Restoring Sage-Grouse Habitat after Fire:
Success of Different Restoration Methods across an Elevation Gradient

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Abstract:

Greater sage-grouse (*Centrocercus urophasianus*) are threatened by a continued loss of sagebrush (*Artemisia* ssp.) habitat. Recent, large scale wildfires have elevated the risk to sage-grouse as it may take up to several decades to more than a century for naturally recovery of sage-grouse habitat (i.e. reestablishment of sagebrush). Sagebrush restoration after wildfires has had limited success and success varies considerably by method, site characteristics and interactions between them. However, almost no information is available to evaluate the potential success of different restoration methods across heterogeneous landscapes. Our objective was to compare different sagebrush restoration methods (broadcast seeding, broadcast seeding and packing, planting sagebrush seedlings, seed pillows, and natural recovery) across elevation gradients ranging from 1219 to > 2134 m (4000 to >7000 ft). We used 350 plots spread across approximately a million acres of sagebrush rangelands in Oregon that burned in two mega-fires in 2012. All sagebrush restoration methods were seeded in the fall of 2013, and then repeated on adjacent plots in 2014 with the exception of sagebrush seedlings; sagebrush seedlings were planted in the spring of 2014 and 2015. For Wyoming big sagebrush plots (elevation 4000 to 5000 ft), plots seeded in the fall on 2013 had on average < 0.01 sagebrush plants/m^2 for all restoration methods. Plots seeded in the fall of 2014 had an average of 11.5 sagebrush plants/m^2 (natural recovery plots had < 0.2 sagebrush plants/m^2). Precipitation was on average 4% less than the 30 year average between September 2013 and August 2014; however, between September 2014 and May 2015 precipitation was on average 24% greater than the 30 year average. For mountain big sagebrush plots (elevation 5500 to 7000 ft), seeded plots were on average 4-fold greater than natural recovery plots (5.3 vs 1.2 plants/m^2) for both seeded years. Perennial bunchgrass competition with sagebrush seedlings may have influenced sagebrush densities particularly in higher elevation plots; mountain big sagebrush plots had on average 7.8 bunchgrasses/m^2, whereas Wyoming big sagebrush plot had on average 1.1 bunchgrasses/m^2. Our research suggests that a hedge betting approach (employing more than one restoration method) can increase the probability of successful restoration. Broadcast seeding seed pillows and bare seed over two years resulted in a sagebrush restoration success rate of 86% compared to 36% if only one method was used in one year. Information generated from this study will help land managers successfully restore sage-grouse habitat after wildfires by pairing restoration methods with site characteristics.

Background and Purpose:

Greater sage-grouse have experienced range-wide declines for the past 60 years (Patterson 1952; Connelly and Braun 1997; Braun 1998; Connelly et al. 2004). The loss of sagebrush habitat is a critical factor driving local sage-grouse populations to extirpation (Aldridge et al. 2008). Sagebrush is critically important for providing hiding cover and food for sage-grouse. In the winter, sage-grouse diets consist almost exclusively of sagebrush leaves (Patterson 1952; Wallestead et al. 1975). The sagebrush biome is one of the most imperiled ecosystems in the United States (Noss et al. 1995) and its conservation is threatened by many factors (Davies et al. 2011). It currently only occupies about 56% of its historic range and is highly fragmented (Schroeder et al. 2004; Knick et al. 2003). Large scale loss and fragmentation of sagebrush rangelands has reduced the distribution of sage-grouse to about one-half its original range (Schroeder et al. 2004). Recent unprecedentedly large wildfires in the last decade have further accelerated the loss of sagebrush habitat. For example, over 1 million acres of sagebrush rangeland burned in southeastern Oregon in three wildfires during a one month period in 2012; roughly 10% of the sage-grouse core habitat in Oregon.

Sagebrush restoration after large wildfires is often critical to accelerate sage-grouse habitat recovery, because they will not occupy large burned areas until the sagebrush recovers (Connelly et al. 2000). Natural recovery of big sagebrush (*Artemisia tridentata* Nutt.) is estimated to take on average 35 to 100 years and 50 to 120 years after wildfires in mountain (*A. t.* ssp. *vaseyana* (Rydb.) Beetle) and Wyoming big sagebrush (*A. t.* ssp. *wyomingensis* Beetle & Young) plant communities, respectively (Baker 2006). With current wide spread loss of sagebrush habitat and severe decline in sagebrush obligate wildlife species, such as sage-grouse (Connelly et al. 2000; Crawford et al. 2004; Davies et al. 2011), waiting several decades to more than a century for recovery is not reasonable or prudent. Sagebrush recovery is often slow because most wildfires occur in the summer before sagebrush seed has developed, thus natural recruitment must occur from older seed that has very low viability (Ziegenhagen and Miller 2009). Young and Evans (1989) reported that sagebrush seed remained viable for only six months under field conditions. Similarly, Wijayratne and Pyke (2009) determined that after two years, sagebrush seed near the soil surface was no longer viable. Deeper buried sagebrush seed may still be viable after two years (Wijayratne and Pyke 2009), but cannot emerge from depths greater than 5-10 mm. Thus, if sagebrush does not establish immediately after the wildfire, which is unlikely in many communities, it must disperse from seed sources outside of the burn. Sagebrush seeds only disperse a few meters from the parent plant (Young and Evans 1989) and in large wildfires this may be many miles away from the interior of the burned area. Without successful sagebrush restoration after large wildfires, sage-grouse and other sagebrush-associated wildlife will face local expiration and which will heighten the need for increased regulatory protection (e.g. under the Endangered Species Act).

Methods and associated success rates for reestablishing sagebrush are highly variable. Additionally, comparisons among different sagebrush restoration methods are lacking.

Broadcast Seeding:

In Idaho, 23 out of 35 areas seeded with Wyoming big sagebrush had no recruitment of sagebrush (Lysne and Pellant 2004). Sagebrush density and cover on the remaining seeded areas was low and not statistically different from the unseeded areas (Lysne and Pellant 2004).

Broadcast Seeding and Packing:

Pressing broadcasted sagebrush seed into the ground with a roller-packer may improve restoration success by improving soil-seed contact (Monsen and Meyer 1990).

Planting Sagebrush Seedlings:

In Nevada and Oregon, establishing Wyoming big sagebrush by planting sagebrush seedlings has been successful (Fig. 1; Davies et al. 2013; McAdoo et al. 2013). For this work, sagebrush seedlings were grown in pot containers to 10-15 cm heights and then planted into communities where sagebrush had been lost.

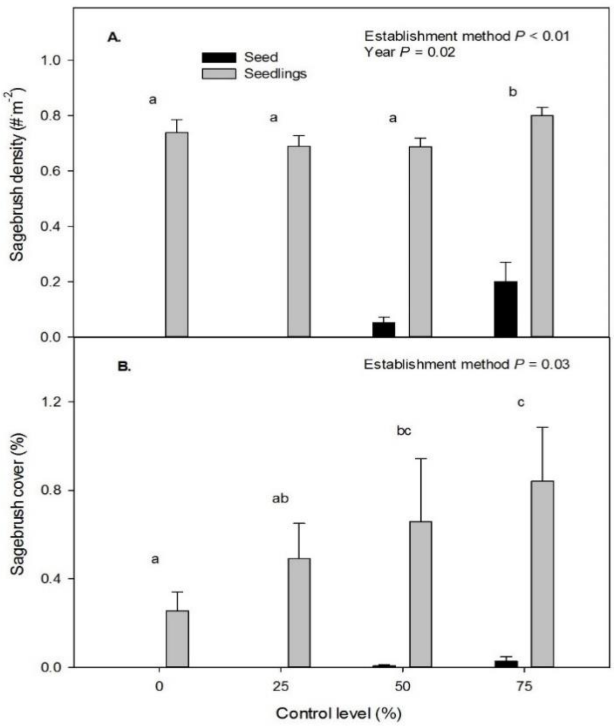

Figure 1. Wyoming big sagebrush cover (A) and density (B) in plots where sagebrush was planted as seedlings or broadcast seeded in crested wheatgrass stands with varying rates of crested wheatgrass control with glyphosate. Sagebrush density is average over the three years of the study and sagebrush cover is from the third year post-treatment. Different lower case letters indicate differences ($P \leq 0.05$) in response variable between control levels applied to crested wheatgrass.

Seed Pillows:

Sagebrush restoration may also be improved by incorporating seed within a "seed pillow" which is a multi-functional seed enhancement technology that our research group is currently developing to improve sagebrush plantability, germination, emergence and seedling growth (Fig. 2). During a precipitation event, the pillow material melts over the seeds, thus providing seed coverage and enhanced conditions for seed germination and growth. Limitations associated with seeds being buried too deep or impaired by soil crusting are diminished as the seedlings grow within an environment that is engineered for enhanced seed germination and emergence. The pillow mass also offers stability to the seed and growing seedlings, which minimizes loss from erosional forces and provides seedlings with the necessary leverage required for root penetration of the soil and site stability.

Within a laboratory grow-room study, we compared seedling emergence of seed pillows and non-treated seeds for Wyoming big sagebrush and common yarrow. Seeds were planted in a poor structured, heavy clay soil, collected from a disturbed Wyoming big sagebrush site. Results indicated that incorporating seeds into a seed pillow increased seedling emergence by 3.7-fold for yarrow (*Achillea millefolium* L.) and 22.0-fold for Wyoming big sagebrush (Fig. 3). Planting sagebrush using seed pillows greatly increases success in pot studies, but needs field testing to further evaluate its utility.

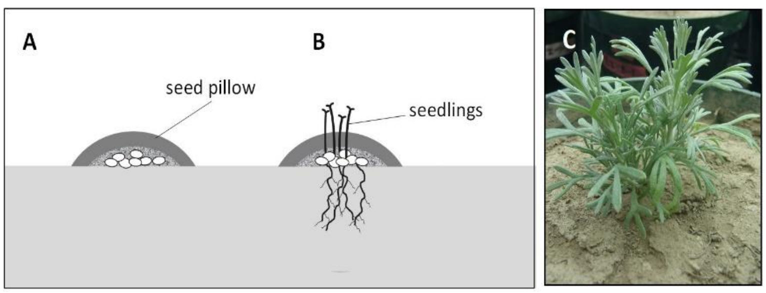

Figure 2. A. Schematic diagram of sagebrush seeds incorporated within a seed pillow. B. Precipitation melts the pillow material over the seeds and enhances seed soil contact for seed germination and emergence. C. Example of Wyoming big sagebrush seedlings growing from a seed pillow.

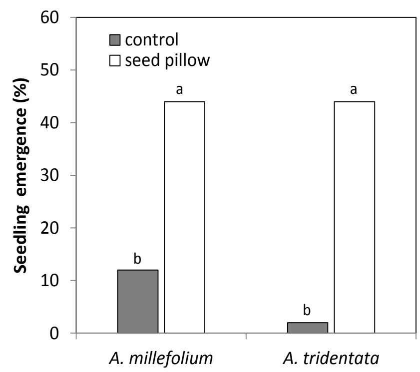

Figure 3. Laboratory results comparing seedling emergence for non-treated seed and seed that was incorporated into seed pillows for common yarrow and Wyoming big sagebrush.

In addition to varying by planting method, sagebrush restoration success probably varies by site characteristics. Boyd and Davies (2012) found that herbaceous restoration using drill-seeding varied up to 24-fold across a post-fire sagebrush landscape in southeastern Oregon. This work underscores the spatial heterogeneity of ecological barriers to seedling establishment and suggests that restoration techniques should vary in accordance with environmental conditions. Restoration of sagebrush could be improved by correctly matching restoration methods (broadcast seeding, broadcasting and roller-packing, planting seedlings, and seed pillows) with environmental conditions. Though planting sagebrush seedlings probably has the most potential for successfully establishing sagebrush in all situations, it is economically prohibitive to apply this treatment across large landscapes, especially if a less expensive method may be successful. Similarly seed pillows and roller-packing after seeding may appreciably improve broadcast seeding success, but also significantly increase costs. Correctly pairing restoration technique and probability of success with environmental constraints will allow land managers to best array these techniques across variable landscapes in the most cost efficient manner.

For this study, we compared different sagebrush restoration methods (broadcast seeding, broadcast seeding and packing, planting sagebrush seedlings, seed pillows, and natural recovery) across elevation gradients ranging from 1219 to > 2134 m (4000 to > 7000 ft) elevation in large recently burned areas in Oregon. The objectives of this study were to: 1) determine where different post-fire sagebrush restoration methods should be applied based on environmental characteristics to efficiently and effectively restore sage-grouse habitat, and 2) evaluate newly developed technologies to restore sagebrush steppe habitat for sage-grouse. We hypothesize that 1) natural recovery and seeding sagebrush will be more successful as elevation increases, 2) improving soil-seed contact by using a roller-packer after seeding sagebrush will improve seeding success, and 3) at lower elevations, seed pillows and planting seedlings will be more successful than other methods at establishing sagebrush.

Site Description and Methods:

Study Area:

The study sites were located in the northern Great Basin in sagebrush steppe rangelands that burned in two wildfires, Holloway (August 5-21, 2012; 461,047 acres) and Long Draw (July 8-15, 2012; 557,648 acres; Fig. 4). These wildfires burned approximately 412,163 ha (~1 million ac). Elevation of the study sites ranged from 1219 to > 2134 m (4000 to > 7000 ft) above sea level. The study sites were located in areas that completely burned with no survival of sagebrush plants. Prior to the wildfires, the plant communities were primarily Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) and mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle, with Wyoming big sagebrush transitioning to mountain big sagebrush with increasing elevation.

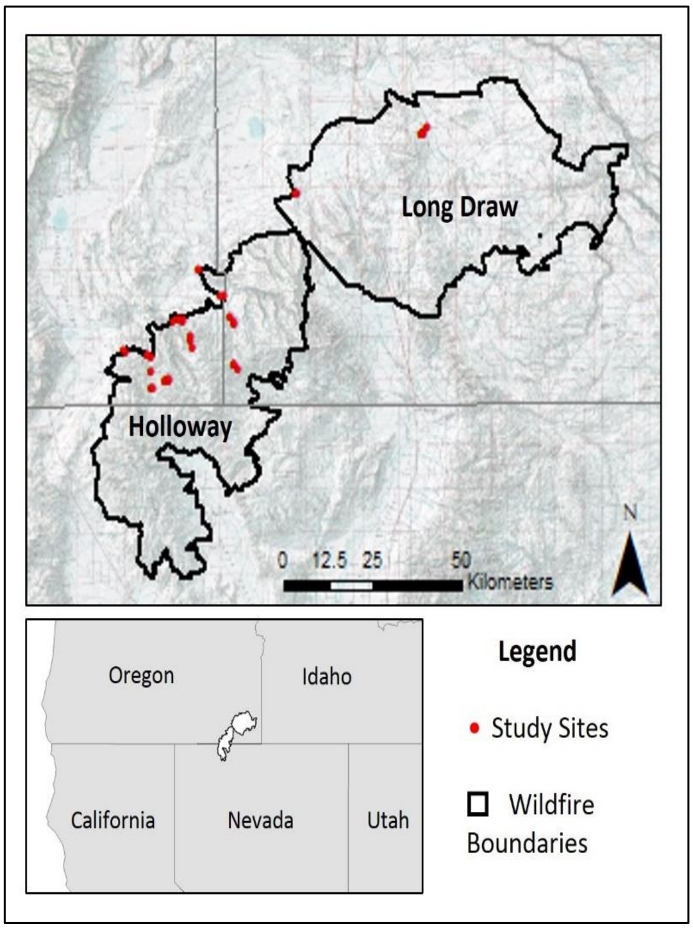

Figure 4. Study site locations in the northern Great

Climate:

Climate is typical for the northern Great Basin, with hot summers, cool winters, and most precipitation occurring in the winter and spring. Average long-term (30-year) annual precipitation ranged from 212 to 593 mm across the study site (Fig. 5; PRISM, 2017). In 2014, annual precipitation ranged from 98% to

110% of the long-term average. However, May and June precipitation in 2014 was 29-35% of the long term average. In 2015, annual precipitation averaged 84-127% of the long-term average, with percent of average decreasing with increasing elevation. May precipitation in 2015 averaged 220% and 212% of the long-term average at the two lowest elevation (1219 and 1372 m). In 2016, annual precipitation ranged from 81-96% of the long-term average.

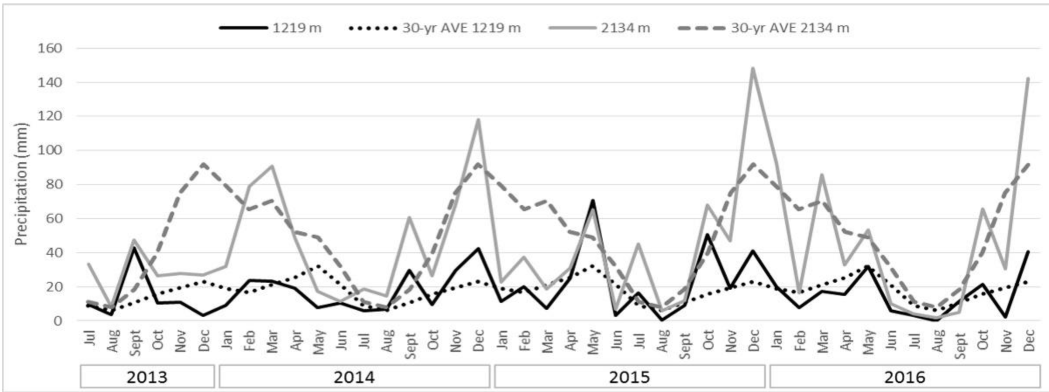

Figure 5. Monthly precipitation during the study and 30-yr average (AVE) at 1219 m and 2134 m study

Experimental Design:

We evaluated sagebrush restoration success with five methods (treatments) across an elevation gradient using a randomized block design. Along the elevation gradient, five replicates were established at seven approximate elevations: 1219, 1372, 1524, 1676, 1829, 1981, and 2134 m (4000, 4500, 5000, 5500, 6000, 6500, 7000 ft). Treatments were randomly assigned within block (site) and included: 1) natural recovery (control), 2) broadcast seeding sagebrush, 3) broadcast seeding sagebrush followed by roller-packing, 4) broadcast seeding sagebrush seed pillows, and 5) plant sagebrush seedlings. Treatments were applied on 35 plots in 2013 (1 year post wildfire), and repeated on adjacent plots in 2014 (2 year post wildfire). The total number of plots was 350 (5 replicates X 7 elevations X 2 years X 5 treatments = 350 plots).

At each replication, treatments were randomly applied to 5 X 10 m plots (with a 2 m buffer between treatment plots) at a rate of 1000 pure live sagebrush seeds per m^2 in late October both years for broadcast seeding, broadcast seeding followed by roller-packing, and broadcast seeding seed pillows. Pure live seed was estimated using the petri dish germination method (Meyer and Monsen 1991). Sagebrush seedlings were planted in late February/early March 2014 and 2015 at a rate of 50 seedlings per m^2. Sagebrush seedlings were grown in cone containers (3.8 cm in diameter at the top and 21 cm tall) in a three-season greenhouse. Sagebrush seedlings were thinned to one individual per cone container and grown to a pre-planting height of approximately 15 cm. Wyoming and mountain big sagebrush seed was provided by the Utah Division of Wildlife Resources Great Basin Research Center (Ephraim, Utah). Wyoming and mountain big sagebrush were planted on sites where it was dominant prior to burning (Wyoming big sagebrush 1219 to 1524 m; mountain big sagebrush 1676 to 2134 m).

Seed Enhancement Technologies

The seed pillows were made by thoroughly mixing dry ingredients and then mixing with liquid ingredients to form a dough (Table 1; Madsen and Svejcar 2016). Dough material was passed through an industrial dough extruder (Moline Machinery LLC, Duluth, Minnesota) that had a rectangular 8 X 16 mm—wide die. Extruded material was then cut into 16 mm lengths creating seed pillows that were 8 mm thick, and 16 mm wide X 16 mm long. Seed pillows were forced air dried and stored in a cool storage area until planting.

Seed pillow formulation evolved between 2013 and 2014 (Table 1).

Table 1. Products and amounts per batch used to produce seed pillows in 2013 and 2014. Weight of sagebrush PLS differed between lot numbers each year.

Ingredients	2013 Batch (g)	2014 Batch (g)
Dry Ingredients		
Calcium Bentonite	31	-
Compost	20.65	29.19
Worm Castings	33	10
Biochar	3.83	-
660 fine powder	3	3
660 fine granules	1.00	1.25
Starch 1500	1.75	-
Zeolite – 75%	-	7.34
IGB-3	-	9.66
Diatomaceous Earth	-	10.19
Sagebrush seed		
ARTRW8	1.29	0.88
ARTRV	1.56	0.62
Liquid Ingredients		
SSC 0.1% 1820	0.10	-
Captan	-	0.01
ASET-4001	-	0.08
Ascend	-	0.18
Water	99.9	90.3
Total	197.08	162.7

- Calcium bentonite has strong absorptive properties that draw fluids from surrounding soil. This ingredient was dropped after 2013 following multiple grow-room trials where it appeared that the absorptive properties hindered seed imbibition likely due to fluctuations in moisture. Zeolite – 75%, IGB-3, and diatomaceous earth was used in 2014 replacing calcium bentonite. These materials are highly absorbent with beneficial additives such as silica, which makes plants more resistant to drought and diseases.
- Local sourced compost was used because of its absorbent nature, ability to hold soluble minerals, and provide nutrients to the seed pillows.
- Worm castings are also nutrient-rich with high levels of microbial activity; it also holds moisture better than plain soils. Worm castings pH was monitored prior to use and where appropriate, leaching techniques were applied to raise the pH.
- Biochar was made via pyrolysis from western juniper trees. Biochar is rich in carbon increasing seed pillow fertility. Additionally, biochar has a dark coloring likely increasing the amount of light and heat absorbed from the sun, which may provide more favorable conditions for planted species. Prior to seeding in 2014, multiple grow-room biochar trials were elevated with no observed seed establishment improvement, hence, biochar was removed from the 2014 recipe.
- Fine granules and 660 fine powder are superabsorbent polymers that absorb and retain large amounts of liquids (up to 300 times it weight). Although the use of this ingredient has been shown favorable with drill seeding applications (i.e., ability to swell and raise in the soil profile; Madsen et

al., 2016), it appears to hinder seed establishment in pillows due to its swelling and shrinking properties which disrupted soil-seed contact.

- Starch 1500 was primarily used for its ability to bind ingredients and maintain desired seed pillow shapes during processing. Seed pillow materials ideally break down following precipitation events providing seed coverage and enhancing seed microsites (Madsen et al. 2014), however, it was observed in the field during the data collection period (June 2014) that pillows remained intact with minimal "break down" of ingredients. Multiple grow-room trials were evaluated for varying amounts of starch leading to the ultimate decision to remove starch from the 2014 seed pillow recipe. During sampling in June 2015, it was observed that seed pillows broke down for both 2013 and 2014 seeding treatments, however, the timing of when this occurred relative to seed germination and establishment is unknown.
- SCC 0.1% 1820 and ASET-4001 are surfactants.
- Captan is a fungicide added to inhibit fungus and bacteria from damaging the seed. Although Captan is a dry ingredient, it was added to the liquids and mixed to create a homogenous blend prior to being added to the dry ingredients.
- Ascend is a plant growth regulator.

Vegetation Measurements:

Vegetation was sampled for three years after initial treatments were applied. Vegetation data were collected in June 2014 (only year 1 treatment plots), 2015 (year 1 and 2 treatment plots), and 2016 (year 1 and 2 treatment plots). Transects were 10m and placed at 1.5m, 2.5m, and 3.5m locations along the 5m side of the treatment plot. Both woody (primarily sagebrush) and herbaceous plant density and cover were measured in 9, 0.2 m^2 quadrats in each treatment plot; the quadrats were placed along each of the 10m transects at the 3m ,5m, and 7m mark. Species density was measured by counting all plants rooted inside the 0.2 m^2 quadrats. Cover of bare ground, rock, litter and basal area of vegetation were also collected within each quadrat.

Sagebrush and other shrub density were measured in 2016 by counting all plants rooted inside the 5 X 10m plot. Sagebrush height and two perpendicular crown widths were measured on 10 (except when plot density was < 10 sagebrush plants) randomly selected sagebrush plants per plot. Volume was determined from the height and perpendicular crown widths. Average sagebrush volume was multiplied by sagebrush density to determine volume per unit area (cm^2/m).

Environmental Characteristics:

We measured a suite of environmental characteristics at each site to ensure a comprehensive evaluation of the relationship between site properties and success of restoration methods. Elevation, aspect, slope and hillshade were all determined using ArcMap 10.0™ (ESRI® 2011. Environmental Systems Research Institute, Redlands, CA) with a 10-m digital elevation map layer (U.S. Geological Survey (USGS), EROS Data Center). Hillshade is a hypothetical illumination of a surface calculated using altitude, azimuth, slope, and aspect (Burrough and McDonell 1998). Soil texture was determined using the hydrometer method (Gee and Bauder 1979) for two soil depths, 0-20 cm and 20-40 cm depths. Soil carbon and nitrogen for each depth was also determined using LECO CNS-2000 (Leco Corporation 2003). Precipitation and temperature was determined using PRISM precipitation maps (PRISM 2017); annual (Oct-Sept) and effective (Oct-June) precipitation for each study site was calculated using PRISM data.

Key Findings:

***Objective 1:* Determine where different post-fire sagebrush restoration methods should be applied based on environmental characteristics to efficiently and effectively restore sage-grouse habitat.**

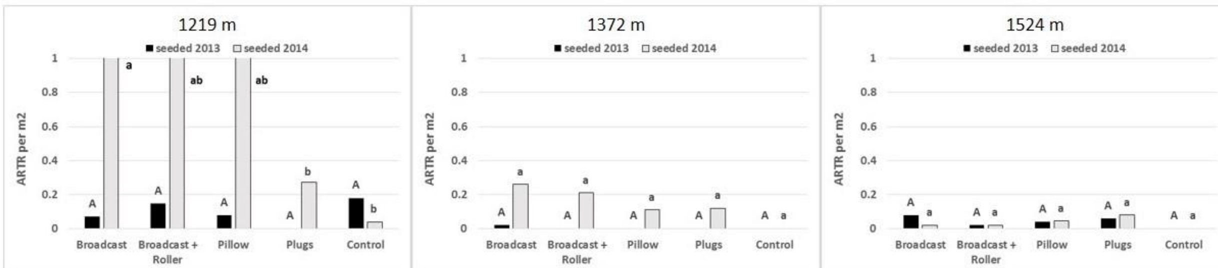

Figure 6. One-way analysis of variance of Wyoming big sagebrush 2016 seeding density by treatments, elevation and seeding year. Average mean differences with different letters within seeding year are significantly different ($P < 0.05$) using the Tukey-Kramer honestly significant difference multiple comparison procedure.

- Wyoming big sagebrush density varied by elevation, treatment, and seeding year. Annual precipitation and treatment had a significant interaction ($P < 0.05$; Fig. 6) and likely influenced sagebrush seeding success at lower elevations (seedings were considered successful if average sagebrush density was ≥ 0.25 plants/m^2). At the 1219 m elevations, precipitation between Sept 2014-May 2015 was 24% above the 30-year normal (244.5 mm compared to 183.9 mm average). May 2015 alone received 70.7 mm of precipitation, the 30-year annual is 32.2 mm. *This suggests that timing of precipitation is critical and having seeds in place when increased precipitation occurs will improve overall seeding success.*

- Treatment differences were significant at 1219 m elevations in the 2014 seeding ($P < 0.05$). Broadcast seeding (11.5 sagebrush/m^2) was significantly greater than any other treatment. Broadcast plus roller and pillows had 3.2 and 3.6 sagebrush/m^2, respectively and were significantly greater than natural recovery (control 0.06 sagebrush/m^2).

- In the 2013 and 2014 seeding, Wyoming sagebrush planted seedlings had on average 0.01 and 0.08 sagebrush/m^2. Sagebrush seedlings were planted at the end of February/early March (2014/2015). May 2014 was 76% below average precipitation (7.6 mm). Similar patterns can be seen in March 2015 where precipitation was 67% below average precipitation (7.1 mm). *The lower precipitation events likely prevented roots from staying in front of the soil drying front causing high mortality of planted sagebrush seedlings. This likely only delayed germination for seeded sagebrush.*

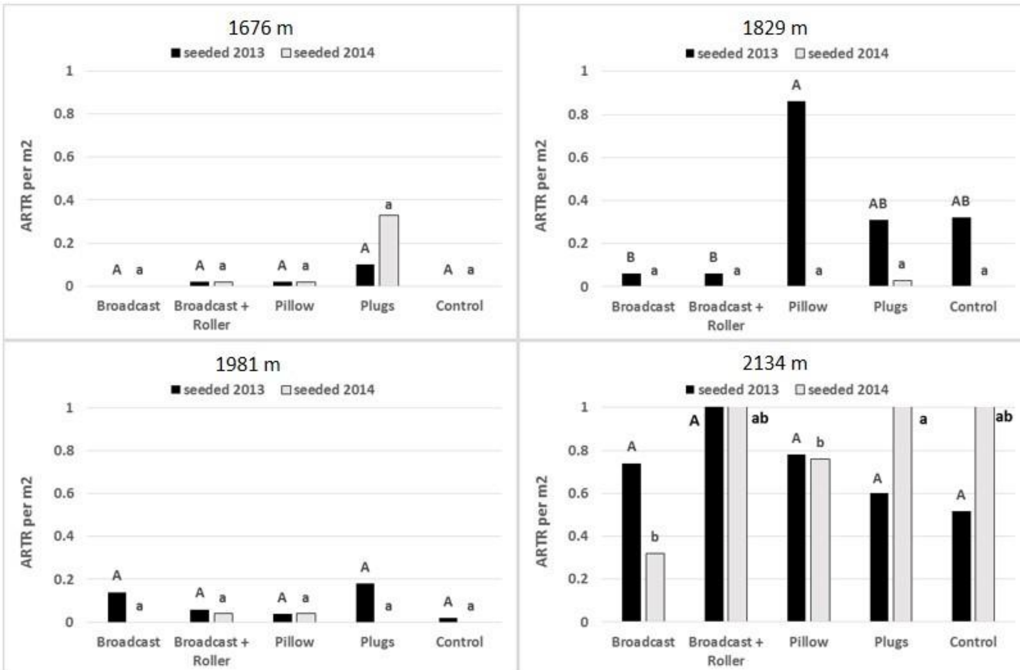

Figure 7. One-way analysis of variance of mountain big sagebrush 2016 seeding density by treatments, elevation and seeding year. Average mean differences with different letters within seeding year are significantly different ($P < 0.05$) using the Tukey-Kramer honestly significant difference multiple comparison procedure.

- *Mountain big sagebrush density increased with increasing elevations in both the 2013 and 2014 seeding* (Fig. 7). At 2134 m, sagebrush planted seedlings had the highest plants/m^2 in 2014 with 1.4 sagebrush/m^2.

- *Natural sagebrush recovery was apparent at 2134 m, suggesting that sagebrush restoration efforts are unnecessary at and above this elevation.*

- *All treatments were successful (sagebrush density ≥ 0.25/m^2) at 2134 m elevation*. Additionally, perennial grass cover was significantly higher than the other mountain big sagebrush sites. *This suggests that although competition was present, sagebrush seedlings were able to establish and compete for resources 2 and 3 years post-wildfire.*

- *Elevation had the highest correlation value for both Wyoming big sagebrush and mountain big sagebrush density* (r = 0.19 and r = 0.21, respectively).

Objective 2: **Evaluate newly developed technologies to restore sagebrush steppe habitat for sage-grouse.** For this objective, we evaluated broadcast-seeding seed pillows with broadcast-seeding bare seed.

- *We found no evidence that seed pillows improved sagebrush establishment and growth across the elevation gradient* (Fig. 9A and B; *P* = 0.917 and 0.120; Fig. 10A and B; *P* = 0.990 and 0.186). Sagebrush density varied by elevation in both the 2013 and 2014 seedings (Fig. 9A and B; *P* < 0.001 and < 0.001). Sagebrush density in the 2013 seeding was greatest at the higher elevations. In contrast, sagebrush density in the 2014 seeding was greatest at the lowest elevation. Sagebrush cover generally increased with elevation in the 2013 seeding. In the 2014 seeding, sagebrush cover was greater in the lowest and highest elevation compared with the mid-elevations (Davies et al. *IN PRESS*).

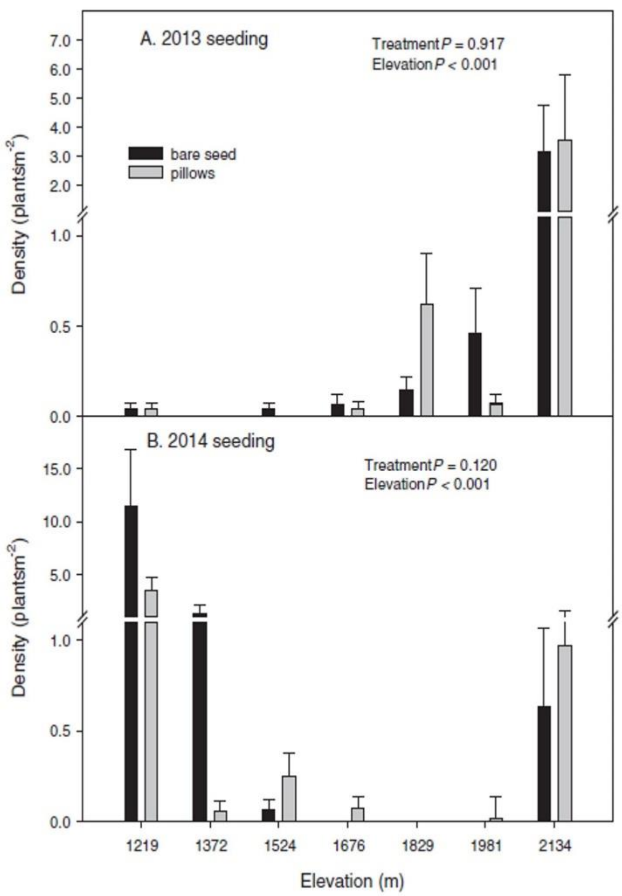

Figure 9. Taken from Davies et al. *IN PRESS.* Sagebrush density (mean ± S.E.) in bare seed and seed pillow treatments broadcast-seeded in 2013 and 2014 across a large elevation gradient in the northern Great Basin. Data were averaged for 2014, 2015, and 2016 for the 2013 seeding and 2015 and 2016 for the 2014 seeding.

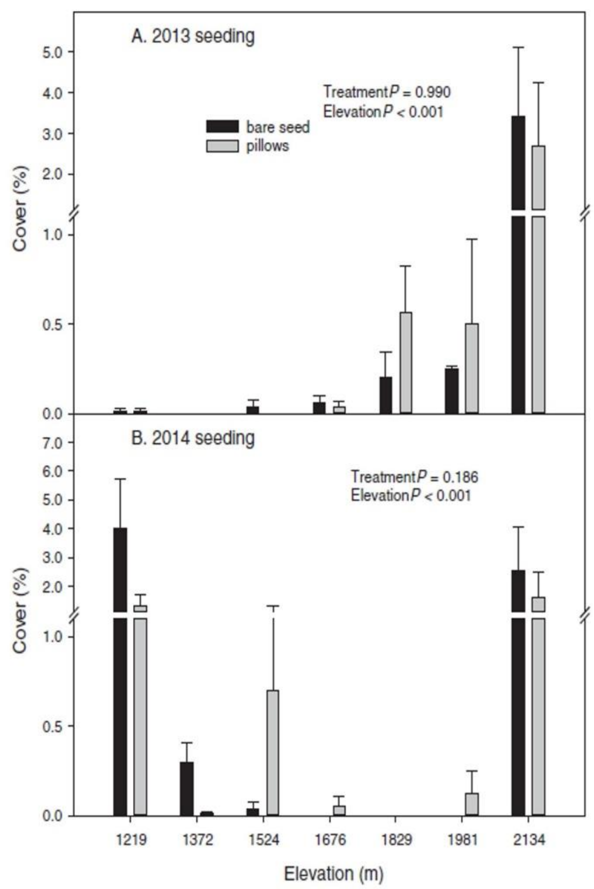

Figure 10. Taken from Davies et al. *IN PRESS.* Sagebrush cover (mean ± S.E.) in bare seed and pillow treatments broadcast-seeded in 2013 and 2014 across a large elevation gradient in the northern Great Basin. Data were averaged for 2014, 2015, 2016 for the 2013 seeding and 2015 and 2016 for the 2014 seeding.

- *Seed pillow formulation used in our study was not advantageous compared with less expensive bare seed for restoring sagebrush after wildfire.* Seed pillow formulation is continuing to evolve and currently being tested in greenhouse and field trials in Utah and Idaho. Additionally, alterations to shape and distribution methods have increased seeding success.

- *Seed pillows did not increase the likelihood of successful sagebrush restoration, however, they were successful (≥ 0.25 sagebrush/m^2) at times when bare seeds were not* (and the same was true for bare seeds; Table 2). If we only required that one of the two methods be successful, sagebrush restoration was successful on 50% of the seedings. Thus, sagebrush restoration success could have been improved by seeding both bare seed and seed pillows (Davies et al. *IN PRESS*).

Table 2. Taken from Davies et al. *IN PRESS*. Sagebrush restoration success using seed pillow and bare seed broadcast-seeded in 2 yr across an elevation gradient in southeast Oregon. Seedings were considered successful if sagebrush density was ≥ 0.25 sagebrush/m^2 averaged across the 5 sites at that elevation. The "Combined" category was considered successful if at least 1 of the methods was successful in at least 1 of the seeding yr at that elevation.

Seeding	Elevation (m)						
yr	1219	1372	1524	1676	1829	1981	2134
2013	Both fail	Both fail	Both fail	Both fail	Pillows successful	Bare successful	Both successful
2014	Both successful	Bare successful	Pillows successful	Both fail	Both fail	Both fail	Both successful
Combined	Success	Success	Success	Fail	Success	Success	Success

- *Seeding both bare seed and seed pillows (aka, bet hedging) may increase the probability of restoration success.* We found that if we had seeded in 2 yr combined with two seeding methods, then our success rate would have been 86% (Davies et al. *IN PRESS*).

Management Implications:

Land managers are often entrusted with restoring 10s to 100s of thousands of acres after wildfires; therefore, any system for selecting the appropriate sagebrush restoration method based on site characteristics needs to be intuitive and should partition landscapes into units large enough to be practical for management. Our research provided land managers with strategies to select the appropriate method to restore sagebrush after large wildfires based on environmental characteristics. For example, natural sagebrush recovery is likely adequate at and above 2134 m (7000 ft) in mountain big sagebrush dominated landscapes.

Using a bet hedging approach, seeding both bare seed and seed pillows for example, may increase the probability of success. Factor(s) limiting seedling establishment in the field vary temporally and spatially. Thus, one seeding method is unlikely to be the best method at every location in every year. Therefore, bet hedging (in this study bare seed and seed pillows) likely increases the probability that at any given location that some seeded species will establish because limiting factors will be mediated for at least a portion of the seeds and that some seeds will likely germinate when conditions are conducive for establishment.

Our results also demonstrate, counter to common assumptions, that lower elevations sagebrush seedings can be successful. Multiyear precipitation likely has a significant interaction with elevation effect on sagebrush establishment. Thus, lower elevations cannot necessarily be assumed to be unrestorable; nor is increasing elevation always positively correlated to increasing establishment of seeded species in the Great Basin.

Relationship to other recent findings and ongoing work:

This research project builds upon ongoing research performed by the Agricultural Research Service at the Eastern Oregon Agricultural Research Center, Brigham Young University and the University of Idaho. We have been evaluating broadcast seeding and planting sagebrush seedlings in exotic annual grass and crested wheatgrass plant communities (Davies et al. 2013; McAdoo et al. 2013). Seed enhancement technologies are continuing to be developed to enhance the establishment of native species (including sagebrush) following disturbance (Madsen et al. 2016; Davies et al. 2017). Additionally, our group is evaluating solid matrix priming techniques (Madsen et al. 2017, *IN REVIEW*) and activated carbon pellets (Davies et al. 2017) to increase potential seeding success following wildfire. We have also implemented new research in the Buzzard Complex Fire (2014) evaluating broadcast seeding mountain big sagebrush and native grasses in higher elevations that were encroached by western juniper. We also are comparing restoring Wyoming big sagebrush with broadcast seeding and fall planting of seedlings in the lower elevations of the Buzzard Complex. We planted seedlings in the fall in the Buzzard Complex because of the limited success we had with spring planting and other research has had good success with fall planting of sagebrush seedlings (e.g. Davies et al. 2013)

Future Work Needed:

Although we have drawn significant conclusions concerning sagebrush restoration over variable environments, research is needed to model sagebrush recovery using data collected from this study with Geographic Information System (GIS). This will provide managers additional tools for prioritizing restoration methods across the landscape. Further work evaluating seed enhancement technologies that will enable seeds to overcome ecological barriers is underway. Continued sagebrush restoration research will benefit sagebrush-steppe ecosystems, and in turn, sagebrush obligate species.

Deliverables:

Proposed	**Description**	**Delivered/Status**
Referred manuscripts	• Davies, K.W., et al. 2017. Evaluating a seed technology for sagebrush restoration across an elevation gradient: support for bet hedging. *Rangeland Ecology and Management*	In press
	• Hulet, A., K. W. Davies, and C.S. Boyd. Post-fire recovery of native and introduced plant species across an elevation gradient.	In preparation
	• Hulet, A., K. W. Davies, M. Madsen, and C.S. Boyd. Restoring sagebrush after mega-fires: success of different restoration methods across an elevation gradient.	In preparation

Invited paper/presentation	• "The Use of Seed Enhancement Technologies to Improve Sagebrush Establishment across an Environmental Gradient" The Next Steppe: Sage-grouse and Rangeland Wildfire in the Great Basin conference, Boise, ID • "Restoring Sagebrush after Mega-Fire" The Society for Range Management annual meeting, Sacramento, CA • "Post-Fire Effects and Restoration Opportunities" University of Idaho Rangeland Fall Forum, Jerome, ID • "Restoring Sagebrush after Mega-Fires: Success of Different Restoration Methods across an Elevation Gradient", The Society for Range Management annual meeting, Corpus Christi, TX • "Sagebrush and Fire: the Good, the Bad, and Why We Should Care" University of Idaho Forest, Rangeland, and Fire Sciences Seminar Series, Moscow, ID • "Research update on post-fire restoration" Oregon/Washington BLM State Range Conservation Meeting. Prineville, OR. 5-10-2016 • "Applications of Object-Based Image Analysis on Rangeland Ecosystems" University of Idaho Geography Seminar Series, Moscow, ID • "Restoring sagebrush after mega-fires: success of different restoration methods across an elevation gradient" SRM Annual Conference, St. George, UT • "Restoring sagebrush after fire" Northwest Basin and Range Ecosystem Symposium. Lakeview, OR • "Sagebrush steppe restoration: research update" Oregon/Washington BLM State Range Conservation Meeting. Burns, OR	November 2014 February 2015 October 2015 January 2016 March 2016 May 2017 September 2016 February 2017 February 2017 May 2017
Field tour	• Field tour with land managers	July 2017
Extension articles	• Pacific Northwest Extension Publication: Selecting the appropriate method to restore sagebrush after large wildfires based on environmental characteristics	In preparation
Webinar	• JFSP Great Basin Fire Science Delivery	Early 2018
Dataset	• Vegetation and environmental characteristics dataset cataloged with the Forest Service R & D data archive	September 2018

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