FINAL REPORT

Title: Post-fire recruitment of Great Basin big sagebrush species: spatial and temporal controls along regional gradients of soil temperature and moisture

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Keywords

Artemisia tridentata; big sagebrush; ecological restoration; plant establishment; post-fire recovery; prescribed fire

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Abstract

In sagebrush-dominated shrublands of western North America, warmer temperatures coupled with annual grass invasions are increasing the frequency and extent of wildfires. Post-fire sagebrush recovery rates are unpredictable and many recent fires have resulted in the apparent loss of sagebrush habitat, resulting in a pressing need to identify management strategies that can promote post-fire sagebrush recovery. Major investments in post-fire seeding treatments have resulted in limited restoration success, and observational results suggest that successful post-fire sagebrush establishment requires favorable weather conditions coincident with the short period of seed viability. Repeating seeding treatments in multiple consecutive years has been suggested as potentially improving restoration success through bet-hedging, increasing the probability that seed availability will coincide with favorable weather conditions. However, this approach has not been tested for sagebrush, and delayed seeding treatment success may also be constrained by competition from other plants establishing after fire.

In this study, we studied natural big sagebrush regeneration patterns in small burns without seed constraints, allowing us to separate the influence of climate and seed availability on post-fire establishment and providing a natural analog to repeated seeding applications. We combined dendrochronological methods, repeated vegetation surveys, and detailed soil environmental measurements from a regional network of experimental prescribed fires to examine the temporal patterns of post-fire big sagebrush establishment along regional climatic gradients. Temporal and spatial patterns of sagebrush establishment were modeled as a function of both annual weather and site-level climate means.

Post-fire sagebrush establishment patterns showed highly episodic establishment, with most sites experiencing pulses of establishment in years in which soils stayed wet for longer. Given favorable soil environmental conditions, establishment probability remained high for up to a decade after fire, suggesting that competition with other established plants is not a major constraint to post-fire sagebrush establishment for some time after fire. Although drier/warmer sites were less likely to have favorable conditions for sagebrush establishment in a given year, all sites appeared to be on track for relatively rapid recovery to pre-burn levels of sagebrush canopy cover, regardless of the frequency of establishment events. These results suggest that, in the interior of larger fires where sagebrush recovery is expected to be limited by a lack of viable seeds, the window of opportunity for restoration efforts such as post-fire seeding or planting may be longer than previously thought. This is an especially important insight for burns in drier portions of the landscape, where there is a lower probability that ephemeral periods of seed availability will coincide with favorable weather conditions to result in successful sagebrush establishment. In those locations, an adaptive management approach that includes the option of repeated seeding will likely increase the probability of sagebrush recovery.

This research has been presented in five scientific and public presentations, and a manuscript and a non-technical summary article on the findings presented in this report are currently in preparation. Once completed, we will distribute these publications through the JFSP Great Basin Fire Science Exchange.

Objectives

The objective of this study was to assess the climatic drivers of natural big sagebrush (*Artemisia tridentata*; hereafter 'sagebrush') recruitment after prescribed fire in the Great Basin. Specifically, we aimed to understand how interannual variation in weather interacts with regional climatic gradients to influence the probability of sagebrush establishment and the rate of post-fire recovery of the plant community. This work was supported by the Graduate Research Innovation (GRIN) award and addresses the 'maintenance and restoration of Great Basin sagebrush habitat' and 'climate change and fire' topic areas identified by JFSP. To achieve our objective, we asked the following questions:

1) How does post-fire sagebrush establishment respond to interannual variability in environmental conditions? We compared annually-resolved sagebrush establishment rates to soil environmental conditions to address this question. We hypothesized that the rate of sagebrush establishment in a specific year would be positively related to spring water availability, but that favorable weather would be more likely to result in an establishment event immediately after a fire, as competition with other plants would inhibit establishment at longer times after fire.

2) How do temporal patterns of sagebrush establishment vary across regional climatic gradients? We hypothesized that the influence of interannual weather on establishment would be mediated by regional variation in climatic patterns. In warmer/drier sites, we expected more pulsed establishment patterns and fewer post-fire establishment episodes, reflecting higher interannual variability in environmental conditions required for recruitment.

3) How is post-fire sagebrush recovery influenced by the frequency of climatically favorable opportunities for establishment? We hypothesized that sagebrush cover would return to pre-fire levels more quickly in sites with frequent establishment episodes, or where post-fire weather was generally favorable for establishment.

Background

Semi-arid landscapes of western North America, including vast sagebrush-dominated shrublands, are forecast to experience dramatic increases in fire frequency and size with climate change in the coming decades (Abatzoglou and Kolden 2013). Additionally, land managers are implementing prescribed fire treatments aimed at reducing tree cover in sagebrush ecosystems exhibiting pinyon-juniper expansion, which will further contribute to an increasing proportion of the landscape impacted by fire. Following both wildland and prescribed fire, a central management objective usually involves the reestablishment of sagebrush and other shrub species, which are critical habitat elements for greater sage-grouse and other sagebrush obligate wildlife (Connelly et al. 2004).

However, the most widespread sagebrush species are not well adapted to fire, and consequently, post-fire sagebrush recovery rates are highly variable and often extremely slow (Baker 2006). Sagebrush does not resprout or regenerate vegetatively, so post-fire recovery must occur through seeds, which are not capable of long-distance dispersal and have very limited (1-2 yr) viability in the soil seed bank (Schlaepfer et al. 2014). To promote post-fire sagebrush recovery in large burns where seed dispersal to the interior is limited, land managers have invested heavily in post-fire seeding. Nonetheless, post-fire sagebrush seeding efforts are often unsuccessful (Arkle et al. 2014, Knutson et al. 2014). Long-term outcomes in large burned areas have been shown to be strongly related to spring soil moisture in the first year after fire for both unseeded (Nelson et al. 2014) and seeded (Shriver et al. 2018) sites, suggesting that successful post-fire sagebrush establishment requires favorable weather conditions coincident with the short period of seed viability. Repeating seeding treatments in multiple consecutive years has been suggested as a strategy for overcoming the restoration challenges posed by the narrow set of conditions leading to post-fire sagebrush recovery (Chambers et al. 2014a, Shriver et al. 2018). Repeated seeding is thought to improve restoration success through bet-hedging, increasing the probability that seed availability will coincide with favorable weather conditions. However, this approach has not been tested for sagebrush, and delayed seeding treatment success may be constrained by competition from other plants establishing after fire (Ziegenhagen and Miller 2009).

In this study, we combine dendrochronological (tree-ring) methods, repeated vegetation surveys, and detailed soil environmental measurements from experimental prescribed fires to examine the temporal patterns of post-fire sagebrush establishment along regional climatic gradients. Studying natural regeneration patterns in small burns without seed constraints can provide a natural analog to repeated seeding applications, informing post-fire management strategies by quantifying the length of the post-fire period in which sagebrush establishment can occur. Evaluating the relationship between annual establishment and the soil environment can predict the probability of establishment in a given year, and quantifying site-level interannual establishment variability allows managers to identify portions of the landscape where sagebrush persistence is at risk (Davis et al. 2019) or where restoration success is most likely to benefit from repeated seeding efforts. In general, a more detailed understanding of ecosystem responses to post-fire environmental conditions may also yield more flexible adaptive-management strategies for restoration and conservation, including anticipatory management based on weather-driven, long-term ecological forecasting (Bradford et al. 2018, Hardegree et al. 2018).

Materials and Methods

Site descriptions

Our study took place in 12 sites across the Intermountain West (Fig. 1) that were burned under prescription. The study sites were a part of two experimental networks of prescribed fire in ecosystems co-dominated by pinyon-juniper woodlands and big sagebrush shrublands. Underdown Canyon (2 sites) was established as a Joint Fire Sciences Program Demonstration Area to study the ecological effects of landscape-scale prescribed fire treatments across a local elevational gradient (Urza et al. 2017, 2019). The Sagebrush Steppe Treatment Evaluation Project pinyon-juniper network (SageSTEP; 10 sites) is a long-term regional-scale study examining the effects of multiple fuel treatments across the Great Basin and adjacent sagebrush-dominated areas (McIver and Brunson 2014). We focused this study on the prescribed fire treatments from both networks, where repeated measures of vegetation have been collected in unburned, pre-burn, and burned locations. Both networks include extensive instrumentation for measuring ambient and soil environmental conditions, providing an unusual opportunity to assess the effect of environmental conditions on plant establishment patterns.

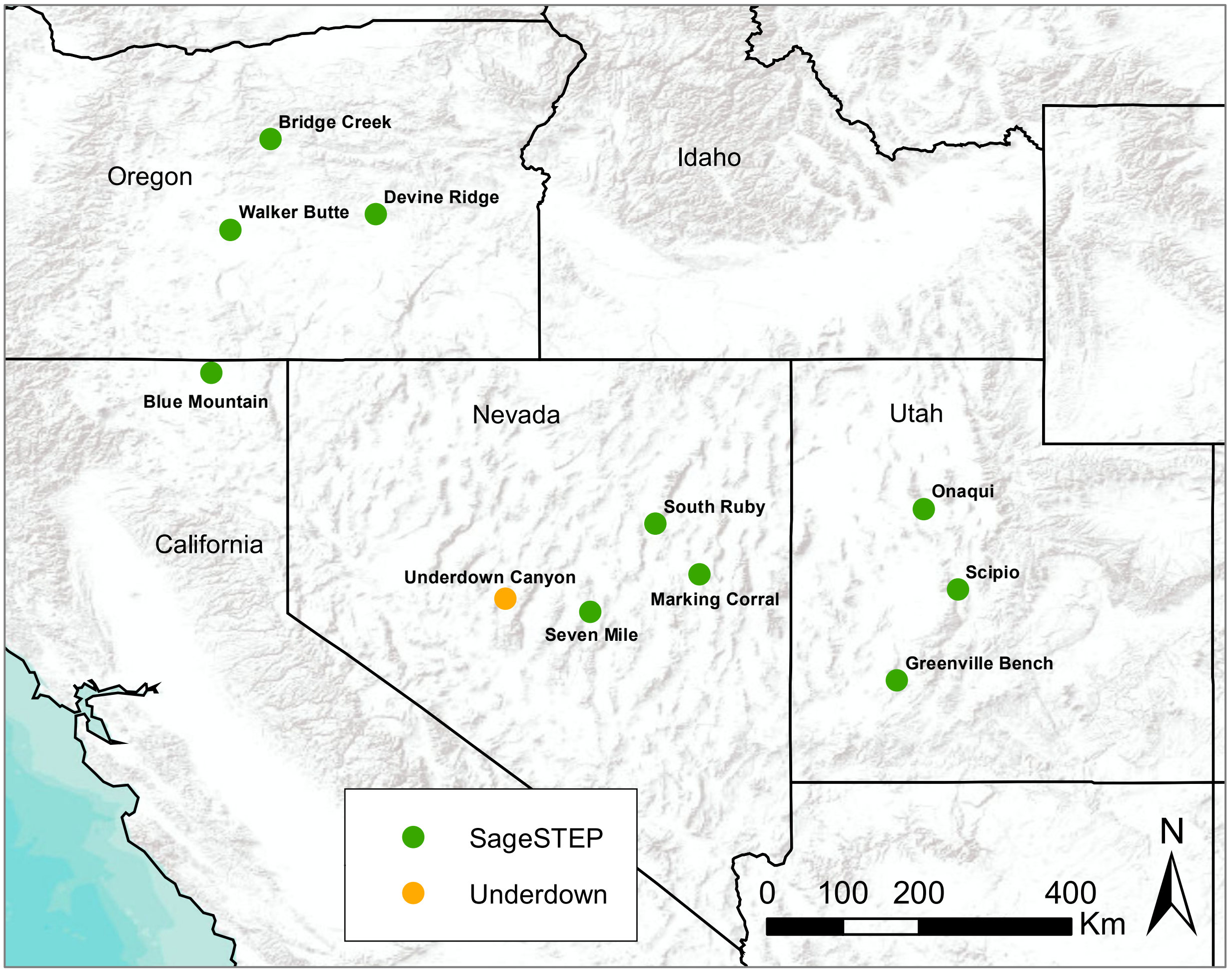

Figure 1. Location of study sites in the Intermountain West, USA.

Sites were located in four states (Utah, Nevada, California, and Oregon) and four Major Land Resource Areas (Malheur High Plateau, Klamath Basin, Central Nevada Basin and Range, and Salt Lake Area). The study sites are distributed across a broad geographical area that encompasses a range of edaphic and climatic gradients (Table 1). Prescribed fire treatments took place between 2004 and 2009 (Table 1), in a ‘stagger-start’ design that increases the variability in post-treatment weather and thus reduces the potential for restricted inferences (Loughin 2006). No post-fire rehabilitation treatments (e.g. seeding or planting) took place in the study sites. Post-treatment weather across the region has been highly variable, characterized by periods of drought punctuated by several cool, wet years (Roundy et al. 2014).

Table 1. Characteristics of the study sites.

Site	Plot Network	Surface Soils	Soil Temperature/ Moisture Regime	Year Burned
Blue Mountain, CA (BM)	SageSTEP	loamy, mixed	frigid/xeric	2007
Bridge Creek, OR (BC)	SageSTEP	sandy loam	mesic/aridic-xeric	2006
Devine Ridge, OR (DR)	SageSTEP	loamy-skeletal, mixed	frigid/xeric	2007
Walker Butte, OR (WB)	SageSTEP	ashy, glassy	frigid/xeric	2006
Marking Corral, NV (MC)	SageSTEP	loamy-skeletal, mixed	cool mesic/aridic-xeric	2006
Seven Mile, NV (SV)	SageSTEP	loamy-skeletal, mixed	cool frigid/xeric	2007
South Ruby, NV (SR)	SageSTEP	loamy, mixed	cool mesic/xeric	2008
Underdown Mid, NV (NM)	Underdown	coarse loamy, mixed	frigid/xeric-aridic	2004
Underdown Upper, NV (NU)	Underdown	coarse loamy, mixed	frigid/xeric-aridic	2004
Greenville Bench, UT (GR)	SageSTEP	gravelly to cobbly sandy loam	warm frigid/xeric	2007
Onaqui, UT (OJ)	SageSTEP	loamy-skeletal, carbonatic	warm mesic/aridic-xeric	2006
Scipio, UT (SC)	SageSTEP	loamy-skeletal, mixed	warm mesic/aridic	2007

Sagebrush establishment dates

Post-fire sagebrush establishment dates were determined using dendrochronological methods with stem sections collected in 2015 (Underdown sites), and 2017 (SageSTEP sites). We randomly located sampling plots within prescribed burn perimeters, but outside of permanent measurement subplots. Three replicate sampling plots were established within each burn perimeter, with the exception of Scipio and Bridge Creek, where smaller burn areas restricted sampling to one and two plot replicates, respectively. Our sampling design included a total of 33 dendrochronology plots in 12 sites.

Sagebrush stem samples were collected from variable-radius plots. Plot radius was based on target sample sizes – we aimed to collect five sagebrush samples per possible establishment year in each plot (e.g., a 2008 burn sampled in 2016 would have had 7 possible establishment years [2009- 2015], so the target sample size would be 5 samples/year x 7 years = 35 samples). Plots were expanded radially from the center point until the target sample size had been met, collecting all sagebrush individuals to ensure a complete demographic profile. If the target sample size was not met within a 5-m radius, up to two additional plots were established at randomized locations nearby to distribute the impact of shrub removal, and samples within nearby plot clusters were pooled for analysis. Height and maximum and perpendicular canopy diameters were measured for each sagebrush individual prior to removal. Stems were cut below the root crown to ensure inclusion of the root-shoot boundary for dating the year of establishment. Split or broken stems were bound with baling wire prior to transport to maintain the stem architecture.

A total of 2,004 sagebrush samples were collected and analyzed. Sagebrush samples were transported to the laboratory for annual growth-ring analysis using standard dendrochronological techniques (Stokes and Smiley 1968). Samples were cross-sectioned with a band saw to expose the pith at the junction of the root crown and stem, and cross sections were sanded with progressively finer-grit sand paper on an electric belt sander until individual cells were visible. We used annual ring counts to determine the year of establishment because the young age of the samples precluded cross-dating methods. Annual growth rings were counted under a stereomicroscope by two individuals, and samples for which the independent ring counts disagreed were re-examined. For stem samples that did not include the pith (n=25), we used overlaid concentric circles to estimate the number of missing years. Prior to analyzing the drivers of post-fire establishment, we removed samples that had established prior to the year of burning (n=409), those that dated to the year of sampling (n=83), and those for which an establishment date could not be reliably determined (n=6). In total, we used 1,506 aged post-fire sagebrush individuals in our post-fire analyses.

Sagebrush measurements

At all sites, shrub canopy cover and density were measured in permanent sampling plots before prescribed fire treatments took place (pre-fire) and at regular intervals after the burn treatment (post-fire). For both site networks, vegetation sampling took place in approximately 0.1 ha permanent subplots within each treatment area.

In the SageSTEP sites, plant canopy cover was measured by species using the line-point intercept method (McIver and Brunson 2014). Sagebrush cover was calculated as the proportion of points contacting the canopy of a sagebrush individual. We used measurements of sagebrush cover for pre-fire and 10-years post-fire, with the exception of the South Ruby site, where the most recent sampling date was 8-years post-fire.

In the Underdown Canyon sites, shrub diameters (longest and perpendicular) and height were measured for all individuals within quadrats distributed along transect lines that were randomly stratified within each sampling plot (Urza et al. 2017). Canopy area was estimated from canopy dimensions assuming an elliptical shape (Peek 1970), and canopy cover was derived by converting to percentage of quadrat area sampled. We used measurements of sagebrush cover for pre-fire and 13-years post-fire.

Site environmental data

Measurement stations were established in each burn site to measure soil temperature and water availability. Soil temperatures and soil water matric potential were measured at 1-3, 13-15, 18-20, and 28-30 cm deep. Data microloggers were programmed to read sensors every 60 s and store hourly averages. Soil temperature and soil matric potential data were used to calculate a suite of seasonal variables expected to be associated with plant growth and cover (Rau et al. 2014, Roundy et al. 2014). Further details on the soil environmental data collection and seasonal variable calculations can be found in Roundy et al. (2018) and Chambers et al. (2007).

For our analysis, we chose a reduced list of soil environmental variables as potential predictors of sagebrush recruitment, based on their expected direct effects on plant-water relations impacting germination and survival. Potential predictor variables included: wet days, wet degree days, start of maximum dry period, degree days, maximum soil temperature, and minimum soil temperature. We tested the effects of this reduced set of soil environmental predictors at the near-surface sampling depth (1-3 cm) for two seasons (spring [March – June] and summer [July-August]).

Statistical analyses

1) We used linear mixed effects models to predict sagebrush establishment per plot, per year, as a function of time since fire and soil environmental variables in the year of establishment. We built models for two response variables: establishment occurrence and establishment abundance.

Establishment occurrence was a binary response variable representing the presence or absence of sagebrush dating to a particular year within a given site. We used a logistic linear mixed effects model with a binomial distribution to model drivers of establishment occurrence.

For the model of establishment abundance, we calculated an establishment index, which relativizes annual establishment based on total establishment abundance in each plot:

$$E.index_{y,p} = A_{y,p} - \frac{\sum A_p}{C(y)}$$

Where $A_{y,p}$ is the number of individuals establishing in a specific year and plot, $\sum A_p$ is the count of all post-fire sagebrush individuals in the plot, and $C(y)$ is the number of possible post-fire establishment years (i.e. years between the fire and sampling). The establishment index is approximately normally distributed, so we used a gaussian distribution in the linear mixed effects model to model drivers of establishment abundance.

All statistical modeling was performed in R (R Core Team 2015), and mixed models were developed using the 'lme4' package (Bates et al. 2015). Site was included as a random intercept. We used pairwise correlations among environmental covariates to reduce the set of candidate predictor variables (Pearson's $r < 0.5$). For both models, the full set of candidate predictor variables included time since fire (quadratic), start of maximum dry period, maximum soil temperature, and either wet days, wet degree days, or degree days. We used AIC for model selection, comparing among a full model and all nested sub-models, and report the models with the strongest support from the data. We scaled the environmental predictor variables (z-score) and report standardized parameter coefficient estimates. P-values were calculated using likelihood ratio tests.

2) For each plot, we calculated two measures of interannual establishment variability: proportion of post-fire years with sagebrush establishment and establishment evenness. Establishment evenness was represented by a Shannon evenness index: $\varepsilon = \sum p_i(\ln p_i)/\ln(y)$; where p_i is equal to the proportion of total establishment occurring in a specific year and y is the total number of years since fire. A perfectly even (uniform) pattern would have a maximum ε value of 1.

We used linear regression models to compare site measures of interannual establishment variability with site means of post-fire soil environmental conditions. For this analysis, we focused on the two soil environmental variables that were the strongest predictors of establishment occurrence: spring wet degree days and the date of the start of the late spring maximum dry period. We excluded one site (Scipio) from this analysis due to low availability of post-fire soil environmental data.

3) For each plot, we used repeated measures of big sagebrush cover and density to calculate two relativized sagebrush recovery indices:

- canopy recovery = post-fire canopy cover / pre-fire canopy cover
- population recovery = post-fire density / pre-fire density

We used linear regression models to predict the big sagebrush recovery indices as a function of time since fire, site means of post-fire soil environmental conditions, and site indices of interannual establishment variability. We used AICc for model selection, comparing among a full model and all nested sub-models, and report the models with the strongest support from the data. The model predicting population recovery excluded one site (South Ruby) for which density data were not available for the latest post-fire sampling year.

Results and Discussion

Drivers of interannual recruitment patterns: when did sagebrush establish?

The vast majority of dated sagebrush individuals established after the prescribed fires took place, but all 12 sites contained sagebrush individuals that were found to have established before the year of fire (Fig. 2). The fact that some sagebrush individuals survived the burns indicates that prescribed burn patterns were patchy, resulting in a fine-scale mosaic of sagebrush mortality. Even though relatively few sagebrush survived the burns, prolific seed production (Schlaepfer et al. 2014) means that the surviving sagebrush individuals likely provided a substantial source of seeds for post-fire regeneration.

Patchy or mosaic burn patterns are common within prescribed burns, especially in sites with low annual herbaceous cover. Prescribed burns typically take place during cooler seasons than wildfires, and the moderate weather conditions during burning often do not result in fire behavior that promotes fire spread between patches of shrubs and perennial bunchgrasses. All of our study sites had low pre-fire cover of annual herbaceous species (Chambers et al. 2014b, Urza et al. 2017) and thus had discontinuous fuel loadings that likely contributed to the mosaic burn pattern. Annual herbaceous plants, including invasive annuals such as cheatgrass (*Bromus tectorum*), provide a continuous bed of fine surface fuels that promote fire spread (Knapp 1996). Fires occurring in sites with a substantial presence of pre-fire annual herbaceous plants, especially those burning in more extreme fire weather conditions, tend to result in more complete sagebrush mortality and a lack of post-fire seed sources (Baker 2006).

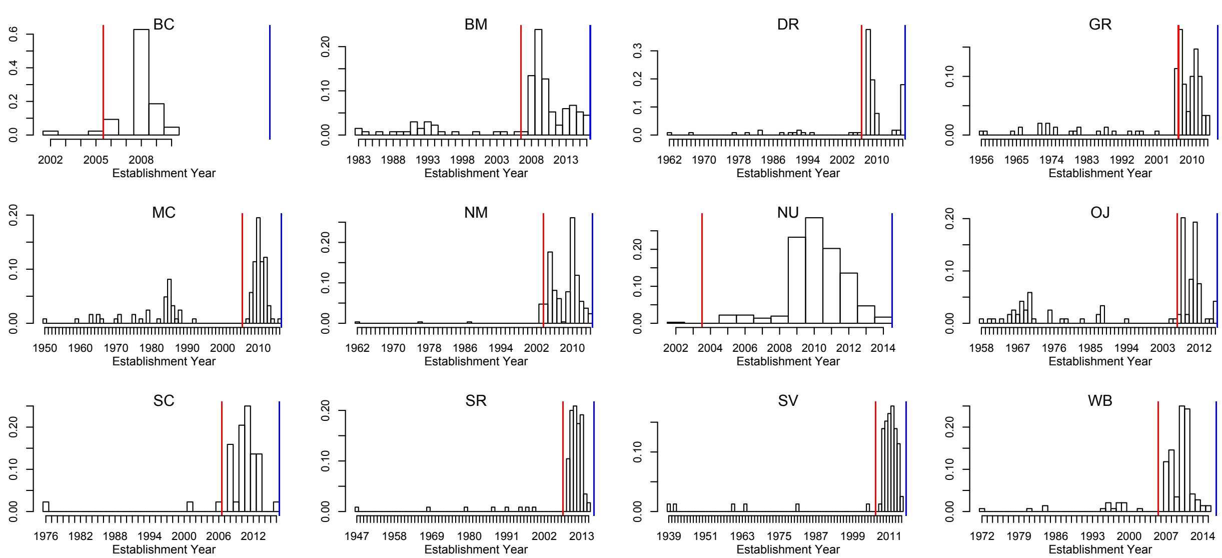

Figure 2. Sagebrush age structure for each site, reconstructed from establishment dates that resulted from tree-ring analyses. The red line indicates the year of fire, and the blue line indicates the year of sampling.

Post-fire sagebrush establishment was highly episodic for all sites (Fig. 3), and our models suggest that sagebrush establishment was primarily driven by spring soil water availability. The date of the start of the maximum late spring dry period – which represents the timing of the seasonal dry-down – was the strongest environmental predictor of both establishment occurrence and establishment abundance (Table 2). Sagebrush establishment was more likely in years in which soils stayed wet for longer (Fig. 4), suggesting that seedling survival is increased by a longer spring wet period that provides more time for carbon assimilation. These results are consistent with previous studies that have found that, given seed availability, the primary bottleneck to sagebrush establishment is first-year survival (Young and Evans 1989), and that the odds of survival are strongly related to the duration of moist soils (Maier et al. 2001, Ziegenhagen and Miller 2009, Nelson et al. 2014, Hourihan et al. 2018). We found that sagebrush establishment was negatively related to spring temperature, represented as either wet degree days or degree days (Table 2; Fig. 4). Warm conditions can increase seedling biomass accumulation (Schlaepfer et al. 2014) but are also associated with increased evapotranspiration, which may have contributed to seedling water stress.

Our results also show a strong influence of time since fire on establishment (Table 2). Establishment peaked approximately 2-6 years after fire (Fig. 4), although some establishment was observed throughout the entire post-fire period in most sites (Fig. 3). Previous research has found a much shorter (1-3 year) post-fire window of opportunity for sagebrush establishment in the interior of a large burn (Ziegenhagen and Miller 2009), and it was hypothesized that this pattern was the result of two processes: 1) the depletion of viable seeds stored in the soil seed bank and 2) competitive effects from other plants establishing after fire. Although competition is clearly an important factor affecting sagebrush establishment in unburned stands (Schlaepfer et al. 2014), our observations suggest that competition does not likely inhibit sagebrush establishment in the years following fire. Instead, our results suggest that given seed availability and adequate spring soil moisture, the window of establishment opportunity extends at least 8-10 years post-fire.

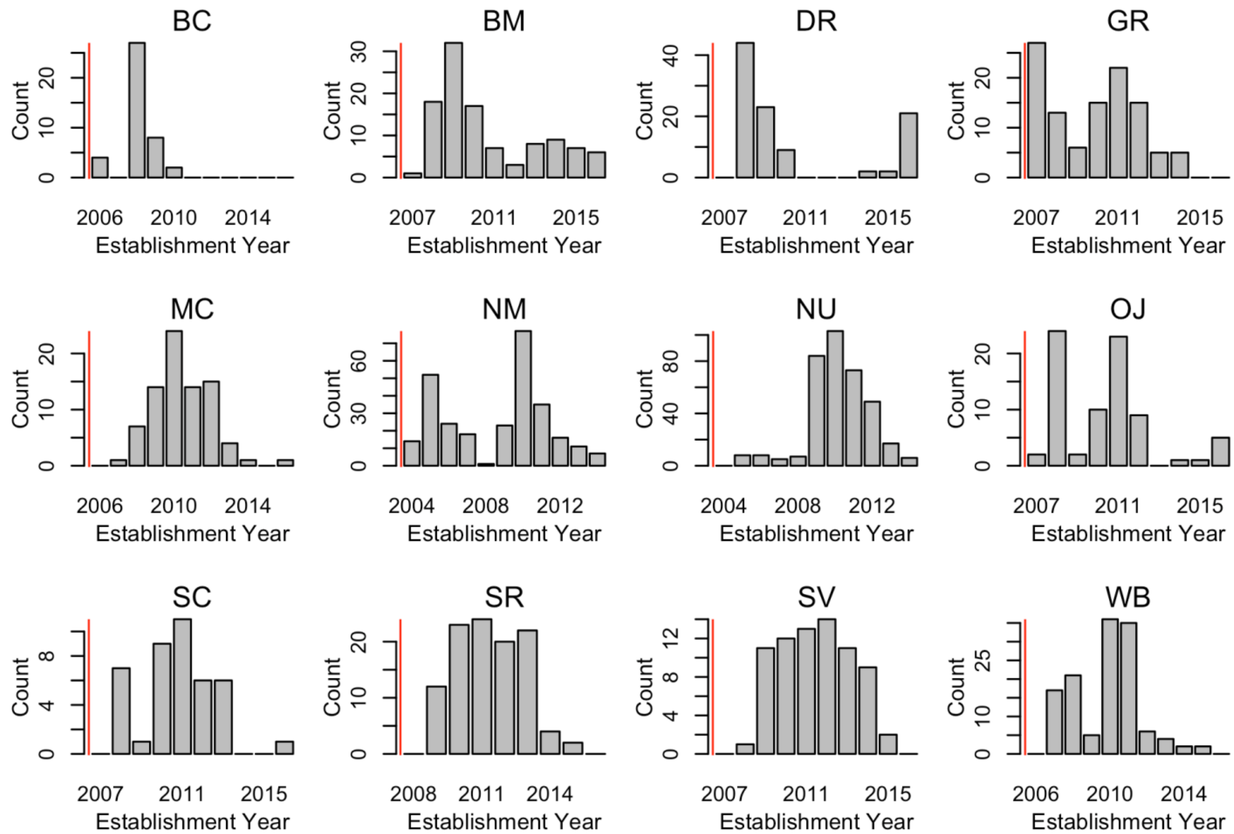

Figure 3. Temporal patterns of post-fire sagebrush establishment at each site. The red line indicates the year of fire.

Table 2. Regression model results: timing of post-fire sagebrush establishment. Regression coefficient estimates (β) and standard errors (SE) from linear mixed-effects models. Site was included as a random intercept.

Dependent variable:	Establishment occurrence *(Binomial)*	Establishment abundance *(Gaussian)*
	β [log odds] (SE)	β (SE)
Wet degree days +	-0.517 (0.228) **	---
Degree days +	---	-1.078 (0.674)
Start of late spring dry period (day) +	0.514 (0.213) **	1.176 (0.569) **
Time since fire (yr)	-8.210 (2.893) ***	-5.576 (7.610)
$(\text{Time since fire (yr)})^2$	-8.898 (2.699) ***	-22.058 (7.112) ***
Constant	0.663 (0.264) **	0.616 (0.651)

Notes:
*p<0.1; **p<0.05; ***p<0.01
+Environmental predictor variables were scaled before analyses, and the slope estimates represent the effect of a change of 1 SD.

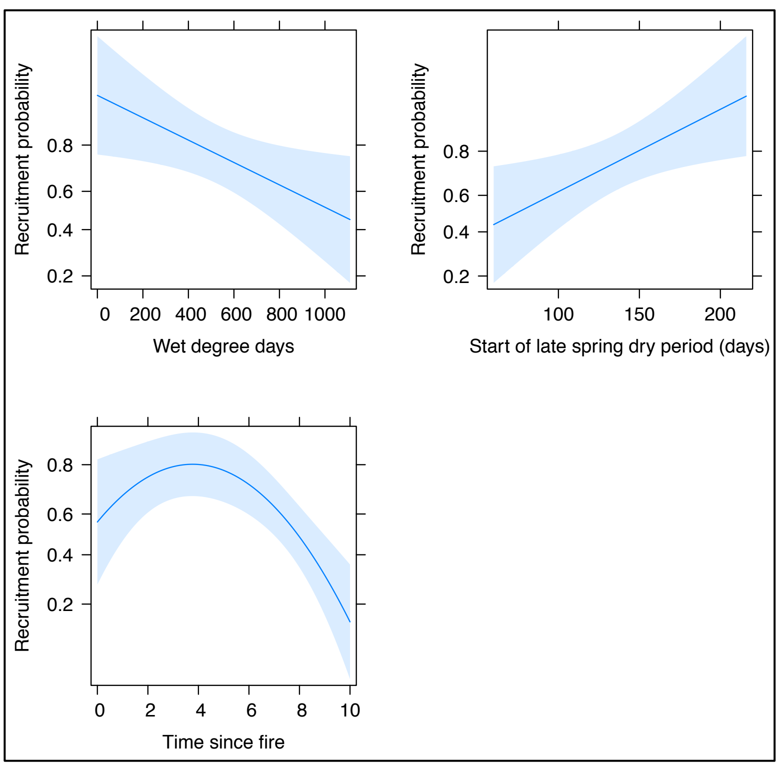

Figure 4. Partial effects plots from the logistic model predicting annual probability of sagebrush recruitment (establishment occurrence). We used a generalized linear mixed-effects model with a binomial response. Site was included as a random intercept.

Interannual establishment variability

We found that interannual establishment variability was weakly related to site-level means of spring soil environmental conditions. Specifically, we found that interannual establishment variability was highest in sites that typically experience an earlier spring soil dry-down (Fig. 5), suggesting that conditions in a given year are less likely to be favorable for sagebrush establishment in relatively dry sites. However, the low sample size (11 sites) impedes our ability to generalize this relationship, and statistical support was limited. The mean start of the late spring dry period was positively but weakly related to the proportion of post-fire years with sagebrush establishment ($R^2 = 0.21$; p=0.09; Fig. 5a) and establishment evenness ($R^2 = 0.07$; p=0.22; Fig. 5b). These relationships should be explored with data from a larger set of sites before being extrapolated to the broader landscape.

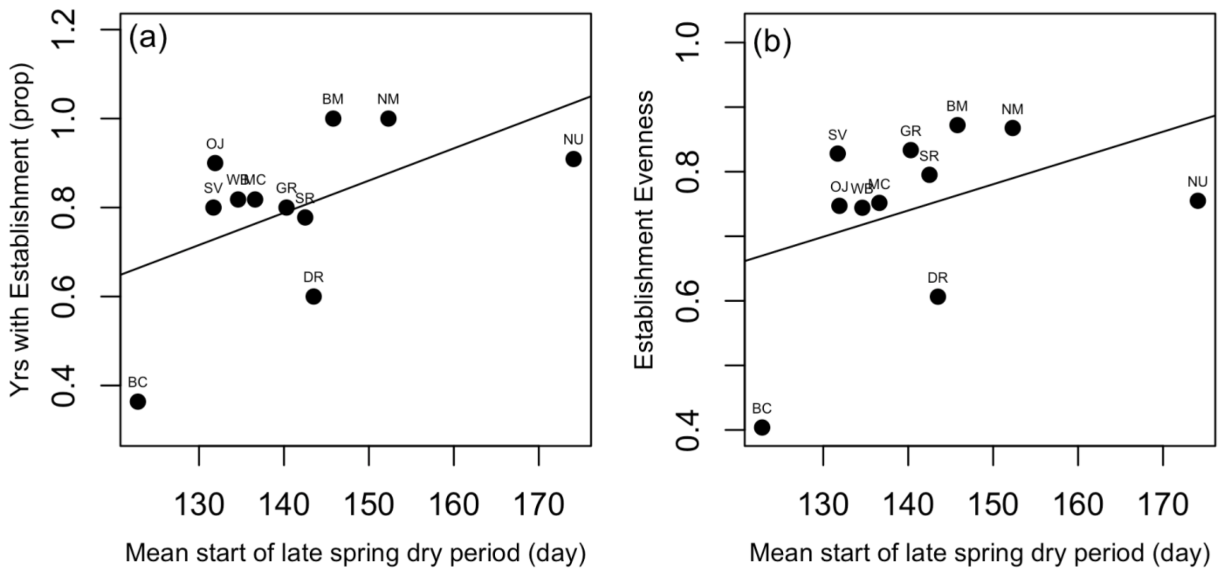

Figure 5. Temporal variability in sagebrush establishment as a function of mean site environmental conditions. (a) The proportion of post-fire years with big sagebrush establishment and (b) post-fire establishment evenness among years, shown as a function of the mean start of the maximum late spring dry period.

Post-fire big sagebrush recovery

Contrary to our expectations, we did not find evidence that sagebrush canopy recovery was strongly related to site climate or to establishment variability. The best-supported model of sagebrush canopy recovery included only time since fire as a predictor variable, and this simple model did reasonably well at predicting canopy recovery ($R^2 = 0.43$; p=0.01; Fig. 6a). This result suggests that climate effects on seedling establishment do not constitute a major constraint to stand recovery for the range of climate included in our study. Our model predicted burned stands to recover to pre-burn levels after an average of 12-13 yrs (Fig. 6a), which is much faster than has been previously estimated (Baker 2006, Nelson et al. 2014). The relatively rapid rate of sagebrush recovery that we observed was likely the result of continuously available seeds from surviving plants and dispersal from plants outside the small burn patches.

We found that population recovery may be weakly related to site environmental conditions. Sites with a later late spring soil dry-down period were, on average, more likely to have sagebrush densities that exceed pre-fire levels after 8-13 years (Fig. 6b), although the relationship was non-significant ($R^2 = 0.21$; p=0.10). Post-fire population density has been shown to change non-linearly after fire, driven by a post-fire recruitment pulse and subsequent seedling mortality followed by a more gradual increase in density as the population stabilizes (Shriver et al. in prep). The relationship between site climate and population recovery should be explored with data from a larger set of sites, along with a more detailed investigation of the population processes driving population recovery (e.g. fecundity vs. seedling survival).

Compared to the overall range of big sagebrush, our study sites were located in relatively high-elevation, cool/moist conditions where sagebrush shrublands overlap with pinyon-juniper woodlands. It is possible that the range of conditions included in our sampling design did not fully capture the marginally suitable environments in which climate strongly constrains post-fire sagebrush recovery. However, the fact that we found rapid post-fire sagebrush recovery in small burns across a broad range of climatic conditions suggests that observed recovery failures may be more limited by seed availability than by climate across a large portion of the landscape.

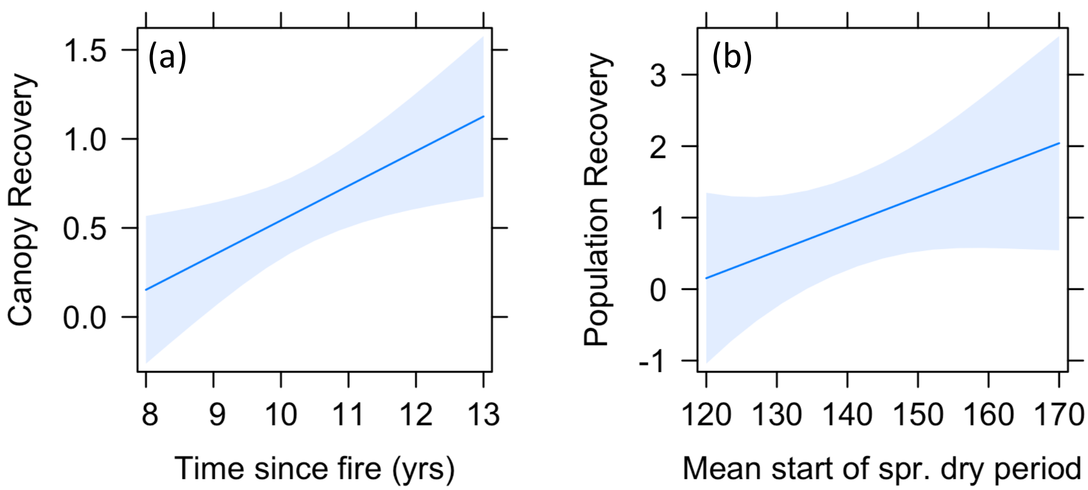

Figure 6. Modeled post-fire sagebrush recovery as a function of the most supported predictor variables. (a) Modeled relationship between canopy recovery and time since fire. (b) Modeled relationship between population recovery and site mean start of spring dry period.

Science Delivery Activities

This project has been shared in multiple presentations, with the goal of targeting members of the scientific community, the resource management community, and the general public. In 2017 the project goals and preliminary findings were presented at the JFSP Fire Science Exchange Network field tour (Reno, NV, 5/17/2017, approximately 50-75 participants), and at the USFS and University of Nevada sponsored field tour on Restoring and Conserving Great Basin Ecosystems (Austin, NV, 7/12/2017, approximately 50 participants). In 2018, this research was also included in two invited outreach presentations to regional stakeholder organizations: at the Nevada Prescribed Fire Alliance Meeting (Reno, NV, 4/19/2018) and at the

Alpine Biomass Collaborative Meeting (Markleeville, CA, 8/7/2018). Together, these presentations reached 150+ members of the management community and the general public.

Additionally, results from this project are being widely shared with the scientific community. This study was presented to members of the scientific community at the Fire Continuum Conference, hosted by the Association for Fire Ecology and the International Association of Wildland Fire (Missoula, MT, 5/22/18). Two peer-reviewed journal articles have been published on post-fire vegetation responses in the Underdown Canyon sites (Urza et al. 2017, 2019). A manuscript on the findings presented in this report is currently in preparation and is expected to be submitted for peer review in the summer of 2019. Once the peer-reviewed article has been published, we will publish a non-technical summary in the SageSTEP newsletter and will distribute it widely through the JFSP Great Basin Fire Science Exchange.

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

Conclusions

Sagebrush stand age structures show some survival of pre-fire sagebrush plants in all of our study sites, meaning that the post-fire seed availability was not limited and suggesting that the observed conditions are not representative of larger, higher-severity fires with complete sagebrush mortality. Nonetheless, the fact that seed availability was not likely limiting allows us to isolate the effect of environmental conditions on post-fire sagebrush establishment, providing important insights into natural regeneration dynamics with clear implications for restoration.

Post-fire sagebrush establishment patterns showed highly episodic establishment, with most sites experiencing pulses of establishment in years with relatively high spring soil moisture. Given favorable soil environmental conditions, establishment probability remained high for up to a decade after fire, suggesting that competition with other established plants is not a major constraint to post-fire sagebrush establishment for some time after fire.

Although our results show that drier/warmer sites were less likely to have favorable conditions for sagebrush establishment in a given year, repeated vegetation surveys suggested that long-term recovery outcomes were not strongly related to interannual variability in establishment. In other words, all sites appeared to be on track for relatively rapid recovery to pre-burn levels of sagebrush canopy cover, regardless of the frequency of establishment events.

Management Implications

In small burns where seed availability was not limiting, establishment occurred during favorable years for at least ten years after fire. This result suggests that, in the interior of larger fires where sagebrush recovery is expected to be limited by a lack of viable seeds, the window of opportunity for restoration efforts such as post-fire seeding or planting may be longer than previously thought. This is an especially important insight for burns in drier portions of the landscape, where there is a lower probability that ephemeral periods of seed availability will coincide with favorable weather conditions to result in successful sagebrush establishment. In those locations, an adaptive management approach can be used to promote sagebrush recovery by increasing the probability that seed availability coincides with favorable conditions. For example, seasonal weather forecasts can be used to prioritize restoration efforts in years when a positive outcome is likely, and repeated seeding could increase restoration success by making seeds available in multiple consecutive years.

Future Research

Future analyses will explore the influence of additional soil environmental characteristics on sagebrush establishment probability. An important step in linking these project results with applied tools for management prioritization will be to combine the observed soil environmental conditions with weather station data and landscape-scale models of soil moisture availability, with the goal of scaling up the annual establishment predictions to the broader landscape. Such a modeling effort would result in spatially-explicit estimates of the probability that a given year will be favorable for sagebrush establishment, which can be used to guide the development of post-fire restoration plans.

Additionally, more detailed demographic analyses are needed to better understand sagebrush recovery after fire. There is currently limited information on the relative influence of specific demographic processes, including seed production, propagule pressure, seedling establishment, growth rates, and plant-plant interactions. These population processes all likely respond individually to interannual weather and broad-scale climate to result in observed demographic structures, and a more mechanistic understanding of the population processes driving stand recovery would inform science-based management and facilitate decision making.

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Appendix B: List of Science Delivery Products

Science outreach

Cheatgrass invasion after prescribed burning in pinyon-juniper woodlands: lessons from a long-term experiment. Alpine Biomass Collaborative Meeting, Markleeville, CA, August 7, 2018.

Landscape prioritization of Rx fire: where is it appropriate to use prescribed fire in sagebrush and pinyon-juniper ecosystems? Nevada Prescribed Fire Alliance Meeting, Reno, NV, April 19, 2018.

Long-term vegetation response to prescribed burns in Underdown Canyon: lessons learned. Field Tour on Restoring and Conserving Great Basin Ecosystems, Austin, NV, July 12, 2017.

Post-fire recruitment of Great Basin big sagebrush. Joint Fire Science Program Fire Science Exchange Network Annual Meeting, Pine Nut Mountains, NV, May 17, 2017.

Scientific presentations

Urza AK, Weisberg PJ, Chambers JC, Board D, and Flake S. Long-term understory vegetation response to prescribed burning in pinyon-juniper woodlands. Fire Continuum Conference, Missoula, MT, May 21-24, 2018.

Publications

SageSTEP newsletter article. *In preparation*.

Urza A. K., P. J. Weisberg, J. C. Chambers, S. G. Kitchen, B. A. Roundy, and D. Board. Post-fire recruitment of Great Basin big sagebrush species: Spatial and temporal controls along regional gradients of soil temperature and moisture. *In preparation*.

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Appendix C: Metadata

This project produced a dataset containing establishment dates and dimensions for 2,004 big sagebrush individuals collected at 12 burned sites. This dataset will be archived on the SageSTEP data archive (www.sagestep.org) and made publicly available as open access material as soon as the resulting peer-reviewed publications are completed or two years after project completion. We will include a citation of the data archive location in all related publications. The associated metadata file has been submitted to JFSP along with this Final Report and will be archived with the dataset.

Dataset Title: Big sagebrush establishment dates and dimension data

Abstract: This dataset contains big sagebrush (*Artemisia tridentata*) establishment dates and shrub dimensions associated with JFSP Project # 16-2-01-27. The data were collected in 12 sites from the SageSTEP and Underdown Canyon prescribed fire networks, which are located in sites co-dominated by sagebrush shrublands and pinyon-juniper woodlands in Nevada, Utah, Oregon, and California. Prescribed burn treatments took place between 2004 and 2008, and sites were sampled between 2015 and 2017. Clusters of sampling plots were randomly located within each prescribed fire site, and all big sagebrush individuals within the plots were measured (canopy diameters and height) and then destructively sampled. A stem sample was collected from each sagebrush individual that included the root collar, and stem samples were sectioned at to the lowest appearance of the pith and progressively sanded. Stem samples were examined under the microscope, and the establishment date was determined based on the count of annual rings. Stem diameters were measured with calipers on the processed stem samples.