Journal of Applied Ecology
British Ecological Society

Journal of Applied Ecology 2012, **49**, 431–438 doi: 10.1111/j.1365-2664.2012.02118.x

Agglomerating seeds to enhance native seedling emergence and growth

Matthew D. Madsen[1]*, Kirk W. Davies[1], C. Jason Williams[2] and Tony J. Svejcar[1]

[1]*United States Department of Agriculture, Agricultural Research Service, Eastern Oregon Agricultural Research Center, 67826-A Hwy 205, Burns, OR 97720, USA; and* [2]*United States Department of Agriculture, Agricultural Research Service, Northwest Watershed Research Center, 800 Park Blvd., Boise, ID 83712, USA*

Summary

1. Restoration in rangelands is constrained by low establishment of species sown from seed. Non-biotic soil-surface crust is one of the major factors limiting reseeding success by acting as a barrier to seedling emergence.

2. The objective of this study was to determine whether seedling emergence could be improved by agglomerating multiple seeds into a single pellet, so that the seedlings growing from the pellet will collectively generate sufficient force to penetrate the soil crust. To evaluate this technology, we compared seedling emergence and biomass production from agglomerated, single and non-coated seed (control) of *Pseudoroegneria spicata*. In the greenhouse, seeds were sown in either crust-forming clay or non-crusting sandy soil and studied for a 25-day period. Starting seed density was constant across treatments.

3. In the clay soil, seedling emergence from the agglomeration treatment was 1·3 and 1·9 times higher than the single seed coating and control, respectively. In the sandy soil, the agglomeration and single seed coating responded similarly, producing 1·4 times more seedlings than the control.

4. Biomass production followed a similar trend as plant density. In the clay soil, increased biomass of the agglomeration treatment was not only because of higher plant densities but was also a product of having greater biomass per plant.

5. *Synthesis and applications*. This short-duration 'proof-of-concept' study indicates that both the seed coating materials used to form the agglomerates and the act of agglomerating the seeds together improve *P. spicata* emergence and plant growth. These results also demonstrate that in the early seedling stage, facilitation outweighs competition in agglomeration plantings. Additional research is needed to verify these results in the field.

Key-words: facilitation, native plants, restoration, seed coating, seeding, seedling emergence, soil physical crust

Introduction

Rangelands constitute nearly half of the Earth's land surface and provide multiple ecosystem services beneficial to human life (Asner *et al*. 2004; Havstad *et al*. 2007). These services are diminished when the functional integrity of rangeland systems is compromised. The loss of native vegetation is one of the most significant land degradation issues facing the world today (Ninan 2001). In many situations, these lands have been degraded to a point where autogenic recovery is impaired and energy-intensive restoration measures are required to restore ecosystem function (Bestelmeyer 2006; Kinyua *et al*. 2010). It is common practice for land managers to seed disturbed areas to facilitate the recovery of desirable vegetation (Allen-Diaz & Bartolome 1998; Martin & Wilsey 2006; Epanchin-Niell, Englin & Nalle 2009). Unfortunately, the success of these seeding efforts is typically less than desirable, especially in arid and semi-arid ecosystems (Seabloom *et al*. 2003; Lysne & Pellant 2004; James, Svejcar & Rinella 2011). Demography research on rangeland seedings in the Great Basin region of the western United States has shown that seedling emergence represents a

*Correspondence author. E-mail: matthew.madsen@oregonstate.edu

Mention of a proprietary product does not constitute a guarantee or warranty of the product by USDA or the authors and does not imply its approval to the exclusion of the other products that also may be suitable. USDA is an equal opportunity provider and employer. The Eastern Oregon Agricultural Research Center is jointly funded by the USDA – Agricultural Research Service and Oregon State Agricultural Experiment Station.

major developmental bottleneck in the progression from seed to an established plant (James & Svejcar 2010; James, Svejcar & Rinella 2011).

One factor that can act as a significant barrier to seedling emergence is the presence of non-biotic soil-surface crusts (U-nger 1984; Awadhwal & Thierstein 1985; Belnap 2003). Soil physical crust is characterized by a dense, relatively impermeable soil-surface feature, which impedes seedling emergence, while decreasing water infiltration and gas exchange (Belnap 2003). To effectively address a physical soil crust problem, expensive management practices must often be performed to increase aggregate stability (Belnap 2003). Where resources are available, this can be achieved by incorporating organic matter or other soil amendments such as gypsum (e.g. Shainberg *et al.* 1989) or polyacrylamide (e.g. Ben-Hur 1994) into the soil. Seedling emergence can also be increased through short-term treatments, such as irrigation to maintain a moist soil surface (Unger 1984), or use of equipment (i.e. rotary hoe) to mechanically break up the soil crust (Bilbro & Wanjura 1982). While these approaches may work in intensive agronomic operations, typically they are impractical for the revegetation of extensive rangeland systems of relatively low economic value. Consequently, there is a need for the development of cost-effective seeding technologies that will enhance seedling emergence in the presence of a soil physical crust (James & Svejcar 2010).

Seed coating technology provides several options for enhancing germination and seedling growth (Taylor & Harman 1990). A common approach for applying the coatings to the seed is through the use of a rotary (or rotostat) seed coater. In general, seeds are coated through this technology using centrifugal forces to mix the seeds, while adhesives (or stickers) are pumped to the centre of the coating chamber onto an atomizing disc, which redirects the liquid outward in small droplets onto the seed. With a binder providing a tacky base, seed coating powder is delivered through an auger feeder onto the moist seeds. Traditionally, coating formulations and application rates have been applied in a manner that produces the desired coating properties (e.g. density, hardness, plasticity and moisture uptake), while keeping the seeds from sticking or clumping together during the coating processes (Gregg & Billups 2010). Madsen, Petersen & Taylor (2010) proposed in US patent application 0267554 a coating technology that alters the traditional approach to seed coating by developing a method that uses rotary seed coating technology to promote the uniform clumping of seeds into pellets (or agglomerates) (Fig. 1). Because the penetration force of emerging seedlings increases with the number of seeds sown in the same location (Edwards 1966; Awadhwal & Thierstein 1985), agglomerated seeds should have improved seedling emergence by having multiple seedlings collectively generating greater emergence force than a single seed (Fig. 1).

Higher seedling densities may increase mortality as a result of competition for limited resources (Connell & Slatyer 1977; Stachowicz 2001); this may be especially true with the plantings of agglomerated seed where cohorts of the same species are occupying the same microsite (i.e. complete niche overlap). It may also be possible that positive interactions (or facilitation) may extend beyond seedling emergence and provide other benefits associated with clustered growth patterns that will outweigh competition and enhance seedling establishment (Hunter & Aarssen1988; Fajardo & McIntire 2011).

The objective of this study was to determine whether seedling emergence of a perennial bunchgrass species could be improved by agglomerating multiple seeds into a single pellet. Comparisons were made using agglomerated seed, coated seed (which was not agglomerated) and non-coated seed (control). The three treatments were evaluated in a clay-loam soil that was susceptible to crusting, and a non-crusting sandy soil. We tested the following hypotheses: (i) agglomerated seeds would have higher emergence than single coated or single non-coated seeds in clay but not sand, and (ii) intraspecific competition would result in lower per-plant biomass in the agglomerated treatment, relative to the other two treatments.

Materials and methods

Evaluations were performed on the native species *Pseudoroegneria spicata* (Prush.) Löve, which is often a major component of native plant communities in the Intermountain West, USA, and is commonly used for restoration of rangeland systems in this region (Ogle, St John & Jones 2010). *Pseudoroegneria spicata* has a wide ecological aptitude growing in relatively low elevation, dry *Artemisia* L. communities and up to high elevation, moist sagebrush-grasslands (Davies, Bates & Miller 2006; Davies & Bates 2010).

SEED COATING

Seed coating was performed at the Eastern Oregon Agricultural Research Center (EOARC) in Burns, OR, USA. The treatments described earlier were applied using a RP14DB® rotary seed coater (BraceWorks Automation and Electric, Lloydminster, SK, Canada).

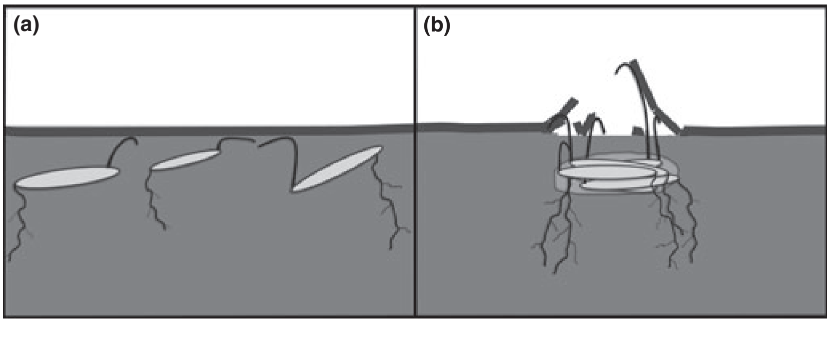

Fig. 1. (a) Illustration of seedling emergence being impeded by a physical soil crust layer, and (b) agglomerate pellet with multiple seedlings collectively generating sufficient force to penetrate through the soil crust.

Agglomerates were created similar to methods proposed by Madsen, Petersen & Taylor (2010). Materials used in this process included the adhesive binder, Selvol-205® (Sekisui Specialty Chemicals America 2009), and the powder filler material, diatomaceous earth (Perma-Guard, Inc., Albuquerque, NM, USA). Selvol-205 was prepared with an 8% solid content, according to Sekisui Specialty Chemicals solution preparation guidelines (Sekisui Specialty Chemicals America 2009). After evaluating several common seed coating powder materials (i.e. limestone, talc, bentonite clay and montmorillonite clay), we generally felt diatomaceous earth formed agglomerates most consistently. Diatomaceous earth is composed of fossilized diatom remains that have sharp and jagged microscopic edges. The structure of the diatomaceous earth may aid in the formation of agglomerates by decreasing the flowability of the coated seed and promoting seed clumping.

A detailed description of the amount and application rate used to form the agglomerated seeds is shown in Table 1. First, we applied a base coating comprised of Selvol-205 and diatomaceous earth. In this phase, Selvol-205 and diatomaceous earth were applied using typical seed coating methods that allows for the product to adhere to the seed and prevent seeds from clustering together. In the second phase, seeds were agglomerated together by increasing the rate of Selvol-205, and only applying diatomaceous earth in periodic short bursts. Generally speaking, through this approach, agglomeration size (i.e. number of seeds per pellet) is primarily dependent upon the amount and rate that Selvol-205® is applied while withholding or limiting diatomaceous earth. Lastly, the agglomerates were coated using methods described in phase 1 earlier, to provide additional structure to the agglomerated seed. After coating, agglomerated seeds were placed on a forced air drier at 25 °C for 4 min. From this batch, we selected agglomerates that had exactly five seeds to be used in the trial.

Single coated seeds were made using the same amount of materials used to form the agglomerates. In this treatment, the coating material was applied at a rate sufficient to keep the seeds from clustering together.

SOIL

Evaluations were performed on clay (31% sand, 22% silt and 47% clay) and sandy (91% sand, 5% silt and 4% clay) textured soils. The clay soil was obtained from the USDA – Agricultural Research Services (ARS), Northern Great Basin Experimental Range (NGBER; Lat: 43°27′34″N, Long: 119°40′15″W), 67 km west of Burns, Oregon, USA. This soil was classified as a clayey, montmorillonitic, frigid and shallow Xeric Argidurids. Soil pH was 7·8, and organic matter content was 1·9% (Soil Survey Staff 2011). We collected the sandy soil from a site 17·6 km south of Burns, OR, USA (Lat: 43°21′23″ N, Long: 119°01′5″W). At this location, the soil is classified as a fine sand, mixed, frigid Xeric Haplocambids. Soil pH was 7·2, and organic matter content was 0·25% (Soil Survey Staff 2011). At both sites, the vegetation community was co-dominated by *Artemisia tridentata* spp. *wyomingensis* (Beetle & A. Young) S.L. Welsh and perennial bunchgrasses, such as *Agropyron cristatum, Stipa thurberiana, Agropyron spicatum* and *Poa sandbergii*.

STUDY DESIGN

Seed treatments were evaluated in the greenhouse at the EOARC using a randomized block split-plot design, with five blocks. Each block contained two 0·2 m^{-2} containers (0·5 × 0·4 m on a side, with a depth of 0·1 m), one with sand and the other with clay soil. Within each container, we hand sowed the three seed treatments, in separate rows, equally spaced, with the location of the row randomized among the treatments. Each row was 0·4 m long and contained 15 seeds, planted 1 cm below the surface. For the rows designated for non-coated and single coated seeds, we evenly distributed the seed across the row. In the rows designated for agglomerated seeds, we sowed three pellets, which each contained five seeds.

RAINFALL SIMULATION AND WATER REGIME

Prior to seeding, we saturated the soil from the bottom-up and then allowed the soil to drain for 24 h. We then seeded the boxes and placed them on a 5% slope, where we applied 15 mm (3·0 L container^{-1}) of water using a portable oscillating-arm rainfall simulator, as described by Meyer & Harmon (1979). To promote soil crust formation, we rained on the soil with an application intensity of 24·7 mm h^{-1}, which approximated the rainfall intensity for a 15-min period, with a 2 year return interval, for the NGBER (Miller, Frederick & Tracy 1973). Over the remainder of the study, pots were watered with a fine mist sprayer. To stimulate seedling germination, the soil was misted once a day with 1·5 mm (0·3 L container^{-1}), for 5 days after seeding. After day 5, the soil was watered weekly with 3·4 mm (6·8 L container^{-1}) that is approximately half the average weekly

Table 1. Batch recipe used to coat 227 g of *Pseudoroegneria spicata* seed. The Table shows the time the seed coater's pump, and powder feeder was turned on and off to apply Selvol-205 and diatomaceous earth, along with their associated rates and amount of material delivered. The amount of Selvol-205 in the table contains 8% by weight of active ingredient. The Table also shows the different speeds the coating pan was run during the coating process

Selvol-205			Diatomaceous earth			Rotor speed	
Time (s) Start–stop	Rate (g s^{-1})	Subtotal (g)	Time (s) Start–stop	Rate (g s^{-1})	Subtotal (g)	Time (s) Start–stop	Rate (% of max.)
6–35	1·000	29·00	36–39	13	39·00	0–120	35
41–120	0·833	65·97	40–120	0·65	52·13	120–220	60
120–210	1·379	124·11	145–147	6	12·00	220–260	50
210–250	0·490	19·60	150–152	6	12·00		
			167–169	6	12·00		
			186–189	6	15·00		
			210–213	8	24·00		
			213–250	1·18	43·48		
Total		238·68			209·61		

amount of precipitation received in the spring (March–May) at the NGBER (Western Regional Climate Center 2010).

MEASUREMENTS

We measured volumetric soil water content and crust penetration resistance to fracture the soil surface, in-between the rows, at three locations per box, approximately every 3 days. Soil water content was measured from the soil surface down to 60 mm, with an ML2x Theta Probe (Delta-T Devices, Cambridge, UK). On the days the soil was designated to be watered, soil water content was measured prior to watering. Crust penetration resistance was determined using a 4·76-mm diameter flat point handheld penetrometer (Model 719-5MRP; John Chatillon & Sons, Kew Garden, NY, USA). Eleven days after seeding, we measured the thickness of the soil crust using a vernier calliper, at three sample locations per box container.

Seedling density of all live seedlings in each row of the box containers was also recorded at the same time that the soil water content and crust penetration resistance was measured at *c.* 3 day intervals. At the conclusion of the study (25 days after seeding), we weighed standing above-ground biomass after oven-drying at 65 °C for 72 h.

DATA ANALYSIS

Seedling density data were analysed using repeated measures mixed-model analysis with an autoregressive order 1 covariance (SAS Version 9.2; SAS 2006). In the model, seed treatments and soil type were considered fixed factors, sampling period was designated as a repeated measure, and blocks were random. We used mixed-model analysis to analyse total biomass, and per-plant biomass. Again, blocks were considered random, while seed treatments and soil type were considered fixed factors. When significant main or interactive effects were found, mean values were separated using the LSMEANS procedure (SAS 2006). Prior to analysis, normality and homogeneity was tested using the Shapiro–Wilk test and Levene's test, respectively (PROC UNIVARIATE; SAS 2006). Each data set was log-transformed to reduce problems with deviance from normality. For all comparisons, a significance level of $P < 0{\cdot}01$ was used. In the text and figures, means are reported with either unique letters to denote significances or with associated standard error.

Results

VOLUMETRIC WATER CONTENT AND SOIL CRUST

Soil moisture in both soil types was at saturation at the start of the study, and by the end of the experiment, it had declined to near wilting point (−1·5 MPa) (Fig. 2). In the clay soil, crust penetration resistance increased rapidly as soil moisture declined, until around day 15. During this period, crust penetration resistance ranged from 0·13 MPa (day 3) to 0·23 MPa (day 15). After day 15, crust strength was highly variable and on average decreased with time (Fig. 2). Crust thickness of the clay soil measured on day 11 was 9·3 ± 0·6 mm. The sandy soil did not form a physical crust (Fig. 2).

PLANT DENSITY

Plant density among seed treatments differed by soil type (Table 2). In the clay soil, on average, the agglomerated seeds emerged earlier and over a longer period of time than the control (Fig. 3). This generally resulted in the agglomeration treatment having higher plant densities than the control. Final plant density in the clay soil showed the agglomeration treatment having approximately two times (1·9 times) more seedlings than the control. Seedling emergence for the single coated seed treatment appeared to have been impaired by physical soil crust similar to the control, for the first half of the study. Between day 14 and 19, this treatment increased in plant density by 35%, while density in the control remained constant. Final seedling density for the single coatings produced an intermediate response when compared to the other two treatments, with single coatings having 1·4 times more seedlings than the control.

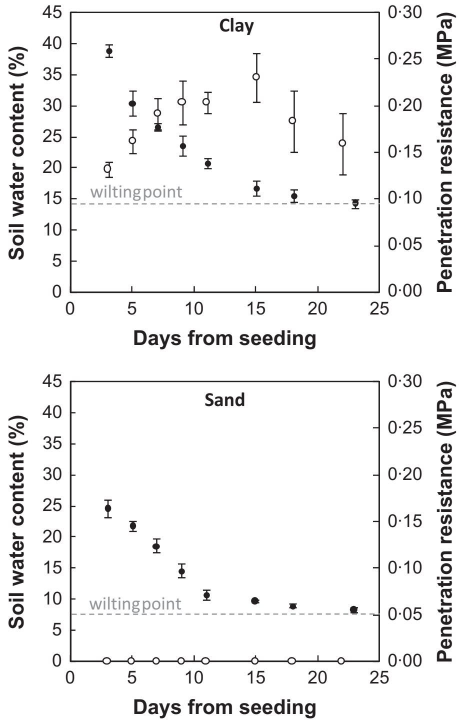

Fig. 2. Mean ± SE soil water content (closed circles) and penetration resistance (open circles) over the course of the study. Dashed line represents permanent wilting point (−1·5 MPa).

Table 2. *P*-values from a mixed-model ANOVA analysis for the effect of seed coating treatments, and soil type, on plant density, total plant biomass, and biomass per plant

Effect	Density	Total biomass	Biomass per plant
Seed treatment	0·018	< 0·001	0·008
Soil	< 0·001	0·077	< 0·001
Soil × seed treatment	< 0·001	0·621	0·833
Time	< 0·001		
Time × soil	0·912		
Seed treatment × time	0·387		
Seed treatment × soil × time	0·294		

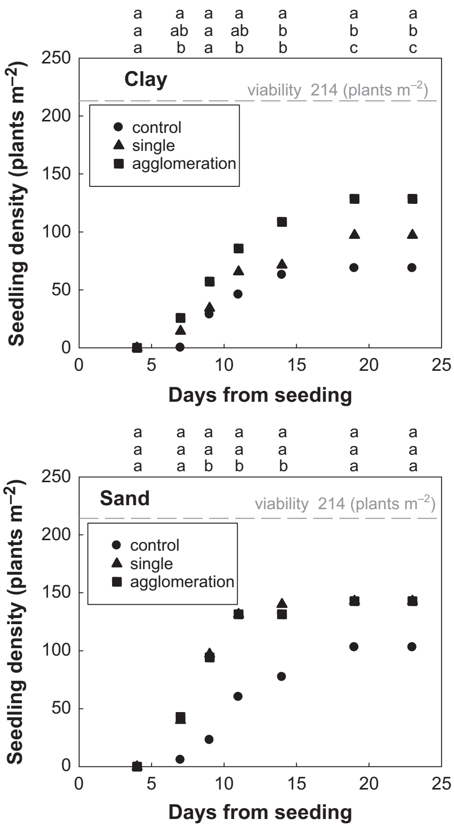

Fig. 3. Comparison of *Pseudoroegneria spicata* plant density over the course of the study grown from none-coated (control), single coated and agglomerated seeds, sown in clay and sandy soil. Plots were sown with 214 PLS m^{-2}. Significant differences ($P < 0{\cdot}01$) between mean density values at each sampling date are shown by unique letters.

In the sandy soil, agglomerated and single coated seed treatments had similar plant densities at each measurement period (Fig. 3). There was some indication that these treatments can improve the rate of seedling emergence in the sandy soil, with early plant density values nearly double that of the control. However, towards the end of the study, the gap between the coating treatments and the control decreased resulting in statistically similar final plant densities (Fig. 3).

ABOVE-GROUND BIOMASS

Differences in biomass were primarily influenced by seed coating treatments and to a lesser extent, soil type (Table 2). In the clay soil the agglomeration treatment had 1·5 times more biomass than the single coated seed treatment and 2·7 times more biomass than the control (Table 3). On a per-plant basis, the control and single coated seed treatments remained similar while the agglomeration treatment had 1·4 times more biomass than the control but was not statistically higher than the single seed coating treatment.

In the sandy soil, there was greater biomass in the single seed coating and agglomeration treatments when compared to the control; however, in this soil type, there was no statistical difference between single coated and agglomerated seed treatments (Table 3). On average, the single seed and agglomerated treatments produced 1·7 and 2·1 times more biomass than the control, respectively. Per-plant biomass followed a similar pattern as total biomass, with both single seed and agglomerated treatments producing similar values, which were 1·4 and 1·6 times greater than the control, respectively.

Table 3. Above-ground biomass and per-plant biomass of *Pseudoroegneria spicata* grown from non-coated (control), single coated and agglomerated seeds, sown in clay and sandy soil

Treatment	Biomass (mg)	Biomass per plant (mg)
Clay		
Control	396·3b	6·1b
Single	742·3ab	7·1ab
Agglomeration	1083·4a	8·9a
Sand		
Control	330·9b	3·0b
Single	585·1a	4·2a
Agglomeration	682·9a	4·8a

Means with different letters are significantly different ($P < 0{\cdot}01$).

Discussion

SEEDLING DENSITY

The results of this study confirmed our hypothesis that agglomerating perennial bunchgrass seeds into pellets enhances seedling emergence in the presence of a crusting soil (Fig. 3). Our data further indicate that the coating materials used to agglomerate seeds together also enhances seedling emergence (Fig. 3). The mechanism by which the agglomeration treatment improves seedling emergence is illustrated in the comparison of seed treatments by soil type. In the clay soil, seedling emergence was limited by crusting soil and drought (Fig. 2). Within this soil type, the single seed coating treatment (which has the same amount of coating material as the agglomeration treatment) had less emergence than the agglomeration treatment yet was greater than the control (Fig. 3). However, in the sandy soil, emergence was limited by drought only (Fig. 2). Within this soil type, the agglomeration and single seed coating treatment both produced a similar increase in seedling emergence over the control (Fig. 3). Greater seedling emergence in the clay soil is probably the result of having multiple seedlings collectively generating sufficient force to penetrate through the soil crust. Seedling emergence force increases when multiple seeds are planted in the same location (Edwards 1966; Awadhwal & Thierstein 1985). In the sandy soil where crust was not a limiting factor. The single seed coating and agglomeration treatments performed similarly, which may be due to the coating material enhancing drought tolerance by increasing the amount and duration of plant available water. As explained previously, the coating material used in this study was comprised of Selvol-205, and diatomaceous earth. Selvol-205 is a partially hydrolysed polyvinyl alcohol product, formulated for increased water sorption (Sekisui Specialty Chemicals

America 2009). Diatomaceous earth has high water absorption and retention properties (Li *et al.* 2000; Shawabkeh & Tutunji 2003). These two coating materials may aid in the absorption and retention of moisture around the seed. Presuming this water was thermodynamically available to the seed, increased moisture availability around the seed would enhance seed imbibition, germination and early seedling growth, in a water-limited environment. Increased moisture provided by the coating may also help maintain plant turgor pressure and subsequently promote seedling emergence thrust through the soil. Diatomaceous earth may also have aided in seedling emergence and survival by providing a source of silicon. The chemical composition of oven dried diatomaceous earth typically contains between 80% and 90% silicon dioxide (Antonides 1997). The application of silicon fertilizer to cereal crops has been shown to increase seedling resistance to both biotic and abiotic stresses (Ahmad, Zaheer & Ismail 1992; Liang 1998; Tuna *et al.* 2008). However, a review of the literature indicates that moisture enhancing seed coatings generally fail to improve rangeland reseeding (i.e. Hull & Klomp 1967 and references therein; Kocher & Stubbendieck 1986; Mangold & Sheley 2007). Therefore, the positive response in seedling emergence from the seed coating materials used in this study merits additional research to verify the mechanisms and controlling variables.

BIOMASS PRODUCTION

As with plant density, increased biomass, in part, can probably be attributed to the agglomeration treatment improving seedling emergence (Fig. 3, and Table 3). Interestingly, in the clay soil, increased above-ground biomass in the agglomeration treatment is not only because of greater plant densities but is also a product of having greater biomass per plant (Table 3). Such a response is contrary to our hypothesis that intraspecific competition would lower biomass production on a per-plant basis. These results may indicate that under the conditions of this study, facilitation played a more important role than competition. Facilitation often outweighs competition effects in harsh and resource-limited environments (Hunter & Aarssen1988; Bertness & Callaway 1994; Callaway & Walker 1997; Brooker & Callaghan 1998; Fajardo & McIntire 2011). As an example, Fajardo & McIntire (2011) compared *Nothofagus pumilio* tree seedlings planted in clusters and spaced apart from each other along a stress gradient in a forest–prairie ecotone in Patagonia, Chile. As stress increased, seedlings planted in dense clusters had higher survival than solitary seedlings (Fajardo & McIntire 2011).

It is probable that the increase in biomass in our agglomeration treatment may be due, in part, to the ability of this technology to better mimic the way plants have evolved to grow in natural systems. Seeds typically grow within groups or clusters because of natural process depositing them within the same microsite. For instance, seeds can be collected within litter material, holes and cracks in the soil surface, or other features that trap wind-blown seeds (Eckert *et al.* 1986; Stamp 1989; Chambers, MacMahon & Haefner 1991; Chambers 2000). Seeds can also be grouped together as a result of caching activities by granivores. Seed caching is considered the primary mechanism of seedling establishment by *Purshia tridentate* (Pursh) DC (antelope bitterbrush) and *Achnatherum hymenoides* (Roemer & J.A. Schultes) Barkworth (Indian rice grass), with two or more mature plants typically growing together (West 1968; Vander Wall 1994).

This study provides justification for additional research to determine what specific facilitative interactions in the agglomeration treatment improved plant growth, in addition to multiple seedlings increasing emergence thrust. For example, early emergence (Fig. 3) may have allowed the seedlings to grow deeper root systems to better utilize moisture resources from a rapidly drying wetting front (Nicotra, Babicka & Westoby 2002; Leck, Parker & Simpson 2008). Moisture availability may also have been improved as a result of increased plant cover in the agglomeration treatment promoting greater soil infiltration, and from the fallow spaces between groups of plants prolonging the duration of available moisture. Multiple seedlings growing within a cluster may indirectly increase the availability of nutrients through promoting microbial activity. We did not measure root growth, but greater above-ground growth would presumably translate into higher below-ground growth as well. More root growth in the agglomerate treatment should result in greater exuded substrate from the roots, which stimulates rhizospheric microbial activity (Whipps 1990). This in turn promotes higher soil mineralization rates and subsequent nutrient availability (Marschner 1995; Hamilton & Frank 2001). The agglomeration treatment may also moderate microsite temperatures, as the plants collectively provided a greater insulating affect from extreme temperatures.

Conclusions and future research

To our knowledge, this is the first seed coating treatment specifically designed to improve seedling emergence in crusting soil by agglomerating multiple seeds together within a single pellet. Enhanced emergence of the agglomeration treatment is most likely to be a function of the coating material decreasing the emergence time, alleviating drought conditions and a result of the greater emergence thrust generated by the seedlings collectively growing from the agglomerated pellet compared with a single seedling. In addition to the agglomeration treatment improving seedling emergence in crusting soils, this research also provides evidence that seedlings growing from agglomerates facilitate greater growth than can be achieved by a single seedling.

These results indicate that current agronomic practices that evenly space seeds may not be the most effective technique for reseeding rangelands with crusting soils. Use of seed agglomeration technology may provide land managers with the ability to efficiently plant seeds within clusters using standard seed drills. Facilitation associated with coating materials and clustered plant growth may increase the probability of the plant establishing on a site, and thus lower the probability of restoration failure.

Further development and evaluation of this technology is needed before it can be recommended as a native plant restoration treatment. Future studies should include: (i) determination of how agglomeration size (i.e. number of seeds per pellet) influences seedling emergence, plant survival and biomass production across different stress gradients; (ii) analysis of the agglomeration procedure, with a focus on how emergence is affected by variability in the materials, application rates and other inputs into the coating process; (iii) evaluation of how seed and plant physiological characteristics of different species function within an agglomeration treatment; (iv) quantification of the long-term survival and plant community structure of agglomeration plantings and (v) determination of the mechanisms that influence seedling growth from an agglomerated pellet (i.e. water infiltration and moisture availability, thermal response to extreme temperatures, microbial response and nutrient availability).

Acknowledgements

We would like to acknowledge Fred Pierson (USDA-ARS, Boise, ID, USA) for technical advice and use of a rainfall simulator. We would also like to thank Kristen Munday, Aaron Inouye, and Suzanne Bichrt for their assistance in conducting this research. We are grateful to Brenda Smith and Brett Bingham (USDA-ARS, Burns, OR, USA) for reviewing earlier versions of this manuscript.

References

Ahmad, R., Zaheer, S.H. & Ismail, S. (1992) Role of silicon in salt tolerance of wheat (*Triticum aestivum* L.). *Plant Science*, **85**, 43–50.

Allen-Diaz, B. & Bartolome, J.W. (1998) Sagebrush-grass vegetation dynamics: comparing classical and state-transition models. *Ecological Applications*, **8**, 795–804.

Antonides, L.E. (1997) Diatomite: U.S. Geological Survey Mineral Commodity Summaries. pp. 24.1–24.4.

Asner, G.P., Elmore, A.J., Olander, L.P., Martin, R.E. & Harris, A.T. (2004) Grazing systems, ecosystem responses and global change. *Annual Review of Environment & Resources*, **29**, 261–299.

Awadhwal, N.K. & Thierstein, G.E. (1985) Soil crust and its impact on crop establishment: a review. *Soil and Tillage Research*, **5**, 289–302.

Belnap, J. (2003) Comparative structure of physical and biological soil crusts. *Biological Soil Crusts: Structure, Function and Management* (eds J. Belnap & O.L. Lange), pp. 177–192. Springer-Verlag, Berlin.

Ben-Hur, M. (1994) Runoff, erosion, and polymer application in moving-sprinkler irrigation. *Soil Science*, **158**, 283–290.

Bertness, M.D. & Callaway, R.M. (1994) Positive interactions in communities. *Trends in Ecology & Evolution*, **9**, 187–191.

Bestelmeyer, B.T. (2006) Threshold concepts and their use in rangeland management and restoration: the good, the bad, and the insidious. *Restoration Ecology*, **14**, 325–329.

Bilbro, J.D. & Wanjura, D.F. (1982) Soil crusts and cotton emergence relationships. *Transactions of the ASAE*, **25**, 1484–1487.

Brooker, R.W. & Callaghan, T.V. (1998) The balance between positive and negative plant interactions and its relationship to environmental gradients: a model. *Oikos*, **81**, 196–207.

Callaway, R.M. & Walker, L.R. (1997) Competition and facilitation: a synthetic approach to interactions in plant communities. *Ecology*, **78**, 1958–1965.

Chambers, J.C. (2000) Seed movements and seedling fates in disturbed sagebrush steppe ecosystems: implications for restoration. *Ecological Applications*, **10**, 1400–1413.

Chambers, J.C., MacMahon, J.A. & Haefner, J.H. (1991) Seed entrapment in alpine ecosystems: effects of soil particle size and diaspore morphology. *Ecology*, **72**, 1668–1677.

Connell, J.H. & Slatyer, R.O. (1977) Mechanisms of succession in natural communities and their role in community stability and organization. *The American Naturalist*, **111**, 1119–1144.

Davies, K.W. & Bates, J.D. (2010) Vegetation characteristics of mountain and Wyoming big sagebrush plant communities in the northern Great Basin. *Rangeland Ecology and Management*, **63**, 461–466.

Davies, K.W., Bates, J.D. & Miller, R.F. (2006) Vegetation characteristics across part of the Wyoming big sagebrush alliance. *Rangeland Ecology and Management*, **59**, 567–575.

Eckert Jr, R.E., Peterson, F.F., Meurissee, M.S. & Stephens, J.L. (1986) Effects of soil surface morphology on emergence and survival of seedlings in big sagebrush communities. *Journal of Range Management*, **39**, 414–421.

Edwards, F.E. (1966) Cotton seedling emergence. *Mississippi Farm Research*, **26**, 4–5.

Epanchin-Niell, R., Englin, J. & Nalle, D. (2009) Investing in rangeland restoration in the arid west, USA: countering the effects of an invasive weed on the long-term fire cycle. *Journal of Environmental Management*, **91**, 370–379.

Fajardo, A. & McIntire, E.J.B. (2011) Under strong niche overlap conspecifics do not compete but help each other to survive: facilitation at the intraspecific level. *Journal of Ecology*, **99**, 642–650.

Gregg, B.R. & Billups, G.L. (2010) *Seed Conditioning Volume Two, Technology-Part A*. pp. 818–834. Science Publishers, Enfield, NH USA.

Hamilton, E.W. & Frank, D.A. (2001) Can plants stimulate soil microbes and their own nutrient supply? Evidence from a grazing tolerant grass. *Ecology*, **82**, 2397–2402.

Havstad, K.M., Peters, D.P.C., Skaggs, R., Brown, J., Bestelmeyer, B., Fredrickson, E., Herrick, J. & Wright, J. (2007) Ecological services to and from rangelands of the United States. *Ecological Economics*, **64**, 261–268.

Hull Jr, A.C. & Klomp, G.J. (1967) Thickening and spread of crested wheatgrass stands on southern Idaho ranges. *Journal of Range Management*, **20**, 222–227.

Hunter, A.F. & Aarssen, L.W. (1988) Plants helping plants. *BioScience*, **38**, 34–39.

James, J.J. & Svejcar, T.J. (2010) Limitations to postfire seedling establishment: the role of seeding technology, water availability, and invasive plant abundance. *Rangeland Ecology and Management*, **63**, 491–495.

James, J.J., Svejcar, T.J. & Rinella, M.J. (2011) Demographic processes limiting seedling recruitment in aridland restoration. *Journal of Applied Ecology*, **48**, 961–969.

Kinyua, D., McGeoch, L.E., Georgiadis, N. & Young, T.P. (2010) Short-term and long-term effects of soil ripping, seeding, and fertilization on the restoration of a tropical rangeland. *Restoration Ecology*, **18**, 226–233.

Kocher, E. & Stubbendieck, J. (1986) Broadcasting grass seed to revegetate sandy soils. *Journal of Range Management*, **39**, 555–557.

Leck, M.A., Parker, V.T. & Simpson, R.L. (2008) *Seedling Ecology & Evolution*. pp. 514. Cambridge University Press, Cambridge, UK.

Li, D., Joo, Y.K., Christians, N.E. & Minner, D.D. (2000) Inorganic soil amendment effects on sand-based sports turf media. *Crop Science*, **40**, 1121–1125.

Liang, Y.C. (1998) Effects of silicon on leaf ultrastructure, chlorophyll content and photosynthetic activity in barley under salt stress. *Pedosphere*, **8**, 289–296.

Lysne, C. & Pellant, M. (2004) *Establishment of Aerially Seeded Big Sagebrush Following Southern Idaho Wildfires*. pp. 14. Tech. Bull. 2004-01. U.S. Department of the Interior, Bureau of Land Management, Idaho State Office, Boise, ID.

Madsen, M.D., Petersen, S.L. & Taylor, A.G. (2010) Seed coating compositions and methods for applying soil surfactants to water-repellent soil. Pub. No. WO/2010/111309. International Application No. PCT/US2010/28371.

Mangold, J.M. & Sheley, R.L. (2007) Effect of soil texture, watering frequency, and a hydrogel on the emergence and survival of coated versus uncoated crested wheatgrass seeds. *Ecological Restoration*, **25**, 6–11.

Marschner, H. (1995) *Mineral Nutrition of Higher Plants*, 2nd edn. Academic Press, San Diego, CA.

Martin, L.M. & Wilsey, B.J. (2006) Assessing grassland restoration success: relative roles of seed additions and native ungulate activities. *Journal of Applied Ecology*, **43**, 1098–1109.

Meyer, L.D. & Harmon, W.C. (1979) Multiple-intensity rainfall simulator for erosion research on row sideslopes. *Transactions of the ASAE*, **22**, 100–103.

Miller, J.F., Frederick, R.H. & Tracy, R.J. (1973) *Precipitation-Frequency Atlas of the Western United States*. pp. 43. NOAA Atlas 2, Volume X-Oregon, National Weather Service, Silver Spring, MD.

Nicotra, A.B., Babicka, N. & Westoby, M. (2002) Seedling root anatomy and morphology: an examination of ecological differentiation with rainfall using phylogenetically independent contrasts. *Oecologia*, **130**, 136–145.

Ninan, L. (2001) Fighting against ourselves: efforts to combat desertification & land degradation. *Currents International Trade Law Journal*, **65**, 66.

Ogle, D.G., St John, L. & Jones, T.A. (2010) *Plant Guide for Bluebunch Wheatgrass (*Pseudoroegneria spicata*)*. pp. 5. USDA-Natural Resources Conservation Service, Idaho and Washington Plant Materials Program.

SAS Institute Inc. (2006) *Software Version 9.2*. SAS Institute Inc, Cary, NC.

Seabloom, E.W., Borer, E.T., Boucher, V.L., Burton, R.S., Cottingham, K.L., Goldwasser, L., Gram, W.K., Kendall, B.E. & Micheli, F. (2003) Competition, seed limitation, disturbance, and reestablishment of California native annual forbs. *Ecological Applications*, **13**, 575–592.

Sekisui Specialty Chemicals America, LLC (2009) *Selvol® Polyvinyl Alcohol... A Versatile High-Performance Polymer*. pp. 16. North American Distributions, Sekisui Specialty Chemicals America, LLC, Dallas, TX.

Shainberg, I., Sumner, M.E., Miller, W.P., Farina, M.P.W., Pavan, M.A. & Fey, M.V. (1989) Use of gypsum on soils: a review. *Advances in Soil Science*, **9**, 1–111.

Shawabkeh, R.A. & Tutunji, M.F. (2003) Experimental study and modeling of basic dye sorption by diatomaceous clay. *Applied Clay Science*, **24**, 111–120.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture (2011) Web Soil Survey. Available at: http://websoilsurvey.nrcs.usda.gov/ (accessed on 5 July 2011).

Stachowicz, J.J. (2001) Mutualism, facilitation, and the structure of ecological communities. *BioScience*, **51**, 235–246.

Stamp, N.E. (1989) Seed dispersal of four sympatric grassland annual species of *Erodium*. *Journal of Ecology*, **77**, 1005–1020.

Taylor, A.G. & Harman, G.E. (1990) Concepts and technologies of selected seed treatments. *Annual Review of Phytopathology*, **28**, 321–339.

Tuna, A.L., Kaya, C., Higgs, D., Murillo-Amador, B., Aydemir, S. & Gergon, A.R. (2008) Silicon improves salinity tolerance in wheat plants. *Environmental Experimental Botany*, **62**, 10–16.

Unger, P.W. (1984) Tillage effects on surface soil physical conditions and sorghum emergence. *Soil Science Society of America Journal*, **48**, 1423–1432.

Vander Wall, S.B. (1994) Seed fate pathways of antelope bitterbrush: dispersal by seed-caching yellow pine chipmunks. *Ecology*, **75**, 1911–1926.

West, N.E. (1968) Rodent-influenced establishment of ponderosa pine and bitterbrush seedlings in central Oregon. *Ecology*, **49**, 1009–1011.

Western Regional Climate Center (2010) Historical climate information. Available at: http://www.wrcc.dri.edu/ (accessed on 5 May 2010).

Whipps, J.M. (1990) Carbon economy. *The Rhizosphere* (ed. J.M. Lynch), pp. 59–97. Wiley, Chichester.

Received 29 August 2011; accepted 8 February 2012
Handling Editor: Brian Wilsey