RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

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RESEARCH ARTICLE

Seed pellets containing activated carbon increase emergence of native plant species used in dryland restoration following herbicide application

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Abstract

Introduction: Over half of dryland ecosystems worldwide are degraded, making restoration a priority. Most dryland restoration efforts use seed-based approaches, which often result in limited establishment of desirable species. The dual challenges of abiotic stressors and invasive species dominance are key barriers to native plant community reestablishment in degraded drylands. Innovative seeding approaches that help overcome these barriers are needed.
Objectives: We tested seed pellets, a seed enhancement technology, with varying compositions and activated carbon amendments, both for herbicide protection and in the absence of herbicide.
Methods: We conducted two greenhouse mesocosm experiments. The first experiment tested the protective effect of activated carbon in seed pellets, produced using a low-tech "Bicycle-Powered Seed Pelletizer," after aminopyralid herbicide (Milestone™) application on diverse seedling emergence. The second experiment examined how seed pellet composition, including variable clay ratios and activated carbon additions in the absence of herbicide, affected seedling recruitment.
Results: Seed pellets improved seedling emergence in both experiments, with 136% and 56% higher odds of emergence from seed pellets compared to broadcast seeding in the first and second experiments, respectively. Composition and activated carbon additions without herbicide treatment had limited effects. Following aminopyralid herbicide treatment, we found significantly higher emergence from seed pellets containing activated carbon.
Conclusions: Seed pellets with activated carbon may be an effective seeding method in dryland ecosystems where herbicide treatment and reseeding are needed. Varying clay content and activated carbon additions had limited impacts without herbicide treatment.
Implications for Practice: Low-tech seed pellets made using a "Bicycle-Powered Seed Pelletizer," should be considered in dryland restoration since pellets improved seedling emergence across all treatments compared to broadcast seeding. Pellet composition had limited effects on emergence under greenhouse conditions, though differences may be more pronounced under low-water field conditions. When invasive species management and seeding are needed simultaneously, seed pellets containing activated carbon provide herbicide protection and offer a low-tech restoration strategy using widely available materials. Without herbicide, activated carbon amendments did not improve emergence. Abiotic stressors and invasion are common challenges; hence, the need for revegetation extends beyond dryland systems. These approaches may be relevant in other degraded systems.

Key words: activated carbon, aminopyralid, drylands, herbicide, milestone™ herbicide, seed enhancement technology, seed pellets, seedling recruitment

Introduction

Drylands, defined as hyper-arid, arid, and/or semiarid ecosystems, cover more than 40% of the Earth's terrestrial surface and support approximately 39% of the human population (Hoover et al. 2020; Shackelford et al. 2021; Duniway et al. 2022). The global extent of dryland ecosystems is expected to increase because of climate change and aridification (Hoover et al. 2020). Drylands are susceptible to land degradation, biodiversity loss, reduced ecosystem functioning, and lower resilience as a result of land use change, overgrazing, and invasion by introduced species, among other anthropogenic drivers (Hoover et al. 2020; Shackelford et al. 2021). Already, over half of drylands are degraded, driven by global change and

Author contributions: EHS, BC, CAH conceived and designed the research; EHS, CAH developed the methodology; CAH supervised the work; EHS, BC conducted the experiments; EHS performed the analysis and wrote the original draft; CAH reviewed and edited the manuscript.

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doi: 10.1111/rec.70316
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.70316/suppinfo

anthropogenic disturbances, making restoration a critical priority (Abhilash 2021; Shackelford et al. 2021). With significant biotic and abiotic barriers to success, these landscapes are unlikely to recover without active intervention (Gann et al. 2019; Shackelford et al. 2021). Active restoration—defined as human intervention when the potential for natural recovery is low or absent (Gann et al. 2019)—is often necessary in these denuded drylands (Shackelford et al. 2021).

Active dryland restoration interventions often include herbicide treatments and/or seed-based restoration (SBR) approaches. These are the most practical methods given the large areas in need of treatment and cost limitations; however, most dryland SBR projects result in little or no establishment of desirable species (Havrilla et al. 2020; Copeland et al. 2021; Shackelford et al. 2021). SBR in drylands faces many major barriers to success, including abiotic limitations (e.g. water limitation and extreme heat) (Shackelford et al. 2021), seed predation (Gornish et al. 2019), invasive species prevalence (James et al. 2011; Shackelford et al. 2021), and degraded soils (Larson et al. 2015). Precision restoration is a proposed framework that applies specific restoration techniques that address ecological barriers to recruitment, focused on the limitations of the desired restoration site (Madsen et al. 2016; Copeland et al. 2021). Innovative, science-based restoration strategies are needed to improve precision restoration tools and overcome ecological barriers to support positive SBR outcomes in drylands in the context of climate change (Svejcar et al. 2023).

Invasive species dominance is a common and difficult barrier to overcome when using SBR efforts in drylands. Invasive species can be problematic because they often modify soil nutrients, change competitive dynamics for limited resources including soil moisture, change the vegetation structure of a community, and some release allelopathic compounds, all resulting in reduced germination and establishment of desirable species (Brown et al. 2021; Garbowski et al. 2021; Svejcar et al. 2022). Further, management or removal of these species can open the possibility of secondary invasion or management-mediated invasion, resulting in further challenges (Pearson et al. 2016; O'Loughlin & Green 2017; Shackelford et al. 2021). Overcoming initial and secondary invasion often requires targeted weed treatments, often in the form of pre-emergent herbicides that provide effective control over a longer period, in combination with revegetation (Pearson et al. 2016; Lazarus & Germino 2022). Pre-emergent herbicides, however, can also impact non-target species by damaging seeds and seedlings, making it difficult to establish desirable species before inevitable competition from secondary invasive species becomes an issue again (Davies et al. 2014; Madsen et al. 2014). Protecting desirable seeds from herbicide impacts allows restoration practitioners to establish native species in the window where herbicide is suppressing weeds effectively, reducing competition in the critical early establishment stage.

Various seed enhancement technologies, defined as techniques that protect seeds, allow for precision seeding and/or improve germination and establishment, have been documented in dryland restoration projects (Brown et al. 2021). Examples of seed enhancement technologies include seed coating, priming, flash flaming to remove appendages, and seed agglomeration (Pedrini et al. 2020; Brown et al. 2021). However, many come with high costs and specialized equipment needs, making these techniques inaccessible to many land managers (Iftekhar et al. 2017; Brown et al. 2021). This work aims to identify relatively low-tech seed enhancement techniques using technology built with widely available materials and ingredients to improve restoration outcomes.

Seed pellets (also referred to as seed balls, seed bombs, seed pillows, and pods in the literature) are a type of low-tech seed enhancement technology. Seed pellets are an agglomeration of seed, clay, amendments, and water that aim to protect seeds, improve germination and establishment, allow for precision delivery of amendments, and ease of deployment across the landscape (Gatherum 1951; Madsen et al. 2016; Gornish et al. 2019). Primary reasons for using seed pellets in dryland restoration are to protect seeds from granivory (Pearson et al. 2019), harsh conditions, and to prevent seed movement off the restoration site until conditions are suitable for germination, such as a large precipitation event (Gornish et al. 2019; Teichroew & Rew 2024). While research into seed pellet technology is increasing, several critical knowledge gaps remain, including uncertainty in best practices for seed pellet composition, such as determining the amount of clay used to bind the pellet together under site-specific environmental conditions, considering appropriate amendments based on site characteristics and desired outcomes, and synthesis methods (e.g. making seed pellets by hand or using a "Bicycle-Powdered Seed Pelletizer" or other methods) (Gornish et al. 2018, 2019; Berto et al. 2024).

Activated carbon is one potential seed pellet amendment that could be beneficial for addressing multiple biotic and abiotic barriers to seed emergence. Activated carbon has been shown to be effective at neutralizing the impacts of various herbicides due to its large surface area and absorptive capacity (Davies et al. 2024) and can be used to protect desirable seeds, and may also influence emergence in the absence of herbicide (Davies et al. 2017; Clenet et al. 2019; Svejcar et al. 2022). Previous work (e.g. Madsen et al. 2014; Davies et al. 2017; Clenet et al. 2019) has shown that including activated carbon protected desirable seeds when used as a seed coating or in Herbicide Protection Pods (HPPs) (Davies et al. 2024). HPPs, a type of extruded seed pellet, as described by Madsen et al. (2014, 2016) are constructed using specialized equipment used in the restaurant industry for pasta making, resulting in uniform 8 mm-thick, 16 mm-long, and 16 mm-wide pods containing seeds. These studies have demonstrated effectiveness when used with pre-emergent herbicides used to target exotic annual grass species (Madsen et al. 2014; Davies et al. 2017). Most studies to date use pre-emergent herbicides in contexts where annual grasses are the invasive species of concern and use relatively low diversity seed mixes for revegetation efforts ranging from a single grass species (e.g. Madsen et al. 2014; Davies et al. 2017), to more diverse seed mixes (Clenet et al. 2020). The diverse mixes are mostly grass dominated but also include at least one forb and/or shrub species (e.g. Davies 2018; Clenet et al. 2020; Munro et al. 2023; Svejcar et al. 2024*a*, 2024*b*). A significant benefit of using activated carbon to neutralize herbicide is that it may allow for single-entry restoration approaches where seeding and invasive species control happen simultaneously rather than requiring a phased approach, where herbicide is applied and seeding occurs months to years later, which is more resource intensive (Sheley et al. 2012; Madsen et al. 2014; Davies et al. 2017). Challenges in using activated carbon include determining the quantity of activated carbon needed to neutralize the herbicide utilized and understanding the germination responses of various species and functional groups to the inclusion of activated carbon both in combination with herbicide and in the absence of chemical weed management (Svejcar et al. 2022).

To address these knowledge gaps, we conducted two greenhouse experiments to test how seed pellet composition, including variable clay ratios and carbon additions, affects seedling recruitment and to explore the protective effect of activated carbon after Milestone (active ingredient: aminopyralid) herbicide treatment. We tested three main hypotheses: (H1) seed pellets increase seedling emergence relative to broadcast seeding because of increased water and nutrient holding capacity of the clay used in seed pellets; (H2) within seed pellet treatments, seedling recruitment varies depending on seed pellet composition (i.e. clay content and carbon additions) because of impacts on seed pellet physical characteristics, including rate of pellet disintegration and changes in nutrient dynamics; and (H3) under herbicide treatment, carbon addition will increase seedling emergence due to the ability of activated carbon to neutralize herbicide. While further field testing will be needed, the greenhouse setting allows for closer monitoring and proof of concept under a highly controlled environment.

Methods

Experimental Design

Two greenhouse experiments were conducted at the Plant Growth Facility at Colorado State University in Fort Collins, Colorado, United States, in the Spring–Summer of 2023. Both experiments used a mesocosm approach. Each mesocosm consisted of a 13.25-L plastic bin with drainage holes, lined with weed cloth to prevent spillage, and filled with 9 cm of play sand as the growing medium. Mesocosm placement on greenhouse benches was fully randomized.

Experiment 1: Activated Carbon × Herbicide. To test potential protective effects of activated carbon in seed pellets following herbicide treatment, we conducted a fully crossed experiment testing seedling emergence under two seeding methods (broadcast seeding or seed pellets), with and without activated carbon (± carbon), and with and without herbicide (± herbicide) (see Fig. 1). This resulted in eight treatment combinations with four replicates of each, for a total of 32 experimental mesocosms.

Experiment 2: Seed Pellet Composition. Separately, to test the effect of seed pellet composition and activated carbon amendments on seedling emergence, we conducted a partially crossed experiment to test seedling emergence under four seeding methods: broadcast seeding and seed pellets with low, medium, or high clay ratios. The seed pellet treatments were further crossed with three activated carbon treatments—no carbon (where straw was used as the amendment), powdered activated carbon, and granular activated carbon. This resulted in 10 treatment combinations, each replicated four times, for a total of 40 mesocosm units (see Fig. 1).

Seed Mix

All mesocosms were seeded with a seed mix consisting of species native to and commonly used in dryland restoration projects in the Colorado Plateau Ecoregion and both include a mixture of warm- and cool-season species (Laushman et al. 2022). The seed mix varied by experiment. In both experiments, five seeds of each species were used per mesocosm. Seeds were sourced primarily from Southwest Seed Inc. (www.southwestseed.com) with three species from Granite Seed (https://nativeseedgroup.com). Both companies provided germination and purity information. For Experiment 1 (Activated Carbon × Herbicide), the functionally diverse seed mix consisted of 19 species (Table S1): eight forbs, eight grasses, and three shrubs. For experiment 2 (seed pellet composition) (Table S2), we used a 12 species seed mix including four forb species, seven grasses, and one subshrub species.

Seed Pellet Treatments

Seed pellets were created using a custom-made, tabletop seed pellet hand crank (Fig. S1), a modified tabletop version of a "Bicycle-Powdered Seed Pelletizer" (Gornish et al. 2018). Using this method, the resulting seed pellets were heterogeneous and less compacted than if made by hand. The recipes used for seed pellets were modified from the "A Bicycle-Powdered Seed Pelletizer for Use in Gardening and Restoration" guide (Gornish et al. 2018). The hand crank seed pellets ranged from 1 to 4 cm and were roughly spherical or oblong. Seed pellets are generally made from seed, clay, and amendment. In experiment 1 (Activated Carbon × Herbicide), activated carbon was added in addition to the seed, clay, and amendment (straw). In experiment 2 (Composition), activated carbon was used as the amendment, and the amount of amendment was manipulated to change the clay-to-amendment ratio. All recipes are included in Table S3.

Herbicide Treatment

In experiment 1 (Activated Carbon × Herbicide), herbicide treatments were applied to designated mesocosms to assess the impacts of herbicide on both seeding methods (broadcast and seed pellets) which were fully crossed with activated carbon additions. Milestone^{TM}, a Corteva Agriscience product with active ingredient aminopyralid, was selected based on site conditions at a related field experiment where a similar native seed

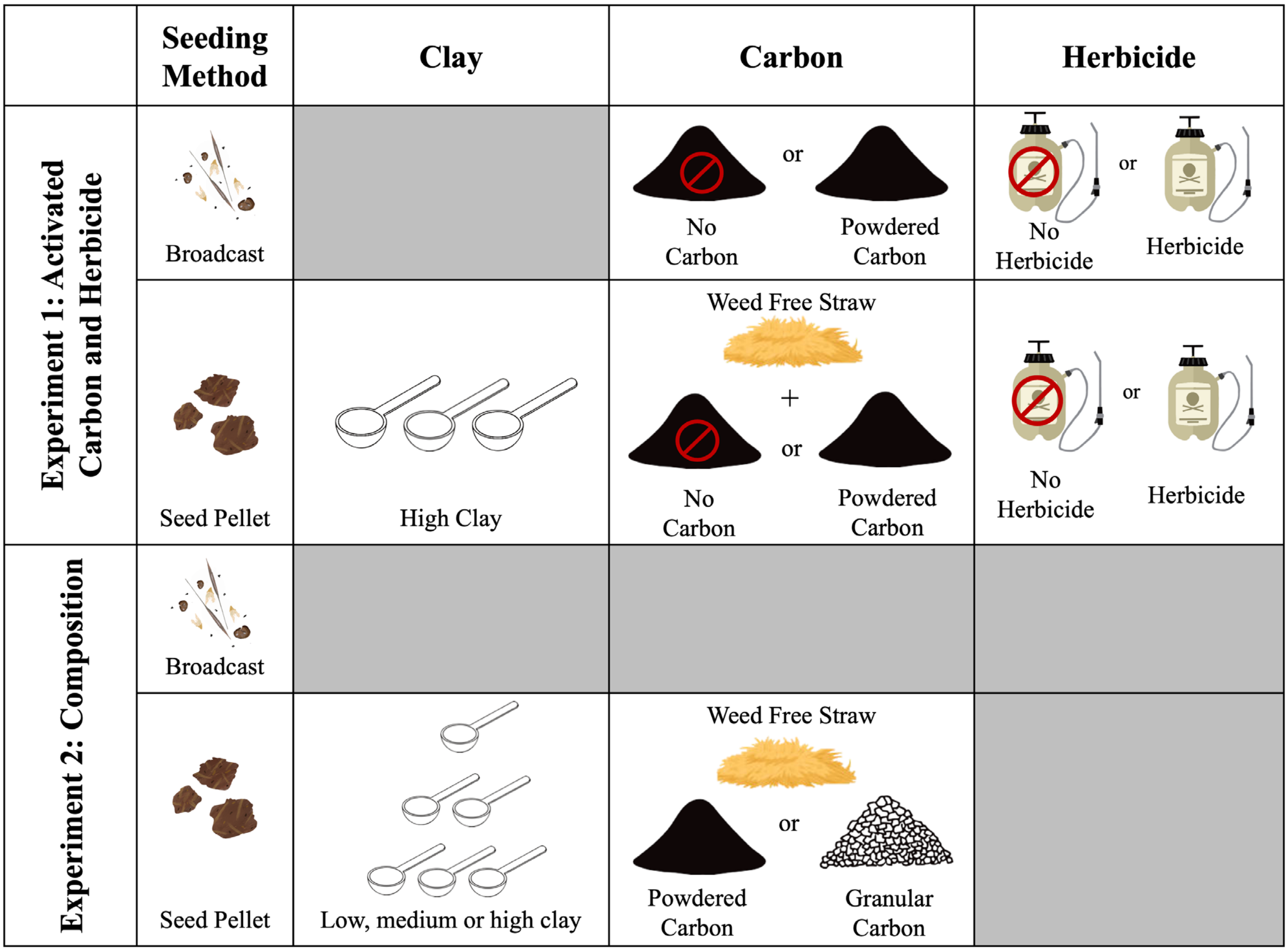

Figure 1. Diagram showing treatment structure for both experiments. In *experiment 1: Activated Carbon and Herbicide*, seeding method (broadcast or seed pellet), activated carbon (no carbon or powdered carbon), and herbicide (no herbicide or herbicide) were fully crossed. In *experiment 2: Composition*, broadcast seeding served as a control, while seed pellets with varying clay content (low, medium, or high) were crossed with activated carbon treatments (none, powdered carbon, or granular carbon).

mix was deployed and Russian knapweed (*Rhaponticum repens*) is the dominant invasive species of concern. Milestone acts as both a pre- and post-emergent broadleaf selective herbicide and is advertised to provide season-long residual control (Corteva Agriscience 2023). Milestone™ herbicide was applied at the recommended rate of 142.2 g active ingredient per hectare (5 fluid ounces per acre) with a non-ionic surfactant at 0.25% of total volume (Corteva Agriscience 2023). Milestone was applied using an HDX multiuse pump sprayer fitted with the standard included cone spray nozzle and calibrated to deliver 25 gal/acre. Calibration accuracy was verified prior to application by collecting spray output over a defined area in three replicate trials and adjusting walking speed (using a metronome) to maintain the target delivery rate (Ozkan 2018). Groups of five mesocosms were sprayed at a time, and the sprayer was repressurized between groups. Herbicide was applied to designated mesocosms 25 days prior to seeding. The average soil half-life for Milestone is 103 days, so this lag time allowed its concentration to decrease to approximately 85% of the initial application strength (WSDOT 2017). Herbicide treatment was not a component of the composition study (experiment 2).

Activated Carbon Treatments

Activated carbon treatments were included in both experiments. In experiment 1 (Activated Carbon × Herbicide), powdered Nuchar SA-20 (Nuchar AG, MWV, Richmond, VA, U.S.A.) activated carbon was included in the designated treatments at a rate of 10 times the average seed weight, selected based on previous work (e.g. Madsen et al. 2014; Davies et al. 2017; Clenet et al. 2019; Brown et al. 2021; Munro et al. 2023). Powdered activated carbon was either broadcast onto the substrate or incorporated as an additional ingredient to the base pellet recipe, including seed, clay, and amendment (weed-free straw) depending on seeding method treatment. The activated carbon is a very fine material, and when broadcast onto the soil surface, much of it aerosolized during the initial watering, so how much remained in the substrate is uncertain.

For experiment 2 (Composition), activated carbon was included as the amendment component in the seed pellets assigned to carbon treatments, using either powdered (Nuchar SA-20, Nuchar AG, MWV, Richmond, VA, U.S.A.) or granular (granular food-grade activated carbon, Lab Alley, Austin, TX, U.S.A.) forms to explore how carbon treatments affected recruitment outcomes.

Watering Protocol

Since precipitation and freeze–thaw cycles are likely main drivers of seed pellet disintegration under field conditions, our watering protocols mimicked rainfall (Davies et al. 2024). Our mesocosms did not experience freeze–thaw conditions, so pellet breakdown does not fully reflect common conditions experienced in the field. We used a custom-made watering device, which consisted of a sprinkler mounted on a frame with a flow regulator to maintain a consistent water application rate (Fig. S2). The watering device calibration was checked biweekly to ensure consistency. For experiment 1 (Activated Carbon × Herbicide), each mesocosm received 6 mm of water every 2 days for an average of 20 mm per week to ensure the bins dried out between watering events, although the level of drying varied based on ambient greenhouse conditions. In experiment 2 (Composition), we used a larger, less frequent precipitation pulse approach, mimicking monsoonal patterns present in some drylands. Each mesocosm received 50 mm of water every 4 days.

Data Collection

For both experiments, we monitored plant emergence for all plant species, which were then analyzed by functional group (i.e. grasses and forbs/shrubs). In experiment 1 (Activated Carbon × Herbicide), we monitored every 2 days for a total of 30 sampling events. We began monitoring after the first seedling emergence. In experiment 2 (Composition), we monitored twice weekly for a total of 11 sampling events. Monitoring began 2 days after seeding with the first seedling emergence.

Statistical Analyses

All data analyses were conducted in R, version 4.3.0 (R Core Team 2023). Since the response variables in both experiments are a proportion of emerged seedlings, a beta regression approach was used (Geissinger et al. 2022). Beta regression was chosen because it appropriately models proportional data bounded between 0 and 1 and accounts for non-normal residual structures common in such data (Geissinger et al. 2022). To test our hypotheses, we used the glmmTMB package (Brooks et al. 2017) to fit mixed-effects beta regression models with a logit link function. Seedling emergence (as a proportion) was the response variable in all models. To account for repeated measures and spatial variability, we included unique identifiers for each mesocosm and greenhouse bench location as random effects in all models. For all models, we conducted post hoc pairwise comparisons using the emmeans package (Lenth 2024), applying a false discovery rate (FDR) adjustment to control for multiple comparisons. An alpha level of 0.05 was used throughout as the significance cutoff to balance the risk of type I error with statistical sensitivity.

To evaluate the effects of herbicide treatment, seeding method, activated carbon addition, and functional group on seedling emergence in experiment 1 (Activated Carbon × Herbicide), we utilized a single mixed-effect beta regression model with all treatment factors and their interactions. Herbicide treatment (presence/absence), seeding method (broadcast/seed pellet), activated carbon addition (presence/absence), and functional group (grass vs. forb/shrub) were included as fixed effects. The model included the same random effects structure to account for repeat measures and spatial variability, as well as the same post hoc testing approach described above.

To compare seedling emergence proportion by seeding method in the composition experiment, we used seeding method (broadcast vs. seed pellets, averaged over all levels of clay-to-amendment ratios) as a fixed effect. The model included the same random effects structure to account for repeat measures and spatial variability, as well as the same post hoc testing approach described above. To test the effects of clay-to-amendment ratios and carbon additions on seedling emergence in seed pellet treatments, we used a mixed-effects beta regression model. Fixed effects included seeding method (seed pellets with low, medium, and high clay-to-amendment ratios) and carbon type (no carbon, powdered carbon, or granular carbon). The same random effects structure and post hoc testing methods were applied.

Results

Experiment 1: Activated Carbon × Herbicide

Impact of Herbicide on Seedling Emergence by Functional Group. Herbicide treatment (Milestone) significantly reduced the odds of emergence by 57% across all functional groups compared to mesocosms not treated with herbicide ($p < 0.0001$, Table 1; Fig. 2). Herbicide treatment likely had a stronger suppressive effect on forb and shrub emergence due to its broadleaf selectivity; forbs and shrubs had 33% lower odds of emergence than grasses under herbicide treatment ($p = 0.016$; Table 1; Fig. 2; Table S4).

Impact of Seeding Method on Seedling Emergence. Seed pellet treatments resulted in 136% higher odds of seedling emergence compared to broadcast seeding holding herbicide treatment constant ($p = 0.0003$; Table 1; Fig. 3), supporting our first hypothesis that seed pellets would result in greater recruitment than broadcast seeding. There was no significant difference in emergence between seed pellet and broadcast seeding under herbicide treatment (Table S5; Fig. 3).

Table 1. Results of a mixed-effects beta regression model evaluating the effects of seeding method (broadcast vs. seed pellet), herbicide treatment (presence/absence), activated carbon additions (presence absence), and functional group (grass vs. forb/shrub) and their interactions on seedling emergence proportion. The model includes random effects to account for repeat measures and spatial variability in greenhouse bench location. Estimates are on the odds scale.

	Response variable: emergence proportion			
Predictor	*Estimate (β)*	*Standard error*	*z Value*	*Pr(>|z|)*
Intercept	0.120	0.016	−15.55	<0.0001
Herbicide	0.428	0.083	−4.35	<0.0001
Seed pellet	2.363	0.438	4.65	<0.0001
Carbon	1.273	0.240	1.28	0.2000
Functional group—forb/shrub	0.674	0.073	−3.66	0.0003
Herbicide:seed pellet	0.200	0.055	−5.85	<0.0001
Herbicide:carbon	0.470	0.131	−2.72	0.0066
Seed pellet:carbon	0.659	0.172	−1.60	0.1099
Herbicide:functional group—forb/shrub	0.669	0.112	−2.40	0.0164
Seed pellet:functional group—forb/shrub	0.678	0.096	−2.73	0.0063
Carbon:functional group—forb/shrub	0.863	0.131	−0.97	0.3335
Herbicide:seed pellet:carbon	11.113	4.304	6.22	<0.0001
Herbicide:seed pellet:functional group—forb/shrub	2.552	0.595	4.02	<0.0001
Herbicide:carbon:functional group—forb/shrub	1.470	0.357	1.59	0.1126
Seed pellet:carbon:functional group—forb/shrub	0.986	0.201	−0.07	0.9436
Herbicide:seed pellet:carbon:functional group—forb/shrub	0.270	0.089	−3.96	<0.0001

Effects of Herbicide, Carbon, Seed Pellets, and Their Interactions on Seedling Emergence. We found significant interactive effects of seeding method, herbicide treatment, and carbon addition, indicating that the treatment factors do not interact in predictable ways but outcomes depend on the treatment components interacting in complex ways. There was a significant interaction among herbicide, seeding method, and carbon addition, showing a strong positive effect of seed pellets containing activated carbon on seedling emergence under herbicide treatment ($p < 0.0001$; Table S6; Fig. 4). This result supports our third hypothesis that the inclusion of activated carbon in seed pellets would increase emergence because of the ability of activated carbon to neutralize herbicide residues.

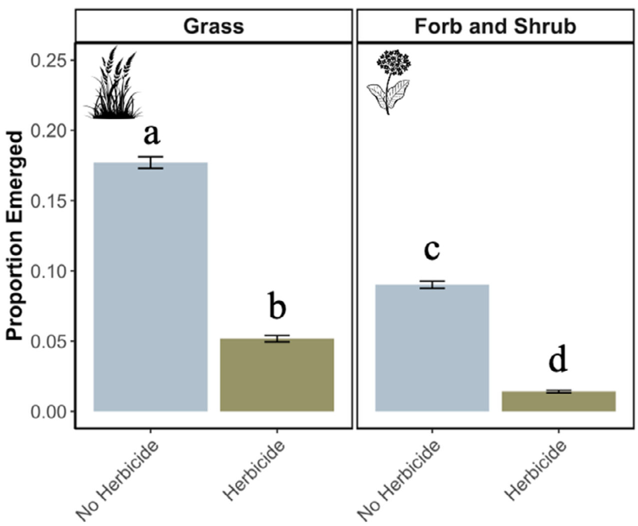

Figure 2. Mean proportion (± SE) of seedlings emerged by functional group (grass vs. forb/shrub) both with and without herbicide treatment averaged across seeding method and carbon addition. Herbicide application significantly reduced emergence across both functional groups ($p < 0.0001$).

Experiment 2: Composition

Seed Pellet Effects on Emergence. Overall, seed pellets increased emergence relative to broadcast seeding. Seedling

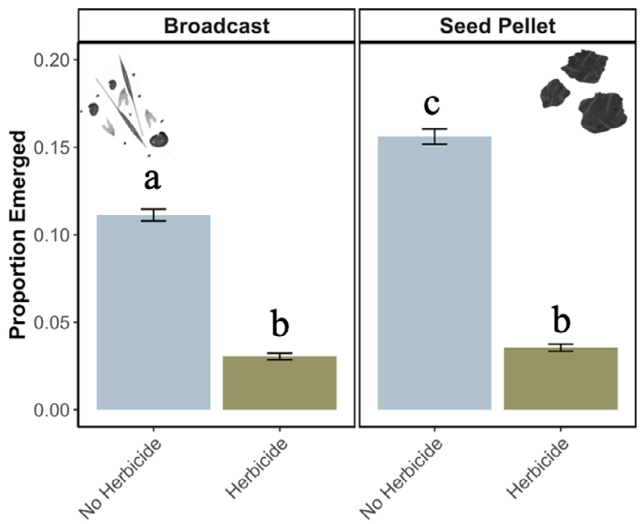

Figure 3. Mean proportion (± SE) of seedlings emerged by seeding method (broadcast vs. seed pellet) with and without herbicide treatment averaged across carbon addition and functional group. Herbicide application significantly reduced emergence across both seeding methods ($p < 0.0001$). Seed pellets had significantly higher emergence than broadcast seeding in the absence of herbicide treatment ($p = 0.0003$), but there was no significant difference in emergence between seed pellets and broadcast seeding under herbicide treatment.

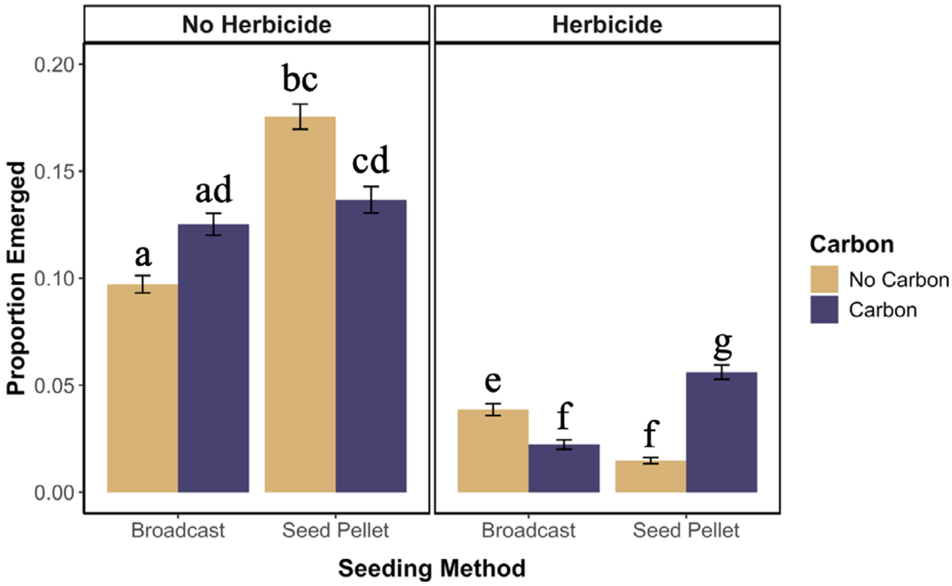

Figure 4. Mean proportion (± SE) of seedlings emerged by herbicide treatment (presence/absence), compared by seeding method (broadcast vs. seed pellet) and carbon addition (presence/absence). Herbicide application significantly reduced emergence across both seeding methods ($p < 0.001$). Lowercase letters indicate significant differences ($p < 0.05$) using a mixed-effects beta regression model.

emergence in the seed pellet treatment had 56% higher odds compared to the broadcast treatments ($p = 0.072$; Table 2; Fig. 5; Table S7), providing additional marginal evidence that seed pellets increase seedling emergence, further confirming hypothesis one.

Interactive Impacts of Clay: Amendment Ratio and Activated Carbon Amendments on Seedling Emergence. There was no effect of percent clay on seedling emergence from seed pellets (all $p > 0.05$; Table 3; Fig. 6; Table S8). However, seedling emergence did vary with carbon addition treatments, with the addition of powdered carbon resulting in approximately twice the odds of seedling emergence compared to those without powdered carbon, holding all other factors constant ($p = 0.015$; Table 3; Fig. 6). There was also a weak interaction between seed pellet clay content and carbon addition type: powdered carbon as an amendment and medium clay-to-amendment ratio seed pellets ($p = 0.083$; Table 3; Fig. 6), indicating the effect of powdered carbon on emergence may depend on the clay-to-amendment ratio in seed pellets. These results provide limited support of our second hypothesis that emergence would vary based on composition and amendments; however, we did not observe the stronger effects we hypothesized.

Table 2. Results of a mixed-effects beta regression model evaluating the effect of seeding method (broadcast vs. seed pellet, averaged across all clay-to-amendment ratios) on seeding emergence proportion. The model includes random effects to account for repeat measures and spatial variability in greenhouse bench location. Seed pellet treatment shows a marginally significant increase in seedling emergence proportion compared to broadcast seeding ($p = 0.072$). Estimates are on the odds scale.

	Response variable: emergence proportion			
Predictor	*Estimate* (β)	*Standard error*	z *Value*	*Pr*(>|z|)
Intercept (broadcast)	0.13	0.032	−8.25	< 0.001
Seed pellets	1.55	0.39	1.80	0.072

Discussion

Seed-based restoration (SBR) in drylands faces many major biotic and abiotic barriers to success and often results in low establishment of desirable seeded species (Havrilla et al. 2020;

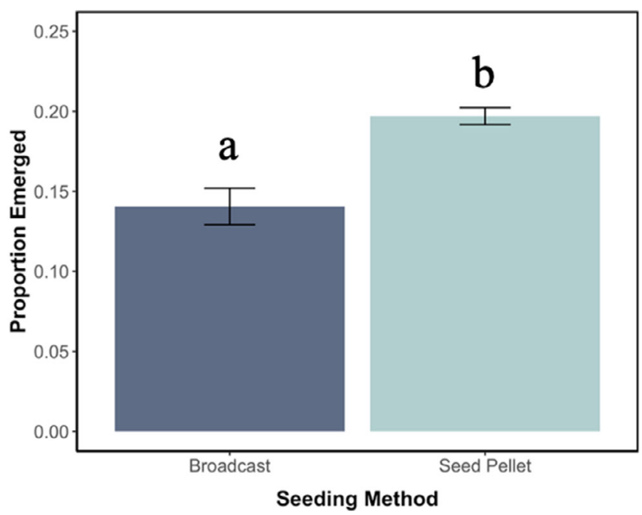

Figure 5. Mean proportion (± SE) of seedlings emerged by seeding method (broadcast vs. seed pellet, averaged across all clay-to-amendment ratios). Seedling emergence was marginally significantly higher in seed pellet treatments compared to broadcast seeding ($p = 0.072$).

Table 3. Results of a mixed-effects beta regression model evaluating the effects of clay-to-amendment ratios within seed pellets, activated carbon amendments, and their interaction on seedling emergence proportion. The model includes random effects to account for repeat measures and spatial variability in greenhouse bench location. Powdered carbon, when used as the amendment in the seed pellets, significantly increased seedling emergence ($p = 0.0145$). A marginally significant interaction was observed between seed pellets with a medium clay-to-amendment ratio and powdered carbon ($p = 0.0833$). Estimates are on the odds scale.

	Response variable: emergence proportion			
Predictor	*Estimate (β)*	*Standard error*	*z Value*	*Pr(>|z|)*
Intercept	0.138	0.03	−9.15	<0.0001
Seed pellet—medium clay	1.312	0.38	0.94	0.3494
Seed pellet—high clay	1.341	0.39	1.02	0.3090
Carbon—powder	2.018	0.58	2.45	0.0145
Carbon—granular	1.018	0.30	0.06	0.9523
Seed pellet—medium clay:carbon—powder	0.500	0.20	−1.73	0.0833
Seed pellet—high clay:carbon—powder	0.663	0.26	−1.03	0.3016
Seed pellet—medium clay:carbon—granular	1.793	0.72	1.46	0.1449
Seed pellet—high clay:carbon—granular	1.425	0.56	0.90	0.3708

Shackelford et al. 2021). To improve SBR outcomes in drylands, restoration techniques that can be precisely deployed to address ecological barriers to establishment that vary across space and time, both within and across sites, are needed (Copeland et al. 2021). Seed pellets are a seed enhancement technology that targets several barriers to establishment, including protecting seeds from desiccation, granivory, and, with activated carbon additions, damage from herbicide used to control invasive species (Gornish et al. 2019; Davies et al. 2024).

Our findings suggest that seed pellets, and specifically, seed pellets with activated carbon following herbicide treatment, have the potential to improve native seedling emergence by neutralizing herbicide residues, a significant bottleneck in dryland restoration supporting our first and third hypotheses (James et al. 2011; Larson et al. 2015; Shackelford et al. 2021). Seed pellets produced using mechanical synthesis methods (e.g. seed pellet bike or a tabletop hand crank version) (Gornish et al. 2018) are a relatively low-tech seed enhancement technology that can improve emergence in dryland ecosystems by increasing water-holding capacity, decreasing evaporative losses, lowering temperatures, and providing thermal stability to seeds (Gornish et al. 2019). Our findings contribute to understanding best practices for seed pellet synthesis.

Supporting some previous work, we found that seed pellets increased seedling establishment compared to broadcast seeding methods in both our composition and activated carbon and herbicide studies (Gornish et al. 2019; Berto et al. 2024; Teichroew & Rew 2024). While seed pellets are often shown to increase seedling emergence, there are examples of cases where seed pellets have negative effects, inhibiting the

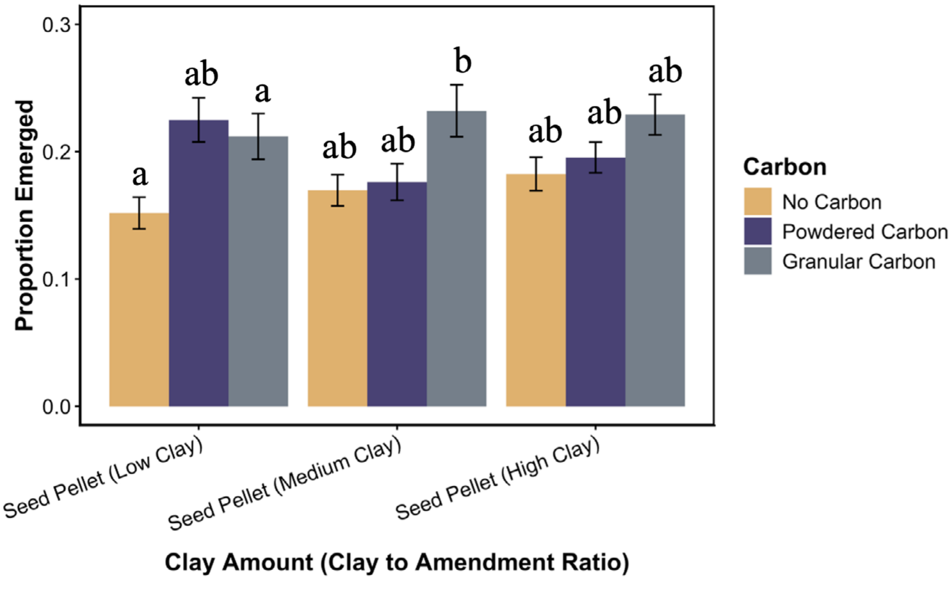

Figure 6. Mean proportion (± SE) of seedlings emerged from seed pellets with variable clay-to-amendment ratios colored by carbon amendments (no carbon, powdered carbon, granular carbon). Lowercase letters indicate significant differences ($p < 0.05$) from a beta regression mixed-effects model with seeding method (including clay-to-amendment ratio) and carbon amendment and their interaction as fixed effects.

emergence and establishment of all or some species tested (Gornish et al. 2019; Baughman et al. 2021; Brown et al. 2023). These declines in emergence from seed pellets may be partially attributable to differences in pellet size (Baughman et al. 2021), seed position within the pellet (Brown et al. 2023), and variable seed pellet recipes including amendment additions including activated carbon (Davies et al. 2024). Similarly to Teichroew and Rew (2024), we found minimal differences in emergence across clay-to-amendment ratios. This is contrary to our second hypothesis but may be due to the relatively high watering rates used in our study. Under more limited water conditions, composition and related seed pellet breakdown may have a larger impact on seedling emergence since breakdown with insufficient moisture may result in seed predation and movement off the restoration site, while seed pellets that fail to disintegrate under high moisture conditions may affect emergence. In the composition study (experiment 2), where herbicide was not used, we found limited impacts of activated carbon additions. Given the expense of activated carbon (Madsen et al. 2016; Davies et al. 2024), we recommend only incorporating activated carbon into seed pellets when deployed in tandem with herbicide.

Activated carbon additions to seed pellets deployed shortly after herbicide treatment increased seedling emergence, suggesting this treatment provided some protection to the encased seeds supporting our third hypothesis. Our synthesis method uses readily available materials to build a simple "Bicycle-Powered Seed Pelletizer" (Gornish et al. 2018), and easy to source base ingredients for seed pellets (seed, clay, and weed-free straw). Previous work using activated carbon to protect from herbicide residues has been in either extruded pellets or as a seed coating, both of which require specialized equipment and ingredients (e.g. Davies et al. 2017; Clenet et al. 2019; Munro et al. 2023). Much of the existing literature is focused on herbicides used to control invasive annual species (Davies et al. 2024), while this work uses a broadleaf selective herbicide, with a long soil half-life, indicating wider applications for using activated carbon to neutralize herbicides and protect seeds (Madsen et al. 2014; Munro et al. 2023; Svejcar et al. 2024b). This research supports the use of seed pellets as a potential restoration approach in drylands, and the use of activated carbon to protect seeds from recently applied herbicide residues. Using this technology for a single restoration intervention rather than a phased approach is a key benefit of seed pellets containing activated carbon (Sheley et al. 2001, 2012; Davies et al. 2014).

Seed pellets containing activated carbon show promise as a dryland restoration strategy, as they can protect seeds following herbicide application and increase seedling recruitment. While pelletizing seeds adds additional effort and inputs compared to broadcast seeding, the resulting potential for small increases in establishment can have large impacts, particularly in areas where more traditional revegetation attempts have failed (Davies et al. 2024). Simultaneous control of invasive species and seeding allows for single-entry restoration that requires fewer resources than a multi-entry approach (Sheley et al. 2001, 2012; Davies et al. 2014). Our approach using a "Bicycle-Powered Seed Pelletizer" offers a low-tech approach to making seed pellets containing activated carbon and requires less specialized equipment than approaches that utilize an extruder, making it more accessible than previous pelletizing and seed coating methods. In addition to using seed pellets with activated carbon, our findings provide support of the continued use of seed pellets in dryland restoration to improve the emergence of desirable seeds compared to broadcast seeding methods. We did not find significant differences in emergence when testing different seed pellet compositions, which did not support our second hypothesis that emergence would vary based on composition. We did find limited evidence of differences in emergence with carbon amendments in the absence of herbicide; however, these effects were not as strong as we expected. The ideal seed pellet recipe likely varies based on specific local abiotic conditions (e.g. water availability, seasonal precipitation patterns, and freeze–thaw cycles) and if chemical weed management is required, so we recommend local testing prior to widespread implementation (Davies et al. 2024).

Limitations and Future Directions

Further research is needed to verify these effects in the field under variable conditions; however, this greenhouse study provides a proof of concept for using bicycle-made seed pellets as a relatively low-tech approach to improve SBR in dryland systems after herbicide application. We concur with Davies et al. (2024) that future studies should explore these effects under field conditions and across a range of precipitation conditions. Low-water conditions are especially critical to study since water is the key limiting resource in drylands and precipitation impacts seed pellet breakdown, which is likely influenced by clay quantity. As herbicide residues bind to soil particles, the strength and length of effective control vary by soil type (Stevenson 1972; Smernik & Kookana 2015), further investigation into how well and for how long activated carbon protects seeds in seed pellets across soil types is also needed. While activated carbon has been shown to be effective at neutralizing at least five herbicides (Davies et al. 2024) and, in this study, a sixth broadleaf selective pre-emergent, this protective effect will need to be tested for additional herbicides using other methods of action. We also do not expect that all species or functional groups will respond similarly to being encased in a seed pellet due to differences in seed traits and emergence requirements, as has been shown in other research (Baughman et al. 2021; Brown et al. 2023; Lieurance et al. 2024). However, we did not have a large enough sample to be able to test the effects for individual species or functional groups in this study. Future research could further investigate species-level or trait responses to seed pellets and clay and activated carbon additions to seed pellets, building on existing research (e.g. Baughman et al. 2021; Brown et al. 2023; Lieurance et al. 2024), to help optimize restoration seed mixes and pellet synthesis. While much of the research on seed pelletizing, including herbicide protection using activated carbon, has been focused on dryland systems (Gornish et al. 2019; Davies et al. 2024), the need for innovative seeding approaches to improve SBR outcomes extends far beyond drylands. Single-entry restoration approaches that allow for herbicide treatment and simultaneous reseeding efforts could be applicable in any system experiencing invasion and requiring revegetation. Further, pelletizing could be considered in any system where SBR approaches, including broadcast and drill seeding, have been unsuccessful in ameliorating specific abiotic and biotic barriers to emergence. Appropriate amendment inclusions in seed pellets will depend on site-specific concerns. These technologies could be applicable in grasslands, postindustrial sites, and other areas, so further research is needed to optimize seed pellet synthesis in other degraded systems.

Acknowledgments

We thank Rose Julian and Jason Wong for assisting with data collection and all members of the Dryland Ecology and Management Lab at Colorado State University for their assistance and support. Constructive comments by Dr. El-Keblawy and anonymous reviewers were greatly appreciated. The data that support the findings of this study are openly available in DRYAD at https://datadryad.org/, reference number 10.5061/dryad.p5hqbzm25.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Tabletop seed pellet hand crank diagram.
Figure S2. Custom watering device diagram with a sprinkler mounted upside down on a PVC frame that fits over each mesocosm.
Table S1. Seed mix used in the Activated Carbon × Herbicide study.
Table S2. Seed mix used in the Composition study.
Table S3. Recipes used in Activated Carbon × Herbicide and Composition studies.
Table S4. Pairwise contrasts of emergence by herbicide treatment and plant functional group.
Table S5. Pairwise contrasts of emergence by herbicide treatment and seeding method.
Table S6. Pairwise contrasts of emergence by seeding method, herbicide treatment, and carbon additions.
Table S7. Pairwise contrast of emergence by seeding method.
Table S8. Pairwise contrasts of emergence by clay-to-amendment ratio and activated carbon additions in seed pellets.

Coordinating Editor: Ali El-Keblawy

Received: 4 August, 2025; Revised: 3 December, 2025; Accepted: 26 December, 2025