FINAL REPORT

Impact of unburned remnant sagebrush versus outplants on post-fire landscape rehabilitation

JFSP PROJECT ID: 18-1-01-48

August 2020

Cara Applestein
Boise State University

Trevor Caughlin
Boise State University

Matthew Germino
US Geological Survey

Table of Contents

List of Tables

List of Figures

Keywords

Sagebrush seed dispersal, seedling recruitment, post-fire regeneration, passive vs active management, aerial seeding

Acknowledgements

Abstract

Nearly half of the vast sagebrush steppe in the western United states has lost many or nearly all native plant species, largely due to the interaction of invasive species and increased wildfire. Re-establishing sagebrush, a keystone component of these ecosystems, has become a management focus in recent decades using aerial broadcast seeding or limited plantings. One promising avenue for improving the planning and assessment of post-fire seedings involves the spatial patchiness of burn patterns and in the recovery of sagebrush after fire. Unburned remnant or post-fire planted islands (or patches) of sagebrush could be valuable seed sources for species recovery in the surrounding burned areas. Information on how much spatial expansion of unburned remnant patches is expected over time could help in the planning of post-fire treatments. However, previous research has indicated that sagebrush seeds do not disperse far, which would imply that unburned or created patches do not contribute much to sagebrush reestablishment effects. Our objective was to determine whether remnant/unburned sagebrush patches contribute to sagebrush recovery in surrounding burned areas surrounding them. We quantified seed rain and seedling establishment in relation to patches of sagebrush that were either unburned remnant or had been planted in the first year or so after wildfire. We conducted a seed trapping experiment across 6 different wildfires during two winters to determine seed transport distances. We paired this with a seedling recruitment study on the Soda wildfire where we mapped distances between remnants and seedlings. We found that although a few seeds did travel much farther than previously recorded (maximum of 26 m), seed dispersal was highly variable across sites and patches, and only a small portion of seeds dispersed farther than a few meters from sagebrush patches. Our seedling recruitment assessment confirmed a limited contribution of remnants to seedling recruitment. Specifically, a microsite was only marginally more likely to have a sagebrush seedling even if there was >50 neighbors within a 40 m radius. There were no differences in the quantity of seeds dispersed from remnant versus actively managed patches. Overall, we found that isolated sagebrush patches are unlikely to significantly contribute to landscape regeneration of sagebrush on large fires and that aerial seeding is likely needed to overcome seed limitations. We did detect substantial variation in site-level sagebrush seed production among years, including one site that did not produce any seed in one year. Future studies addressing spatial and temporal variability of sagebrush seed production may help elucidate more about seed availability in burned areas.

Objectives

The questions for this student GRIN study were originally:

> Question 1: Is post-fire sagebrush reestablishment enhanced in the vicinity of unburned islands? Are there gradients of establishment from islands?
> How do characteristics of islands relate to recovery patterns (shape, density, plant heights) of sagebrush into the burn?
> Question 2: Does post-fire sagebrush establishment around sagebrush islands differ if the island is an unburned remnant compared to man-made created by planting seedlings?
> Question 3: How does seed rain and seedling establishment vary with distance from sagebrush island patches?

We made a subtle but more effective articulation of our original questions to the following questions:

> Question 1: How does seed rain vary with distance from sagebrush island patches?
> Question 2: How variable is seed rain on the landscape?
> Question 3: Is post-fire sagebrush reestablishment enhanced in the vicinity of unburned islands?
> Question 4: Does post-fire seed rain around sagebrush islands differ if the island is an unburned remnant (passive management) compared to man-made (active management) created by planting seedlings or seeding?

The rationale for this adjustment was that we saw very little recruitment occurring around patches where we were trapping seeds. We paired our seed trapping study with seedling recruitment monitoring at a site with known successful recruitment. We also discovered that seed rain (deposition) was so variable in time and space that it was necessary to increase our sample size and determine different sources of variation in seed rain. We expanded the initial definition of "human-made" islands to include those created by seeding, due to the use of this method as a common management technique of re-establishing sagebrush.

Background

Nearly half of the western rangelands occupied by sagebrush steppe have experienced loss of native species as a result of increased wildfire and exotic grass invasions (Miller et al. 2011). As a result, there has been significant management effort involved in seeding or planting sagebrush for post-fire rehabilitation, albeit with mixed success (Pilliod et al. 2017, Knutson et al. 2014). Schlaepfer et al. (2014) concluded that despite a significant scientific focus on sagebrush regeneration, there was a greater need for understanding seed dispersal and microsites when considering post-fire sagebrush regeneration. Seed dispersal distances of sagebrush stands have typically been reported as < 1-2m from the maternal plant from a very limited number of studies, several of these descriptive in nature (Goodwin 1956; Young and Evans 1989; Welch 2005). Despite this, there has been indication of seedling recruitment occurring out several hundred meters from remnant adults into burned areas (Mueggler 1956). Some of this recruitment could come from short-lived soil seed banks, particularly if buried seed becomes exposed after burning, but these seed banks only persist for about 2-3 years under the right conditions and fire can significantly reduce viable seed bank (Young and Evans 1989, Allen et

al. 2008, Wijayratne and Pyke 2012). If soil seed banks do contribute to seedling re-establishment, they are likely to be quickly exhausted, making persistent seed production from nearby remnant sagebrush more important. Big sagebrush seeds germinate readily, with minimal dormancy (except for *ssp. vaseyana*). Germination rates can be as high as 90% (Young et al. 1991).

While several studies have examined post-fire regeneration of big sagebrush, these studies have not specifically addressed the impact of unburned remnant patches (or newly created patches) within a larger burn context and the focus has been heavily on *A. t.* ssp. *vaseyana* (DiCristina and Germino 2006, Lesica et al. 2007, Ziegenhagen and Miller 2009, Nelson et al. 2014). Stand recovery rates are typically substantially slower for *A. t.* ssp. *tridentata* and ssp. *wyomingensis* (Lesica et al. 2007). For many taxa and ecosystem types globally, seed availability - particularly from remnant patches - is a strong determinant of plant succession after large-scale disturbances (Turner et al. 1998). One simplified, first-principle prediction is that the probability of seed from outside a disturbance reaching the interior of the disturbed area is negatively related to the size of the disturbance area (Turner et al. 1998). Early post-fire seedling recruitment of *A. t.* ssp. *wyomingensis* and ssp. *tridentata* is also strongly affected by suitable microsite conditions (Germino et al. 2018). It is unclear whether seed produced by remnant patches (or newly created patches) is adequate to ensure that some seeds reach suitable microsites, particularly given the assumed short seed dispersal distances. Much of the sagebrush population forecasting work that is currently being done focuses on regional scales based on large scale climate projections (Palmquist et al 2016, Kleinhesselink and Adler 2018). However, this work is often not directly applicable to single project land management decisions. There is a need for near-term ecological forecasting that can inform site management decisions and incorporate new data through adaptive management (Dietze et al. 2018).

Materials and Methods

Sites
In the winter of 2018/2019, we conducted seed trapping at 3 sagebrush-steppe sites: on the Idaho side of the 2015 Soda Wildfire, the 2018 Alkie Wildfire, and on the campus of the Idaho Botanical Garden in Boise, Idaho. In the winter of 2019/2020, we conducted seed trapping on the Oregon side of the 2015 Soda Wildfire (Oregon side), 2013 Pony Wildfire (burned 2013), and 2016 Table Rock fire (Figure 1). Patterns of seedling recruitment were evaluated in the fall of 2019 at the 2015 Soda Wildfire.

The dominant sagebrush type at all sites was *A.t. wyomingensis* with some *A.t. tridentata*. The Pony fire also had *A.t. xericensis*.

Seed trapping
Seed traps (Figure 2) were deployed from November through January in each of the two winters. Traps were positioned relative to sagebrush patches, which, in turn, were selected using the following criteria: (1) patches smaller than 0.05 ha, (2) there had to be at least 5 individual reproductive plants in each patch, (3) the topography of the patch had to be relatively flat with <20° slope, and (4) patches had to be isolated enough so that no other seed-bearing sagebrush plants in the surrounding area could be any closer to the traps than the individuals in the patch. In a few cases, all seeds were clipped and removed from single individuals outside of a patch that were located closer to transect lines, in order to create the criteria. Patches were designated as either "active" management (seeded or outplanted) or "passive management" (unburned remnants or formed from natural recruitment) based on maps of

management actions from the Bureau of Land Management or the City of Boise.
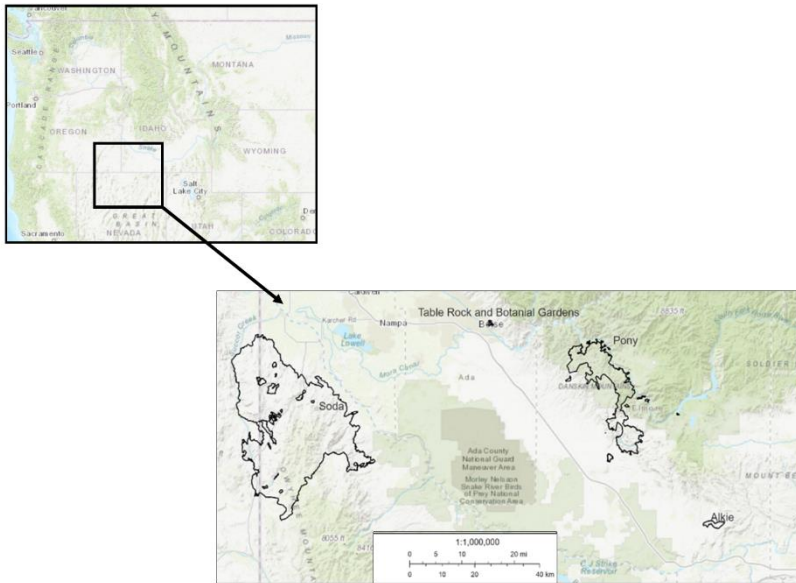
Figure 1: Site locations for seeding trapping and seedling recruitment monitoring

Traps were arranged along two transects per patch (except for the one patch at the Botanical Gardens, which had four transects. Traps were set in a line along a transect angle starting from the base of the patch. All transects were isolated enough so that no reproductive individuals were any closer to the traps than the plants in the patch. Given this requirement, the first transect angle was aligned as close as possible against the prevailing wind direction at the site (so that seeds were likely to blow towards the traps) and the second angle was aligned as close as possible with the prevailing wind direction at the site (less likely for seeds to blow towards the traps). Trap distances were measured from the base of the individual reproductive sagebrush plant where each transect began (termed "base individual plant" below).

Vertical traps were constructed from two 5x5 cm wooden stakes set 50 cm apart with 0.9oz

Figure 2: Pictures of seed traps deployed in the field

white woven fabric that captured seeds but allowed airflow (medium white row cover 6 ft x 100 ft), AgFabric, Corona, CA) stapled between them. The fabric was then sprayed with Tanglefoot. We additionally placed traps directly under the canopy of a base individual plant. In year 1, we placed one canopy trap per patch and these were circular bundt pans filled with marbles to prevent seeds from blowing out. In year 2, we placed one canopy trap under each base individual plant (2 per patch) and these traps were square 10x10 cm frames with sprayed AgFabric stapled on (canopy base individual plant. Some vertical traps failed because of weather or animal interference (including all traps at the 3 passive management patches at the Pony fire) and these were excluded from analysis. A summary of the trap methods, specifications, and deployment dates is listed in Table 1.

Table 1: Site and trap specification information for the seed trap study.

	Year 1	Year 2
Vertical trap size (cm)	50 x 91 rectangle	50 x 76 rectangle
Under canopy trap size (cm)	25.4-radius pan (with 2.5 center hole)	10 x 10 square
Trap distances (m)	2, 4, 7, 10, 13	2, 4, 6, 10, 14, 18, 22, 26
Sites	Soda, Botanical Garden, Alkie	Soda, Table Rock, Pony
Type of sagebrush islands	Soda & Alkie - Passive management, Botanical Gardens - Active management	Soda & Table Rock - Both active and passive management, Pony - Active management
Number of patches	7	15
Total number of vertical traps (subtracting traps that were lost)	69	239
Total number of canopy traps	10	36
Dates of collection		
Soda	11/24/2018 - 12/21/2018	Round 1: 11/22/2019-12/17/2019, Round 2: 12/17/2019 -1/10/2020
Botanical Garden	12/4/2018 - 12/22/2018	-
Alkie	11/26/2018 - 1/3/2018	-
Table Rock	-	Round 1: 11/22/2019-12/14/2019, Round 2: 12/14/2019 - 1/6/2020
Pony	-	Round 1: 11/23/2019-12/18/2019, Round 2: 12/18/2019 - 1/7/2019

Seed counts

The number of seeds in each 10 cm height increment was determined for each seed trap in the lab, after retrieving each trap. In February 2019, we conducted germination tests on seeds collected from the traps, as well as seeds collected directly off plants located close to our trapping locations.

Patch characteristics

At each patch, we recorded the following information for ten individual plants (or all plants if the patch was composed of fewer than 10 plants): crown diameter, height to the highest seed on the plant, height to the lowest seed on the plant, number of flowering stalks, and average length of flowering stalks (of 3 representative stalks). If there were more than 10 individual plants in the patch, the first two plants measured were the base individual plants for the transects, then the three tallest plants in the patch, then five additional representative plants. If there were fewer than 50 plants in a patch, the number of reproductive and non-reproductive plants were counted directly. If there were more than 50 plants in a patch, we estimated number of individuals by counting the number of plants in randomly distributed subplots (the number of which were proportional to the size of the patch) and scaling this number up to the patch size.

Estimating Plant Fecundity
We estimated maximum seed production per individual by multiplying number of flowering stalks by the average stem length by 8.2 (mean number of flower heads per 1cm stalk length) by 3.7 (mean flowers per head). The mean number of flower heads and mean flowers per head were taken from Winward and Tisdale (1977) morphological measurements on *A. tridentata wyomingensis*.

Seedling recruitment data
We found very little evidence of seedling recruitment around the seed trapping patches during initial reconnaissance. The need for patches to be isolated in order to accurately determine seed dispersal distances meant that we often eliminated non-isolated patches with fuzzy recruitment borders. In order to collect seedling recruitment data, in the summer of 2019, we thus revisited 30 plots previously monitored in 2016 on the Soda Wildfire where remnants were recorded within 100 m of the plot. We recorded the locations of all seedlings within the 13m-radius plot and the locations of remnants (either individuals or patches) both inside the plot and within 200m of the plot center. We then overlaid a 3x3m grid on top of the plot and calculated the number of seedlings in each grid cell and the distances (in meters) to all the remnant sagebrush within a 200 m radius.
In order to parameterize our seedling recruitment models, we included additional data collected during the 2019 Soda monitoring from 130 plots that had no remnant sagebrush within 200m.

Modeling: Seed dispersal model
We used a hierarchical Bayesian model to estimate seed dispersal kernels (an equation defining the relationship between seed rain and distance from the reproductive plant) from our seed dispersal data, including estimated plant fecundity and number of remnants in the patch. After initial exploration of different kernels, we used a negative exponential kernel suggested by Bullock (2000), with a modification for incorporating height caught on the trap. We compared models with different sources of variation including:
1) No landscape variation
2) Site identity only
3) Site identity x Patch identity
4) Transect identity
5) Site identity x Patch identity x Transect identity
6) Site identity x Patch identity x Trap identity
7) Site identity x Patch identity x Transect identity x Trap identity

We compared model fit using mean absolute error from 10-fold cross validation. The best fitting

model was then used to estimate seed contribution to a 3x3m cell from single remnants between 1 and 200 m away from the cell.

Modeling: Seedling recruitment model

We first considered a simplified Bayesian generalized linear model to determine if the number of established seedlings was larger when there were more neighbors within 40 m of plot, with seeding rate taken into consideration.

We then used the estimated seed contribution from the seed dispersal model combined with the seed contribution known from the aerial seeding rate on the Soda Wildfire (in terms of pure live seed) in a second hierarchical Bayesian model to estimate the probability of establishment based on microsite characteristics (exotic annual grass and perennial grass cover, fertile island cover in first year after fire, heatload, elevation, and whether there was a remnant located in the cell). All of these covariate data, except for the remnant presence, have previously been analyzed and published in Germino et al. 2018. This seedling recruitment model will be available online via Shiny apps (see Science Delivery Actions).

Results and Discussion

Nearly no sagebrush seeds were produced at our Alkie fire sampling areas in 2018, and additional weeks of sampling added to the nominal ~3 week sampling period still did not yield any seed. Only a few seeds were observed in traps directly below sagebrush crowns, and so we excluded seed traps from the Alkie burn site from the analysis.

Question 1: How does seed rain vary with distance from sagebrush island patches?

Many traps did not catch seeds, but we did find 2 seeds each on two of the traps set at 26m from the patch. This confirms that sagebrush seeds can travel farther than 1-2m from the plant, in contradiction to previous studies (Goodwin 1956; Young and Evans 1989) or assertions that have been made in many publications on early demographic patterns of sagebrush (e.g., Welch 2005, Germino et al. 2018).

Average fecundity across sites was estimated at ~30,000 seeds/plant. If this fecundity and a patch size of 25 plants was assumed, the median number of seeds estimated for a 9 m^2 area from the seed dispersal model simulation is shown in Figure 3. Median seed rain drops off to near zero at about 12 m distance from the patch of sagebrush mother/seed plants.

Figure 3: Median seed rain / 9m² by distance from patch in meters estimated from 10000 simulations of the seed dispersal model that includes transect variance

However, estimates of seed rain were extremely variable. If we considered the 90% CI of the same 10000 seed rain simulations, the number of seeds dispersed to 20 m could be as high as ~60 seeds/9 m² and as low as 0 right next to the patch.
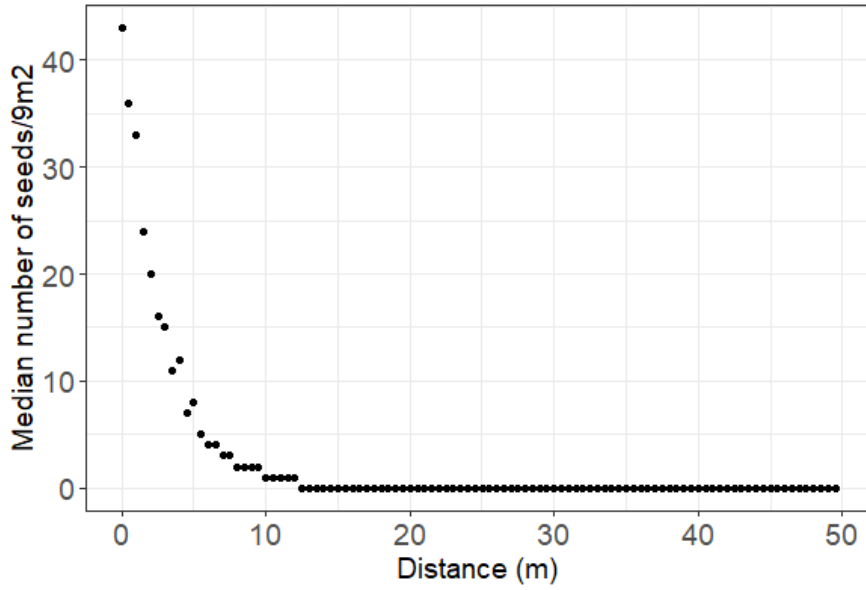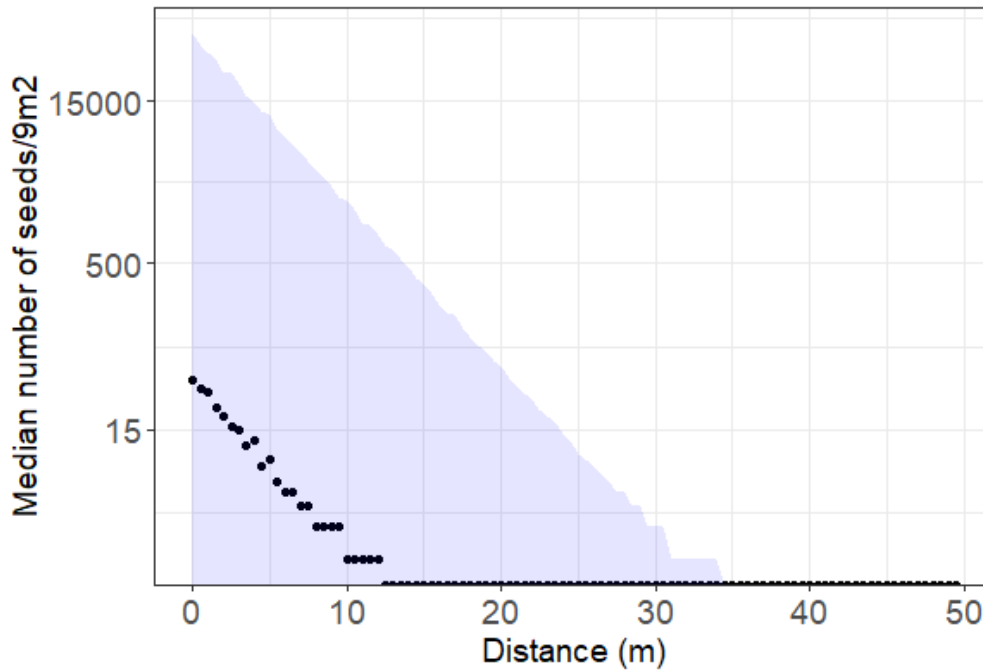

Figure 4: Median seed rain/9 m² by distance from patch in meters estimated from 10000 simulations of the seed dispersal model that includes transect variance with 90% credible intervals shown as blue shading

These results indicate that seed rain from sagebrush patches is variable and difficult to predict, and while considerable seed transport occurs beyond the 1-2 m distance from mother plants of sagebrush, the majority of seeds fall within 5 m of host plants. Only 17% of seeds dispersed travel farther than 5 m. Patches of unburned sagebrush are unlikely to be a reliable source of seed rain for reseeding large areas unless the remnant seed plants are both abundant and well dispersed around the burn area. The median seed rain of 1 seed/9 m^2 at 10 m from a patch of 25 plants is very small when compared with aerial seeding rates used in management. For comparison, pure live seeding rates for the 2015 Soda wildfire ranged from ~ 853 - 2247 seeds/9 m^2. It is possible that at the higher end of seed rain estimates patches could contribute more than this seeds rate, but this is unpredictable.

Question 2: How variable is seed rain on the landscape?

We compared different sources of variation in seed rain for seed dispersal model fit. Mean maximum absolute error was high. The model that incorporated variation for transect had the lowest error compared to the other models. This indicates that variability in seed rain is best explained at the microsite level (transect, likely related to wind direction) rather than across a larger site level only (whole fire) or even the patch level. Bold text indicates the best fitting model.

Table 2: Comparison of maximum absolute error between seed dispersal models with different sources of variation

Model	Mean Maximum Absolute Error	Lower 2.5% Maximum Absolute Error	Upper 97.5% Maximum Absolute Error
Model 1: No landscape variation	181.5	1.4	1999.3
Model 2: Site Only	167.6	1.4	1720.2
Model 3: Site x Patch	138.3	1.4	1302.9
Model 4: Transect	**12.2**	**1.4**	**106.4**
Model 5: Site x Patch x Transect	1673.2	1.4	5199.0
Model 6: Site x Patch x Trap	103.2	1.4	185.9
Model 7: Site x Patch x Transect x Trap	43787.5	1.4	145622.6

Estimated fecundity (# seeds/plant) was variable across years and sites, with plants at the Soda Fire in year 2 showing the highest estimated fecundity. However, estimated fecundity did not strongly align with the number of seeds caught per trap. On average, more seeds per trap were caught at the Botanical Garden in year 1. This may indicate a matter of phenological timing in dispersal. Strong wind events are likely to disperse seeds farther from the plant, but if winds do not occur at a time when seeds are fully developed and easily released, fewer seeds may travel farther than the canopy area of the plant. Although the Pony fire had the highest estimated fecundity, this site also experienced more snow events during the dispersal period than the others, which could possibly have impeded wind dispersal.
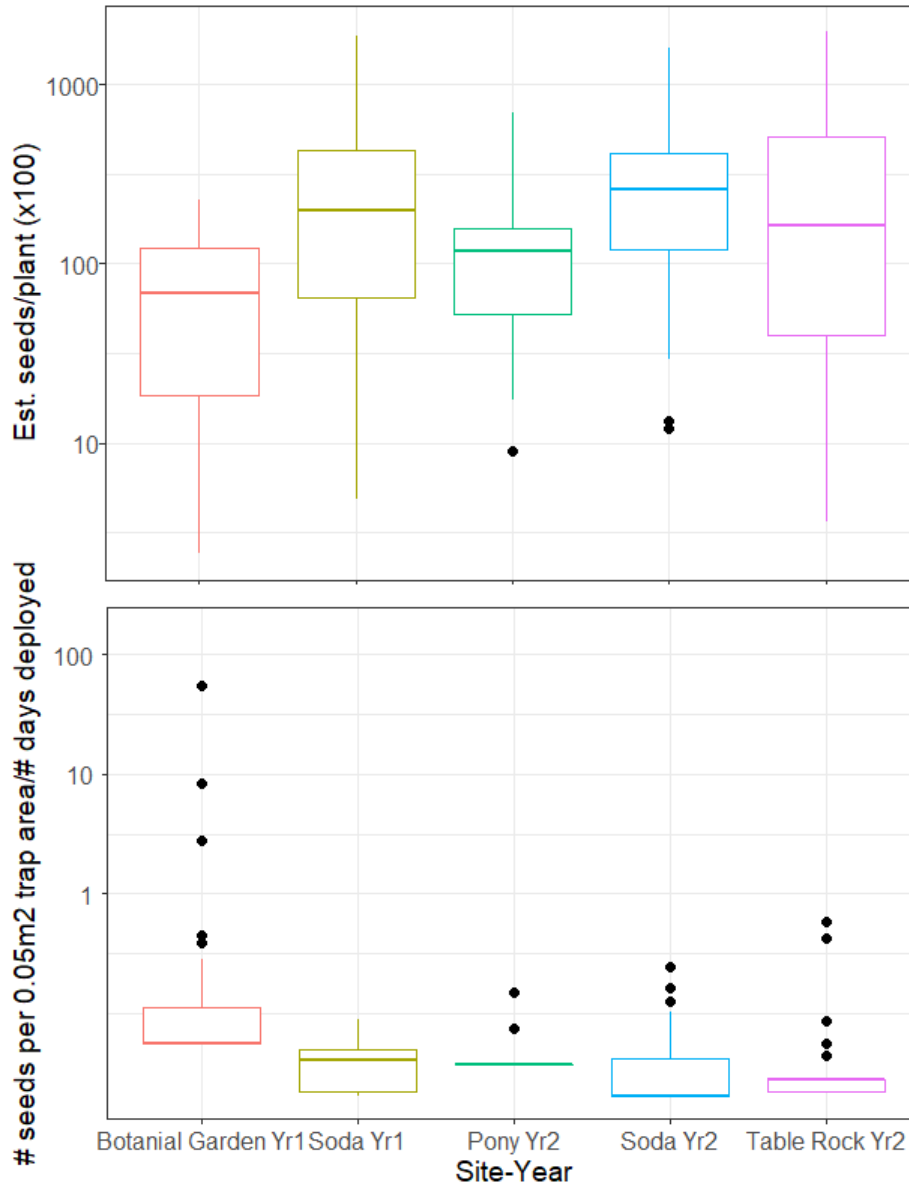
Figure 5: Estimated fecundity (# seeds/plant) across sites (top) and number of seeds caught per 0.05m² trap area standardized by the number of days deployed (bottom). Does not include under the canopy traps.

Question 3: Is post-fire sagebrush reestablishment enhanced in the vicinity of unburned islands?

We considered whether plot cells on the 2015 Soda wildfire with more remnant sagebrush patches (individuals or small groups) within 12 m had more seedling recruitment than those without remnant neighbors within 12 m when accounting for aerial seeding rate. We found a small positive effect of having more remnant neighbors on seedling recruitment (Bayesian probability of direction = 100%, equivalent to a frequentist p-value of <0.0001). Figure 5 shows the modeled median seedling recruitment per 9 m² as related to the number of remnant neighbors within 12 m with no aerial seeding. The median estimated number of seedlings/9 m² is 1 with 200 neighbors within 12 m.
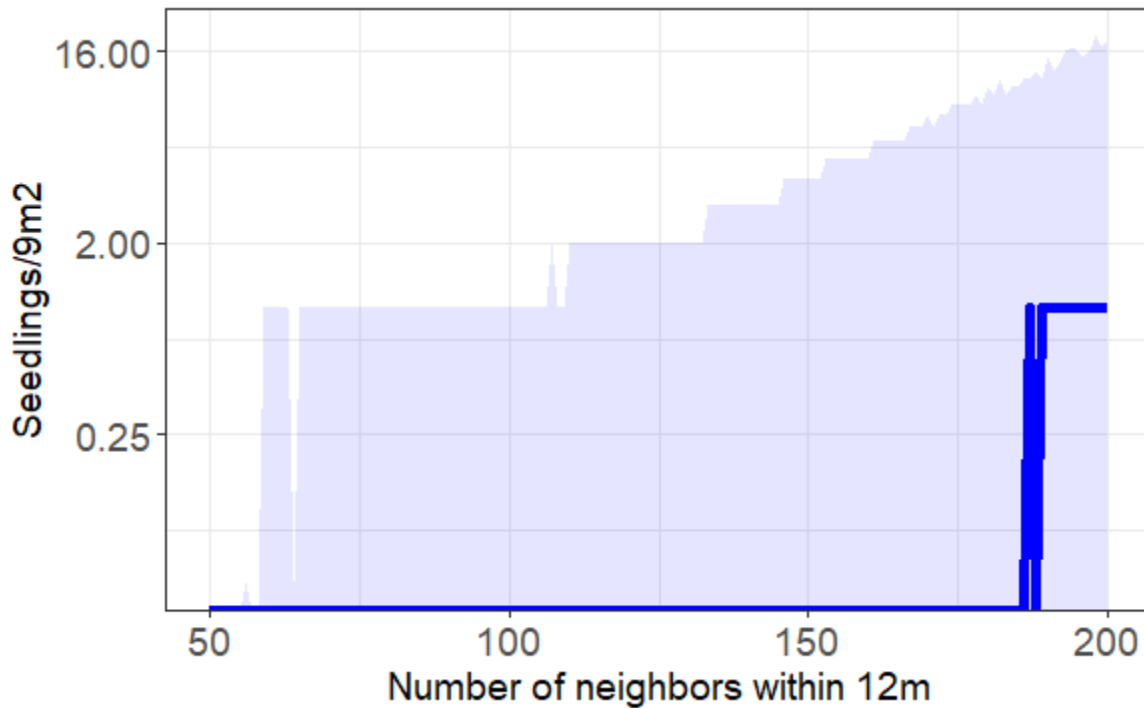
Figure 6: Modeled median seedling recruitment per 9 m² (blue line) as related to number of remnant neighbors within 40m. The blue ribbon shows the 90% credible intervals. No seedlings are predicted with the 90% credible interval range for fewer neighbors than 50.

While we were able to detect a small contribution of remnant neighbor patches to seedling recruitment, the effect was small. Plot cells with fewer than 50 remnant neighbor individuals or small groups were not expected to have seedling recruitment in the absence of aerial seedling. It is likely only large unburned islands will appreciably contribute to recruitment.

Question 4: Does post-fire seed rain around sagebrush islands differ if the island is a natural, unburned remnant compared to man-made island created by planting seedlings or seeding?

We compared the number of seeds caught on vertical traps standardized by trap area and number of days deployed between unburned remnant islands (passive management) and man-made islands created by planting or seeding (active management), taking into account trap distance in a Bayesian generalized linear. There was no significant difference in the number of seeds trapped between passive and active management patches (Bayesian probability of direction = 63.65%, equivalent to a frequentist p-value of 0.7). Since we found no difference between the two, we did not consider active vs passive management when building our seed dispersal models.

Science Delivery Actions

Initial results were presented at the Association for Fire Ecology conference in Tuscon, Arizona in November 2019, at the NSF GEM3 Idaho EPSCOR meeting in December 2019, and at the Ecological Society of America Conference virtually held in August 2020. The primary field trip was scheduled as

14

part of the joint meeting of the Great Basin Consortium and Great Basin Chapter of Society for Ecological Restoration (nearly 200 registered) was cancelled a week prior to the delivery date in March 2020 due to the Covid-19 pandemic shutdown. However, the research was presented in numerous field tours that cumulatively involved hundreds of attendees from around the USA, such as the national Climate Adaptation Science Center meeting participants (May 13, 2019) and the Sage Grouse Initiative annual meeting (>200 participants; May 23, 2019). We also delivered webinars describing the research, such to the Idaho National Science Foundation EPSCoR program (March 29, 2019),

A shiny apps model for the seed dispersal model has been deployed and is available here: https://sagebrushseeddispersal.shinyapps.io/seeddispersalmodel/

Conclusions (Key Findings) and Implications for Management/Policy and Future Research

We found that although sagebrush seeds can disperse farther than previously recorded, unburned or created patches as they normally occur (i.e. sparsely across burned areas) are unlikely to provide a significant seed source for population regeneration of burned landscapes. Median estimated seed rain, even within distances of less than 12 m from patches, was far less than typical aerial seeding rates. We detected a small contribution from remnant neighbors to seedling recruitment on the Soda wildfire, but only when there were a large number of neighboring sagebrush seed plants. When we consider that the proportion of sagebrush steppe burned each year is increasingly in large units of 100,000 ha or more, the burned area within 12 m from unburned sagebrush patches that could potentially receive some amount of seed rain is likely to be very small. This aligns with previous findings that seed availability is limiting in large disturbances (Turner et al. 1998 for many taxa; Germino et al. 2018 for sagebrush specifically) and underscores the importance of aerial seeding as a management action for increasing seed availability. Variability in seed production in space and time appeared to be a more important variable potentially affecting sagebrush seed availability than dispersal distances and is a topic that merits more investigation.

Literature Cited

Allen EA, Chambers JC, and Nowak RB. 2008. Effects of a spring prescribed burn on the soil seed bank in sagebrush steppe exhibiting pinyon-juniper expansion. Western North American Naturalist 68(3): 265-277

DiCristina K, Germino M. 2006. Correlation of neighborhood relationships, carbon assimilation, and water status of sagebrush seedlings establishing after fire. Western North American Naturalist 441-9.

Dietze MC, Fox A, Beck-Johnson LM, Betancourt JL, Hooten MB, Jarnevich CS, Keitt TH, Kenney MA, Laney CM, Larsen LG, Loescher HW, Lunch CK, Pijanowski BC, Randerson JT, Read EK, Tredennick AT, Vargas R, Weathers KC, and White EP. 2018. Iterative near-term ecological forecasting: Needs, opportunities, and challenges. Proceedings of the National Academy of Sciences, 115(7), 1424-1432. doi:10.1073/pnas.1710231115

Miller RF, Knick ST, Pyke DA, Meinke CW, Hanser SE, Wisdom WJ, and Hild AL. 2011. Characteristics of sagebrush habitats and limitations to long-term conservation. Greater Sage-Grouse: Ecology and Conservation of a Landscape Species and its Habitats. Studies in Avian Biology 38: 145-184

Germino MJ, Barnard DM, Davidson BE, Arkle RS, Pilliod DS, Fisk MR, Applestein C. 2018. Thresholds and hotspots for shrub restoration following a heterogeneous megafire. Landscape Ecology 1177-94.

Goodwin DL. 1956. Autecological studies of Artemisia tridentata Nutt [PhD thesis]. Pullman, WA, USA: Washington State University

Kleinhesselink AR and Adler PB. 2018. The response of big sagebrush (*Artemisia tridentata)* to interannual climate variation changes across its range. Ecology 0(0), 1-11. doi:10.1002/ecy.2191

Knutson KC, Pyke DA, Wirth TA, Arkle RS, Pilliod DS, Brooks ML, Chambers JC, and Grace JB. 2014. Long-term effects of seeding after wildfire on vegetation in Great Basin shrubland ecosystems. Journal of Applied Ecology 51(5): 1414-1424

Lesica P, Cooper SV, and Kudray G. 2007. Recovery of big sagebrush following fire in southwest Montana. Rangeland Ecology and Management 60(3): 261-269

Mueggler WF. 1956. Is sagebrush seed residual in the soil of burns or is it wind-bourne? Res, Bite 35. Odgen, UT: US Department of Agriculture, Forest service, Intermountain forest and range experiment station: 298-305

Nelson ZJ, Weisberg PJ, and Kitchen SG. 2014. Influence of climate and environment on post-fire recovery of mountain big sagebrush. International Journal of Wildland Fire 23:131-142

Palmquist KA, Schlaepfer DR, Bradford JB, and Lauenroth WK. 2016. Spatial and ecological variation in dryland ecohydrological responses to climate change: Implications for management. Ecosphere, 7(11): 1-20.

Pilliod DS, Welty JL, Toevs GR. 2017. Seventy-five years of vegetation treatments on public rangelands in the Great Basin of North America. Rangelands 39(1):1-9

Schlaepfer DR, Lauenroth WK, and Bradford JB. 2014. Natural regeneration processes in big sagebrush (*Artemisia tridentata)*. Rangeland Ecology and Managament 67(4):344-357

Sullivan LL, Clark AT, Tilman D, Shaw AK. 2018. Mechanistically derived dispersal kernels explain species-level patterns of recruitment and succession. Ecology 99(11):2415-20.

Turner MG, Baker WL, Peterson CJ, and Peet RK. 1998. Factors influencing succession: lessons from large, infrequent natural disturbances. Ecosystems 1998(1): 511-523

Welch BL. 2005. Big sagebrush: a sea fragmented into lakes, ponds, and puddles. Fort Collins, CO, USA: US Dept of Agriculture, Forest Service, Rocky Mountain Research Station. Gen. Tech Report RMRS-GTR-144. 210 p

Wijayratne UC and Pyke DA. 2012. Burial increases seed longevity of two *Artemisia tridentata* (Asteraceae) subspecies. American Journal of Botany 99(3): 438-447

Winward AH, Tisdale EW. 1977. Taxonomy of the *Artemisia tridentata* complex in Idaho. University of Idaho; 1977.

Young JA and Evans RA. 1989. Dispersal and germination of big sagebrush (*Artemisia tridentata*) seeds. Weed Science 37(2): 201-206

Young JA, Palmquist DE, Evans RA. 1991. Temperature profiles for germination of big sagebrush seeds from native stands. Rangeland Ecology & Management/Journal of Range Management Archives 44(4):385-90.

Ziegenhagen LL and Miller RF. 2009. Post-fire recovery of two shrubs in the interiors of large burns in the intermountain west, USA. Western North American Naturalist 69(2): 195-205

Appendix A: Contact Information for Key Project Personnel

Cara Applestein
Student investigator
PhD Graduate Student
Boise State University
Department of Biology
caraapplestein@u.boisestate.edu
202-602-2619

Trevor Caughlin
PI
Assistant Professor
Boise State University
Department of Biology
trevorcaughlin@boisestate.*edu*
208-426-3530

Matthew Germino
Co-PI
Supervisory Research Ecologist
US Geological Survey
mgermino@usgs.gov
208-426-3353

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery

1. Articles in peer-reviewed journals:
   - Sagebrush seed dispersal from islands (planned/in preparation)
2. Graduate thesis (masters or doctoral):
   - Doctoral thesis (expected May 2022)
3. Conference or symposium abstracts
   - "A hierarchical Bayesian approach to quantify variability in seed dispersal and recruitment after landscape-scale disturbance" presented at the Ecological Society of America (ESA) virtual conference in August 2020.
   - "Patterns of seed dispersal from remnant sagebrush islands post-fire" presented at the Association for Fire Ecology conference in November 2019.
4. Website development
   - Seed dispersal shiny apps model available here: https://sagebrushseeddispersal.shinyapps.io/seeddispersalmodel/
5. Presentations/webinars/other outreach/science delivery materials.
   - "Impact of unburned remnant sagebrush on post-fire landscape rehabilitation" info sheet

prepared and given to land managers (Joe Weldon, Amy Stillman, Cindy Fritz, Martha Brabec) who helped with site access.

Appendix C: Metadata

There will be six types of data included in the data release:

1. Seed trap data: counts of seeds caught on each 10cm height increment and in canopy traps for two years across 6 sites.
2. Plant fecundity data: plant characteristics of 10 plants in each patch including height to tallest seed on the plant, height to lowest seed on the plant, canopy diameter, number of flowering stalks, average length of flowering stalks, and estimated fecundity for two years across 6 sites.
3. Germination data: germination test on seeds caught off vertical traps and collected from nearby plants in year 1.
4. Patch information: Patch characteristics including number of reproductive plants, patch size, management type, percent cover of perennial and annual grass and perennial forbs, and angles of trap transects across 6 sites during two years.
5. Seedling recruitment data: number of seedlings counted in each 3x3m grid cell on the Soda wildfire in 2019, as well as associated plot data of vegetation type cover, and landscape variables.
6. Distances to remnants: distances between remnant individuals and small patches and each 3x3m grid cell where seedlings were counted on the Soda wildfire in 2019.

   Seedling recruitment data was collected much more intensively than initially planned at a single site because of limited/no recruitment at many of the seed trapping sites. Seed trap data was collected at both active and passive management patch locations on each of the three year 2 sites (rather than at only active or only passive at each site). We did not take overhead photos of trap locations because the time of year that trapping occurred meant the ground was covered with snow at times. The seedling recruitment data was collected at plots where we previously collected vegetation type cover data for a different project so this data was used, rather than collecting new data. The distances between remnants and seedling grid cells was added to the data collection.