012. Carbon storage in the Mediterranean upland shrub communities of Montesinho National Park, northeast of Portugal. Agrofor. Syst. 86, 463–475.

Fulbright, T.E., Davies, K.W., Archer, S.R., 2018. Wildlife response to brush management: a contemporary evaluation. Rangel. Ecol. Manag. 71, 35–44.

Gang, H., Xue-yong, Z., Yu-qiang, L., Jian-yuan, C., 2012. Restoration of shrub communities elevates organic carbon in arid soils of northwestern China. Soil Biol. Biochem. 47, 123–132.

Harniss, R.O., Murray, R.B., 1973. 30 years of vegetal change following burning of sagebrush-grass range. J. Range Manag. 26, 322–325.

Knapp, P.A., 1998. Spatiotemporal patterns of large grassland fires in the Intermountain West, USA. Glob. Ecol. Biogeogr. Lett. 7, 259–273.

Knick, S.T., Dobkin, D.S., Rotenberry, J.T., Schroeder, M.A., Matthew Vander Haegen, W., van Riper, C., 2003. Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats. Condor 105, 611–634.

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. J. Appl. Ecol. 51, 1414–1424.
Laycock, W.A., 1967. How heavy grazing and protection affect sagebrush-grass ranges. J. Range Manag. 20, 206–213.
Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L., 2009. Climate and wildfire area burned in western US ecoprovinces, 1916–2003. Ecol. Appl. 19, 1003–1021.
Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. SAS System for Mixed Models. SAS Institute, Inc. Cary, North Carolina, p. 633p.
Lysne, C.R., Pellant, M.L., 2004. Establishment of Aerially Seeded Big Sagebrush Following Southern Idaho Wildfires. Department of the Interior, Bureau of Land Management, Boise, ID, p. 14 p Technical Bulletin 2004-01.
McAdoo, J.K., Boyd, C.S., Sheley, R.L., 2013. Site, competition, and plant stock influence transplant success of Wyoming big sagebrush. Rangel. Ecol. Manag. 66, 305–321.
McAdoo, J.K., Swanson, J.C., Murphy, P.J., Shaw, N.L., 2017. Evaluating strategies for facilitating native plant establishment in northern Nevada crested wheatgrass seedings. Restor. Ecol. 25, 53–62.
McLean, A., Tisdale, E.W., 1972. Recovery rate of depleted range sites under protection from grazing. J. Range Manag. 25, 178–184.
Medina-Roldán, E., Paz-Ferreiro, J., Bardgett, R.D., 2012. Grazing exclusion affects soil and plant communities, but has no impact on soil carbon storage in upland grassland. Agric. Ecosyst. Environ. 149, 118–123.
Miao, R., Jiang, D., Musa, A., Zhou, Q., Guo, M., Wang, Y., 2015. Effectiveness of shrub planting and grazing exclusion on degraded sandy grassland restoration in Horqin sandy land in Inner Mongolia. Ecol. Eng. 74, 164–173.
Mikoko, D., Krug, C.B., Milton, S.J., 2005. Competition and herbivory influence growth and survival of shrubs on old fields: implications for restoration of renosterveld shrubland. J. Veg. Sci. 16, 685–692.
Monsen, S.B., Stevens, R., Shaw, N.L., 2004. Restoring Western Ranges and Wildlands. USDA – Forest Service, Fort Collins, CO, USA RMRS-GTR-136. 884 p.
Nafus, A.M., Svejcar, T.J., Davies, K.W., 2016. Disturbance history, management, and seeding year precipitation influences vegetation characteristics of crested wheatgrass stands. Rangel. Ecol. Manag. 69, 248–256.
Owen, M.K., Norton, B.E., 1992. Interactions of grazing and plant protection on basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*) seedling survival. J. Range Manag. 45, 257–262.
Porensky, L.M., Leger, E.A., Davidson, J., Miller, W.W., Goergen, E.M., Espeland, E.K., Carroll-Moore, E.M., 2014. Arid old-field restoration: native perennial grasses suppress weeds and erosion, but also suppress native shrubs. Agric. Ecosyst. Environ. 184, 135–144.
Prevéy, J.S., Germino, M.J., Huntly, N.J., 2010. Loss of foundation species increases population growth of exotic forbs in sagebrush steppe. Ecol. Appl. 20, 1890–1902.
PRISM, 2019. PRISM Climatic Group. http://prism.nacse.org/explorer/ Last Accessed: September 24, 2019.
Rinella, M.J., Hammond, D.H., Bryant, A.M., Kozar, B.J., 2015. High precipitation and seeded species competition reduce seeded shrub establishment during dryland restoration. Ecol. Appl. 25, 1044–1053.
Schroeder, M.A., Aldridge, C.L., Apa, A.D., Bohne, J.R., Braun, C.E., Bunnell, S.D., Connelly, J.W., Deibert, P.A., Gardner, S.C., Hilliard, M.A., Kobriger, G.D., McAdam, S.M., McCarthy, C.W., McCarthy, J.J., Mitchell, D.L., Rickerson, E.V., Stiver, S.J., 2004. Distribution of sage-grouse in North America. Condor 106, 363–376.
Shaw, N., Monsen, S.B., 1986. 'Lassen' antelope bitterbrush: a browse plant for game and livestock ranges. Rangelands 8, 122–124.
Shipley, L.A., Davila, T.B., Thines, N.J., Elias, B.A., 2006. Nutritional requirements and diet choices of the pygmy rabbit (*Bachylagus idahoensis*): a sagebrush specialist. J. Chem. Ecol. 32, 2455–2474.
Shriver, R.K., Andrews, C.M., Arkle, R.S., Barnard, D.M., Duniway, M.C., Germino, M.J., Pilliod, D.A., Welty, J.L., Bradford, J.B., 2019. Transient population dynamics impede restoration and may promote ecosystem transformation after disturbance. Ecol. Lett. 22, 1357–1366.
Suring, L.H., Rowland, M.M., Wisdom, M.J., 2005. Identifying species of conservation concern. In: Wisdom, M.J., Rowland, M.M., Suring, L.H. (Eds.), Habitat Threats in the Sagebrush Ecosystem – Methods of Regional Assessment and Applications in the Great Basin. Alliance Communications Group, Lawrence, KS, pp. 150–162.
Torstenson, W.L., Mosley, J.C., Brewer, T.K., Tess, M.W., Knight, J.E., 2006. Elk, mule deer, and cattle foraging relationships on foothill and mountain rangeland. Rangel. Ecol. Manag. 59, 80–87.
Uresk, D.W., Cline, J.F., Rickard, W.H., 1976. Impact of wildfire on 3 perennial grasses in south-central Washington. J. Range Manag. 29, 309–310.
van Zonneveld, M.J., Gutierrez, J.R., Holmgren, M., 2012. Shrub facilitation increases plant diversity along an arid scrubland-temperate rainforest boundary in South America. J. Veg. Sci. 23, 541–551.
Wan, H., Bai, Y., Hooper, D.U., Schönbach, P., Gierus, M., Schiborra, A., Taube, F., 2015. Selective grazing and seasonal precipitation play key roles in shaping plant community structure in semi-arid grasslands. Landsc. Ecol. 30, 1767–1782.
Westerling, A.L., Gershunov, A., Brown, T.J., Cayan, D.R., Dettinger, M.D., 2003. Climate and wildfire in the western United States. Bull. Am. Meteorol. Soc. 84, 595–604.
Wong, N.K., Dorrough, J., Hirth, J.R., Morgan, J.W., O'Brien, E., 2007. Establishment of native perennial shrubs in an agricultural landscape. Aust. Ecol. 32, 617–625.
Yensen, E., Quinney, D.L., Johnson, K., Timmerman, K., Steenhof, K., 1992. Fire, vegetation changes, and population fluctuations of Townsend's ground squirrels. Am. Midl. Nat. 128, 299–312.
Zhao, H., Zhou, R., Su, Y., Zhang, H., Zhao, L., Drake, S., 2007. Shrub facilitation of desert land restoration in the Horqin sand land of Inner Mongolia. Ecol. Eng. 31, 1–8.