Vegetation Impacts of Recurring Fires on Sagebrush Ecosystems in Washington: Implications for Conservation and Rehabilitation

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Abstract

Thousands of hectares of high quality sagebrush shrub-steppe burned in south-central Washington in 2000 and 2007, particularly on the Arid Lands Ecology Reserve (ALE) on the Hanford Reach National Monument. Extensive rehabilitation efforts took place on ALE to control invasive species and establish native species following each of these fires. Permanent vegetation monitoring plots were established throughout this area in the mid-1990s, remonitored in 2001-2004, and monitored again in 2009-2010. This combination of rehabilitation treatments and monitoring provided a unique opportunity to better understand the individual and cumulative effects of recurring fires and restoration in this landscape. We investigated changes in vegetation and biological soil crust (BSC) cover over time and assessed the performance of restoration plantings of Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*). Repeated fires have re-structured and simplified plant communities. Community responses to repeated fires and restoration treatments depend on the traits of the key species present. For example, high elevation communities are resilient to repeated fire as the dominant species are able to resprout after burning, whereas low elevation communities are strongly affected because big sagebrush is unable to resprout after burning. Low elevation areas that have lost their shrub component are unlikely to be dominated by shrubs again in the near future without significant active management. Vegetation dynamics in the sagebrush shrub-steppe can be related to the balance between grasses and shrubs and to the degree of invasion by non-native species. BSC cover and composition differ between successional stages and are affected by various abiotic and biotic factors. The effectiveness of sagebrush plantings varies among stocktypes in both seedling survival and economic costs. Given the large scale of these fires, active management is essential if the re-establishment of a shrub component is desired at low elevation sites. Our results can inform immediate management decisions regarding present and future post-fire habitat rehabilitation measures on ALE and other shrub-steppe sites, and provide critical insight into the long-term dynamics of this significant ecosystem.

Background and Purpose

Sagebrush shrub-steppe is among the most imperiled ecosystems in North America (Noss et al. 1995). Degradation of this system generally involves the loss of native shrubby and herbaceous species and increased dominance of non-native annual grasses (principally cheatgrass, *Bromus tectorum*). Invasion by non-native annual grasses is facilitated by, and leads to, a fire regime characterized by greater fire frequency and extent (Whisenant 1990). The net result of these altered processes is the practical elimination of major shrub components of this system, particularly Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*). This positive feedback between invasive species and fire leads to the conversion of diverse plant communities with distinct shrub, herbaceous, forb and biological soil crust (BSC) layers, to virtual monocultures of cheatgrass (West 2000) with little habitat value for other species. In Washington state, this ecosystem is at even greater risk because most of the deep-soil communities dominated by big sagebrush have been converted to dryland and irrigated agricultural production (Vander Haegen et al 2000). The loss of this ecosystem component increases the urgency to conserve these systems, and to understand how best to manage them in the face of the above-mentioned threats and of climate change.

The Hanford Reach National Monument (HRNM) was established in 2000 to protect some of the most extensive and ecologically significant shrub-steppe habitats in Washington, including large expanses of deep-soil communities (Soll et al. 1999; Evans et al. 2003). The Fitzner-Eberhardt Arid Lands Ecology Reserve (hereafter referred to as ALE), a 77,000 acre portion of HRNM, comprised the highest quality examples of shrub-steppe remaining in the state at the time. However, virtually all of ALE burned in the 24 Command Fire (27 June - 2 July 2000), which consumed 163,000 acres (Figure 1). This fire was the largest and most severe fire to have burned in this area in recorded history. Restoration seeding and shrub planting treatments were carried out after the 2000 fire. Unfortunately, the Milepost 17 Fire (13 August 2007) and the Wautoma Command Fire (16-17 August 2007) reburned 77,000 acres of land, including much of ALE.

Figure 1. Fire perimeters and permanent vegetation monitoring plots on ALE.

In this study, we addressed **Task 5: 2007 Fires – Re-Measurement Opportunities**, as outlined in JFSP Request for Applications 2008-1. The area of our study is described below (see 'Study Description and Location'). Briefly, we collected vascular plant and biotic soil crust data on permanent vegetation plots previously sampled in the 1990s and from 2001-2004. By integrating new and historical data, we were able to address questions relating to the *effects of fire on shrub-steppe vegetation*, including the *cumulative effects of two extensive burns in short succession*. In addition, by monitoring vegetation change in areas where rehabilitation treatments were implemented after the 2000 fire, we quantified the *effect of these treatments* in the face of another large fire.

This project had two objectives. The first objective was to **quantify the effects of two successive fires on shrub-steppe vegetation**. Specifically, we were interested in how the 2007
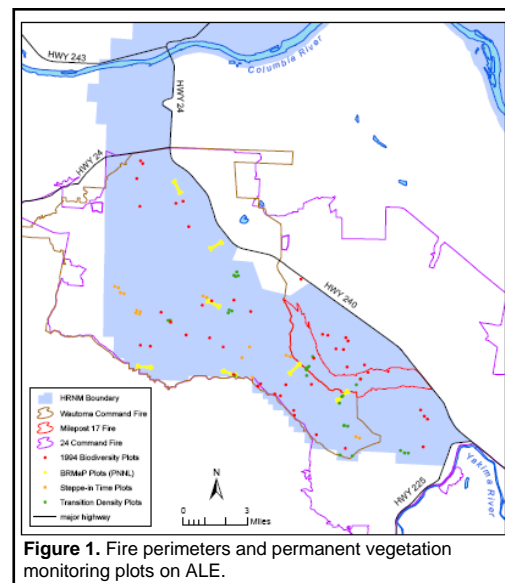
fires altered the various biological components of the system, hether the trends in community composition and structure that were noted following the 2000 fire continued, or were modified by a second fire in short succession , whether these trends suggest that a fundamental change in state has occurred in the ecosystem, and whether the observed changes in vegetation composition could be related to pre-fire fuel characteristics and to measures of fire severity for the 2000 and 2007 fires. The second objective was to determine if rehabilitation treatments after the 2000 fire affected the recovery of shrub-steppe communities after a second fire. Specifically, we were interested in how the 2007 fires affected the rehabilitation plantings that were carried out following the 2000 fire, and what these findings suggest regarding the nature and value of post-fire habitat rehabilitation measures at this site, considering long-term vegetation trajectories.

In this final report, we summarize our results in terms of these two objectives. The specific questions that we answered changed somewhat during this project as a result of data availability and research results. For example, we determined that fire severity could not be estimated with sufficient accuracy from the available data, which are intended for use in forested systems. We also decided to focus more attention on the BSC due to the participation of a student with strong interests in this component of the system.

Study Description and Location

Study Area

The primary focus of this study was the lands that comprise the Fitzner-Eberhardt Arid Lands Ecology Reserve (hereafter ALE), which lies within the southwestern portion of the Hanford Reach National Monument (HRNM) in Benton County, Washington. ALE was formally established in 1967 by the Atomic Energy Commission in recognition of the rich and relatively undisturbed character of its native shrub-steppe ecosystem (O'Connor and Rickard 2003). In 2000, ALE was incorporated into HRNM, and is co-managed by the U.S. Fish and Wildlife Service (USFWS) and the U.S. Department of Energy. Because most of ALE burned in 2000 and 2007, comparable data from unburned communities were obtained from shrub-steppe sites outside of ALE. These included sites on public and private lands elsewhere in Benton County, including sites in the Horse Heaven Hills (hereafter HHH) owned and managed by the U.S. Bureau of Land Management.

Our study area is within the Columbia Basin, the hottest, driest part of Washington (Franklin and Dyrness 1973, Rickard et al. 1988, Soll et al. 1999). Elevations range from 435-3500 ft (130-1060 m) above sea level. Annual precipitation varies with elevation, and ranges from an average of 6.3 inches (16 cm) at the lowest elevations to 13.8 inches (35 cm) along the crest of Rattlesnake Mountain (DOE-RL 2001).

Most of the landscape of ALE was dominated by sagebrush (*Artemisia*) species when the Hanford Nuclear Reservation was established in 1943. Between 1957 and 1998, wildfires reduced the shrub-dominated portion of ALE to < 20 percent of its extent at the mid-point of the 20th century (Rickard et al 1988, Soll, et al 1999). When ALE was established, the major plant communities included shrublands dominated by Wyoming big sagebrush at low and middle elevations, primarily in the northern portion of ALE. Shrublands dominated by three-tip sagebrush (*A. tripartita*), sometimes with big sagebrush or rabbitbrush (*Chrysothamnus* and *Ericameria* spp.) as important components, occurred at middle to higher elevations, primarily on northerly aspects. Other shrubland types included a small black greasewood (*Sarcobatus vermiculatus*) community and areas characterized by winterfat (*Eurotia lanata*). Shrubland

understories were dominated by native bunchgrasses such as bluebunch wheatgrass (*Pseudoroegneria spicata*) and Sandberg's bluegrass (*Poa secunda*), and associated hemishrubs and forbs (Wilderman 1994). Soil surfaces in relatively undisturbed native grasslands and shrublands were characterized by a biological soil crust composed of mosses, lichens, fungi, algae, and cyanobacteria (Link et al. 2000, Johansen et al. 1993), especially on silt-loam soils.

Where previous wildfires or human activities had removed the big sagebrush, perennial and annual grasses dominated the landscape. Bluebunch wheatgrass-Sandberg's bluegrass was the most common perennial grassland association, occurring at elevations above 800-1000 ft (250-300 m). Needle-and-thread (*Hesperostipa comata*) dominated another perennial grassland association at lower to middle elevations, often on sandy soils. Idaho fescue (*Festuca idahoensis*) was important at higher elevations and on more northerly aspects, often in association with threetip sagebrush and bluebunch wheatgrass. Cheatgrass, a non-native annual grass, was widespread at low elevations.

Sampling Design and Field Data

This study involved the resampling of a large number of permanent vegetation plots throughout ALE and in nearby shrub-steppe areas. Many of these plots were established during the 1990s in several different studies. Sampling methods for most of the studies were carefully documented by Evans and Lih (2005), permitting us to use the same methodologies as in prior measurements. In general, these consisted of 5 x 20 m plots, or transects along which quadrats were systematically laid out and measured (see details below). Plots on ALE had been georeferenced in 2004 and were relocated via GPS. A number of plots off ALE had to be relocated using approximate map locations, a careful search for remaining markers, and/or help from local land owners and managers. Some of the off-ALE sites have been destroyed either due to the removal of marker posts or because of land-use conversion.

Field data collection for this project occurred in Spring 2009 and Spring 2010. While sampling the originally planned plots, we also identified a need to understand how BSCs respond to fire, and located relevant sets of permanent plots that could address this need. We prioritized resampling of those plots with the most complete set of past measurements, and those that, due to their burn history, strengthen the statistical power of planned analyses.

The general location, number of plots, date of establishment, remonitoring occurrence, and parameters measured are summarized here:

1. **Biodiversity Plots** (ALE; n = 42; established in 1994; resampled in 2001-2004, 2009-2010). Percent cover estimates of vascular plant species and microbiotic crust in 5 x 20 m plots. Assessment of bunchgrass density.
2. **Biological Resource Management Plan (BRMaP) Plots** (ALE; n = 25 in 7 plots; established by 1997; resampled 2001-2004, 2009-2010). Percent cover estimates of vascular plant species, microbiotic crust, and litter in twenty 20 x 50 cm quadrats per transect.
3. **Steppe-in-Time (SIT) Transects** (ALE: 6 transects established in 1992, 3 transects in 1996; outside ALE: 23 transects established in 1992 (including several unburnt since they were established); most plots resampled in 1993, 1997, 2001-2004, 2009, 2010). Percent cover estimates of vascular plant species, microbiotic crust, and litter in twenty 20 x 50 cm quadrats per transect.
4. **Transition Density Plots** (ALE; n = 32; established in 2001; resampled in 2002-2004, 2009, 2010). Cheatgrass density within 20 x 20 cm quadrats and vegetation presence in 1

x 1 m quadrats at 25 m intervals along 100 m transects.

5. **Rehabilitation Vegetation Plots** (ALE; n = 30; established in 2003; resampled in 2004). Percent cover of vascular plant species, microbiotic crust, and litter in twenty 20 x 50 cm quadrats along 100 m transects. These plots were not remonitored during this project as they were not of high enough priority given our logistic constraints.

6. **Sagebrush Survival Plots** (ALE; n = 26; established in 2002; resampled in 2003, 2004, 2009, 2010). Survival and vigor of planted sagebrush plugs located along belt transects. These plots were supplemented by data from sagebrush survival plots established to monitor sagebrush survival in the first 3 years after plantings in 2001, 2005, 2006, and 2007. In total, we analyzed the survival and performance of sagebrush seedlings in 153 plots.

7. **Ponzetti Plots** (HHH; n = 48 in 12 sites; established in 1998; resampled in 2010). Percent cover of vascular plant and biological soil crust species in 0.5 x 4 m quadrats.

8. **BSC plots** (ALE and HHH; n = 20; established by E Dettweiler-Robinson in 2010). Percent cover of vascular plants, and presence of bryophyte and lichen species, in five 20 x 50 cm quadrats along 100 m transects.

Data Manipulation and Storage

The permanent nature and repeated sampling of the vegetation plots meant that there were large quantities of historical data to be organized and analyzed. These data had previously been stored in multiple spreadsheets and often lacked metadata. Significant effort was devoted to compiling, organizing, and cleaning up the large historical data sets associated with the permanent plots. We built Microsoft Access databases to house the data. In addition, all field data collection sheets from our project, along with those available that were collected historically, were scanned and archived electronically.

Most plots had associated permanent photographic monitoring points. We collated historical photographs from previous researchers and those taken during the course of our project. Where necessary, photographs were digitized and their metadata amended to include the date the image was taken and the plot and GPS location where it was taken. The file name associated with each digital image file was modified to reflect the plot identity and date of the image. A photograph index was created as an MS Excel spreadsheet. In total, we processed over 1,000 photographs documenting changes on these plots between 1992 and 2010.

We compiled information about fire histories for ALE and HHH, and about restoration treatments (aerial seeding, drill seeding, herbicide application) on ALE. Fire perimeter data from 1980-2010 were obtained from MTBS (http://mtbs.gov) and GeoMAC (http://www.geomac.gov). We also found references in the literature to fires prior to 1980 (Rickard et al. 1988, O'Connor and Rickard 2003), but could not locate sufficiently accurate fire perimeters for inclusion in GIS. Data on restoration treatments were compiled by USFWS staff at HRNM and provided as GIS layers. By overlaying our fire and restoration perimeters onto maps of plot locations, we generated a detailed disturbance history for each plot at each monitoring date. Key variables included the time since last disturbance (by fire or restoration type) and the number of disturbances experienced before that monitoring date.

We examined the possibility to use georeferenced delta Normalized Burn Ratio (dNBR) and burn severity data from the 2000 and 2007 fires (available through the Monitoring Trends in Burn Severity (MTBS) project; http://fsgeodata.fs.fed.us/mtbs/) to assign fire severity scores to each plot. However, we determined that this information was not useful for our purposes as the

burn severity data do not adequately capture the variability of vegetation responses within grassland and shrubland communities. We also investigated the possibility of using aerial photography to identify patches of big sagebrush-dominated vegetation, but found limited success with this approach.

Vascular Plants

More than 250 vascular plant species were recorded over the course of the study. Plants were identified using Hitchcock and Cronquist (1973), but nomenclature was updated to follow the USDA PLANTS database (USDA, NRCS 2011). During our field work, we collected 127 herbarium specimens which have been archived in the Hyde Herbarium, University of Washington Botanic Gardens.

There was extensive historical data associated with the permanent plots sampled during this study. While compiling these data, we checked for consistency in identifications and for evidence of obvious misidentifications. Where necessary, records were amended following consultation with the original collectors or herbarium specimens they had collected.

Biological Soil Crusts (BSCs)

During our field work, we sampled the BSC in 500 quadrats (5 per plot). About 50 species of bryophytes and lichens were recorded during this study, including *Texosporium sancti-jacobi*, a lichen listed as Threatened in Washington (WADNR 2005). When unknown species were encountered, voucher specimens were collected. It is difficult to physically separate BSC species, so all samples from the same quadrat were kept in a single package. These packages are archived in in the Burke Herbarium, University of Washington.

Data Analysis

This study capitalized on random disturbance events (wildfires) and therefore could not utilize optimal experimental design techniques such as replication and randomization (van Mantgem et al. 2001). Similarly, we did not propose the implementation of any experimental treatments. However, our study had a Before-After/Control-Impact (BACI) design (Underwood 1994). Differences among data sets in sampling design and sampling frequency prevented a global analysis of all data. Instead, we developed specific research questions and focused on those data sets most appropriate for particular questions. During these analyses, we also identified the appropriate experimental units for statistical analysis: some data were analyzed at the plot level, others at the transect level, and still others at the quadrat level.

Different research questions required different analytical techniques. The techniques we have used most commonly to date are briefly described here. With the exception of structural equation modeling, these techniques were commonly conducted in R (R Development Core Team 2011). We are continuing to explore other techniques (e.g., partial redundancy analysis, partial canonical correlation analysis, species area curves) that are not described here.

Cluster Analysis was used to identify groups of plots with similar composition. The appropriate number of groups was chosen by examining the resulting dendrograms and using scree plots to determine how the amount of explained variation changed as the numbers of groups increased.

Non-metric multidimensional scaling (**NMDS**; Clarke 1993) is an ordination technique that permits visualization of differences in community composition. NMDS arranges data points in a configuration that minimizes the inter-point distances (stress). As is standard with compositional data, we removed rare species (those occurring on < 5% of plots) from these analyses and used the Bray–Curtis distance measure. Initial analyses were completed using up to 400 runs, random starting locations, and from one to five dimensions. Choice of final dimensionality was made by balancing ease of interpretability with the desire to minimize stress. Visualization was further aided by varying symbol shape among groups, overlaying 'ordihulls' around observations within the same group, and/or overlaying continuously distributed explanatory variables as vectors or isoclines. When the ordinated data included time series, we also visualized community trajectories by translating the positions of all years of data for each plot so that the initial year was located at the origin and all subsequent years were in their same relative locations to it and each other.

Permutational analysis of variance (**PERMANOVA**; Anderson 2001) is a straightforward extension of MANOVA that makes no assumptions about normality or heteroscedasticity, and is applicable to multivariate response data and to any linear model, including repeated measures designs. The test statistic from this test is a pseudo-F statistic. We used the Bray-Curtis distance measure, and 9999 permutations to calculate the significance of the pseudo-F statistic. For consistency with other analyses, rare species were removed prior to these analyses. PERMANOVA was completed using R or the PERMANOVA+ extension of the PRIMER software package.

Structural Equation Modeling (Grace 2006) is a means of assessing complex multivariate hypotheses about the relationships among variables. We built *a priori* conceptual models summarizing our understanding of the ecological system, and then tested how well they fit given the covariance structure of the actual data.

Indicator Species Analysis (ISA; Dufrêne and Legendre 1997) is a means of identifying species that are more strongly associated with one group than expected by chance. Indicator Values (IV) are calculated independently for each species as the product of its relative abundance and frequency, and statistical significance is assessed using 999 Monte Carlo randomizations.

Generalized linear modeling (**GLM**; Crawley 2005) was used to analyze proportional data such as numbers of seedlings that lived vs died. By using a quasibinomial error distribution, this technique explicitly accounted for the fact that proportions are bounded between 0 and 1.

Key Findings

Here, we summarize our key findings for each objective.

Objective A. Quantify the Effects of Two Successive Fires on Shrub-Steppe Vegetation

- **Repeated large fires have led to a significant re-structuring and simplification of plant communities**. For example, four plant communities could be clearly identified when the BRMaP plots were first sampled in 1996, but only two were identifiable in 2009.
- **Community responses to repeated fires and restoration treatments depend on the traits of the key species present.** For example. the ability to resprout following severe burns, rapidly reach reproductive age, and disperse over large distances seem to be key determinants of whether plants are 'winners' or 'losers' following repeated disturbances. Wyoming big

sagebrush is an obligate seeder whereas three-tip sagebrush is able to resprout following burning. Longleaf phlox (*Phlox longifolia*) resprouts readily from its woody stem base and can produce seed in the first year following fire. This, combined with competitive release due to the removal of the shrub canopy, has allowed it to become the dominant species in some areas where big sagebrush was formerly abundant (Figure 2).

Figure 2. Permanent plot photographs of a Steppe-in-Time transect in 1996, 2002, and 2009 showing the strong changes in community structure and composition as a result of the fires in 2000 and 2007. This plot has changed from dominance by big sagebrush to a mixture of Sandberg's bluegrass, longleaf phlox, balsamroot, and the occasional large native bunchgrass.
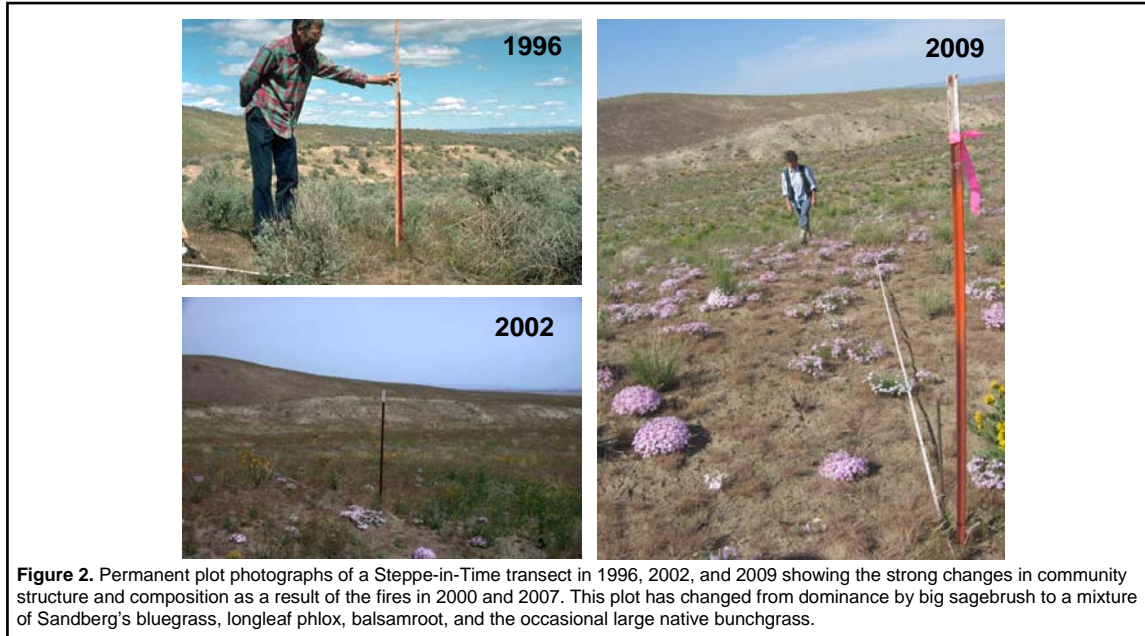
- **High elevation communities are remarkably resilient to the effects of repeated fire**. These communities were dominated by three-tip sagebrush, Idaho fescue, and bluebunch wheatgrass in the 1990s, and changed minimally in compo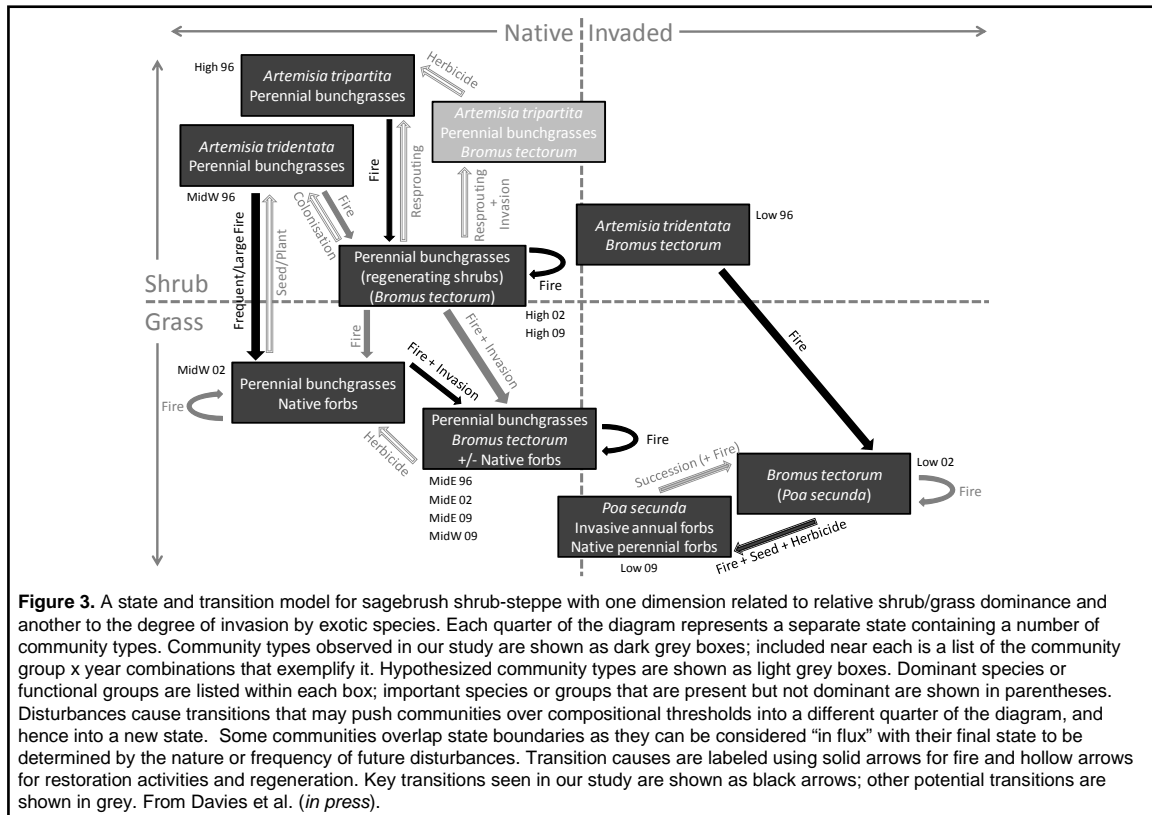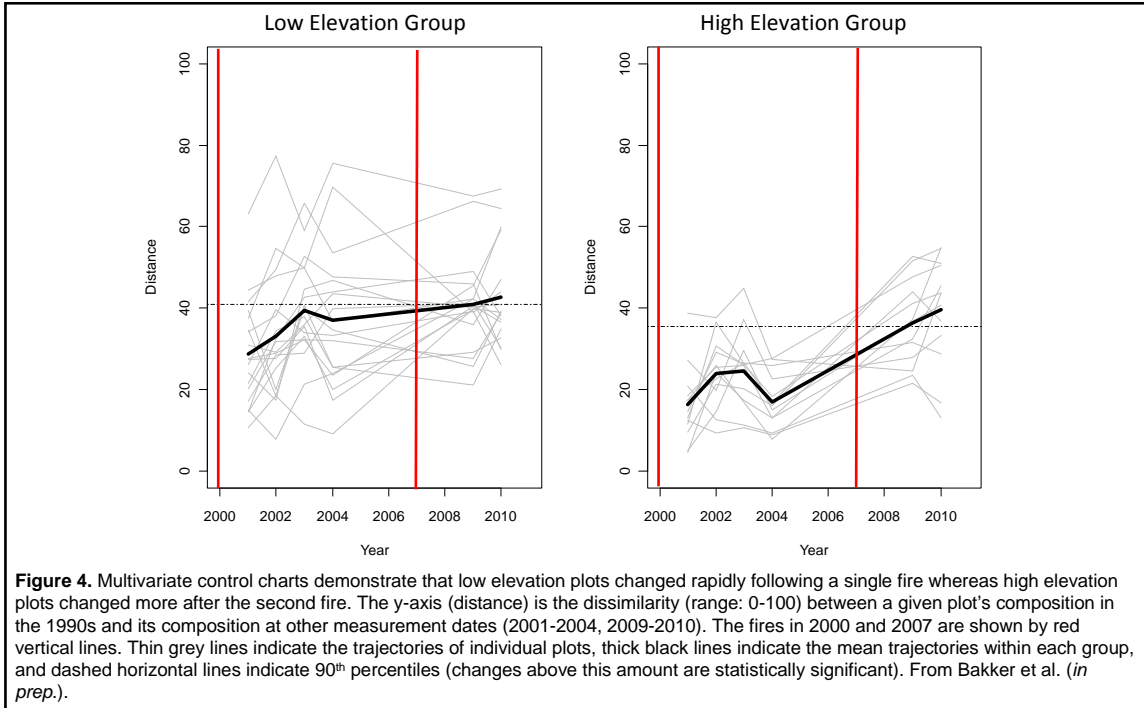sition following the 2000 and 2007 fires bedcause the key species were able to resprout following burning. However, these communities also had lower abundances of invasive species prior to the fires and thus likely experienced reduced propagule pressure from them following the burns. These transects were not targeted for herbicide applications because of the low abundance of invasive species, but it is salient to note that cheatgrass increased significantly in abundance after the 2007 fire.
- **Low elevation areas that have lost their shrub component are unlikely to be dominated by shrubs again in the near future without significant active management.** These communities were previously dominated by Wyoming big sagebrush, which is an obligate seeder and unable to resprout following burning. Recent fires were of such large size that they eliminated big sagebrush seed sources from much of the landscape.
- **Where cheatgrass had been abundant prior to the fires, it was often substantially reduced afterwards.** This change is not simply a response to repeated fires, however, as our study area received active restoration treatments (i.e., herbicide applications) targeted at controlling cheatgrass. Cheatgrass abundance increased rapidly following the 2000 fire, when herbicide treatments were not done as extensively, suggesting that the low densities after the 2007 fire are a result of herbicide application. Currently, these low-elevation communities are often dominated by other weedy or invasive species (e.g. Russian thistle (*Salsola kali*) and narrowleaf goosefoot (*Chenopodium leptophyllum*)), but we suggest that these areas will

rapidly become cheatgrass-dominated if herbicide applications cease and/or native perennial species do not occupy the growing space.
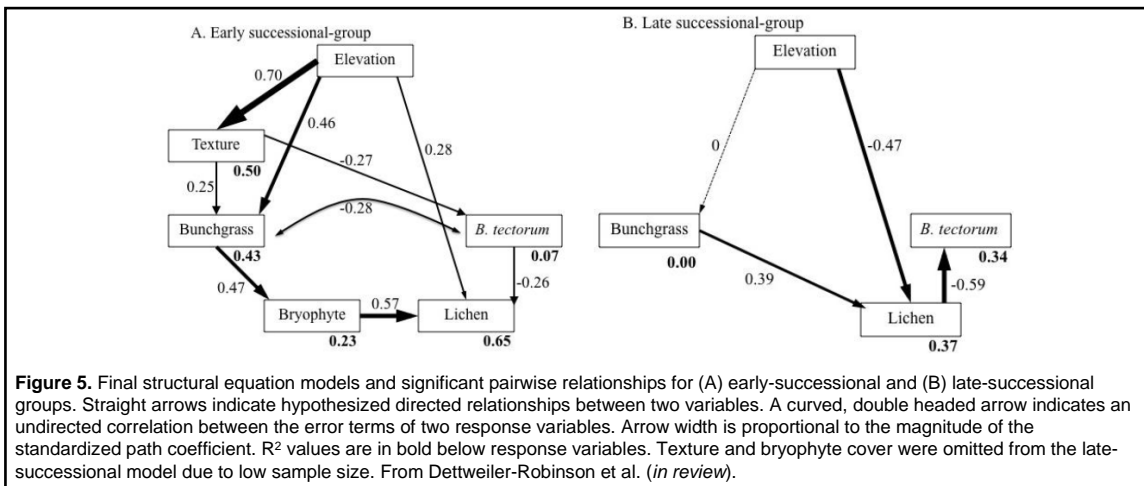
- **Vegetation dynamics in the sagebrush shrub-steppe can be related to the balance between grasses and shrubs and to the degree of invasion by non-native species** (Figure 3). State-and-transition models are common in the sagebrush shrub-steppe, but often the transitions among states are not related to specific axes. This model can also incorporate multiple disturbances and differing species responses due to variation in the traits they possess.

Figure 3. A state and transition model for sagebrush shrub-steppe with one dimension related to relative shrub/grass dominance and another to the degree of invasion by exotic species. Each quarter of the diagram represents a separate state containing a number of community types. Community types observed in our study are shown as dark grey boxes; included near each is a list of the community group x year combinations that exemplify it. Hypothesized community types are shown as light grey boxes. Dominant species or functional groups are listed within each box; important species or groups that are present but not dominant are shown in parentheses. Disturbances cause transitions that may push communities over compositional thresholds into a different quarter of the diagram, and hence into a new state. Some communities overlap state boundaries as they can be considered "in flux" with their final state to be determined by the nature or frequency of future disturbances. Transition causes are labeled using solid arrows for fire and hollow arrows for restoration activities and regeneration. Key transitions seen in our study are shown as black arrows; other potential transitions are shown in grey. From Davies et al. (*in press*).

- **Novel approaches for analyzing compositional change can yield new insights about vegetation recovery and dynamics.** Univariate responses such as total species richness or total cover can mask changes in composition. New techniques such as multivariate control charts (Anderson and Thompson 2004) can visualize compositional change, including responses to management actions and recovery following disturbance (Figure 4).

Figure 4. Multivariate control charts demonstrate that low elevation plots changed rapidly following a single fire whereas high elevation plots changed more after the second fire. The y-axis (distance) is the dissimilarity (range: 0-100) between a given plot's composition in the 1990s and its composition at other measurement dates (2001-2004, 2009-2010). The fires in 2000 and 2007 are shown by red vertical lines. Thin grey lines indicate the trajectories of individual plots, thick black lines indicate the mean trajectories within each group, and dashed horizontal lines indicate 90th percentiles (changes above this amount are statistically significant). From Bakker et al. (*in prep.*).

- **Fire alters the successional status of the biological soil crust (BSC).**
- **The relative importance of abiotic and biotic factors controlling BSC cover differs between successional stages.** Native vegetation mediated some abiotic effects on early-successional transects, but abiotic and biotic factors both affected BSC cover on late-successional transects. Cheatgrass had a weak negative effect on lichen cover on early-successional transects but was negatively affected by lichen cover on late-successional transects (Figure 5).
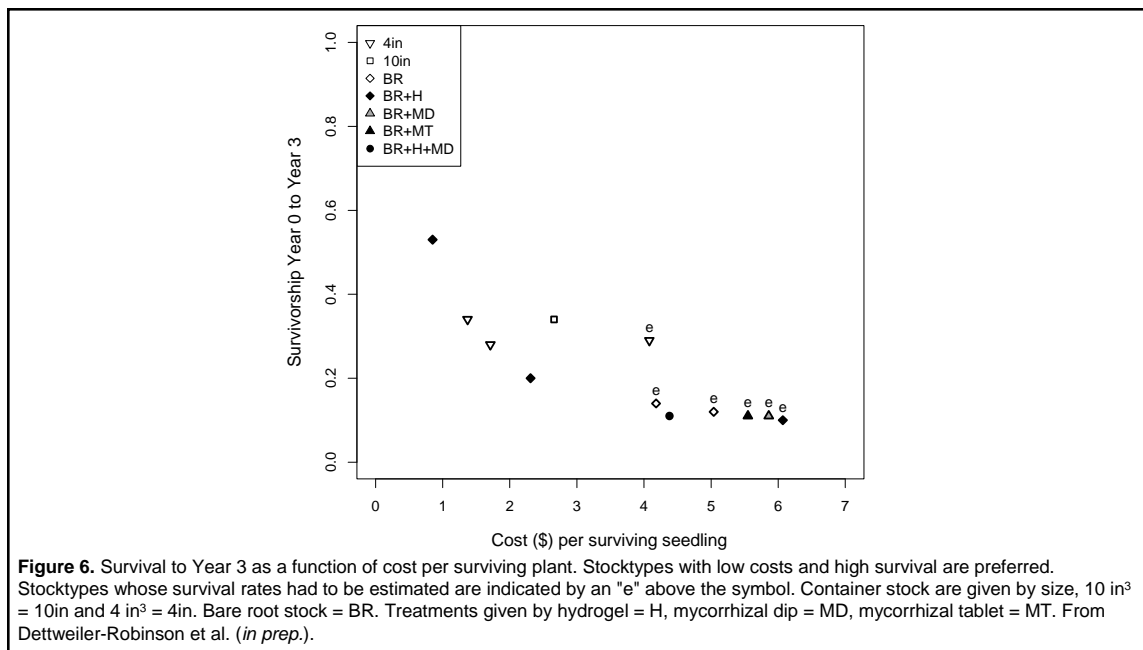

Figure 5. Final structural equation models and significant pairwise relationships for (A) early-successional and (B) late-successional groups. Straight arrows indicate hypothesized directed relationships between two variables. A curved, double headed arrow indicates an undirected correlation between the error terms of two response variables. Arrow width is proportional to the magnitude of the standardized path coefficient. R^2 values are in bold below response variables. Texture and bryophyte cover were omitted from the late-successional model due to low sample size. From Dettweiler-Robinson et al. (*in review*).

- **BSC composition differs with successional stage, elevation, vegetation, and soils**. Some BSC species are significant indicators of early- and late-successional stages.
- **BSC composition is surprisingly dynamic.** BSC are slow growing, and there is little published long-term data about the stability of BSC composition and rates of species

turnover. By remeasuring the BSC community on permanent plots 11 years after they were established, we found a surprisingly large amount of species turnover. On average, the correlation in composition on the two dates was ~60%. Plots that burned recently changed more in composition, largely due to species loss. Gains in species were associated with warmth of the soil surface as measured by heat load index.

Objective B. Determine Effects of Rehabilitation Treatments

- **Container stock and bareroot stock with a hydrogel dip are the most ecologically and economically effective of the 7 stock types tested for outplanting Wyoming big sagebrush.** Averaged across all stock types, survival averaged 52% to Year 1 and 28% to Year 3. Mycorrhizal inoculation of bare root stock did not affect seedling survival and was not warranted economically (Figure 6). Advantages of outplanting compared to direct seeding are the higher and more predictable survival rate – though low compared to outplantings in other ecosystems – and more rapid development of habitat structure.

Figure 6. Survival to Year 3 as a function of cost per surviving plant. Stocktypes with low costs and high survival are preferred. Stocktypes whose survival rates had to be estimated are indicated by an "e" above the symbol. Container stock are given by size, 10 in^3 = 10in and 4 in^3 = 4in. Bare root stock = BR. Treatments given by hydrogel = H, mycorrhizal dip = MD, mycorrhizal tablet = MT. From Dettweiler-Robinson et al. (*in prep.*).

- **At low to mid elevations, the re-establishment of a shrub component may not be viable without aggressive action.** The large extent of the 2000 and 2007 fires removed big sagebrush, and other species that are not able to resprout after burning, from extensive areas and further eliminated the seed sources from which new individuals could establish. Re-establishment of a big sagebrush community within the next few decades therefore will not occur without active management. Big sagebrush could and has been planted in these areas, but the repeated fires that result in part from the dominance of cheatgrass have made it difficult for planted seedlings to survive and reproduce. Re-establishment of a shrub component in these areas would require active management of fuel structure.

Management Implications

The products from this project are directly relevant to a broad spectrum of land managers working in sagebrush shrub-steppe systems, including the US Fish and Wildlife Service, Department of Energy, Department of Defense, Bureau of Land Management, and Washington Department of Fish and Wildlife. In addition to providing important insights into how multiple disturbances interact with plant traits to drive vegetation dynamics, our results provide HRNM managers with extensive, on-site information about the direction, rate, and magnitude of changes in vegetation composition and structure that have occurred over the last two decades and after two large fires. They also supply critical data for evaluating the success of previous rehabilitation efforts, and for guiding decisions regarding future post-fire management actions.

Objective A. Quantify the Effects of Two Successive Fires on Shrub-Steppe Vegetation

Although the occurrence of fires in rapid succession (2000 and 2007) is unusual in the fire history record for the sagebrush shrub-steppe, it is likely to be increasingly common in the future due in part to the presence of species such as cheatgrass that have enhanced fuel continuity and led to a fire regime with greater fire frequency and extent. On ALE, repeated fires and herbicide applications appear to have significantly, but no doubt temporarily, reduced populations of cheatgrass at lower elevations. Cheatgrass abundance declined immediately following the first fire but increased rapidly in degraded, low-elevation communities that did not receive herbicide. After the second fire, followed by repeated herbicide applications, cheatgrass abundance remained low. However, the fires and herbicide applications have created significant amounts of empty niche space for which native and invasive plants are now competing. In our opinion, controlling invasive populations and preventing re-invasion must be a high management priority to ensure that all components of a healthy native shrub-steppe, including BSC, bunchgrasses, forbs, subshrubs, and large shrubs, can establish and persist across the landscape.

Understanding how plant communities will respond to repeated fires and to management actions can be enhanced by careful consideration of the functional traits of the key species in the communities and of the key species that could invade them. For example, three-tip sagebrush communities at high elevations appear resilient to repeated fires. However, the abundance of cheatgrass appears to be increasing in this area; monitoring is clearly warranted to determine whether aggressive management is necessary to prevent it from dominating these areas. Although the shrubs, graminoids and forbs in this area may be resilient to repeated fires, the BSC community is unlikely to be as resilient.

The reduced abundance of cheatgrass at lower elevations in the first few years after a fire presents an opportunity, though short-lived (Humphrey and Schupp 2001, Eiswerth et al. 2009), in which to re-establish important native species such as bunchgrasses and shrubs. Significant efforts were made to re-establish populations of native plants at lower elevations of ALE, but given the short time interval since these were applied it remains too early to judge their success. Future fires may provide similar windows that could be capitalized on if sufficient resources – particularly seed – are available in advance.

Containing the spread of cheatgrass may require novel approaches to interrupt fuel continuity and break its connection with a higher frequency fire regime. For example, managers could identify zones in which cheatgrass is aggressively controlled and fuels are managed to maintain low continuity and loads. These areas could serve as buffers to protect nearby areas and thereby increase the restoration success in the protected areas. Another potential strategy is to

increase a focus on biocontrol of cheatgrass (Meyer et al. 2007). Or, managers could focus on rapidly filling niches with species – perhaps chosen on the basis of traits such as phenology or rooting depth – that can effectively compete with cheatgrass for resources while not resulting in the same degree of fuel continuity. These options are controversial to varying degrees, and clearly require additional research before they could be adopted wholesale.

Our state and transition model (Figure 2) is more quantitative than most and could be used to guide management by indicating potential pathways by which recovery or development to desired vegetation communities can occur. By delineating two thresholds (shrub/grass dominance and degree of invasion), it can help managers determine the degree of effort that would be required to achieve various target communities. Multivariate control charts could also be implemented in a management context by, for example, providing a simple visual representation of the degree of similarity between a community's current composition and the desired composition as specified by managers. Both of these tools require additional development and validation before they are fully useful for managers, however.

Our analysis of BSC can be used to prioritize actions by managers seeking to prevent the degradation of or to restore BSC communities. For example, protection could focus on areas at higher elevations with low cheatgrass cover and mature vegetation cover, as these have the highest BSC cover and most mature BSC composition. Bunchgrasses could be planted to create appropriate habitats for BSC. Control efforts could be targeted at coarse-texture soils where cheatgrass is most likely to invade, and at late-successional areas with diminished BSC cover. Some BSC species can function as indicators of early- and late-successional states; monitoring these species could provide rapid insight into the successional stage of the BSC community. Finally, the presence of *Texosporium sancti-jacobi*, a lichen listed as Threatened in Washington (WADNR 2005) but not previously identified on these plots, indicates that further study of the BSC community is warranted.

Objective B. Determine Effects of Rehabilitation Treatments

The outcome of rehabilitation and restoration efforts frequently depends upon factors beyond the control of practitioners (Monsen et al. 2004). Disturbed sites in the sagebrush shrub-steppe are challenging to restore due to their warm, semiarid climate, the presence of aggressive invasive species, and the frequent occurrence of wildfires. In the interior Columbia Basin, the probability of restoring healthy native shrub-steppe within this habitat type has been rated as no better than moderate (Bunting et al. 2003). Altered fire regimes in particular challenge our ability to restore functional shrub layers in this landscape, and the outcomes of future restoration efforts in the region will depend as much upon effective fire management as on the technical elements of restoration science (Monsen et al. 2004). Given these challenges, restoration practitioners need to select shrub stocktypes that are likely to achieve ecological objectives while being economically viable. Outplanting seedlings is a valuable approach for restoring shrubs in some shrub-steppe ecosystems, provided they are located in a landscape context that maintains connectivity with remnant patches and that provides protection from invasion fronts and ignition sources.

Small ($4\ \text{in}^3$) container stock and bareroot stock that received a hydrogel dip before planting were the most effective of the stock types evaluated in terms of survival and economic costs. Climatic conditions are highly variable in the sagebrush steppe, and this variability can be a challenge for successful restoration. Survival was more consistent among planting years for

container stock than for bare root stock. If bareroot stock is used, it should receive a hydrogel dip immediately before planting. Mycorrhizal inoculations were not effective in terms of enhancing survival and health.

Knowledge of the relationship between survival and economic costs can also be used to adjust planting densities. For example, more seedlings should be planted if they are cheap but have low expected survival, and fewer seedlings should be planted if they are expensive but are expected to have better survival. Finally, simple monitoring of seedling survival and health one year after planting can provide insight into the likelihood that the future stand will develop as anticipated. Such an 'early warning' system would be advantageous if, for example, managers could use it to identify when and where supplementary plantings were necessary to reach target densities. Additional research is required to understand the longer-term performance of seedlings, including the rate at which they grow and how quickly they begin to provide wildlife habitat.

Relationship to Other Recent Findings and Ongoing Work on This Topic

Objective A. Quantify the Effects of Two Successive Fires on Shrub-Steppe Vegetation

Following repeated disturbance, communities change rapidly in response to the large amounts of empty niche space available. Propagule pressure (Lockwood et al. 2005) may play a crucial role in determining the extent to which alien species are able to take advantage of this situation. We propose a state-and-transition model for the sagebrush shrub-steppe that has some important differences from those presented previously, specifically the need to separately account for grass/shrub and native/invasive states as well as the impacts of compounded disturbances and species traits. Nevertheless, our conclusions are similar to those of Hemstrom et al. (2002) and McIver et al. (2010), whose models also suggest that aggressive restoration work will be required to re-establish 'classic' shrub-steppe vegetation on highly disturbed, lower-elevation sites. To succeed, these efforts will also need to continue to control invasive species and their effects on fuel loads and fuel continuity.

The directionality within the network of relationships controlling BSC cover in our study largely match those observed in hot deserts of southern Utah, where the BSC is dominated by cyanobacteria (Chaudhary et al. 2009), indicating that these hierarchical relationships may be broadly applicable. Plant functional groups can have opposing effects: native bunchgrasses had a positive effect whereas cheatgrass had a negative effect on BSC cover. These nuances can be masked when all functional groups are grouped together; Chaudhary et al. (2009) found a negative relationship between total vegetation cover and BSC cover. Determining which functional groups to examine may depend on the life history, phenology, litter deposition patterns, and other traits of the species in the community. Additionally, our data supported the hypothesis that mature BSC can impede cheatgrass, suggesting that the direction of net effects may change with successional stage.

Our study of changes in BSC composition over an 11 year period provides a baseline for assessing rates of change in this community within the Columbia Basin. Our results support a recent study indicating that BSC communities are more dynamic than previously supposed (Belnap et al. 2006).

Objective B. Determine Effects of Rehabilitation Treatments

Mortality of Wyoming big sagebrush seedlings is highest in the first year after outplanting and decreases over time. Our survival rates three years after planting fell within the ranges reported by previous studies (Meikle et al. 1995, Durham et al. 2001, Durham and Sackschewsky 2004, Washington Closure Hanford 2005, Durham and Sackschewsky 2009). Variation in survivorship rates among studies can be attributed to multiple interacting factors, including differences in environment, vegetation, interannual climate variation, and stock and planting quality.

Future Work Needed

Our proposed state-and-transition model (Figure 2) and multivariate control charts (Figure 3) could be used to guide management in the sagebrush shrub-steppe ecosystems. However, both of these tools require additional development and validation before they are fully useful for managers.

Research is needed into novel management approaches that may permit the continued persistence of species that are vulnerable to more frequent fires. For example, efforts might seek to break the connection between cheatgrass and a higher frequency fire regime by identifying areas in which fuel management, including fire breaks, are priority actions. These areas would serve as buffer zones to protect nearby areas and thereby increase restoration success in the protected areas. On highly disturbed sites at low elevations, we suggest a focus on restoring function and rapidly filling niches with species that can effectively compete with cheatgrass for resources. Analysis of species traits may give insight into potentially competitive species.

Invasive species such as cheatgrass alter fuel quantity, continuity, and spatial arrangement in sagebrush shrub-steppe ecosystems. Restoration and management actions can further alter fuel structure. We see a need for models of shrub and grass fuels in the sagebrush shrub-steppe as a function of abiotic conditions, disturbance history, and plant community composition. These models could be used to examine the spatial and temporal dynamics of fuels, and to explicitly link changes in fuel structure with community dynamics. Products might include the development of predictive models relating fuels to commonly collected plant community data, the application of state-and-transition models to fuels and to communities, and the development of models describing the fuelbeds of communities within the sagebrush steppe.

The sagebrush shrub-steppe ecosystem is experiencing significant changes in disturbance regimes and climate. These factors, along with abiotic conditions (e.g., soil type, aspect), determine species distributions. Understanding the implications of these changes requires that we determine the relative importance of these factors in determining the distributions of key species. Once this is understood, we could forecast potential changes in species distributions in response to projected climatic changes and anticipated disturbance regimes. Species that have disjunct current and future distributions would be of particular management concern.

Deliverables Crosswalk table

We used a variety of methods to deliver project results to end users. Deliverables are summarized here and detailed in the 'Additional Reporting' section of this report. We have acknowledged support from JFSP during all of these activities.

A project website was established early in the project and provides general information about the project, our original proposal, presentations, and other reports. It also provides links to the JFSP, USFWS, and TNC websites. The website is hosted by the University of Washington.

We participated in a large number of field demonstrations and tours. Field tours of our project were provided in Spring 2010 and Spring 2011; the latter was part of the 'Columbia Basin Landscapes Workshop' that featured a number of JFSP-supported projects and was directed toward state, federal, and private land managers. Guest lectures were given to the Washington Native Plant Society, TNC, and students in several courses at the University of Washington. In total, these activities reached at least 550 individuals. We were unable to participate in the Society for Range Management summer field tour as originally proposed.

We presented our research results at a large number of regional, national, and international meetings, workshops, and symposia. We were not able to tally attendance at all of these events, but had numerous interactions with interested individuals.

Several manuscripts resulting from this project have been submitted or are being actively prepared for publication in peer-reviewed journals. One is 'in press' at *Ecological Applications* and should be published next year; another is in review at the *Journal of Arid Environments*. Several other manuscripts are near submission, while others require additional development. We will share published manuscripts with land managers working in shrub-steppe systems.

Annual reports were submitted to JFSP as requested in September 2009 and September 2010. This final report is our last formal obligation to JFSP, although we will continue to finalize manuscripts and see them through the publication process.

This project supported one graduate student, whose thesis research will be published as two refereed publications. This project also supported two post-doctoral Research Associates, several undergraduate students, and several field technicians.

Finally, the extensive historical and new data associated with this project necessitated that we build resources to compile and organize it. We built relational databases to organize the data. We digitized historical images and incorporated metadata with each image. Finally, we developed collections of plants and of biological soil crusts that are housed in herbaria at the University of Washington.

Proposed	Delivered
Website	http://depts.washington.edu/firesale/
Field Demonstration/Tours (at least two)	27, to > 550 individuals
SRM Summer Field Tour	N/A
Conference/Symposia/Workshop – Invited paper/presentation	15 (12 oral, 3 posters)
Regional Meetings	Included in 'Invited paper' category above
Refereed Publications	2 (1 in press, 1 in review), plus 6 in preparation
Non-refereed Publications	Annual reports to JFSP in September 2009 and 2010; final report to JFSP in December 2011
Masters Thesis	Dettweiler-Robinson 2011
Datasets	5 databases, 1 photo collection, 2 herbarium collections

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Dettweiler-Robinson, E., J.D. Bakker, and J.B. Grace. *In review*. Controls of biological soil crust cover and composition in sagebrush shrub-steppe. *Journal of Arid Environments*.

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Wilderman, D.W. 1994. *Plant communities of the Fitzner/Eberhardt Arid Lands Ecology
      Reserve and the north slope of the Hanford Site: Findings of the 1994 inventory*. The
      Nature Conservancy of Washington, Seattle, WA. 51 pp. plus appendix.

Additional Reporting

Project deliverables are summarized here. Where a deliverable has been uploaded to the JFSP website, it is noted by the 'JFSP ID' number at the end of the entry.

Final Report

Bakker, J.D., P.W. Dunwiddie, S.A. Hall, J.R. Evans, G.M. Davies, and E. Dettweiler-Robinson. 2011. *Vegetation Impacts of Recurring Fires on Sagebrush Ecosystems in Washington: Implications for Conservation and Rehabilitation*. Final report to the Joint Fire Science Program for Project 08-1-5-20. 26 p.

Website

Fires @ ALE. Research project website. http://depts.washington.edu/firesale/ (JFSP ID 8261)

Field Tours, Workshops, and Guest Lectures

Fires on ALE field tour. May 12, 2010. Organized by the US Fish and Wildlife Service (USFWS) and facilitated by staff from the USFWS, The Nature Conservancy, and the University of Washington. 43 individuals from 23 organizations participated. (JFSP ID 8906)

Davies, G.M. *The impact of multiple wildfires on sagebrush-steppe ecosystems*. Guest seminar at The Nature Conservancy, Seattle, WA. October 2010. ~ 10 participants.

US Fish and Wildlife Service. *Columbia Basin Landscapes Workshop: Linking Science and Management to Improve Restoration Success in the Shrub Steppe*. Kennewick, WA, 26th - 28th April 2011. 125 participants. (JFSP ID 9576)

Dettweiler-Robinson, E. *Diversity in the desert workshop*. Central Puget Sound Chapter, Washington Native Plant Society, Seattle, WA, 9th December 2011. 6 participants.

Dettweiler-Robinson, E. *Restoration in arid environments*. Guest lecture in ESRM 362 ("Introduction to Restoration Ecology"), University of Washington, Seattle, WA, 22nd November 2010. 70 participants.

Dettweiler-Robinson, E. *Restoration in arid lands*. Guest lecture in ESRM 362 ("Introduction to Restoration Ecology"), University of Washington, Seattle, WA, 21st November 2011. 62 participants. (JFSP ID 9577)

Dettweiler-Robinson, E. *"Diversity in the Desert"* in-house field trips for BIOL 180 ("Introductory Biology"), University of Washington, Seattle, WA. 21 trips between October 2010 and December 2011, with ~12 students per trip.

Professional Presentations and Invited Talks

Presentations at conferences and citations are reported here in chronological order. A '*' denotes the presenter.

*Dettweiler-Robinson, E., G.M. Davies, J.D. Bakker, P.W. Dunwiddie, J. Evans, S.A. Hall, and J. Downs. *The impact of multiple wildfires on sagebrush-steppe communities: implications for restoration*. 36th Annual Natural Areas Conference, Vancouver, WA. September 15-18 2009. [invited presentation] (JFSP ID 8262)

*Davies, G.M., E. Dettweiler-Robinson, J. Bakker, P. Dunwiddie, J. Evans, S. Hall, and J. Downs. *The impact of multiple wildfires on trajectories of change and stable states in*

sagebrush-steppe ecosystems. 4th International Fire Ecology and Management Congress: Fire as a global process. Savannah, GA. November 30 - December 4 2009. [invited presentation] (JFSP ID 8923)

*Davies, G.M., J.D. Bakker, E. Dettweiler-Robinson, P.W. Dunwiddie, J. Evans, and S.A. Hall. *The impact of multiple wildfires on trajectories of change and stable states in sagebrush-steppe ecosystems*. In: Oregon Chapter/Northwest Section Meeting of The Wildlife Society: emerging environmental issues and the role of wildlife science. Bend, OR. February 11-12 2010. (JFSP ID 8922)

*Dettweiler-Robinson, E., G.M. Davies, J.D. Bakker, P.W. Dunwiddie, J. Evans, S.A. Hall, D. Wilderman, and J. Downs. *Addressing trajectories of community change of sagebrush shrub-steppe following multiple wildfires and implications for restoration*. Graduate Student Symposium, School of Forest Resources, University of Washington, Seattle, WA. February 19 2010. (JFSP ID 8925)

*Dettweiler-Robinson, E., G.M. Davies, and J.D. Bakker. *Addressing trajectories of community change of sagebrush shrub-steppe following multiple wildfires and implications for restoration*. In: Society for Ecological Restoration NW & The Wildlife Society WA Regional Conference 2010. Tulalip, WA. February 16-18 2010. (JFSP ID 8924)

*Bakker, J.D., G.M. Davies, E. Dettweiler-Robinson, P.W. Dunwiddie, J.R. Evans, S.A. Hall, J. Downs, M. Marsh, and R. Haugo. *Long-term effects of multiple wildfires and management on the Arid Lands Ecology Reserve*. Columbia Basin Landscapes Workshop: Linking Science and Management to Improve Restoration Success in the Shrub Steppe. Kennewick, WA. April 26-28 2011. (JFSP ID 9568)

*Newsome, H. *Planting seedlings to regenerate critical shrub components in shrub-steppe; a viable tool for land managers*. Columbia Basin Landscapes Workshop: Linking Science and Management to Improve Restoration Success in the Shrub Steppe. Kennewick, WA. April 26-28 2011. (JFSP ID 9561)

*Davies, G.M., J.D. Bakker, E. Dettweiler-Robinson, J. Evans, P. Dunwiddie, J. Downs, and M. Marsh. *Patterns and drivers of long-term change in sagebrush-steppe vegetation communities*. 54th Symposium of the International Association for Vegetation Science, Lyon, France. June 20-24 2011. (JFSP ID 9570)

*Dettweiler-Robinson, E., and J.D. Bakker. *Biotic and abiotic characteristics interact with fire history to influence biological soil crust cover and composition in the Columbia Basin*. 96th Annual Meeting of the Ecological Society of America, Austin, TX. August 7-12 2011. (JFSP ID 9569)

*Bakker, J.D., G.M. Davies, and E. Dettweiler-Robinson. *Using multivariate control charts to communicate long-term changes in community composition*. Society for Ecological Restoration: 4th World Conference on Ecological Restoration, Mérida, Mexico. August 21-24 2011. (JFSP ID 9571)

*Dettweiler-Robinson, E., J.R. Evans, H. Newsome, R. Haugo, G.M. Davies, J.D. Bakker, P.W. Dunwiddie, D. Pyke, and T. Wirth. *Restoring Wyoming big sagebrush following wildfire using nursery-grown stock: Contrasting methods and predicting survival*. * Society for Ecological Restoration: 4th World Conference on Ecological Restoration, Mérida, Mexico. August 21-24 2011. (JFSP ID 9572)

*Bakker, J.D., and E. Dettweiler-Robinson. *Distribution and maintenance of biological soil crusts in the Columbia Basin*. 65th Annual Meeting of the Society for Range Management, Spokane, WA. January 2012. [invited presentation]

Posters

Posters at conferences are reported here in chronological order. A '*' is used to denote the presenter.

*Davies, G.M., E. Dettweiler-Robinson, J.D. Bakker, P.W. Dunwiddie, S. Hall, and M. Gregg. *Vegetation monitoring to improve conservation*. In: Conservation Colloquium: conservation in practice from Anthropology to Zoology. University of Washington, Seattle, WA. March 3 2010. (JFSP ID 8921)

Davies, G.M., J.D. Bakker*, E. Dettweiler-Robinson, J. Evans, P.W. Dunwiddie, J. Downs, and M. Marsh. *Using multivariate control charts to communicate long-term changes in sagebrush-steppe vegetation communities*. Columbia Basin Landscapes Workshop: Linking Science and Management to Improve Restoration Success in the Shrub Steppe. Kennewick, WA. April 26-28 2011. (JFSP ID 9574)

*Dettweiler-Robinson, E., and J.D. Bakker. *Biotic and abiotic characteristics interact with fire history to influence biological soil crust cover and composition in the Columbia Basin*. Columbia Basin Landscapes Workshop: Linking Science and Management to Improve Restoration Success in the Shrub Steppe. Kennewick, WA. April 26-28 2011. (JFSP ID 9573)

Graduate Education

Dettweiler-Robinson, E. 2011. *Multiple fires and landscape factors affect vegetation composition over time and interact to affect biological soil crust cover*. MSc thesis. University of Washington, Seattle, WA. 67 p. (JFSP ID 9575)

Publications In Print / In Press

Davies, G.M., J.D. Bakker, E. Dettweiler-Robinson, P.W. Dunwiddie, S.A. Hall, J. Downs, and J. Evans. *In press*. Trajectories of change in sagebrush-steppe vegetation communities in relation to multiple wildfires. *Ecological Applications*. (JFSP ID 9596)

Publications Under Review

Dettweiler-Robinson, E., J.D. Bakker, and J.B. Grace. *In review*. Controls of biological soil crust cover and composition in sagebrush shrub-steppe. *Journal of Arid Environments*. (JFSP ID 9597)

Publications In Preparation

Bakker, J.D., G.M. Davies, and E. Dettweiler-Robinson. *In preparation*. Using multivariate control charts to communicate long-term changes in community composition. Target journal: *Ecological Applications*.

Davies, G.M., J.D. Bakker, E. Dettweiler-Robinson, and M. Marsh. *In preparation*. Compounded disturbances and community composition in the shrub-steppe: untangling the effects of repeated fires and post-fire restoration. Target journal: *Rangeland Ecology and Management*.

Davies, G.M., E. Dettweiler-Robinson, and J.D. Bakker. *In preparation*. A quantitative State-and-Transition Model for the sagebrush steppe. Target journal: *Rangeland Ecology and Management*.

Dettweiler-Robinson, E., J.D. Bakker, J.R. Evans, H. Newsome, G.M. Davies, T.A. Wirth, D.A. Pyke, R. Easterly, D. Salstrom, and P.W. Dunwiddie. *In preparation*. Restoring Wyoming big sagebrush following wildfire: stock performance and economics. Target journal: *Restoration Ecology*.

Dettweiler-Robinson, E., G.M. Davies, J.R. Evans, J.D. Bakker, and D. Wilderman. *In preparation*. Multiple fires increased loss of bunchgrass density and cover. Target journal: *Rangeland Ecology and Management*.

Dettweiler-Robinson, E., J. Ponzetti, and J.D. Bakker. *In preparation*. Fire and annual grass invasion increase rates of compositional change and species turnover of biological soil crust within a decade. Target journal: *The Bryologist*.

Datasets

Relational databases (Microsoft Access) containing data from various sets of permanent plots. Data are available upon request from authors. There are five databases:

- Biodiversity plots, Biological Resource Management Plan (BRMaP) plots, and Steppe-in-Time (SIT) transects
- Transition Density plots
- Sagebrush Survival plots
- Ponzetti plots
- BSC plots

List of photographs of permanent plots, including date, plot, and location of each image. Available upon request from authors.

List of vascular plant specimens collected during this project and housed in the Hyde Herbarium, University of Washington Botanic Gardens. (JFSP ID 9599)

List of biological soil crust samples collected during this project and housed in the Burke Herbarium, University of Washington. (JFSP ID 9600)