Long-term impacts of wildfire on fuel loads, vegetation composition, and potential fire behavior and management in sagebrush-dominated ecosystems

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Abstract

An understanding of the long-term vegetation structure, patterns of fuel succession, and potential for reburn in sagebrush-dominated ecosystems is important for managing the landscape at a temporal scale that is appropriate for the ecological interactions in these systems. Our overarching research objective was to fill existing knowledge gaps about long term fire effects by 1) remeasuring a suite of long-term post-fire studies, 2) quantifying fuels accumulation in a chronoseries of time-since-fire plots, and 3) measuring the impact of repeated burns on fuel composition, structure, and reburn potential. Finally, this research project provided data on two previously understudied sagebrush ecosystem types, basin big sagebrush (*Artemisia tridentata spp. tridentata)* and low sagebrush (*Artemisia arbuscula*).

Seventeen years following fire (17YPF) Wyoming big sagebrush communities at Hart Mountain National Antelope Refuge (HMNAR) were dominated by native herbaceous vegetation, with 8% cover of broad-leaved forbs and bunchgrasses in the understory, compared to 4% cover in unburned controls. Seventeen years after fires, shrub cover was 0.4-4% in burned plots compared to 13-24% in unburned controls. In 17 years, overstory fuels only recovered to 13% of pre-fire levels and understory fuels only reached 25% of pre-fire levels. This resulted in potential fire behavior that was far lower in burned plots than in unburned controls, with rates of spread under the highest fire danger modeled scenario ranging from 0.4-2 m min^{-1} in burn plots and 3-6 m min^{-1} in controls (P<0.01).

Similar resilience to fire was seen in the more mesic mountain big sagebrush communities 29 years following high severity wildfire at HMNAR. Shrub cover was over 50% before fire, and declined to 10% 1YPF, then continuously increased with time since fire to 26% at 29YPF. Bunchgrass cover was fairly consistent, ranging from 29% prefire to 20% 1YPF and 28% at 29YPF. Cheatgrass cover was only 2% prefire, increased to over 30% for the first 8 years, and then declined as natives successfully outcompeted it. At 29YPF, cheatgrass cover was back down to 3%.

In basin big sagebrush sites 25-26 years post fire, total fuel recovery was variable, recovering to 7-191% of pre fire levels at Bear Creek (BEAR) and to 113-209% at John Day Fossil Beds National Monument (JODA) Repeated burns at JODA significantly altered fuels composition. Fifteen years after a single fire (15YPF), herbaceous fuels made up 44%, and shrubs were 39% of total fuels. Total fuel loads of twice-burned sites (2xB; 26 *and* 15 YPF) had a composition of 71% herbaceous and 12% shrub mass. Total fuel loads in 15YPF and 2xB sites ranged from 4-6 Mg ha^{-1} and did not differ by site (P=0.85). Potential fire behavior was not different between 26YPF and 15YPF plots, but in some cases was higher for herbaceous-dominated 2xB plots.

Collectively, these studies show higher levels of resilience to fire than is typically discussed in the sagebrush steppe, in part because the studied ecosystems were in good condition pre-fire, but also because the longer post-fire monitoring time may be more appropriate to capture patterns of succession in these ecosystems. We saw no cases of post-fire conversion to invasive dominance. In some cases, we saw previously-burned areas acting as a fuel break, likely reducing the intensity of the next fire event. Further, unburned control plots were dominated by woody vegetation and exhibited losses in herbaceous understory, possibly indicating that they are outside of their natural fire return interval. Our results illustrate that management of all ecosystem components, including natural disturbance and a mosaic of successional stages is important for persistent resilience, and that suppression of all fires in the sagebrush steppe may create long-term losses of heterogeneity in good condition sagebrush ecosystems. Additionally, this study underscores the need for additional studies looking at multiple decades of post-fire response in the sagebrush steppe.

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List of Abbreviations/Acronyms

2xB – Twice burned

DWD – Downed woody debris

FCCS- Fuel Characteristic Classification System

FFT – Fuel and Fire Tools

HMNAR – Hart Mountain National Antelope Refuge

JODA – John Day Fossil Beds National Monument

JFSP – Joint Fire Science Program

YPF – Years post fire

Keywords

Artemisia tridentata, *Artemisia arbuscula*, FCCS, fire behavior, fuel loads, Hart Mountain, John Day Fossil Beds, long-term fire effects, prescribed burning, sagebrush steppe.

Acknowledgements

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1. Background and Purpose of the Study

1.1 Overview

In a recent JFSP-funded synthesis of the effects of fire in the Great Basin, Miller et al. (2013) stated that largest gaps in our understanding of sagebrush dominated ecosystems were 1) a lack of long-term fire studies (>10 years) and 2) studies that evaluated the effects of repeated burns. This study directly addressed both of these gaps. By conducting four parallel field and fire modeling experiments, we quantified the long term influence of past fires on fuel loads, vegetation composition, and subsequent wildfire behavior, effects, and management in four sagebrush ecosystems of the Northern Great Basin and Columbia Plateau. We sampled long-term effects of fires in Wyoming big sage, basin big sage, and mountain big sagebrush communities. Using a chronosequence approach, we also sampled fuels accumulation over time in low sage, mountain big sage, and Wyoming big sagebrush ecosystems. In areas that reburned in basin big sagebrush ecosystems, we were able to assess the influence of one vs. two burns on fuel composition and structure and reburn potential. Finally, we used fire behavior models to assess reburn potential, and to identify where past fires have altered fuel loads such that the potential for future fire is impacted. In each sagebrush community, we located previously burned sites where pre- and immediate post-fire composition and fuels data were previously collected, and we involved all original researchers in our resampling efforts to ensure consistent methodology. Together, these experiments determine how past wildfires of differing ages and cover types influence patterns of fuels recovery and the potential for additional fire in the sagebrush steppe.

1.2 Objectives and Hypotheses

The overarching goal of this research was to provide a deeper understanding of long-term fuel load accumulation and vegetation composition following fire in sagebrush ecosystems, with special emphasis on 1) changes in fuel loads and potential fire behavior in historical fire and control (unburned) plots, 2) changes in native and invasive community composition in historical fire and control plots, 3) impacts of repeated fires on fuel loads and plant community composition, and 4) modeling of reburn potential in fire and control plots. All intended objectives were met and hypotheses were tested.

Specific objectives and hypotheses were as follows:
Objective I: Determine the long-term changes in fuel loads and potential fire behavior where historical prefire and immediate postfire data exists in three dominant big sagebrush communities.

- *Hypothesis Ia*: Fire will result in a shift from a dominance of woody fuel to a dominance of fine fuels with a concomitant reduction in total fuel loads.
- *Hypothesis Ib*: Rates of fuel recovery will vary by sagebrush type. Fuel loads will be greater and shrubs will recover more rapidly in *A. tridentata* ssp. *vaseyana* than in *A. tridentata* ssp *tridentata* or *A. tridentata* ssp. *wyomingensis*.
- *Hypothesis Ic*: In the early post-fire years, potential fire behavior variables (flame length, rate of spread, fireline intensity) will be lower in burned plots than in unburned controls.

Objective II: Analysis of fuel loads and vegetation structure along a time-since-fire chronosequence in three sagebrush ecosystems

- *Hypothesis IIa*: Burned plots will have decreased woody fuels and reductions in fire intensity compared to unburned control plots.
- *Hypotheses IIb*: More mesic sagebrush communities (*A. tridentata* ssp. *tridentata)* will return to pre-fire fuel loads and potential fire behavior more rapidly than the more arid

communities (*A. tridentata* ssp. *wyomingensis*).

Objective III: Quantification of long term fuel load and vegetation changes in twice burned *A. tridentata* ssp. *tridentata* plant communities

- *Hypothesis III*: Herbaceous fuels will remain the dominant portion of the fuel load for longer time periods in twice burned plots than in plots which burned only once.

Objective IV: Use historical and current field fuels data and fire modeling to quantify the influence of past wildfires on potential fire behavior and management.

- *Hypothesis IVa*: Potential fire behavior variables will be lower in all plant communities in areas which have burned as compared to unburned controls
- *Hypotheses IVb*: Effectiveness of prior fires as a fuels treatment will vary by plant community, with more mesic communities (*A. tridentata* ssp. *tridentata*) recovering faster than aridic (*A. tridentata* ssp. *wyomingensis*) communities.

2. Study description and location

2.1 Location and Partners

All study sites were in sagebrush steppe ecosystems located in the Northern Great Basin and Columbia Plateau. Sites were managed by Federal agencies (National Park Service, U.S. Fish and Wildlife Service, and USDA Bureau of Land Management) for sustainability of native shrublands and wildlife habitat as well as for recreation and have been free of domestic ungulate herbivory for several decades. Hart Mountain National Antelope Refuge (HMNAR) in south central Oregon is managed by the U.S. Fish and Wildlife Service and contains both Wyoming and mountain big sagebrush ecosystems. At this site we studied burn plots in mountain big sagebrush sites that were burned in 1985 (Pyle 2013) and Wyoming big sagebrush sites that burned in 1997 (Wrobleski 1999, Wrobleski and Kauffman 2002). Additionally, this site maintains excellent historical fire records, allowing us to set up the fuels chronosequence study in Wyoming, mountain, and low sagebrush ecosystems. The Sheep Rock Unit of the John Day Fossil Beds (JODA), in central Oregon is dominated by basin big sagebrush. At this site we have permanent plots in nearly pristine condition with few impacts by invasive species where fuel loads and fire behavior data from 1988 burns exist (Sapsis 1990, Sapsis and Kauffman 1991). Additionally, some of the JODA plots reburned in 2005, allowing investigation of the impacts of one vs. two fires on fuels accumulation and reburn potential. Near this site we have additional plots burned in basin big sagebrush in 1988 on the BLM Prineville District. At these sites we have pre- and post-fire fuels data from spring- and fall-burned plots (Kauffman and Cummings 1989).

2.2 Methods

2.2.1 Sampling Design

Experiment 1: Quantification of long term vegetation change in burned and unburned plots (where prefire and immediate postfire data exists). We have led prior research, and have access to historical data sets from previous work JODA (Sapsis 1990, Sapsis and Kauffman 1991), HMNAR (Wrobleski 1999, Wrobleski and Kauffman 2002, Pyle and Crawford, Pyle 2013), and Prineville BLM (Kauffman and Cummings 1989). In these sites we quantified long term changes in fuel loads from analysis of both burned and control (unburned) areas.

Experiment 2: Analysis of fuel loads and vegetation structure along a time-since-fire chronosequence. HMNAR maintains excellent geospatial fire records. For the most widespread sagebrush communities (*A. tridentata ssp. wyomingensis, A. tridentata ssp. vaseyana*. *A. arbuscula*) at this site, we quantified long term patterns of fuel dynamics and vegetation composition change following fire in each community type. We located and measured sites in early-, mid- and late-seral stages of succession as well as in sites with no fire record.

Experiment 3: Quantification of long term vegetation change in twice burned Artemisia tridentata ssp. tridentata and Artemisia tridentata ssp. vaseyana plant communities. We resampled sites from studies at JODA conducted by Sapsis (1990) and Sapsis and Kauffman (1991). At these sites, some of the previously burned plots have since re-burned, allowing us to quantify the impacts of repeated fires on fuel loads and vegetation community composition.

Experiment 4: Fire Behavior Modeling. To address critical questions about the impacts of past wildfires on future fire incidence and behavior, we used data collected in Experiments 1-3 to model potential fire behavior in burned and unburned plots using fire simulation models. Simulations were run through the range of environmental (fire weather) conditions expected at each site to estimate the range of low to high intensity fire expected. These simulations allowed us to (1) determine the difference in potential fire behavior between burn and control plots, and evaluate the effectiveness of prior burns as an effective fuels reduction treatment, and determine the impacts of repeated burns on fuel loads and the potential for future fire.

2.2.2 Field Measurements

Historical plots were updated, maintained, and mapped. When original projects were initiated, GPS technology was not in wide use. As such we relocated all plots and collected the GPS data for all sites to insure ease of relocation and sampling in the future. Physical plot markers (rebar, posts) at each site were updated.

2.2.3 Fuel Loads

Fuel quantification replicated methods used in prior studies. Fuel loads were measured prior to burn treatments and immediately following fires in historical studies. At all of the sites, we destructively harvested herbaceous fuels as well as litter and duff layers in 30 x 60 cm subplots (n= 8 for each plot) at equal intervals along permanent transects. Samples were weighed after collection, oven dried to a constant mass, and then reweighed to determine dry weight. The biomass (fuel load) of shrubs was determined from measurement of the cover and volume of all shrubs in 5 - 1 x 20 m plots placed adjacent to the permanent transects. For each shrub rooted within the plot, we calculated elliptical crown area and volume based on shrub canopy diameter and height. Elliptical crown area is computed as:

$$A = (W1 * W2 * \pi)/4$$

where A is the crown area, W1 is the longest crown dimension, and W2 is the longest crown dimension perpendicular to W1. Shrub volume was calculated as the elliptical area multiplied by the measured height. Shrub biomass was calculated from regression equations using shrub volume as the independent variable, developed for the dominant shrubs; sagebrush (*Artemisia tridentata* spp. Champlin 1991), antelope bitterbrush (*Purshia tridentata*) and gray rabbitbrush (*Chrysothamnus nauseosus*). We developed the equations for bitterbrush and gray rabbit brush through destructive sampling of 20 plants of each species in previous research (Kauffman et al 2006). Biomass for green rabbitbrush (*Chrysothamnus viscidiflorus*) and gray horsebrush (*Tetradymia canescens*) was calculated using the gray rabbitbrush equation. Biomass for all other shrub species was calculated using the antelope bitterbrush equation.

2.2.4 Community Composition

At all sites we sampled vegetation composition and structure the way (transect length and spacing, etc.) that it was originally measured. Along permanent transects, we measured canopy cover of all plant species as well as litter and bare ground. Measurements were taken in 30 x 60 cm subplots at equal intervals.

2.2.4 Fire Behavior Modeling

To quantify the impact that previous fires have on potential fire behavior, we parameterized the fire behavior modeling system Fuel Characteristic Classification System (FCCS) in the Fuel and Fire Tool (FFT) using *in situ* fuels data collected on all burn and control plots. FCCS predicts surface fire behavior using ecosystem-specific fuels data and localized environmental scenarios (*i.e* fuel moisture content through the typical fire season for a region). For each site, fuelbeds were initialized using the standard fuelbed 56: Sagebrush shrubland, and then fuel parameters were modified to represent the fuels quantified *in situ*. Environmental scenarios were chosen to represent the range of fuel moisture expected as vegetation phenology progresses from the active growing season (fully green scenario;

D2L4 scenario in FFT), through partially curing stages (1/3 cured and 2/3 cured scenarios; D2L3 and D2L2, respectively), to late in the summer, when fuels are completely dry and risk of high intensity fire is greatest (fully cured scenario; D2L1). Model runs were done for each fire and control plot) across each environmental scenario. Model outputs chosen to characterize potential behavior included rate of spread (ROS; m sec^{-1}), flame length (FL; m), and reaction intensity (RI; the rate of heat released per unit area of the flaming front; kW m^{-2}).

2.2.5 Data Analysis

Mixed model analysis was used to test the differences in mean vegetation cover and fuel load by category (shrub, live herbaceous, dead herbaceous, grass litter, shrub litter), and potential fire behavior (ROS, FL, RI) between treatments (burn history or control). To test proportional fuel-loads by category, fuels by category per plot were relativized by fuel type category at the subplot level. Relativization at this level has been shown to have utility in examining shifts in composition of species or other ecological variables of concern (McCune and Grace, 2002), in this case fuel categories. Differences in means were considered significant if P values were <0.05. RStudio, version 0.98.1091 was used for all analyses.

3. Key findings

3.1 Post-fire fuel succession in Wyoming big sagebrush ecosystems

Prior to fires, overstory biomass was 3444 kg ha^{-1} and understory biomass (DWD, herbaceous fuels, and litter) was 1545 kg ha^{-1} (Wrobleski, 1999). Cover of sagebrush averaged 22% across all plots before treatments (Ellsworth et al., 2016). Within burned patches (*i.e.* excluding unburned islands), all overstory biomass and 80±8% of the understory fuels were consumed. The postfire mass was 309 kg ha^{-1} (Wrobleski, 1999). Seventeen years after fires, sagebrush mass was 438 kg ha^{-1} and understory fuels were 390 kg ha^{-1}. In unburned control plots, total fuels had increased since measurement in 1997 with overstory fuels totaling 4352 kg ha^{-1} and understory fuels accumulating to 1662 kg ha^{-1} (Figure 1). Total fuel loads were 7-fold greater in controls (6015 kg ha^{-1}) than burned plots (831kg ha^{-1}; $P<0.01$). Shrub biomass was ten times higher in control (4353 kg ha^{-1}) than burns (438 kg ha^{-1}; $P<.01$). Shrub litter was nearly 4 times greater in controls (203.7± 23.5 kg ha^{-1}) than in burns (54.0±17.7 kg ha^{-1}; $P<.01$). Total understory fuels (DWD, shrub litter, grass litter, standing dead, and live) were over four times higher in controls (1662 kg ha^{-1}) than burn plots (390 kg ha^{-1}; $P<0.01$).

In general, the 17 year sites were dominated by perennial grasses with a sparse cover of young sagebrush. Grass litter was an order of magnitude greater in burn plots (89 ha^{-1}) than in control plots (9 kg ha^{-1}; $P<0.01$). Standing dead grass biomass was three times greater in burned plots (45 kg ha^{-1}) than in controls (15 kg ha^{-1}). Live grass and herbaceous fuels in burns (20 kg ha^{-1}) were more than double that of controls (6 kg ha^{-1}; $P<0.01$), and total herbaceous fuels (live + standing dead + litter) were 5 times greater in the burned plots (154 kg ha^{-1}) compared to controls (30 kg ha^{-1}; $P<0.01$). Total shrub cover (control= 29%, burn=3%; $P=0.01$), and cover of Wyoming big sagebrush (control=21%, burn=2%; $P<0.01$) were greater in the control plots (Table 1).

When fuels were relativized by the total at the subplot level, there was a dominance of herbaceous fuels in burned plots (51%), and a dominance of woody fuels (88%; shrubs and DWD) in unburned controls. Shrub litter made up 10-12% of fuel loads, and did not differ across treatments (*P*=0.67; Table 2). Shrubs comprised 61% of total biomass in control plots and 22% in seventeen-year-old burns (*P*<0.01). Downed wood comprised nearly twice as much of the fuel load (27%) in controls than in burns (14%; *P*=0.02). In contrast, herbaceous fuels composed 51% of the fuel load but only 1.6% in controls. Proportional grass litter was over 50 times greater in the burns (29%) than controls (0.5%; P<0.01). Standing dead herb and grass fuels comprised 15% of the total fuel load compared to 0.9% in controls (*P*<0.01), and live herbs and grasses as a comprised 6.4% of the total fuel load compared to 0.2% in controls (*P*=0.01; Table 2).

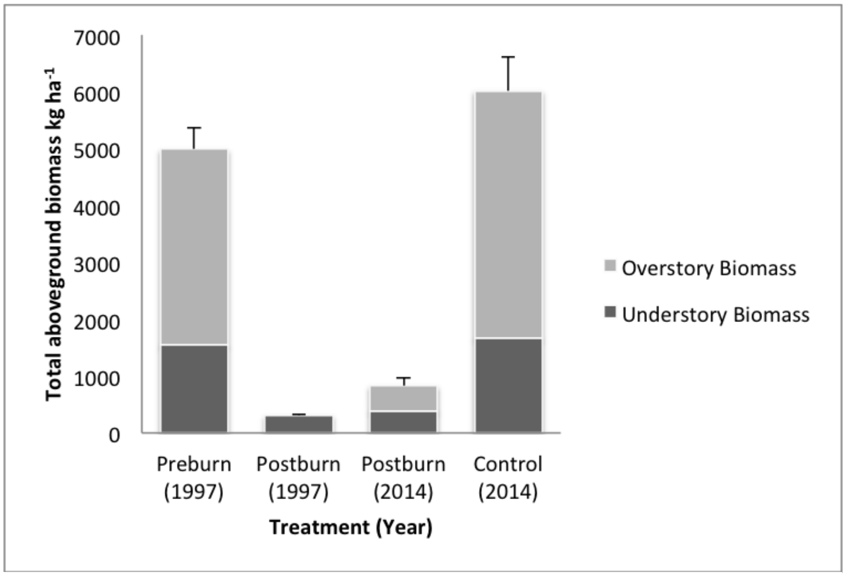

Figure 1. Total fuels (aboveground biomass; kg ha^{-1}) partitioned into overstory (light grey) and understory (dark grey) before, immediately after, and 17 years after prescribed fire at Hart Mountain National Antelope Refuge, Oregon, USA. The understory consists of downed wood, grass litter, standing dead grass, live herbaceous vegetation, and shrub litter.

Table 1. Fuel accumulation (kg ha^{-1}) by fuels category for Wyoming big sagebrush communities 17 years after prescribed fire and in adjacent unburned controls.

Fuels Category (kg ha^{-1})	Control	Burn	F-value	P-value
Downed woody debris	1428 ± 245	191 ± 67	23.74	<0.01
Shrub Litter	204 ± 24	54 ± 18	22.51	<0.01
Grass Litter	9 ± 3	89 ± 11	38.78	<0.01
Standing Dead	15 ± 1	45 ± 9	25.85	<0.01
Live	6.4 ± 1.6	20 ± 4	10.28	<0.01
Herbaceous Fuels	30 ± 5	154 ± 20	53.47	<0.01
Total Understory	1662 ± 244	390 ± 67	24.97	<0.01
Shrubs	4352 ± 646	438 ± 149	34.92	<0.01
Total	6015 ± 780	831 ± 193	41.65	<0.01
Shrub Cover (%)	29 ± 3	3 ± 1	164.33	<0.01
ARTRW Cover (%)	21 ± 2%	2 ± 1	66.75	<0.01

Table 2. Summary of fuels as a percentage of total fuels. Downed woody debris (DWD), litter accumulated under shrubs (Shrub Litter), detached grasses and herbs (Grass Litter), standing dead grasses and herbs (Standing Dead), live grasses and herbs (Live), Total Herbaceous Fuels (Grass Litter, Standing Dead, and Live); and shrub biomass as a percentage of unburned control for Wyoming big sagebrush communities at HMNAR initially burned September 1997, resampled Spring 2014.

Fuels Category	Control (% of total)	Burn (% of total)	F-value	P-value
DWD	27 ± 4	14 ± 4	5.45	0.02
Shrub Litter	11 ± 3	12 ± 3	0.18	0.67
Grass Litter	1 ± 0.2	29 ± 4	46.68	<0.01
Standing Dead	1 ±. 0.3	15 ± 2	41.13	<0.01
Live	0.2 ± 0.04	6 ± 2	18.44	<0.01
Herbaceous Fuel	2 ± .05	51 ± 6	70.12	<0.01
Total Understory	40 ± 5	78 ± 6	28.12	<0.01
Shrubs	61 ± 5	22 ± 6	28.12	<0.01

3.2 Vegetation recovery in Wyoming big sagebrush ecosystems

B. tectorum was the only annual grass present in plots, averaging 0.2% to 8%, with no significant differences across sample years (mixed model, *P*=0.56) or treatments (mixed model, *P*=0.07). A suggestion of higher *B. tectorum* cover in burn plots was largely driven by increased cover at one of the burned plots (Lek) both before and after fires (Figure 2).

Annual forb species frequently encountered were predominantly small native species, averaging 1% cover across all plots prior to fires. Fire increased annual forb cover in the first post-fire growing season to an average of 31% in burn plots, significantly higher than the 12% average cover in control plots for that year. Seventeen years after fire, cover of annual forbs averaged 2% cover across all plots, with no differences between treatments (*post hoc* multiple comparison, *P*=0.65; Figure 3a). There was a significant year effect, indicating that annual forb cover

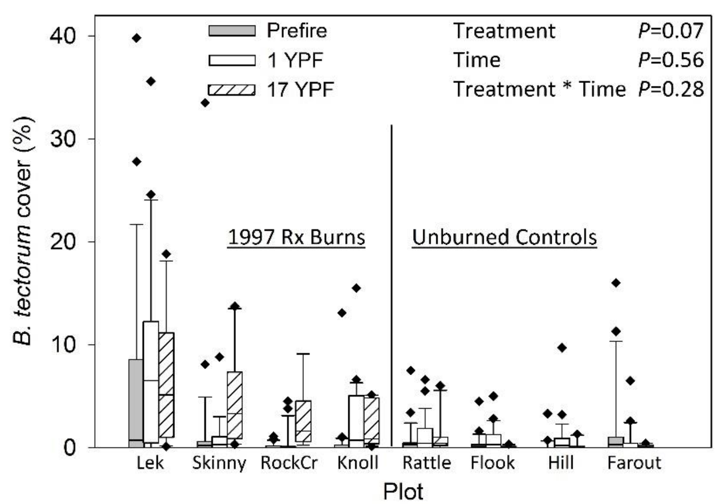

Figure 2. Mean *Bromus tectorum* cover in prescribed fire and unburned control plots prefire (gray bars), one-year post-fire (1 YPF; white bars), and 17 years post fire (17 YPF; striped bars) in Wyoming big sagebrush ecosystems at Hart Mountain National Antelope Refuge, Oregon. Boxplots show the middle 50% of the distribution of the data around a median. Error bars show the top 25% of the distribution. Diamonds are outlier data points.

across both burn and control treatments was higher 1YPF than either pre-treatment or 17YPF (mixed model, *P*<0.01), and a significant year*treatment interaction (mixed model, *P*<0.01), indicating that fire increased annual forb cover 1YPF, but this increase did not persist into the drier 17YPF period (Figure 3a).

The most frequently encountered perennial forb species included *Astragalus* species, *Crepis acuminata* and *C. modocensis*, *Eriogonum* species, and *Phlox longifolia*. There was a strong year effect (mixed model, *P*<0.01) with much lower cover 17YPF than in either pre-fire or 1YPF (Figure 3b). There was higher perennial forb cover in control plots than in burn plots, even prefire (mixed model, *P*=0.01), but no evidence of a treatment*time interaction (mixed model, *P*=0.17)

Native bunchgrasses included deep-rooted *Achnatherum hymenoides*, *Achnatherum thurberianum*, *Elymus elymoides*, *Elymus lanceolatus*, *Hesperostipa comata*, *Leymus cinereus*, and *Pseudoroegneria spicata* as well as shallow-rooted *Poa secunda.* There were no non-native perennial grasses. Total deep-rooted bunchgrass cover averaged 6% (range 4-7%) before fires. Fire reduced deep-rooted bunchgrass cover 1YPF to 4%, compared to 6% in unburned control plots (mixed model multiple comparison, *P*=0.03). Seventeen years following fires, deep-rooted bunchgrass cover in burned plots was 5% while in control plots it had decreased to 1% cover (mixed model treatment*time effect: *P*<0.01; Figure 4). *Poa secunda*, the only shallow-rooted bunchgrass species, averaged 4% cover and we saw no evidence that this species was impacted by fire treatments (mixed model treatment effect, *P*=0.59), was variable through time (mixed model year effect, *P*=0.70), or that treatments had different trajectories through time (mixed model treatment*time, *P*=0.35).

Shrub cover was dominated by *Artemisia tridentata* ssp. *wyomingensis*, with occasional occurrences of *Artemisia arbuscula*, *Ericameria nauseosa*, *Chrysothamnus*

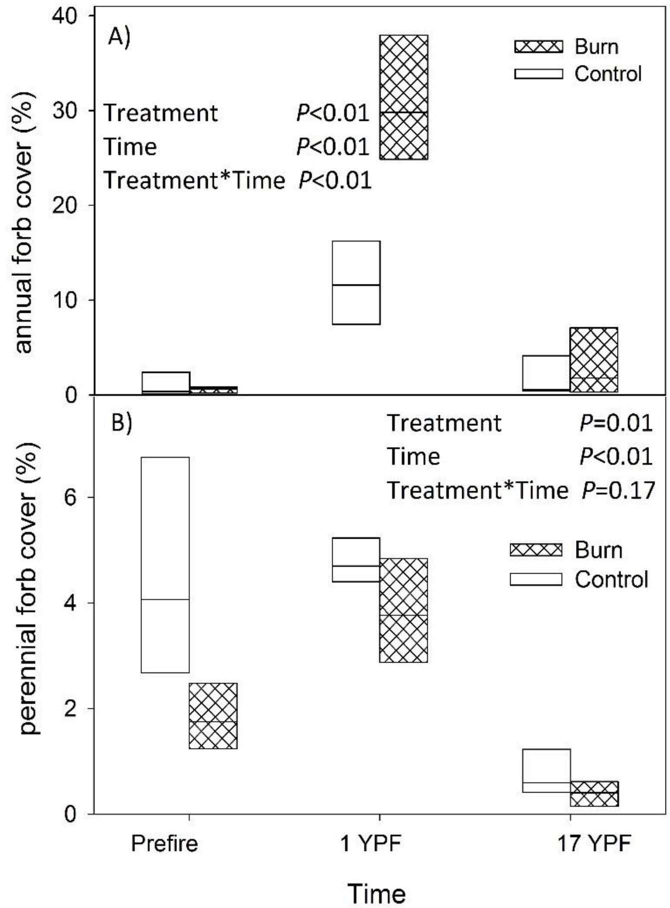

Figure 3. Annual (A) and perennial (B) forb cover in prescribed fire (striped) and unburned control plots prefire, one-year post-fire (1 YPF), and 17 years post fire (17 YPF) in Wyoming big sagebrush ecosystems.

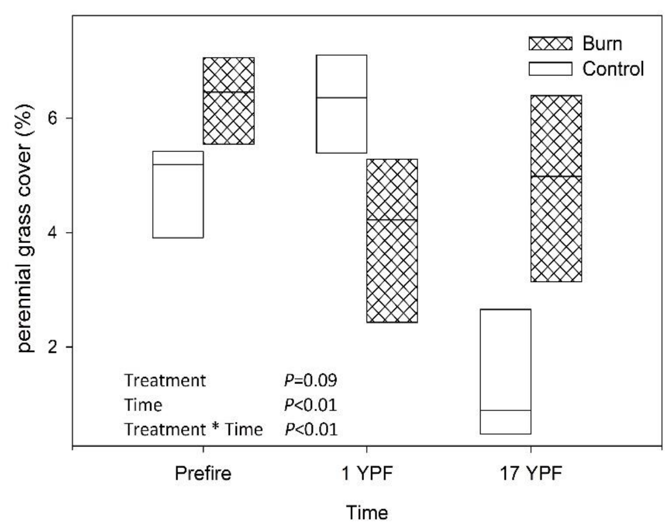

Figure 4. Deep-rooted perennial bunchgrass cover in prescribed fire (striped) and control plots prefire, one-year post-fire, and 17 years post fire in Wyoming big sagebrush ecosystems

viscidiflorus and *Tetradymia* species. Total shrub cover in all plots averaged 26% cover before prescribed fires (Figure 5). Post-fire transects were intentionally placed in areas where biomass was completely consumed, thus shrub cover following fires was <1 % in all burned plots, and 30% in unburned control plots 1YPF. 17YPF, shrub cover in burned plots averaged 2%, with 18% cover in unburned control plots. There was a significant year*treatment interaction effect (mixed model, *P*<0.01), indicating that fire treatments altered the trajectory of shrub cover through time (Figure 5).

Despite the low shrub cover in burned areas 17YPF, we saw evidence that shrubs were recolonizing burned areas. 1YPF, the mean distance between a random point within the burn perimeter (beginning of shrub transects) and the nearest reproductive age sagebrush plant was 16.6 m. By 17YPF, this distance had decreased to 2.5 m (Mann-Whitney test, *P*<0.01; Figure 6).

Bare ground before treatments averaged 27% cover (range 20-33%). Fire increased bare ground 1YPF to 83% (range 82-85) compared to 49% (range 45-53%) in controls, and by 17YPF there was more bare ground in unburned control plots (mean 65%, range 60-68%) than in burned plots (mean 54%, range 32-69%; mixed model year effect, *P*<0.01; treatment effect, *P*=0.01; year*treatment interaction, *P*<0.01). Litter cover before treatments averaged 72% (range 63-80%). Fire decreased litter cover 1YPF to 16% compared to 52% in controls, but by 17YPF there was more litter in burned plots (mean 47%) than in unburned controls (mean 35%; year effect, *P*<0.01; mixed model treatment effect, *P*<0.01; year*treatment interaction, *P*<0.01).

3.3 Reburn potential in mid-succession Wyoming big sagebrush ecosystems

Potential fire behavior was markedly less in the 17-year old burned sites than in unburned

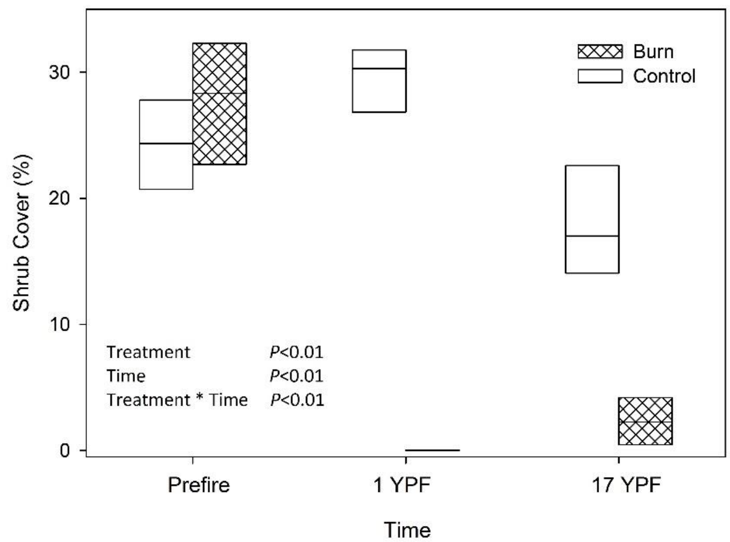

Figure 5. Shrub cover in prescribed fire (striped) and unburned control (white) plots prefire, one-year post-fire (1 YPF), and 17 years post fire (17 YPF) in Wyoming big sagebrush ecosystems at Hart Mountain National Antelope Refuge, Oregon.

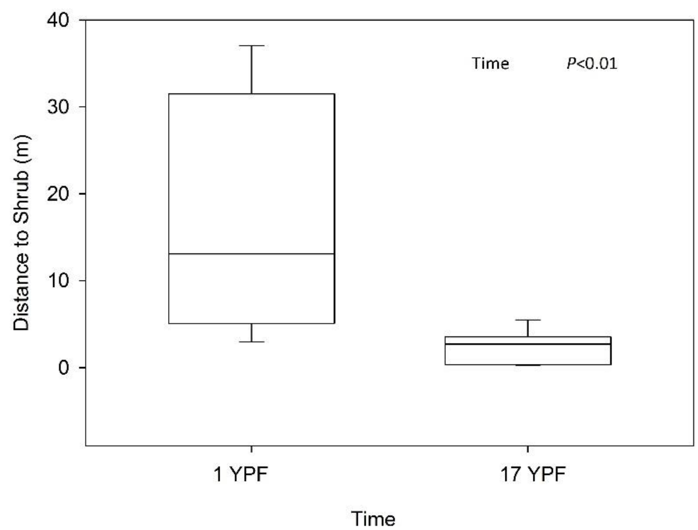

Figure 6. Distance from a random point to the nearest mature sagebrush plant one-year post-fire (1 YPF) and 17 years post fire (17 YPF) in Wyoming big sagebrush ecosystems at Hart Mountain National Antelope Refuge, Oregon. Boxplots show the middle 50% of the distribution of the data around a median. Error bars show the top and bottom 25% of the distribution.

control plots. Rate of spread in burned plots ranged from an average of 0.4 ± 0.2 m min^{-1} under a fully green environmental scenario to 1.4 ± 0.7 m min^{-1} when fuels were fully cured. Unburned control plots ranged from 1.5 ± 0.5 m min^{-1} to 5.2 ± 1.8 m min^{-1} under the same environmental conditions (Figure 7). Similarly, modeled flame lengths were reduced by prescribed fire. When fuels were fully green, flame lengths averaged 0.1 ± 0.1 m in burn plots and 0.5 ± 0.1 m in control plots. Under dry fuel conditions (fully cured environmental scenario), flame lengths reached 0.3 ± 0.2 m in burned plots and 1.0 ± 0.3 m in unburned controls. Reaction intensity averaged 27 ± 23 kW m^{-2} when fuels were green in burned plots and 171 ± 57 kW m^{-2} in control plots. When fuels were fully cured, representing the period when fire danger would be highest, reaction intensity was 311 ± 104 kW m^{-2} in unburned controls but only 54 ± 23 kW m^{-2} in burned plots (Figure 7).

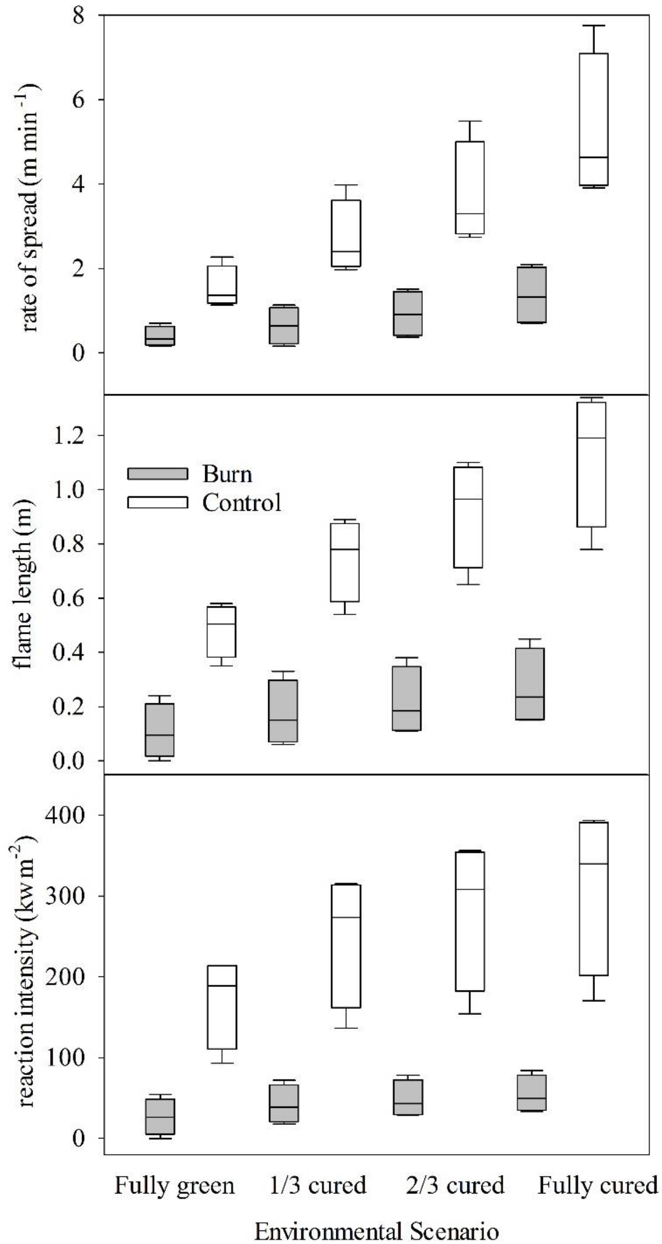

Figure 7. Rate of spread (top), flame length (center), and reaction intensity (bottom) outputs from fire behavior modeling in 17-year-old burn and adjacent unburned control plots in Wyoming big sagebrush ecosystems at Hart Mountain National Antelope Refuge, OR, USA

3.4 Impacts of reburn in basin big sagebrush ecosystems

Bear creek

Fires reduced total fuel loads by nearly 4 fold, (prefire, 28 Mg ha^{-1}; post-fire, 7 Mg ha^{-1}). Twenty-five years post fire fuels fuels recovery was highly variable, ranging from 2-69 Mg ha^{-1}. Fires reduced shrub fuel loads from 11 to 3 Mg ha^{-1} immediately post-fire, and 25YPF shrub fuel loads were double (22 Mg ha^{-1}) pre-fire levels (Figure 8). Proportional shrub fuels were lower before (40%) and immediately after (39%) fire than at 25 YPF (71%). Pre-fire sagebrush canopy cover was 30% pre-fire, declined to 5% post-fire, and by 25YPF was 77% (Figure 9). Density of sagebrush at 25YPF was 7600 ± 2017 sagebrush ha^{-1}. Mean height of mature sagebrush at 25 YPF was 1.4 ± 0.24m.

Before burns, downed wood fuel was 7 Mg ha^{-1}, was reduced post-fire to 2 Mg ha^{-1}, and after 25YPF recovered to 4 Mg ha^{-1} (Figure 8). Herbaceous fuels made up only 1-3% of total fuels for all time periods. Herbaceous fuels were reduced from 0.7 to 0.13 Mg ha^{-1} by fire, and after 25YPF were 0.2 Mg ha^{-1}. Pre-fire duff fuel loads were 9 Mg ha^{-1}, comprising 30% of fuels, and immediately post fire they declined to 2.4 Mg ha^{-1} and 32% of total fuel. By 26YP duff fuels had not recovered, measuring only 0.6 Mg ha^{-1} and making up 3% of total fuels (Figures 8-9).

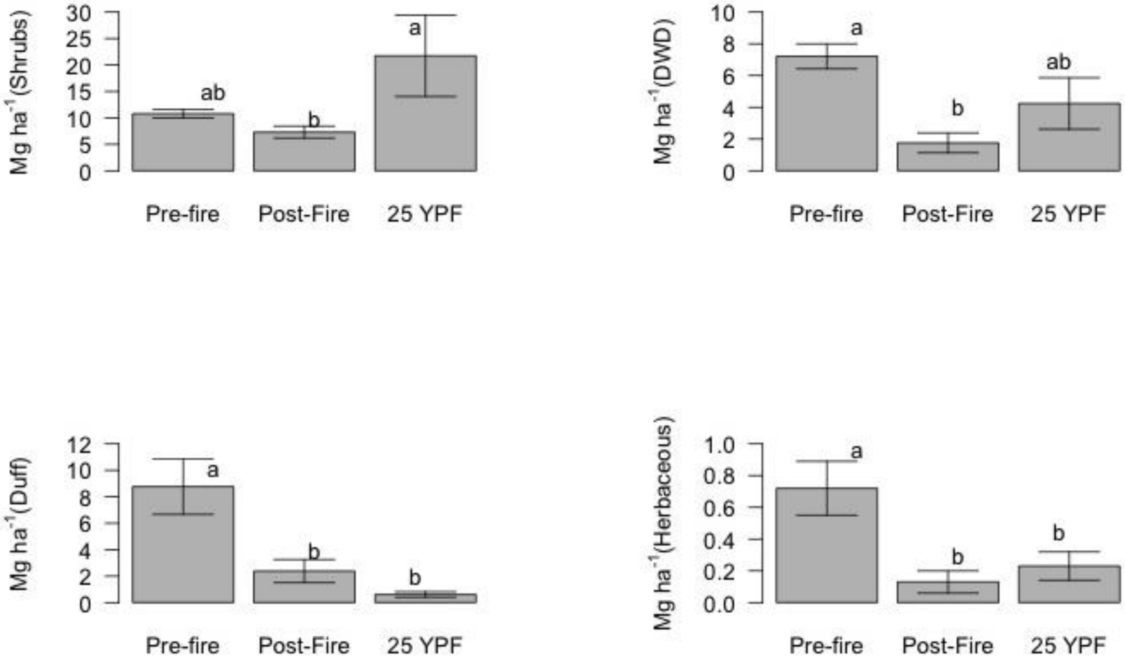

Figure 8. Fuel loads by category at Bear Creek, North-Central Oregon pre-fire, immediately post-fire, and 25 years following fires (25 YPF). Different letters signify a significant difference in fuels loads.

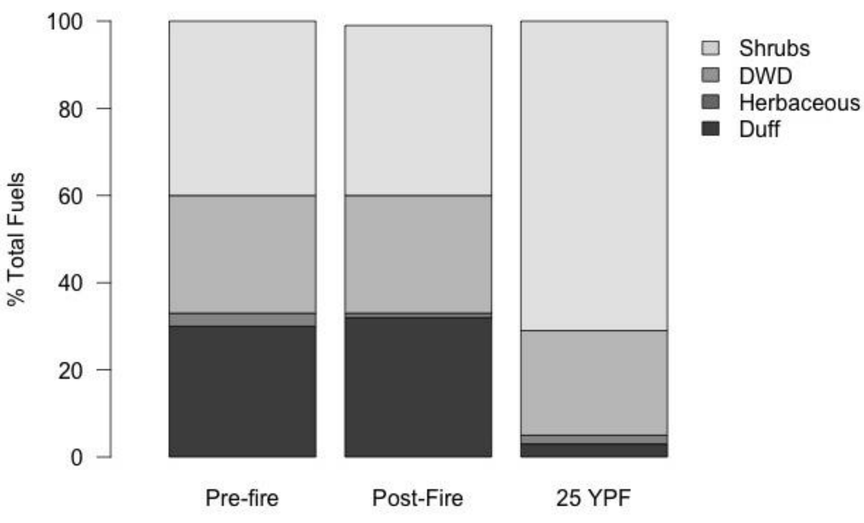

Figure 9. Relative fuel loads (Shrub, downed woody debris, herbaceous (live and dead grass and forbs) and duff (including detached shrub leaves and bryophytic material), at Bear Creek in North Central Oregon pre-fire, immediately post-fire, and twenty-five years post fire.

John Day Fossil Beds, Sheep Rock Unit
Sapsis (1990) previously reported that pre-fire fuel loads ranged from 6-11 Mg ha^{-1} and that fire consumed approximately 90% of fuels (Sapsis and Kauffman, 1991). At 26YPF, total fuel loads averaged 9.3 Mg ha^{-1}. In the 15 YPF sites, total fuel loads were 4.5 Mg ha-^{1}, and in twice-burned sites (2xB) total fuels averaged 4.6 Mg ha^{-1}. Total fuel loads did not vary significantly between 15YPF and twice burned sites, though composition was different (Figure 10). Shrub mass differed between fire histories (P<0.01), with higher shrub fuels in 26YPF plots (5.2 Mg ha^{-1}) than either in 15YPF (1.8 Mg ha^{-1}) or 2xB (0.6 Mg ha^{-1}) plots (Figure 11). Relative shrub fuel loads in all once burned sites were higher than those in 2xB plots (Figure 12). Prior to burning, sagebrush cover in the 26 YPF plots was 8% (Sapsis, 1990). In 2014 it was 18 ± 2%. In the 15YPF and 2xB plots, sagebrush canopy cover was significantly lower, at 4% and 1%, respectively. In 2014, the mean density of sagebrush in 26 YPF sites was 3028 ± 533 sagebrush ha^{-1}, significantly higher than that of either plot that burned 15 years ago (P <0.01). The mean density of sagebrush at 15YPF plots in 2014 was 1200 ± 601 sagebrush ha^{-1}, and at 2xB plots in 2014 it was 160 ± 106 sagebrush ha^{-1}. Height of mature sagebrush was not significantly different (P=0.25), at 0.76 ± 0.14m across all fire histories.

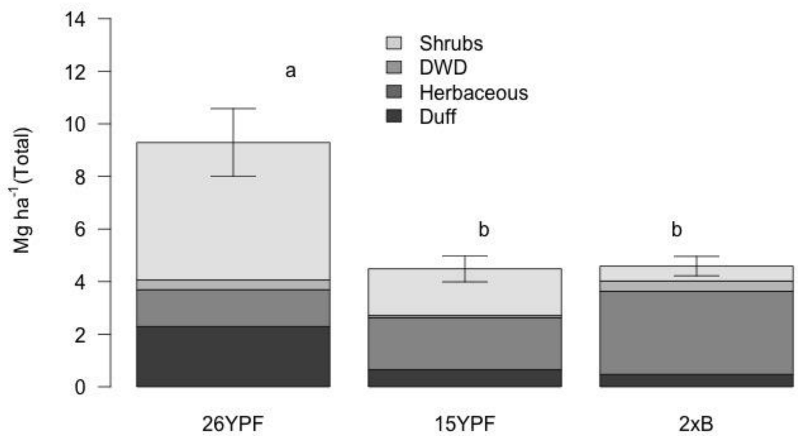

Figure 10. Fuel loads (Mg ha^{-1}) at John Day Fossil Beds, Sheep Rock unit, for plots with various fire histories: twenty-six years since fire (26 YPF, n=4), fifteen years post fire (15YPF, n=3), and twice burned (both 15 and 26 years ago; 2xB, n=5).

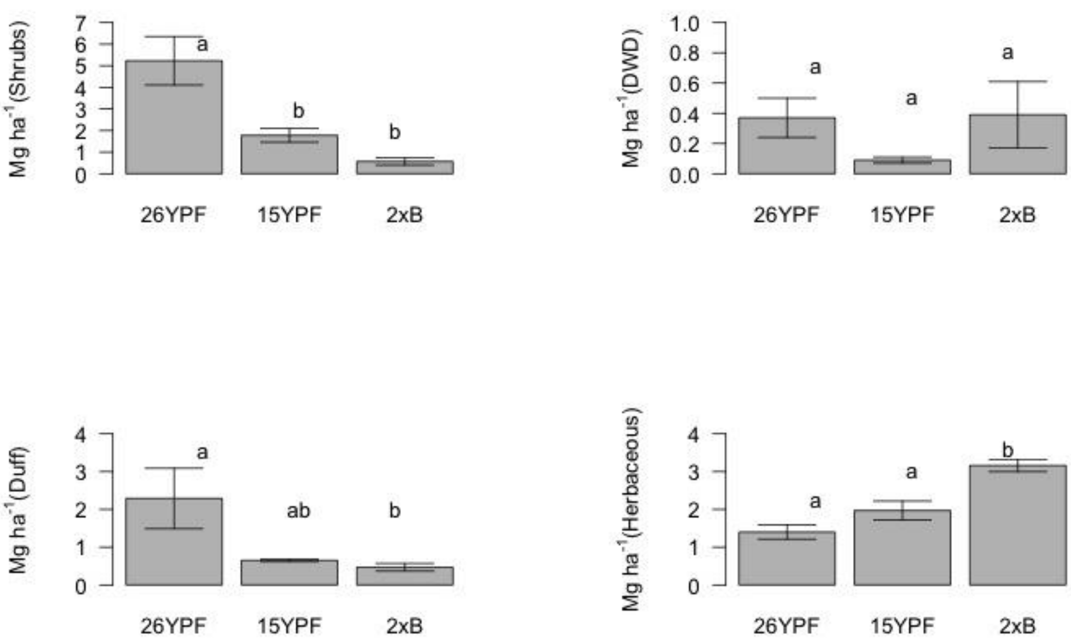

Figure 11. Fuel loads by category for all three fire histories at John Day Fossil Beds, Sheep Rock unit. Same letters over bars signifies no significant difference in fuels loads.

3.5 Fire potential in burned basin big sagebrush ecosystems

Despite changes in fuel loads due to fire history in basin big sagebrush communities at John Day Fossil Beds, few differences were seen in potential fire behavior (Figure 13). Rate of spread ranged from 2.4-10.5 m min^{-1} and was no different between once-burned plots at 26 and 15 YPF (*P*=0.74). Similarly, plots that burned once 15YPF and plots that were twice burned (2xB) had similar expected fire behavior (*P*=0.11). Twice burned plots had more rapid rates of spread across the simulated fire season than 26YPF plots due to the large amount of herbaceous fuels carrying the fire. There was only a slight increase in fire behavior with increasing simulated curing, indicating that fuels are likely to burn well throughout the fire season. Similarly, flame lengths in 2xB plots averaged 1.4 m, which was higher than the 0.9 m flame lengths in 26YPF plots (*P*=0.01), but not different from 15YPF plots (*P*=0.18), which averaged 1.1m. There was no significant increase in flame length over the range of environmental conditions (*P*=0.26). Reaction intensity did not change over the range of environmental conditions (*P*=. 28). 2xB plots had more variable and higher reaction intensity (885 ± 66 kW m^{-1}) than either 15 YPF or 26YPF plots (*P*<0.05). More recently burned 15YPF plots had marginally higher reaction intensity (652 ± 86 kW m^{-1}) than plots burned 26 previous (430 ± 74 kW m^{-1}; *P*=0.06).

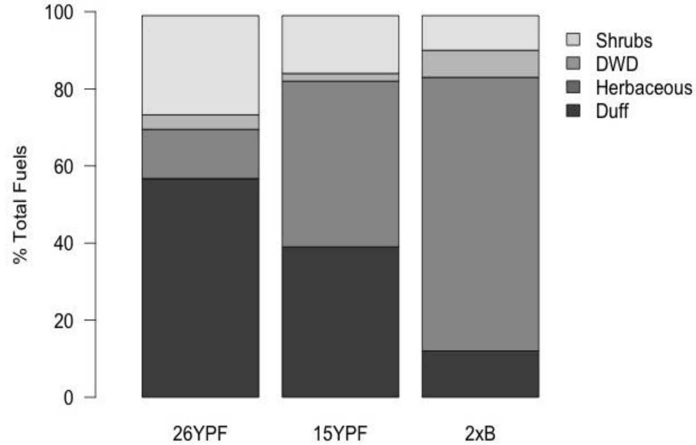

Figure 12. Relative fuel loads (shrub fuel, downed woody debris, herbaceous fuels (live and dead grass and forbs) and duff fuels, at John Day Fossil Beds, for plots with various fire histories: twenty-six years post fire (26 YPF), fifteen years post fire (15YPF), and twice burned (2xB).

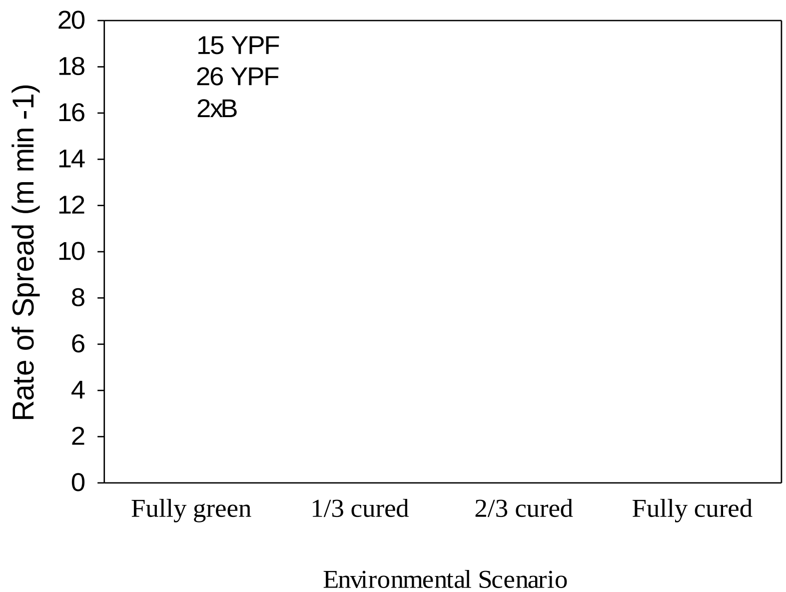

Figure 13. Rate of spread of a potential fire in previous fires that burned once at 26 and 15 years ago, and in fires that burned twice, both 15 and 26 years ago in basin big sagebrush ecosystem at John Day Fossil Beds, Oregon.

3.6 Fuel succession across three sagebrush community types: A chronosequence approach

Low Sagebrush

Total fuels in low sagebrush averaged 0.59 Mg ha^{-1} in early successional communities, 2.99 Mg ha^{-1} in mid-successional communities, and 4.32 Mg ha^{-1} in late successional communities (Figure 14). There were no shrub fuels 1 YPF, but they returned by the mid-succession period (mid-, 1.04 Mg ha^{-1}; late, 0.92 Mg ha^{-1}). There was no downed wood at 1 YPF, but this fuel component increased to 0.13 Mg ha^{-1} by mid-succession, and to 0.34 Mg ha^{-1} by late succession. Herbaceous fuels were low early after fire, at 0.45 Mg ha^{-1}, increasing to 1.40 Mg ha^{-1} in mid-succession, and decreasing again to 0.57 Mg ha^{-1} as woody fuels began to dominate again late in succession. Duff accumulated with time since fire, with fuel loads in early succession only 0.14 Mg ha^{-1}, at mid-succession reaching 0.42 Mg ha^{-1}, and late-succession = 2.49 Mg ha^{-1}. There was no low sagebrush cover just after fire (0%), and shrub cover accumulated to 9.5% by mid succession and to 29% in late succession (Figure 14)

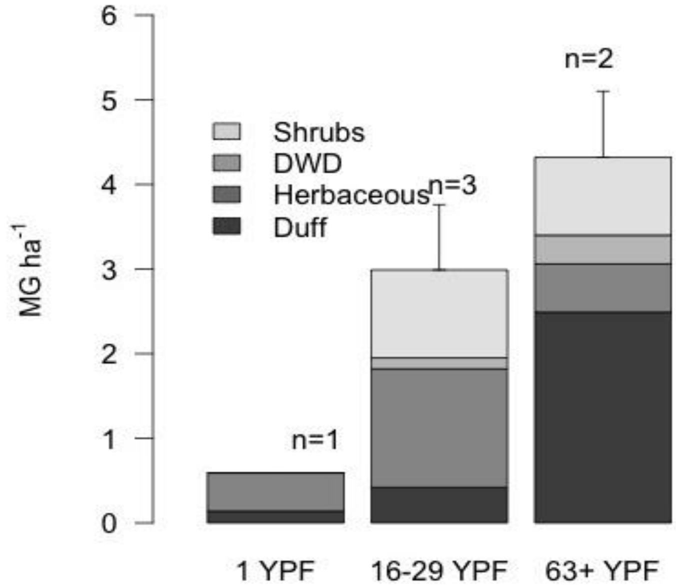

Figure 14. Hart Mountain National Antelope Refuge fuels by category (Mg ha^{-1}), stacked to show total fuels at sites in low sagebrush communities for three post fire (YPF) successional stages. Error bar shows standard error of total fuels.

Wyoming Big Sagebrush
Total fuels in areas with no fire on record (at least 62 years) were higher (5.58 Mg ha^{-1}) than total fuels in early (1.60 Mg ha^{-1}) or mid (1.05 Mg ha^{-1}) successional stages (P<0.01). Late successional stages also had more shrub fuels (4.35 Mg ha^{-1}) than mid (0.35 Mg ha^{-1}) or early (0 Mg ha^{-1}) seral stages (P<0.001). Downed wood was higher in late (0.99 Mg ha^{-1}) seral stages compared to early (0.0 Mg ha^{-1}) and mid (0.11 Mg ha^{-1}) seral stages (P=0.02). Total herbaceous fuels and duff litter did not vary significantly between seral stages P=0.45. Shrub cover was greater in late (28.9%) compared to early (0%) and mid (2.5%) seral stages (P<0.01; **Figure 15**).

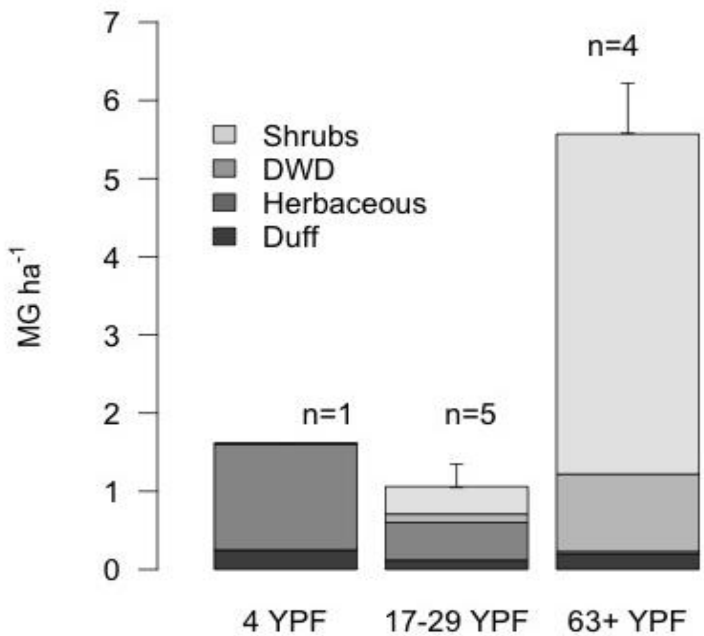

Figure 15: Hart Mountain National Antelope Refuge fuels by category type, stacked to show total fuels at sites in Wyoming big sagebrush communities for three post fire (YPF) successional stages. Error bar shows standard error of total fuels.

Mountain big sagebrush
Total fuels were highest (26 Mg ha^{-1}) in very late (62+ YPF) seral stages, but did not differ between late (12 Mg ha^{-1}), mid (9 Mg ha^{-1}) and early (1.7 Mg ha^{-1}) stages (P<0.01; Figure 16). Shrub fuels were absent from early successional stages (0.0 Mg ha^{-1}). By mid-succession they began to increase (3 Mg ha^{-1}), and reached 7 Mg ha^{-1} by late and 14 Mg ha^{-1} by very late successional stages. Downed wood was variable and did not differ significantly between successional stages (early, 0.0 Mg ha^{-1}; mid, 1.66 Mg

ha^{-1}; late, 0.25 Mg ha^{-1}; very late, 2.97 Mg ha^{-1}). Herbaceous fuels ranged from 1.4-2.9 Mg ha^{-1} and did not vary by successional stage (P=0.4). Duff litter was greater in very late (7.5 Mg ha^{-1}) seral stages than in early (0.3 Mg ha^{-1}), mid (1.1 Mg ha^{-1}) and late (2.3 Mg ha^{-1}) stages.

4 Management Implications

4.1 Post-fire resilience

Post-fire resilience in the sagebrush steppe was evident across all studied ecosystems. We saw post-fire increases in native herbaceous vegetation. While fire reduced or eliminated shrub cover in the short-term, there was a capacity for shrubs to regenerate in burned areas.

4.2 Model sagebrush ecosystems

Our results are representative of those expected for model sagebrush ecosystems, which were in good condition pre-fire and have minimal invasive species or land use change impacts. We caution that these results may not be representative of sites that are dominated by invasive grasses prior to fire, that have warmer or dryer soil conditions, or that have been degraded by overgrazing or other land uses.

4.3 Shifts from early to late succession

As expected, we saw fuel loads accumulate through time with shifts from early succession herbaceous fuels to late succession woody fuels.

4.4 Fuelbreaks in Wyoming big sagebrush

Historical fires acted as fuelbreaks, causing significant reductions in potential fire behavior in Wyoming big sagebrush communities.

4.5 Fuelbreaks in basin big sagebrush

Fires in basin big sagebrush communities did not decrease potential fire behavior, and twice burned basin big sagebrush sites had higher potential for fire spread in some cases due to persistent native herbaceous plant dominance.

4.6 Transient flush of invasive grass

The flush of invasive annual grass seen immediately post-fire was reduced to pre-fire levels within the first post-fire decade as native plants outcompeted early successional invasives.

4.7 Loss of herbaceous understory in late-succession Wyoming big sagebrush

Wyoming big sagebrush sites with dense sagebrush canopies that had no fire on record in some cases had lost the herbaceous understory. In contrast, sites that had burned 17 years prior were dominated by native bunchgrasses and were starting to be recolonized by sagebrush.

4.8 Persistent herbaceous composition after reburn

Reburn (2 fires in 26 years) in basin big sagebrush ecosystems shifted composition towards persistent native herbaceous dominance with little to no shrub recovery.

5 Relationship to other recent work and ongoing work on this topic

5.1. Miller, R. F., J. C. Chambers, D. A. Pyke, F. B. Pierson, and J. C. Williams. 2013. Fire effects on vegetation and soils in the Great Basin Region and the role of site characteristics. Fort Collins, CO: USA: Department of Agriculture, Forest Service. RMRS-GTR-308. 169 p

The current research is in direct response to the calls from this JFSP-sponsored synthesis demonstrating a need for long-term research, for research on the impacts of multiple fires, and research in understudied basin big sagebrush communities.

5.2 SageSTEP project

An ongoing long-term experiment evaluating methods of sagebrush steppe restoration in the Great Basin http://www.sagestep.org/. The SageSTEP project is currently in year 10 of an ongoing data collection effort to monitor trends in vegetation, fuels, and ecosystem recovery in prescribed fire and other restoration treatments in Wyoming big sagebrush ecosystems. The ongoing effort will fill substantial holes in knowledge about the duration of restoration treatment effectiveness and how it relates to patterns of succession and fuels recovery. Ellsworth has recently joined this project as a PI (most original PIs have/are soon retiring).

5.3 Agricultural Research Service, Eastern Oregon Agricultural Research Center, Burns, Oregon.

The ARS research team has a large body of recent and ongoing research looking at interactions between fuels, vegetation, domestic grazing, and restoration treatments such as juniper reduction and seeding alternatives.

5.4 Sage grouse initiative

A partnership of ranchers, researchers, and managers working to understand and conserve critical habitat for the greater sage-grouse. On the western portion of the sage grouse range, the dominant threats are changes in wildfire regimes and invasive species. The current research provides information on the natural role of fire and where it is appropriate to incorporate fire into management for this species of conservation concern.

6 Future work needed

6.1 Research utilizing long-term data sets

Substantial work has been done in the sagebrush steppe, but the data sets are underutilized. As a result of this study, and in particular in tracking down historical data sets, we've discovered that manager offices are a gold mine of long-term monitoring data that could be analyzed and presented. There would be substantial cost savings to investing in further using these data rather than starting from scratch and collecting from new experimental designs.

6.2 Understanding of interactions between climate change, invasive species, and altered fire regimes

The interactions between invasive species and altered fire regimes has been well-studied. Far less understood is the role that climate change will modify those relationships.

6.3 Impacts of altered fire regimes on non-target wildlife species

Much of the recent work on fire and invasives in the sagebrush steppe in recent years has been inside a context of protecting habitat for the greater sage-grouse, which use late-successional, closed-canopy sagebrush. Far less is known, however, how protections for sage grouse impact non-target wildlife species, which may use a variety of successional stages, patch types, and interact uniquely with the natural disturbance regimes of the area.

6.4 Human dimensions of rangeland ecology and management at the interface of increased fire, invasive species, climate change, and sustainable agriculture.

Values surrounding rangeland resources are often polarized as producers, managers, and the environmental community frequently disagree on the management of these lands. A greater understanding of these values is needed to elucidate areas where disparate user groups are at odds, and where they are likely to collaborate and cooperate on issues of resource management and conservation.

7 Deliverables

7.1 Deliverable crosswalk table

Proposed	Explanation	Status
We anticipate journal articles on the following topics: 1) long term shifts in fuel loads and potential for future fire, 2) long-term shifts in fuels and vegetation composition, 3) effects of repeated fires on fuel loads and potential fire behavior	[1]Long-term shifts in vegetation structure and composition – published in Ecosphere [2]Long term shifts in fuel loads and potential for future fire – in review for Ecological Applications [3]Effects of repeated fires on fuel loads and potential fire behavior – in prep for Range Ecology and Management	[1]Completed [2]In Review [3] In Preparation
Land managers will be trained on field methodology for ongoing data collection and monitoring	Trained field crews from HMNAR, University of Nevada Reno, and Oregon State University on data collection and monitoring protocols and led training on field identification of sagebrush steppe plant species	Completed:
Protocol will detail methods of data collection for ongoing monitoring at field sites	Protocol outlining methods for ongoing monitoring of study sites	Completed
Webinar – Great Basin Fire Science Delivery	In coordination with the Great Basin Science Delivery program, a webinar entitled "Mid-succession fire effects and reburn potential in model sagebrush ecosystems" was presented Friday, July 28, 2017. Available online https://www.youtube.com/watch?v=o2Mck116tas&t=8s	Completed
Undergraduate Student Training and Mentoring	7 Oregon State University undergraduate students gained job experience and learned about the sagebrush steppe as a result of participation in the project. 4 of these used this experience to gain internship credit towards their degrees	Completed

7.2 Additional Deliverables (not in project proposal)

- Graduate student supervision: S. Reis completed a M.S. thesis on objectives central to this project
- Field tour for land managers, agency personnel, and local policymakers – We were able to host a field tour, showcasing the response of sagebrush ecosystems to fire. Field sites were visited, and early data presented. Local policy-makers, NGO representatives, agency managers, and researchers were in attendance.
- Research symposium – A research symposium showcasing some early work from this project was presented at the Ecological Society of America annual meeting
- Keynote speaker – Ellsworth presented an invited talk on 20th century fire science in rangeland ecosystem at the Central Oregon Prescribed Fire Symposium in Bend, OR

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