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PRACTICE AND TECHNICAL ARTICLE

Testing the effects of seed pellet composition to aid in semiarid restoration seeding

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Restoring and revegetating semiarid regions with native perennial grasses is an extremely difficult task, often unsuccessful due to harsh abiotic conditions. We conducted studies evaluating the use of seed pellets to improve restoration seeding success in controlled and field environments. In a controlled setting, we evaluated the impacts of clay volume, pellet size, and watering rate on seedling establishment and pellet disintegration. The amount of clay, size of pellets, and watering rate were varied in a full factorial design. Seedlings emerged from 40% of the pellets. Clay content did not impact seedling emergence, but larger pellets (2.5 cm) were more likely to produce seedlings. However, when smaller pellets (1.5 cm) produced seedlings, a higher proportion emerged (15 vs. 9%). In the field, we compared seedling establishment monthly, overall summer recruitment, and disintegration of seed pellets made with 10% and 55% clay to broadcast seed and a non-seeded control using a randomized design. Seedling emergence was higher for both the 10% (1.4 seedlings) and 55% clay pellets (1.0 seedling) than the control treatments (0.5 seedlings), and also higher for the 10% clay pellets than broadcast treatments (0.8 seedlings). Additionally, we found that seedling establishment and recruitment were unaffected by pellet disintegration. End-of-season recruitment was higher in 10% clay pellets (2.6 seedlings) than in 55% clay pellets (1.2 seedlings) and control treatments (1.0 seedling). We also found that 2.5 cm pellets had slightly higher recruitment, indicating that larger pellets may be more suited to seedling survival in semiarid environments.

Key words: native perennial grasses, rangeland, restoration seeding, revegetation, seed balls, seedling recruitment

Implications for Practice

- Pellets 2.5 cm in diameter were more likely to produce seedlings, both in controlled and field environments, suggesting they may be a better option for restoration projects.
- Seedling establishment was higher in pellets containing 10% clay than the non-seeded control and broadcast treatments. While this difference was small, it suggests seed pellets have the potential to improve upon broadcast restoration efforts.
- Pellet disintegration did not impact seedling establishment or recruitment, but the timing of disintegration may still have implications for seed predation.

Introduction

Rangelands across the world have been degraded and overused, leading to unstable ecosystems in need of restoration (Harris 1991; Young & Allen 1997; Reynolds et al. 2007). Drill seeding native species to revegetate rangelands offers relatively high success rates but is not applicable on steep or rocky terrain (Roundy & Call 1988), and the associated disturbance may negatively impact restoration goals (Davies et al. 2024). When drill seeding is not feasible, the most accessible revegetation method is broadcasting seed. However, attempts to restore semiarid regions with broadcast native species are often unsuccessful due to low precipitation and seed predation (Gornish et al. 2019; Havrilla et al. 2020). A review by Shackelford et al. (2021) reported that 17% of dryland restoration projects worldwide saw no establishment of seeded species within the monitoring period. These widespread barriers have stimulated investment into developing seed enhancement technologies to improve seedling establishment in semiarid and arid regions (Berto et al. 2024).

One type of seed enhancement technology aiming to increase the establishment and recruitment of seeded species is to agglomerate seeds into a protective pellet. In the 1940s, several organizations in the southwestern United States developed agglomerations containing seed, organic material, and a binding

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agent (Gatherum 1951). They were known as seed pellets (or seed balls) and were intended to mitigate the major issues with semiarid restoration: low precipitation and seed predation (Gatherum 1951). However, reduced germination due to mechanical damage that occurred during production limited the success of these pellets, and they were not widely adopted (Stevenson 1949; Wagner 1949; Gatherum 1951). A resurgence of the topic occurred in the mid-2010s (Lucas 2011; Madsen et al. 2016; Gornish et al. 2019). New production methods (hand rolling and rotary seed coaters) aimed to reduce mechanical injury to seeds, while new formulations aim to encourage disintegration when adequate precipitation has fallen to promote germination while still protecting the seeds from predation for as long as possible. A review by Berto et al. (2024) highlighted the positive impacts seed pellets can have on seedling growth, along with the increased interest in advancing these technologies. They also highlight a need for connecting laboratory, glasshouse, and field experiments (Berto et al. 2024).

Our study aimed to add to the growing literature around seed pelleting technologies by comparing pellet composition and size in both controlled and field environments. First, we assessed different volumes of clay, pellet sizes, and watering rates to see how these factors impacted pellet efficacy in a controlled environment. Our objectives were to determine if (1) the ratio of clay: organic material: seed, (2) pellet size, or (3) watering rate affected seedling establishment and pellet disintegration in a controlled setting. We also evaluated seedling establishment, seedling recruitment, and pellet disintegration for two different volumes of clay, broadcast seeding, and a non-seeded control in a field study.

Methods

Controlled Environment

Seed pellets were constructed with clay, organic material (cow manure), soil, and seed following the recommendations of Gornish (2019). The volume of clay, size of pellets, and watering rate were varied in a full factorial design (4 clay levels × 3 pellet sizes × 4 watering rates). We wanted to test the impact of clay without lowering the total amount of material in a pellet, as that would increase the density of seed/pellet. Therefore, we replaced the removed clay with soil in three of our pellet compositions. Pellets were made with the following ratios of clay:manure:soil:seed (1) 5:3:0:1 (55% clay) (Gornish 2019), (2) 5:3:5:1 (35% clay), (3) 3:3:7:1 (20% clay), or (4) 1.5:3:9.5:1 (10% clay). Pellets were 1.5, 2, or 2.5 cm in diameter. Daily watering rates were calculated from mean winter and spring storm rates in southwestern Montana (0, 25, 75, and 125 mL) (Spark 2022).

Pellets were made with dry blush stoneware clay (Archie Bray, Helena, MT, U.S.A.) (lat. 46°36′49″N, long. 112°04′58″W), cow manure (Montana State University Horticultural Farm, Bozeman, MT, U.S.A.) (lat. 45°39′42″N, long. 111°04′24″W), soil (1:1:1 mineral loam: peat moss: sand mixture) (PGC Primer 2023), and a perennial grass seed mix (with seed <1 year old purchased from Nature's Seed, Lehi, UT, U.S.A.) (lat. 40°24′34″N, long. 111°52′39″W). The seed mix contained the Natural Resources Conservation Service recommended ratios of Idaho fescue (*Festuca idahoensis* Elmer), Western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), and Bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve) (20.2 kg/ha) (Pokorny 2020). Materials were combined and formed into spheres by hand, using water as a tackifier, then dried at 44°C for several days.

Pellets were placed on top of soil (50:50 loam soil and sphagnum peat moss) (PGC Primer 2023) in square pots (10 cm width; one pellet/pot) in the Montana State University greenhouses (Bozeman, MT, U.S.A.) (lat. 45°40′05″N, long. 111°03′12″W). The greenhouse was set to 23/6°C with 14 hours of light. Two trials with six replicates were run for each clay volume, size, and watering rate ($n = 288$/trial). The prescribed amount of water was poured directly over each pellet every 3 days. Pellets were identified as disintegrating if they broke into smaller pieces. After 21 days, the total number of emerged seedlings was counted.

A subset of dried pellets were disintegrated to count the number of seeds present in each pellet type ($n = 10$ per clay: size combination) (Table 1). The total number of seedlings that emerged from each pellet was relativized by starting seed number and expected germination rate (of newly purchased seed provided by seller) to calculate the proportion of seeds that emerged. These proportions were used in our analyses.

Field Study

A randomized trial of seed pellets with two clay volumes was established at the Red Bluff Research Ranch (lat. 43°36′03″N, long. 111°37′20″W) and the Highland Ranch (lat. 45°40′55″N, long. 110°21′48″W) in southwestern Montana, United States. Five replications of four treatments (non-seeded control, broadcast seed, 1.5:3:9.5:1 [10% clay] pellets, and 5:3:0:1 [55% clay] pellets) were randomly located in 0.5 m^2 plots within an area of 60 × 20 m with low levels of Cheatgrass (*Bromus tectorum* L.) (canopy cover <15%). Seed pellets were constructed as above and were placed in each plot to reach the Natural Resources

Table 1. Mean number of seeds expected to germinate and emerged seedlings per pellet by clay content and pellet size, conducted in a controlled environment.

	55% clay		*35% clay*		*20% clay*		*10% clay*	
Diameter (cm)	*Mean seeds*	*Mean seedlings*	*Mean seeds*	*Mean seedlings*	*Mean seeds*	*Mean seedlings*	*Mean seeds*	*Mean seedlings*
1.5	17	0.4	10	0.2	15	0.6	12	0.6
2	45	1.2	26	0.6	32	1.3	26	1.2
2.5	64	2.0	35	0.9	30	1.4	37	1.8

Conservation Service recommended broadcast seeding rate (Pokorny 2020). This resulted in 10 pellets/plot for the 10% clay pellets (four 2.5 cm, three 2 and 1.5 cm) and 6 pellets/plot for the 55% clay pellets (two of each size). Each pellet location was marked with colored toothpicks to aid in relocation. Pellets were placed in the field on 2 May 2024 and were monitored once a month from May through August for plot-level seedling establishment and pellet intactness. Percent cover of bare ground, litter, *B. tectorum*, perennial grasses, and forbs were also recorded. Final seedling recruitment (seedling survival) was recorded as the number of seedlings counted in August. We recorded seedling recruitment for individual pellets in addition to total plot recruitment. Total monthly precipitation from May–August was estimated from nearby Local Climatological Data stations (NOAA 2024) (Red Bluff: lat. 45°47′15″N, long. 111°09′47″W) (Highland: lat. 45°41′54″N, long. 110°26′54″W).

Data Analysis

For the controlled environment study, we examined the effects of clay content, pellet size, and watering rate on proportional seedling establishment. Variation in trial and repetition were accounted for as random intercept adjustments. To assess the effects of clay content, pellet size, and watering rate on seedling emergence, a zero-altered negative binomial model with a logit link was used from the pscl package (Zeileis et al. 2008). To examine the effects of clay content, pellet size, and watering rate on the odds a pellet would disintegrate, we used a generalized linear mixed effects model with a Bernoulli distribution and analysis of variance (ANOVA). Due to the high predictability of the model with respect to clay (55% clay pellets always failed to disintegrate), they were removed from the analysis. To reflect a natural system, water was treated as a continuous variable in all models.

For the field study, the effects of seeding treatment, month of observation, and site on seedling establishment were examined with a generalized linear mixed effects model with a Poisson distribution and ANOVA. Spatial variation and repeated measures were accounted for as random intercept adjustments. To assess the effect of pellet disintegration on seedling establishment, this same model was run excluding non-seeded control and broadcast treatments and including the proportion of pellets that disintegrated as a fixed effect. Seedling recruitment at the end of the summer was evaluated by seeding treatment, pellet size, cover of *B. tectorum*, native grasses, forbs, bare ground, and litter using the same analysis. Finally, to examine the effects of clay volume, pellet size, month of observation, and site on the proportion of pellets that disintegrated, we used a linear mixed effects model and ANOVA.

All models were assessed for normality and equal variance assumptions, and no transformations were necessary. All three-way and two-way interactions were assessed and retained if significant. Non-significant factors were removed through stepwise model selection to obtain the most parsimonious final models. Estimated means and pairwise comparisons were completed using the emmeans package (Lenth 2024). All data analysis was performed in R Studio (R Core Team 2024).

Results

Seedling Establishment in Controlled Environment

Within the 3-week study period, 40% of pellets produced seedlings. Pellet size and watering rate did impact the odds a pellet produced seedlings (Fig. 1; Table S1). Pellets 2.5 cm in diameter were more than twice as likely to produce seedlings than pellets 1.5 cm in diameter ($z = 2.53$; $p = 0.011$; Table S1; Fig. 1). The odds of producing seedlings increased drastically over the watering gradient ($z = 12.66$; $p < 0.001$; Table S1).

When pellets did produce seedlings, clay content had no impact on the mean proportion of seedlings produced, but pellet size did have an impact (Table S2). Pellets 1.5 cm in diameter produced an average of 15% of potential seedlings, while 2 or 2.5 cm pellets produced an average of 9% of potential seedlings (Fig. 2). Additionally, the proportion of seedlings produced increased by fourfold over the watering gradient ($z = 7.13$; $p < 0.001$; Table S2; Fig. 2).

When odds of producing seedlings and mean proportion of seedlings produced were considered together, there were no differences between clay content nor pellet size (Table S3).

Pellet disintegration was low across all treatments; only 6% of the pellets disintegrated, and none of the 55% clay pellets disintegrated. Clay content ($\chi^2_2 = 31.80$; $p < 0.001$), size ($\chi^2_2 = 14.21$; $p < 0.001$), and watering rate ($\chi^2_1 = 52.51$; $p < 0.001$) all impacted the odds of disintegration (Table S3). The 10% clay pellets were 0.09 times more likely to disintegrate than either the 20% clay ($t = -3.86$; $p < 0.001$) or 35% clay pellets ($t = -4.08$; $p < 0.001$; Fig. 3). Pellets 2.5 cm in diameter were 0.14 times less likely to disintegrate than pellets 1.5 or 2 cm in diameter ($t = -2.88$; $p = 0.004$; Fig. 3). The odds that a pellet would disintegrate increased with increasing water amounts,

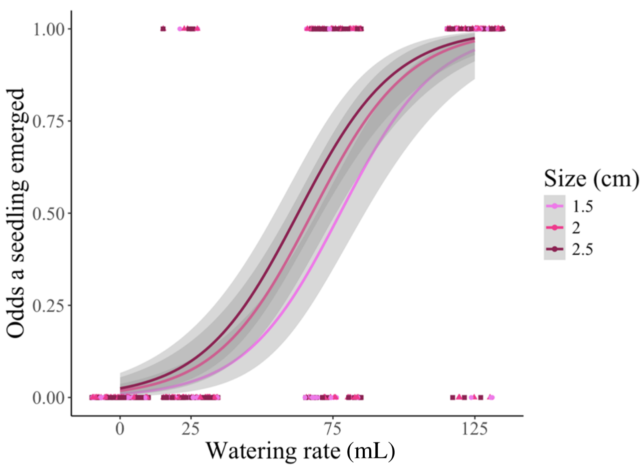

Figure 1. Effect of daily watering rate (mL) on the odds seedlings emerged from different-sized pellets (1.5, 2, and 2.5 cm). There were no differences between clay content, so the data were combined. Seedlings were counted after 21 days in a controlled environment. Colored trend lines show the change in odds of emergence associated with watering rate surrounded by gray 95% CI bands. Pellets 1.5 cm in diameter had significantly lower ($\alpha = 0.05$) odds of producing a seedling than pellets 2.5 cm in diameter.

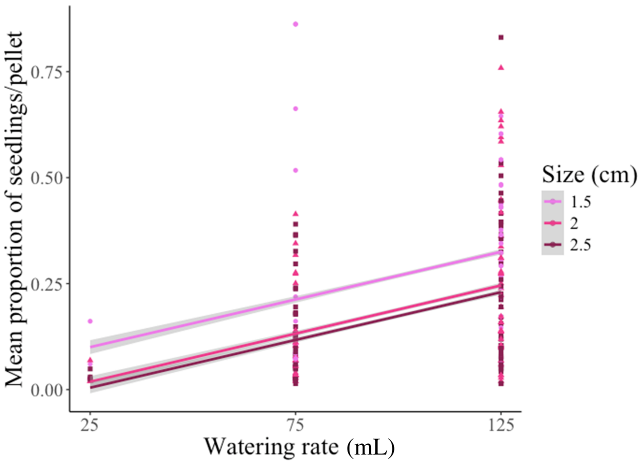

Figure 2. Effect of daily watering rate (mL) on the mean proportion of seedlings produced by different-sized pellets (1.5, 2, and 2.5 cm). There were no differences between clay content, so the data were combined. Seedlings were counted after 21 days in a controlled environment. Trend lines represent linear sample trends surrounded by gray 95% CI bands and data points. Pellets 1.5 cm in diameter produced a significantly higher proportion ($\alpha = 0.05$) of seedlings than pellets 2 or 2.5 cm in diameter.

with the odds of disintegration reaching 63% at 125 mL for the 10% clay pellets ($t = 5.39$; $p < 0.001$; Table S4; Fig. 3).

Seedling Establishment and Summer Recruitment in Field Study

An average of 1.4 seedlings/plot emerged from the 10% clay pellet treatment, which was higher than both the non-seeded control ($z = -4.25$; $p < 0.001$) and broadcast seeded treatments ($z = -2.56$; $p = 0.052$), which averaged 0.5 and 0.8 seedlings, respectively (Table S5). An average of 1.0 seedling emerged from the 55% clay pellets, which was higher than the non-seeded control treatment ($z = -2.77$; $p = 0.029$; Table S5). The lowest emergence occurred in May for all treatments (all $p < 0.001$), with no differences between emergence in June, July, and August (all $p > 0.800$; Tables S5 & 2; Fig. 4). Total monthly precipitation peaked in May for both sites at 6–8 cm (Fig. 4).

Table 2. Mean number of emerged seedlings and final recruitment by seeding treatment and date of observation, from a field study in southwestern Montana.

Month	*Non-seeded control*	*Broadcast*	*55% clay*	*10% clay*
May	0.1	0.2	0.3	0.4
June	0.7	1.2	1.4	2.0
July	0.8	1.3	1.6	2.2
August	0.8	1.4	1.7	2.3
Final recruitment	1.0	1.3	1.2	2.6

Analysis of final seedling recruitment (survival) in August showed that percent bare ground, litter, native grasses, forbs, and *Bromus tectorum* did not impact seedling recruitment (all $p > 0.45$) across all treatments. Seedling recruitment was higher in the 10% clay pellet treatment (2.6 seedlings) than in the non-seeded control treatment (1.0 seedling; $z = -2.68$; $p = 0.037$) and 55% clay pellet treatment (1.2 seedlings; $z = 2.34$; $p = 0.090$; Tables 2 & S6).

The 55% clay pellets were 25% more likely to disintegrate than the 10% clay pellets ($t = 3.21$; $p = 0.005$). On average 60% of the 55% clay pellets disintegrated and 35% of the 10% clay pellets disintegrated: much higher than under controlled conditions. The larger 2.5 cm pellets had slightly higher seedling recruitment than 2 cm pellets ($z = -2.92$; $p = 0.010$; Table S7). There was also

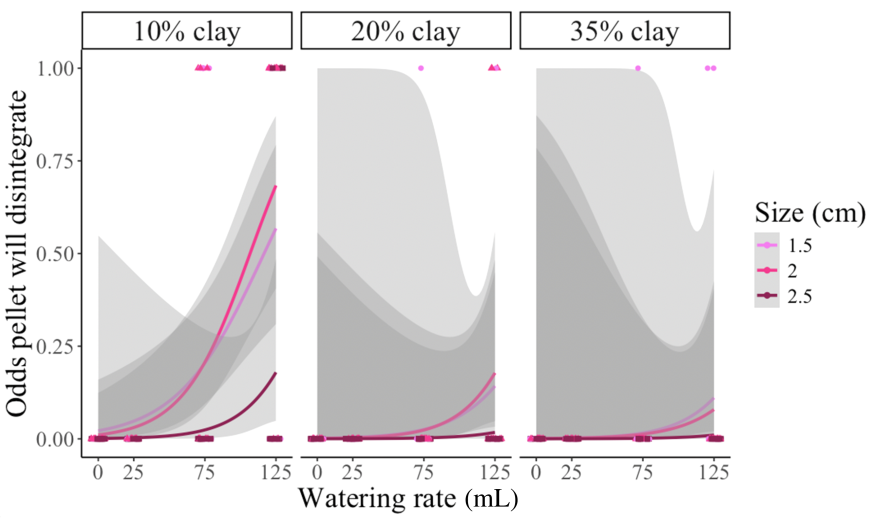

Figure 3. Effect of daily watering rate (mL) on the odds of pellet disintegration for different-sized pellets (1.5, 2, and 2.5 cm). No pellets disintegrated in the 5:3:0:1 (55% clay) treatment, and thus are not shown. Pellets were observed for 21 days in a controlled environment. Raw data points of success or failure (disintegrated or not) for each pellet are jittered horizontally for visualization, and the colored trend lines show the change in odds of disintegration associated with watering rate surrounded by gray 95% CI bands. Pellets 1.5 or 2 cm in diameter had significantly higher ($\alpha = 0.05$) odds of disintegrating than pellets 2.5 cm in diameter.

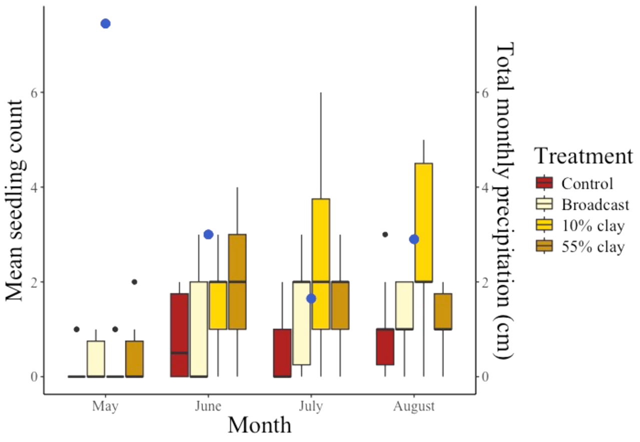

Figure 4. Change in mean seedling count by seeding treatment over time relative to total monthly precipitation (cm). Treatments were applied in two semiarid grasslands in southwestern Montana. Large blue dots represent total monthly precipitation values obtained from Local Climatological Data stations averaged between the two sites (NOAA 2024). The dark central line of each boxplot represents the sample median. Small black dots represent outliers that occur outside of the first and third quartiles of the data. Pellets made with 10% clay had significantly higher ($\alpha = 0.05$) seedling establishment odds than control and broadcast treatments. Pellets made with 55% clay had significantly higher ($\alpha = 0.05$) seedling establishment odds than the control treatment. Seedling emergence was significantly lower ($\alpha = 0.05$) in May than in all other months.

evidence that 1.5 cm pellets disintegrated more often than 2 cm ($z = 3.06$; $p = 0.006$) and 2.5 cm pellets ($z = 2.75$; $p = 0.016$; Table S8). Surprisingly, but importantly, the number of pellets that disintegrated did not impact seedling recruitment ($t = -0.97$; $p = 0.331$; Table S9).

Discussion

Restoring arid and semiarid rangelands is an extremely difficult yet essential task land managers must navigate globally; low precipitation and seed predation are regarded as the largest barriers to seeding success (Gornish et al. 2019; Havrilla et al. 2020). Development and assessment of seed enhancement technologies (including seed pellets) is garnering attention among restoration ecologists (Berto et al. 2024). We assessed if seed pellets improved revegetation efforts and what aspects of their construction influenced their efficacy.

We found that 40% of pellets produced at least one seedling in a controlled environment, and the efficacy of seed pellets depended on the size of the pellets and the amount of water received, but not on their clay content. Pellets 2.5 cm in diameter were twice as likely to produce seedlings as pellets 1.5 cm in diameter. However, when they did produce seedlings, pellets 1.5 cm in diameter produced a higher proportion of seedlings. Pellet disintegration was low across all treatments, but the highest rate occurred for 10% clay pellets of 1.5 or 2 cm and increased with increased watering. These patterns were also observed in the field, with smaller pellets being more likely to disintegrate, but larger pellets showing higher seedling emergence. In addition, we found no evidence that disintegration was impacting seedling recruitment. These results suggest that larger pellets (2.5 cm) should be selected for restoration as they displayed higher seedling establishment and recruitment. This is potentially due to larger pellets providing protection from predation, creating an improved microclimate, or providing more nutrients to support growth. There is evidence that seed pelleting can reduce germination or seedling emergence due to the restrictiveness of materials, but this is often accompanied by improved biomass for the seedlings that do emerge (Berto et al. 2024). This could perhaps be a benefit in semiarid and arid restoration projects, skewing emergence toward larger seedlings that could be primed to better survive drought stress that often limits survival.

In the field, more seedlings emerged from both the 10 and 55% clay pellets than the non-seeded control treatment, and more seedlings emerged from the 10% clay pellets than the broadcast seed treatment. These differences were statistically significant; however, seedling recruitment was still low across all seeding treatments (1–2 seedlings/0.5 m^2). While drill seeding tends to see higher recruitment than these results (Svejcar et al. 2023), it is not always a feasible option for restoration. In these scenarios, restorationists often turn to broadcast seeding, with limited success (Madsen et al. 2015). In our study, we saw a slight improvement in establishment with our 10% clay pellets over broadcast seeding, suggesting this approach has the potential to improve restoration seeding outcomes, if only slightly.

We also found that a higher proportion of the 55% clay pellets disintegrated than the 10% clay pellets. However, as mentioned above, there was no evidence that disintegration impacted seedling establishment or recruitment. One driving motivation behind this study was the low seedling recruitment and pellet disintegration observed in previous field work (Teichroew et al. 2022). From those results, we believed that the lack of disintegration may be inhibiting seedling establishment and aimed to increase pellet disintegration in this study. However, we also do not want the pellets to disintegrate too easily, as that may limit the impact seed pellets are proposed to have on seed predation. While seed predation was not measured in this study, it is likely an important factor. Limited seed availability due to seed predation has been well documented, but its impact on restoration efforts is not well understood and warrants further research (Larios et al. 2017; Lucero & Callaway 2018). Striking a balance between pellets that minimally inhibit seedling emergence but still provide protection against predation will be important in advancing this approach, and our results suggest using 2.5 cm pellets made with 10% clay may be most effective.

To our knowledge, no other seed pellet studies have evaluated the impacts of clay volume, pellet size, or the ability of pellets to disintegrate. Our results suggest that pellet size can impact the proportion of seedlings that emerged in both controlled and field environments, that clay content can impact seedling establishment and recruitment in the field, but the ability for pellets to disintegrate does not impact establishment or recruitment. While this study only assessed basic pellet ingredients, the addition of more organic material or another ingredient designed to reduce seed predation (e.g. chili powder; Pearson et al. 2018) or improve water retention (e.g. water holding crystals; Brown et al. 2019) could additionally address limitations on recruitment due to seed predation and water limitations. The feasibility and financial implications of scaling up this technique also warrant further research. In this study, we made and distributed the pellets by hand, which is not feasible for large-scale restoration projects. Alternative approaches to increase production efficiency include rotary seed coaters (Gornish 2019) or culinary extruding devices (Madsen et al. 2016). In conclusion, this study reinforces that seed pellets may be a useful solution to aid in restoring semiarid and arid rangelands where drill seeding is not available. We have identified several aspects that can be manipulated to improve their success, including using pellets that are 2.5 cm in diameter and containing 10% clay.

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Supporting Information

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

Table S1. Odds of seedling emergence evaluated by pellet size, clay level, and watering rate from the binomial portion of zero-altered negative binomial model for our controlled environment study.

Table S2. Mean proportion of seedlings evaluated by pellet size, clay level, and watering rate from the negative binomial count portion of zero-altered negative binomial model for our controlled environment study.

Table S3. Estimated differences in mean proportion of seedlings evaluated by clay content and pellet size from combined response of zero-altered negative binomial model of a controlled environment study.

Table S4. Odds of pellet disintegration evaluated by clay level, pellet size, and watering rate from a drop in deviance test of a controlled environment study.

Table S5. Estimated differences in log-mean seedling recruitment evaluated by seeding treatment and date of observation.

Table S6. Estimated differences in log-mean seedling recruitment evaluated by seeding treatment in August from emmeans contrasts from a generalized linear mixed model.

Table S7. Estimated differences in log-mean seedling recruitment evaluated by pellet size in August from emmeans contrasts from a generalized linear mixed model.

Table S8. Estimated differences in proportion of pellets that disintegrated evaluated by pellet size in August from emmeans contrasts from a generalized linear mixed model.

Table S9. Log-mean seedling recruitment evaluated by field site, clay level, pellet size, and pellet disintegration, in August from a generalized linear mixed effects model.

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