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ARTICLE

Special Feature: Sagebrush Steppe Treatment Evaluation Project

Fuel reduction treatments reduce modeled fire intensity in the sagebrush steppe

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Abstract

Increased fire size and frequency coupled with annual grass invasion pose major challenges to sagebrush (*Artemisia* spp.) ecosystem conservation, which is currently focused on protecting sagebrush community composition and structure. A common strategy for mitigating potential fire is to use fuel treatments that alter the structure and amount of burnable material, thus reducing fire behavior and creating access points for fire suppression resources. While there is some recent information on the impacts of fuel treatments on ecological communities, we have little information on fuel treatment effectiveness at modifying fire behavior in sagebrush ecosystems. We present 10 years of data on fuel accumulation and the resultant modeled fire behavior in prescribed fire, mowed, herbicide (tebuthiuron or imazapic), and untreated control plots in the Sagebrush Treatment Evaluation Project (SageSTEP) network in the Great Basin, USA. Fuel data (i.e., aboveground burnable live and dead biomass) were collected in each treatment plot at Years 0 (pretreatment), 1, 2, 3, 6, and 10 posttreatment. We used the Fuel and Fire Tool fire behavior modeling program to test whether treatments impacted potential fire behavior. Prescribed fire initially removed 49% of the total fuel load and 75% of shrubs, and fuel loads remained reduced through Year 10. Mowing shifted fuels from the shrub canopy to the ground surface but did not change the total fuel amount. Prescribed fire and mowing increased herbaceous fuel by the second posttreatment year and that trend persisted through Year 10. Tebuthiuron treatments were ineffective at altering fuel loads. Imazapic suppressed herbaceous vegetation by 30% in Years 2 and 3 following treatment. The modified fuel beds in fire and mow treatments resulted in modeled flame lengths that were significantly lower than untreated control plots for the duration of the study, with shorter term reductions in reaction intensity and rate of spread. Understanding fuel treatment effectiveness will allow natural resource managers to evaluate trade-offs between protecting wildlife habitat and reducing the potential for high-intensity wildfire.

KEYWORDS
Artemisia tridentata, *Bromus tectorum*, custom fuel model, FCCS, fire modeling, fuel breaks, Fuel Fire Tool, fuel load, Great Basin, herbicide, Fuel and Fire Tool, rangeland, SageSTEP, Special Feature: Sagebrush Steppe Treatment Evaluation Project

INTRODUCTION

Arid and semiarid shrublands around the world have been altered by nonnative grass invasions (D'Antonio & Vitousek, 1992; Rahlao et al., 2009), modifying vegetation composition and structure at scales from site-specific plant communities (Blank, 2010; Damasceno et al., 2018) to broad landscapes (Ellsworth et al., 2014; Kerns et al., 2020). These invasions contribute to species' decline and extinctions (Gilbert & Levine, 2013), modify ecosystem processes and functions (Batten et al., 2008; Hoffmann & Haridasan, 2008), and create new, degraded stable states that are difficult or impossible to reverse (Cox & Allen, 2008). Invasive grasses modify fuel loads and arrangements, creating horizontal continuity of combustible material (Rossiter et al., 2003). These altered fuel beds are often more flammable and more conducive to fire spread than the heterogeneous vegetation that they replace (Brooks et al., 2004; Setterfield et al., 2013). Annual grasses colonize quickly following fire, often outcompeting native species and converting native vegetation to invasive grass on landscape scales (Rossiter et al., 2003). This invasive grass-fire feedback results in large-scale land cover changes, and losses of biodiversity and ecosystem services (Charles & Dukes, 2007; Gabbard & Fowler, 2007; McKinney & Lockwood, 1999; Pejchar et al., 2005), and contribute to human-caused changes in climate (Bradley et al., 2006; D'Antonio & Vitousek, 1992; Smith et al., 2000).

Sagebrush ecosystems of the western United States are widespread, but their sustainability is threatened by these annual grass invasions (Bates et al., 2011; Chambers, Miller, et al., 2014; Crawford et al., 2004), land cover change, altered fire regimes, and a changing climate (Brooks et al., 2004; Chambers et al., 2007; Coates et al., 2016). The drier sagebrush ecosystems, often existing at lower elevations, are dominated by Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*). Historically, wildfire was estimated to occur only every 50–100 years due to slow accumulation of fuels and poor fuel continuity (Baker, 2006; Bukowski & Baker, 2013; McIver et al., 2010; Mensing et al., 2006; Wright & Bailey, 1982). This relationship, however, has been substantially disrupted by invasive annual grasses (Balch et al., 2013; D'Antonio & Vitousek, 1992), increasing horizontal fuel continuity (Davies & Svejcar, 2008), and facilitating ignition and fire spread (Brooks et al., 2004), resulting in fire frequencies that are about double that of historical conditions (Balch et al., 2013; Bradley et al., 2006). Major challenges in sagebrush steppe conservation are altered fire regimes, and the resultant uncharacteristic fire behavior now widely exhibited across the sagebrush biome. The increasing emphasis on sagebrush conservation and the reduction of large, invasive grass-fueled wildfires suggests that management treatments to reduce fuels could be beneficial (McIver et al., 2010). While expansion of invasive annual grasses is creating more fire prone situations across the sagebrush biome, increasing shrub cover threatens to outcompete understory native herbaceous vegetation and lead to more severe fire effects in other areas (Davies, Bakker, et al., 2012; Ellsworth et al., 2016; Hulet et al., 2015; Pyke et al., 2014). In these areas, fuel treatments may have the added benefits of breaking up continuous woody cover, providing anchor points for fire suppression, and reducing flammable fuel loads (Davies, Bakker, et al., 2012; McIver et al., 2010).

Broadly, fuel treatments are activities that reduce or redistribute burnable material with the ultimate goal of decreasing fire intensity or burn severity (Reinhardt et al., 2008). In sagebrush ecosystems, fuel treatments often include mechanical thinning, application of herbicide, and prescribed fire (Miller et al., 2013, 2019). Mechanical treatments (i.e., mowing) are used to remove top growth of sagebrush and other shrubs, reducing the shrub canopy, and moving a portion of woody fuel to downed wood on the soil surface. Reducing shrub height reduces flame lengths, facilitating access for suppression resources, and may limit the negative impacts of future wildfire. Higher perennial grass mortality has been observed under and near sagebrush plants compared to shrub interspaces; therefore, a reduction in sagebrush density is a preemptive pre-wildfire strategy to reduce burn severity should a wildfire occur (Hulet et al., 2015). Removing a portion of the shrub canopy is expected to increase herbaceous fuel (Beck et al., 2012; Ellsworth et al., 2020), which may inadvertently result in more rapid fire spread. Applications of broadleaf-specific herbicide were commonly applied to sagebrush canopies through the 1970s to enhance understory vegetation for livestock forage. For example, tebuthiuron is a pelleted, soil-active herbicide that is used to inhibit photosynthetic activity of sagebrush, causing plant mortality. Plants rooted within a 50-cm radius of application are impacted (Olson & Whitson, 2002), but plants farther away are unharmed, providing a patchwork thinning treatment and potentially increasing herbaceous vegetation (Whitson & Alley, 1984). While chemical treatments are effective, they convert standing live woody fuels to standing dead fuels in the short term (Pyke et al., 2014) and to duff and downed woody debris in the long term. The increased ground fuels may contribute to more smoldering rather than flaming combustion, which causes increased soil heating and plant and seed mortality and, ultimately, decreased postfire species richness and cover of native perennial grasses in some sagebrush ecosystems (Weiner et al., 2016). Chemical treatments thus modify fuel structure but do not remove flammable materials from the treatment site. Prescribed fire breaks up woody fuel continuity, reduces overall fuel loads (Reis et al., 2019), and enhances herbaceous vegetation (Ellsworth et al., 2020). However, invasive annual grasses often increase following fire (Miller et al., 2013; Swanson et al., 2018), and habitat quality for sagebrush obligate species may decline after large, continuous fires (Beck et al., 2009; Knick et al., 2005). The condition of the site and vegetation composition before fire (Ellsworth & Kauffman, 2017), soil temperature and moisture regime (Chambers, Miller, et al., 2014), and degree of invasion by exotic annual grasses (Swanson et al., 2018) strongly influence postfire response. Preemergent herbicides such as imazapic provide variable suppression of invasive annual grasses in the short term (Elseroad & Rudd, 2011), giving time for perennial plants to establish dominance. In some cases, annual grasses decreased by 63%–67% (Baker et al., 2009; Pyke et al., 2014), but other studies show only 20% reduction (Owen et al., 2017), and success of invasive suppression is highly dependent on timing and rate of application (Mangold et al., 2017). Suppression effects were consistently limited to the first 1–3 years after treatment (Davison & Smith, 2007; Morris et al., 2017; Pyke et al., 2014). Where suppression of invasive grass is achieved, fire risk may be reduced, as annual grass both cures earlier than native plants and increases horizontal continuity of surface fine fuels (Abatzoglou & Kolden, 2011).

Empirical fire models are built around mathematical equations that predict fire spread (Rothermel, 1972) based on the amount, type, and arrangement of burnable material (fuels) and weather conditions. Fire behavior is commonly predicted using models that are parameterized with fuel structure and composition data (i.e., cover, height, and biomass) that are collected in situ or with existing standard fuel models (Heinsch & Andrews, 2010; Scott & Burgan, 2005). The Fuel Characteristic Classification System (FCCS) in the Fuel and Fire Tool (FFT) (Prichard et al., 2013) allows users to input site-specific fuel and weather data to estimate potential fire behavior (e.g., rate of spread and flame length), as well as to inform prescribed fire planning and fuel hazard assessments. This model improved upon earlier systems (i.e., BehavePlus; Heinsch & Andrews, 2010) by incorporating a modified version of Rothermel's (1972) equations that allowed for greater flexibility in user inputs to fuel loads, ultimately allowing the user to set fuel input parameters to represent a heterogeneous and layered fuel structure (i.e., canopy, subcanopy, understory, surface fuel, ground fuel, and piles; Sandberg et al., 2007) that more accurately represents field conditions. Fire models have inherent limitations, warranting caution in applying them to real-world scenarios. For example, many assume that the fuel bed is continuous and uniform, assumptions that are rarely met in nature (Alexander & Cruz, 2013; Rothermel, 1972). Further, models do not handle changing or anomalous weather events well, so firebrand spread and subsequent spotfire ignition, shifts from headfire to backing or flanking fire spread, and convection columns and fire whirls are poorly accounted for in modeled outputs (Alexander & Cruz, 2013). Despite these limitations, modeled fire behavior studies have provided valuable information, in particular, for risk assessments (i.e., Ager et al., 2011) and in comparison among land use treatments or management alternatives (Brose & Wade, 2000; Evans et al., 2015; Parsons et al., 2018).

Despite the need for designing and employing effective fuel treatments to mitigate wildfire, there has been little research on the effects or longevity of fuel reduction treatments on potential fire behavior in sagebrush ecosystems. Relatively more literature exists with emphasis on forested ecosystems (i.e., Beverly et al., 2020; Johnston et al., 2021; Pique & Domenech, 2018) and on risk assessment (i.e., Syphard et al., 2011). Here, we used a long-term and broad-scale data set to describe fuel structure and accumulation for 10 years following fire, mechanical, and herbicide treatments in Wyoming big sagebrush communities across the northern Great Basin and quantified how those patterns impacted potential future fire behavior (flame length, rate of spread, and reaction intensity). We hypothesized that (1) prescribed fire treatments would reduce modeled fire intensity (Keeley, 2009) due to reduced cover and fuel loads; (2) mowing treatments would reduce modeled flame lengths due to modified fuel structure but not affect the modeled rate of spread or reaction intensity; (3) tebuthiuron treatments would be less effective because fuel structure and arrangement remained essentially unchanged; (4) imazapic treatments would reduce potential fire behavior; (5) modeled fire behavior metrics would increase with increased levels of simulated fine fuel curing; and (6) treatment effectiveness would decline with time since treatment, with only prescribed fire-treated plots reducing modeled fire behavior through the 10-year study period. Evaluating fuel treatment effects on fuel loads and subsequent modeled fire behavior will allow managers to weigh the trade-offs of prescribed fire, mechanical, and chemical treatments in sagebrush ecosystems.

METHODS

Study sites

The Sagebrush Steppe Treatment Evaluation Project (SageSTEP) is a long-term experimental study composed of a network of sites that are spatially distributed across a broad range of environmental conditions in the Great Basin of the western United States. We focused on six sites within the Shrubland Network (Onaqui, Owyhee, Gray Butte, Rock Creek, Moses Coulee, and Saddle Mountain; Figure 1, Table 1; McIver & Brunson, 2014). The Shrubland Network spans Wyoming big sagebrush

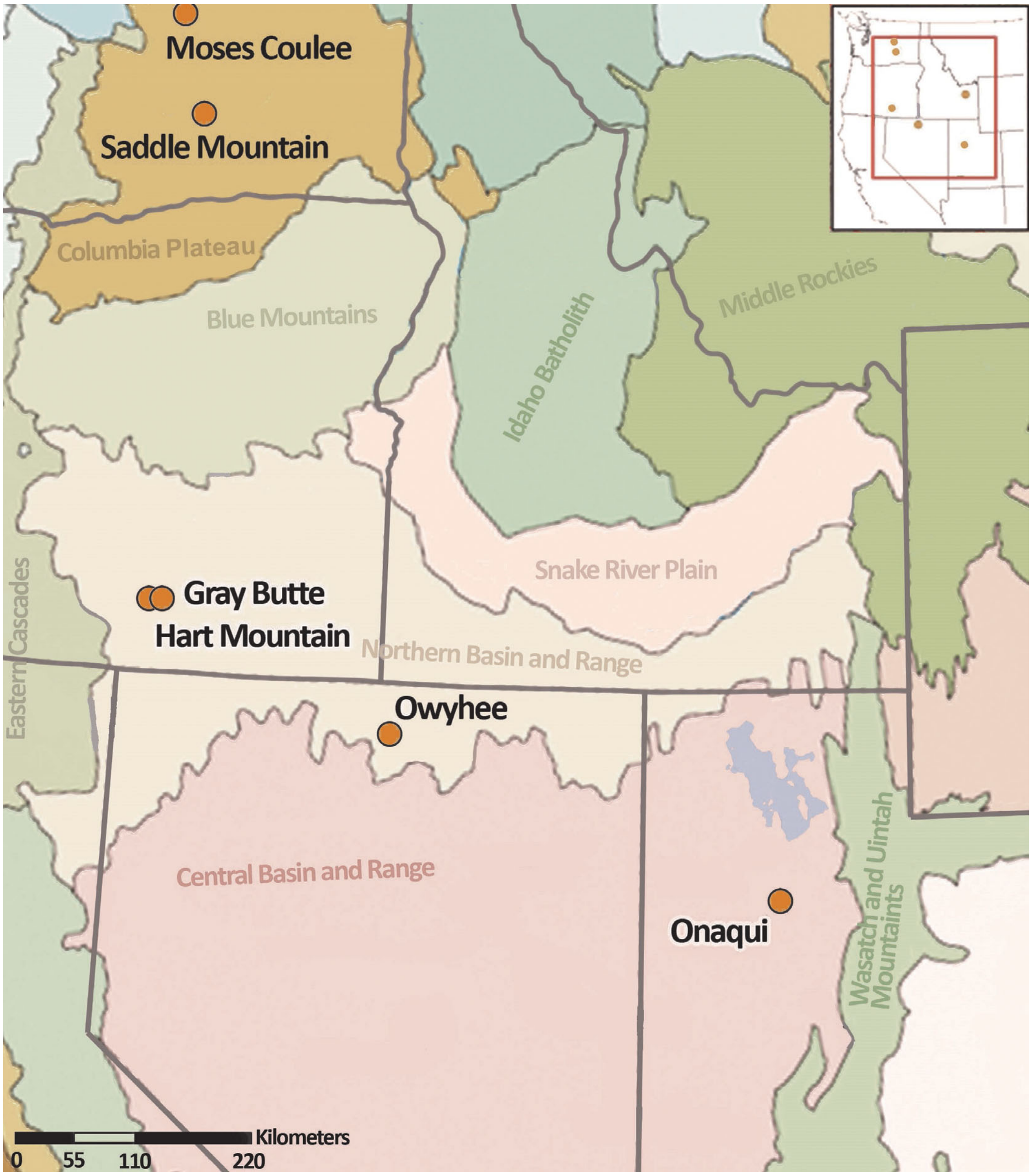

FIGURE 1 Six experimental sites in the Sagebrush Steppe Treatment Evaluation Project in the Great Basin, USA, overlaid on Level III Ecoregions (US Environmental Protection Agency; Omernik & Griffith, 2014)

TABLE 1 SageSTEP site descriptions, including site name and state, year treated, percent plot area burned in prescribed fire, elevation, understory vegetation, surface soil structure, and soil temperature/moisture regime

Site	Year treated	Percentage burned	Elevation (m)	Understory vegetation	Soil surface structure	Soil temp./ moisture regime
Onaqui, UT	2006	79	1750–1850	Bluebunch wheatgrass, slender wheat grass	Fine-loamy	Mesic/xeric
Owyhee, NV	2008	45	1700–1750	Thurber needlegrass, bluebunch wheatgrass, squirreltail, Sandberg bluegrass, wild rye	Fine-silty to fine-loamy	Mesic/xeric
Gray Butte, OR	2008	50	1450–1600	Squirreltail, Thurber needlegrass	Fine-loamy to loamy mixed	Frigid/xeric
Rock Creek, OR	2007	40	1450–1600	Squirreltail, Thurber needlegrass	Fine-loamy to loamy mixed	Frigid/xeric
Moses Coulee, WA	2008–2009[a]	55	515–530	Bluebunch wheatgrass, squirreltail, Sandberg bluegrass	Loamy-skeletal to coarse-loamy over sandy	Mesic/xeric
Saddle Mountain, WA	2008	65	262–286	Bluebunch wheatgrass, Indian ricegrass, bottlebrush squirreltail	Coarse-silty	Mesic/xeric

[a]Prescribed fire treatment occurred 1 year after mow and herbicide treatments due to site constraints.

communities that vary in resistance to invasive plants and resilience to disturbance due to differing environmental characteristics and remaining perennial vegetation (Chambers, Miller, et al., 2014; Chambers, Pyke, et al., 2014). Elevation ranges from 270 m on the Columbia Plateau to 1800 m in the Great Salt Lake area. Annual precipitation ranges from 152–228 mm on drier sites to 228–381 mm on more mesic sites (Table 1). Soils have silty to coarse-loamy textures. None of the sites had a fire on record in the 50 years prior to study initiation. Livestock grazing was eliminated from all sites for at least one growing season before the project's start and through the duration of the study. Additional details about site selection and biophysical characteristics are in McIver and Brunson (2014).

Experimental design

At each site ($N = 6$), four woody fuel reduction treatment plots were delineated. Prior to treatment, measurement subplots were assigned within each planned treatment plot to capture the natural variation of perennial grass cover. One hundred potential subplot locations (0.1 ha) were randomly located to represent the range of variability in each treatment plot. Each of the 100 potential subplot locations was placed into one of three groups: perennial grass cover >20%, 10%–19%, or <10%. We then randomly selected 18 or 24 subplot locations from each group as permanent measurement subplots. At study initiation, subplots were dominated by shrubs and other native plants, but cheatgrass (*Bromus tectorum*) was also present in 81% of the subplots (Pyke et al., 2014).

At each site, four woody fuel reduction treatments were applied across the entire area of each treatment plot (prescribed fire, mechanical, tebuthiuron, or untreated control). Pretreatment data were collected and treatments were applied the same year (2006–2008), giving a staggered design (Loughin, 2006). All four treatments were applied the same year at a single site, but different sites had different treatment years (Table 1). Fire management officers for each prescribed fire treatment selected the plot based on safety, access, and existing control points. The other treatments were randomly applied to the remaining three plots at each site within a couple months of fire treatments. Plot sizes ranged from 20 to 81 ha, depending on individual land manager's willingness to remove sagebrush on their land (Pyke et al., 2014). Prescribed fire treatments were applied in late summer and early fall with the intention of consuming most woody vegetation. Where fires were incomplete, additional spot treatments were applied to scorch every shrub within each subplot. Mechanical treatments were applied to remove about 50% of shrub cover using a tractor with a rotary deck mower set at a height of 35.6–38.1 cm. Since sagebrush does not resprout, this treatment is expected to break up shrub cover and redistribute woody biomass to the soil surface. Tebuthiuron (trade name Spike 20P) was applied aerially at 1.68 kg ha^{-1} with a target objective of top killing 50% of shrubs. Half of the subplots within each treatment plot were also treated with imazapic (split-plot factor, trade name Plateau) with the goal of reducing annual grasses. Imazapic treatment rates ranged from 105 to 140 g ha^{-1}, depending on the amount of litter remaining after the fuel reduction treatments. Additional treatment details are in Pyke et al. (2014).

Field data collection

All field measurements were taken during the peak growing season (May–June) in the year immediately preceding treatment (Year 0) and annually following treatments. We report data from Years 0, 1, 2, 3, 6, and 10 following treatment. Shrub fuel was estimated in all plots using allometric relationships created for each site relating shrub canopy height, greatest width, and perpendicular width for all shrubs >15 cm tall and >10% live canopy (Bourne & Bunting, 2011). Herbaceous live, standing dead, downed wood, and litter fuel were measured in situ in eight 0.25-m^2 quadrats per subplot (detailed fuel collection methods in Stebleton & Bunting, 2009). Fuel samples were dried at 70°C to a constant mass and weighed. Plant cover was measured on five 30-m transects using the line-point method with 300 points per subplot (Herrick, 2017). Measurements were averaged across subplots receiving the same combination of woody fuel and imazapic treatments to give a plot-level estimate.

Fire behavior modeling

To estimate the impact that fuel reduction treatments had on fire behavior through the 10-year study period, we parameterized the fire behavior modeling system FCCS in the FFT (Prichard et al., 2013) using in situ data collected on each combination of woody fuel and imazapic treatment (prescribed fire, prescribed fire + imazapic, mechanical reduction, mechanical reduction + imazapic, tebuthiuron, tebuthiuron + imazapic, control, and control + imazapic) at each site in Years 0, 1, 2, 3, 6, and 10. Fire simulations were done at the treatment plot level, giving six replicate treatments for each treatment × year combination. The FFT estimates surface fire behavior using ecosystem-specific fuel data and environmental scenarios (i.e., moisture content through the typical fire season). For each site, fuelbeds were initialized using the standard fuelbed 56: sagebrush shrubland, and then, fuel parameters were customized to represent the quantity and arrangement of fuels in each treatment plot, giving individual custom fuel models for each treatment plot at each site for Years 0, 1, 2, 3, 6, and 10. Environmental scenarios in the FFT model are calculated by inclusion of a moisture-dampening coefficient, which has a linear relationship with model outputs, such that moist fuels generate reduced fire behavior metrics, and drier fuels result in more intense modeled fire behavior (Prichard et al., 2013). 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 (one-third cured and two-thirds 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). Slope assumptions for each model run were based on the average % slope (range 0%–10%; McIver & Brunson, 2014), and wind speed assumptions were based on the 80th percentile wind speed over the summer (June–September) from the nearest remote automated weather station for the study years. Independent model runs were done for each custom fuel model at each environmental scenario. Model outputs chosen to characterize fire behavior included rate of spread (ROS; in meters per minute), flame length (FL; in meters), and reaction intensity (RI; the rate of heat release per unit area of the flaming front; in kilowatts per square meter per minute) (Byram, 1959; Keeley, 2009).

Analysis

Treatment effects on fuel loads in Years 0, 1, 2, 3, 6, and 10 were tested using linear mixed models. Response variables were shrub fuel, herbaceous fuel, downed wood, litter, and total fuel. Sagebrush treatment (prescribed fire, mechanical, tebuthiuron, and control), imazapic treatment (split-plot factor, nested within sagebrush treatment), and time since treatment (hereafter, year) were fixed factors, and site was a random factor. Subplot was the subject factor in all models, and year was the within-subject factor. Additional fuel load metrics including cover and fuel height have previously been analyzed and published in Pyke et al. (2014), Bourne and Bunting (2011), Stebleton and Bunting (2009), and Wozniak and Strand (2019). The sensitivity of field fuel load parameters to model output can be found in Appendix S1.

Linear mixed models were also used to test for differences in the rate of spread, flame length, and reaction intensity (response variables) as a function of environmental scenario (i.e., fuel moisture conditions), sagebrush treatment, imazapic treatment, and year. Two-way interactions that included sagebrush treatment, imazapic treatment, and year were used to test differences in the duration of treatment effectiveness. Sites were treated as replicates, thus included in all models as a random factor. Subplot was the subject factor in all models. Significant differences among groups were determined using Tukey-Kramer honestly significant difference post hoc analysis. Analyses were performed with IBM SPSS 24 (IBM Corp, 2016).

RESULTS

Fuels summary

Total fuels averaged 7927 kg ha^{-1} (SE = 1140 kg ha^{-1}) across all plots with no treatment plot differences prior to treatments ($p = 0.35$; Figure 2). Shrub fuels made up the largest fuel component (53% of total fuel) with no pretreatment differences ($p > 0.05$). There were no plot differences prior to treatments for herbaceous (4% of total), litter (6%), or downed wood fuels (32%) ($p > 0.05$; Figure 2). Site did not significantly affect fuel loads for any fuel category (Table 2). Imazapic only affected herbaceous fuels, while the sagebrush treatments affected fuel components differently depending upon year (Table 2). Fuel load results are discussed by treatment to assist in understanding subsequent fire behavior analyses.

Controls

Total fuel in control plots did not vary through time ($p = 0.99$; Figure 2), but there was some interannual variability in fuel components. Shrubs significantly increased from pretreatment shrub fuel loads across control plots ($p = 0.03$). Herbaceous fuels were lower in Years 0, 1, and 6 than Years 2, 3, and 10 ($p < 0.05$). Litter fuel was a minor component in control plots and was lower in Years 3 and 6 than all other years ($p = 0.03$). Downed woody fuel loads had significant variability across years, with a decline in Year 3 compared to Years 0–2, and increased downed wood in Years 6 and 10 ($p = 0.02$).

Prescribed fire

Overall, prescribed fire was most effective at reducing fuel loads (Figure 2). Total fuel 1 year postfire was 49% of pretreatment and 60% of control fuels. Shrub fuel was reduced by 75% the year after prescribed fire. In the decade following prescribed fire, shrubs slowly recovered but only reached 35% of the pretreatment level and 27% of control plots after 10 years ($p = 0.02$). Prescribed fire resulted in a 40% initial reduction in standing herbaceous fuel ($p = 0.046$). In Years 2, 3, 6, and 10, herbaceous fuels in burned plots exceeded that of controls by 74%, 93%, 117%, and 61%, respectively ($p < 0.05$). Litter was reduced by 77% the first year following prescribed fire ($p = 0.01$) but was back to pretreatment levels 6 years later ($p = 0.24$). More than half of the downed woody surface fuels were consumed by fire and remained significantly lower through the study period ($p = 0.01$).

Mechanical

Mechanical treatments primarily shifted woody fuel from the shrub canopy to the herbaceous, downed wood, and litter layers but did not alter total fuel loads ($p = 1.00$; Figure 2). Shrub fuel decreased 63% in the first post-treatment year. Ten years later, shrub fuel was 43% lower

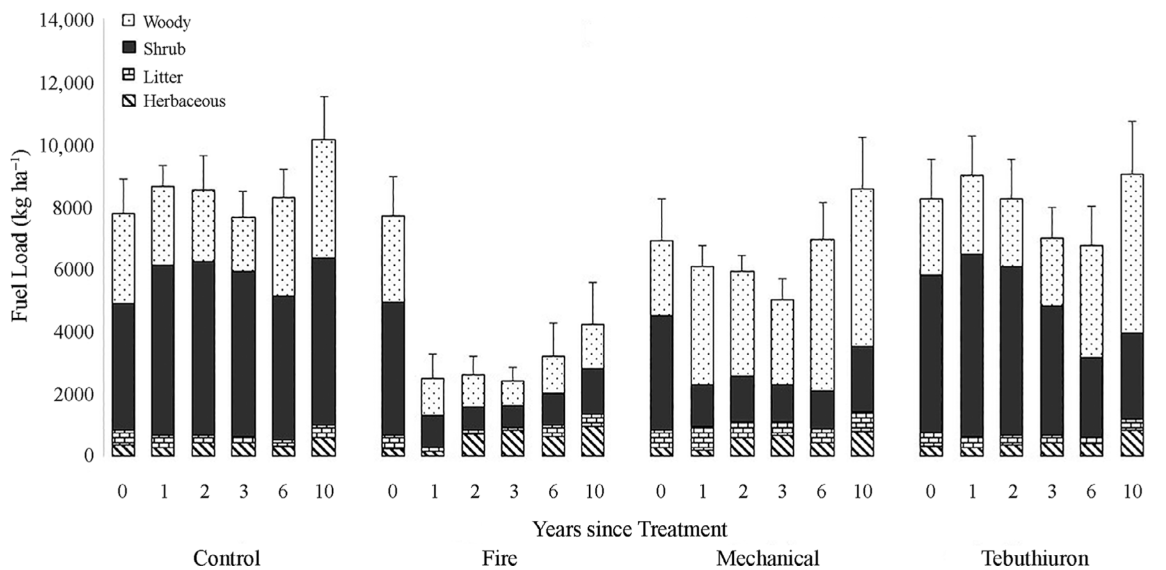

FIGURE 2 Mean herbaceous, litter, shrub, and downed woody debris (woody) fuel (in kilograms per hectare) in control, prescribed fire, mechanical, and tebuthiuron treatment plots 0, 1, 2, 3, 6, and 10 years posttreatment at six Wyoming big sagebrush sites across the Great Basin, USA. Error bars represent standard error for total fuel load

TABLE 2 Linear mixed models predicting total fuel, shrub fuel, herbaceous fuel, litter fuel, and downed wood fuel as a function of sagebrush fuel reduction treatment (Sage trmt: prescribed fire, mechanical, tebuthiuron, or untreated control), imazapic (split-plot treatment nested within sage trmt: treated or not treated), and year (years posttreatment [0, 1, 2, 3, 6, 10]) from six replicate sites across the Great Basin, USA

			Total fuel		Shrub		Herbaceous		Litter		Downed wood	
Source	**df_N**	**df_D**	***F***	***p***	***F***	***p***	***F***	***p***	***F***	***p***	***F***	***p***
Intercept	1	5	25.0	**<0.001**	22.5	**<0.001**	24.5	**<0.001**	21.8	**<0.01**	101.5	**<0.001**
Site	5	250	1.58	0.12	1.55	0.12	1.55	0.12	1.53	0.13	1.41	0.16
Sage trmt	3	250	8.11	**<0.001**	68.6	**<0.001**	9.78	**<0.001**	24.2	**<0.01**	29.3	**<0.001**
Imazapic	1	250	2.76	0.10	1.08	0.30	4.32	**0.04**	1.00	0.32	0.33	0.57
Year	5	250	0.000	1.00	2.21	0.05	42.72	**<0.001**	5.92	**<0.001**	8.33	**<0.001**
Sage trmt × year	15	250	0.000	1.00	3.42	**<0.001**	3.29	**<0.001**	2.45	**<0.001**	2.16	**<0.001**
Imazapic × year	5	250	0.000	1.00	0.08	1.00	1.91	0.09	0.63	0.70	0.21	0.96
Sage trmt × imazapic	3	250	1.18	0.32	0.39	0.76	0.19	0.90	0.19	0.90	0.04	0.99

Note: Bolded text denotes statistical significance.

compared to pretreatment level and 55% lower than controls ($p < 0.01$). Mechanical treatments initially reduced herbaceous fuel by 28% compared to pretreatment and 27% compared to controls, but by the second posttreatment year herbaceous fuel was more than double pretreatment levels and 39% higher than controls. By 10 years posttreatment, herbaceous fuel was 196% above pretreatment levels and 61% higher than controls ($p < 0.05$). Litter fuel increased in the first posttreatment year ($p < 0.01$), but litter in all other years was not significantly different from pretreatment ($p > 0.05$). Downed woody fuel increased by 57% in the year following mow treatments and by Year 10 was 110% higher than pretreatment and 25% higher than controls ($p > 0.05$).

Tebuthiuron

The tebuthiuron treatment did not modify total fuel loads at any time period following treatment ($p = 1.00$; Figure 2). Tebuthiuron had a delayed effect on shrub response, with no differences between treatment and control in Years 1, 2, or 3 following treatment ($p > 0.05$). At the sixth year posttreatment, shrub fuel had declined to 51% of the pretreatment level and 55% of controls and remained reduced at 10 years posttreatment ($p < 0.05$). No change in herbaceous fuel was observed the first 6 years posttreatment ($p > 0.05$). Herbaceous fuel increased by 181% in Year 10 from pretreatment levels ($p < 0.01$), but was not significantly different from control plots ($p = 0.30$). Litter fuel was significantly lower than pretreatment levels during Years 2, 3, and 6 posttreatment ($p < 0.01$) but was not significantly different from controls ($p = 0.35$). Downed woody fuel was no different from pretreatment levels in Years 1–3, or from controls in Years 1–6, but increased by Year 10 ($p < 0.05$), as shrub canopies declined.

Imazapic

Suppression of herbaceous vegetation using imazapic had no impact on total fuel, shrub, litter, or downed wood (Table 2). Herbaceous fuel was suppressed by 30% with imazapic but only in Years 2 and 3 posttreatment. There was no interaction among imazapic and sagebrush treatments for any fuel component.

Fire behavior

Modeled rate of spread, flame length, and reaction intensity increased as fuel moisture decreased and herbaceous fuel cured (environmental scenarios), which mimics the natural fire season from early season when herbaceous vegetation is still green to the end of season when all herbaceous vegetation is dead or dormant (Table 3, Figures 3–5). Additionally, site was a significant random effect on the rate of spread, flame length, and reaction intensity (Table 3).

Rate of spread

The rate of modeled fire spread was significantly affected by fire, mechanical, and imazapic treatments but not tebuthiuron treatments (Table 3). In pretreatment plots, rate of spread was not significantly different among treatments (Figures 3 and 6). In Year 1, the modified fuel beds in fire and mechanical treatments reduced rates of spread by 71% when green and 75% when cured. This effect

TABLE 3 Linear mixed models predicting rate of spread, flame length, and reaction intensity as a function of environmental scenario (% moisture by fuel class), sagebrush fuel reduction treatment (Sage trmt: prescribed fire, mechanical, tebuthiuron, or untreated control), imazapic (split-plot treatment nested within sage trmt: treated or not treated), and year (years post treatment [0, 1, 2, 3, 6, 10]) from six replicate sites across the Great Basin, USA

			Rate of spread		Flame length		Reaction intensity	
Source	**df_N**	**df_D**	***F***	***p***	***F***	***p***	***F***	***p***
Intercept	1	5	347.8	**<0.001**	356.2	**<0.001**	270.7	**<0.001**
Site*	5	1111	15.4	**<0.001**	35.1	**<0.001**	27.5	**<0.001**
Environmental scenario	3	1111	211.3	**<0.001**	212.2	**<0.001**	83.6	**<0.001**
Sage trmt	3	1111	58.5	**<0.001**	213.9	**<0.001**	133.7	**<0.001**
Imazapic	1	1111	9.4	**0.002**	1.7	0.20	0.1	0.71
Year	5	1111	45.8	**<0.001**	38.4	**<0.001**	48.7	**<0.001**
Sage trmt × year	15	1111	5.9	**<0.001**	11.4	**<0.001**	6.3	**<0.001**
Imazapic × year	5	1111	1.5	0.19	0.6	0.67	0.9	0.45
Sage trmt × imazapic	3	1111	0.4	0.74	1.2	0.31	1.9	0.13

Note: Bolded text denotes statistical significance. *Site is treated as a random factor.

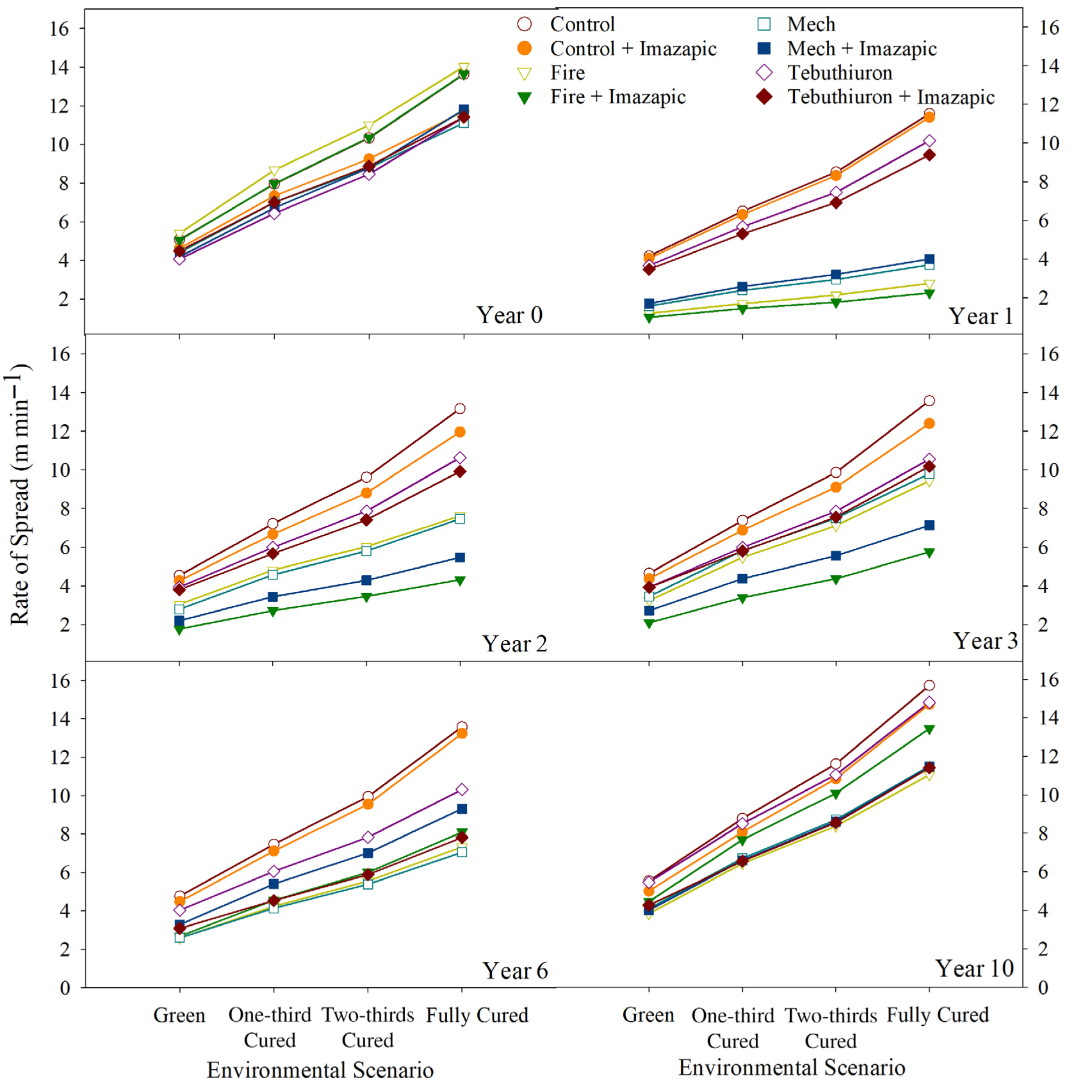

FIGURE 3 Modeled mean fire rate of spread (in meters per minute) in control, control + imazapic, prescribed fire, prescribed fire + imazapic, mechanical treatment, mechanical + imazapic, tebuthiuron, and tebuthiuron + imazapic plots across four curing scenarios (fully green, one-third cured, two-thirds cured, and fully cured) in SageSTEP plots across the Great Basin, USA, in Years 0, 1, 2, 3, 6, and 10 after treatment

generally was sustained, and by Year 10, fire and mechanical treatments maintained a lower rate of spread compared to control and tebuthiuron treatments although reductions were less pronounced than in Year 1. Imazapic treatments reduced modeled rates of spread by an additional 0.5 m min^{-1} relative to plots receiving only the shrub treatment ($p = 0.002$), but imazapic treatment effects did not differ across shrub treatments ($p = 0.74$) or years ($p = 0.19$).

Flame length

Fire and mechanical treatments modified modeled flame length, but tebuthiuron and imazapic had no effect on flame length (Table 3). In Year 0, there were no differences in modeled flame length across treatments (Figures 4 and 7). However, fire and mechanical treatments significantly reduced flame lengths by 55% in Year 1 compared to controls and tebuthiuron. By 10 years posttreatment, fire and mechanical treatments maintained lower modeled flame lengths than control treatments ($p < 0.05$).

Reaction intensity

Modeled reaction intensity was significantly affected by sagebrush fuel treatments depending on year but was not affected by the imazapic treatment (Table 3). Reaction intensity averaged 462.5 kW m^{-2} min^{-1} pretreatment

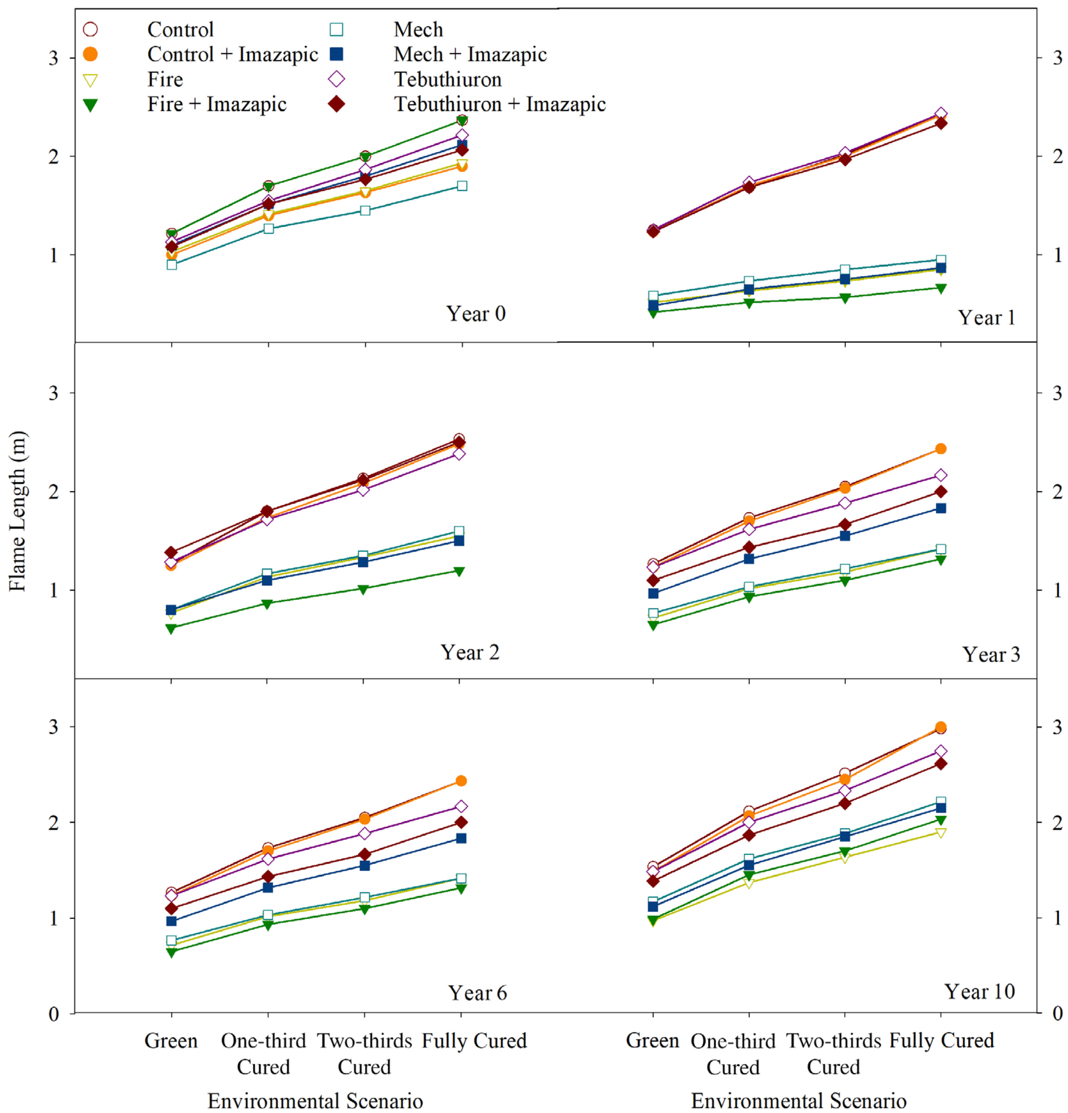

FIGURE 4 Modeled mean flame length (in meters) in control, control + imazapic, prescribed fire, prescribed fire + imazapic, mechanical treatment, mechanical + imazapic, tebuthiuron, and tebuthiuron + imazapic plots in SageSTEP plots across four curing scenarios (fully green, one-third cured, two-thirds cured, and fully cured) in SageSTEP plots across the Great Basin, USA, in Years 0, 1, 2, 3, 6, and 10 after treatment

when herbaceous fuels were fully green and reached 728.3 kW m^{-2} min^{-1} when fully cured (Figure 5). In Year 1, fire and mechanical treatments with and without imazapic reduced reaction intensity by 44% when fully green and 51% when fully cured ($p < 0.001$), but tebuthiuron treatments did not reduce reaction intensity. By Year 10, fire and mechanical treatments maintained a lower modeled reaction intensity than controls and tebuthiuron although less pronounced than previous years (Figures 5 and 8).

DISCUSSION

Reduction of woody fuels and subsequent release of the herbaceous understory from shrub competition resulted in changes in modeled fire behavior metrics (rate of spread, flame length, and reaction intensity) that differed by shrub fuel treatment. As hypothesized, prescribed fire plots had the greatest reductions in modeled fire behavior metrics, as this treatment was the only one to remove a large portion of the total fuel load from the sites (Pyke et al., 2014; Wozniak & Strand, 2019). Shrub and downed woody fuel remained present but was sparse throughout the 10 years after prescribed fire, while herbaceous fuel increased without increasing total fuel loads. This is consistent with two prescribed fire studies on similar sites, which showed large reductions in shrub cover following fire and slow recovery of the sagebrush canopy in the 17–18-year study periods (Reis et al., 2019; Wambolt & Payne, 1986). By contrast, both studies had large increases in perennial grass production immediately

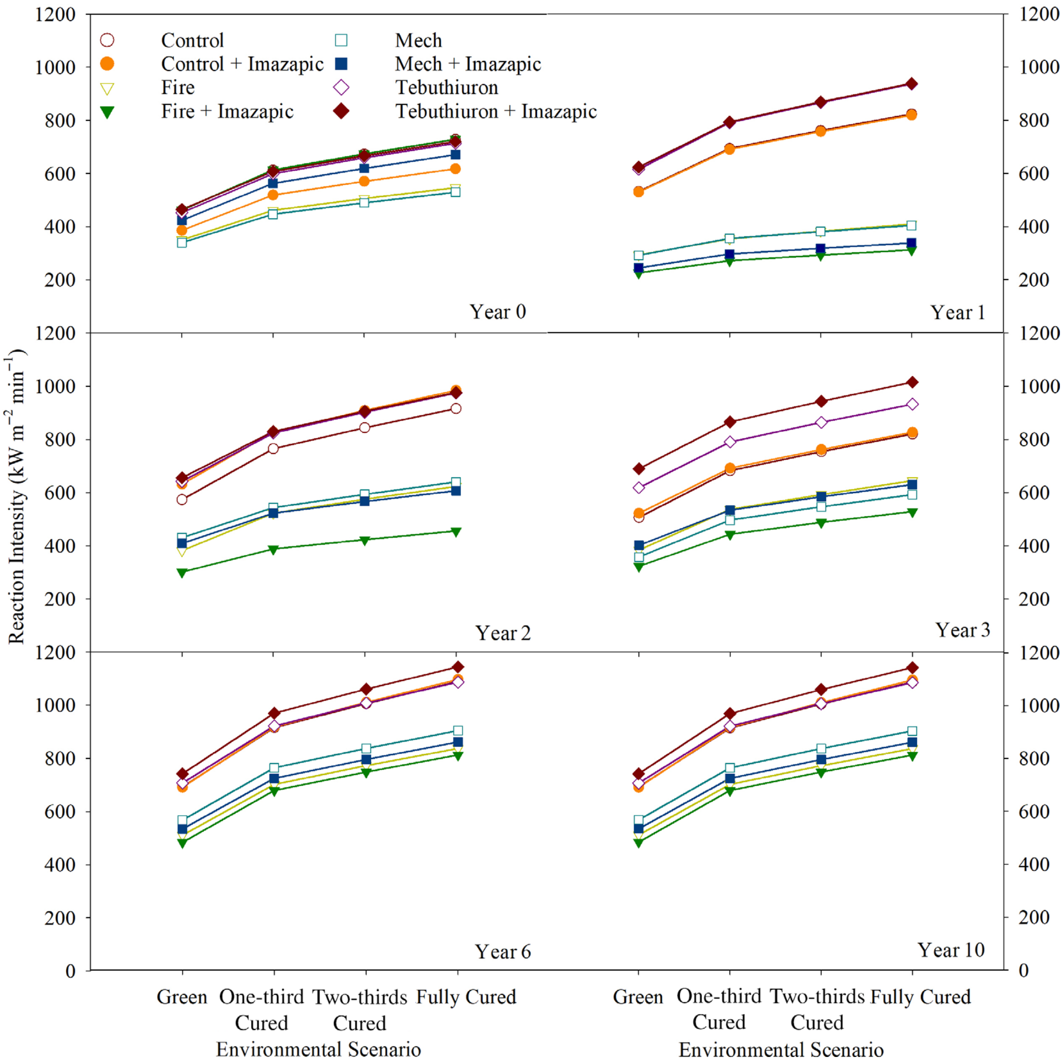

FIGURE 5 Modeled mean reaction intensity (in kilowatts per square meter per minute) in control, control + imazapic, prescribed fire, prescribed fire + imazapic, mechanical treatment, mechanical + imazapic, tebuthiuron, and tebuthiuron + imazapic plots in SageSTEP plots across four curing scenarios (fully green, one-third cured, two-thirds cured, and fully cured) in SageSTEP plots across the Great Basin, USA, in Years 0, 1, 2, 3, 6, and 10 after treatment

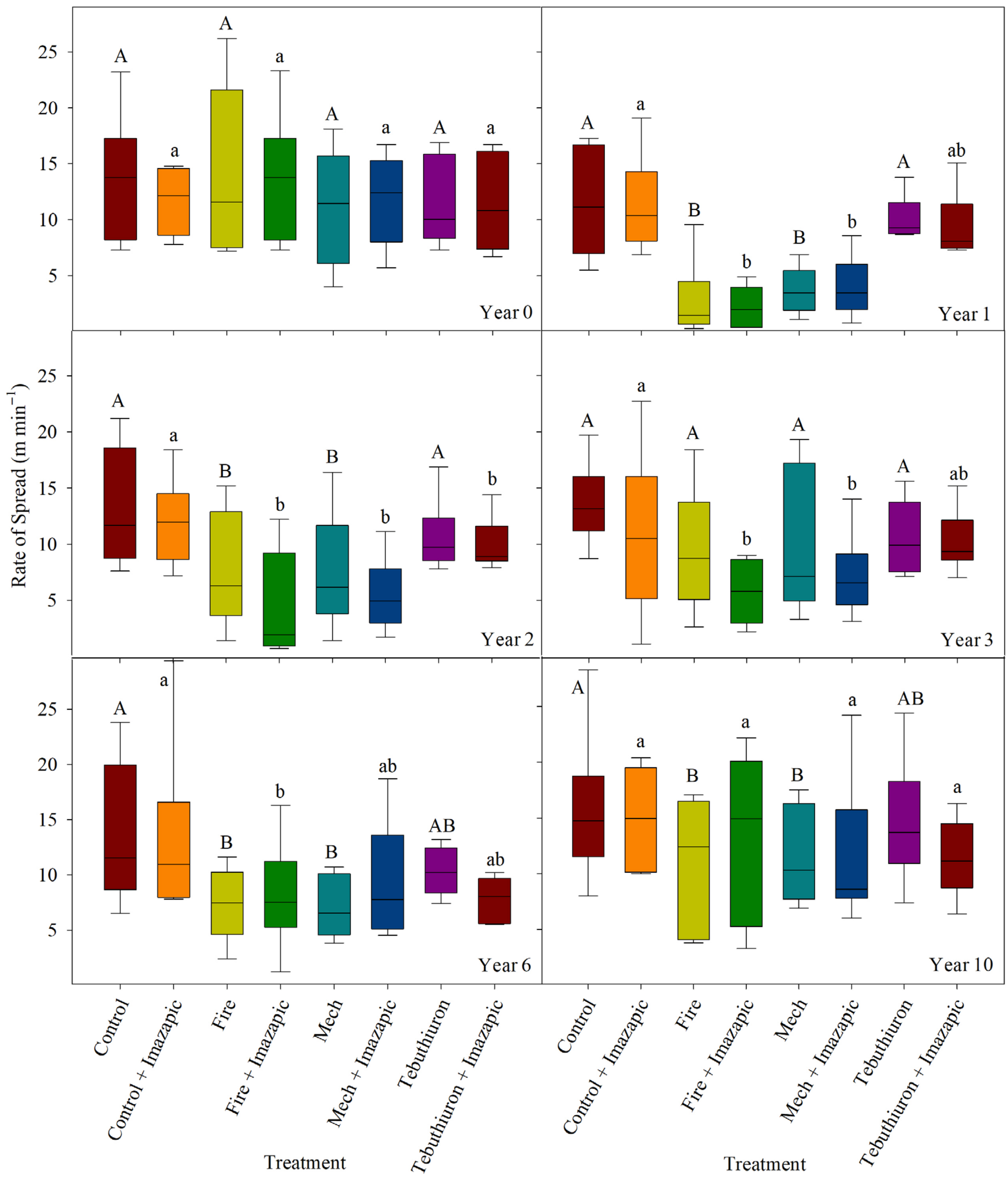

FIGURE 6 Rate of modeled fire spread (in meters per minute) in control, control + imazapic, prescribed fire, prescribed fire + imazapic, mechanical treatment, mechanical + imazapic, tebuthiuron, and tebuthiuron + imazapic plots in a fully cured moisture scenario in SageSTEP plots across the Great Basin, USA, in Years 0, 1, 2, 3, 6, and 10 after treatment. Lines within boxes represent treatment means; error bars represent one standard error; different upper case letters represent significant differences among treatments without imazapic; different lower case letters represent significant among between treatments with imazapic

following burn treatments that persisted through the 17–18-year study periods, which can result in increased fire behavior metrics (Brown, 1982; Ellsworth et al., 2020). The increases in herbaceous fuel in this study were primarily driven by perennial deep-rooted grasses through Year 6. In Year 10, perennial cover returned to levels seen in the control and there was a concomitant increase in annual grasses (Pyke et al., 2022). Fire has been described as a major catalyst for conversion of perennial vegetation to increasing annual invasive dominance in sagebrush ecosystems. However, postfire responses have ranged from a complete state change and annual grass dominance to positive native bunchgrass recovery without annual grass invasion depending on initial species composition (Creutzburg et al., 2012; Shinneman et al., 2019).

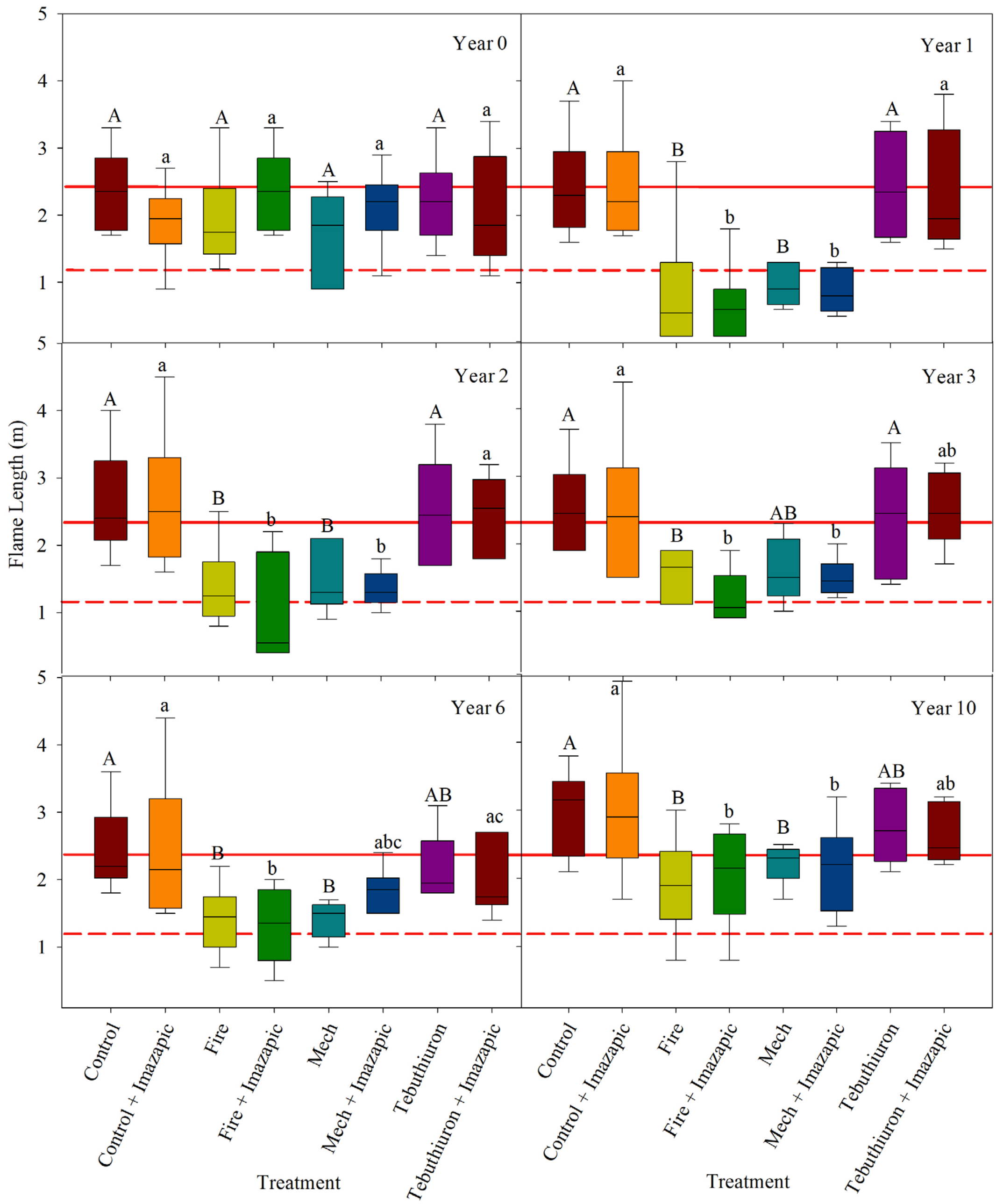

FIGURE 7 Flame length (in meters) in control, control + imazapic, prescribed fire, prescribed fire + imazapic, mechanical treatment, mechanical + imazapic, tebuthiuron, and tebuthiuron + imazapic plots in a fully cured moisture scenario in SageSTEP plots across the Great Basin, USA, in Years 0, 1, 2, 3, 6, and 10 after treatment. Lines within boxes represent treatment means; error bars represent one standard error; different upper case letters represent significant differences among treatments without imazapic; and different lower case letters represent significant differences among treatments with imazapic. Flame lengths less than 1.2 m (4 feet; dashed line) are typically fought with hand lines. Flame lengths between 1.2 and 2.4 m (4–8 feet) require heavy equipment, such as bulldozers, fire retardant, and helicopter drops. Flame lengths above 2.4 m (8 feet; solid red line) are indicative of crowning, spotting, and running fires that are difficult for suppression resources to safely control

Prescribed fire decreased modeled fire rate of spread, flame length, and reaction intensity 1 year postburn; however, long-term effects on the fire behavior metrics differed. While modeled fire spread increased to control levels by Year 3 and then slightly decreased again in Years 6 and 10, flame lengths remained consistently lower throughout the 10 years. The increase in herbaceous fuel likely increased fuel continuity assuring rapid fire spread, while the reduction of woody and shrub fuels likely decreased flame length. The reduction in reaction intensity with prescribed fire was short-lived in this study, and other studies have found grasses to even

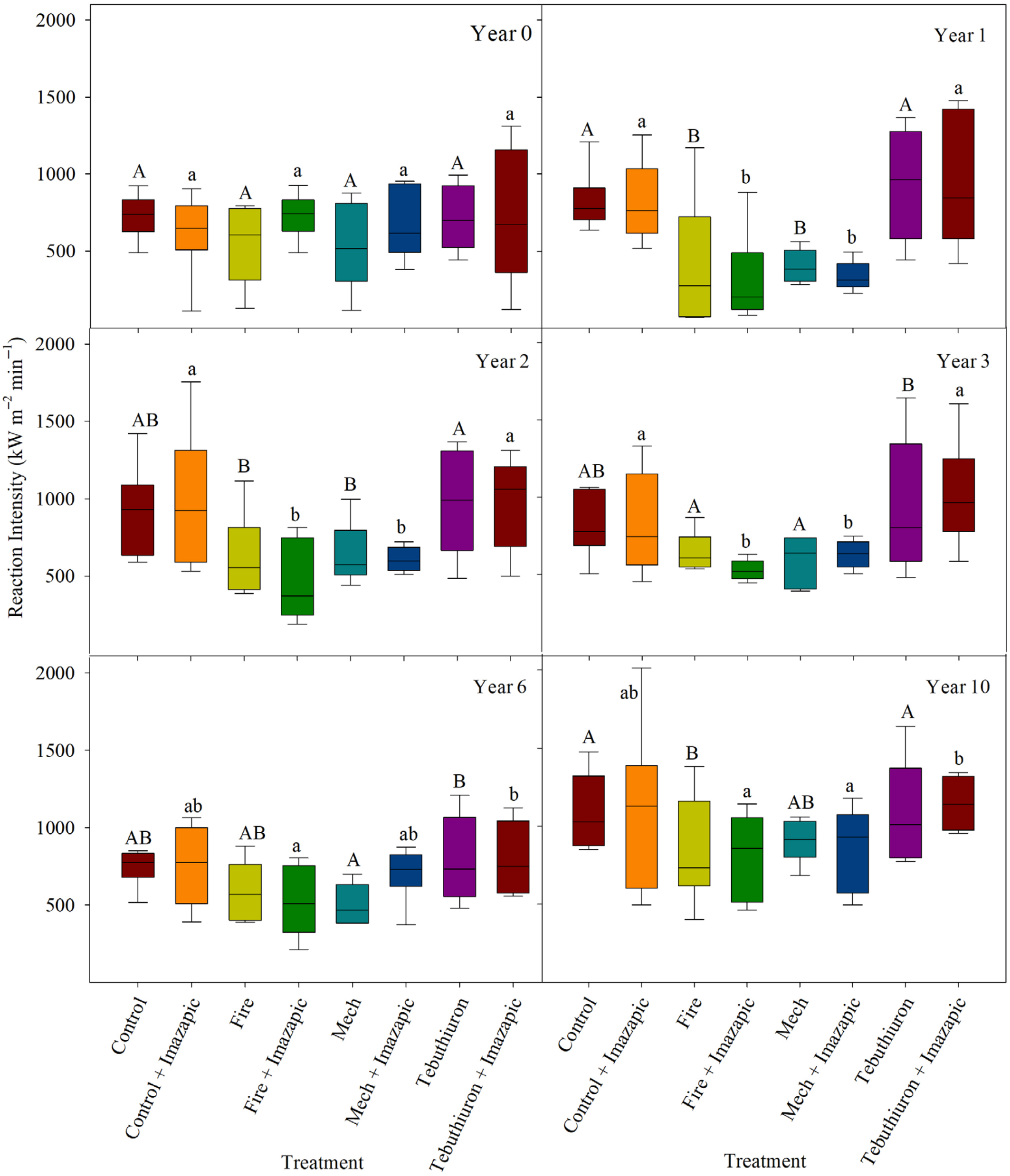

FIGURE 8 Reaction intensity (in kilowatts per square meter per minute) in control, control + imazapic, prescribed fire, prescribed fire + imazapic, mechanical treatment, mechanical + imazapic, tebuthiuron, and tebuthiuron + imazapic plots in a fully cured moisture scenario in SageSTEP plots across the Great Basin, USA, in Years 0, 1, 2, 3, 6, and 10 after treatment. Lines within boxes represent treatment means; error bars represent one standard error; different upper case letters represent significant differences among treatments without imazapic; and different lower case letters represent significant differences among treatments with imazapic

increase reaction intensity, particularly on more productive sites (Ellsworth et al., 2020; Wragg et al., 2018).

Mechanical treatments redistributed woody fuel by moving some woody fuel from the live shrub canopy to the soil surface, but did not decrease total fuel loads. For the first year, mowing suppressed herbaceous fuels, but herbaceous productivity exceeded pretreatment or control plots in the second year and remained higher at 10 years posttreatment. We anticipated a reduction only in modeled flame length due to the mow treatment, but we found that mowing was nearly as effective as prescribed fire at reducing reaction intensity and fire rate of spread. However, the reduction in modeled fire spread and reaction intensity lessened in Year 3 onward, whereas reduced modeled flame lengths were maintained the entire 10 years. Mow treatments reduce vegetation height, thus reducing flame lengths; however, since total fuels were not reduced, the increases in surface fuels (primarily herbaceous) allowed modeled fire to spread with similar intensity. Similar to a postfire response, the disturbance caused by mowing can enhance invasive grasses and forbs and thus herbaceous fuels (Davies, Bates, & Nafus, 2012; Pyke et al., 2014; Swanson et al., 2018). Therefore, mowing is not a good choice for sagebrush shrublands with degraded understories (Davies, Bates, & Nafus, 2012). In contrast, mow treatments may be a viable option to reduce fire risk where the native understory is in good condition (Pyke et al., 2014; Swanson et al., 2018).

Herbicide treatments were ineffective at reducing fuels and/or fire behavior metrics. Tebuthiuron, which targeted broad-leaved shrubs, had no initial effects in the first 2 years and minor delayed mortality beginning in the third posttreatment year. Dead shrubs remained standing through the 10 years, so fuel structure was not significantly altered. While intended to reduce annual grasses, we found that imazapic only had a short term (2–3 years) effect on herbaceous fuels and thus only a slight reduction on modeled fire spread. Pyke et al. (2022) found that imazapic had negative effects on cheatgrass only up to Year 3 at these sites, and this short-lived annual grass suppression has been found elsewhere (Davison & Smith, 2007; Elseroad & Rudd, 2011). Although there was no imazapic effect on deep-rooted bunchgrasses or annual forbs (Pyke et al., 2022), imazapic had unexpected negative consequences on shallow-rooted Sandberg bluegrass (*Poa secunda*). Imazapic has been found to have negative effects on native forb (Baker et al., 2009) and shrub germination although not established shrubs (Owen et al., 2017).

Prescribed fire and mowing treatments modified modeled fire behavior with implications for suppression response throughout the 10-year period, as hypothesized. Fires generating flame lengths of less than 1.2 m can be approached safely from the fire front using hand crews, fire trucks, and hose lays, and a hand line cleared of all burnable material is expected to contain the fire spread (Andrews et al., 2011). When flame lengths reach 1.2–2.4 m, the fire intensity becomes too great to be fought safely from the flaming front, and air support (i.e., water drops using helicopters and retardant drops using fixed-wing airplanes) and heavy equipment (i.e., bulldozers) are needed to contain the fire (Andrews & Rothermel, 1982; Brown, 1982). Fires with flame lengths over 2.4 m generate high intensities, which are difficult to control and generally require indirect suppression tactics, such as backburning, air support, and building fire lines well ahead of the flaming front (Brown, 1982; National Wildfire Coordinating Group, 2014). Prior to treatments, almost all plots across the network exceeded the 1.2-m flame length threshold (Figure 7) for direct attack in the fully cured moisture scenarios, thus requiring indirect attack. Prescribed fire and mow plots consistently kept modeled fire intensity reduced enough that direct suppression activities were possible, which ultimately reduces resources needed, total fire size, and suppression costs. Our results confirmed our prediction that modeled fire behavior would increase across all treatments with increased fuel curing, mimicking increased risk of higher intensity fire later in the fire season (Strand et al., 2014). This is a function of decreasing fuel moisture from early to late season. When fuel moisture content is high, ignition is difficult, and heat energy is used to evaporate the moisture in the fuel before the fire can spread. By contrast, cured fuels contain low moisture, so the fire's energy goes directly into the active fire front (Brown, 1982; Cohen & Deeming, 1985), generating more intense fire behavior and often larger fires (Qi et al., 2016; Wright, 2013; Wright & Prichard, 2006).

Management implications

The efficacy and spatial arrangement of fuel reduction treatments, as well as initial site conditions are highly influential on potential for access and fire suppression, as well as for protecting valuable natural resources. Treatment effectiveness may depend on weather conditions for prescribed burning, appropriate use of machinery, and adequate herbicide application. Additionally, practitioners should consider the broader landscape to strategically place treatments where they are readily accessible by fire personnel and take advantage of existing roads, prevailing wind direction, and local topography to best protect valued resources. Repeated treatments will need to be considered when initial treatment begins to lose effectiveness, as we begin to see near the later years of this study. Finally, understanding pretreatment condition and inherent site characteristics, such as resilience to disturbance and ability to resist invasion, can help guide placement of treatments and estimate the likelihood that the fuel treatments will be ultimately beneficial rather than contribute to further degradation (Chambers et al., 2019; Chambers, Miller, et al., 2014; Shinneman et al., 2019).

In recent years, management efforts have focused on simultaneously preventing fire spread while managing for a desirable sagebrush community composition and wildlife habitats. While there are both operational and ecological benefits from fuel reduction treatments in some cases, in other areas the disturbance from treatments has led to a decline in habitat quality for shrub-associated wildlife species of conservation concern, such as pygmy rabbits (Pierce et al., 2011) and greater sage grouse (Beck et al., 2012). On the other hand, wildfire itself and postfire annual grass invasions have also led to declines in seed-dispersing small mammals (Ostoja &

Schupp, 2009) and birds (Coates et al., 2016; Holmes & Robinson, 2013; Knick & Rotenberry, 2000), and modify forage availability for wildlife (Schuyler et al., 2021). Thus, fragmenting late successional sagebrush canopy to mitigate fire risk to avoid potential future loss of sagebrush has been aptly described as a conservation paradox (Shinneman et al., 2018).

Caution should be exercised in interpreting modeled fire behavior metrics. While fire behavior models are useful, particularly in evaluating among treatment alternatives, there is an infinite combination of fuel parameter and moisture scenarios in reality, and only a limited subset of those have been modeled and validated during wildfires. The three standard fuel models most commonly used to represent generalized sagebrush steppe fuel loads (GS1, shrubs are about 0.3 m [1 foot] high and low grass load; GS2, shrubs are 0.3–1 m [1–3 feet] high and moderate grass load; and SH2, shrubs cover at least 50% of the site; grass sparse to nonexistent; moderate fuel load; Scott & Burgan, 2005) were modeled using BehavePlus 6.0 (Heinsch & Andrews, 2010) across four curing scenarios (fully green, one-third cured, two-thirds cured, and fully cured) and overlaid on a random subset of 10% of the model runs from this study (see Appendix S1), showing reasonable agreement across models for these fuel types and giving confidence to modeled output. Anomalous or extreme weather conditions such as >95% fire weather, firebrand spread, and subsequent spotfire ignition, shifts from headfire to backing or flanking fire spread, and convection columns and fire whirls are outside of the modeled conditions and will result in more extreme fire behavior than the model predicts.

This work provides the first information on the long-term effectiveness of fuel reduction treatments at mitigating modeled fire behavior in sagebrush ecosystems. Implementation of these fuel treatments, however, requires understanding how both plant and animal communities respond to fuel treatments, as well as future implications for fire regimes. The locations and distributions of these treatments, as well as potential additional treatment types currently in use, such as targeted grazing, repeat herbicide, greenstripping, and roadside disking, need to be considered.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Shaff, 2020) are available from the USGS data repository: https://doi.org/10.5066/P90APJ96.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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