Effects of Fuel Reduction Treatments on Surface Fire Behavior in Juniper Woodland Ecosystems

by

Claire L. Williams

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Environmental Sciences
(Honors Scholar)

Presented March 5, 2021
Commencement June 2021

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Abstract approved:____

Lisa M. Ellsworth

Juniper (*Juniperus* spp.) woodlands are native but expanding ecological communities that were historically limited by the natural fire return interval of the sagebrush (*Artemisia* spp.) steppe. These woodlands are often a mix of pinyon pine (*Pinus* spp.) and juniper that have increased significantly over the last century. This expansion has lengthened the fire return intervals and has resulted in a decrease in understory vegetation, leading to a shift in fuel sources from the surface to the crowns of the trees. This is a concern for sagebrush conservation and the conservation of sagebrush-associated wildlife species. Fuel reduction treatments are being performed throughout the Great Basin in an attempt to limit the expansion of juniper woodlands and potentially reduce fire risk. The treatments focused on in this study are prescribed fire, mechanical (cut and drop of the trees), and untreated control. I used existing field data from a 10 year experiment paired with the Fuel and Fire Tools fire behavior modeling program to determine how treatments impacted potential surface fire behavior in juniper woodlands. Treatments shifted post-treatment surface fuel loads towards increased herbaceous and shrub cover when compared to the pre-treatment data. Prescribed fire and mechanical treatment both significantly impacted modeled fire behavior metrics: rate of spread (ROS; m/min), reaction intensity (RI; kW m^{-2} min^{-1}), and flame length (FL; m). Prescribed fire increased the rate of spread by 25 fold, tripled the flame length, and increased reaction intensity by 30.5% in fully cured plots from year 0 (pre-treatment) to year 10 following treatment. Rate of spread increased by 15 fold, flame length by 3.8 fold, and reaction intensity roughly doubled in fully cured mechanical treatment plots in year 10 compared to pretreatment and to control. This has important management implications - prescribed fire and mechanical treatments in juniper woodlands are likely to both increase herbaceous vegetation as well as increase fire behavior, indicating potential tradeoffs between desired vegetation and wildfire risk.

Key Words: Pinyon-juniper woodlands, prescribed fire, fuel treatments, woodland expansion, sagebrush restoration, rangeland management

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

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Abstract

Juniper (*Juniperus* spp.) woodlands are native but expanding ecological communities that were historically limited by the natural fire return interval of the sagebrush (*Artemisia* spp.) steppe. These woodlands are often a mix of pinyon pine (*Pinus* spp.) and juniper that have increased significantly over the last century. This expansion has lengthened the fire return intervals and has resulted in a decrease in understory vegetation, leading to a shift in fuel sources from the surface to the crowns of the trees. This is a concern for sagebrush conservation and the conservation of sagebrush-associated wildlife species. Fuel reduction treatments are being performed throughout the Great Basin in an attempt to limit the expansion of juniper woodlands and potentially reduce fire risk. Treatments focused on in this study are prescribed fire, mechanical (cut and drop of the trees), and untreated control. I used existing field data from a 10 year experiment paired with the Fuel and Fire Tools fire behavior modeling program to determine how treatments impacted potential surface fire behavior in juniper woodlands. The treatments shifted post-treatment surface fuel loads towards increased herbaceous and shrub cover when compared to the pre-treatment data. Prescribed fire and mechanical treatment both significantly impacted modeled fire behavior metrics: Rate of spread (ROS; m/min), reaction intensity (RI; kW m^{-2} min^{-1}), and flame length (FL; m). Prescribed fire increased the rate of spread by 25 fold, tripled the flame length, and increased reaction intensity by 30.5% in fully cured plots from year 0 (pre-treatment) to year 10 following treatment. Rate of spread increased by 15 fold, flame length by 3.8 fold, and reaction intensity roughly doubled in fully cured mechanical treatment plots in year 10 compared to pretreatment and to control. This has

important management implications - prescribed fire and mechanical treatments in juniper woodlands are likely to both increase herbaceous vegetation as well as increase fire behavior, indicating potential tradeoffs between desired vegetation and wildfire risk.

Introduction

Changing climate patterns, increased anthropogenic ignitions, and the increased spread of invasive grasses such as cheatgrass (*Bromus tectorum*) have altered fire regimes in the sagebrush (*Artemisia* spp.) steppe. In many areas dominated by invasive grasses, the frequency and severity of wildfires has increased, but in other areas fire suppression, overgrazing, and an increase in juniper and pinyon trees have lengthened fire return intervals (Miller et al. 2019, Chambers et al. 2014). This departure from historical conditions is a concern in sagebrush ecosystems, due to the critical habitat that they provide for species of conservation concern, and the negative ecological impacts, such as reduced biodiversity (Davies et al. 2011, Mahood and Balch 2019), loss of perennial native plant cover (Ellsworth et al. 2020, Pyke et al., in review), and increased runoff and soil erosion (Pierson et al. 2010) that increased fire intensity and frequency has caused in these areas (McIver et al. 2010).

Juniper (*Juniperus* spp.) woodlands are native, but increasing, ecological communities that historically were limited by the natural, more frequent fire return interval (Miller et al. 2019). These woodlands are a mix of pinyon pine (*Pinus* spp.) and juniper that have significantly increased in the past century (Miller and Tausch 2002). The expansion of juniper woodlands is occurring mainly at mid to high elevations (Chambers et al. 2014) at the more mesic, productive end of the sagebrush steppe. The increase in tree density in juniper woodlands is due to intensive livestock grazing, increasing atmospheric CO_2 levels (which leads to more efficient water use in conifers), and fire suppression (Miller et al. 2019). Climate change, which is causing higher temperatures and abnormal precipitation patterns, has contributed to the increase and spread of juniper woodlands, wildfire, and invasive annual grasses (Miller et al. 2019). Competition by juniper woodland tree species for water and resources has led to a decline in native understory shrub and herbaceous communities, and has also led to an increased risk of larger high severity canopy fires as the juniper outcompetes the understory, resulting in reduced surface fire spread but a potential increase in the potential for canopy fires (Chambers et al. 2013, Miller et al. 2014).

Juniper expansion has been categorized into three distinct phases, with trees becoming increasingly dominant (Miller et al. 2005). In phase I, the dominant vegetation is shrubs and herbaceous vegetation (perennial bunchgrasses and forbs) with some trees present. In phase II, the understory and the trees become co-dominant. In phase III, trees are the dominant vegetation and have the most influence on the area's ecological processes (Miller et al. 2005). The encroachment of juniper woodlands has environmental consequences, including loss of understory perennial shrubs and herbs (Roundy et al. 2020, McIver et al. 2010), increased runoff and soil erosion (Peterson and Stringham 2008, Pierson et al 2010), reduced habitat for wildlife species of conservation concern (*ie.* greater sage-grouse [*Centrocercus urophasianus*]), altered plant community composition, and reduced biodiversity (Miller et al. 2005).

Historically, fire return intervals ranged from 20-50 years in the mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) steppe, which was frequent enough to limit juniper encroachment (Davies et al. 2019, Miller et al. 2005). Longer periods without fire has allowed juniper woodlands to expand (Davies et al. 2019, Romme et al. 2009). The increase in juniper woodlands increases the amount of canopy fuels, potentially resulting in more severe wildfires (Miller et al. 2019, Romme et al. 2009, Freund et al. 2021). As juniper woodlands progress through the three phases, shrub and herbaceous vegetation decline, shifting the majority of fuel from the surface to the canopy by phase III (Miller et al. 2005).

Fuel treatments are management tools that reduce the amount of burnable material, with the ultimate goal of decreasing fire intensity or severity of future fires (Reinhardt et al. 2008) and contribute to ecological restoration (Dittel et al. 2018). Two common fuel reduction treatments used in juniper woodlands are mechanical cut-and-drop (trees are felled and left where they were cut down) and prescribed burning (McIver and Brunson 2014, Miller et al. 2005). Prescribed burning is intended to reduce shrubs and trees in the short term, with longer-term recovery of perennial bunchgrasses (Chambers et al. 2014, Davies et al. 2011, Rau et al. 2008, McIver and Brunson 2014). Mechanical treatments are done with the goal of reducing tree competition, thus increasing available resources for the shrub and herbaceous understory (Boyd et al. 2017, Dittel et al. 2018).

In an attempt to mitigate future fire risk, and ultimately better conserve sagebrush steppe ecosystems, long-term research is being conducted to evaluate the effects of different fuel reduction treatments. Fuel (flammable biomass) data has been collected annually for over 10 years as part of the Sagebrush Steppe Treatment Evaluation Project (SageSTEP), a broad-scale and long-term sagebrush steppe treatment evaluation project with 11 sites across four states in the Intermountain West (McIver et al. 2010; Freund et al. 2021). In this thesis I will focus specifically on the effectiveness of fuel reduction treatments at reducing three metrics of fire intensity: reaction intensity (heat per unit area of the flaming front), rate of spread, and flame length. I hypothesized that 1) prescribed fire treatments would reduce subsequent modeled surface fire behavior compared to untreated controls because it reduces overall fuel loads; 2) mechanical treatments would increase modeled surface fire behavior compared to untreated controls, particularly reaction intensity (the heat per unit area) because it creates additional burnable material on the ground surface, 3) fire behavior metrics would all increase with increased fuel curing throughout the growing season, and 4) treatment effectiveness at reducing surface fire behavior would decrease with time post-treatment. Evaluation of treatments impacts on fuel loads and modeled fire behavior will provide land managers with information needed to evaluate tradeoffs between desired vegetation composition and fire risk.

Methods

Study Sites

The Sagebrush Steppe Treatment Evaluation Project (SageSTEP) is a network of study sites across four states in the Western U.S. (Figure 1). I used data from eleven different sites within the Juniper Woodland Network: (Bridge Creek, Blue Mountain, Divine Ridge, Greenville Bench, Marking Corral, Onaqui, Scipio, South Ruby, Stansbury, Seven Mile, and Walker Butte) (McIver and Brunson 2014). The sites are spread across Oregon, northern California, Nevada, and Utah (McIver et al. 2010). Three different types of juniper woodlands are present throughout the eleven sites: Pinyon-Juniper in Nevada, Utah Juniper in Utah, and Western Juniper in Oregon and California (McIver et al. 2010, Wozniak and Strand, 2019). Dominant tree species in Pinyon-Juniper woodlands are Utah Juniper (*Juniperus osteosperma*) and singleleaf pinyon-pine (*Pinus monophylla*). Utah Juniper *(Juniperus osteosperma)* and Colorado pinyon-pine *(Pinus edulis)* are the dominant tree species within Utah Juniper woodlands and Western Juniper *(Juniperus occidentalis)* is the main tree species in Western Juniper woodlands (Wozniak and Strand, 2019). Elevation across all sites ranges from 1400 to 2500 meters, and annual mean precipitation ranges from 305-356 mm (Bernau et al. 2018, Wozniak and Strand, 2019). There were no recorded fires at any of the sites for the 50 years before the study began. Further information about site characteristics and site selection can be found in McIver and Brunson (2014).

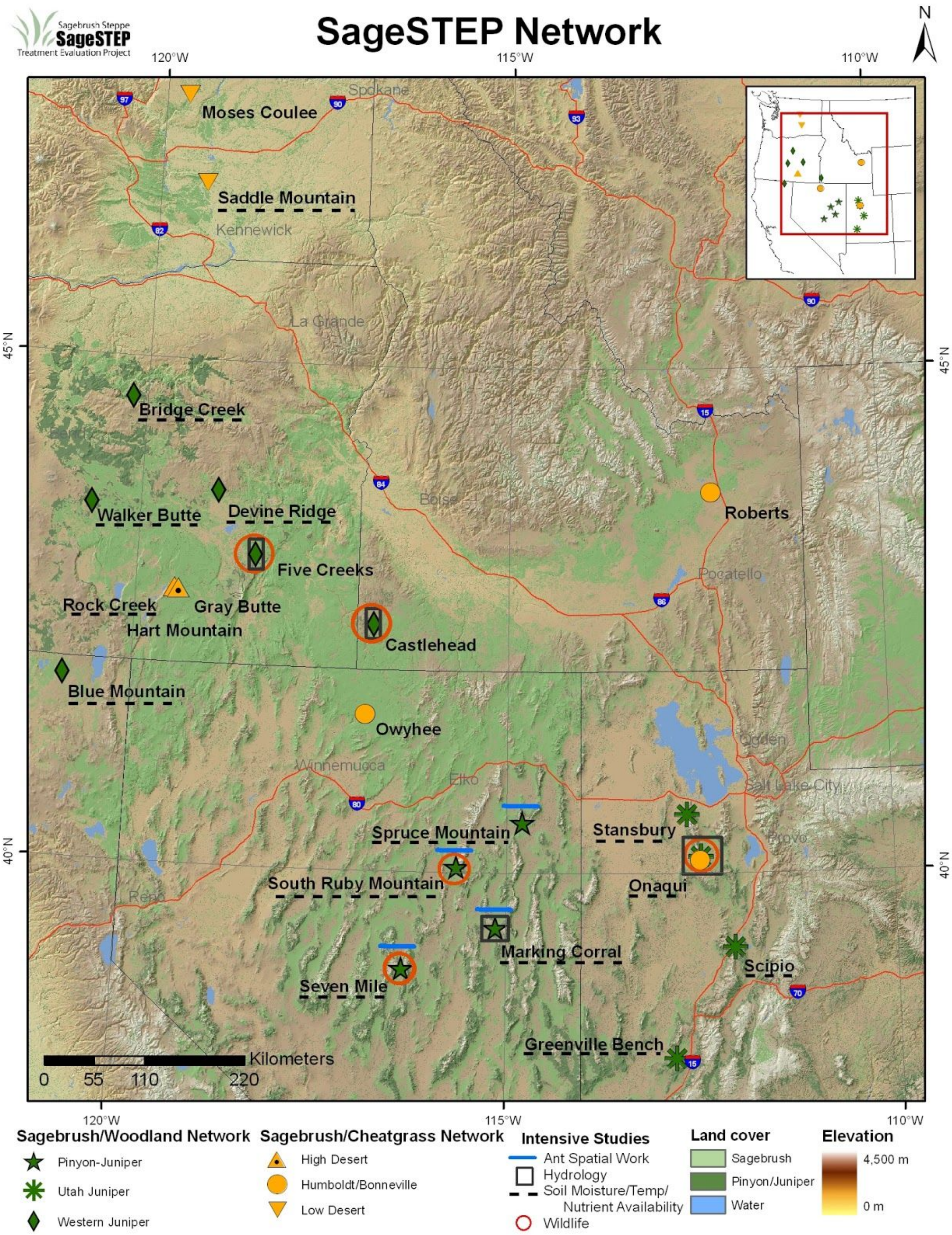

Figure 1. Map of Woodland network (green symbols) and Sagebrush network site map (SageStep.org). Sites used in this study are Bridge Creek, Blue Mountain, Divine Ridge, Greenville Bench, Marking Corral, Onaqui, Scipio, South Ruby, Stansbury, Seven Mile, and Walker Butte.

Experimental design

At each site (N=11), three 10-25 ha plots were delineated. Within each of these plots, fifteen measurement subplots of 0.1 ha were chosen randomly from a larger set of potential subplots (McIver and Brunson 2014). These subplots spanned a condition gradient that was determined by the amount of trees present in the site before treatment (McIver and Brunson 2014). Each subplot was categorized as woodland phase I, II, or III (Miller et al. 2005) before treatment to understand the difference that treatment has on each phase (Wozniak and Strand, 2019).

At each site, plots were randomly selected for treatment (unmanipulated control, prescribed fire, or mechanical; (see Appendix, Image 1, 2, and 3; McIver and Brunson 2014). Treatments were applied in 2006, 2007, or 2008 (depending on site and manager availability) with the intention to remove all trees (mechanical and prescribed fire treatments) and to reduce the shrub layer (prescribed fire treatment only) (McIver and Brunson 2014). Both treatments were applied during the same year at each individual site. Pre-treatment data was collected prior to the application and is represented as Year 0 in the data. There was a wildfire at the Stansbury site in year 2 of the study, so the data from years 3 - 10 were excluded. South Ruby burned during year 10 and the data from that year is also excluded. Most sites contain all three phases at all three treatments, but the Bridge Creek site does not have a Phase 3 control plot and the Walker Butte site does not have a Phase 3 prescribed fire plot (Figure 1). Prescribed fires were done during the fall with the intention of burning 100% of the plot. Any surviving trees were individually ignited to achieve complete canopy consumption. For the mechanical treatment, all trees > 0.5 m tall were cut at the base with a chainsaw and left where they fell in the plot (Wozniak and Strand, 2019).

Field data collection

Field measurements were collected from April to June during the peak growing season. Data were collected before treatment (Year 0), and then once annually following the treatments. Years 0, 1, 2, 3, 6, and 10 of data collection are reported here. All trees within each plot that were taller than 0.5 m were included in the tree density measurements. Their height, crown base height, longest canopy diameter, and perpendicular canopy diameter were also measured and recorded. Tree and shrub fuel loads were estimated using site-specific allometric equations from tree and shrub height, canopy dimension, and volume (more details on the equations can be found in Wozniak and Strand, 2019). The equations were developed by Sabin (2008) and Tausch (2009) and more information on the fit of these models for each site in the SageSTEP network can be found in Stebleton and Bunting (2009) and Bourne and Bunting (2011). Herbaceous live fuel was measured using 0.25 m^2 quadrats. Live herbaceous and standing dead herbaceous biomass was dried in an oven at 50°C for 48 hours before being weighed (Wozniak and Strand, 2019). 10-hour, 100-hour, 1000-hour (sound), and 1000-hour (rotten) fuels data was collected for down woody debris using the planar-intercept method (Brown et al. 1982). Litter and duff fuel were collected using 0.065 m^2 quadrats (Wozniak and Strand 2019).

Fire Behavior Modeling

To determine the impact that the fuel reduction treatments had on surface fire behavior over the 10 year study, I utilized the fire behavior modeling system Fuel Characteristic Classification System (FCCS) in the Fuel and Fire Tool (FFT) model (Prichard et al. 2013). The FCCS predicts surface fire behavior using localized fuel data, wind speeds, and fuel moisture scenarios to reflect conditions throughout a typical fire season. I used field data to create custom fuel models representing fuel amount, structure, and arrangement for each treatment (mechanical, prescribed fire, and control) and year (0, 1 , 2 , 3, 6, and 10) combination. Custom fuel beds were constructed starting with the pre-set fuelbed 58: Western Juniper/sagebrush savannah - post prescribed burn for all burned plots or 69: Western Juniper/sagebrush-bitterbrush shrubland for all pre-treatment, control, and mechanical thinning plots. Then, *in situ* fuels data were entered to represent the amount and type of fuels at each site, generating a custom fuel model for treatment by year combination. The custom fuel beds were used to predict the surface fire behavior for each site and treatment at each time period following fire. Moisture scenarios were selected to mimic the progression of vegetation moisture content through the growing season from spring greenup through fall curing, when vegetation has dried out and there is a higher risk of fire. The modeled environmental scenarios in FFT used to represent fuel moisture were the following: fully green (D2L4), ⅓ cured (D2L3), ⅔ cured (D2L2), and fully cured (D2L1). Moisture scenarios are calculated with a moisture damping coefficient, which has a linear relationship with the model outputs, such that more extreme fire behavior is predicted with drier fuels and reduced fire behavior with moist fuels (Prichard et al. 2013). The slope was set to 13%, the average slope of all woodland plots in the SageSTEP network, and windspeed was set to12 kph, based on the mean 80th percentile wind speed over the summer (June-September) from the nearest remote automated weather station across all sites and study years. Each custom fuel model was run at each moisture scenario to predict surface rate of spread (ROS; m/min), reaction intensity (RI; kW m^{-2} min^{-1}), and flame length (FL; m).

Analysis

Linear mixed models were used to test for differences in the response variables (rate of spread, flame length, and reaction intensity) as a function of fuel moisture scenarios, juniper treatments, juniper phase, and year post-treatment (hereafter, year). Interactions between year*treatment, year*phase, treatment*phase, and year*treatment*phase were used to test whether fuel treatment effectiveness differed by phase or through time (Table 1). Sites were considered replicates within the study and treated as a random factor in all models. The Turkey-Kramer honest significant difference (HSD) post hoc analysis was used to determine the differences between groups. Analyses were performed using IBM SPSS 24 (IBM Corp 2016).

Results

Fuels Summary

Total fuels in year 0 averaged 37.95 Mg ha^{-1}, and total fuels in year 10 averaged 28.15 Mg ha^{-1} (a 26% average decrease in total fuel load) across all subplots, phases and treatments. Total surface fuels averaged 6.29 Mg ha^{-1} across all the plots in year 0. In year 10, surface fuels averaged 13.3 Mg ha^{-1} (an 111% increase from year 0). The downed woody fuels were the largest portion of the surface fuel load (55% of total fuel load) in all post-treatment years. Data on the standing tree fuels across all subplots, phases, and treatments was reported in Stebleton and Bunting (2009) and Wozniak and Strand (2019). In year 0, standing tree fuels averaged 31.69 Mg ha^{-1} and in year 10 tree fuels averaged 14.85 Mg ha^{-1} (53% decrease) across all treatments. The tree live fuel load ranged from 3.4 Mg/ha in phase I woodlands to 16.8 Mg/ha in phase 3 woodlands (Stebleton and Bunting 2009, Wozniak and Stand 2019). In year 10, the tree fuel load ranged from 1.67 Mg/ha to 8.4 Mg/ha in phase I to phase III woodlands (Stebleton and Bunting 2009, Wozinak and Stand 2019).

Controls. The surface fuel loads in the control plots were highest in phase I plots and lowest in phase III plots (Figure 2). The shrub fuel loads decreased over time for every phase and every treatment year. Pre-treatment shrub fuels ranged from a mean of 1.1 Mg/ha in phase III woodlands to a mean of 3.3 Mg/ha in phase I woodlands. Post-treatment shrub fuels ranged from a mean of 0.5 Mg/ha in phase III woodlands to a mean of 3.0 Mg/ha in phase I woodlands. Pre-treatment herbaceous fuels ranged from a mean of 0.12 Mg/ha in phase III woodlands to a mean of 0.32 Mg/ha in phase I, and 10 years later they ranged from a mean of 0.20 to 0.40 Mg/ha in phase III to phase I woodlands, respectively. Downed woody pre-treatment fuel loads ranged from a mean of 2.5 Mg/ha in phase III woodlands to 3.1 Mg/ha in phase I, and by year 10 they ranged from a mean of 3.6 to 4.5 Mg/ha in phase III to phase I woodlands, respectively.

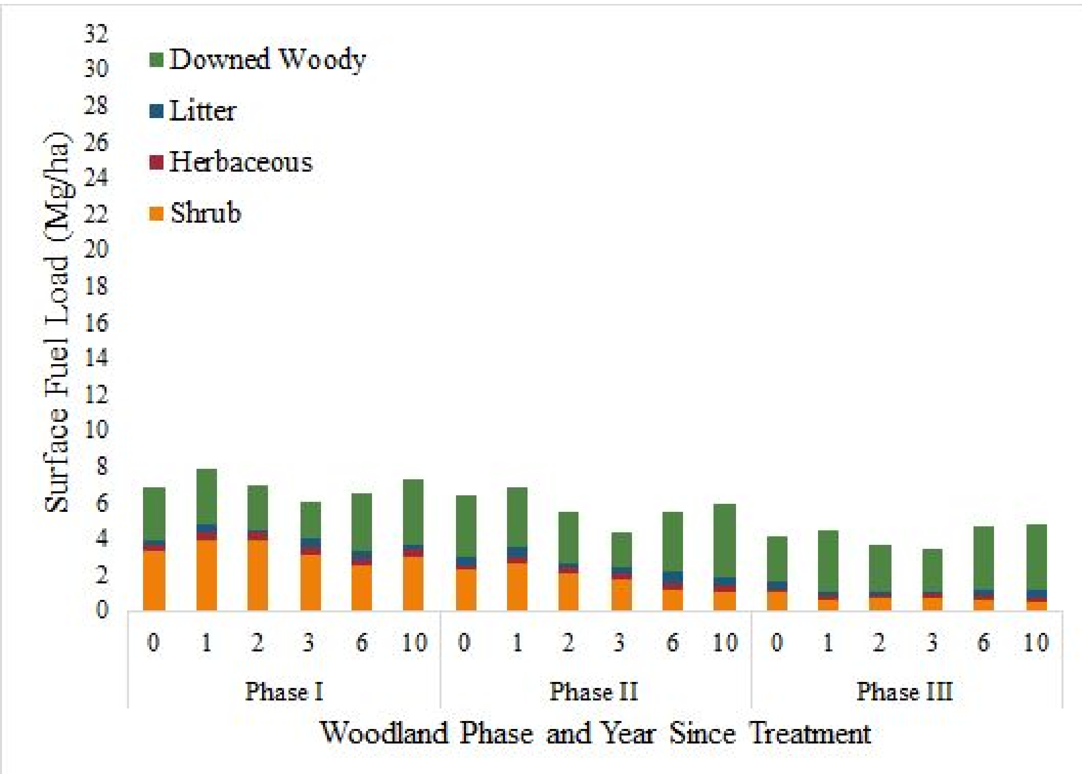

Figure 2. Mean surface fuel loads (shrub, herbaceous, litter, and downed wood) (Mg ha^{-1}) in control plots for woodland phases I, II, III in years 0, 1, 2, 3, 6, and 10 following treatment.

Mechanical. Mechanical treatments resulted in an increase in downed woody fuel, especially in phase III (Figure 3). Downed woody pre-treatment fuel loads ranged from 3.4 Mg/ha in phase I woodlands to 4.4 Mg/ha in phase III, and by year 10 they ranged from 8.4 Mg/ha in phase I to 26.7 Mg/ha in phase III woodlands. Pre-treatment shrub fuels ranged from 0.8 Mg/ha in phase III woodlands to 3.2 Mg/ha in phase I woodlands. Post-treatment shrub fuels ranged from 1.9 Mg/ha in phase III woodlands to 4.5 Mg/ha in phase I woodlands by year 10. Pre-treatment herbaceous fuels ranged from 0.16 Mg/ha in phase III woodlands to 0.30 Mg/ha in phase I, and 10 years later they ranged from 0.52 to 0.56 Mg/ha in phase III to phase I woodlands, respectively. Pre-treatment litter fuel loads ranged from 0.40 Mg/ha in phase I to 0.60 Mg/ha in phase III woodlands, compared to the post-treatment fuel load in year 10 which ranged from 0.34 Mg/ha in phase I to 0.32 Mg/ha in phase III.

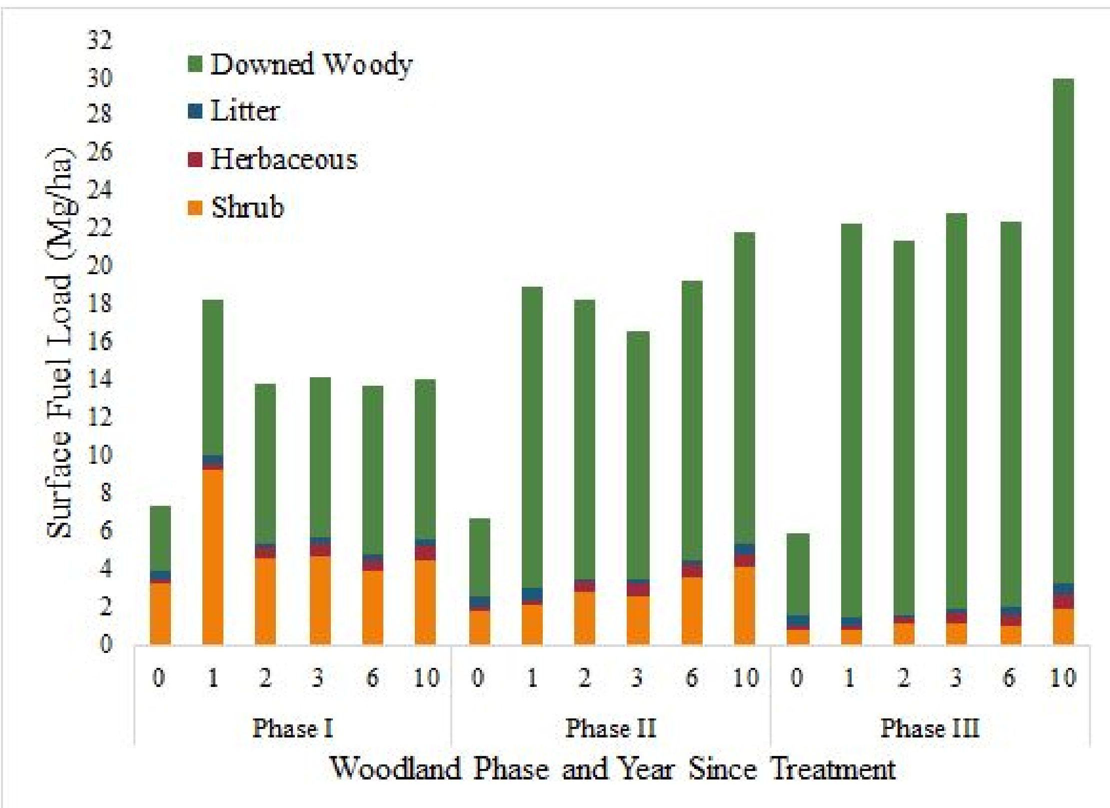

Figure 3. Mean surface fuel loads (Mg ha^{-1}) following mechanical treatment plots in Woodland phases I, II, III in years 0, 1, 2, 3, 6, and 10 post treatment.

Prescribed Fire. Pre-treatment downed woody fuel loads ranged from a mean of 4.0 Mg/ha in phase I woodlands to 3.2 Mg/ha in phase II and phase III (Figure 4). By year 10 following prescribed fire, they ranged from a mean of 6.1 Mg/ha in phase I to 13.4 Mg/ha in phase III woodlands. Pre-treatment herbaceous fuel loads ranged from a mean of 0.2 Mg/ha in phase III woodlands to 0.3 Mg/ha in phase I woodlands. Post-treatment fuels averaged 0.8 Mg/ha in phase I and III woodlands during year 10. The mean year 10 post-treatment herbaceous fuel load increased to 0.9 Mg/ha in phase II woodlands. Pre-treatment litter fuel loads ranged from 0.3 Mg/ha in phase I to 0.2 Mg/ha in phase III woodlands, compared to the post-treatment fuel load in year 10 which ranged from 0.3 Mg/ha in phase I to 0.5 in phase III. The mean pretreatment shrub fuel load ranged from 0.8 Mg/ha in phase III woodlands to 3.5 Mg/ha in phase I woodlands. Post-treatment shrub fuels ranged from 1.3 Mg/ha in phase III woodlands to 1.0 Mg/ha in phase I woodlands by year 10.

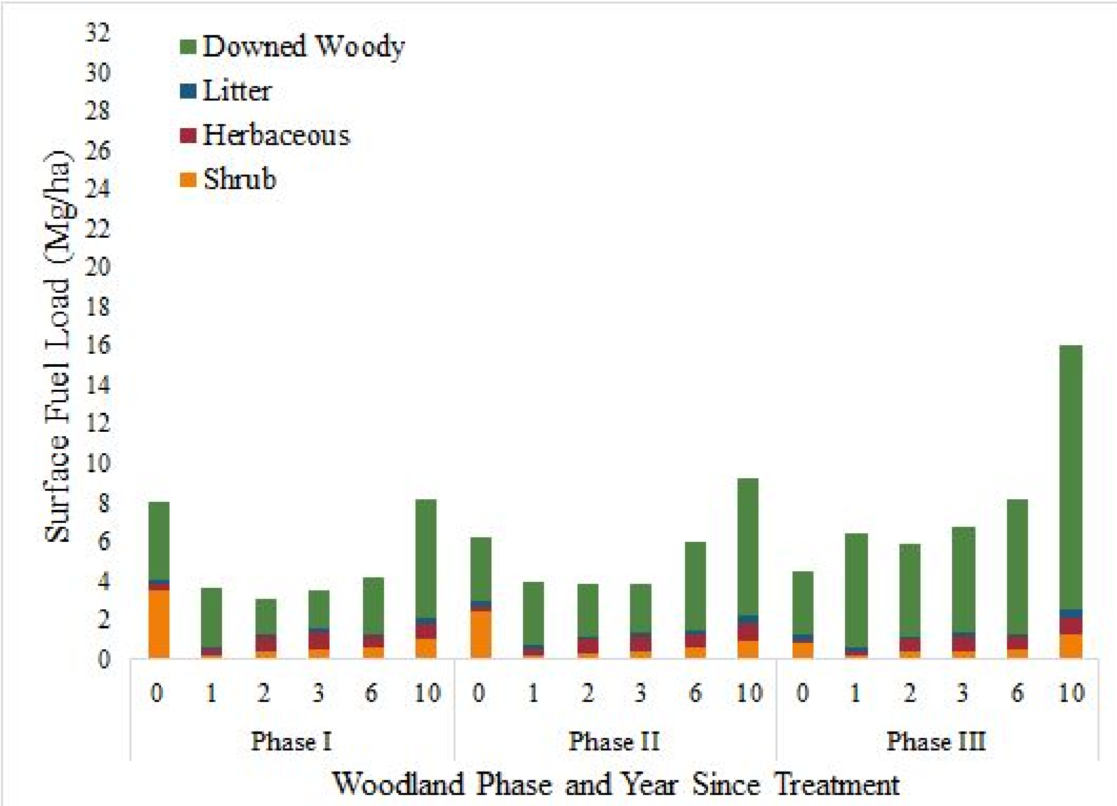

Figure 4. Mean shrub, herbaceous, litter, and downed woody fuel (Mg ha^{-1}) in prescribed fire treatment plots for Woodland phases I, II, III in years 0, 1, 2, 3, 6, and 10 post treatment.

Fire Behavior

Rate of spread, flame length, and reaction intensity all increased as fuel moisture decreased and the herbaceous fuel cured, mimicking the natural fire season. Year, treatment, phase, and environmental scenario all had a significant effect on the rate of surface fire spread, flame length and reaction intensity (Table 1).

Table 1. Linear mixed models predicting the rate of fire spread, flame length, and reaction intensity as a function of environmental scenario (% moisture by fuel class), juniper fuel reduction treatment (prescribed fire, mechanical, or untreated control), and year (years 0, 1, 2, 3, 6, and 10 post-treatment) from eleven replicate sites across the Great Basin, USA.

	Rate of Spread		**Flame Length**		**Reaction Intensity**	
Source	**F**	***P***	**F**	***P***	**F**	***P***
Intercept	51.5	<0.01	170.5	<0.01	134.7	<0.01
Year	44.1	<0.01	210.3	<0.01	32.5	<0.01
Treatment	246.2	<0.01	875.7	<0.01	248.9	<0.01
Phase	6.2	<0.01	66.6	<0.01	232.6	<0.01
Environmental Scenario	69.3	<0.01	276.5	<0.01	196.5	<0.01
Year*treatment	12.3	<0.01	46.4	<0.01	20.4	<0.01
Year*phase	4.9	<0.01	2.821	<0.01	6.0	<0.01
Treatment*phase	10.9	<0.01	1.055	0.377	46.6	<0.01
Year*trmt*phase	3.3	<0.01	0.872	0.624	4.0	<0.01

Rate of Spread. Modeled surface rate of spread was not significantly different in the pre-treatment plots, but increased with both prescribed fire and mechanical treatments (Figure 5). Rate of spread in mechanical treatments was 15x higher than in untreated controls in fully cured plots, and prescribed fire treatments increased the rate of spread by 25 fold compared to untreated controls. Greatest differences between treatments occurred when fuels were fully cured, and less variability between treatments was observed when herbaceous fuels were green. (Figure 5).

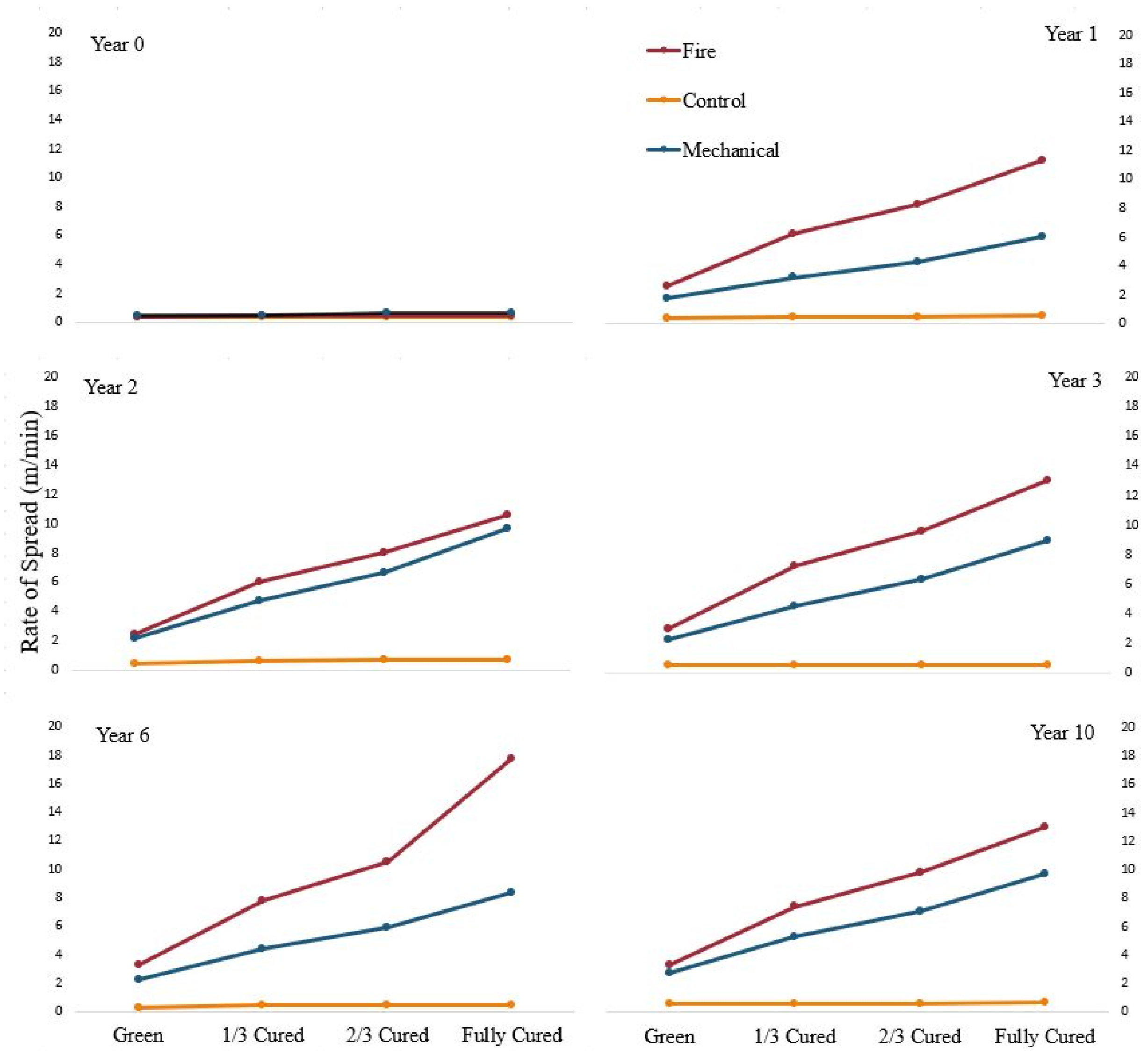

Figure 5. Rate of spread by treatment type in years 0, 1, 2, 3, 6, and 10 following treatment as a function of environmental scenario (modeled fuel moisture content).

Flame Length. There was no variation in flame length across all treatments and environmental scenarios prior to treatment. Flame lengths were higher in fire and mechanical plots compared to the untreated control flame lengths in every year post-treatment in all environmental scenarios and across all juniper phases (Table 1, Figure 6). The fully cured mechanical treatment plots had a mean 3.8 fold increase in flame lengths. Prescribed fire treatments tripled flame length in fully cured plots during year 10 compared to pre-treatment and untreated control plots (Figure 6).

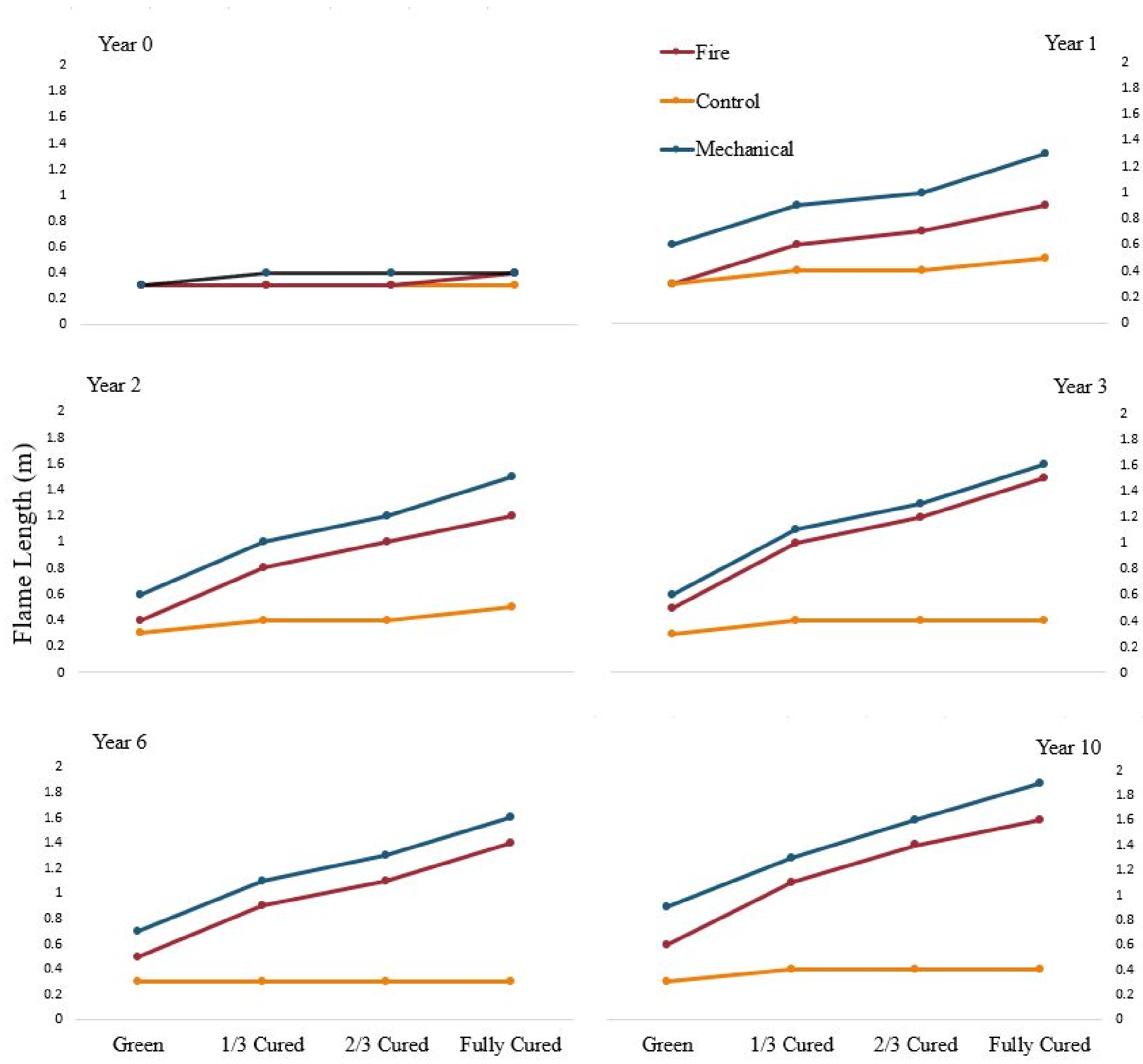

Figure 6. Flame length (m) by treatment type in years 0, 1, 2, 3, 6, and 10 following treatment as a function of environmental scenario (modeled fuel moisture content).

Reaction Intensity. The modeled reaction intensity prior to treatment ranged from 158.3 kW m^{-2} min^{-1} when fully green to 307.7 kW m^{-2} min^{-1} when herbaceous fuels were fully cured (Figure 7). Reaction intensity was higher overall in year 10 compared to the first post-treatment year. The mechanical treatment had higher reaction intensities across all post-treatment years and all environmental scenarios than control or fire treatments. Reaction intensity increased by 92.7% from year 0 to year 10 in the fully cured mechanical treatment plots. The prescribed fire plots reduced reaction intensities through year 6, but by year 10 the reaction intensity was not significantly different than control plots (Table 1, Figure 7).

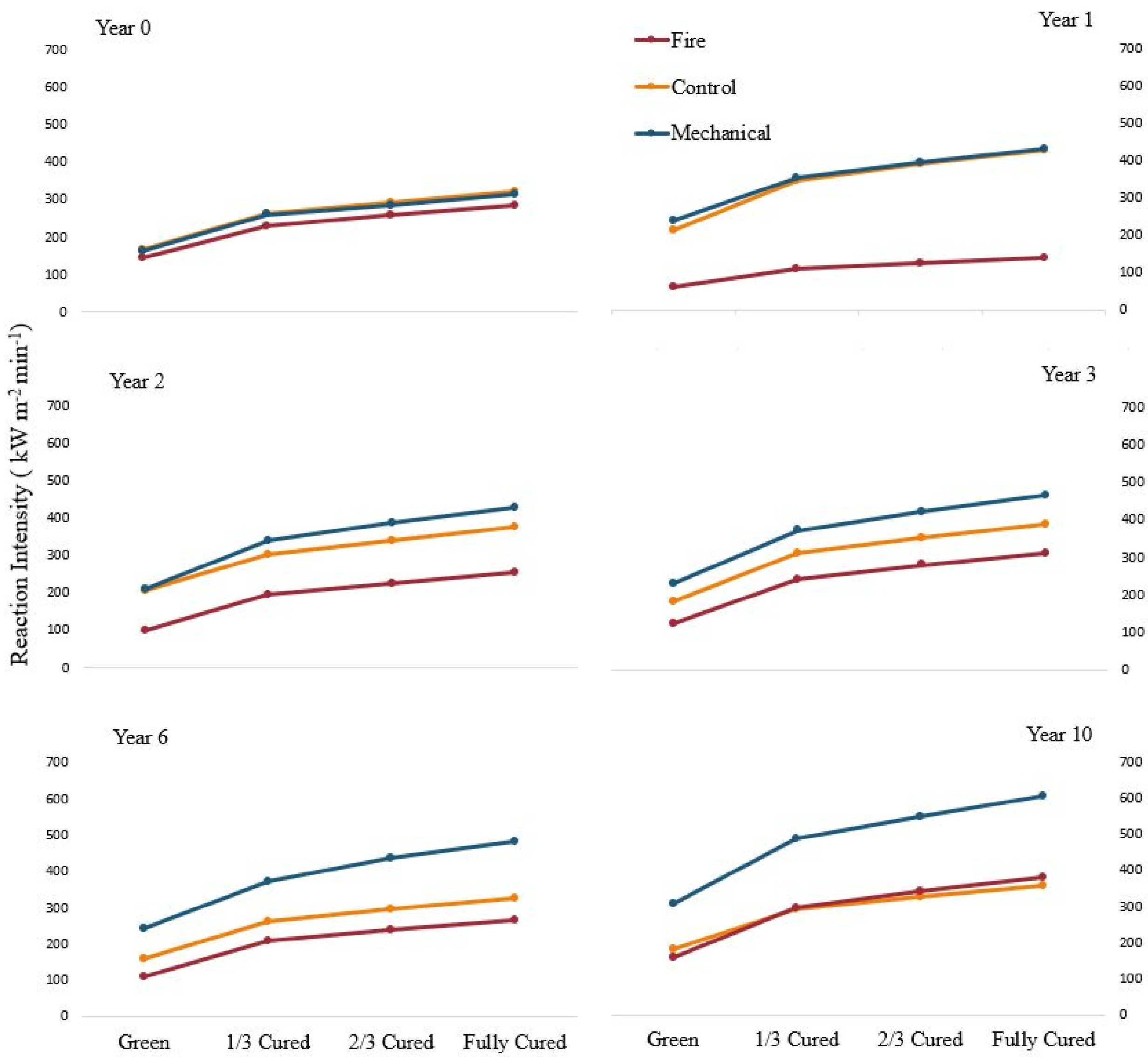

Figure 7. Reaction intensity (kW m^{-2} min^{-1}) by treatment type in years 0, 1, 2, 3, 6, and 10 post-treatment as a function of environmental scenario (modeled fuel moisture content).

Discussion

The treatments discussed in this paper are used throughout the Great Basin region to reduce juniper woodlands to restore and increase native shrub and herbaceous vegetation (Miller et al. 2014, McIver and Brunson 2014, Baughman et al. 2010). Sagebrush is essential for sage-grouse habitat and reducing juniper cover to below 4% has been shown to be important for increasing and maintaining sage-grouse survival rates (Coates et al. 2017). Sage-grouse rely on areas of continuous sagebrush ecosystems to maintain healthy populations (Coates et al. 2017, Knick et al. 2013). The native perennial bunch grasses are also critical habitat components for sage-grouse, other wildlife species, and for domestic livestock. However, while the goal of fuel reduction treatments is to increase sagebrush and herbaceous vegetation, those post-treatment increases create ecosystems that support more intense surface fire behavior than pre-treatment juniper woodlands.

Contrary to my first hypothesis, the prescribed fire treatment increased modeled flame length and rate of surface fire spread when compared to the pre-treatment and control plots due to the increase in flammable herbaceous surface fuels following fire. Prescribed fire also resulted in the higher rates of modeled surface fire spread than mechanical treatments. By removing trees, the treatment freed-up the water and nutrients that the trees had been consuming, allowing the herbaceous vegetation, both native and non-native, to increase (Miller et al. 2014, Rau et al. 2008, Roundy et al. 2014). The increase in herbaceous fuels (See Appendix, Image 1) and resulting increase in modeled surface fire behavior is consistent with earlier results from these study sites, as well as in results from Bernau et al. (2018), Young et al. (2013), Freund et al. (2021), and Bates et al. (2005). The Greenville Bench site photos (Appendix, Image 1) of the prescribed fire treatment plots clearly shows the progression of vegetation and a visible increase in grasses. Prescribed fire and mechanical cut treatments are performed all over the Great Basin as fuel reduction treatments (Young et al. 2014, McIver and Brunson 2014, Chambers et al. 2014, Boyd et al. 2017). While treatments can restore native shrub and grass cover, an increase in invasive annual grasses is also common (Dittel et al. 2018, Freund et al. 2021) (Figure 5 and 6).

Mechanical treatments moved all of the fuel load into surface fuels, which increased all measures of surface fire intensity compared to controls. This is consistent with my second hypothesis, that mechanical treatments would increase modeled surface fire behavior, particularly reaction intensity. In response to the mechanical treatment, reaction intensity roughly doubled in fully cured mechanical treatment plots in year 10 compared to pretreatment and to control (Figure 7). As part of the mechanical treatment, trees are cut down and then left where they fall, increasing the amount of downed woody fuel available on the surface (Figure 3) (See Appendix, Image 3). This accounts for the large increased reaction intensity caused by mechanical treatments.

I anticipated that fire behavior metrics would increase with increased fuel curing, and the results were consistent with this hypothesis. Modeled surface rate of spread, flame length, and reaction intensity all increased with increased fuel curing and decreased levels of moisture (Figures 5, 6, and 7). Cured fuels contain very little moisture, making ignition easier and resulting in increased surface fire behavior compared to fully green fuels (Brown 1982, Wright 2013).

Before the expansion of juniper woodlands, the vegetation consisted mainly of shrubs, like sagebrush, and native annual bunchgrasses, which historically had more frequent wildfire than the woodlands that replaced them. With the concomitant increase in annual grasses though, there is risk of increases in invasive annual grass following disturbances such as wildfire or fuel reduction treatments (Freund et al. 2021, Ellsworth et al. in press, Pyke et al. in press). Mechanical and prescribed fire treatments resulted in an increase of surface fuels, in the form of both native shrubs and grasses as well as invasive cheatgrass, consistent with what has been seen in other studies (Ellsworth and Kauffman 2017, Dittel et al. 2018, Freund et al. 2021). Invasions of annual grasses can alter the fire regime of an area and create a cycle where invasive annuals exacerbate fire, which increases invasive annual grasses (Brooks et al. 2004, Pyke et al. 2016). The steady upward trend of the modeled rate of spread over the 10 year period (Figure 5) indicates that these treatments are not effective at reducing surface fire intensity. I hypothesized that treatment effectiveness would decrease throughout the study period. Instead, modeled fire behavior began to increase in year 1 and continued to increase with time since treatment, contrary to the fourth hypothesis. However, further research is needed to determine the climatic conditions (windspeed, fuel moisture) under which we would see transmission of flames into the canopy of control plots and, potentially, more intense fire behavior (Chambers et al. 2013, Miller et al. 2014).

It is important to consider the desired management outcomes of the land when considering treatments. Reducing the extent of juniper woodlands using the fuel reduction treatments discussed in this paper is likely to result in increased surface fire behavior in the area the next time that it burns. However, these same treatments have been successful at creating or restoring habitat for sage-grouse or other wildlife species, and at increasing forage for livestock.

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Appendix: Time-series images

Year 0

Year 1

Year 10

Image 1. Greenville Bench site photos of prescribed burn treatment plots in years 0, 1, and 10 (SageSTEP).

Year 0

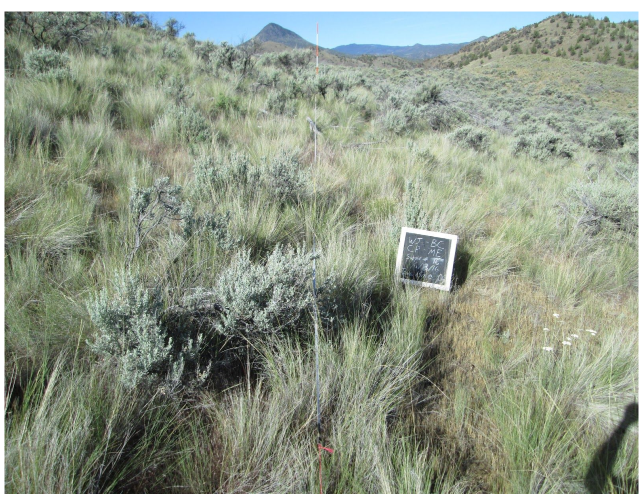
Year 1

Year 10

Image 2. Scipio site photos of control treatment plots for years 0, 1, and 10.

Year 0

Year 1



Year 10

Image 3. Bridge Creek site photos of mechanical treatment plots for years 0, 1, and 10.

Literature Cited

Bernau, C.R., Strand, E.K. & Bunting, S.C. 2018. Fuel bed response to vegetation treatments in juniper-invaded sagebrush steppe. Fire Ecology 14(1).

Bourne, A., Bunting, S. 2011. Guide for Quantifying Post-treatment Fuels in the Sagebrush Steppe and Juniper Woodlands of the Great Basin. Bureau of Land Management, Denver, CO. Technical Note 437.

Boyd, C. S., Kerby, J. D., Svejcar, T. J., Bates, J. D., Johnson, D. D., & Davies, K. W. 2017. The sage‐grouse habitat mortgage: Effective conifer management in space and time. Rangeland Ecology & Management 70(1): 141–148.

Brown, J.K., R.D. Oberheu, and C.M. Johnston. 1982. Handbook for inventorying surface fuels and biomass in the Interior West. National Wildfire Coordinating Group NFES-2125. 48 p.6.

Baughman, C., Forbis, T. A., Provencher, L. 2010. Response of Two Sagebrush Sites to Low-Disturbance, Mechanical Removal of Piñyon and Juniper. Invasive Plant Science and Management, 3(2): 122-129.

Chambers J.C., Miller R.F., Board D.I., Pyke D.A. Roundy B.A., Grace J.B., Schupp E.W., Tausch R.J. 2014. Resilience and resistance of sagebrush ecosystems: implications for state and transition models and management treatments. Rangeland Ecology and Management 67: 440–454.

Davies, K. W., Boyd, C. S., Beck, J. L., Bates, J. D., Svejcar, T. J., Gregg, M. A.. 2011. Saving the sagebrush sea: An ecosystem conservation plan for big sagebrush plant communities, Biological Conservation, 144(11): 2573-2584.

Davies, K.W., Rios, R.C., Bates, J.D., Johnson, D.D., Kerby, J., Boyd, C.S. 2019. To burn or not to burn: Comparing reintroducing fire with cutting an encroaching conifer for conservation of an imperiled shrub‐steppe. Ecology and Evolution. 9: 9137– 9148.

Dittel, J. W., Sanchez, D., Ellsworth, L. M., Morozumi, C. N., and Mata-Gonzalez, R. 2018. Vegetation Response to Juniper Reduction and Grazing Exclusion in Sagebrush-Steppe Habitat in Eastern Oregon. Rangeland Ecology and Management 71(2): 213-219.

Ellsworth, L. M. and Kauffman, J. B. 2017. Plant community response to prescribed fire varies by pre-fire condition and season of burn in mountain big sagebrush ecosystems. Journal of Arid Environments, 144(1): 74-80.

Ellsworth, L. M., Kauffman, J. B., Reis, S. A., Sapsis, D., and Moseley, K. 2020. Repeated fire altered succession and increased fire behavior in basin big sagebrush–native perennial grasslands. Ecosphere 11(5):e03124. 10.1002/ecs2.3124

IBM Corp. 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp.

Knick, S. T., Hanser, S. E., Preston, K.L. 2013. Modeling ecological minimum requirements for distribution of greater sage‐grouse leks: implications for population connectivity across their western range, U.S.A. Ecology and Evolution 3(6): 1539-1551.

Mahood, A. L., and Balch, J. K.. 2019. Repeated fires reduce plant diversity in low‐elevation Wyoming big sagebrush ecosystems (1984–2014). Ecosphere 10(2):e02591. 10.1002/ecs2.2591

McIver, J.D.; Brunson, M.; Bunting, S.C., and others. 2010. The Sagebrush Steppe Treatment Evaluation Project (SageSTEP): a test of state and transition theory. Gen. Tech. Rep. RMRS-GTR-237. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 16 p.

McIver, J.D.; Brunson, M. 2014. "Multidisciplinary, Multisite Evaluation of Alternative Sagebrush Steppe Restoration Treatments: The SageSTEP Project," Rangeland Ecology and Management, 67(5): 435-439.

Miller, R. F.; Chambers, Jeanne C.; Evers, Louisa; Williams, C. Jason; Snyder, Keirith A.; Roundy, Bruce A.; Pierson, Fred B. 2019. The ecology, history, ecohydrology, and management of pinyon and juniper woodlands in the Great Basin and Northern Colorado Plateau of the western United States. Gen. Tech. Rep. RMRS-GTR-403. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 284 p.

Miller R. F., Ratchford J., Roundy B. A., Tausch R. J., Pereia C., Hulet A., Chambers J.C. 2014. Response of conifer encroached shrublands in the Great Basin to prescribed fire and mechanical treatments. Rangeland Ecology and Management 67:468–481.

Miller, R.F., Bates, J.D., Svejcar, T.J., Pierson, F.B., and Eddleman, L.E. 2005. Biology, ecology, and management of western juniper (*Juniperus occidentalis*). Oregon State University Agricultural Experiment Station Technical Bulletin 152, 82 pp.

Petersen, S. L., Stringham, T. K. 2008. Infiltration, Runoff, and Sediment Yield in Response to Western Juniper Encroachment on Southeast Oregon. Rangeland Ecology and Management 61(1): 74-81.

Pierson, F. B., Williams, C. J., Kormos, P. R., Hardegree, S. P., Clark P. E., and Rau, B. M. 2010. Hydrologic Vulnerability of Sagebrush Steppe Following Pinyon and Juniper Encroachment. Rangeland Ecology and Management 63(6): 614-629.

Prichard, S. J., Sandberg, D. V., Ottmar, R. D., Eberhardt, E., Andreu, A., Eagle, P., and Swedin, K. 2013. Fuel Characteristic Classification System version 3.0: technical documentation. Page PNW-GTR-887. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Pyke, D. A., Shaff, S. C., Chambers, J. C., Schupp, E. W., Newingham, B. A., Gray, M. L., Ellsworth, L. M. Ecological responses after ten years of fuel treatments within Wyoming big sagebrush communities. Ecosphere, in press.

Pyke D. A., Chambers J. C., Beck J. L., Brooks M. L., Mealor B. A. 2016. Land Uses, Fire, and Invasion: Exotic Annual *Bromus* and Human Dimensions. In: Germino M., Chambers J., Brown C. (eds) Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US. Springer Series on Environmental Management. Springer, Cham.

Rau, B. M., Chambers, J. C., Blank, R., and Johnson, D.W.. 2008. Prescribed Fire, Soil, and Plants: Burn Effects and Interactions in the Central Great Basin. Rangeland Ecology and Management 61(2): 169-181.

Reinhardt, E. D., R. E. Keane, D. E. Calkin, and J. D. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management 256:1997–2006.

Roundy, B. A., Miller, R. F., Tausch, R. J., Chambers, J. C., and Rau, B. M.. 2020. Long‐term effects of tree expansion and reduction on soil climate in a semiarid ecosystem. Ecosphere 11(9):e03241. 10.1002/ecs2.3241

Roundy, B. A., Miller, R. F., Tausch, R. J., Kert Young, April Hulet, Ben Rau, Brad Jessop, Jeanne C. Chambers, Dennis Eggett. 2014. "Understory Cover Responses to Piñon–Juniper Treatments across Tree Dominance Gradients in the Great Basin," Rangeland Ecology and Management, 67(5): 482-494.

Sabin, B.S., 2008. Relationship between allometric variables and biomass in Western Juniper (*Juniperus occidentalis*). MS Thesis, Oregon State University, Corvallis, OR.

Stebleton, A., and S. Bunting., 2009. Guide for quantifying fuels in the sagebrush steppe and juniper woodlands of the Great Basin. Technical Note 430. Bureau of Land Management, Denver, CO BLM/ID/PT-09/002+2824. 81p.

Tausch, R.J. 2009. A structurally based analytic model for estimation of biomass and fuel loads of woodland trees. Natural Resource Modeling 22: 463–488.

Wright, C. S. 2013. Models for predicting fuel consumption in sagebrush-dominated ecosystems. Rangeland Ecology & Management 66:254–266.

Wozniak, S., and E. Strand. 2019. Fuels Guide for Sagebrush and Pinyon-Juniper Treatments: 10 Years Post-Treatment. Reports:1–143