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PRACTICE AND TECHNICAL ARTICLE

# Evaluating performance of three types of carbon seed coatings on seedling development

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**Sagebrush Steppe native plant restoration faces many hurdles to success, including extreme temperature and precipitation variability and non-native plant invasions. Multi-year preemergent herbicides are an option for annual grass control, but also prevent germination of native seeded species. Seed enhancement technologies have been recently developed and tested to shield native seeds from herbicide effects using activated carbon, giving them a competition-free window to germinate and develop. Several issues need to be addressed to scale these technologies appropriately to contend with the massive spatial extent of sagebrush (*Artemisia tridentata* spp.) steppe restoration needs, such as the ability to produce seed enhancement technologies at high volume and making them compatible with existing rangeland seeding practices. In this lab study, we evaluated the efficacy of traditional herbicide protection pellets (HPPs) versus smaller commercial coatings at protecting native seed from the preemergent herbicide imazapic. We then tested house-made coatings against those produced by Germains Seed Technology. Finally, we tested to see if the order of seeding and spraying affects the efficacy of high carbon industrial coatings and HPP technologies. Though no technology achieved complete protection, commercial seed coatings were able to achieve results comparable to HPPs with roughly 60% less activated carbon and 80% less dry materials; this smaller size is expected to reduce cost and simplify logistics of handling, storage, and delivery at scale. We also found no difference in the effectiveness of commercial seed coatings whether seeding happened before, or after spraying.**

**Key words: dryland restoration, invasive annual grasses, preemergent herbicide, seed coatings**

### Implications for Practice

- Restoration of sagebrush landscapes to address annual grass requires solutions that are simple to implement and scalable across millions of hectares.
- When combined with preemergent herbicides, seed enhancement technologies offer a promising method for protecting native seeds from herbicide mortality while also allowing desired establishing plants to experience a competition-free window.
- Delivering these benefits in a commercially produced, smaller package will allow rapid and widespread implementation by land management agencies using existing restoration planting methods.

## Introduction

Restoration of sagebrush (*Artemisia tridentata* spp.) steppe systems is complicated by many factors, including competition from invasive annual grasses (IAGs), IAG-increased probability of severe wildfire, and the extreme levels of interannual climate variability inherent in semiarid rangelands (Svejcar et al. 2017). These factors create conditions that make restoration logistically challenging while reducing the rates of success (Boyd & Davies 2012; Shriver et al. 2018). To mediate some of these issues, preemergent herbicides have been used to temporarily reduce the competitive effects of IAGs on perennial plants. Though preemergent herbicides largely spare established native perennial plants (Applestein et al. 2018), restoration seedings are vulnerable to its effects, creating an apparent tradeoff between herbicide benefits and successful native seedling establishment.

Seed enhancement technologies can mitigate the negative aspects of herbicide use, allowing native species establishment in the window of reduced competition from IAGs. One promising

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solution involves surrounding seeds in a protective material to reduce the effect of herbicides through adsorption (Davies et al. 2017). Herbicide protection pellets (HPPs), produced using extrusion equipment, are cylinders of activated carbon and binders containing multiple seeds (often eight), and have field- and lab-proven benefits to both native seed germination and survival rates (Davies et al. 2018; Clenet et al. 2020; Baughman et al. 2023; Brown et al. 2023*a*). However, several key issues make scaling up this technology challenging.

The quantities of seed needed for annual restoration activities in sagebrush steppe ecosystems are immense; the Bureau of Land Management seeded 1.36 million hectares in the past decade in an effort to revegetate Great Basin landscapes impacted by wildfire (Pilliod et al. 2021). Effective restoration will hinge upon activities that balance cost, feasibility, and probability of success, meaning that seed enhancement technologies need to be highly scalable. HPPs use a large amount of activated carbon and inert ingredients per seed, which makes adds complexity to storage and seeding (Holfus et al. 2021). Specifically, HPPs cannot easily be seeded using traditional rangeland seeding equipment due to their size and shape (Baughman et al. 2021). Single-seed coating, encrusting, and pelleting—which are all techniques employed by seed technology companies and use standard coating equipment—may offer an opportunity to overcome the challenges associated with scaling up production and improving delivery of herbicide protection technology using standard seeding equipment (e.g. rangeland drills) if protection properties can be maintained (Holfus et al. 2021; Baughman et al. 2023). Coating is a widely practiced technique in the agricultural industry to improve seed handling and homogenize this size and shape of seeds in mixes, and is currently being tested using native plant seeds (Pedrini et al. 2023). By using less material in coatings, we can also potentially reduce restoration costs and lessen the risk of seedling impacts from pellet compaction.

Despite advancements in seed protection technology, the specific mechanism conferring herbicide protection and the time window when protection is necessary are poorly understood, further hindering scalability. Due to the complex nature of shrub steppe restoration (i.e. highly variable weather conditions, availability of suitable equipment, and personnel limitations), prescriptive restoration strategies that require stringent timelines are logistically infeasible (Boyd & Svejcar 2009; Svejcar et al. 2017). Preferred application methods for seed enhancement technologies could involve “one-pass” herbicide and seeding applications, or flexibility in the order of the herbicide and seeding components. The potential for this flexibility, however, depends on the specific mechanism by which seed enhancement technologies confer resistance to herbicides. If HPPs create a physical shield or “umbrella” during herbicide application to leave an herbicide-free footprint (Madsen et al. 2014), smaller individual seed coatings and post-spray seeding would likely disadvantage seedlings. In contrast, if herbicide protection happens primarily during the seed imbibition stage, less protective material and greater application flexibility may be compatible with successful restoration outcomes.

To investigate the potential for alternative delivery of herbicide protection seed technology, we performed a series of three experiments. (1) We compared emergence, survival, and aboveground biomass (AGB) of bottlebrush squirreltail (*Elymus elymoides*) and bluebunch wheatgrass (*Pseudoroegneria spicata*) between bare seed, HPPs, and an in-house “vortex”-coated seed (as an initial prototype of a single-seed carbon coating) in the presence and absence of preemergent herbicide. (2) Following initial evaluation of an in-house produced seed coating, we partnered with Germains Seed Technology (Gilroy, CA, U.S.A.) to investigate the efficacy of a production-scale seed coating at low and high rates of activated carbon for bluebunch wheatgrass compared to HPPs and bare seed. (3) We then performed an herbicide sequence experiment to identify the time when herbicide protection primarily occurs, using bluebunch wheatgrass as a model species. Specifically, we measured emergence time, rate of emergence, survivorship, and AGB for bare seed and commercially produced coated seed subject to herbicide application before or after seeding. Objective 3 was designed to assess the potential for flexibility in herbicide application and seeding in restoration, while also helping to explain the mechanism by which carbon coatings provide herbicide protection.

We hypothesized that in the absence of a preemergent herbicide, seed enhancement technologies would not affect total emergence, seedling survival, or vigor. We also posited that coated seed would have greater total emergence, seedling survival, and vigor in the presence of preemergent herbicide relative to uncoated (bare) control seed, and that emergence, survival, and AGB would not differ between pre- and post-seeding herbicide application. This work begins to bridge the gap between plot-level herbicide protection studies and upscaled solutions for sagebrush steppe restoration.

## Methods

### Experiment 1: Evaluation of an In-House Produced Vortex-Coated Seed Relative to HPPs and Bare Seeds With and Without Preemergent Herbicide

**Seed Enhancement Technology Preparation.** Two extruded HPP batches were made for the study (one for each species), both composed of 44.4% Pelbon bentonite clay, 34.9% Darco GroSafe-activated carbon (Cabot, Billerica, MA, U.S.A.), 14.3% Deschutes Recycling compost fines (Bend, OR, U.S.A.), and 6.4% Worm Gold castings (Wallace Labs, El Segundo, CA, U.S.A.) following Brown et al. (2019). Calculations to determine the quantity of seed added to each batch utilized the most recent viability and mean whole seeds per bulk gram estimates for each lot, with a target of 8 pure live seed (PLS) per average HPP, following Baughman et al. (2023).

We produced in-house vortex coating following Holfus et al. (2021). For the purposes of this study, a mean application rate of 18 mg of activated carbon per seed was applied (ranging 15–20 mg activated carbon per seed) requiring an average of 4.5 mg binder per seed. The vortex method produces a coating with larger pockets and lower integrity compared to rotary pellets which allows it to fall apart easily when moistened.

**Laboratory Experiment and Analyses.** The study was conducted at the Eastern Oregon Agricultural Research Center Seed Lab (Burns, OR, U.S.A.) in a climate controlled common grow room (16–22°C) under Platinum LED P1200 lights (Platinum LED Lights, LLC, Kailua, HI, U.S.A.) with a 12-hour light, 12-hour dark photoperiod. Lights were set to "veg" mode at the recommended height of 61 cm (distance between top of pot and bottom of light). Soil used for this experiment was a sifted (1 mm mesh), sandy loam collected 1 November, 2019 and 12 October 2020 from the Northern Great Basin Experimental Range (Riley, OR, U.S.A.). Field soil was mixed 1:1 with a commercially purchased sand (i.e. coarse playground sand). Samples were sown in square plastic pots (14 $cm^2$ and 2.5 L volume) lined with weed cloth and filled with 2100 mL of media by volume, leaving ≤1 cm of space between the soil surface and top of pot. Soil was gently tamped down to maintain uniformity in compaction. Pots were saturated and weighed after 24 hours to assess volumetric water content at field capacity. Containers were then left to dry for 3 days after saturating to ensure that they were moist but below field capacity when sown, because sagebrush steppe soils rarely achieve field capacity.

In each pot, 25 PLS were placed on the soil surface in a grid pattern then dusted with dry sieved soil to achieve a seeding depth of 2–3 mm. Though minimal, this coverage is necessary to prevent seed loss and movement during herbicide application and irrigation. More importantly, it provides enough seed–soil contact to achieve germination without limiting herbicide efficacy. HPPs were sown by placing them on the surface and pressed to create a depression approximately 1 mm in depth to cradle each pellet and prevent movement. HPPs, unlike bare or coated seed, were developed to be surface sown, so our comparisons represent best use-case scenarios. We sowed HPPs by weight at a rate of 25 PLS per pot (approximately three to four pellets). Immediately after planting, half the samples were treated with 730 mL/ha (10 oz./acre) formula of Plateau (23.6% ammonium salt of imazapic; BASF Corporation, Research Triangle Park, NC, U.S.A.) applied with a hand-held sprayer. All samples were watered 4–5 hours after sowing with a 1.9 L/minute Fogg-It nozzle (Fogg-It Nozzle Company, Belmont, CA, U.S.A.). This initial moisture amount was chosen to mimic a light rain (2.54 mm) and move the herbicide from the surface into the upper soil profile and mimic natural wetting/drying cycles (Baughman et al. 2021). For the following 3–4 days, containers were misted as needed to keep the surface moist. For the remainder of the study, pots were kept moist by hand watering every 1–2 days. Emergence was monitored every day for the duration of the experiment (50 days). Emergence was calculated as a percent of viable seed sown by dividing the total number of emerged seedlings by the number of total viable seeds sown for each sample unit (i.e. pot).

Survivorship was assessed at the conclusion of the study by recording the number of live seedlings in each container; seedlings were considered living if they had any remaining green tissue. Survivorship was calculated as a percent of emerged seedlings by dividing the number of plants surviving to the end of the experiment by the total number of seedlings to emerge per experimental unit. Seedling size was assessed by sampling leaf number and AGB of live seedlings at the conclusion of the study. The number of leaves for each seedling was recorded, and then the leaf number was calculated as the mean number of leaves per living seedling in each experimental unit. Living biomass was collected by clipping seedlings in each pot at their root collar and placing in an envelope, and was similarly expressed as the mean biomass per living seedling in each experimental unit. Envelopes were placed in a laboratory drying oven at 75°C for a minimum of 5 hours or until additional drying time did not further reduce weights, then weighed using an analytical balance. AGB was calculated as the mean weight per living seedling in each experimental unit.

Response variables (emergence, survivorship, leaf number, and AGB) were evaluated and analyzed independently using R *stats* package and data visualization in the *ggpubr* package procedure to examine data distributions, assess normality, identify outliers, and ascertain whether data transformations were required (R v4.2.1, R Core Team 2023). We then used a linear mixed-effects model framework with the *nlme* R package to determine whether there was a seed treatment, herbicide, or seed treatment by herbicide effect for each response variable using block as a random factor (Pinheiro et al. 2022). Following the initial model run, we performed post hoc multiple comparisons for significant main or interactive effects using *emmeans* (Lenth 2022). Results were considered significant at $p \leq 0.05$.

### Experiment 2: Evaluation of a Commercially Produced Herbicide Protection Coating Relative to HPPs and Bare Seed With and Without Preemergent Herbicide

**Seed Enhancement Technology Preparation.** We acquired commercial coatings from Germains Seed Technology which incorporated powdered activated carbon at a high and low rate (66% of the high rate) into a proprietary high integrity formula. The carbon, binder, and other ingredients, including their ratios, are protected intellectual property and cannot be disclosed. HPP formulation followed the recipe described in experiment 1.

**Laboratory Experiment and Analyses.** Laboratory experimental procedures followed those outlined in experiment 1. Viability of the bare bluebunch wheatgrass was 74.5% (results obtained via germination test in Petri dishes with 20 seeds per dish and 10 replicates). Emergence, survivorship, and AGB were calculated as in experiment 1. Data analyses followed procedures outline in experiment 1.

### Experiment 3: Effects of Preemergent Herbicide Application Timing Relative to Seeding on Herbicide Protection Efficacy

**Seed Enhancement Technology Preparation.** We obtained Germains Seed Technology rotary-coated seed as outlined in experiment 2. The recipe was similar to experiment 2, but we worked with Germains to lower the integrity to improve seedling emergence. HPP formulation followed the same recipe as described in experiment 1.

**Laboratory Experiment and Analyses.** Viability of the bare bluebunch wheatgrass was 94.5% (results obtained via germination test in Petri dishes with 20 seeds per dish and 10 replicates). The pre-seeding herbicide treatment occurred 1 hour prior to seeding and the post-seeding herbicide treatment occurred approximately 1 hour after seeding; seeds were sown as in experiment 1. The preemergent herbicide imazapic was applied at the same rate as experiment 1 using a hand-held spray bottle. Watering occurred every 1–2 days for the eight-week duration of the experiment.

## Results

### Experiment 1: Evaluation of In-House Produced Vortex-Coated Seed Relative to HPPs and Bare Seeds With and Without Preemergent Herbicide

In the absence of herbicide, the percent of viable bottlebrush squirreltail seedlings that emerged was higher for in-house coatings than for the HPP treatment (Fig. 1; seed treatment × herbicide interaction; $F_{[2,54]} = 8.69$, $p = 0.0005$, $t_{[45]\text{Bare-HPP}} = 2.54$, $p = 0.05$). Bluebunch wheatgrass emergence was approximately 46% lower for the HPP treatment than for the in-house coating, which did not differ from bare seed (Fig. 1; seed treatment × herbicide interaction; $F_{[2,44]} = 8.04$, $p = 0.0011$, $t_{[45]\text{HPP-In House}} = -3.45$, $p = 0.01$; $t_{[45]\text{In House-Bare}} = 2.25$, $p = 0.24$). In the presence of herbicide, in-house-coated bottlebrush squirreltail was the only treatment to exhibit significantly higher seedling emergence (approximately 42%) relative to bare seed ($t_{[45]\text{Bare-In House}} = -5.91$, $p < 0.01$). None of the tested seed technologies improved bluebunch wheatgrass emergence when treated with preemergent herbicide ($t_{[44]\text{Bare-HPP}} = 1.53$, $p = 1.00$; $t_{[44]\text{Bare-In House}} = -1.42$, $p = 0.71$; $t_{[44]\text{HPP-In House}} = -1.56$, $p = 0.62$).

Survivorship was not inhibited by seed treatment in the absence of herbicide of either species tested (Fig. 1; seed treatment × herbicide interaction; bottlebrush squirreltail $F_{[2,45]} = 50.34$, $p < 0.0001$; bluebunch wheatgrass $F_{[2,44]} = 10.72$, $p = 0.0002$). With herbicide present, bottlebrush squirreltail survivorship in the HPP and in-house treatments was higher than bare seed (approximately 488 and 473%, respectively) and comparable to non-herbicide control values ($t_{[45]\text{Bare-HPP}} = -10.44$, $p < 0.01$; $t_{[45]\text{Bare-In House}} = -10.07$, $p < 0.01$). Bluebunch wheatgrass HPP and in-house coating survivorship in the presence of herbicide were also higher than bare seed (48 and 43%, respectively; $t_{[44]\text{Bare-HPP}} = -4.88$, $p < 0.01$; $t_{[44]\text{Bare-In House}} = -3.89$, $p < 0.01$), but approximately 20 and 35% lower than bare seed in the absence of herbicide ($t_{[44]\text{Bare-HPP}} = 3.26$, $p = 0.01$; $t_{[44]\text{Bare-In House}} = 4.62$, $p = <0.01$).

In the absence of herbicide, leaf number and AGB did not differ among seed treatments for either species (Fig. 1). When treated with herbicide, both species produced less AGB and fewer leaves relative to herbicide controls, and there were no discernable differences among carbon seed treatments by species (herbicide treatment; AGB $F_{[1,44]} = 101.17$–$116.23$, $p < 0.0001$; leaves $F_{[1,44]} = 117.87$–$150.69$, $p < 0.0001$).

### Experiment 2: Evaluation of a Commercially Produced Herbicide Protection Coating Relative to HPPs and Bare Seed With and Without Preemergent Herbicide

In the absence of herbicide, all carbon seed treatments reduced bluebunch wheatgrass emergence by 21–37% compared to bare seed (Fig. 2), had no effect on survivorship, and produced AGB that was equal to or greater than bare seed (Fig. 2).

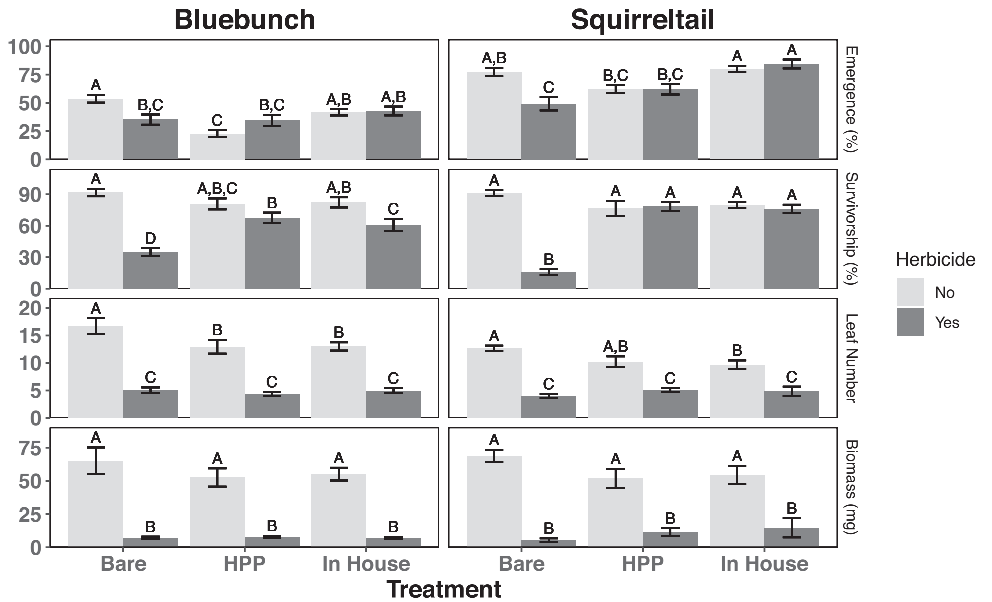


Figure 1. Dry aboveground biomass (mg), emergence (% of viable seed), survivorship (%), and leaf count (±1 SE) of bluebunch wheatgrass (*Pseudoroegneria spicata*), bottlebrush squirreltail (*Elymus elymoides*), and for bare seed, HPPs, and in-house vortex-coated seed in the absence and presence of the preemergent herbicide, imazapic. Letters indicate significant differences between treatments ($p < 0.05$ Tukey's honestly significant difference test).

Preemergent herbicide treatments reduced emergence for all seed treatments relative to untreated bare seed (Fig. 2; seed treatment × herbicide interaction; $F_{[3,63]} = 6.27$, $p = 0.0009$; $t_{[63]\text{Bare-High Carbon}} = 4.90$, $p < 0.01$; $t_{[63]\text{Bare-Low Carbon}} = 7.21$, $p < 0.01$; $t_{[63]\text{Bare-HPP}} = 7.26$, $p < 0.01$); in the presence of herbicide HPP, low-, and high-rate coating survival was 305, 263, and 252% higher than bare seed, respectively (Fig. 2; seed treatment × herbicide interaction; $F_{[3,63]} = 38.66$, $p < 0.01$; $t_{[63]\text{Bare-HPP}} = -13.75$, $p < 0.01$; $t_{[63]\text{Bare-Low Carbon}} = -11.82$, $p < 0.01$; $t_{[63]\text{Bare-High Carbon}} = -11.35$, $p < 0.01$). HPP survivorship was approximately 10% higher than the commercial coatings and comparable to non-herbicide controls (Fig. 2; $t_{[63]\text{HPP-High Carbon}} = 2.41$, $p = 0.25$; $t_{[63]\text{HPP-Low Carbon}} = 1.95$, $p = 0.52$, $t_{[63]\text{Hpp-Bare}} = -2.68$, $p = 0.15$). Herbicide-treated samples had notably less AGB accumulation compared to untreated bare seed, meaning none of the seed technologies provided complete protection (seed treatment × herbicide interaction; $F_{[3,62]} = 4.66$, $p = 0.0053$; $t_{[63]\text{Bare-High Carbon}} = 7.72$, $p < 0.01$; $t_{[63]\text{Bare-Low Carbon}} = 6.48$, $p < 0.01$; $t_{[63]\text{Bare-HPP}} = 7.26$, $p < 0.01$). We found no differences among seed treatments in the presence of herbicide (Fig. 2; $t_{[63]\text{High Carbon-HPP}} = 2.36$, $p = 0.28$; $t_{[63]\text{High Carbon-Low Carbon}} = 2.32$, $p = 0.30$; $t_{[63]\text{HPP-Low Carbon}} = -0.04$, $p = 1.00$).

### Experiment 3: Effects of Preemergent Herbicide Application Timing Relative to Seeding on Herbicide Protection Efficacy

In the absence of herbicide, the HPP seed treatment had 53% lower emergence compared to bare seed, while the commercial coating did not differ from bare seed (seed treatment × herbicide interaction; $F_{[4,69]} = 7.50$, $p < 0.0001$, $t_{[69]\text{HPP-Bare}} = -5.77$, $p < 0.01$; $t_{[69]\text{High Carbon-Bare}} = 2.72$, $p = 0.16$; $t_{[69]\text{Low Carbon-Bare}} = 0.24$, $p = 1.00$). Emergence did not differ between pre- and post-seeding herbicide application by seed treatment (Fig. 3), and herbicide-treated commercial seed coating was the only activated carbon treatment with higher emergence values relative to bare seed. Survivorship among seed treatments was similar in the absence of herbicide, indicating that the HPP and commercial coating did not have a negative impact on 8-week laboratory establishment (seed treatment × herbicide interaction; $F_{[4,72]} = 3.45$, $p = 0.0123$). All herbicide-treated samples had lower survivorship relative to no-herbicide controls except for the commercial coatings in the post-seed herbicide combination (Fig. 3). Commercial coating improved survivorship relative to bare seed by 74%, indicating it provided some protection from herbicide. Survivorship did not differ between pre- and post-seeding herbicide application by seed treatment (Fig. 3). In the absence of herbicide, AGB did not differ between seed treatments (herbicide treatment; $F_{[2,72]} = 209.48$, $p < 0.001$). Herbicide exposure resulted in seedlings with less AGB relative to controls (Fig. 3). None of the seed treatments improved AGB when treated with herbicide.

## Discussion

Our results indicate that seed coating is a promising direction for seed enhancement technology research, with performance of in-house produced vortex and commercial produced coatings comparable to (and in a few cases exceeding) current best performing HPP formulations. Though none of the evaluated seed technology formulations provided complete protection from the negative effects of herbicide, both bluebunch wheatgrass and bottlebrush squirreltail exhibited improved performance in the presence of herbicide when treated with HPPs, in-house produced vortex and commercial coatings compared to bare seed. In-house and commercial seed coatings were able to achieve results

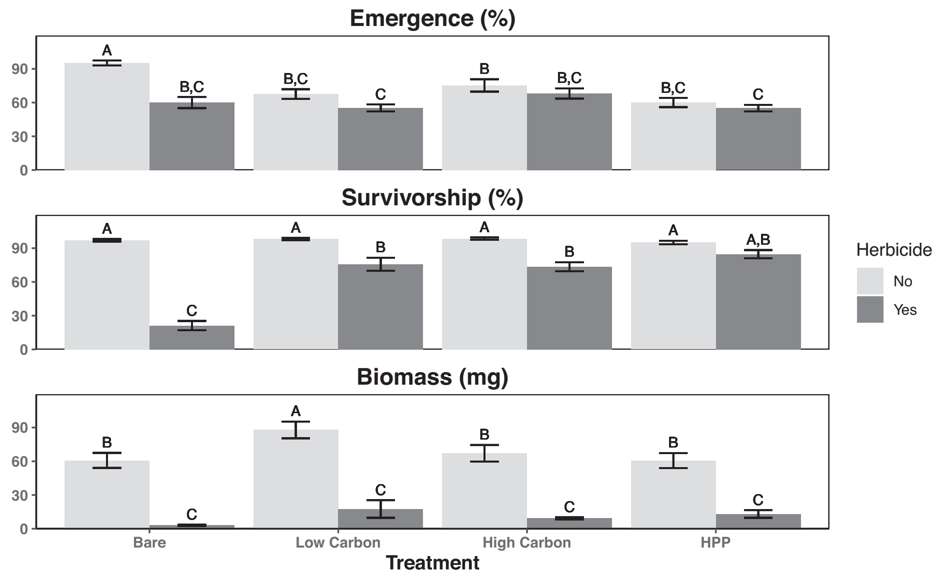


Figure 2. Dry aboveground biomass (mg), emergence (% of viable seed), and survivorship (%) (±1 SE) of bluebunch wheatgrass (*Pseudoroegneria spicata*) for bare seed, commercially produced herbicide protection coatings (low and high rate), and HPPs in the absence and presence of the preemergent herbicide, imazapic. Letters indicate significant differences between treatments ($p < 0.05$ Tukey's honestly significant difference test).

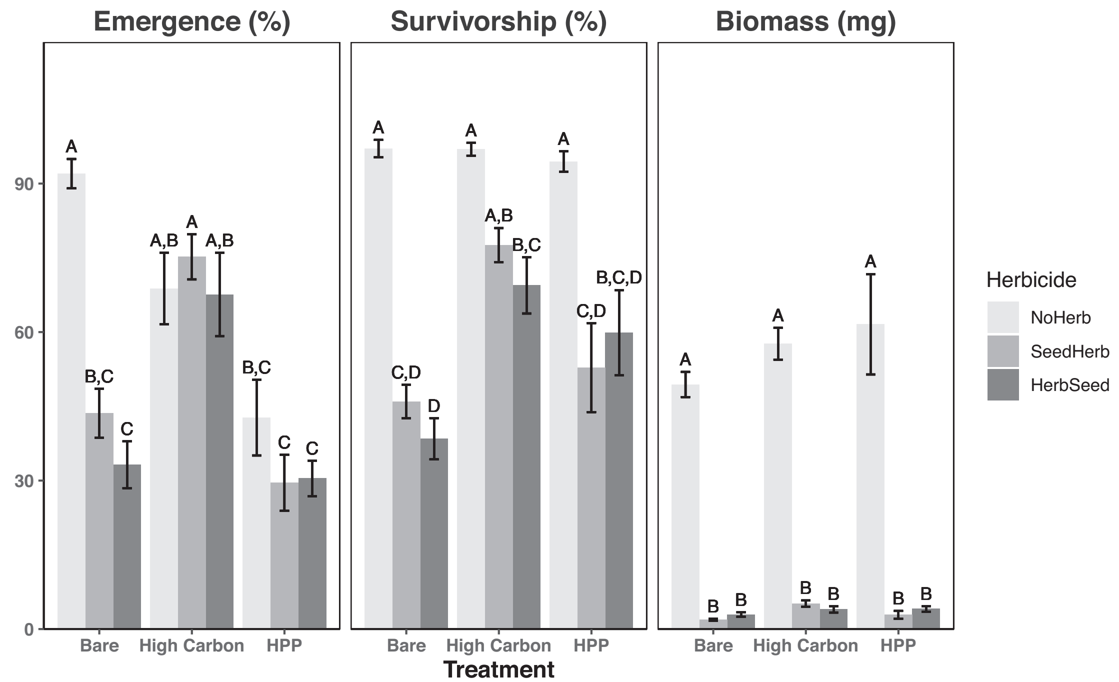


Figure 3. Dry aboveground biomass (mg), emergence (% of viable seed), and survivorship (%) (±1 SE) of bluebunch wheatgrass (*Pseudoroegneria spicata*) for bare seed, commercially produced herbicide protection coatings, and HPP treatments with the preemergent herbicide imazapic applied before (HerbSeed) and after (SeedHerb) seeding with a no-herbicide control (NoHerb). Letters indicate significant differences between treatments ($p < 0.05$ Tukey's honestly significant difference test).

comparable to HPPs with roughly, on a per seed basis, 60% less activated carbon and 80% less dry material, reducing cost, and simplifying handling, storage, and seeding logistics. Original HPP formulations also posed issues to small and shallow-seeded species as they could not push through the coating due to compaction and volume of material (Baughman et al. 2021; Alfonzetti et al. 2022). By reducing the size of HPPs, the authors were able to achieve increased early performance in Sandberg bluegrass (*Poa secunda*), balancing considerations for emergence and herbicide protection (Baughman et al. 2021). This balance has been an important aspect in the single-seed coating formulation development. Our approach contrasts with alternative successful solutions, like positioning seeds closer to the exterior of the pellet to reduce emergence issues while preserving herbicide protection (Brown et al. 2023*b*). We designed the initial in-house vortex coating with the goal of reducing ingredients, binder, and integrity to eliminate up-front seed treatment costs and create an easily scalable technology. Here, we saw little tradeoff between technology size and effectiveness, addressing scalability concerns and refuting initial worries that coated seed would fail to protect germinating seeds (Madsen et al. 2016).

Though we were able to achieve partial herbicide protection with less carbon, general tradeoffs of using herbicide protection pelleting and coating continue to exist. For example, though HPPs and coated seeds of bluebunch wheatgrass (experiment 1, both coated seed treatments for experiment 2) and bottlebrush squirreltail (experiment 2) had greater survival over bare seed in the presence of herbicide, bluebunch wheatgrass survival was lower in HPP in experiment 1 and coated seed treatments (experiments 1 and 2) in the presence of herbicide than that of bare seed controls in the absence of herbicide. This suggests that further improvements to seed technology formulations are needed to reduce potential negative impacts of the seed technology on seed performance.

Our work provides multiple lines of evidence that both seed technology formulations (pellet and coating) can help to overcome important barriers to seed-based restoration, but does not clarify long-term tradeoffs. Like other studies, seeds coated with herbicide protection technologies exhibited reduced emergence and growth despite improved survival when treated with preemergent herbicide (Clenet et al. 2019; Munro et al. 2023). Though we did not take explicit measurements of seedling health, many surviving seedlings in herbicide protection treatments exhibited chlorosis and stunted growth. Our initial monitoring period only allowed us to speculate on how seedling vigor might affect long-term survival. Thus, long-term monitoring is needed to determine the effects of incomplete herbicide protection on survival, growth, and seed set. Furthermore, our study did not evaluate the effects of seed technology benefits in the context of IAG competition, which is critical to quantifying the benefits and tradeoffs associated with establishment in a competition-free environment (using preemergent herbicide and herbicide protection technology) relative to establishment in a high-competition environment with no or minimal herbicide presence (no-herbicide use). In other words, how much seedling damage is tolerable in exchange for a relatively competition-free establishment environment? Finally, our findings also suggest that the benefits of herbicide protection are likely agnostic to the order of seeding and herbicide application, presumably with most of the herbicide impact incurred during seed imbibition.

Improving the ease of adoption of restoration technologies is paramount to successful management outcomes. By developing a product that is compatible with existing seeding equipment and by providing comparable results in a smaller package, current herbicide protection technologies will reduce cost and logistic barriers to application. The seed needs in sagebrush steppe restoration are vast, and likely reductions in seed technology production, storage, and shipping costs and compatibility with existing seeding methods are not trivial benefits. Before full-scale adoption of activated carbon herbicide technologies can occur, however, more research is needed to improve seed protection efficacy of seed technologies and to evaluate tradeoffs between herbicide and protection impacts and the benefits of establishment in the absence of invasive annual grass competition.

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## LITERATURE CITED

Alfonzetti M, Tetu SG, Mills CH, Gallagher RV (2022) Assessing the efficacy of extruded pellets and microbial amendments for native vegetation. Restoration Ecology 31:e13587. https://doi.org/10.1111/rec.13857

Applestein C, Germino MJ, Fisk MR (2018) Vegetative community response to landscape-scale post-fire herbicide (imazapic) application. Invasive Plant Science and Management 11:127–135. https://doi.org/10.1017/inp.2018.18

Baughman OW, Eshleman M, Griffen J, Rios R, Boyd C, Kildisheva OA, Olsen A, Cahill M, Kerby JD, Riginos C (2023) Assessment of multiple herbicide protection seed treatments for seed-based restoration of native perennial bunchgrasses and sagebrush across multiple sites and years. PLoS One 18:e0283678. https://doi.org/10.1371/journal.pone.0283678

Baughman OW, Griffen J, Kerby J, Davies KW, Clenet D, Boyd C (2021) Herbicide protection pod technology for native plant restoration: one size may not fit all. Restoration Ecology 29:e13323. https://doi.org/10.1111/rec.13323

Boyd CS, Davies KW (2012) Spatial variability in cost and success of revegetation in a Wyoming big sagebrush community. Environmental Management 50:441–450. https://doi.org/10.1007/s00267-012-9894-6

Boyd CS, Svejcar TJ (2009) Managing complex problems in rangeland ecosystems. Rangeland Ecology & Management 62:491–499. https://doi.org/10.2111/08-194.1

Brown VS, Erickson TS, Hobbs RJ, Manstrantonis S, Ritchie AL (2023*a*) Carbon-based pelleting, soil ripping and herbicide application can be used to overcome plant recruitment barriers in Grey Stinkwood (*Jacksonia furcellata*). Ecological Management & Restoration 24:119–127. https://doi.org/10.1111/emr.12583

Brown VS, Richie AL, Stevens JC, Hanks TD, Hobbs RJ, Erickson TE (2023*b*) Seed positioning in extruded pellets: does it matter? Restoration Ecology 31:e13784. https://doi.org/10.1111/rec.13784

Brown VS, Ritchie AL, Stevens JC, Harris RJ, Madsen MD, Erickson TE (2019) Protecting direct seeded grasses from herbicide application: can new extruded pellet formulations be used in restoring natural plant communities? Restoration Ecology 27:488–494. https://doi.org/10.1111/rec.12903

Clenet DR, Davies KW, Johnson DD, Kerby JD (2019) Native seeds incorporated into activated carbon pods applied concurrently with indaziflam: a new strategy for restoring annual-invaded communities? Restoration Ecology 27:738–744. https://doi.org/10.1111/rec.12927

Clenet DR, Davies KW, Johnson DD, Kerby JD (2020) Herbicide protection pods (HPPs) facilitate sagebrush and bunchgrass establishment under imazapic control of exotic annual grasses. Rangeland Ecology & Management 73:687–693. https://doi.org/10.1016/j.rama.2020.07.002

Davies KW, Boyd CS, Madsen MD, Kerby J, Hulet A (2018) Evaluating a seed technology for sagebrush restoration across an elevation gradient: support for bet hedging. Rangeland Ecology & Management 71:19–24. https://doi.org/10.1016/j.rama.2017.07.006

Davies KW, Madsen MD, Hulet A (2017) Using activated carbon to limit herbicide effects to seeded bunchgrass when revegetating annual grass-invaded rangelands. Rangeland Ecology & Management 70:604–608. https://doi.org/10.1016/j.rama.2017.04.004

Holfus CM, Rios RC, Boyd CS, Mata-González R (2021) Preemergent herbicide protection seed coating: a promising new restoration tool. Rangeland Ecology & Management 76:95–99. https://doi.org/10.1016/j.rama.2021.02.005

Lenth R (2022) emmeans: estimated marginal means, aka least-squares means. R package version 1.8.2.

Madsen MD, Davies KW, Boyd CS, Kerby JD, Svejcar TJ (2016) Emerging seed enhancement technologies for overcoming barriers to restoration. Restoration Ecology 24:S77–S84. https://doi.org/10.1111/rec.12332

Madsen MD, Davies KW, Mummey DL, Svejcar TJ (2014) Improving restoration of exotic annual grass-invaded rangelands through activated carbon seed enhancement technologies. Rangeland Ecology & Management 67:61–67. https://doi.org/10.2111/REM-D-13-00050.1

Munro TP, Ritchie AL, Erickson TE, Nimmo DG, Price JN (2023) Activated carbon seed technologies provide some protection to seedlings from the effects of post-emergent herbicides. Restoration Ecology 31:e13875. https://doi.org/10.1111/rec.13875

Pedrini S, Webber Z, D'Agui H, Dixon K, Just M, Arya T, Turner T (2023) Customise the seeds, not the seeder: pelleting of small-seeded species for ecological restoration. Ecological Engineering 196:107105. https://doi.org/10.1016/j.ecoleng.2023.107105

Pilliod DS, Jeffries MI, Welty JL, Arkle RS (2021) Protecting restoration investments from the cheatgrass-fire cycle in sagebrush steppe. Conservation Science and Practice 3:e508. https://doi.org/10.1111/csp2.508

Pinheiro J, Bates D, R Core Team (2022) nlme: linear and nonlinear mixed effects models. R package version 3.1–157.

R Core Team (2023) R: a language and environment for statistical computing. https://www.r-project.org/ (accessed 30 Jul 2022)

Shriver RK, Andrews CM, Pilliod DS, Arkle RS, Welty JL, Germino MJ, Duniway MC, Pyke DA, Bradford JB (2018) Adapting management to a changing world: warm temperatures, dry soil, and interannual variability limit restoration success of a dominant woody shrub in temperate drylands. Global Change Biology 24:4972–4982. https://doi.org/10.1111/gcb.14374

Svejcar T, Boyd C, Davies K, Hamerlynck E, Svejcar L (2017) Challenges and limitations to native species restoration in the Great Basin, U.S.A. Plant Ecology 218:81–94. https://doi.org/10.1007/s11258-016-0648-z

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