Improving Restoration Success of Winterfat: Influences of Hydrophobic Seed Coatings and Planting Depth on Seedling Emergence

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Improving Restoration Success of Winterfat: Influences of Hydrophobic Seed Coatings and Planting Depth on Seedling Emergence

Kyle Andrew Cook

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

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ABSTRACT

Improving Restoration Success of Winterfat: Influences of Hydrophobic Seed Coatings and Planting Depth on Seedling Emergence

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Master of Science

In western North America, winterfat (Krascheninnikovia lanata (Pursh) A. Meeuse & Smit) is a valuable protein-rich subshrub whose restoration has been limited by poor seed flowability and low rates of seedling establishment. Seed flowability can be limited by a dense covering of hairs on winterfat fruits that can cause them to clog in mechanized equipment. Seedling establishment can be limited by premature germination of fall-sown seeds that can cause over-winter seedling mortality from freezing, pathogen attack, and winter drought. Seed coatings may provide a way to overcome both of these barriers to winterfat restoration. Coatings can compress hairs against the fruit and improve seed flowability, and a hydrophobic polymer within seed coatings can repel water and delay germination of fall-sown seeds until spring, when winter hazards have subsided, and conditions are more conducive to seedling establishment.

With the advent of this technology, there is a need to establish cultural practices, such as optimal planting depth, for coated winterfat fruits. In chapter 1 of this thesis, we evaluated the influence of planting depth, seed coatings, and their interactions on winterfat seedling emergence under laboratory and field conditions. We predicted that seedling emergence would be greatest from shallow planting depths, and that coatings would not affect emergence. Results generally supported our hypothesis, with seedling emergence being highest from surface-sown and shallow-planted seeds for both non-coated (control) and coated winterfat fruits in laboratory and field conditions. Emergence from surface-sown seeds was more than two-fold greater than from the deepest planting depth (12.7 mm). Seed coatings improved emergence of surface-sown seeds compared to the control by 52 – 168% in the laboratory but had no effect in the field. As predicted, emergence was similar between coated and non-coated fruits when sown below the soil surface in both laboratory and field conditions. These results suggest that seed coatings may improve winterfat restoration success by improving flowability without inhibiting emergence, allowing the species to be used in more seeding projects.

Winterfat seed coatings may be improved with the use of a hydrophobic polymer to delay germination of fall-sown seeds until spring. In chapter 2 of this thesis, we compared seedling emergence from non-coated seeds, calcium carbonate coated seeds (blank-coated), and seeds coated with calcium carbonate plus an exterior hydrophobic coating. We counted the number of live seedlings and those that had died after emerging, and calculated mortality percentages for each treatment. We hypothesized that emergence would be greatest from hydrophobic-coated seeds, and the results supported our hypothesis. Seedling emergence from hydrophobic-coated seeds was three-fold greater than the control, and five-fold greater than blank-coated seeds. Mortality percentages were highest for the control, lower for blank-coated seeds, and lowest for hydrophobic-coated seeds. Thus, hydrophobic seed coatings can improve winterfat seedling emergence, and so could be instrumental restoring this valuable species to degraded rangelands.

Keywords: winterfat, seed coatings, hydrophobic, planting depth
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Table 2-1. Study site characteristics ............................................................................................. 55
In western North America, winterfat (*Krascheninnikovia lanata* (Pursh) A. Meeuse & Smit) has had limited use in restoration projects due to the appendages on the fruit (utricle) impeding flow through planting equipment. Seed coatings have been shown to overcome this barrier by improving the flowability of the fruits, which allows this valuable species to be included in seeding projects. With the advent of this technology, there is a need to establish cultural practices, such as optimal seeding depth, for coated winterfat fruits. We evaluated the effects of planting depth, seed coatings, and their interactions on winterfat seedling emergence. We hypothesized that emergence would be greatest from shallow planting depths and that the seed coating would have no influence on seedling emergence. We conducted studies in the laboratory and at four sites within the Great Basin Region of the United States. Results from these studies generally supported our hypothesis. We found that emergence was generally greatest from surface-sown and shallow-planted seeds for both non-coated (control) and coated fruits in laboratory and field conditions. Emergence from surface sown seeds was more than two-fold greater than from the deepest planting depth (12.7 mm). In the laboratory, seed coating improved emergence of surface-sown seeds between 52 - 168%. However, this response did not extend to the field, where coated and non-coated fruits had similar seedling emergence when planted on the soil surface. In both laboratory and field trials, seedling emergence was similar between coated and non-coated fruits when they were sown below the soil surface. Since seed
coatings can improve the flowability of winterfat fruits without inhibiting emergence, they may improve restoration success of the species by increasing its use in rangeland seeding projects. Efforts are now needed to continue the advancement of this innovative technology by determining how seed coatings influence winterfat seeding success on larger spatial scales that replicate conditions used by land managers.

INTRODUCTION

Rangeland ecosystems are among the most expansive biomes on earth, and approximately 20% of these landscapes are severely degraded (Millennium Ecosystem Assessment 2005). Many systems have been altered by human disturbances such as infrastructure development, land-use conversion, and overgrazing (Sayre et al. 2012; Jonas et al. 2018), which has contributed to the fragmentation of wildlife habitat, displacement of native plant species, and invasion of exotic weeds (Braun et al. 2002; Davies et al. 2011). Additionally, sites invaded by annual grasses like cheatgrass (*Bromus tectorum* L.), medusahead wildrye (*Taeniatherum caput-medusae* (L.) Nevski), and Ventenata (*Ventenata dubia* (Leers) Coss.) have become more prone to catastrophic wildfires that promote further degradation (Dantonio & Vitousek 1992; Fryer 2017). Such degraded landscapes have exhibited declines in biodiversity, reductions in primary productivity, and collapses of fundamental ecosystem processes (Dantonio & Vitousek 1992; Balch et al. 2013; Owen et al. 2013). In response, land managers and rangeland stakeholders worldwide are making large monetary investments to restore and preserve these ecosystems (James et al. 2012; Bodin et al. 2021).

Restoration projects often involve the direct seeding of native and other desirable plant species to areas where they have been reduced or displaced (Shackelford et al. 2021). Successful seeding projects can restore ecosystem processes, direct plant communities according to
management objectives, and improve resistance and resilience to future disturbances (Ethridge et al. 1997; Chambers et al. 2014). However, success rates of seeding projects are highly variable and can be especially low in arid and semi-arid environments where precipitation is limited and competition from weeds is often severe (Chambers et al. 2000; Hardegree et al. 2016). In these areas, studies have suggested that less than 10% of planted seeds survive to maturity (James et al. 2012; Jensen et al. 2022). Failed seedings can impose considerable economic losses and ecological disadvantages as they offer no return on investment and leave vacant niches that serve as vacuums for weed invasion (Hobbs & Norton 1996; Chambers et al. 2007; James et al. 2012). Thus, while the benefits of rangeland seeding projects can be great, there is a need to improve their success rates.

Occasionally, there are species-specific constraints that limit restoration success (Boyd and Van Acker 2003). In western North America, winterfat (Krascheninnikovia lanata (Pursh) A. Meeuse & Smit) is a low-growing, half-shrub that would be of value to include in restoration projects, but its use is constrained because of poor seed flowability through planting equipment and low establishment rates (Bai et al 1998; Monsen & Stevens 2004; Thacker et al. 2023). Winterfat’s high crude protein content (> 10%) makes it a valuable forage, especially during the winter when food resources are scarce (Monsen & Stevens 2004; Kitchen & Jorgensen 2001; Ogle et al. 2012). Winterfat has been removed from or reduced in critical wildlife habitat areas, however, as a result of historic overgrazing by domestic livestock, frequent wildfires in annual grass invaded sites, and other anthropogenic disturbances (Hild 2007; Freeman et al. 2014; Souther et al. 2019). Restoring winterfat to these ecosystems has proven difficult, partly due to the species’ unique seed morphology (Thacker et al. 2023). The seed is enclosed within four bracts that compose the fruit (a utricle), which is densely covered in fine, silky hairs (Booth &
Griffith 1984). These hairs cause fruits to bridge and clog in mechanized planting and mixing equipment (Thacker et al. 2023). Removing seeds from fruits by threshing can improve flowability, but it is not recommended as threshing can damage root caps and inhibit germination and seedling establishment (Booth & Schuman 1984). Consequently, the species is often excluded from restoration plantings or is included at low seeding rates (Thacker et al. 2023).

Polymer seed coatings can improve the flowability of seeds that are difficult to handle (Pedrini et al. 2016). Thacker et al. (2023) demonstrated that the hairs on winterfat fruits could be reduced in length using a flash-flaming technique (Guzzomi et al. 2016), which helped prepare the surface of the fruit to accept an exogenous seed coating. This treatment allowed winterfat fruits to be sown without bridging or clogging in the seeding equipment (Thacker et al. 2023). Cook et al. (Chapter 2 of this Thesis) demonstrated that winterfat fruits could be coated without a flash-flaming pre-treatment. The hairs on winterfat fruits can be contained within the polymers and powder filler materials of the coatings, transforming fruits into more dense, uniform structures that flow freely through equipment.

Now that winterfat can be sown using standard rangeland seeding equipment, there is a need to establish basic planting protocols, such as determining the optimal depth coated fruits should be planted. Planting seeds at the correct depth is crucial for optimizing seed germination, seedling emergence, and plant establishment (Benvenuti et al. 2001; Grundy et al. 2003; Rawlins et al. 2009). Polymer seed coatings may modify the optimal seeding depth required for a specific species (Boyd and Van Acker 2003). For winterfat, multiple studies suggest that planting depths should not exceed 6.3 mm, and emergence is often best when seeds are sown on the soil surface (Springfield 1970; Ogle et al. 2012). Coatings may require seeds to expend more energy during germination, as they impose an added barrier through which the radicle must penetrate. In this
case, seedlings may not have sufficient energy reserves to emerge from deeper planting depths. For surface-sown seeds, Booth & Schuman (1983) suggested that winterfat utricle hairs anchor fruits to the soil, encouraging radicle penetration into the soil and promoting seedling establishment. Applying a coating may alter this hair-soil interaction and negatively impact emergence. Conversely, absorptive materials within coatings (i.e., polymers and powders) may have a wicking effect, as they provide a medium for moisture to pass from the soil to the seed, thus improving seed-soil contact and aiding in seed germination (Blunk et al. 2017; Anderson et al. 2021). These and other seed coating interactions could have various effects on emergence processes across planting depths, and there is a need to evaluate these effects before coatings can be considered a viable restoration tool for winterfat.

Objectives of this study were to evaluate the influences of seed coatings, planting depths, and interactions between the two on winterfat seedling emergence under laboratory and field conditions. We hypothesized that emergence would be greatest at shallow planting depths and that the seed coating would have no influence on seedling emergence.

MATERIALS & METHODS

*Plant Materials and Seed Coating*

Winterfat fruits were sourced near Elko, Nevada, in the fall of 2020 and stored at the Utah Division of Wildlife Resources Great Basin Research Center’s seed warehouse (Ephraim, UT). In the warehouse, average ambient temperature was 1.1 – 2.2°C, and relative humidity was 8 – 10%. Coating took place in November 2021 at Brigham Young University (Provo, Utah) in a 31-cm diameter rotary drum seed coater (Universal Coating Systems, Independence, OR).

In preparation for coating, inert matter (i.e., sticks and other debris) was removed by
passing the fruits through a 10 mm sieve. Coating was performed on 125 g batches of fruit with the coater set to 23% of its maximum speed. While the fruits were spinning in the coater, 150 ml of water was applied to the atomizing disc, which evenly dispersed the water onto the fruits. Next, 100 g of limestone powder was poured directly onto the wetted fruits. Next, 60 ml of Agrimer-15 binder, prepared with a 40% solid content (Ashland, Inc., Covington, KY), was applied to the atomizing disc at about 2 ml/s using a peristaltic pump. Then 1,300 g of calcium carbonate and 140 g of binder were added in small alternating increments, with the calcium carbonate powder applied directly to the seed while the binder was pumped onto the atomizing disc. After coating, fruits were dried for 30 min on a forced air dryer at 43°C, then stored in the cooler at 4°C until planting.

*Laboratory Trial*

The laboratory trial compared emergence of winterfat seedlings from non-coated and coated fruits planted at four depths within three soil types (Figure 1-2). Soils were collected from three rangeland sites in central Utah, Lookout Pass (40.139003, -112.507367), Little Sahara State Park (39.764, -112.319), and Spanish Fork (40.07494, -111.60329). Lookout Pass and Little Sahara had established stands of winterfat nearby. As measured by the Environmental Analytics Lab (Brigham Young University, Provo, UT.), soil from Lookout Pass was determined to be a loam (38.2% sand, 19.3% clay, 42.6% silt) with a pH of 7.68, Little Sahara was a sandy-loam (58% sand, 11.4% clay, 30.4% silt) with a pH of 7.40, and Spanish Fork was a loamy-sand (79.4% sand, 9.3% clay, 11.3% silt) with a pH of 7.52. Collected soil was prepared for the trial by using a 10 mm sieve to remove rocks, debris, and large aggregates. Sieved soil was placed in separate 25.5 x 53.3 x 6 cm plant flats with drainage holes.

The study was arranged in a randomized block split-plot design with eight replicates.
Each block contained the three different soil types (loam, sandy-loam, loamy-sand) (split-plot factor), which were planted with separate rows containing coated and non-coated winterfat fruits at depths of 0 mm (surface), 3.2 mm, 6.3 mm, or 12.7 mm (Figure 1-2).

Seeds were sown using handheld cement groovers that had been modified to create furrows at the desired planting depths. Fruits were hand-placed in the bottom of the furrows and buried. This was done to imitate a seed drill that creates a furrow of a given depth, and then drops the seed into the furrow before closing it. For surface planting, fruits were placed onto the soil and no furrows were made. Planting rows were 53.3 cm long, 3.5 cm apart, and contained 21 pure live seeds (PLS).

Flats were placed in a walk-in growth chamber (Environmental Growth Chambers, Chagrin Falls, OH, USA) that was set to a constant temperature of 15°C. Lights in the chamber provided a 12 h photoperiod, with a maximum photosynthetically active radiation flux density of approximately 780 µmol m⁻²s⁻¹, at the soil surface. Flats were watered to field capacity immediately after planting, then three times per week throughout the study. The study was conducted for three weeks, with the location of the blocks within the chamber re-randomized three times per week. Seedling emergence was counted at the end of each week of the study, with emergence recorded when cotyledons were visible.

Field Trials

Studies were conducted at four sites in the Great Basin region of the Western United States in the state of Utah (Figure 1-1). Three were on rangelands and one was on a mine tailings impoundment. Rangeland research sites were located near Sage Valley (39.5462, -112.0683), and near the towns of Santaquin (39.9073, -111.8163), and Enterprise (37.5889, -113.7157). The mineland tailings location was associated with the Rio Tinto Kennecott Copper Mine near the
town of Magna (40.72055, -112.09511). Soil, climate, and ecological characteristics of each location can be found in Table 1.

Sage Valley is an Upland Loam Wyoming big sagebrush ecological site (R028AY310UT) in Juab County that burned in 2019 during the Goat Canyon fire. After the fire, the area became dominated by annual weeds such as Russian thistle (*Salsola tragus* L.), field bindweed (*Convolvulus arvensis* L.) and houndstongue (*Cynoglossum officinale* L.). The Santaquin location is an Upland Stony Loam Wyoming big sagebrush ecological site (R028AY334UT) in Juab County. It is within a Wildlife Management Area maintained by the Utah Division of Wildlife Resources. The area where our seeding took place was degraded and dominated by bulbous bluegrass (*Poa bulbosa* L.), field bindweed, jointed goatgrass (*Aegilops cylindrical* Host) and cheatgrass (*Bromus tectorum* L.). The Enterprise site is a Semidesert Shallow Loam Wyoming big sagebrush site (R028AY243UT) in Washington County, which burned in the Flatt Fire in June 2021. Before the fire, the area had been heavily invaded by cheatgrass.

The Rio Tinto Kennecott tailings impoundment is in Salt Lake County. Soil-substrate on the impoundment is a sediment material from the mine’s refining process that extracts copper, molybdenum, and other metals from native ore. After extraction of these minerals, the remaining sediment material is moved to the tailings impoundment. This material will either become the permanent soil-substrate for the site or will be capped with 1 m of topsoil cover. Our experiment was conducted on a site that did not have a topsoil cover.

To control competing vegetation, Sage Valley, Santaquin, and Enterprise were treated 30 days before planting with a mixture of glyphosate (Big and Tough, Gordon’s Farm, Kansas City, MO, USA) and 2,4-D (Southern Ag., Boone, NC, USA). The mixture was applied at a rate of
350 g of acid equivalent (a.e.) ha\(^{-1}\) glyphosate and 840 g a.e. ha\(^{-1}\) 2,4-D. The Magna site had little established vegetation within the study area, so herbicide was not applied at this location.

Treatments in the field trial were identical to the laboratory trial, including two coating treatments, non-coated (control), and coated winterfat fruits, and four planting depths (0, 3.2, 6.3, and 12.7 mm). At each study site, a randomized complete block design was implemented with eight replicate blocks. Each block had a 6 x 2 m plot with eight furrowed rows, one for each treatment combination. Furrows were 2 m long, 15 cm deep, 30 cm wide at the bottom, and 50 cm apart. U-shaped furrows were made with furrowers attached to a plow bar pulled by a tractor. Within each furrow, seeds were hand-planted at a rate of approximately 157 pure live seeds (PLS) m\(^{-1}\) using the same cement groovers that were used in the laboratory trial described above. Studies were planted from October to December of 2021, and emergence was counted in May of 2022.

Statistical Analyses

For the laboratory trial, we evaluated the effects of soil type, seed treatment, and planting depth on seedling emergence using a generalized linear mixed-effects model (GLM) with a Poisson response distribution fit with a Logit link using JMP Pro (version 16 SAS Institute, Inc., Cary, NC, USA). Soil type, planting depth, seed treatment, and their interactions were included in the model as fixed effects. Block was included as a random effect. Pairwise comparisons were performed to assess differences between planting depth and seed treatment using the Tukey-Kramer honestly significant difference multiple comparison method. A student t-test was also used to compare the level of difference between seed treatments within each planting depth.

For the field trial, we evaluated the effects of seed treatment and planting depth on total seedling emergence using a GLM with a Poisson response distribution fit with a Logit link. Here,
seed treatment, planting depth, and seed treatment crossed with planting depth were defined as a fixed effect, while site, block, and site crossed with block was defined as random effects. Significant differences were examined between planting depth and seed treatment using the Tukey-Kramer honestly significant difference multiple comparison method.

Seedling emergence data were also analyzed without the effect of seed treatment. For this analysis, planting depth was defined as a fixed effect and site, block, and site crossed with block were defined as random effects and pairwise comparisons between different planting depths using the Tukey-Kramer honestly significant difference multiple comparison method. For all laboratory and field trial comparisons, we used a significance level of $P < 0.05$.

RESULTS

Field Trial Weather

During the seed incubation period (i.e., October through May), precipitation was generally well below the long-term average at all sites, except for October and December (Figure 1-3). Temperatures during this time were slightly warmer than average in November and somewhat cooler than average in February. In May, when emerged seedlings were counted, Enterprise had no detectible precipitation, Santaquin and Magna precipitation was near average, and Sage Valley was 61% of the 30-yr average. Temperatures in May were near average at Enterprise and slightly cooler than average at all other sites (Figure 1-3).

Laboratory Trial

Soil type had the strongest influence on seedling emergence ($F_{2,161} = 76.7$, $P=0.001$), with loam and sandy-loam soils generally having higher seedling emergence than the loamy-sand soil (Figure 1-4). There was also a weak interaction between soil type and planting depth
(F3,161 = 2.5, P = 0.022), with planting depth influencing emergence in loam and sandy-loam soils but not in loamy-sand soils (Figure 1-4). In general, seedling emergence tended to be higher at shallower sowing depths, with a sharp decline in seedling emergence at 12.7 mm (Figure 1-4). For example, seedling emergence from control seed in a loam soil dropped by 28% between a 6.3 mm and 12.7 mm planting depths (P=0.014), and by 58% in sandy-loam soil between these two depths (P=0.004). However, for loamy-sand soils, there was generally not a major difference in seedling emergence between planting depths (Figure 1-4).

Seed treatment did not affect seedling emergence (F1,161 = 3.2, P = 0.073), but there was a strong interaction between planting depth and seed treatment (F3,161 = 17.8, P < 0.001). Seedling emergence from surface-sown seeds that were coated was 70% (P=0.001), 52% (P=0.007), and 168% higher (P=0.001) than the control, in loam, sandy-loam, and loamy-sand soils, respectively. Within the remaining planting depths, seedling emergence was similar between the seed treatments (Figure 1-4).

Planting depth influenced seedling emergence for both non-coated and coated seeds in most scenarios (F2,30 =24.9, P=0.001). Non-coated seeds in loamy-sand soil was the only scenario where planting depth was not significant. For both treatments, emergence was generally greatest at shallow planting depths (Figure 1-4). For non-coated seeds in loam soils, both 3.2 mm and 6.3 mm planting depths yielded approximately 30% greater emergence than 12.7 mm planting depths (P=0.023; P=0.014). In sandy-loam soils, 0, 3.2, and 6.3 mm planting depths each yielded more than two-fold greater emergence than 12.7 mm (P=0.033; P=0.001; P=0.004). For coated seeds in all soil types, surface-sown seeds produced better emergence than 12.7 mm planting depths, showing an increase of two-fold in loam (P=0.001), four-fold in sandy-loam (P=0.001), and eight-fold in loamy-sand soils (P=0.001). For coated seeds in loam and sandy-
loam soils, surface-sown seeds produced approximately 40% greater emergence than 6.3 mm planting depths ($P=0.004$; $P=0.008$).

Within planting depths, seed treatments influenced emergence to varying degrees ($F_{2,30} = 17.8$, $P=0.001$). In loamy-sand soils, emergence percent was greater for control seeds than coated seeds at 3.2 mm ($P=0.011$) and 12.7 mm planting depths ($P=0.016$). However, when planted on the soil surface, emergence of coated seeds was significantly greater than non-coated seeds, showing an increase of 70% in loam soils ($P=0.001$), 52% in sandy-loam soils ($P=0.007$), and nearly three-fold in loamy-sand soils ($P=0.001$). In loam and sandy-loam soils, there were no statistically significant interactions between treatments at any other planting depths.

**Field Trials**

In the field, seedling emergence was influenced by planting depth ($F_{2,30} = 5.08$, $P=0.002$) but not by seed treatment ($F_{2,30} = 0.343$, $P=0.559$) or their interaction ($F_{2,30} = 0.528$, $P=0.664$). On average, there was a general decline in seedling emergence with increasing planting depth (Figure 1-5). The total number of emerged seedlings from surface-sown seeds was more than two-fold greater than from the 12.7 mm planting depths ($P=0.006$) (Figure 1-5).

**DISCUSSION**

Sowing seeds at an optimal depth is essential to maximizing seed germination, emergence, and plant establishment (Ott et al. 2003; James & Svejcar 2010; Ye et al. 2019). We evaluated how planting depth influenced seedling emergence of coated and non-coated winterfat fruits in laboratory and field studies. As hypothesized, seedling emergence was greatest at shallower planting depths. Contrary to the hypothesis, coated fruits markedly improved seedling emergence in the laboratory trial compared to non-coated fruits when sown on the soil surface.
However, this response did not extend to the field, where coated and non-coated fruits had similar seedling emergence. As predicted, in both laboratory and field trials seedling emergence was similar between coated and non-coated fruits when they were sown below the soil surface. These findings suggest that current protocols for planting non-coated winterfat fruits also generally apply to coated fruits. Studies suggest that winterfat fruits should not be planted deeper than 6.3 mm, and that the best results may come from even shallower seeding depths or surface-sowing (Springfield 1970; Ogle et al. 2012). Similarly, we found relatively high seedling emergence from 0 – 6.3 mm sowing depths, but at 12.7 mm seedling emergence rapidly declined regardless of if winterfat fruits were coated. The only place where this effect was not pronounced was in the laboratory trial within loamy-sand soil. This unique response is most likely because of differences in soil texture. Heavier textured soils can prevent the emergence of deeply sown seeds by reducing gas exchange around the seeds (Benvenuti and others 2001; Benvenuti 2003). If germination does occur, heavy textured soils can provide greater mechanical resistance to emerging seedlings attempting to penetrate out of the soil (Shiel and Yuniwo 1993; Nabi et al. 2001). Hence, the courser-textured, loamy-sand soil used in this study may not have had as great of resistance to seedling emergence as the other heavier soil texture types. Additionally, overall seedling emergence in loamy-sand soil was relatively low. In conducting this research, we observed that flats containing loamy-sand soil dried out more quickly than the other two soil types. It is possible that the relatively higher drainage and lower water holding capacity of this courser-textured soil was the reason the soil dried out quicker and why seedling emergence was limited.

Since these results indicate that seed coatings do not inhibit winterfat seedling emergence, future studies could consider customizing the treatment to address specific biological
and abiotic barriers that limit winterfat seedling establishment. For example, winterfat seedlings are prone to mortality from pathogen attack, and fungicide coatings may be applied to winterfat fruits to minimize this risk (Nelson et al. 1990; Garvin et al. 2004; Hoose et al. 2022). As another example, an exterior coating of hydrophobic polymer may be applied to blank-coated fruits to repel water, slow imbibition, and delay germination of fall-sown seeds until spring (Madsen et al. 2016; Baughman et al. 2022; Chapter 2 of thesis). In doing so, over-winter seedling mortality from freezing, pathogen attack, or winter drought may be reduced, and seedling emergence and survival may be improved.

Our laboratory finding that coated fruits produced considerably better emergence than non-coated fruits when sown on the soil surface could be the result of the seed coating providing improved seed-soil contact. We observed that the hairs on non-coated fruits seemed to suspend the fruits slightly above the soil surface, while coated fruits settled deeper into the soil (Figure 1-2). Consequently, it is possible that soil moisture was more available to coated fruits than to non-coated fruits, which could explain the improved emergence we observed from the coated treatment. However, field trials had similar seedling emergence between rows planted with coated and non-coated fruits when sown on the soil surface. In the field, non-coated fruits may have settled into the soil throughout the winter, resulting in similar seed-soil contact and available water between treatments. This is compatible with Booth’s (1984) suggestion that hairs anchor fruits to the soil and promote emergence. Regardless, coatings appear to either improve or have no significant impact on emergence of surface sown seeds.

Management Implications

Poor seed flowability is a primary obstacle preventing the restoration of winterfat to degraded rangelands because it deters land managers from including the species in seeding
projects at adequate rates. Seed coatings may solve this problem by allowing winterfat fruits to flow freely through mechanical seeding equipment. Coatings improve flowability without reducing seedling emergence, which stands in contrast to other methods used to improve winterfat seed flowability. Mechanical cleaning, for instance, typically involves removing seeds from the fruits, which can damage root caps and reduce seed germination and seedling vigor (Booth 1983). In addition, coated winterfat fruits can be planted according to the seeding depth requirements already established for non-coated winterfat (Ogle et al. 2012), with seedling emergence being highest when fruits are sown at or near the soil surface. Therefore, since seed coatings do not inhibit seedling emergence, do not impose a major change on winterfat planting protocols, and can alleviate poor seed flowability, they may improve restoration success of the species by allowing it to be included effectively in more seeding projects.

Seed coatings impose the extra cost of materials and labor, but coating processes have become more efficient with continued research. Thacker et al. (2023) demonstrated that coatings could improve winterfat seed flowability, but a pre-treatment of flash-flaming was necessary to apply a seed coating. Insights provided by Thacker et al. (2023) enabled us to coat winterfat without that pre-treatment, and with minimal amounts of low-cost materials, such as calcium-carbonate. Thus, the seed coating used in this study should be more cost-effective. Future research could evaluate the costs and labor required to coat winterfat using industrial-sized equipment.
LITERATURE CITED


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Figure 1-1 – Locations of study sites near Magna, Santaquin, Sage Valley, and Enterprise, Utah, USA.
Figure 1-2 – (Left) photo showing a non-coated (control) winterfat (*Krasheninnikovia lanata* (Pursh) A. Meeuse & Smit) fruit. Note how the hairs suspend the non-coated fruit above the soil surface, possibly decreasing seed-soil contact compared to coated fruits. (Right) photo showing blank-coated winterfat fruits. In the laboratory trial, coated fruits may have experienced improved seed-soil contact compared to non-coated fruits.
Figure 1-3 – Monthly precipitation and temperature averages throughout the study (2021-2022), compared to the 30-year averages (1991-2021) for study sites near Sage Valley, Magna, Santaquin, and Enterprise, Utah, USA.
Figure 1-4 – Average (±SE) percentages of winterfat (*Krasheninnikovia lanata* (Pursh) A. Meeuse & Smit) seedling emergence from non-coated and coated fruits in three soil types, loam, sandy-loam, and loamy-sand, during the laboratory trial. Differing lower case letters indicate significant differences between planting depths and seed treatments. Asterisks indicate significant differences between seed treatments within a planting depth. For all comparisons, a significant level of *P*<0.05 was used.
Figure 1-5 – Average (±SE) plant density of emerged winterfat (*Krasheninnikovia lanata* (Pursh) A. Meeuse & Smit) seedlings at study sites near Sage Valley, Magna, Santaquin, and Enterprise in Utah, USA. Differing lower case letters indicate significant differences in total seedling emergence between planting depths (*P*<0.05).
Table 1-1 – Characteristics of study sites near Sage Valley, Magna, Santaquin, and Enterprise, Utah, USA. Climate data is based on 30-year averages from PRISM models (PRISM Climate Group 2022). Soil data is sourced from web soil survey (Soil Survey Staff 2022).

<table>
<thead>
<tr>
<th>Site</th>
<th>Coordinates (N, E)</th>
<th>Habitat Type (ESD)</th>
<th>Elevation (m)</th>
<th>Average Annual Precipitation (mm)</th>
<th>Mean Temperatures Jan Low, July High (°C)</th>
<th>Soil Surface Texture</th>
<th>Soil pH</th>
<th>Organic Matter (%)</th>
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<tr>
<td>Sage Valley</td>
<td>39.5462, -112.0683</td>
<td>Bonneville Big Sagebrush (R028AY310UT)</td>
<td>1611</td>
<td>320.5</td>
<td>-8.8, 32.9</td>
<td>Loam</td>
<td>8.5</td>
<td>3.00</td>
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<tr>
<td>Magna</td>
<td>40.72055, -112.0951</td>
<td>Mine Wash</td>
<td>1308</td>
<td>417.1</td>
<td>-5.5, 33.5</td>
<td>Sandy loam</td>
<td>7.9</td>
<td>0</td>
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<tr>
<td>Santaquin</td>
<td>39.9073, -111.8163</td>
<td>Wyoming Big Sagebrush (R028AY334UT)</td>
<td>1569</td>
<td>437.2</td>
<td>-7.6, 32.7</td>
<td>Stony loam</td>
<td>7.6</td>
<td>2.00</td>
</tr>
<tr>
<td>Enterprise</td>
<td>37.5889, -113.7157</td>
<td>Wyoming Big Sagebrush (R028AY243UT)</td>
<td>1628</td>
<td>383.6</td>
<td>-8.3, 32.1</td>
<td>Gravelly loam</td>
<td>7.6</td>
<td>1.50</td>
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</table>
CHAPTER 2

Improving Winterfat Seedling Emergence Using Hydrophobic Seed Coatings

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ABSTRACT

Direct seeding of native plant species is a widespread technique in rangeland restoration, but numerous factors can limit success. Restoration of winterfat (*Krascheninnikovia lanata* (Pursh) A. Meeuse & Smit) may be constrained by poor seed flowability and premature seed germination that can cause over-winter mortality of fall-sown seeds. Hydrophobic coatings may address these barriers by improving seed flowability and delaying germination of fall-sown seeds until spring when conditions are conducive to seedling establishment. We compared seedling emergence from seeds that were left uncoated, coated with calcium carbonate (blank-coated), and coated with calcium carbonate plus an exterior hydrophobic coating. We also counted the number of seedlings that had died after emerging and calculated mortality percentages for each treatment. Studies were planted in the fall of 2021 at four sites within the Great Basin Region of the United States. The number of emerged seedlings produced from hydrophobic-coated seeds was three-fold greater than non-coated seeds and five-fold higher than blank-coated seeds. The percentage of seedlings that died after emerging was highest for non-coated seeds and lowest for hydrophobic coatings. These results suggest that coating alone may not improve seeding success, but coating seeds with a hydrophobic polymer to delay germination can improve seedling emergence of winterfat. Thus, seed coatings could be instrumental restoring winterfat to degraded rangelands.
INTRODUCTION

Rangeland ecosystems comprise nearly half of the earth’s terrestrial surface, and many of these systems have deteriorated over the last century (Schlesinger et al. 1990; Dantonio & Vitousek 1992; Booth et al. 2003). Anthropogenic disturbances like land-use conversion, infrastructure development, and overgrazing have contributed to the fragmentation and degradation of wildlife habitat, displacement of native plant species, and the proliferation of weeds in their place (Braun et al. 2002; Davies et al. 2011). These degraded landscapes have become less capable of supporting wildlife, reduced in their ability to provide ecosystem services, and more prone to catastrophic wildfires (Dantonio & Vitousek 1992; Balch et al. 2013; Owen et al. 2013). In response, government agencies and rangeland stakeholders worldwide are making large investments to restore and preserve these ecosystems (James et al. 2012; Bodin et al. 2021).

Direct seeding is one of the most widespread restoration techniques used to establish native and other desirable plant species following disturbance or weed invasion (Shackelford et al. 2021). Successful seedings can direct plant communities toward desirable states, build resistance and resilience to future disturbances, and improve the delivery of ecosystem products and services (Ethridge et al. 1997; Chambers et al. 2014). Native seeding projects, however, are often costly and success rates are notoriously low (Boyd & Davies 2012). While actual success rates are unknown, studies have suggested that less than 10% of planted seeds survive to become mature plants (James et al. 2011; Jensen et al. 2022). This is especially true in dryland ecosystems where precipitation is limited, drought is common, and annual weed invasion is often severe (Chambers et al. 2000; Hardegree et al. 2016). In these areas, even the most well-equipped projects frequently fail (Menz et al. 2013; Svejcar & Kildisheva 2017). Failed seedings
impose substantial economic losses and ecological disadvantages as they offer no return on investment and leave vacant niches that serve as vacuums for weed invasion (Hobbs & Norton 1996; Chambers et al. 2007; James et al. 2012). Such heavy consequences highlight the urgent need for innovative strategies to improve seeding success rates.

Developing effective solutions requires an understanding of the obstacles that limit seedling establishment, which are often unique to sites and species or functional groups. In the Great Basin region of North America, one such obstacle is the rapid germination of fall-planted seeds, which can lead to seedling mortality during the winter (James et al. 2011; Madsen et al. 2016; Fund et al. 2019; Baughman et al. 2022). In this region, seeds are generally planted in the fall with the intent that seeds will germinate and establish in the spring when temperatures increase, and moisture is available for plant growth (James et al. 2011; Boyd & James 2013). In separate studies, James et al. (2011) and Boyd & James (2013) showed that approximately 80% of fall-planted bunchgrass seeds germinated before winter, but less than 15% of those emerged in the spring. Similar patterns have been observed in species of shrubs and forbs (Chambers 2000; Garvin et al. 2004), with mortality anticipated to be caused by freezing soils (Boyd & Lemos 2013; Roundy & Madsen 2016), pathogen attack (Nelson et al. 1990; Garvin et al. 2004), winter drought (James et al. 2011), and failed seedling emergence through non-biotic soil-surface crust (Madsen et al. 2012). Planting seeds in the spring could alleviate over-winter mortality, but this practice is usually impractical due to low seed availability, contractor schedule constraints, and short windows of favorable planting conditions (Hardegree et al. 2016; Baughman et al. 2022). Additionally, over 80% of rangeland plants exhibit seed dormancy which require winter conditions in order to be broken (Baskin & Baskin 2014; Kildisheva et al. 2019). Therefore, fall-planting is ideal, but pre-winter germination can undermine seedling establishment of numerous
species (James et al. 2011; Madsen et al. 2016; Fund et al. 2019; Baughman et al. 2022).

Winterfat (*Krascheninnikovia lanata* (Pursh) A. Meeuse & Smit) is an example of a valuable rangeland plant whose seeding success may be limited by pre-winter germination (Bai et al., 1998). Winterfat is an excellent protein source, especially during the winter when food resources are scarce (Monsen & Stevens 2004; Kronberg 2015). However, historic overgrazing by domestic livestock has displaced this species from critical winter habitat ranges, negatively affecting numerous wildlife species (Davies et al. 2009; Freeman et al. 2014; Souther et al. 2019). Winterfat seed germination can occur rapidly during brief bouts of warm weather in late fall or early winter, but these seedlings often cannot persist through the winter (Booth & Romo 1998). Additionally, this species has seen limited use in restoration plantings due to its poor seed flowability through mechanized equipment (Booth & Schuman 1983; Booth & Griffith 1984; Thacker et al. 2023). Poor seed flowability is due to the species’ unique seed morphology; the seed is enclosed within four bracts that compose the fruit (a utricle), which is densely covered in fine, silky hairs (Booth & Griffith 1984). These hairs cause fruits to bridge and clog in mechanized equipment like rangeland drills, broadcast seeders, and seed mixing equipment. This lack of seed flowability discourages the use of winterfat in restoration plantings. If winterfat could be successfully seeded, its restoration to the landscape would significantly improve the health of degraded rangelands (Carey 1995; Souther et al. 2019).

Hydrophobic seed coatings may address seed flowability and pre-winter germination issues. Thacker et al. (2023) demonstrated that seed coatings could compress hairs against the fruits, creating a uniform structure that does not bridge or clog in equipment. It may also be possible to coat winterfat fruits with a hydrophobic polymer that temporarily repels water, preventing imbibition and germination until spring when the coating has degraded (Madsen et al. 2016; Fund et al. 2019; Baughman et al. 2022).
Hydrophobic coatings may prevent fall-planted seeds from germinating during brief warm-spells of late fall and winter and allow for their germination in the spring when conditions are more conducive to seedling emergence. By delaying germination until spring, the amount of time that seedlings are exposed to winter threats like freezing, pathogen attack, and winter drought may be reduced, and the likelihood of their emergence in the spring may be increased.

Hydrophobic coatings have been studied in agriculture to delay germination of crop seeds (Johnson et al. 2004; Stendahl 2005), and in rangeland restoration for species like bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Love) (Madsen et al. 2016; Baughman et al. 2022) and basalt milkvetch (*Astragalus filipes* (Torr) ex A. Gray) (Fund et al. 2019). Our objective was to evaluate the effects of hydrophobic seed coatings on winterfat seedling emergence. We hypothesized that hydrophobic coatings would improve seedling emergence compared to non-coated seeds.

**MATERIALS & METHODS**

*Study Sites*

Studies were conducted at four Utah sites in the Great Basin region of the Western United States (Figure 2-1). Three were on rangelands and one was on a mineland tailings impoundment. Rangeland research sites were located near Sage Valley (39.5462, -112.0683), Santaquin (39.9073, -111.8163), and Enterprise (37.5889, -113.7157). The mine tailings site is located near the town of Magna on Rio Tinto’s Kennecott mine (40.72055, -112.09511). Climate, soil, and vegetation characteristics for each location can be found in Table 2-1.

Sage Valley is an Upland Loam big sagebrush ecological site (R028AY310UT) in Juab
County that burned in 2019 in the Goat Canyon fire. The area is dominated by annual weeds such as Russian thistle (*Salsola tragus* L.), field bindweed (*Convolvulus arvensis* L.) and houndstongue (*Cynoglossum officinale* L.). The Santaquin location is an Upland Stony Loam ecological site (R028AY334UT) in Juab County that is dominated by Wyoming big sagebrush. It is within a Wildlife Management Area maintained by the Utah Division of Wildlife Resources. The area where our seeding took place was degraded and dominated by bulbous bluegrass (*Poa bulbosa* L.), field bindweed, jointed goatgrass (*Aegilops cylindrica* Host) and cheatgrass (*Bromus tectorum* L.). The Enterprise site is a Semidesert Shallow Loam Wyoming big sagebrush site (R028AY243UT) in Washington County, which burned in the Flatt Fire in June 2021. Before the fire, the area had been heavily invaded by cheatgrass.

The Rio Tinto Kennecott tailings impoundment is in Salt Lake County. Soil-substrate on the tailings impoundment is a sediment material from the mine’s refining process. At this mine, copper, molybdenum, and other metals are extracted from native ore. After the minerals are extracted, the remaining sediment material is moved to the tailings impoundment. This material will either become the permanent soil substrate for the site or will be capped with 1 m of topsoil cover. Our experiment was conducted on a site that did not have a topsoil cover.

To control competing vegetation, Sage Valley, Santaquin, and Enterprise were treated 30 days prior to planting with a mixture of glyphosate (Big and Tough, Gordon’s Farm, Kansas City, MO, USA) and 2,4-D (Southern Ag., Boone, NC, USA). The mixture was applied at a rate of 350 g of acid equivalent (a.e.) ha⁻¹ glyphosate and 840 g a.e. ha⁻¹ 2,4-D. The Magna site had little established vegetation within the study area, so herbicide was not applied at that location.

*Seed Coating*

This study tested two separate seed coatings, one comprised primarily of calcium
carbonate (limestone) (Clayton Calcium, Parma, ID), hereafter referred to as a “blank coating” and the other containing limestone and an additional layer of ETHOCEL™ Standard 10 ethylcellulose polymer (Dow Chemical, Midland, MI), which is hereafter is referred to as the “hydrophobic coating” (Figure 2-2). The blank coating was permeable to water, allowing us to test the effect of seed coating alone on winterfat establishment. This blank coating also provided a smooth base for the addition of ETHOCEL™, which is a hydrophobic cellulose ether-based material (Adeleke 2019). The hydrophobic properties provided by ETHOCEL™ were the primary barrier to keeping seeds from imbibing moisture. Germination is presumed to take place after this hydrophobic coating material degrades over the winter.

Winterfat fruits were sourced near Elko, Nevada, in the fall of 2020 and stored at the Utah Division of Wildlife Resources Great Basin Research Center’s seed warehouse (Ephraim, UT). Coating took place in November 2021 at Brigham Young University (Provo, Utah) in a 31-cm diameter rotary drum seed coater (Universal Coating Systems, Independence, OR) (Madsen et al. 2016).

In preparation for coating, inert matter (i.e., sticks and other debris) was removed by passing the fruits through a 10 mm sieve. Coating was performed on 125 g batches of fruit with the coater set to 23% of its maximum speed. While the fruits were spinning in the coater, 150 ml of water was applied to the atomizing disc, which evenly dispersed the water onto the fruits. 100 g of limestone powder was then poured directly onto the wetted fruits. Next, 60 ml of a solution containing 40% Agrimer-15 binder in water (Ashland, Inc., Covington, KY), was applied to the atomizing disc at about 2 ml/s using a peristaltic pump. Then 1,300 g of calcium carbonate and 140 g of binder were added in small alternating increments, with the calcium carbonate powder applied directly to the seed while the binder was pumped onto the atomizing disc. After coating,
fruits were dried for 30 min on a forced air dryer at 43°C, then stored in the cooler at 4°C until planting.

Hydrophobic coatings were applied to blank-coated fruits. Each batch contained approximately the same number of seeds as batches in the blank coating process. The hydrophobic coating was applied to the blank-coated fruits by adding 800 g of a 7% ETHOCEL™ acetone solution. ETHOCEL™ was applied to the atomizing disk using a peristaltic pump. During the application of this polymer, heated air (46°C) was blown through the fruits from the bottom of the chamber wall of the seed coater to volatilize off the acetone carrier. The rotary drum was set to 20% of its maximum speed during this process.

Experimental Design

At each site, we installed studies in a randomized complete block design with seven replicate blocks. Each block contained three seed treatments, non-coated (control), blank-coated, and hydrophobic-coated seeds planted in furrowed rows. Furrows were 2 m long, 15 cm deep, and 30 cm wide at the bottom, with a 50 cm spacing between rows. U-shaped furrows were made with furrowers attached to a plow bar pulled by a tractor. Within each furrow, seeds were hand-planted at a rate of approximately 148 pure live seeds (PLS) m⁻¹.

Data Collection and Analysis

The number of emerged seedlings within each row was counted in May 2022. As part of this assessment, the emerged seedlings were recorded as being alive or dead. The percent mortality of emerged seedlings was calculated by dividing the number of dead seedlings by the total number of seedlings. Data from the Santaquin and Enterprise sites were excluded from our analysis because emergence was extremely low. There were only three living seedlings at Santaquin and two at Enterprise, equating to less than 0.01% emergence at these sites. This could
have been due to low precipitation and thick soil crusts at both sites. Subsequently, we only analyzed data from Sage Valley and Magna locations for this study. Statistical analyses were performed using JMP Pro (version 16 SAS Institute, Inc., Cary, NC, USA). Seedling emergence data of live and dead seedlings was analyzed using Generalized Linear Mixed-effects models with a Poisson response distribution fit with a Log link. In the models, seed treatment was included as a fixed effect and sites, blocks, and sites crossed with blocks were considered random effects. The percent mortality of emerged seedlings was assessed with a binomial distribution fit with a logit link. Again, seed treatment was included as a fixed effect, and sites, blocks, and sites crossed with blocks were considered random effects. These analyses used a Tukey-Kramer honestly significant difference multiple comparison method to test for differences between seed treatments ($P < 0.10$).

RESULTS

Environmental Conditions

During the seed incubation period (i.e., October through May), precipitation was generally well below the long-term average at all sites, except for October and December (Figure 2-3). Temperatures were slightly warmer than average in November and somewhat cooler than average in February. In May, Enterprise had no detectible precipitation, Santaquin and Magna precipitation was near average, and Sage Valley was 61% of the 30-yr average. Temperatures in May were near average at Enterprise and slightly cooler than average at all other sites (Figure 2-3).

Influence of Seed Coatings on Emergence and Mortality

Seed treatment affected the total number of seedlings that emerged ($F_{2,30} = 10.3, P =$
0.004), established ($F_{2,30} = 13.2, P = 0.001$), and died after emerging ($F_{2,25} = 2.8, P = 0.080$). The total number of seedlings that emerged from the hydrophobic treatment, which included live seedlings and those that had died after emerging, was two-fold greater than the control ($P=0.044$), and four-fold greater than blank coated seeds ($P=0.001$) (Figure 2-4). The total number of seedlings that emerged from blank-coated seeds was 58% lower than the control ($P=0.075$).

The number of seedlings that had emerged and were still living at the time of counting was three-fold and five-fold greater in the hydrophobic treatment compared to the control ($P=0.003$) and blank-coated seeds ($P=0.001$), respectively.

The percentage of seedlings that died after emerging was highest for the control, lower for blank coatings, and lowest for hydrophobic coatings. Here the percentage of dead seedlings was approximately two-fold higher for the control than for hydrophobic-coated seeds ($P=0.067$) (Figure 2-5). The percentage of dead seedlings from blank-coated seeds was statistically similar to both hydrophobic-coated seeds and the control (Figure 2-5).

**DISCUSSION**

Rangeland seeding projects are implemented to establish native and desirable plants on degraded landscapes, but the success rates of these projects have been highly variable (James et al. 2011; Boyd & Davies 2012; Shackelford et al. 2021). Winterfat is a valued protein-rich subshrub that has had limited seeding success in restoration projects in western North America, which may be partly due to pre-winter seed germination (Booth & Schuman 1983; Booth & Griffith 1984; Thacker et al. 2023). To address this limiting factor, we evaluated the use of a hydrophobic seed coating as a means to repel water, slow imbibition, and delay germination until
The results of this study generally supported our hypothesis that a hydrophobic seed coating can improve seeding success of fall-sown seeds. Here, we found that a hydrophobic seed coating yielded three-fold more established plants than the control. On average, non-coated seeds produced one plant/m² and hydrophobic-coated seeds produced three plants/m² (Figure 2-4). These findings corroborate similar results from studies that evaluated the influence of hydrophobic coatings on the emergence of dryland bunchgrasses (Madsen et al. 2016; Baughman et al. 2022) and forbs (Fund et al. 2019). Based on these studies, hydrophobic coatings seem to reduce winter mortality and improve emergence for multiple rangeland plant species when pre-winter germination is a potential threat to seedling establishment.

In this study, the timing of seed germination was not measured for any of the treatments, so we cannot say with certainty that the hydrophobic coating delayed germination or that this was the mechanism that resulted in a higher number of live seedlings. However, this mechanism has been successfully demonstrated on bluebunch wheatgrass by Baughman et al. (2022), and we anticipate that it was the delay of germination by the hydrophobic coating that improved seeding success in this study. Additionally, the hydrophobic seed coating treatment had a lower percentage of dead plants relative to the control. Likely, seedlings from hydrophobic-coated seeds emerged later than the control, probably during the spring, and so they were exposed to lethal winter conditions for less time than seedlings from non-coated seeds. However, it should be noted that actual mortality rates could have been higher than the ones measured since we only recorded the number of dead seedlings we could detect during sampling. Some seedlings could have emerged, died, decomposed, and gone unrecorded. For blank coatings, the total number of emerged seedlings, including live and dead seedlings, was lower than the control, while the number of live seedlings was similar to the control. It is possible that blank-coated seeds
germinated earlier than the control, possibly during favorable conditions during late fall, and germinated seedlings died and became undetectable by the time of counting. Our observations in laboratory trials (Chapter 1 of this Thesis) are that blank coatings may improve seed-soil contact compared to non-coated seeds, which could have caused the coated seed to germinate before the control. Hence these observations may indicate that if winterfat is to be coated, this treatment should include a hydrophobic coating layer or seeding should take place during the winter to avoid mortality associated with premature germination.

In the context of winterfat restoration and the use of a hydrophobic seed coating, there is still a need for more research. In this study, we only tested one hydrophobic coating application rate. Higher application rates of hydrophobic material within coatings may delay germination longer than lower rates and may improve seedling success rates. However, the optimum amount of time to delay germination and enhance seeding success could vary based on site conditions, such as soil moisture and the number of freeze-thaw events during the winter. Since winter conditions can be difficult to predict, varying hydrophobic coating application rates within the same seed lot could serve as a bet-hedging strategy (Madsen et al. 2016; Brown et al. 2021). For example, one seed mix could contain seeds coated with hydrophobic material at low, medium, and high rates to account for multiple winter moisture and temperature scenarios. This strategy diversifies the potential responses of the seeding to a variety of environmental conditions, which should reduce the likelihood of seeding failure (Baughman et al. 2022).

While the hydrophobic coating produced substantially more plants than the control, the emergence rates of this treatment were still low relative to the number of seeds that were sown. Of the seeds sown, only 0.8% and 2.4% of control and hydrophobic-coated seeds produced an established plant in two of the four sites used in the analysis of this study. The other two study
sites were excluded because seedling emergence was severely limited or absent, which is possibly due to extremely dry conditions throughout the study. These results highlight the difficulty of improving seeding success rates in dryland environments and demonstrate the need for novel seeding techniques and technologies to improve restoration efforts during drought conditions.

The application of hydrophobic seed coatings could make winterfat seeding projects more cost-effective. Seed coatings impose the extra cost of materials and labor, which may strain already limited budgets. However, since planting winterfat at adequate seeding rates is not currently practical and plantings are commonly unsuccessful for this species, the benefits of applying seed coatings may outweigh the costs. The likelihood of success could increase with the ability to plant winterfat in more restoration projects at adequate seeding rates and improved establishment from delayed germination. Thus, despite the cost, monetary waste may be reduced by improving seeding success. Additionally, winterfat coating processes have become more efficient with ongoing research. Thacker et al. (2023) had to flash-flame winterfat fruits to apply a polymer seed coating. Insights provided by Thacker et al. (2023) enabled us to coat winterfat without that pre-treatment. Thus, the seed coating used in this study should be more cost-effective. Further, our coating improved upon the research of Thacker et al. (2023) by demonstrating that a hydrophobic barrier could be applied to the outside of the seed coating to delay germination. Hence, this coating treatment can address two major restoration barriers (i.e., poor flowability and premature germination), which further improves the performance and potential cost-efficiency of the technology.

Management Implications

Restoration of winterfat to degraded landscapes is highly sought after but difficult to
achieve because of poor seed flowability and low seeding success. These two barriers can be addressed using hydrophobic seed coatings, which allow seeds to flow freely through mechanical seeding equipment and reduce the occurrence of premature germination, encouraging plant establishment during the spring when lethal winter conditions have passed. While other strategies to overcome these barriers have been studied, hydrophobic coatings could offer certain advantages. For instance, mechanical cleaning can improve flowability of winterfat seeds by removing them from the fruits. However, this practice can reduce germination, emergence, and seedling vigor (Booth 1983). In contrast, hydrophobic coatings allow intact winterfat fruits to flow freely, and can result in improved emergence. In addition, hydrophobic coatings may be an efficient way to improve seedling establishment, since they allow seedlings to bypass multiple winter hazards rather than addressing just one. For instance, fungicide seed coatings could protect winterfat seedlings from pathogen attack but may leave them vulnerable to freezing and winter drought. By delaying germination, hydrophobic coatings may reduce the likelihood of seedling mortality from a variety of winter hazards.

To build upon the results of this study, we suggest that future research be conducted to refine the hydrophobic seed coating process, such as by testing various rates of hydrophobic material within coatings. Future research could also consider evaluating the use of industrial-sized coating equipment to apply the treatments in this study in landscape-scale seeding projects.
LITERATURE CITED


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https://scholarsarchive.byu.edu/etd/8928.
Figure 2-1 – Locations of study sites near Magna, Santaquin, Sage Valley, and Enterprise, Utah, USA.
Figure 2-2 – Photo showing non-coated (control), blank-coated, and hydrophobic-coated winterfat (*Krasheninnikovia lanata* (Pursh) A. Meeuse & Smit) fruits.
Figure 2-3 – Monthly precipitation and temperature averages throughout the study (2021-2022), compared to the 30-year averages (1991-2021) for study sites near Sage Valley, Magna, Santaquin, and Enterprise, Utah, USA.
Figure 2-4 – Average densities of live and total winterfat (*Krasheninnikovia lanata* (Pursh) A. Meeuse & Smit) seedlings at Sage Valley and Magna study sites in Utah, USA. The live category included seedlings that were alive at the time of counting, and the total category included live seedlings plus those that had died after emerging. Seeds were planted in November 2021 and counted in May 2022. Treatments included non-coated (control), blank-coated, and hydrophobic-coated seeds. Differences at the $p < 0.10$ level are indicated by different letters above each bar within live and total categories.

Figure 2-5 – Percentage of winterfat (*Krasheninnikovia lanata* (Pursh) A. Meeuse & Smit) seedlings found dead at the time of sampling relative to the total number of emerged seedlings for non-treated (control), blank-coated, and hydrophobic-coated seeds. Differences at the $p < 0.10$ level are indicated by different lower case letters.
Table 2-1 – Characteristics of study sites near Sage Valley, Magna, Santaquin, and Enterprise, Utah, USA. Climate data is based on 30-year averages from PRISM models (PRISM Climate Group 2022). Soil data is sourced from web soil survey (Soil Survey Staff 2022).

<table>
<thead>
<tr>
<th>Site</th>
<th>Coordinates (N, E)</th>
<th>Habitat Type (ESD)</th>
<th>Elevation (m)</th>
<th>Average Annual Precipitation (mm)</th>
<th>Mean Temperatures Jan Low, July High (°C)</th>
<th>Soil Surface Texture</th>
<th>Soil pH</th>
<th>Organic Matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sage Valley</td>
<td>39.5462, -112.0683</td>
<td>Bonneville Big Sagebrush (R028AY310UT)</td>
<td>1611</td>
<td>320.5</td>
<td>-8.8, 32.9</td>
<td>Loam</td>
<td>8.5</td>
<td>3.00</td>
</tr>
<tr>
<td>Magna</td>
<td>40.72055, -112.09511</td>
<td>Mine Wash</td>
<td>1308</td>
<td>417.1</td>
<td>-5.5, 33.5</td>
<td>Sandy loam</td>
<td>7.9</td>
<td>0</td>
</tr>
<tr>
<td>Santaquin</td>
<td>39.9073, -111.8163</td>
<td>Wyoming Big Sagebrush (R028AY334UT)</td>
<td>1569</td>
<td>437.2</td>
<td>-7.6, 32.7</td>
<td>Stony loam</td>
<td>7.6</td>
<td>2.00</td>
</tr>
<tr>
<td>Enterprise</td>
<td>37.5889, -113.7157</td>
<td>Wyoming Big Sagebrush (R028AY243UT)</td>
<td>1628</td>
<td>383.6</td>
<td>-8.3, 32.1</td>
<td>Gravelly loam</td>
<td>7.6</td>
<td>1.50</td>
</tr>
</tbody>
</table>