Restoring North America's sagebrush steppe ecosystem using seed enhancement technologies

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Abstract. Rangelands occupy over a third of global land area, and in many cases are in less than optimum condition as a result of past land use, catastrophic wildfire and other disturbance, invasive species, or climate change. Often the only means of restoring these lands involves seeding desirable species, yet there are few cost effective seeding technologies, especially for the more arid rangeland types. The inability to consistently establish desired plants from seed may indicate that the seeding technologies being used are not successful in addressing the primary sources of mortality in the progression from seed to established plant. Seed enhancement technologies allow for the physical manipulation and application of materials to the seed that can enhance germination, emergence, and/or early seedling growth. In this article we examine some of the major limiting factors impairing seedling establishment in North America's native sagebrush steppe ecosystem, and demonstrate how seed enhancement technologies can be employed to overcome these restoration barriers. We discuss specific technologies for: (1) increasing soil water availability; (2) enhancing seedling emergence in crusting soil; (3) controlling the timing of seed germination; (4) improving plantability and emergence of small seeded species; (5) enhancing seed coverage of broadcasted seeds; and (6) improving selectivity of pre-emergent herbicide. Concepts and technologies in this paper for restoring the sagebrush steppe ecosystem may apply generally to semi-arid and arid rangelands around the globe.

Keywords: Seed technology, revegetation, annual grasses, wildfire, seedling emergence, pre-emergent herbicides

Introduction

The sagebrush steppe ecosystem of western North America is undergoing rapid ecological change as native perennial plant communities are displaced by exotic annual grasses and forbs (D'Antonio *et al.* 1992). The loss of sagebrush rangelands has resulted in more than 350 sagebrush-associated animals and plants being identified as species of conservation concern (Suring *et al.* 2005), and is directly impacting rangeland ecosystem goods and services by decreasing forage production and quality, reducing recreation opportunities, degrading water resources, and increasing fire frequencies (Davies *et al.* 2011).

Conversion from native sagebrush steppe to exotic forblands or grasslands is typically driven by severe disturbances that compromise ecological resilience and impair autogenic recovery of native species, resulting in biological vacuums that exotic species exploit (Young and Clements 2003). Catastrophic wildfires are one of the most widespread forms of disturbance and vector pathways to weed invasion (D'Antonio *et al.* 1992). For sites dominated by exotic annual communities, wildfire activity generally increases due to greater biomass, continuity, and flammability of fine fuels (Davies and Nafus 2013). Because the exotic annual communities typically have faster postfire recovery rates compared to native species, a 'grass-fire cycle' is developed, which promotes the dominance and spread of exotic annuals (Balch *et al.* 2013). Cheatgrass (*Bromus tectorum* L.) is an exotic annual that is among the most widespread of these invasive weeds and currently dominates over 10 million ha of former sagebrush steppe (Pellant *et al.* 2004), and an additional 24 million ha are at risk of invasion (Pellant and Hall 1994).

Expansion of piñon (*Pinus* ssp.) and juniper (*Juniperus* spp.) woodlands has also been associated with decline of the sagebrush steppe (Davies *et al.* 2011). Estimates show that piñon-juniper woodlands have experienced a 10-fold increase in spatial extent since European settlement and now occupy over 40 million hectares (Romme *et al.* 2009). Piñon-juniper woodlands shift fuel conditions from primarily light understory fuels that produce moderate burn frequencies, to heavier canopy fuels that limit fire frequency initially. However, as these woodlands persist on site, infilling processes continue to improve fuel continuity, and eventually produce landscapes that are susceptible to high intensity stand-replacing crown fires (Miller and Tausch 2002). In recent decades, high intensity wildfires in piñon-juniper woodlands have increased in size and frequency throughout the Intermountain West, and left behind landscapes that are susceptible to further degradation through weed encroachment and erosion (Miller and Tausch 2002).

Land practitioners can halt the shift to an introduced annual community by successfully seeding desired plant species (Ott *et al.* 2001). In the arid regions of the sagebrush steppe, success rates for seeding efforts with native plants are notoriously low (James *et al.* 2011); however, due to the underreporting of negative results in the literature, the true efficacy of seeding practices is unknown (Hardegree *et al.* 2011). Once a site transitions to a weed-dominated system, restoration costs increase dramatically, while the probability of restoring perennial plant dominance to the system is reduced even further (Eiswerth *et al.* 2009).

The inability of current restoration practices to consistently establish native plants from seed may indicate that these practices do not address the primary sources of mortality in the progression from seed to established plant (James *et al.* 2011). This is because much of the effort to restore rangelands with desired species has been based on the scaling-up of out dated row crop agriculture technologies (*e.g.* seeding with seed drills), without taking the time to define specific ecological barriers to restoration success or practices to overcome these barriers. It is now clear that traditional interdictory-based approaches to solving the annual grass problem have not been sufficient to offset losses, despite large monetary investments (Gebert *et al.* 2008). Additionally, the very notion of reliable establishment from seed is at odds with an ecosystem noted for extreme temporal variation in environmental conditions (Boyd and James 2013). To sustain the ecological integrity and productivity of western North American rangelands there is a substantial need to develop methodologies and technologies that result in the post-disturbance establishment of functional plant communities.

The expansive, complex nature of rangeland systems produces a diverse array of abiotic and biotic factors that may limit restoration success, including: drought, soil crusting, extreme temperatures, competition from weeds, salinity, predation, and infertile soils. One consistency held among rangeland sites is that the limiting factors impairing establishment have their greatest impact during the early stages of plant development (James *et al.* 2011). Subsequently, restoration practices that can avoid or improve tolerance to limiting abiotic and biotic stresses during early stages of plant development should have a higher likelihood of success.

Seed enhancement technologies allow for the physical manipulation and application of materials to the seed that can influence germination, emergence, and/or early seedling growth as well as facilitate planting and the delivery of other materials required at the time of sowing (Taylor 2003; Halmer 2008). Film coating, encrusting, seed coating, and pelleting techniques are commonly used enhancement technologies in the seed industry for applying materials to the surface or external portions of the seed (Taylor 2003). Some of the materials being applied through these technologies include application of macro and micronutrients, soil surfactants, plant growth regulators, beneficial microorganisms, humic substances, biopolymers, hydrophilic and hydrophobic materials, and various plant protection agents including fungicides, insecticides, and predator deterrents. Seed enhancement technologies can also alter the physiological status of the seed through hydration methods such as priming, steeping, hardening, soaking, and pre-germination (Gregg and Billups 2010).

It is our working hypothesis that the major barriers to restoration success can be alleviated by applying seed enhancements that are designed to address specific barriers to plant establishment for the site and time the seed is sown. In this article we examine some of the major limiting factors impairing seedling establishment in North America’s native sagebrush-steppe ecosystem, and demonstrate how “precision seed enhancement” technologies may be deployed for overcoming these restoration barriers. Specifically, we discuss technologies for: (1) increasing soil water availability; (2) improving seedling emergence in crusting soil; (3) enhancing plantability of small seeded species; (4) controlling the timing of seed germination; (5) providing seed coverage, and (6) lowering competition from weeds by improving the selectivity of pre-emergent herbicides. In general, the technologies discussed in this article diverge from the common methods employed in the seed industry and provide new conceptual ideas for improving rangeland seeding success.

Precision seed enhancement technologies

Overcoming soil water repellency using surfactant seed coatings

Soil water repellency (or hydrophobicity), is one factor that may significantly limit post-fire recovery in semiarid shrub and woodland plant communities where high amounts of resins, waxes, or aromatic oils, and associated thick litter layers existed prior to the fire (Doerr *et al.* 2000; Madsen *et al.* 2011; 2012a). Piñon and juniper are examples of woody vegetation types that are strongly correlated with the presence of soil water repellency (Madsen *et al.* 2011; Zvirzdin 2012). Zvirzdin (2012) recorded soil water repellency persisting for over three years after major catastrophic wildfires in Utah, USA. Because the persistence of this soil condition exceeds favorable post-fire recovery time frames, it needs to be taken into consideration as land managers plan restoration treatments.

Within fires that generate high temperatures, water repellency is often destroyed at the soil surface and intensified slightly below, resulting in an extremely water repellent layer overlaid by a wettable surface layer (Doerr *et al.* 2009; Fig. 1). Madsen *et al.* (2012a) found that this subsurface water repellent layer disconnected the wettable surface layer from underlying soil moisture reserves, which led to decreased water retention in the seed zone and subsequent poor germination and seedling survival. This composition of wettable soil overlaying water repellent soil also promotes soil instability. During a precipitation event, the wettable surface layer quickly becomes saturated, enabling water, soil, and debris to swiftly flow down slope (Doerr *et al.* 2009).

The application of soil surfactants is a best management practice for the treatment of soil water repellency in golf courses and sports fields (Throssell 2005; Kostka and Bially 2005) and is becoming more popular in various sectors of the agricultural industry (Lowery *et al.* 2004). Use of soil surfactants in wildland systems has also been evaluated for reducing post-fire erosion and improving reseeding success (DeBano and Conrad 1974; Madsen *et al.* 2012a). While these wildland studies have shown soil

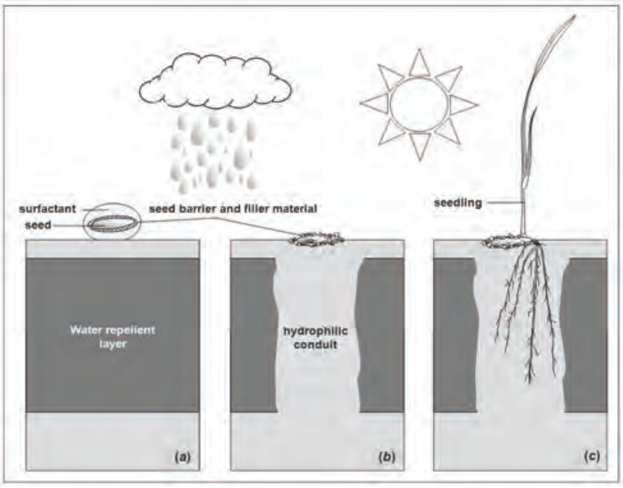

Figure. 1. (*a*) Illustration of a seed coated with a soil surfactant to overcome hydrophobic soil conditions. (*b*) Precipitation releases the surfactant into the soil overcoming the water repellent layer, resulting in a hydrophilic conduit within the microsite of the seed. (*c*) Enhanced soil moisture promotes seed germination and seedling survival. Reproduced from Madsen *et al.* (2012b).

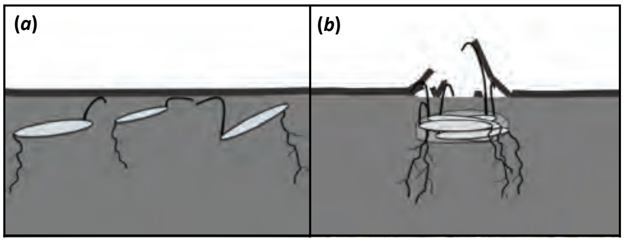

Figure 2. (*a*) Illustration of seedling emergence impeded by a soil crust layer, and (*b*) agglomerate pellet with multiple seedlings collectively generating sufficient force to penetrate through the soil crust. Reproduced from Madsen *et al.* (2012c).

surfactants to be effective in mitigating post-fire soil water repellency, their use in wildland restoration treatments has been limited. One of the main constraints has been the method of application. In anthropogenic systems irrigation water is typically used as a carrier in the delivery of soil surfactants. In wildland systems such an approach can be logistically prohibitive where the surfactant needs to be applied across large land areas with steep and rugged terrain (Rice and Osborn 1970). A potential solution to this problem was recently developed by Madsen *et al*. (2012b). In this approach, the surfactant is applied to the seed using seed coating technology. Once planted, precipitation transfers the surfactant from the seed into the soil where it ameliorates water repellency at the seed microsite. In the laboratory, surfactant seed coating (SSC) technology has been shown to increase soil water infiltration, percolation, and retention in the area around the seed, improving seedling emergence and plant survival. Field research by Madsen *et al.* (2013a) has shown SSC technology can increase plant cover and density of established plants by over 2-fold. These results illustrate the potential for SSC technology to maintain ecological integrity in post-fire ecosystems limited by soil water repellency or drought conditions.

Agglomerating Seeds to Enhance Native Seedling Emergence and Growth

In the sagebrush steppe ecosystem, seedling emergence represents a major developmental bottleneck in the progression from seed to established plant (James and Svejcar 2010; James *et al.* 2011; Boyd and James 2013). Non-biotic soil-surface crusts can act as a significant barrier to seedling emergence (Awadhwal and Thierstein 1985; Madsen *et al.* 2012c). Intensive approaches for alleviating soil crust issues, such as irrigation, or use of equipment to mechanically break up the soil crust, are often not practical and too expensive to use in rangelands.

Madsen *et al.* (2012c) developed a new coating method that alters the traditional approach to seed coating to promote the clumping of seeds into pellets (or agglomerates) (Fig. 2). Agglomerated seeds may have improved seedling emergence because the penetration force of emerging seedlings increases with the number of seeds sown in the same location (Awadhwal and Thierstein 1985; Fig. 2). Greenhouse evaluations of this technology showed that in a crusting heavy clay soil, agglomerated seeds emerged earlier and over a longer period of time (Madsen *et al.* 2012c). Seedling emergence at the conclusion of the study was 2-fold higher with the agglomeration treatment compared to non-coated seeds. This study also suggests that facilitation associated with clustered plant growth extended beyond seedling emergence. Seedlings growing in clusters had higher biomass than those from non-agglomerated seeds, which indicate that facilitation may play a more important role than intraspecific competition.

These results indicate that current seeding practices that evenly space grass seeds, may not be the most effective technique for seeding 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.

Extruded seed pellets to facilitate planting of small, low vigor, or difficult to germinate seeds

In arid systems, seed coverage at an appropriate depth is one of the most critical factors for successfully establishing native plant materials from seed (Ott *et al.* 2003; Monson *et al.* 2004; James and Svejcar 2010). Seedling emergence can be curtailed as a result of improper seed placement (*i.e.* seeds planted either too deep or shallow). As an example, James and Svejcar (2010) found that seedling density was more than seven-fold higher when sown at the proper depth, in comparison to seeding with a rangeland drill, which has only minimal control on seed placement.

Small or low vigor species can be especially susceptible to being planted at depths that prevent seedling emergence. For example, the keystone plant species of the sagebrush-steppe ecosystem, big sagebrush (*Artemisia tridentata* Nutt. ssp.) produces seeds that are approximately 0.5 mm in size. When drill seeding big sagebrush, strict attention must be paid so that the drilling depth does not exceed 3 mm (Jensen *et al.* 2001). Due to the depth restrictions of big sagebrush, land managers typically will use broadcast seeding methods to apply the seed.

Our research group is seeking to improve seedling emergence of small-seeded species by using what we have coined "seed extrusion technology" to produce pellets that encapsulate seeds within an environment that is engineered to enhance seedling emergence and plant growth (Fig. 3). The extruded pellets are formed with equipment that is similar to what is used in the food industry to produce pastas. In the process of producing extruded pellets, a seed dough mixture is extruded through a circular die, cut into ~10 mm long pellets, and then dried. In addition to seed, there is a host of materials that can be incorporated within the "dough"; including water sensitive binders, hydrophilic filler materials, super-absorbent-polymers, fungicides, plant growth regulators, humates, fertilizers, inoculates, deterrents, and soil surfactants.

Through this technology, when the pellets are drill seeded with the top of the pellet near the soil surface, the emerging seedlings by-pass restrictive near surface soil layers (such as soil physical crust; Fig. 3). The high water absorbency of the materials used also causes the pellet to swell, which pushes seeds to the surface and creates small voids or conduits for the emerging seedlings to follow. Extruded seed pellet technology may allow small seeds or low-vigor species to be planted in the same drill row as relatively larger seeds that require deeper drill depths. Subsequently, the collective group of seeds can be planted at deeper soil depths where soil water potential levels are more conducive for seed germination and seedling survival.

In a laboratory grow-room study we compared seedling emergence of pelleted and non-pellet seeds, sown 10 mm below the soil surface, for Wyoming big sagebrush (*Artemisia tridentate* Nutt.ssp. *wyomin-gensis* Beetle & Young) and common yarrow (*Achillea millefolium* L.). Seeds were planted in a poorly structured, heavy clay soil collected within a disturbed Wyoming big sagebrush site. Results indicated that incorporating seeds into an extruded pellet increased seedling emergence by 3.7-fold for common yarrow and 22.0-fold for Wyoming big sagebrush (unpublished data).

Seed that is associated with a high percentage of other plant parts can be difficult to use in standard seed drills. However, flow can be increased by incorporating seed materials into an extruded pellet. For example, >80% of a sagebrush seed lot is non-seed parts (*i.e.* achenes, seed bracts, leaves, and fine stems). This material causes bridging within the seed box, and subsequently can only be sown using specialized planters. By incorporating sagebrush seed and associated non-plant parts into the pellet, it may be possible for the material to better flow through the drill. Furthermore, because seeds are encompassed within a mass of material, settling may be decreased within the drill box, which may eliminate the need for carriers, such as rice hulls.

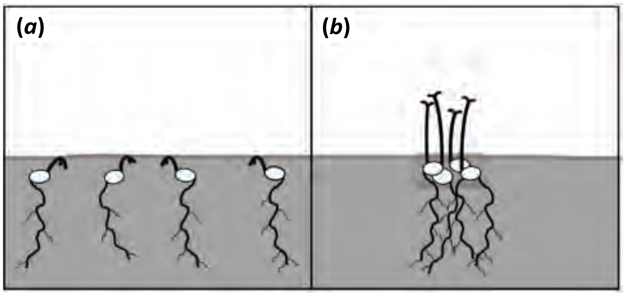

Figure 3. (*a*) Illustration of seedling emergence being impeded by a physical soil crust layer, and (*b*) seeds in an extruded seed pellet that are able to bypass the soil crust

Extruded pellets may also allow the delivery of soil amendments at rates that are several hundred percent higher than can be delivered using standard seed coating and pelleting technologies. This technology also provides the ability to mix different species within the same pellet. For difficult-to-establish species, we have hypothesized that a companion-plant could be incorporated into the pellet to facilitate seedling emergence and growth.

Time-release seed coatings to prevent early germination of fall-sown seeds

In the cold desert regions of North America, seeds are typically planted in late fall, which allows seed dormancy to be released and insures that seeds are in place in the spring when soil temperature and moisture are more favorable for seed germination and plant establishment (Monson *et al.* 2004). However, many of the cool season bunchgrasses , which are often planted in sagebrush steppe restoration projects, exhibit minimal to no dormancy at the time of seeding (*e.g.* bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve), bottlebrush squirreltail (*Elymus elymoides* (Raf.) Swezey), Sandberg bluegrass (*Poa secunda* J. Presl), and Idaho fescue (*Festuca idahoensis* Elmer). Recent research (James *et al.* 2011; Boyd and James 2013) indicates that when seeds are planted during the fall period, germination is often rapid and may reach 70% prior to winter onset, but emergence of germinated seeds does not occur prior to the spring period. Thus, the future performance of germinated but non-emergent seedlings can be decreased by the harsh overwinter soil environment. Laboratory results by Boyd and Lemos (2013) have shown that freezing even for short durations, can cause significant mortality of germinated but non-emergent seedlings. Seeds planted in the fall may also experience high mortality from pathogens. Fungal disease organisms can cause seed and seedling mortality through seed rot, damping-off, seedling blights, and root rot. These diseases are most severe where cool, moist conditions occur (Harper *et al.* 1965). After planting, rangeland seedlings are incubated under these types of conditions for several months prior to emergence, which can result in significant losses to seeds and seedlings from pathogens (Aanderud *et al.* 2012).

Hydrophobic or time-release seed coatings have had some use for controlling the timing of seed imbibition for agricultural crops (Johnson *et al.* 2004). This technology may also have application for rangeland seedings by delaying seed imbibition and subsequent germination of fall planted seeds until spring. One of the challenges our research group is striving to overcome in utilizing this technology is keeping the coating materials from cracking as a result of fall freezing events. Loss of the coating material may not be an issue if the soil remains near freezing. However, if the seed is allowed to imbibe moisture and germinate within an intermediate warm period during late fall or early winter it is probable that mortality will occur as the seedling is subjected to ensuing freezing conditions. Our research group is attempting to improve time-release seed coating technology by enhancing the plasticity of the coating materials so that they can withstand the number of soil freeze-thaw events that are anticipated to occur during the fall and early winter period at the site the seeds will be planted. We anticipate that this approach will minimize seedling mortality over the winter period, while allowing seeds to be in place to capture essential early spring moisture.

Seed pillows for enhancing seed coverage of broadcast seed

In many situations, it is not possible to use ground-based equipment, such as seed drills, due to a host of logistical constraints, such as the site being too steep and/or rocky, high densities of tree skeletons, lack of financial or logistical resources, and cultural constraints (Vallentine 1989; Bryan *et al.* 2011). Under these conditions, land managers are constrained to using broadcast aerial seeding (Monson *et al.* 2004). With this method, successful germination and establishment is highly dependent on the seed falling within a safe site that contains adequate nutrients and moisture and is protected from predation (Harper *et al.* 1965; Chambers 2000). Particularly within arid low elevations sites, where the seed bed has not been prepared, studies have shown that aerial seeding alone is not a reliable restoration approach (Nelson *et al.* 1970; Ott *et al.* 2003; Lysne and Pellant 2004). For example, Lysne and Pellant (2004) found that aerially seeded big sagebrush failed to establish on 23 of 35 post-fire rehabilitation projects.

To improve broadcast-seeding success, we have developed the "seed pillow", which is comprised of a pillow-shaped agglomeration of absorbent materials and other beneficial additives, with seeds attached on the underneath side of the pillow (Fig. 4). To increase the probability that the pillow lands upright (*i.e.* seed side down) the seed side of the pillow is weighted. The shape of the pillow is also designed to improve coverage by having a flat bottom and convex top (Fig. 4). With this shape, a broadcasted seed pillow tumbling along the soil surface is more likely to come to arrest with the bottom of the pillow towards the ground. During a precipitation event, the pillow material melts over the seeds, thus providing seed coverage and enhanced conditions for seed germination and growth. Biostimulants mentioned above for including in extruded seed pellets could also be utilized in the seed pillow. For more rapid germination, seeds could also be primed (Hardegree 1994) prior to incorporating into the pillow or treated to break seed dormancy (*e.g.* chemical and mechanical scarification, stratification, hormonal treatments).

Unlike drill seeding methods that are typically constrained to fall plantings when the soil is dry, we anticipate seed pillow technology will allow land managers to plant under a variety of soil conditions, including soils that are wet or frozen, which is typical of early spring conditions. By planting in the spring, land managers could circumvent the harsh environmental extremes associated with fall plantings such as winter drought, predation, freezing temperatures, and pathogen attack. This technology has the potential to be applied to a variety of seed sizes and types, which allows for seeding a diversity of native plant species. Because seeding with seed pillows does not require the use of disks or other mechanical equipment to plant the seed, the technology may be used to increase abundance of limiting species without disturbing native species that are already present on the site.

In a greenhouse study, we compared seedling emergence and plant growth between seeds attached to pillows and non-treated seeds (control). Model species included bluebunch wheatgrass and crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.). Seeds were broadcast on the soil surface in 14x14 cm pots. We found that the pillow treatment produced 3.9 and 5.1 times more seedlings than the control for crested wheatgrass and blueblunch wheatgrass, respectively (unpublished data). This study provides justification for additional research to fully determine the utility of seed pillow technology and illustrates the potential for this technology to transform rangeland broadcast seeding efforts.

Improving herbicide selectivity through herbicide protection pod technology

Cost-effective strategies are limited for successfully reestablishing native perennial sagebrush-steppe species in areas dominated by exotic annual grasses (Eiswerth *et al.* 2009). This is because native perennial seedlings do not compete effectively with exotic annual grass seedlings; these annual grasses have higher plant and seed bank densities, faster germination velocity and growth rates, and greater germination potential (Chambers *et al*. 2007). The superior competitive ability of exotic annuals necessitates the need for removal or reduction of these weeds prior to reseeding native or desired non-native perennial species (Monson *et al*. 2004).

The most effective control of exotic annual grasses has been achieved with pre-emergent, *i.e.* soil active, herbicides (Davies 2010; Kyser *et al.* 2007; Monaco *et al.* 2005). Imazapic is one such herbicide that has been shown to effectively control exotic annual grasses when applied appropriately (Davies and Sheley 2011; Kyser *et al.* 2007), however, the selectivity window of this herbicide is narrow

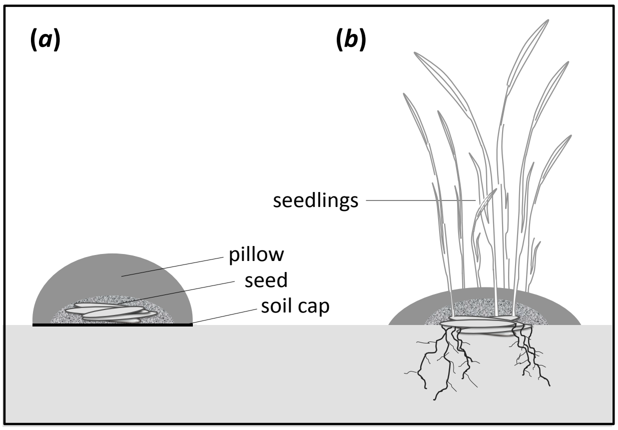

Figure 4. (*a*) Illustration of seeds attached to a seed pillow. (*b*) Precipitation melts the pillow material over the seeds and enhances seed soil contact.

and significant non-target plant injury can occur if incorrect herbicide application rates are utilized concurrently with reseeding efforts (Kyser *et al.* 2007). Often, seeding efforts are postponed for up to a year following imazapic application to allow herbicide activity to decline to a level that minimizes non-target plant injury (Davies 2010). However, when seeding is delayed, the exotic species targeted for control may reestablish (Sheley *et al.* 1996). Not only does this reestablishment limit seeding success, but restoration that requires multiple steps is typically more expensive and energy demanding than single step approaches (Sheley *et al.* 2001).

Herbicide selectivity has been improved in row crops through "banding", by applying a band of activated carbon to deactivate herbicide over the seed row (Lee 1973). A limitation of banding is that the technique does not provide complete control because weed seed within the band will also be protected from herbicide (Lee 1973).

It has been proposed that the selectivity of a range of herbicides for weeds can be further improved by coating crop seeds with activated carbon (Cook and O'Grady 1978; Hagon 1977). Commercial seed coatings are typically applied using rotary and drum coaters; through these technologies the coating can form thin films up to around 1-2 mm thick (Gregg and Billups 2010). Unlike banding, an activated carbon seed coating only provides protection to the seed and potentially a thin layer around the seed. We assume that protection from herbicide is decreased as the radical from the germinated seed extends into the soil and is subject to herbicide uptake.

Madsen *et al.* (2013b) has developed a new seed enhancement technology designed to combine the protective ability of activated carbon banding with the selectivity of seed coating. Designated as "herbicide protection pods" (HPP's), the technology uses the same extrusion equipment as described previously, to pass a dough mixture containing seed, water sensitive binders, activated carbon, and other additives, through a rectangular die. The extruded material is then cut into short strips and dried. In the field, HPP's are sown flat with the top of the pod level with or just below the soil surface (Fig. 5). This seeding method is anticipated to provide sufficient coverage of activated carbon for the seeded species to neutralize herbicide uptake, while minimizing herbicide protection to weed species.

Activated carbon-coated seeds and HPP technology have been evaluated in a laboratory grow-room, with bluebunch wheatgrass as the model seeded species and cheatgrass as the exotic invasive. In this study, bluebunch wheatgrass was either left uncoated, coated with activated carbon or incorporated into HPPs. Cheatgrass was sown in all treatments. After planting, growing pots were sprayed with 70, 105, 140, or 210 g active ingredient (ai)/ha of imazapic or left unsprayed. Cheatgrass biomass dominated the growing space in the unsprayed treatments. Imazapic effectively controlled cheatgrass and untreated bluebunch wheatgrass. Seeds coated with activated carbon showed increased herbicide protection when imazapic was applied at its lowest rate, 70 g ai/ha. Seeds incorporated into HPPs were protected from imazapic regardless of herbicide application rate. When averaged across the four imazapic applications rates (excluding the unsprayed control) the HPP treatment had 4.8, 3.8, and 19.0-fold higher bluebunch wheatgrass density, height, and biomass compared to the uncoated seed treatment. These results indicate that HPPs and, to a lesser extent, activated carbon seed coatings, may make it possible for land managers to use a single entry system to plant desired species while simultaneously applying imazapic at rates necessary for weed control.

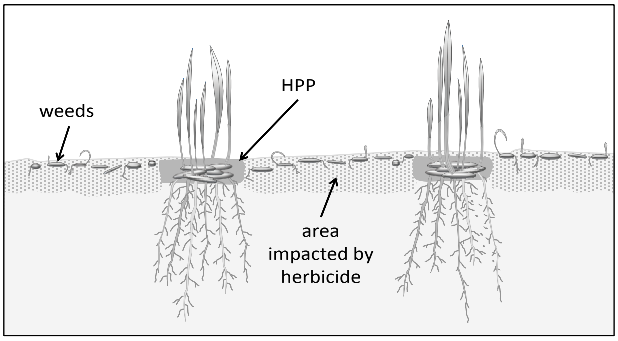

Figure 5. Illustration of a weed infested area that was planted with seed that was incorporated within herbicide protection pods (HPP's). The site was treated with pre-emergent herbicide, which controlled weed species while activated carbon in the HPP's deactivates herbicide in the immediate vicinity of the sown seed and allows for plant growth. Reproduced from Madsen *et al.* (2013b).

Economic savings associated with improved restoration success

One of the greatest economic impacts associated with the invasion of exotic annual grasses in the sagebrush steppe ecosystem is the subsequent increase in wildfire suppression costs (GAO 2007; Gebert *et al.* 2007 and 2008; Taylor *et al.* 2013). For example, the exotic annual grass cheatgrass has significantly increased fire frequency and is disproportionately represented in the largest wildfires in the western United States (Balch *et al.* 2013). Gebert *et al.* (2008) showed that wildfire suppression expenditures by the U.S. land management agencies, (*i.e.*, Forest Service and Bureau of Land Management), can exceed a billion dollars a year.

The successful establishment of perennial grasses can slow or halt the spread of exotic annuals (Davies *et al.* 2011). Therefore seeding of desired species into degraded sagebrush steppe could result in considerable savings in wildfire suppression costs. However, economic analysis by Taylor *et al.* (2013) demonstrated that for degraded Wyoming big sagebrush sites (which represent the more arid but dominant portions of the sagebrush steppe) it is typically not feasible to seed because there is a low probability that restoration efforts will be successful. Subsequently, Taylor *et al.* (2013) suggest that treatment success rates have to be improved or treatment cost lowered, or some combination of the two, in order for restoration treatments to be economically efficient.

Precision seed enhancement technologies may significantly increase the cost of the seeds planted; however, given the typically low success rates of rangeland seedings we anticipate that these costs can be more than offset through improved success rates and in some instances lower implementation expenses. Our conversations with regional land managers suggest that the probability of successfully restoring a diverse community of native species in the sagebrush steppe may be less than 10%; in other words, 90% or more of the funds used to seed native species are without positive return. The actual cost of a successful restoration treatment on a unit area basis can be thought of as the cost of the treatment divided by the probability of success (Boyd and Davies 2012). If we assume a rehabilitation cost of US$250 per hectare and a 10% probability of success, the cost outlay for every successfully rehabilitated hectare is US$2,500. If the success rate is increased to 50% using precision seed enhancement technologies, then cost per successful hectare drops to US$500 (potential savings of US$2000 for each successfully rehabilitated hectare).

With respect to the seed pillow technology, it is anticipated that restoration costs can be lowered by allowing seeds to be distributed across the landscape through broadcast methods, which are approximately 1/3 the cost of drill seeding. We anticipate that HPP technology will lower restoration costs for seeding native plants in exotic annual grass communities by allowing land managers to seed and spray soil active herbicide in 'one-pass', rather than having to apply restoration treatments in stages across two or more years (Sheley *et al.* 2001). Lastly, if precision seed enhancement technologies increase seeding success versus traditional methods, then seeding rates can be decreased, which lowers seed expenditures.

Conclusions

Based on current trends, it is probable that without viable improvement in seeding methods, our inability to restore even a bare minimum of plant-functional communities or ecological processes will ultimately result in a handful of disconnected intact sagebrush plant communities "islands" within a sea of degraded sagebrush steppe (Davies *et al.* 2011). Thus, it is imperative that reliable seeding methods be developed before the sagebrush steppe is lost and subsequent devastation incurred to North America's food supply, biodiversity, and wildlife. Recent research has provided important information that highlights the ecological barriers driving native seeding success, or lack thereof, in the sagebrush steppe (Chambers *et al.* 2007; James *et al.* 2011, Boyd and James 2013). It is critical that this and other forthcoming information be used to develop cost-effective restoration approaches in order to prevent rangeland degradation and promote the sustainability of rangeland ecosystem services.

We believe that precision seed enhancement technologies have the capacity to meet this exigency by applying seed treatments that are formulated to address spatial, temporal, and species-specific barriers limiting seedling success. Our research group has obtained preliminary data that indicates seedling establishment may be improved through the use of: (1) surfactant seed coatings to increase soil water availability in post-fire water repellent soil; (2) seed agglomerates for enhancing seedling emergence in crusting soil; (3) time-release seed coatings to prevent pre-germination of fall-sown seeds; (4) extruded seed pellets for improving seed handling characteristics and emergence of small seeded species; (5) seed pillows for providing seed coverage and enhanced conditions for seed germination and seedling growth; and (6) herbicide protection pods for improving selectivity of pre-emergent herbicides.

There is a potential for precision seed enhancements to yield direct and significant savings in the cost of successfully restoring a unit area of land through improved seedling establishment rates and reduction in the time and amount of seed required for seeding projects. Indirect savings may also be realized by maintaining functioning ecosystems through lowering wildfire suppression costs and maintaining landscapes that support both anthropogenic activities and a diversity of wildlife habitats.

It should be stressed that the precision seed enhancements shared in this paper are in their early stages of development. Additional research is needed to continue to refine these technologies and establish their utility through multiyear large-scale field trials. Concepts discussed in this paper for restoring the sagebrush steppe ecosystem may apply generally to arid rangelands and other systems throughout the globe.

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