

Long-Term Effects of Fire on Vegetation Structure and Predicted Fire Behavior in Wyoming Big Sagebrush Ecosystems

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ABSTRACT

Fire historically occurred across the sagebrush steppe, but little is known about how patterns of post-fire fuel accumulation influence future fire in Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) communities. To quantify change in fuel composition and structure in intact sagebrush ecosystems, we sampled 17 years following prescribed fire in eight approximately 400 ha plots (4 burned, 4 unburned control) at Hart Mountain National Antelope Refuge, OR, USA. Fuels data were used to model potential fire behavior in burn and control plots across four environmental scenarios that mimic drying of fuels through the fire season. Seventeen years after fire total fuel loads were 7 × higher in controls (6015 kg ha⁻¹) than burned plots (831 kg ha⁻¹; $P < 0.01$). Herbaceous fuels were 5 times greater in burns ($P < 0.01$).

Shrub fuel was nearly 10 times higher in unburned plots ($P < 0.01$), and litter under shrubs in controls was 3.75 times greater than in burns ($P < 0.01$). Potential fire behavior was lower in burned plots than in unburned controls across all environmental scenarios. In the driest scenario, potential rate of spread ranged from 0.4 to 1.5 m min⁻¹ in burns and 2.7 to 5.5 m min⁻¹ in controls ($P < 0.01$). Maintaining resilience in these ecosystems at multiple spatial and temporal scales may include a consideration of the natural role of fire in good condition Wyoming big sagebrush ecosystems. This study shows that under these conditions, fire can promote good condition mid-successional ecosystems and can act as a fuel break, slowing the spread and decreasing the intensity of a future wildfire.

Key words: *Artemisia tridentata* ssp. *wyomingensis*; FCCS; Fire behavior; Hart Mountain; Long-term fire effects; Prescribed burning; Sagebrush steppe.

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HIGHLIGHTS

- Native herbaceous fuel dominated 17 years after fire in Wyoming big sagebrush
- 17 years after fire, total fuels were 7× higher in unburned controls than in burns
- Prescribed fire reduced potential fire behavior in future wildfires

INTRODUCTION

Sagebrush steppe ecosystems are widespread across the western USA, and interacting factors including land use change, urban development, overgrazing, invasive species, and altered fire regimes currently threaten their sustainability (Crawford and others 2004; Miller and others 2011; Miller and Eddleman 2001). As a result, sagebrush-dominated ecosystems currently occupy approximately 60% (214,000 km²) of their historic range (360,000 km²) and have largely been replaced by invasive-dominated grasslands (Miller and others 2011). Big sagebrush (*Artemisia tridentata* Nuttall) is the most widespread of sagebrush species (Shultz 2009), and the Wyoming big sagebrush subspecies (*A. tridentata* ssp. *wyomingensis* [Beetle & Young]) covers the largest area of big sagebrush subspecies (Miller and Eddleman 2001; Tisdale 1994). Wyoming big sagebrush occurs at 700–2150 m elevation (Tisdale 1994), where annual precipitation is 18–30 cm (Miller and Eddleman 2001; Shultz 2009), and on soils that contain argillic, caliche, or silica layers (Miller and others 2011). Compared to other big sagebrush subspecies, this range is generally lower in elevation, lower in precipitation, and at a higher temperature range (Mahalovic and McAurthur 2004; Miller and Eddleman 2001; Shultz 2009; Tisdale 1994). Because of this, Wyoming big sagebrush communities have lower inherent resiliency following disturbances (Chambers and others 2014), a slower rate of succession following fire (Baker 2011), and longer reported historic fire return intervals (50–100 years or more; Baker 2006; Baker 2011; Baker 2013; Miller and Heyerdahl 2008; Miller and others 2011; Miller and Rose 1999; Wright and Bailey 1982).

Exotic annual grasses often disrupt fire regimes of Wyoming big sagebrush communities, as they can affect frequency, intensity, extent, type, and seasonality of fire (Brooks and others 2004). In 2015, it was estimated that 18% of the Northern Great Basin had negligible cheatgrass cover, 50% had less than 10% cheatgrass cover, 23% had 11–25% cover, and 10% of

the area had greater than 25% cover (Boyte and Wylie 2015). Higher densities of cheatgrass and areas of recent expansion tend to follow land use change, with increased cheatgrass near cultivation, roads, and powerlines (Bradley and Mustard 2006). The fine fuels contributed by annual grasses such as cheatgrass (*Bromus tectorum* L.) and Medusahead rye (*Taeniatherum caput-medusae* L.) promote fire by increasing horizontal fuel continuity and creating a fuel-packing ratio that facilitates ignition and fire spread (Brooks and others 2004; Davies and Svejcar 2008). This alteration of fuels often results in a positive feedback loop between fire and invasion (Brooks and others 2004; Chambers and others 2014). As a result, fire can occur as frequently as less than 10 years between fire events (Miller and others 2013; Miller and Eddleman 2001; Westoby and others 1989; Whisenant 1990). In contrast, sagebrush steppe ecosystems in good ecological condition (that is, with a low abundance of exotic grasses) benefit from maintenance of the natural fire regime, and there are negative impacts of fire exclusion, such as loss of herbaceous understory cover, overly dense sagebrush cover, and juniper expansion (Ellsworth and others 2016).

Our objective was to describe long-term shifts in fuel composition and structure with time since fire in relatively intact, mid-successional Wyoming big sagebrush communities, and to quantify how those patterns of fuels accumulation impact potential future fire behavior. To do this we (1) quantified fuel accumulation in prescribed burns and adjacent, unburned control plots (> 50 years since fire) 17 years after ignition, and (2) used in situ fuels data to model potential fire behavior (flame length, rate of spread, reaction intensity) in 17-year-old burn and control plots. We hypothesized that (1) total fuel loads would be greater in unburned plots than in those burned 17 years prior; (2) shrub and woody fuels would dominate vegetation structure in the control plots, and herbaceous fuels would dominate in burn plots; (3) non-herbaceous litter and other plant litter that accumulated underneath shrub crown area would be one of the largest fuel components in both control and burned plots; (4) plots that burned 17 years prior would have lower potential fire behavior than unburned plots; and (5) intensity of potential fire behavior would increase in all plots with increased levels of simulated fine fuel curing.

MATERIALS AND METHODS

Study Area

This study was conducted at Hart Mountain National Antelope Refuge (HMNAR), located 105 km

northeast of Lakeview, OR, in Lake County, USA, (42°25'N' 119°40'W). Elevation at the refuge ranges from 1340 m in Warner Valley to 2460 m on Warner Peak (USFWS 1994), but most of the refuge is 1800–2000 m in elevation. Annual precipitation falls mostly as snow and varies based on elevation, from 15 to 20 cm along the western escarpment to 30–45 cm on the mountain. On average, the majority of HMNAR receives fewer than 50 frost-free days per year (USFWS 1994). HMNAR encompasses approximately 120,000 ha in area. Cattle grazing was discontinued on the site beginning in 1991, and all animals were removed by 1994. Feral horses (estimated 200–300 animals) were removed from the refuge in 1999, but trespass animals (reaching ~ 250 individuals) were documented on the refuge from 2005 to 2012 before complete removal.

Experimental Design

Eight adjacent plots were randomly assigned to either prescribed fire (Lek, Skinny, Rock Creek, and Knoll) or unburned control (Rattlesnake, Flook, Hill, Farout; no fire on record, ≥ 50 years) treatments ($N = 4$ for each treatment) in 1997 (Figure 1). All plots were located in the northeastern portion of HMNAR with elevations ranging from 1550 to 1615 m, with flat topography. Each burn unit was approximately 400 ha in area. Soils at all eight plots were frigid cobbly clay loams of the Ratto–Coglin series, indicating increased potential post-fire resilience and resistance to invasion as compared to soils with mesic soil temperature regimes (Chambers and others 2014). Prior to treatment, vegetation was late-succession Wyoming big sagebrush co-dominated by bottlebrush squirreltail (*Elymus elymoides* (Raf.) Swezey) and Sandberg bluegrass (*Poa sandbergii* Presl), with each having 4–5% cover prior to fires (Wroblewski 1999). Less than 2% cheatgrass (*Bromus tectorum* L.) cover was measured prior to treatment (Wroblewski and Kauffman 2003).

Ignition

Prescribed burn plots were ignited by heli-torch using a ring-fire ignition pattern between 23 and 27 September, 1997. On average, 47% of the area within the plots was burned. Within the burned areas, all sagebrush biomass and approximately 80% of the understory biomass was consumed (Wroblewski 1999). Understory fuel moisture for dead herbaceous vegetation ranged from 4.4 to 6.5%, and moisture of 10-h wood fuels was 5.5–8.0%. Flame lengths were 2.0–4.4 m, rate of spread

ranged from 4.6 to 12.0 m min⁻¹, and residence time was 0.6–2.6 min. Wind speed during the burns ranged from 6.4 to 9.7 km h⁻¹ (Wroblewski 1999).

Field Measurements

In this paper we define fuels as the total above-ground biomass of the sagebrush sites. Fuels were separated on the basis of ecological and fire behavior parameters. The fuel biomass was measured on burned and unburned sites in June and July of 2014 in order to determine total fuel accumulation (total aboveground biomass) 17 years following fire. Fuels were divided into overstory (all living shrubs and dead shrubs still attached to the ground surface) and understory. Understory fuels were subdivided and quantified in the following categories: live herbaceous plant material (hereafter, live), standing dead herbaceous plant material (standing dead), detached graminoid and herbaceous plant material (grass litter), detached shrub leaves, organic duff and bryophytic materials (shrub litter), and downed woody debris (DWD). Within each plot, ten 20 m permanent transects were established in 1997 and were relocated in this study.

Prior to ignition in September, 1997, overstory fuels were collected in the burn plots, and all methods were replicated in 2014. The line intercept method was used to determine shrub cover in each plot (Canfield 1941). Length and height of all living and dead shrubs that crossed transects were recorded by species. Canopy gaps less than 20 cm were included in measurements. Overstory shrub biomass was calculated using the Wyoming big sagebrush specific equation from Champlin (1982):

$$\begin{aligned} \text{Total overstory biomass (kg ha}^{-1}\text{)} \\ = -2419.043 + 93.548(L) + 62.537(H) \end{aligned}$$

where (L) = the line intercept canopy cover in cm of sagebrush and (H) = the height in cm. Dead shrubs were multiplied by 0.25 to determine biomass as described by Champlin (1982).

Prior to ignition and 1 YPF (years post-fire), understory fuels were measured by clipping to bare mineral soil in 25 20 × 50 cm quadrats randomly located in each treatment and control plot. In 2014, along each transect ($n = 10$ per plot) three 20 × 50 cm (0.1 m²) quadrats were established at meter marker 6, 12, and 18. Vegetation in each quadrat was clipped to mineral soil, and all burnable material was sorted in the field into the following fuels categories: live, grass litter, shrub litter, and DWD. These samples were transported to

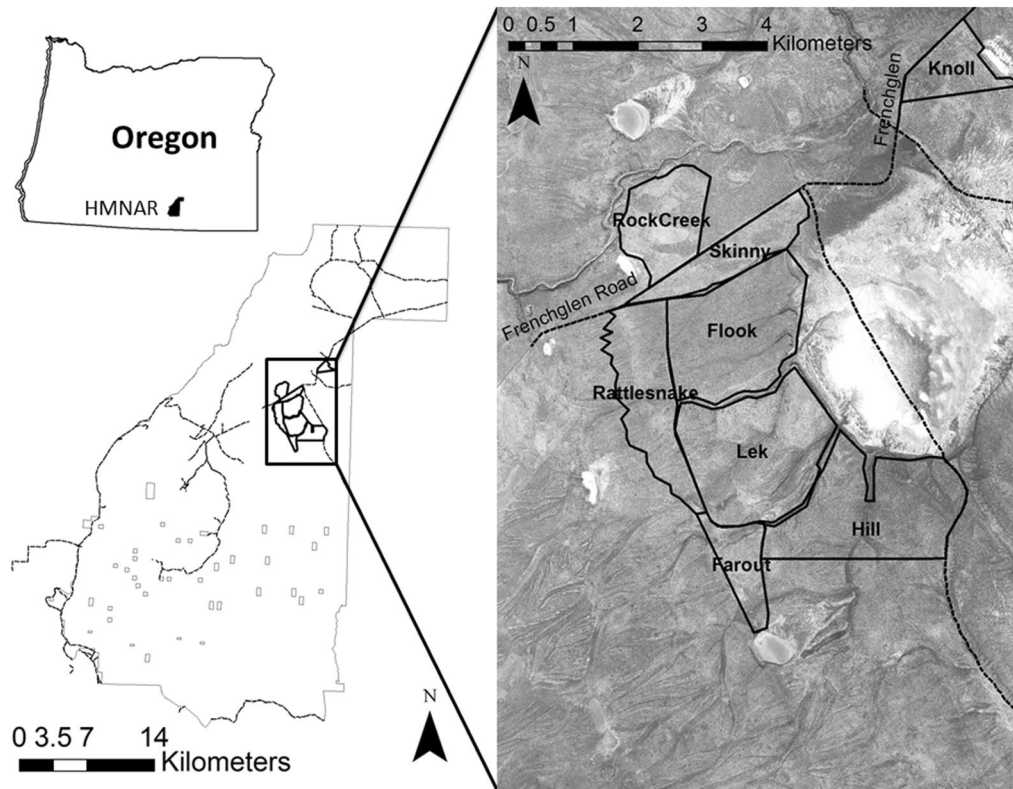


Figure 1. Wyoming big sagebrush fire (Lek, Skinny, Rock Creek, and Knoll) and control (no fire in the 50-year fire record: Rattlesnake, Flook, Hill, and Farout) plots at Hart Mountain National Antelope Refuge, South-central Oregon, USA.

Oregon State University and dried in ovens at 70 °C for 48 h and weighed. Downed wood mass was determined using the planar intersect method described in Brown (1974).

Fire Behavior Modeling

To quantify the impact that previous prescribed fires have on potential fire behavior 17 years after fire, we parameterized the fire behavior modeling system fuel characteristic classification system (FCCS) model 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 (that is, 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 (Supplemental Table 1). 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). Independent model runs were done for each fire and control plot ($N = 4$ per treatment) at 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}).

Data Analysis

Analysis of variance (ANOVA) was used to test the differences in mean shrub cover and fuel loads by category (shrub, live herbaceous, dead herbaceous, grass litter, shrub litter), and potential fire behavior (ROS, FL, RI) between treatments (burned or control). To examine the proportion that each category of fuels contributes to the total fuel load, the mass of each fuel type was divided by the total fuel at the subplot level. Relativization at this level has been shown to have utility in examining shifts in composition of species or other ecological vari-

ables of concern (McCune and others 2002), in this case fuel-type categories. Differences in means were considered significant if P values were < 0.05 . Means are reported with standard errors (mean \pm SE). RStudio, version 0.98.1091 was used for analyses.

RESULTS

Fuel Succession

Prior to fires, overstory biomass was 3444 kg ha^{-1} and understory biomass (DWD, herbaceous fuels, and litter) was 1545 kg ha^{-1} (Wroblewski 1999). Cover of sagebrush averaged 22% across all plots before treatments (Wroblewski 1999). Within burned patches (that is, excluding unburned islands), all overstory biomass and 80 \pm 8% of the understory fuels were consumed. The post-fire mass was 309 kg ha^{-1} (Wroblewski 1999). Seventeen years after fires, sagebrush mass was $438 \pm 149 \text{ kg ha}^{-1}$ and understory fuels were $390 \pm 67 \text{ kg ha}^{-1}$. In unburned control plots, total fuels had increased since measurement in 1997 with overstory fuels totaling $4352 \pm 646 \text{ kg ha}^{-1}$ and understory fuels accumulating to $1662 \pm 244 \text{ kg ha}^{-1}$ (Figure 2). Total fuel loads were sevenfold greater in controls ($6015 \pm 780 \text{ kg ha}^{-1}$) than burned plots ($831 \pm 193 \text{ kg ha}^{-1}$; $P < 0.01$). Shrub biomass was ten times higher in controls ($4353 \pm 646 \text{ kg ha}^{-1}$) than in burns ($438 \pm 149 \text{ kg ha}^{-1}$; $P < 0.01$). DWD in controls was 7.5 times higher ($1428 \pm 245 \text{ kg ha}^{-1}$) than in burns ($191 \pm 67 \text{ kg ha}^{-1}$; $P < 0.01$). Shrub litter was nearly 4 times greater in controls ($203.7 \pm 23.5 \text{ kg ha}^{-1}$) than in burns ($54.0 \pm 17.7 \text{ kg ha}^{-1}$; $P < 0.01$). Total under-

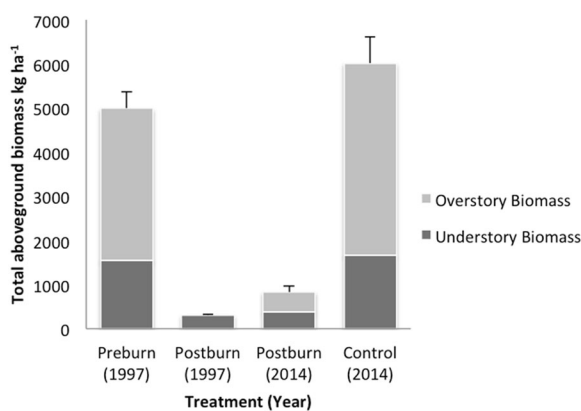


Figure 2. Total fuels (aboveground biomass; kg ha^{-1}) partitioned into overstory (light gray) and understory (dark gray) before, immediately after, and 17 years after prescribed fire at Hart Mountain National Antelope Refuge, Oregon, USA. The understory consists of downed wood, grass litter, standing dead grass, live herbaceous vegetation, and shrub litter.

story fuels (DWD, shrub litter, grass litter, standing dead, and live) were over four times greater in controls ($1662 \pm 244 \text{ kg ha}^{-1}$) than burn plots ($390 \pm 67 \text{ kg ha}^{-1}$; $P < 0.01$).

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 ($89 \pm 11 \text{ kg ha}^{-1}$) than in control plots ($9 \pm 3 \text{ kg ha}^{-1}$; $P < 0.01$). Standing dead biomass was three times greater in burned plots ($45 \pm 9 \text{ kg ha}^{-1}$) than in controls ($15 \pm 0.5 \text{ kg ha}^{-1}$). Live grass and herbaceous fuels in burns ($20 \pm 4 \text{ kg ha}^{-1}$) were more than double that of controls ($6 \pm 1.6 \text{ kg ha}^{-1}$; $P < 0.01$), and total herbaceous fuels (live + standing dead + litter) were 5 times greater in the burned plots ($154 \pm 20 \text{ kg ha}^{-1}$) compared to controls ($30 \pm 5 \text{ kg ha}^{-1}$; $P < 0.01$). 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).

Relative Fuel Composition

When fuels were relativized by the total at the subplot level, there was a dominance of herbaceous fuels in burned plots (51% of total fuel load) and a dominance of woody fuels (88%; shrubs and DWD) in unburned controls. Proportional shrub litter made up 10–12% of fuel loads and did not differ across treatments ($P = 0.67$; Table 2). Shrubs comprised 61 \pm 5% of total biomass in control plots and 22 \pm 6% in 17-year-old burns ($P < 0.01$). Downed wood comprised nearly twice as much of the fuel load (27 \pm 4%) in controls than in burns (14 \pm 4%; $P = 0.02$). In contrast, herbaceous fuels composed 51 \pm 6% of the fuel load but only 1.6 \pm 0.05% in controls. Proportional grass litter was over 50 times greater in the burns (29 \pm 4%) than controls (0.5 \pm 0.2%; $P < 0.01$). Standing dead herb and grass fuels comprised 15 \pm 2% of the total fuel load compared to 0.9 \pm 0.3% in controls ($P < 0.01$), and live herbs and grasses as a comprised 6.4 \pm 1.5% of the total fuel load compared to 0.2 \pm 0.04% in controls ($P = 0.01$; Table 2).

Potential Fire Behavior

The potential fire behavior was markedly less in the 17-year-old burned sites than in unburned control plots. Rate of spread in burned plots ranged from an average of $0.4 \pm 0.2 \text{ m min}^{-1}$ under a fully green environmental scenario to $1.4 \pm 0.7 \text{ m min}^{-1}$ when fuels were fully cured. Unburned control plots ranged from 1.5 ± 0.5 to $5.2 \pm 1.8 \text{ m min}^{-1}$ under the same environmental conditions (Figure 3; Table 3). Similarly, modeled flame lengths

Table 1. Fuel Accumulation (kg ha⁻¹) by Fuels Category for Wyoming Big Sagebrush Communities at Hart Mountain National Antelope Refuge 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 in Burned and Adjacent Unburned Controls

Fuels category	Control (% of total)	Burn (% of total)	F value	P value
DWD	27 ± 4	14 ± 4	5.5	0.02
Shrub litter	11 ± 3	12 ± 3	0.2	0.67
Grass litter	1 ± 0.2	29 ± 4	46.7	< 0.01
Standing dead	1 ± 0.3	15 ± 2	41.1	< 0.01
Live	0.2 ± 0.04	6 ± 2	18.4	< 0.01
Herbaceous fuel	2 ± 0.05	51 ± 6	70.1	< 0.01
Total understory	40 ± 5	78 ± 6	28.1	< 0.01
Shrubs	61 ± 5	22 ± 6	28.1	< 0.01

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 combined), and shrub biomass as a percentage of unburned control for Wyoming big sagebrush communities at HMNAR initially burned September 1997, resampled Spring 2014.

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 3; Table 3).

DISCUSSION

Fire in a Wyoming big sagebrush ecosystem in relatively good ecological condition served to reduce woody fuel loads, reducing the potential for high intensity fire behavior for the first decades

following fire. In part, this is due to the low invasive grass cover, which ranged from 0.2 to 8.4% 17 years post-fire (Ellsworth and others 2016) and the increased resistance to invasion often seen in Wyoming big sagebrush communities on frigid soils (Chambers and others 2014). Across many Wyoming big sagebrush communities, however, post-fire shifts to dominance by invasive grass have been documented (Brooks and others 2004; Miller and others 2013), perpetuating negative feedbacks between invasion and fire (D'Antonio and Vitousek 1992). In a long-term study of Wyoming big sagebrush communities at the John Day Fossil Beds, OR, Reed-Dustin (2015) found that cheatgrass cover 15 years post-fire was still 69%, likely indicating a system that has been converted to annual dominance. In some cases, however, even when cheatgrass is a dominant component of the fuel load post-fire, in the absence of repeated fires it may lose dominance with time as perennial plants recover (Mata-González and others 2007; Morris

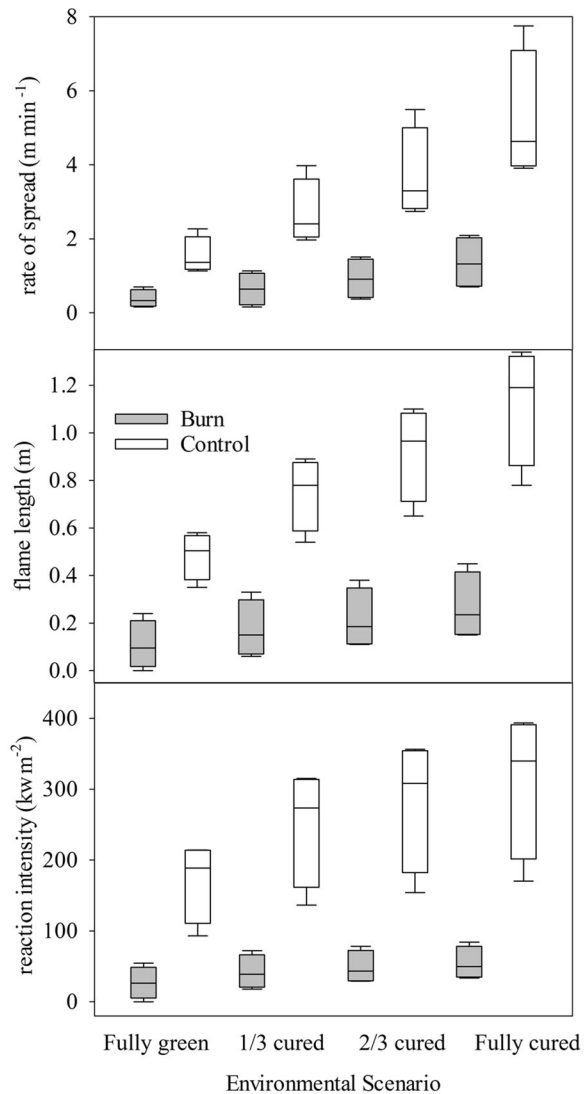


Figure 3. Rate of spread (top), flame length (center), and reaction intensity (bottom) outputs from fire behavior modeling in 17-year-old burn and adjacent unburned control plots in Wyoming big sagebrush ecosystems at Hart Mountain National Antelope Refuge, OR, USA.

and Leger 2016). This emphasizes that post-fire recovery Wyoming big sagebrush is highly variable by site (Wambolt and others 2001) and is highly dependent on soil temperature and moisture regimes, precipitation, aspect, and pre-fire condition, among other factors (Chambers and others 2014; Murphy and others 2013).

As hypothesized, total fuel loads 17 years after fire remained higher in unburned controls by almost an order of magnitude than in burn plots, primarily because woody fuels were much greater in control than in the burned plots. This is consis-

tent with the slow rates of shrub recovery observed in these ecosystems, even in sites in good ecological condition (Ellsworth and others 2016). Native herbaceous fuels still dominated the fuel composition of the burned plots and remained far higher than the unburned controls (Table 2). Woody fuels (shrubs and downed wood) were nearly ten times more abundant in the control plots compared to the burned plots, but shrubs were recovering 17 YPF.

Within burned plots, there was high variability in shrub recovery, as only 12 of the 40 burned sub-plots had any shrubs at all, demonstrating the patchy nature of succession in burned sagebrush. Shrubs establish from seed sources from outside of the burned perimeter, from unburned islands (Miller and others 2013), or from within the burn area when weather conditions are favorable (Ziegenhagen and Miller 2009). Shrub litter was an important component of the biomass in both control and burn plots. These fuels are largely consumed via smoldering combustion, and cause prolonged heating, potentially altering soil properties, and can damage perennial bunchgrasses, and kill seeds dormant in the soil seedbank (Rein and others 2008), thus modifying post-fire succession. Due to the continued reductions in fuels with time since fire in treatment plots relative to control plots, we saw lower potential fire intensity across all environmental scenarios in burned plots than in controls. This shows that in good condition sagebrush steppe, historical fires that are not dominated by invasive grasses can serve as fuel breaks to slow the spread of wildfire across the range of fuel moisture conditions experienced throughout the summer fire season. We caution, however, that under extreme weather conditions (that is, high windspeeds, red flag warning conditions, steep topography) that rapid fire spread would still be expected.

If future climate scenarios lead to a warmer climate and drought-like conditions as predicted (Cook and others 2015), the ranges of sagebrush communities may shift upward in elevation with communities currently dominated by mountain big sagebrush (*Artemisia tridentata* spp. *vaseyana* (Rydb.) Beetle) shifting to dominance by Wyoming big sagebrush, and current Wyoming big sagebrush communities shifting into desert shrub communities (Chambers and others 2014; Creutzburg and others 2015). These shifts are also predicted to be punctuated after years where large areas of the landscape burn (Creutzburg and others 2015). Therefore, it is of particular importance to understand patterns of recovery and post-fire fuels

Table 3. Analysis of Variance Results Comparing Fire Behavior Model Outputs (Rate of Spread, Flame Length, and Reaction Intensity) in Treatment (Burn or Control) and Environmental Scenarios (Fully Green, 33.3% Cured, 66.6% Cured, and Fully Cured) in 17-Year-Old Burn and Control Plots at Hart Mountain National Antelope Refuge, South-central OR, USA

Factor	df	Mean square	F	P value
Rate of spread				
Intercept	1	135.47	130.23	< 0.001
Treatment	1	48.51	46.64	< 0.001
Environmental scenario	3	7.90	7.59	< 0.001
Error	27	1.04		
Flame length				
Intercept	1	8.16	263.72	< 0.001
Treatment	1	3.16	102.20	< 0.001
Environmental scenario	3	0.23	7.42	< 0.001
Error	27	0.03		
Reaction intensity				
Intercept	1	701,490.51	172.44	< 0.001
Treatment	1	354267.32	87.09	< 0.001
Environmental scenario	3	10,386.23	2.55	0.08
Error	27	4067.98		

accumulation, not only in Wyoming big sagebrush communities, but in adjacent sagebrush communities as well, and future post-fire management actions like re-seeding should anticipate these predicted shifts.

Maintaining or increasing resilience in these threatened and important ecosystems at multiple spatial and temporal scales may include a consideration of the natural role of fire in good condition Wyoming big sagebrush ecosystems. This study shows that under these conditions, fire can promote good condition early and mid-successional ecosystems that are integral to wildlife species of concern (Ellsworth and others 2016) and can act as a fuel break, slowing the spread and decreasing the intensity of a future wildfire. Management actions that increase the heterogeneity and diversity of successional stages and fuel loads across the landscape should be considered to promote long-term resistance to large fires and promote a mosaic of mid- and late-succession sagebrush as well as patches of intact early seral herbaceous communities.

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