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Herbicide Protection Pods (HPPs) Facilitate Sagebrush and Bunchgrass Establishment under Imazapic Control of Exotic Annual Grasses ☆,☆☆

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ABSTRACT

Revegetation of exotic annual grass–invaded rangelands is a primary objective of land managers following wildfires. Controlling invasive annual grasses is essential to increasing revegetation success; however, preemergent herbicides used to control annual grasses prohibit immediate seeding due to nontarget herbicide damage. Thus, seeding is often delayed 1 yr following herbicide application. This delay frequently allows for reinvasion of annual grasses, decreasing the success of revegetation efforts. Incorporating seeds into herbicide protection pods (HPPs) containing activated carbon (AC) permits concurrent high preemergent herbicide application and seeding because AC adsorbs and renders herbicides inactive. While HPPs have, largely in greenhouse studies, facilitated perennial bunchgrass emergence and early growth, their effectiveness in improving establishment of multiple species and functional groups in the field has not been assessed. Five bunchgrass species and two shrub species were seeded at two field sites with high imazapic application rates as bare seed and seed incorporated into HPPs. HPPs significantly improved establishment of sagebrush (*Artemesia tridentata* Nutt. Spp. *wyomingensis* Beetle & Young) and crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.) over the 2-yr study. Three native perennial grass species were protected from herbicide damage by HPPs but had low establishment in both treatments. The two remaining shrub and grass species did not establish sufficiently to determine treatment effects. While establishment of native perennial bunchgrasses was low, this study demonstrates that HPPs can be used to protect seeded bunchgrasses and sagebrush from imazapic, prolonging establishment time in the absence of competition with annual grasses.

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Introduction

Exotic annual grasses negatively impact rangelands around the world (D'Antonio and Vitousek 1992) and limit success of efforts to reestablish seeded vegetation in degraded rangelands (Brandt and Seabloom 2012; Svejcar et al. 2017). Seeding of desired species following wildfires is a crucial tool used by managers to mitigate ecological damage after wildfires in degraded sagebrush rangelands (Eiswerth and Shonkwiler 2006; James and Svejcar 2010; Pyke et al. 2013). Revegetation efforts are intended to decrease postfire erosion and limit positive feedback of the annual grass-fire cycle (Eiswerth and Shonkwiler 2006; Pyke et al. 2013). However, if exotic annual grasses were present before the fire, rapid postfire increases in exotic annual grasses often limit the success of seeding attempts because they are competitive with perennial grasses at the seedling stage (Clausnitzer et al. 1999; Humphrey and Schupp 2004; James and Svejcar 2010).

In order to increase revegetation success post fire in areas with exotic annual grasses, preemergent herbicides are often used to control these invasive annual grasses (Sheley and Krueger-Mangold 2003; Sheley et al. 2007). Perennial bunchgrasses are usually seeded 1 yr after preemergent herbicide application to avoid nontarget species damage (Huddleston and Young 2005; Davies et al. 2014). Once established, mature perennial bunchgrasses are able to limit exotic annual grass dominance, decreasing the risk of catastrophic wildfire and providing habitat and forage for wildlife

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and livestock (D'Antonio and Vitousek 1992; Duncan et al. 2004; Davies and Nafus 2013; Madsen et al. 2016; Davies and Johnson 2017). Waiting a year following herbicide application reduces the risk of nontarget damage to seeded species but may also allow for the reinvasion and dominance of annual grasses (Huddleston and Young 2005; Sheley et al. 2012; Madsen et al. 2014). Sheley et al. (2012) evaluated a single-entry approach for medusahead (*Taeniatherum caput-medusae* [L.] Nevski)–invaded rangelands treated with concurrent herbicide and desired species seeding. A single-entry approach is more cost efficient and allows seeded species the opportunity to establish while competition from invasive annual grasses is limited, but it necessitates a low herbicide rate, which may not sufficiently control invasive annual grass enough for successful revegetation (Sheley 2007; Sheley et al. 2007; Sheley et al. 2012; Davies et al. 2014). Therefore, use of higher herbicide application rates to achieve more complete, longer-lasting control of annuals may be necessary for the single-entry approach to be a practical option in annual grass–invaded rangelands (Kyser et al. 2007; Sheley et al. 2012).

Herbicide protection pods (HPPs) are a recent seed enhancement technology that employs activated carbon (AC) to adsorb and render the herbicide inactive to protect desired seed from damage (Madsen et al. 2014). HPPs allow a more effective single-entry approach by protecting seeds of desired species from higher rates of herbicide application, necessary for lasting, effective control of annual grasses (Madsen et al. 2014; Davies 2018; Clenet et al. 2019). In combination with preemergent herbicides, HPPs can prolong the length of time when seeded species can establish in the absence of competition from exotic annual grasses (Madsen et al. 2014).

Research has shown that HPPs are capable of protecting perennial bunchgrasses from preemergent herbicides (Davies et al. 2017; Davies 2018; Clenet et al. 2019). However, none of these studies have evaluated using HPPs after wildfire or evaluated HPPs effects for more than one growing season. These studies were also limited by not being a field study (Clenet et al. 2019), imazapic was applied in the spring instead of the more standard fall application (Davies 2018), and only evaluated one bunchgrass, which was an introduced species (Davies et al. 2017). Only a few species have been tested thus far, and the use of HPPs with native bunchgrass and shrub species in the field has not yet been fully explored. Sagebrush, the dominant shrub in this ecosystem, has shown promise in a laboratory study (Clenet et al. 2019) but has sporadic establishment in the field. Thus, the one attempt to evaluate sagebrush with HPPs failed because not enough sagebrush was established to compare HPPs to bare seed (Davies 2018). While controlled laboratory studies are valuable, they do not provide the full range of environmental conditions that will ultimately determine the efficacy of HPPs (Clenet et al. 2019). Sagebrush is an essential component of the sagebrush-steppe and provides multiple ecosystem services, as well as providing forage, shelter, and other habitat services for wildlife (Reynolds and Trost 1980; Vander Haegen et al. 2000; Longland and Bateman 2002; Holthuijzen and Veblen 2015). Sagebrush is difficult to establish from seed, and any seed enhancement technology that improves sagebrush establishment would be a valuable tool in sagebrush-steppe restoration (Knutson et al. 2014; Davies and Bates 2017; Ott et al. 2017). Information from field studies evaluating efficacy of HPPs for promoting establishment of shrubs and multiple species of native grasses are therefore essential to determining if HPPs are a viable technology for use in rangeland revegetation efforts (Davies et al. 2017).

To address this, we performed a 2-yr, two-site study with the purpose of evaluating the effectiveness of HPPs for protecting five species of perennial bunchgrass and two shrub species from a high rate of postfire imazapic application in exotic grass–invaded sagebrush-steppe. We hypothesized that survival of seedlings protected via HPPs would result in greater density, cover, and size of established plants compared with bare seed.

Materials and methods

Study sites

The study was conducted at two sites (Wagontire and Gap Ranch) that were burned by the 2017 Cinder Butte Fire in southeastern Oregon. Both sites were formerly big sagebrush (*Artemisia tridentata* Nutt.)-bunchgrass communities that had been invaded by exotic annual grasses. The Wagontire site is located at 43°19.749Ń, 119°50.341Ẃ with 1 511 m elevation and the Gap Ranch site is located at 43°26.74Ń, 119°50.258Ẃ with 1 439 m elevation. Wagontire has a slope of 12% and a northeastern aspect with a Pernty gravelly silt loam soil (USDA NRCS 2019). Gap Ranch is relatively flat (slope = 2%) with a Gradon gravelly fine sandy loam soil (USDA NRCS 2019). Both sites are a Droughty Loam 11-13 PZ Ecological site (R023XY316OR).

Long-term (1979–2018) mean annual precipitation was 290 mm for Wagontire and received 212 mm in 2018, 73% of the mean (Great Basin Weather Applications 2019). Long-term mean annual precipitation was 298 mm for Gap Ranch, and in 2018 it received 198 mm, 67% of the annual mean (Great Basin Weather Applications 2019). During the growing season (April–July) of 2018, Wagontire and Gap Ranch received 86% and 67%, respectively, and in 2019, 141% and 142%, respectively, of long-term mean growing season precipitation (Great Basin Weather Applications 2019). Test sites were 20×30 m and fenced to exclude livestock.

Experimental design and measurements

At each site, seven species were planted: bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), basin wildrye (*Leymus cinereus* Scribn. & Merr. Á. Löve), Sandberg bluegrass (*Poa secunda* J. Presl), squirreltail (*Elymus elymoides* [Raf.] Swezey), crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.), Wyoming big sagebrush (*Artemisia tridentata* Nutt. Spp. *wyomingensis* Beetle & Young), and antelope bitterbrush (*Purshia tridentata* [Pursh] DC.). Species were planted using two seeding treatments, bare seed (BS), and herbicide protection pods (HPP) replicated four times in a randomized design. Each replicate included two 5-m imitated drill rows (seeded by hand in a furrow) of each seeding treatment. The two rows of the same treatment were parallel to and 40 cm apart from each other while rows of contrasting treatments were separated by 1 m. End to end the rows had a buffer of 2 m.

In each 5-m row, 200 pure live seed (pls) $\cdot$ m^{-1} for each species were planted, except bitterbrush where 100 pls $\cdot$ m^{-1} were seeded. This resulted in 500 pls $\cdot$ row^{-1} for bitterbrush and 1 000 pls $\cdot$ row^{-1} for all other species. HPPs were composed of 43% calcium bentonite, 33% activated carbon, 6% worm castings, 14% compost, and 4% seed by dry weight. Dry materials were mixed thoroughly and then water was added to achieve a doughy consistency that could be passed through a pasta extruder (Model TR110, Rosito Bisani, Los Angeles, CA). Dough was pushed through an 8-mm diameter circular die for all species except for bitterbrush, which had larger seeds and was extruded through a 16×8 mm die. All extruded pods were cut into pods ~15 mm in length.

Species were planted on 16 September 2017. The sites were sprayed 1 d after planting with imazapic (Panoramic 2 SL, Alligare, Opelika, AL) at 210 g ai$\cdot$ha^{-1} (highest recommended rate for rangelands), to simulate a one-pass application, using a hand-operated backpack sprayer (Solo, Newport News, VA). During application, temperature was 18.3°C and 16.6°C, maximum wind speed was 11.4 km$\cdot$h^{-1} and 12.9 km$\cdot$h^{-1}, and relative humidity was 17% and 18% for Wagontire and Gap Ranch, respectively.

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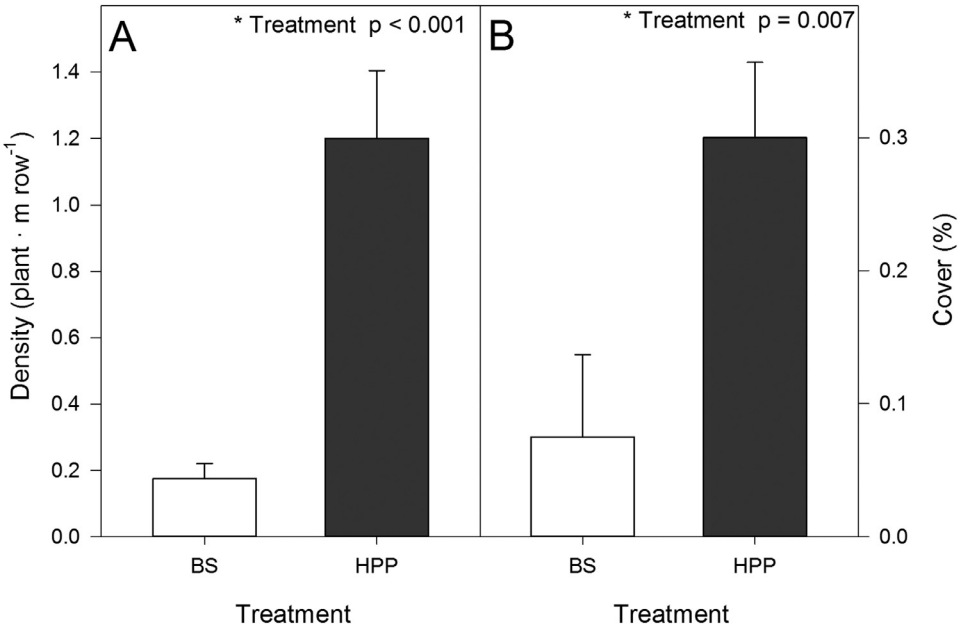


Fig. 1. Wyoming big sagebrush density (A, mean + standard of error [SE]) and cover (B, mean + SE) for two treatments (Herbicide protection pods [HPP] and Bare seed [BS]) averaged over site in 2019. Asterisk (*) indicates significance ($P \leq 0.05$).

Density of seeded species was determined by counting all seedlings in rows in late June 2018 and 2019. Plant height was also measured for five randomly selected grass plants and shrub plants per row. Plant height was estimated by measuring the height of the tallest vegetative structure present on the plant. Canopy diameter was also measured for five randomly selected shrubs per row. If fewer than five plants were present, all plants were measured. Cover of seeded species was visually estimated using 0.2-m^2 quadrats at 1.5 m, 2.5 m, and 3.5 m centered over each row. Cover and density measurements of invasive annual grass species were taken at 10 random points within the sites using 0.2-m^2 quadrats. Another 10 random points were measured outside of the sites to evaluate the effectiveness of imazapic control by comparing annual grass density and cover between herbicide treated and untreated areas.

Statistical analysis

All analyses were performed using R Software version 3.5.2 (R Core Team 2018). Analysis of variance (ANOVA) using linear mixed effects models was used to compare six of seeded species incorporated into HPPs with bare seed when imazapic was applied to control invasive annual grasses using the {nlme} R package (Pinheiro et al. 2017). Each species was analyzed separately. Fixed effects of the perennial bunchgrasses were seeding treatment, site, yr, and their interactions, with replication as a random effect. Each species had four replicates. Site was included as a fixed effect because the two sites had differing environmental conditions, making it possible to test for a treatment by site interaction. The compound symmetry model was selected as the correlation structure used within the model based on Akaike information criterion to account for potential correlation within a year. Applying a cautionary approach, and as determined by visual analysis of error residuals, variances between yr were allowed to vary within the model when necessary. Antelope bitterbrush was not analyzed because most seed was consumed by rodents within a few weeks of planting and any seedlings that emerged were lost to herbivory.

Wyoming big sagebrush response was only analyzed in the second yr of the study because there were no plants were detected in the first yr, yielding a treatment-by-yr interaction ($P < 0.001$). The fixed effects for the sagebrush mixed model were treatment and site and their interaction, while the random effect was replicate. Site was included as a fixed effect for the same reasons as explained earlier. Normality of model residuals was supported by visual analysis of graphs, and thus all data were not transformed. Differences were considered significant at $P \leq 0.05$. Means and standard errors are reported in text and figures.

Results

Exotic annual grass control at Wagontire was 93% in the first yr and dropped to 46% the second yr. Control of exotic annual grasses was greater at Gap Ranch with 100% and 96% control in the first and second yr, respectively.

In the second yr (2019), sagebrush density was influenced by treatment ($F_{1,6} = 54.23$, $P < 0.001$) and was almost 7 × greater in the HPP compared with bare seed (BS) treatment (Fig. 1A). Sagebrush cover was influenced by treatment ($F_{1,6} = 16.20$, $P = 0.007$) and was about 3 × greater in HPP compared with the BS treatment (see Fig. 1B). Sagebrush diameter and height were not influenced by treatment ($F_{1,6} = 0.001$, $F_{1,6} = 0.002$, $P > 0.05$).

Bluebunch wheatgrass density was influenced by treatment and yr ($F_{1,18} = 8.38$, $P = 0.009$ and $F_{1,18} = 14.82$, $P = 0.001$, respectively). Bluebunch wheatgrass density was greater in the HPP treatment compared with the BS treatment in both yr, and by 2019, bluebunch wheatgrass density was about 4 × greater in the HPP compared with BS treatment (Fig. 2A). Basin wildrye density was influenced by treatment, yr, with a treatment-by-yr interaction effect (see Fig. 2B; $F_{1,18} = 6.84$, $P = 0.018$; $F_{1,18} = 12.92$, $P = 0.002$; and $F_{1,18} = 4.79$, $P = 0.042$; respectively). In both yr, basin wildrye density was greater in the HPP treatment. However, the difference between treatments in the second yr decreased due to poor survival of plants (HPP = 0.2 ± 0.1 plants · m row, BS = 0.1 ± 0.1 plants · m row). Sandberg bluegrass density was influenced by treatment, yr, and the treatment-by-yr interaction (see Fig. 2C; $F_{1,18} = 7.74$, $P = 0.012$; $F_{1,18} = 77.03$, $P < 0.001$; and $F_{1,18} = 5.79$, $P = 0.027$; respectively). Sandberg bluegrass density was greater in the HPP treatment compared with BS in both yr, with a greater magnitude

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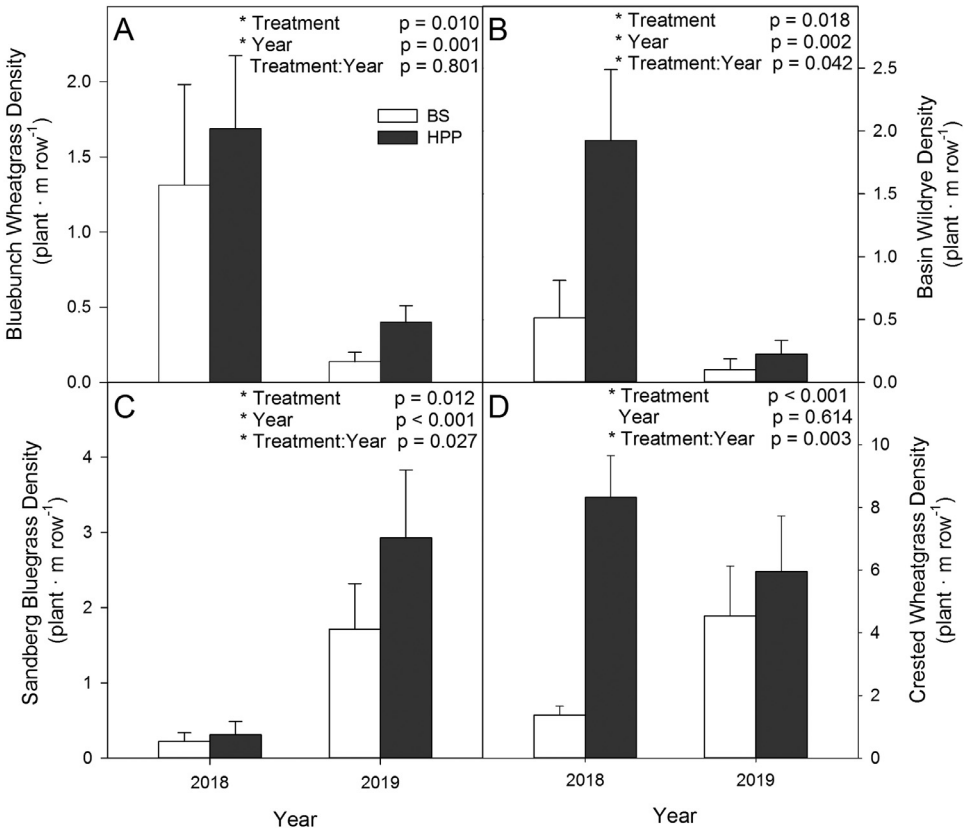


Fig. 2. A, Bluebunch wheatgrass, B, basin wildrye, C, Sandberg bluegrass and crested wheatgrass density (mean + SE) for two treatments (Herbicide protection pods [HPP] and Bare seed [BS]) averaged over sites in 2018 and 2019. Asterisk (*) indicates significance at $P \leq 0.05$. Note different y-axis scales.

of difference in 2019. Crested wheatgrass density was significantly affected by seeding treatment, with a treatment-by-yr interaction (see Fig. 2D; $F_{1,18} = 27.38$, $P < 0.001$ and $F_{1,18} = 12.06$, $P = 0.003$, respectively). Crested wheatgrass density was greater in the HPP treatment compared with BS for both yr. However, this difference narrowed in the second yr of the study. Squirreltail density did not differ between seeding treatments ($F_{1,18} = 0.03$, $P = 0.855$) and was low by the second yr at 0.38 ± 0.1 plant · m row and 0.51 ± 0.1 plants · m row for bare seed and HPP treatments, respectively.

Of the native perennial bunchgrasses, only bluebunch wheatgrass cover differed between seeding treatments ($F_{1,18} = 5.37$, $P = 0.032$). Bluebunch wheatgrass cover was greater in the HPP treatment in both yr and was approximately 5 × greater in the HPP compared with the BS treatment in the second yr (Fig. 3A). Crested wheatgrass cover was influenced by treatment and yr, with a treatment-by-site interaction ($F_{1,18} = 19.23$, $P < 0.001$; $F_{1,18} = 11.24$, $P = 0.004$; and $F_{1,18} = 4.23$, $P = 0.05$; respectively). The treatment-by-site interaction was due to a difference of magnitude of the effect between the two treatments, but the trend of HPP being greater than BS remained consistent across sites and yr (see Fig. 3B). Additionally, in 2019, crested wheatgrass cover was more than 2 × greater in the HPP treatment compared with the bare seed treatment. Squirreltail, basin wildrye, and Sandberg bluegrass cover were not influenced by treatment ($F_{1,18} = 1.57$, $P = 0.227$; $F_{1,18} = 0.17$, $P = 0.685$; and $F_{1,18} = 0.09$, $P = 0.757$; respectively). Squirreltail, basin wildrye, and Sandberg bluegrass cover were low and quite variable for both the HPP treatment (1.3 ± 0.9, 1.3 ± 1.2, and 0.7 ± 0.3, respectively) and the BS treatment (0.4 ± 0.3, 3.3 ± 3.2, and 1.7 ± 0.5, respectively) in 2019.

Bluebunch wheatgrass height was influenced by treatment and yr ($F_{1,18} = 9.41$, $P = 0.007$ and $F_{1,18} = 7.25$, $P = 0.015$, respectively). Bluebunch wheatgrass height was greater in the HPP treatment (Fig. 4A). Crested wheatgrass height was influenced by treatment and yr ($F_{1,18} = 7.04$, $P = 0.016$ and $F_{1,18} = 218.88$, $P < 0.001$, respectively). Crested wheatgrass height was greater in the HPP treatment compared with BS (see Fig. 4B). Squirreltail, basin wildrye, and Sandberg bluegrass height were not influenced by treatment ($F_{1,18} = 0.08$, $P = 0.778$; $F_{1,18} = 0.62$, $P = 0.441$; and $F_{1,18} = 0.02$, $P = 0.894$, respectively).

Discussion

Our results show that herbicide protection pods can decrease herbicide effects on seeded perennial bunchgrasses and sagebrush when imazapic is applied to control invasive annual grasses. By the second yr of this study, Wyoming big sagebrush density was 7 × greater and bluebunch wheatgrass density was 4 × greater when incorporated into HPPs compared with bare seed applications. Our results, as well as other studies, demonstrate that HPPs can be effective at protecting multiple species from different functional groups from preemergent herbicides in a variety of sites invaded by exotic annual grasses (Davies et al. 2017; Davies 2018; Clenet et al. 2019). HPPs likely have benefits over bare seed when high rates of imazapic are applied because activated carbon adsorbs and renders the preemergent herbicide inactive around the seeds, allowing them to grow while invasive annual grasses are controlled (Madsen et al. 2014; Davies et al. 2017).

Wyoming big sagebrush is often difficult to establish from seed (Lysne and Pellant 2004; Knutson et al. 2014; Ott et al. 2017). One prior field study attempting to use sagebrush with HPPs was inconclusive because sagebrush failed to establish enough to allow for a comparison between HPPs and bare seed (Davies 2018). Therefore, our current study is the first one to show that HPPs can be effective used with sagebrush in the field. The results of

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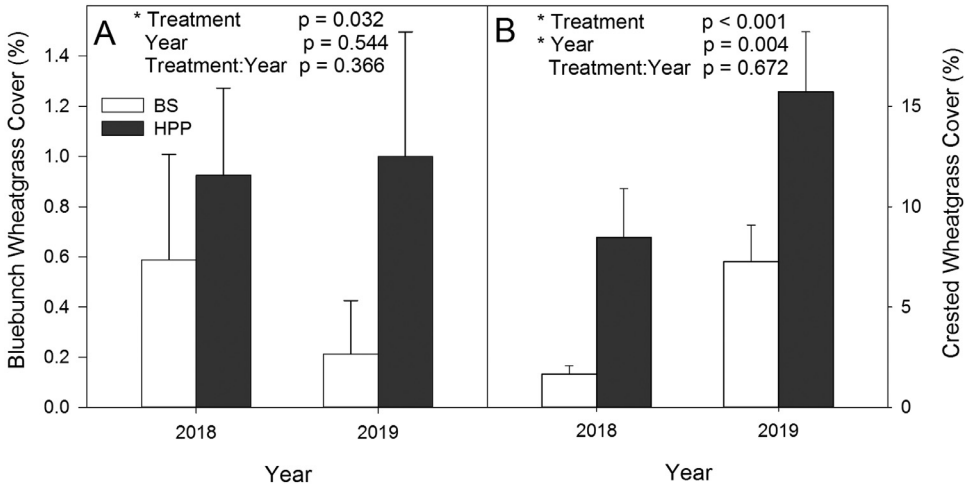


Fig. 3. A, Bluebunch wheatgrass and B, crested wheatgrass cover (mean + standard of error) for two treatments (Herbicide protection pods [HPP] and Bare seed [BS]) averaged over sites in 2018 and 2019. Asterisk (*) indicates significance at $P \leq 0.05$. Note different y-axis scales.

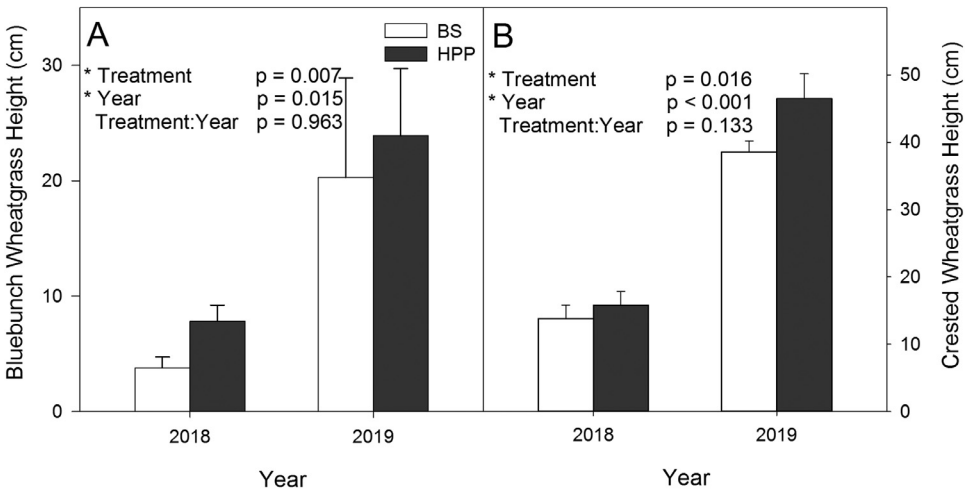


Fig. 4. A, Bluebunch wheatgrass and B, crested wheatgrass height (mean + standard of error) for two treatments (Herbicide protection pods [HPP] and Bare seed [BS]) averaged over sites in 2018 and 2019. Asterisk (*) indicates significance at $P \leq 0.05$. Note different y-axis scales.

this study also show that, when in conjunction with preemergent herbicide control of exotic annual grasses in the field, the benefit of the HPPs can outweigh potential limitation to sagebrush emergence and early growth. This study found that HPPs had no effect on sagebrush seedlings after emergence, contrary to a previous lab study demonstrating negative HPP effects on early sagebrush growth (Clenet et al. 2019). This may have been because HPPs broke down following multiple freeze-thaw events in the field (personal observation).

In this study, the density of sagebrush seedlings was 1.2 ± 0.2 plants · m row^{-1} in the HPP treatment. These rows were planted in imitation of a rangeland drill, which generally spaces rows ~12 in (30.5 cm) apart. Extrapolating to a density · m^{-2} based off of a rangeland drill, this study resulted in 4.8 ± 0.8 plants · m^{-2}. A study that had similar precipitation conditions found that broadcast seeding resulted in < 0.1 plants · m^{-2} (Boyd and Obradovich, 2014). The HPP treatment of this study resulted in plant density far exceeding the average density (~0.5 plants·m^{-2}) of mature sagebrush plants in relatively intact Wyoming big sagebrush plant communities (Davies and Bates 2010). However, sagebrush seedlings often experience significant mortality in their first few yr of life (Boyd and Obradovich, 2014). While the sagebrush seedlings in this study may experience significant mortality in the following yr, beginning with a greater number of sagebrush increases the probability of a proficient number of seedlings surviving to maturity.

Sagebrush was only detected in the second yr of the study, probably because more optimal springtime conditions occurred in 2019 (Great Basin Weather Applications 2019). Wyoming big sagebrush and other native plants tend to establish more reliably in yr with average or above-average growing season precipitation (Hardegree et al. 2011; Davies et al. 2018), and a proportion of sown Wyoming big sagebrush seeds have been shown to stay viable, especially when buried, for at least 2 yr (Wijayratne and Pyke 2012). Since Wyoming big sagebrush is notoriously difficult to establish reliably from seed, any technology that facilitates establishment could have wide applicability for managers across the sagebrush steppe (Knutson et al. 2014; Davies and Bates 2017; Ott et al. 2017).

In this study, overall establishment was more limited with native bunchgrasses compared with the introduced bunchgrass, crested wheatgrass. Bluebunch wheatgrass had the best establishment (1.6 ± 0.44 plants · m^{-2} in the HPP treatment) among the large native perennial bunchgrasses, but crested wheatgrass establishment was 15 × greater. The limited establishment of native perennial bunchgrasses compared with the introduced bunchgrass

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used is similar to results reported by other authors (Hull 1974; Boyd and Davies 2010; Davies et al. 2015). Native perennial bunchgrasses generally establish infrequently and do not establish as well as introduced species in yr with unfavorable precipitation patterns; thus, limited success in the first yr of the study was not unexpected (Boyd and Davies 2010; James and Svejcar 2010; Davies et al. 2015). When conditions were more conducive in the second yr of the study to native bunchgrass establishment, it is likely that few viable seeds remained. James et al. (2011) found that by the second yr, < 1% of ungerminated native perennial grass seeds were still viable. While low establishment rates made it difficult to detect treatment effects for all native bunchgrasses, HPPs were effective as a technology used to protect seeded species from damage by imazapic. Sandberg bluegrass may have also had greater seed treatment differences than was captured, due to the resprouting of prefire survivors within the plots, which made it difficult to identify planted individuals. Additionally, the common HPP formulation used may have induced differing degrees of establishment rates, and different species may require slightly different HPP mixtures. Refinement of HPPs to meet individual restoration species' needs may further improve the effectiveness of HPPs with native perennial bunchgrass species. For example, small seeded species may need smaller pod diameters to facilitate emergence.

While the results of this study suggest that HPPs increased cover and density of crested wheatgrass compared with bare seed, by the second yr of the study the difference had decreased between the two treatments (see Fig. 3B and Fig. 2D, respectively). This is probably, to some degree, an artifact of the study design instead of an accurate representation of treatment effects over time. BS and HPP treatment rows were planted only 1 m apart, which may have allowed seed from HPP-established crested wheatgrass, which produced seed in the first yr of the study, to disperse into the bare seed treatment, inflating the density and cover of crested wheatgrass in the bare seed treatment. Further field studies in which treatments are applied to larger areas and are spread farther apart to diminish edge effect are probably necessary to determine the long-term effects of using bare seed versus HPPs.

The success of HPP technology at protecting perennial bunchgrass and sagebrush seed from damage by imazapic indicates that this technology is effective with multiple functional groups. The increased establishment of sagebrush, crested wheatgrass, and bluebunch wheatgrass incorporated into HPPs indicates that HPPs may improve restoration success in annual grass-invaded sagebrush-steppe rangelands. While HPPs are more costly than bare seed, the tradeoff of increased establishment success and decreased necessity for repeated application of herbicide and seeding attempts could make this technology valuable (Madsen et al. 2016). Additionally, increased establishment of perennial bunchgrass species, which are competitive with invasive annual grasses when mature, can decrease the redominance by invasive annual grasses (Davies and Johnson 2017; Sheley and James 2010). Decreased cover of invasive annual grasses decreases the continuity of the fuel bed, potentially leading to a reduction in the extent of wildfires and future cost of restoration (Epanchin-Niell et al. 2009; Davies and Nafus 2013; Reed-Dustin et al. 2016).

HPPs are tools that have the potential to increase revegetation success in rangelands around the world where annual grasses are treated with preemergent herbicides. This includes exotic annual grass–invaded areas of Australia and the Qinghai-Tibetan Plateau (Dong et al., 2005; Prober and Thiele, 2005). Greater revegetation success will be even more critical in the face of predicted climate changes and increasing atmospheric CO_2 levels, which are likely to favor invasive annual grass growth and distribution and alter wildfire characteristics and regimes (Smith et al. 1987; Bradley 2009; Abatzoglou and Kolden 2011; Creutzberg et al. 2015).

Management implications

Herbicide protection pods limited herbicide toxicity to species seeded within them and thus allowed bunchgrass species and sagebrush to be seeded concurrently with imazapic application to control exotic annual grasses. This suggests that HPPs can be used effectively with multiple plant functional groups when exotic annual species are controlled with a preemergent herbicide. This will allow seedlings a longer establishment window before experiencing substantial competition from exotic annuals and could facilitate establishing perennial dominated communities that will be resistant to reinvasion and dominance by exotic annual species. Further refinements of HPPs are warranted, with respect to tailoring size and matrix formulation to specific individual or groups of revegetation species and with other preemergent herbicides. More importantly, however, will be scaling up the production of HPPs to decrease their cost and make them readily available for restoration projects. It is important to note that this study included sites between 1 439 and 1 511 m (4 721 and 4 957 ft) in elevation and encompassed a year with above-average precipitation. Seedings at hotter and drier sites not followed by a yr with adequate precipitation may not perform as well as seen in this study. Regardless, HPPs are promising tools for managing exotic annual grass invasions and improving postfire restoration and revegetation.

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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