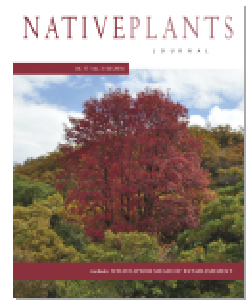
Extruded seed pellets: A novel approach for enhancing sagebrush seedling emergence

Matthew D Madsen, April Hulet, Karma Phillips, Jerry L Staley, Kirk W Davies, Tony J Svejcar



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Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young [Anthemideae]) plant community near Burns, Oregon. Photo by Kirk Davies

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ABSTRACT

Small or low-vigor species can be susceptible to being planted at depths that prevent seedling emergence. As an example, sagebrush (*Artemisia* spp. L. [Anthemideae]) seed is often prone to being planted at depths where the seedlings cannot emerge from the soil. We evaluated a potential solution to this problem that incorporates seed within an extruded pellet that is designed to enhance seedling emergence through the swelling action of the pellet creating conduits for the emerging seedlings to follow. We quantified the swelling capacity of the extruded pellet and evaluated how the technology improves seedling emergence and plant growth of Wyoming big sagebrush (*Artemisia tridentate* Nutt. ssp. *wyomingensis* Beetle & Young), over a range of seeding depths (5, 10, and 15 mm [0.2, 0.4, and 0.6 in]), within silt-loam and sandy-loam soils. Swelling capacity of the pellets in the silt-loam soil was approximately twice that of the sandy-loam soil. At all planting depths, pellets improved seedling emergence between 2.3- to 10.0-fold in the silt-loam soil. In the sandy-loam soil, no treatment effect occurred for seedling emergence at the 5 mm and 15 mm depths, but pellets enhanced emergence at the 10 mm depth by 3.1-fold. Some indications suggest that seedlings produced from the extruded pellets had greater growth than untreated seed. This technology opens up the possibility for sagebrush (and potentially other small-seeded species) to be seeded at deeper soil depths where soil water potential levels are more conducive for seed germination and seedling survival. Future development and field testing are merited.

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KEY WORDS

seeding depth, seed enhancement technology, Wyoming big sagebrush, seedling emergence, planting techniques, rangeland restoration, soil physical crust, Anthemideae

NOMENCLATURE

USDA NRCS (2004)

CONVERSIONS
1 mm = 0.04 in
1 cm = 0.4 in
1 l = 0.26 gal

The sagebrush (*Artemisia* spp. L. [Anthemideae]) biome is considered one of the most imperiled habitats in North America, as it has been substantially reduced in area and quality (Noss and others 1995). A major source of habitat loss and degradation can be attributed to sagebrush systems experiencing larger, more severe, and more frequent wildfires compared to historical conditions (Keane and others 2008). With this habitat loss, many sagebrush-associated species, such as greater sage-grouse (*Centrocercus urophasianus* [Phasianidae]) are declining in population (US Fish and Wildlife Service 2010). Survival of sage-grouse and other sagebrush-associated species is dependent on land managers' ability to prevent the loss of intact systems and to effectively restore areas that have been degraded (Stiver and others 2006; Arkle and others 2014).

Sagebrush species are the major keystone plants of the sagebrush biome (Davies and others 2011). After a wildfire most sagebrush species are killed by the fire and their seed typically will not persist in the soil for more than a year or 2 (Chambers 2000; Wijayratne and Pyke 2009). Therefore, rapid post-fire regeneration of sagebrush needs to occur by seed from outside of the burned area. Maximum dispersal distances are only about 30 m (33 yd) from the parent plant. Consequently, after a large-scale, high-intensity wildfire, nearby seed sources may not be available for natural recovery (Wagstaff and Welch 1990). For this reason land managers often seed sagebrush after wildfire and other disturbances (Shaw and others 2005).

Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) is a dominant shrub on the more arid portions of the sagebrush biome. Efforts to reestablish this species have typically failed to produce shrub densities that meet management objectives. Lysne and Pellant (2004) found that aerially seeded big sagebrush failed to establish on 23 of 35 post-fire rehabilitation projects. Arkle and others (2014) assessed greater sage-grouse habitat on 826 plots associated with 101 post-wildfire seeding projects and found that none of the treated plots met sage-grouse breeding season sagebrush overstory guidelines, few (2 of 313) met brood-rearing

Representative Wyoming big sagebrush environment near Burns, Oregon. Photo by Kirk Davies

Example of a burned Wyoming big sagebrush plant community within the 2007 Milford Flat Wildfire near Milford, Utah. Photo by Matthew Madsen

overstory guidelines, and only 2% potentially met winter overstory guidelines.

To sustain North America's sagebrush biome, novel approaches are needed that can be used to restore degraded landscapes with shrub cover that meet wildlife habitat requirements (Arkle and others 2014). Wyoming big sagebrush seeding efforts are limited by a host of abiotic and biotic constraints. In arid systems, seed coverage at an appropriate depth is one of the most critical factors for successfully establishing native plant materials from seed (James and Svejcar 2010). The small size of sagebrush seed (~1 mm or less) presents a unique challenge, particularly when using seeding equipment, such as seed drills, which are necessary to plant large areas. Planting guides for Wyoming big sagebrush suggest that strict attention must be paid to drilling depth, so seeds are placed no deeper than 5 mm (Jacobson and Welch 1987), but optimal planting depths as shallow as 2 mm have been suggested (Jensen and others 2001; Lambert 2005). Fine-textured soils (with a higher percentage of silt and clay) are inherently more limiting on seedling emergence when seeds are planted too deep, particularly if soils are susceptible to forming a physical soil crust (Wood and others 1982; Madsen and others 2012).

Madsen and Svejcar (2011) filed a US patent to improve seedling emergence of small-seeded species using "seed extrusion technology." Through this approach, seeds are incorporated into pellets that are engineered to enhance seedling emergence and plant growth (Figure 1). Extruded pellets are formed with equipment modified from the food processing industry to extrude pasta dough. In the process of making extruded pellets, a dough is formed from seed and a host of materials that aid in seed germination, seedling emergence, and early plant growth. Depending on species and site conditions, example additives that could be added into the dough recipe include water-sensitive binders, hydrophilic clay filler materials, super-absorbent polymers, fungicides, plant growth regulators, humates, fertilizers, inoculates, deterrents, and soil surfactants

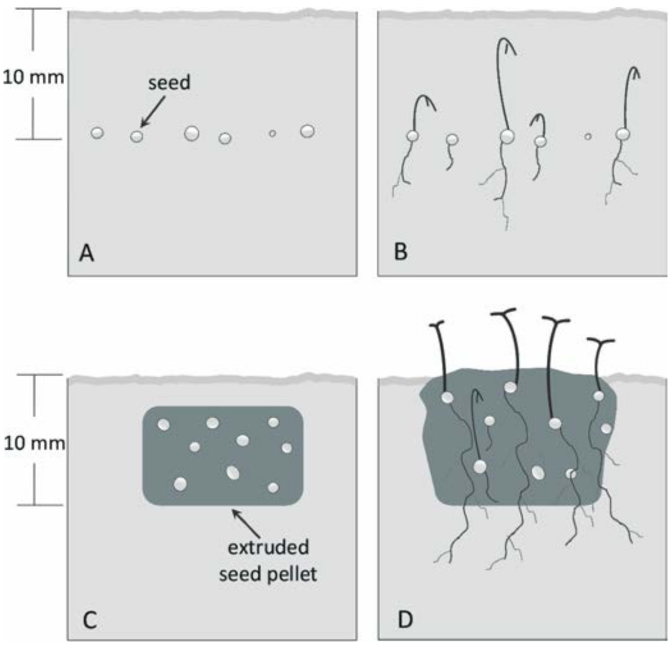

Figure 1. Theoretical illustration of sagebrush seed planted at a 10 mm depth in the soil (A); emerging seedlings are unable to extend out of the soil at this depth (B); extruded seed pellet with sagebrush seed planted at the same depth raises seed closer to the soil surface (C); after watering, the pellet swells, further optimizing the position of the seeds in the soil and allows emerging seedlings to bypass the soil crust layer and emerge from the soil (D).

(Madsen and Svejcar 2011). The dough mixture is extruded through a circular die, cut into ~10 mm long pellets, and dried over forced air. When the pellets are drill seeded with the top of the pellet near the soil surface, the emerging seedlings bypass restrictive near-surface soil layers, such as soil physical crust (Figure 1). The high water absorbency of the materials used in the pellet causes the pellet to swell, which pushes seeds to the surface and creates small voids or conduits for the emerging seedlings to follow (Figure 1).

The objective of this study was to quantify the swelling capacity of extruded pellets and to determine the potential benefit on Wyoming big sagebrush seedling emergence and early planting growth, over a range of seeding depths and within different soil types (sandy-loam and silt-loam soils).

MATERIALS AND METHODS

Research Location, Plant Material, and Soils

Research was conducted at the Eastern Oregon Agricultural Research Center's seed coating and grow-room facilities (Burns, Oregon). Wyoming big sagebrush seed was donated by the Utah Division of Wildlife Resources Great Basin Research Center (Ephraim, Utah). Seed had been cleaned to 30% purity and at the time of the study had an 80% germination rate.

Silt-loam and sandy-loam soils were obtained from a Wyoming big sagebrush–steppe community type, located at the USDA Agricultural Research Service's Northern Great Basin Experimental Range, southwest of Riley, Oregon (silt-loam collection site = 43.45, 119.7; sandy-loam location site = 43.483333, 119.71667). Soil was excavated from a maximum depth of 25 cm, with the top 2 cm of soil and litter discarded to remove existing seeds. The silt-loam soil was classified as a fine-loamy, mixed, frigid Aridic Haploxeroll, with a pH of 7.4, organic matter content of 1.5%, and unsaturated hydraulic conductivity of 3.3 cm/h (1.3 in/h) (Soil Survey Staff 2014). The sandy-loam soil was classified as a fine-loamy, mixed, frigid Argiduridic Argixerolls, with a pH of 7.2, organic matter content of 1.5%, and unsaturated hydraulic conductivity of 10.2 cm/h (4.02 in/h) (Soil Survey Staff 2014).

Seed Treatments

Recipes used to produce extruded sagebrush pellets are shown in Table 1, along with manufacturer names and product suppliers. Extruded pellets were made with approximately 12 pure live seeds (PLS)/pellet. In general, sagebrush seed has relatively low emergence rates and based on preliminary trials we determined that a minimum of 12 PLS/pellet was required to improve the consistency of each pellet producing a seedling. In addition to seed, dry materials used in the extruded pellet recipe included calcium bentonite, biochar, worm castings, compost, super-absorbent polymer, and starch. These ingredients were chosen based on preliminary research trials conducted prior to this study. In choosing ingredients, effort was made to develop a pellet that remained rigid enough to avoid crumbling during shipping and planting; conversely, after planting, the pellet should rapidly dissolve so emerging seedlings would not be constrained within the pellet. Additionally, materials were chosen to improve water retention and to improve fertility within the seedling microsite. We found that partially pre-gelatinized maize starch provided pellets with both rigidity for planting and rapid breakdown when it was exposed to water after planting. Additionally, calcium bentonite improved pellet hardness when dry and aided in moisture retention after planting. Biochar, worm castings, compost, and super-absorbent polymer allowed for a rapid breakdown of the pellet upon hydration and decreased resistance to an emerging seedling. Biochar, worm castings, and compost may also aid in improving fertility within the seed microsite.

Biochar was produced in-house using western juniper (*Juniperus occidentalis* Hook. var. *occidentalis* [Cupressaceae]) wood chips burned in a "top-lit updraft" gasifier with a 208-l (55-gal) burn chamber (Saravanakumar and others 2007). After burning, biochar was ground using a model 4E Electric Grinding Mill (Midland Scientific, Omaha, Nebraska). Worm castings and compost were air-dried and passed through a 1.0 mm sieve to remove large debris. Both powder and fine granule super-absorbent powders were used in the pellets. While both sizes of super absorbent powders aid in water

TABLE 1

Recipe for producing approximately 11,000 extruded seed pellets, along with trade names and suppliers for use in silt-loam and sandy-loam soils.

Material	Trade name	Supplier	Recipe silt-loam soil (g)	Recipe sandy-loam soil (g)
Dry material				
Sagebrush seed		Utah Division of Wildlife Resources (Ephraim, UT)	181.2	215.8
Calcium bentonite	Pelbon	American Colloid Company (Hoffman Estates, IL)	2213.4	2213.4
Biochar		Produced in-house	273.5	273.5
Worm castings	Worm Gold	California Vermiculture (Cardiff, CA)	2658.1	2658.1
Compost		Deschutes Recycling (Bend, OR)	1474.4	1474.4
Super-absorbent powder	Stockosorb	Evonik Corporation (Greensboro, NC)	214.2	214.2
Super-absorbent granules	Stockosorb	Evonik Corporation (Greensboro, NC)	89.3	267.8
Starch	Starch 1500	Colorcon (Indianapolis, IN)	110.7	110.7
Liquids				
Surfactant	ASET-4001	Aquatrols Corporation of Amercia (Paulsburo, NJ)	7.1	7.1
Plant growth regulator	Ascend	Winfield Solutions (St Paul, MN)	21.4	21.4
Water (tap)			4993.0	6745.0

retention and swelling of the pellet, we had previously observed that the larger size super-absorbent granules can make voids in the pellet and soil to aid in seedling emergence. Preliminary trials conducted on the 2 soil types used for this study showed that infiltration rates had a strong impact on pellets' swelling capacity. The swelling capacity of extruded pellets was less in the sandy-loam soil than in the silt-loam soil. Because of faster infiltration rates in the sandy-loam soil, less water was directed toward the pellet, and the soil did not remain at an elevated moisture level. Thus, when super-absorbent levels were increased to improve swelling in the sandy-loam soil, we discovered that the amount of swelling in the silt-loam soil became too great, causing pellets to rise completely out of the soil. In an attempt to maximize the efficacy of the pellet in both soils, we applied 3 times more super-absorbent powder in pellets that were planted in the sandy-loam soil. This amount of super-absorbent material was the maximum amount we could use in the recipe and still allow the material to flow through our treatment machinery (explained below).

Liquid materials used in the recipe included tap water, a non-ionic alkyl terminated block co-polymer surfactant, plant growth regulator formulated with cytokinin, gibberellic acid, and indolebutyric acid. Soil surfactant was included to allow for rapid wetting of the pellet and seed, and plant growth regulators accelerated seed germination and seedling growth.

Extruded seed pellets were made in a TR-100 Pasta Machine (Rosito Bisani Imports, Los Angeles, California) (Figure 2). Prior to adding the liquids, the dry material was thoroughly mixed. Liquid materials were combined and then slowly added to the dry material while it was mixing over a period of approximately 1 min. The liquid and dry materials were then mixed

Figure 2. Production of extruded seed pellets with a TR-100 Pasta Machine. Photo by Matthew Madsen

for an additional 3 min and then extruded through the pasta machine. These mixing times and liquid amounts produced a "friable" dough that would effectively flow through the auger. Excess water or mixing times tended to compact the dough and cause it to bind on the walls of the extruder. Seed dough material was extruded through an 8-mm round die. After exiting the die, the extrusion stream was cut into approximately 10 mm lengths using a rotary wire cutter that was retrofitted onto the pasta machine (Figure 2). For the purpose of this laboratory study, we used only pellets that were 10 mm in length to improve consistency in seeding rates.

Study 1: Pellet-Swelling Capacity

Swelling height of extruded pellets was examined at planting depths of 5, 10, and 15 mm within silt-loam and sandy-loam soils in a randomized block split-plot design. The study was split by soil type. Each soil type was placed in a 16-l wooden box (50 × 40 cm on a side), with a soil depth of 8 cm. Within the box, 8 experimental blocks were designated. A block consisted of 12 pellets evenly spaced and randomly assigned to 1 of 3 planting depths. Pellets were planted in the soil so the bottom of the pellet was at the desired planting depth and oriented horizontal to the soil surface. For example, at a 5 mm planting depth, the top of an 8 mm pellet would stick out of the soil 3 mm, and a pellet with the same diameter planted at 10 mm would be 2 mm below the soil surface.

Prior to planting, soils were watered to 50% of the field capacity (volumetric soil water content of soil was 18.7% and 19.5% for silt-loam and sandy-loam soils, respectively). Field capacity was determined through the container capacity method on 3 replicate 41 mm diameter soil cores for each soil type (Cassel and Nielsen 1986). After planting, boxes were watered with 15 mm of water, which was the amount of water needed to bring the silt-loam soil to field capacity and 96% of the water needed to bring the sandy-loam soil to field capacity. Watering was performed with a fine-mist sprayer, applied at a rate of 33 mm/h (1.3 in/h).

Distance from the soil surface to the top of the pellet was measured both prior to and after watering. Location of the pellet in the soil was determined by subtracting the distance from a fixed metal bar to the soil surface and distance from the bar to the top of the pellet. Swelling capacity out of the soil was calculated as the difference in the change in height between the top of the pellet and soil surface prior to watering and after watering.

Study 2: Seedling Emergence and Plant Growth

Extruded seed pellets were compared against untreated seeds at planting depths of 5, 10, and 15 mm (2 seed treatments × 3 planting depths = 6 treatments) within silt-loam and sandy-loam soils in a randomized block split-plot design. The study was split by soil type. For each soil type, 10 replicate boxes were filled with soil as described in Study 1. Within a box, the 6 seeding treatments were planted with 1 treatment per row. Rows were 40 cm long and contained approximately 120 seeds. Because of the small size of the seed and sagebrush's inherently high amount of non-seed parts that are not able to be logistically cleaned from the seed, we determined the number of seeds/g in the seed mix and then used this ratio to estimate the weight required to equal 120 seeds. For the rows with extruded seed pellets, 10 pellets (with 12 seeds/pellet) were evenly spaced across the row.

Soil containers were placed in an environment-controlled grow-room set at a constant temperature of 21 °C (69.8 °F), 12-h day length, and 632 W • m^{-2} of fluorescent lighting. Initial watering of the pellets was performed in the same manner as described in Study 1. Over the remainder of the study, wooden boxes were watered to approximately 70% of field capacity twice a week. At the conclusion of the study (73 d after planting), we counted the number of seedlings, measured plant height, and oven-dried (65 °C [149 °F] for 72 h) aboveground biomass.

Data Analysis

Pellet-swelling height was analyzed using a mixed model analysis of variance (SAS Institute 2006). In the model, planting depth and soil type were considered fixed factors, and blocks were random. The SLICE option with a Bonferroni adjustment was employed in the LSMEANS procedure to determine significant differences in swelling height between soil types.

Seedling density data were used to estimate seedling emergence by dividing number of seedlings in a row by the total number of pure live seeds planted. For the pellet treatments, we also estimated the number of seedlings that emerged from a pellet by dividing the number of seedlings in a row by the number of pellets sown. Per-plant biomass was estimated by dividing the

Wyoming big sagebrush seedlings. Photo by Matthew Madsen density of plants by total oven-dried biomass in the row. We used mixed model analysis to analyze plant emergence, height, total biomass, and per plant biomass. Again, blocks were considered random and seed treatments, planting depth, and soil type were considered fixed factors. Seed treatment × planting depth interactions and seed treatment × soil type interactions were significant; therefore, the LSMEANS procedure was used to compare seed treatment means within a planting depth and soil type using the SLICE option with a Bonferroni adjustment. Mixed model analysis was also used to compare the number of seedlings within a pellet, with blocks considered random and planting depth and soil type as fixed factors. For all comparisons in the study, significance was determined at $P \leq 0.05$. In the text and figures, means are reported with their associated standard error to evaluate significant differences between comparisons not determined through the LSMEANS procedure.

RESULTS

Study 1

The ability of the extruded pellet to swell after planting and change its location in the soil was strongly influenced by soil type and planting depth (Table 2). We also noted a two-way interaction between soil type and planting depth due to differences in swelling response at the 5 mm planting depth (Table 2; Figure 3).

Measurements of pellet-swelling height in the silt-loam soil at the 5 mm planting depth were not representative of the actual swelling capacity of the pellet. For this soil and planting depth, we observed that the pellet expanded with watering to an extent that caused it to rise out of the soil and flatten out on the soil surface (Figure 3A). At the 10 and 15 mm planting depths, swelling heights were similar to each other, with an average increase in pellet height of 4.8 ± 0.03 mm (Figure 3A). This amount of swelling allowed the top of the pellet at the 10 mm planting depth to rise out of the soil 2.7 ±0.3 mm, and at the 15 mm depth, the pellet was 2.2 ± 0.5 mm below the soil surface (Figure 3B).

TABLE 2

Results from mixed-model ANOVA for measurements recording the distance the extruded pellets swelled when planted in different soil types and at different planting depths. Results also show distance from soil surface to the swollen extruded seed pellet.

Effect	Swelling height		Distance from soil surface	
	F	Pr > *F*	F	Pr > *F*
Soil	6.68	< **0.012**	5.85	< **0.017**
Depth	8.09	**0.001**	163.77	< **0.001**
Soil × Depth	25.28	< **0.001**	24.05	< **0.001**

Notes: P values in bold are statistically significant ($P \leq 0.05$).

Pellets sown at the 5 mm depth in the sandy-loam soil did not swell and flatten out on the soil as they did in the silt-loam; they increased in height by 3.2 ± 0.3 mm (Figure 3A). Swelling height of pellets sown at 10 and 15 mm was similar, with an average increase in height of 1.9 ± 0.02 mm—less than half that of the silt-loam soil (Figure 3A). After watering the top of the pellets at the 10 and 15 mm, planting depths were 0.1 ±0.3 and 5.1 ± 0.3 mm from the soil surface, respectively (Figure 3B).

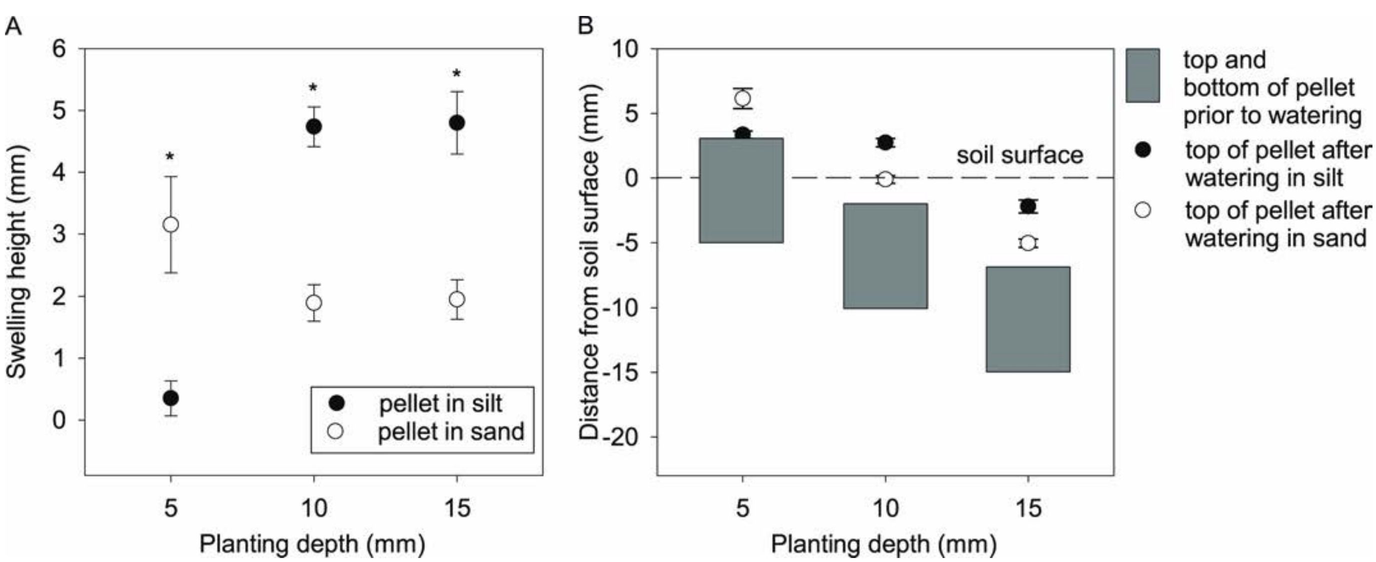

Figure 3. Change in height of extruded seed pellets sown at 3 different planting depths in silt-loam and sandy-loam soil (A); location of the bottom and top of the pellet prior to watering (represented by gray squares) and height of the top of the pellet after watering in silt-loam and sandy-loam soils (B). Asterisks indicate significant difference between seeding treatments at a given depth (P <0.05).

Study 2

Analysis of variance showed that seed treatment, soil, planting depth, and their two-way interactions had a significant impact on seedling emergence (Table 3). For the untreated seed in the silt-loam soil, the highest number of seedlings was found at the 5 mm depth (9.3 ± 2.3% emergence), which was more than 4-fold greater than at planting depths of 10 mm and 15 mm (Figure 4A). Seedling emergence from extruded pellets was similar with planting depth (range 20.9–21.5% emergence) and was 2.3-, 10.0-, and 9.6-fold greater than that produced from untreated seed placed at 5, 10, and 15 mm, respectively (Figure 4A).

In the sandy-loam soil, seedling emergence from untreated seed and the extruded pellet were similar at the 5 mm depth (18.4 ± 2.4% and 15.6 ± 2.3% emergence, respectively) (Figure 4A). At the 10 mm and 15 mm planting depths, seedling emergence declined for the untreated seed, with the 5 mm planting depth having 4.3- and 55.3-fold higher emergence, respectively (Figure 4A). Extruded pellets improved seedling emergence at the 10 mm depth by 3.1-fold and yielded emergence values similar to the 5 mm depth. Unlike in the silt-loam soil, extruded pellets showed no improvement at the 15 mm planting depth, with seedling emergence values near zero for both treatments.

Soil type was a strong driver of the number of seedlings that were produced from an individual pellet (Table 3). In the silt-loam soil, the number of seedlings/pellet was similar with depth, averaging 2.1 ±0.14 seedlings/pellet (data not shown). In the sandy-loam soil, seedlings/pellet declined with planting depth, with an average seedlings/pellet at the 5, 10, and 15 mm equal to 1.56 ± 0.23, 1.33 ± 0.20, and 0.18 ±0.06, respectively (data not shown).

Significant differences in individual plant heights were found for all main effects (Table 3). For untreated seeds, a weak trend was observed with plant height increasing at decreasing planting depth for both soil types (Figure 4B). In the silt-loam soil, seedlings grown from pellets had similar plant heights regardless of planting depth (Figure 4B). Although plant heights were higher on average for extruded pellets in the silt-loam soil, they were not significantly higher than for untreated seeds (Figure 4B). In the sandy-loam soil, a strong decline in seedling height was found with planting depth, particularly at the 15 mm depth for untreated seeds. As with the silt-loam soil, seedlings growing from a pellet did not decline in height with planting depth and produced significantly taller seedlings at the 10 and 15 mm depth than from untreated seeds. Seedlings grown from extruded pellets in the sandy-loam soil were 1.6- and 3.4-fold taller than seedlings grown from untreated seeds.

Biomass of individual plants had a similar response as plant height (Figure 4C). Again, no significant differences were found between seed treatments in the silt-loam soil for all seeding depths. In the sandy-loam soil at the 10 and 15 mm planting depths, plants from extruded pellets were 2.0- and 4.5-fold larger, respectively, than from untreated seeds (Figure 4C).

Total biomass produced from treatments, in general, followed a similar response as plant emergence (Figure 4D). In the silt-loam soil treatment, response mirrored that of plant emergence. The sandy-loam soil also had a similar response as plant emergence, with the exception that plant biomass from extruded pellets at the 10 mm depth was 5.9-fold greater than from untreated seeds (Figure 4D).

DISCUSSION

This study provides a proof of concept, under controlled laboratory conditions, that extruded seed pellets can facilitate seedling emergence of Wyoming big sagebrush. Extruded seed pellets provided the greatest improvement in seedling

TABLE 3

Mixed-model ANOVA results for the effect of seed technology, soil type, planting depth and their interactions on seedling emergence, average plant height, average biomass per plant, and total biomass production.

Effect	Seedling emergence		Seedlings/pellet		Plant height		Biomass/plant		Total biomass	
	F	Pr > *F*	F	Pr > *F*	F	Pr > *F*	F	Pr > *F*	F	Pr > *F*
Treatment	113.47	< **0.001**			12.23	**0.001**	9.48	**0.003**	128.85	< **0.001**
Soil	18.53	< **0.001**	36.72	< **0.001**	5.43	**0.022**	0.00	0.989	7.19	**0.009**
Depth	38.69	< **0.001**	11.50	< **0.001**	5.67	**0.005**	3.25	**0.043**	26.83	< **0.001**
Treatment × Soil	61.38	< **0.001**			2.73	0.101	8.00	**0.006**	19.84	< **0.001**
Treatment × Depth	9.53	< **0.001**			2.56	0.082	1.97	0.146	9.91	< **0.001**
Soil × Depth	17.28	< **0.001**	13.36	< **0.001**	2.04	0.135	1.14	0.323	11.50	< **0.001**
Treatment × Soil × Depth	1.67	0.193			0.79	0.457	0.36	0.696	4.09	**0.019**

Notes: P values in bold are statistically significant ($P \leq 0.05$).

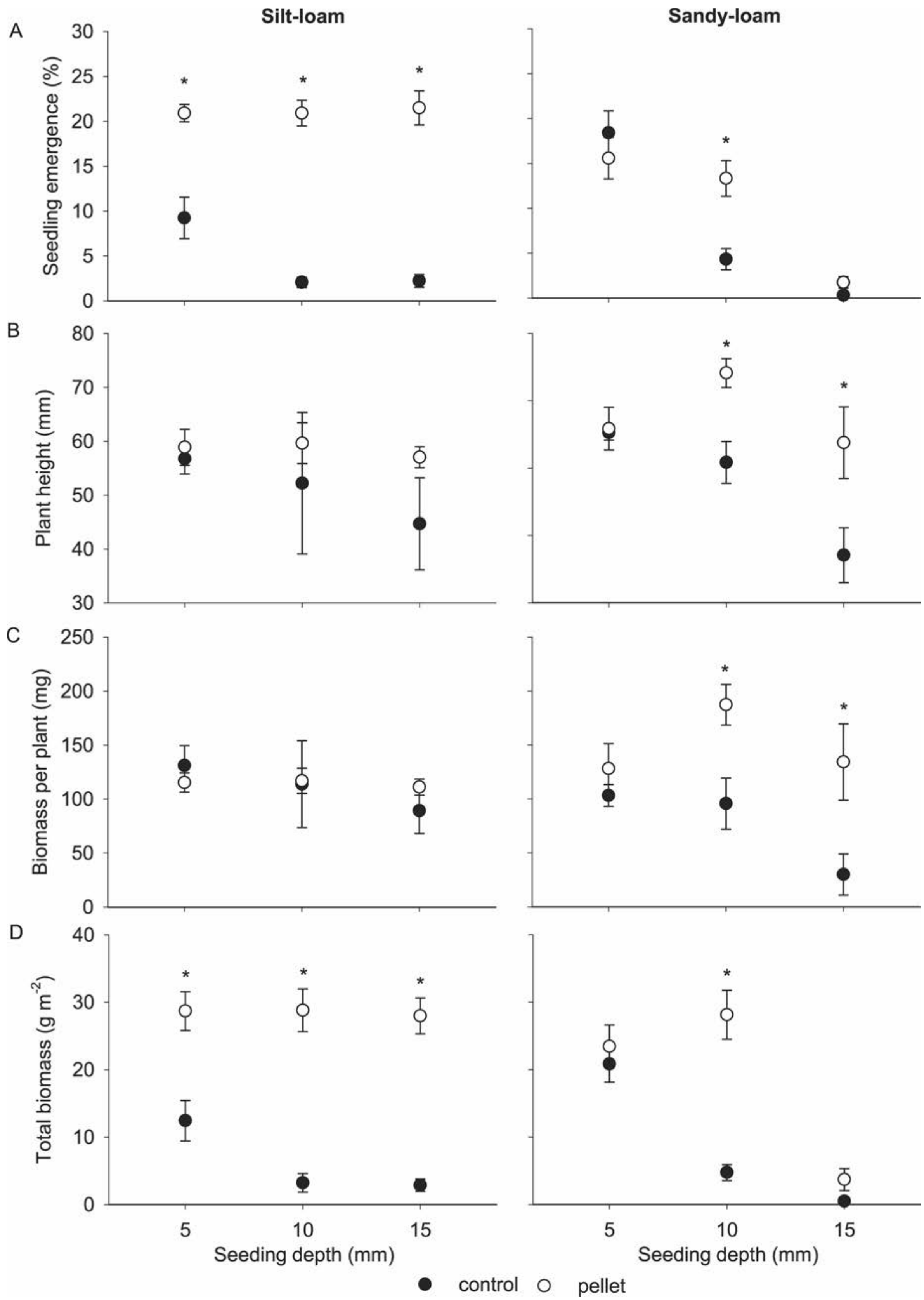

Figure 4. Seedling emergence, plant height, biomass per plant, and total biomass (mean ± SE) produced from untreated seed versus seed in an extruded pellet, sown at 5, 10, and 15 mm planting depths in silt-loam and sandy-loam soil. Asterisks indicate significant difference between seeding treatments at a given depth ($P < 0.05$).

emergence in silt-loam soil. Seeds planted in finely textured soils (with a higher percentage of silt and clay) were inherently more susceptible to poor emergence if planted too deep in the soil (Jacobson and Welch 1987). Fine-textured soils also have a tendency to crust after heavy rains or irrigation events, further impairing seedling emergence (Awadhwal and Thierstein 1985). In this study, seedling emergence of untreated seed sown in the silt-loam soil was severely limited at planting depths of 10 mm and greater. Even at a 5 mm planting depth, seedling emergence was low in the silt-loam soil. Extruded seed pellets improved seedling emergence by several fold at all planting depths in the silt-loam soil. We attributed the increase in plant emergence produced by the extruded pellet to the size and shape of the pellet, the pellet's swelling capacity, and the materials used to form the pellet. The pellet itself elevated seeds off the bottom of the drill row. Seeds sown in the extruded pellet varied between 0 to 8 mm (pellet diameter) up from the bottom of the drill row. The variation in seed height within the pellet would be significant for sagebrush given the small size of the seed (~1 mm) and relatively shallow optimum planting depth required (2.0–5.0 mm; Jacobson and Welch 1987; Lambert 2005). For example, in a drill row that is 10 mm deep, untreated seed would be planted at 10 mm, whereas seeds in a pellet would range between 2 and 10 mm below the soil surface assuming that seeds are distributed throughout the pellet. Seeds can be further elevated within the soil when precipitation events are sufficient to cause the pellet to swell. In this study, pellets sown at a 10 mm depth in silt-loam soil increased in height by almost 5 mm after watering, which raised the top of the pellet above the soil surface. These results may indicate that when extruded pellets are sown at a depth of 10 mm or less, the emerging seedlings may be able to bypass restrictive surface soil layers (such as soil physical crust) by allowing seedlings to emerge directly out of the pellet (see Figure 1).

In the sandy-loam soil, seedling emergence at the 5 mm planting depth was higher than that produced from the silt-loam soil, and at this depth untreated seed produced about the same plant densities as did the pellet. This result indicates that emergence was less limited at this depth in sandy-loam soil. Improved emergence produced from untreated seed out of the sandy-loam soil in comparison to the silt-loam soil is expected given that in low organic soils a sandy-loam texture typically has greater emergence capability due to larger soil pore spaces and given that the soil is less likely to form a physical soil crust (Brady and Weil 2002). Extruded pellets enhanced seedling emergence at the 10 mm planting depth, although it was not to the same extent as in the silt-loam soil and did not improve seedling emergence at the 15 mm depth.

Differences in seedling emergence from pellets between soil types may be attributed to differences observed in pellet swelling. Increased pellet swelling in the silt-loam soil may be attributable to differences in infiltration rates between the 2 soil types. Slower infiltration rates in the silt-loam soil appeared to better direct water toward the pellet during watering, causing the pellet to swell. In the sandy-loam soil, high infiltration rates allowed the added water to quickly drain through the soil, thus minimizing the amount of free water available for absorption into the pellet.

An interesting finding of this study is that the extruded pellet treatment at the 10 and 15 mm planting depths produced taller and larger individual seedlings in the sandy-loam soil compared to seedlings grown from untreated seed. While not significantly different, this trend also occurred in the silt-loam soil where pellets produced slightly taller and larger seedlings than did untreated seed. Improved plant growth in the extruded pellet treatment relative to untreated seed may be caused by the pellet raising the seeds closer to the soil surface. Having seeds closer to the soil surface may allow them to emerge faster and to subsequently grow larger. While not directly demonstrated for sagebrush, seedling vigor has been shown to decline for some species when seeding depths are below optimal (for example, Mutz and Scifres 1975; Liu and Han 2008). Also important, note that while seeds are being raised higher in the soil they are still connected to the larger pellet mass that extends deeper into the soil, where soil water potential levels are more conducive for seed germination and seedling growth (Harper and others 1965; Harper and Benton 1966). A properly engineered pellet with high water absorptivity may be able to distribute moisture adsorbed from the bottom of the pellet to seeds and seedlings near the top of the pellet (see Figure 1). Extruded pellets may also provide enhanced moisture and nutrient availability for rapid seed germination and emergence that would allow seedlings to begin growing earlier and faster. This response could be more profound in the sandy-loam soil, which has inherently lower water and nutrient retention capacities (Brady and Weil 2002).

Plant facilitation may also play a role in effecting seedling vigor. The collective grouping of seeds within the same microsite during planting may be more similar to the way plants grow in natural systems (Madsen and others 2012). Seeds often grow within groups or clusters due to physical process, such as wind and water movement depositing seeds in microsites or within cracks or imprints in the soil surface (Eckert and others 1986; Stamp 1989; Chambers and others 1991; Chambers 2000). Seeds can also be cached together through harvesting activities by insects and rodents (Vander Wall 1994). There may be multiple positive interactions associated with group plantings (Hunter and Aarssen 1988; Bertness and Callaway 1994; Fajardo and McIntire 2011). For example, seedling growth may be enhanced through 1) increased soil moisture, by having multiple seedlings growing within the same location, water retention and infiltration into the soil is improved; 2) increased root penetration as competition from clustered seedlings can direct growth deeper into the soil (Leck and oth-

Wyoming big sagebrush seedlings growing in research trial. Photo by Matthew Madsen

ers 2008); 3) enhanced mineralization, provided indirectly through greater microbial activity as a result of higher concentrations of root mass within a microsite (Whipps 1990); and 4) moderation of plant temperature—although not applicable to this laboratory study, in the field increased biomass may provide greater insulation from extreme temperatures (Fajardo and McIntire 2011).

Future research is merited for determining appropriate methods for sowing extruded pellets in the field and under variable moisture conditions. It is possible that the field logistics of planting sagebrush seed may be improved with extruded pellets. In addition to the seed, extruded pellets incorporate non-seed parts associated with sagebrush (such as, achenes, seed bracts, leaves, and fine stems) within a pellet, which may improve flow from a seeder by minimizing bridging within a seed box (as compared to non-treated seeds). Furthermore, because seeds are attached to a larger unit, carriers such as rice hulls may not need to be incorporated with the seed to prevent the small seeds from settling in the seed box of a drill.

Plant scientists also need to understand how extruded pellets should be seeded within a seed mix. Different seed burial requirements of seed mixtures make it difficult to maximize establishment for all species. Seeding methods that provide light post-seeding soil coverage tend to produce higher plant densities for small-seeded species, whereas large-seeded species can have higher densities in relatively deeper drill rows (Montalvo and others 2002). This tendency is especially true when less sophisticated seed drills are used that are not equipped with multiple seed boxes to accommodate different seed sizes and seeding depth regulators (Wiedemann 2005). Current best management practices for seeding big sagebrush do not recommend seeding this species in the same drill row as larger-seeded grasses and forbs (Richardson and others 1986; Shaw and others 2005). It may be possible that the extruded pellet could allow planting of sagebrush seed (and potentially other small-seeded species) within the same drill row as large-seeded species, with the depth of the drill row optimized for the large-seeded species—a scenario that could markedly improve the logistics of seeding sagebrush within a mixture of seeded species.

Extruded seed pellets may further minimize seeds from being planted either too deep or too shallow where environmental variables such as rugged topography, rocky soils, changing soil textures, and surface disturbances hinder the ability of the seed drill to consistently place seeds at an optimal depth. Through the extruded pellets' ability to swell and raise seeds closer to the soil surface, seeds planted at depths below optimal would migrate closer to the soil surface. If seeds are planted above the soil surface or erosion removes overlying surface layers, the filler materials in the pellet may maintain seed coverage.

CONCLUSIONS

Sagebrush seedling emergence from untreated seed can be significantly impaired when seeds are sown at depths of 5 mm or deeper in silt-loam soil and 10 mm or deeper in sandy-loam soil. Incorporating sagebrush seed into an extruded seed pellet overcomes emergence limitations by raising seeds above the bottom of the drill row. Swelling of the pellet further raises seeds in elevation in the drill row, appears to disrupt physical soil crust, and creates voids in the soil from which seedlings can emerge. Improved emergence and plant growth may also be facilitated by the extruded pellet improving moisture and nutrient availability. Extruded sagebrush pellets should be planted approximately 10 to 15 mm into the soil for a silt-loam soil and not more than 10 mm for a sandy-loam soil. Further research is merited for refining the technology, such as adjustments in filler material compositions and application rates, size and shape of the extruded pellet, and determining the optimal number of seeds per pellet. Additional research is needed for further testing and refining the technology through laboratory and field trials and adapting the technology for other species.

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