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Region-Wide Ecological Responses of Arid Wyoming Big Sagebrush Communities to Fuel Treatments

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Abstract

If arid sagebrush ecosystems lack resilience to disturbances or resistance to annual invasives, then alternative successional states dominated by annual invasives, especially cheatgrass (*Bromus tectorum* L.), are likely after fuel treatments. We identified six Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young) locations (152–381 mm precipitation) that we believed had sufficient resilience and resistance for recovery. We examined impacts of woody fuel reduction (fire, mowing, the herbicide tebuthiuron, and untreated controls, all with and without the herbicide imazapic) on short-term dominance of plant groups and on important land health parameters with the use of analysis of variance (ANOVA). Fire and mowing reduced woody biomass at least 85% for 3 yr, but herbaceous fuels were reduced only by fire (72%) and only in the first year. Herbaceous fuels produced at least 36% more biomass with mowing than untreated areas during posttreatment years. Imazapic only reduced herbaceous biomass after fires (34%). Tebuthiuron never affected herbaceous biomass. Perennial tall grass cover was reduced by 59% relative to untreated controls in the first year after fire, but it recovered by the second year. Cover of all remaining herbaceous groups was not changed by woody fuel treatments. Only imazapic reduced significantly herbaceous cover. Cheatgrass cover was reduced at least 63% with imazapic for 3 yr. Imazapic reduced annual forb cover by at least 45%, and unexpectedly, perennial grass cover by 49% (combination of tall grasses and Sandberg bluegrass [*Poa secunda* J. Presl.]). Fire reduced density of Sandberg bluegrass between 40% and 58%, decreased lichen and moss cover between 69% and 80%, and consequently increased bare ground between 21% and 34% and proportion of gaps among perennial plants > 2 m (at least 28% during the 3 yr). Fire, mowing, and imazapic may be effective in reducing fuels for 3 yr, but each has potentially undesirable consequences on plant communities.

Key Words: *Bromus tectorum*, resistance and resilience, fire, mowing, tebuthiuron, imazapic

INTRODUCTION

Sagebrush ecosystems are prevalent in the western United States, covering nearly 500 000 km^2 (Miller et al. 2011). Within the sagebrush biome, Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) communities occur on the most arid and some of the least productive lands. Shifts among community phases within reference states were historically driven by infrequent fires (around 100 yr; Baker 2011; Miller et al. 2011). These fires likely burned in mosaics, where fires removed woody species and shifted burned plant communities from shrub grassland mixtures to perennial grasslands with scattered sagebrush (Miller et al. 2011). After fires, cool-season bunchgrasses tended to dominate herbaceous component, whereas forbs likely were only minor components (generally less than 10% cover) within reference or relic communities (Franklin and Dyrness 1988; Miller et al. 2011).

Historical fire dynamics have been disrupted by land uses and introductions of fire-adapted plants. Since Euro-American settlement, livestock grazing supplanted fire as the most pervasive driver of community dynamics within Wyoming big sagebrush communities. Historically, these lands experienced inappropriate grazing practices that tended to shift plant communities from shrub-grass codominance to largely shrub-dominated communities with a minor component of perennial grass (Mack 1986; Knapp 1996; Miller et al. 2011). Introductions of invasive annual grasses such as cheatgrass (downy brome, *Bromus tectorum* L.) in the late 1800s quickly led to cheatgrass dominance of interspaces among perennial plants and to reductions in biological soil crusts that once dominated these positions within communities (Miller et al. 2011). Infilling of spaces between perennial plants led to a continuous fuel source that changed fire dynamics within these communities, substantially reducing intervals between fires (Brooks et al. 2004; Link et al. 2006; Miller et al. 2011).

Land managers are concerned about reducing the extent of wildfires, because fires threaten wildlife habitat and increase

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exotic species. Fuel management within Wyoming big sagebrush communities has several purposes (Pyke 2011). Reduction in woody plant dominance, most often represented by sagebrush, reduces fire intensity and severity. Fuel breaks that provide anchor points for fire suppression or allow fire managers to compartmentalize fires in smaller blocks are typical fuel treatment objectives (D. Havelina, Bureau of Land Management, National Interagency Fire Center, Boise, ID, USA, pers. comm.). In addition, fuel treatments along roads or travel corridors reduce the potential for fire spread into adjacent sagebrush communities, and reductions of annual grasses may decrease fire spread and size. In addition, there may be a release of fire-adapted perennial plants, increasing the opportunity for restoration of important species.

Fuel manipulations within Wyoming big sagebrush communities may be risky when cheatgrass is present, even if cheatgrass is not dominant before treatments. Prescribed fires potentially increase N availability (Rau et al. 2011), which may favor those cheatgrass seedlings from which seeds escape the fire and germinate (Miller et al. 2013). Mowing tends to reduce woody plant cover and may thin woody plant density if mowing heights are low (Davies et al. 2011; Hess and Beck 2012). However, with lower mowing height and more undulating soil surfaces, there is a risk of soil disturbance. This may create vegetation voids and safe sites for cheatgrass establishment and growth. In spite of this, shifts from cheatgrass-dominated to perennial-plant–dominated communities with adequate time indicate that some of these communities may have sufficient resilience to recover (Allen-Diaz and Bartolome 1998; Rew and Johnson 2010). Shrub reductions through chemical thinning with tebuthiuron modify fuel structure as dead plants or branches lose their leaves to the litter layer while increasing herbaceous plants that are released from competition (Olsen and Whitson 2002). Imazapic may have the potential for multiple years with reduced annual grass cover, thus likely reducing fine fuels after other fuel treatments are applied (Vollmer 2005; Davidson and Smith 2007), but other studies warn of death to or reduced cover of desirable herbaceous plants (Baker et al. 2009; Elseroad and Rudd 2011).

Most previous studies of sagebrush community dynamics consist of case studies within a local area on a single ecological site or across many locations with divergent dominant species; this may limit comparability (Allen-Diaz & Bartolome 1998; West and York 2002; Davies et al. 2011; Beck et al. 2012). To our knowledge, no one has attempted to apply consistent fuel-management techniques throughout a geographic region with the use of treatments and replicated sites with similar ecological potentials. Fuel treatments tend to disturb perennial bunchgrasses less than shrubs in the short term (Pyke et al. 2010); therefore adequate cover of perennial bunchgrasses may compensate for the loss of shrub cover after fuel treatments. Without adequate perennial bunchgrass cover, death of sagebrush individuals may increase spatial distances among perennial plants, leading to a potential increase in cheatgrass cover (Reisner 2010; Reisner et al. 2013). We wished to determine if pretreatment spatial distances of perennial plants might influence the posttreatment plant or soil surface responses after fuel treatments. In addition, we evaluated the impact of a factorial combination of fuel treatments (prescribed fire, mowing, tebuthiuron, and no treatment, with and without applications of imazapic) on biomass, cover, and density of major plant species or life forms (Wyoming big sagebrush, perennial grasses, annual and perennial forbs, and cheatgrass) as well as important land health indicators (cover of mosses and lichens, and of bare mineral soil) over 3 yr.

We addressed the following specific questions relating to the application of fuel treatments on relatively intact Wyoming big sagebrush-grassland communities across six sites in the northern Intermountain West: 1) what is the effect of fuel treatments on the cover, biomass and density of native perennial plants and on the invasive annual grass, cheatgrass; 2) can variance in responses be reduced by including the number or size of basal gaps among perennial plants; 3) do responses change over the first 3 yr after treatments; and 4) what is the effect of fuel treatments on indicators previously shown as being positively related to cheatgrass cover?

We anticipated that treatment applications would affect differentially not only species relative dominance (cover and biomass), but also the size and distribution of gaps among perennial vegetation and the cover of biological soil crusts. We hypothesized that prescribed fire would be the most disruptive to the community, because it not only temporarily reduces sizes of surviving plants, but it also kills some plants, creating space for surviving plants to expand and new plants to recruit. If communities are resilient, surviving perennial plants should increase their size relative to untreated areas, reducing indicators of potential cheatgrass expansion (interperennial plant gaps and bare soil). Three years is a typical monitoring and research period for tracking vegetation dynamics after treatments for drawing short-term conclusions; therefore, we examined these dynamics and report these initial findings.

METHODS

Our experiment was conducted on the seven locations of the SageSTEP 'sage-cheat' experiment (see map in McIver and Brunson 2014). The Roberts Idaho location was removed from analysis and will not be discussed further for two reasons: 1) a poor burn throughout the fire treatment; and 2) a wildfire that burned the majority of the location in the fourth year of study. Soils at the six remaining locations ranged from silty to coarse–loamy textures at elevations between 270 m in the Columbia Plateau of Washington to 1 800 m in the Great Salt Lake area of Utah (Table 1). Because of delayed timing of the fire treatment at Moses Coulee, this treatment was treated as missing for Moses Coulee, and was accounted for by the use of a maximum likelihood estimation in the analysis. Locations occurred in four states (Nevada, Oregon, Utah, and Washington) and covered five major land resource areas (Columbia Basin, Columbia Plateau, Malheur High Plateau, Owyhee High Plateau, and Great Salt Lake) (US Department of Agriculture, Natural Resources Conservation Service [USDA NRCS] 2006) and three Level III Ecoregions (Columbia Plateau, Northern Basin and Range, Central Basin and Range) (US Environmental Protection Agency [US EPA] 2011). None of these locations had burned in the last 50 yr, based on fire records from land owners. Cattle grazing (moderate utilization) was halted at least one growing season before treatments were applied. Grey

Table 1. Site locations, elevations, major land resource areas (MLRAs), EPA ecoregions, soil textures, soil mapping units, and ecological sites.[1]

Site	Latitude/ longitude	Elevation (m)	MLRA	Level III ecoregion	Soil surface texture	Soil map units (slope; soil temperature: moisture regime)	Ecological site (site identification number)
Rock Creek	lat 42°43′17″N long 119°29′32″W	1 510	Malheur High Plateau	Northern Basin and Range	Fine–loamy to loamy mixed	Brace-Raz complex (2–15%; frigid: xeric)	Shallow loam 8–10 P.Z. (R024XY017OR)
Gray Butte	lat 42°42′45″N long 119°26′27″W	1 500	Malheur High Plateau	Northern Basin and Range	Fine loamy to loamy mixed	Brace-Raz complex (2–15%; frigid: xeric)	Shallow loam 8–10 P.Z. (R024XY017OR)
Moses Coulee	lat 47°37′17″N long 119°40′51″W	520	Columbia Plateau	Columbia Plateau	Loamy–skeletal to course–loamy over sandy	Strat-Tubsprings-Skaha complex (0–15%; mesic: aridic)	Stony 9–15 P.Z. (R008XY202WA) Dry Loamy 9–15 P.Z. (R008XY101WA) Very Shallow 9–15 P.Z. (R008XY301WA)
Saddle Mountain	lat 46°44′32″N long 119°20′29″W	270	Columbia Basin	Columbia Plateau	Course–silty	Warden very fine sandy loam (0–5%; mesic: xeric)	Loamy 6–9 P.Z. (R007XY102WA)
Onaqui	lat 40°12′4″N long 112°27′41″W	1 800	Great Salt Lake Area	Central Basin and Range	Fine–loamy	Taylors flat loam (1–5%; mesic: xeric)	Semidesert loam (R028AY220UT)
Owyhee	lat 41°23′16″N 116°52′54″W	1725	Owyhee High Plateau	Northern Basin and Range	Fine-silty to fine loamy	Dacker-Zevadez association (0–4%; mesic: xeric)	Loamy 8–10 P.Z. (R025XY019NV)

[1]P.Z. indicates precipitation zone.

Butte and Rock Creek are on the Hart Mountain National Antelope Refuge, OR, and have been free of livestock grazing for nearly 10 yr. Effective precipitation ranged from drier sites (152–228 mm) to moister sites (228–381 mm).

Before fuel treatments were applied, vascular plant communities had similar dominant species, though they occurred on various ecological sites, major land resource areas, and ecoregions (Table 1). Soils of most sites were listed as xeric soil moisture regimes with the exception of the drier soils of Moses Coulee, which were aridic. Soil temperature regimes at four of these sites were mesic and the other two were frigid. Locations were selected with environmental conditions representative of areas that are susceptible to cheatgrass dominance if they became degraded, but with sufficient perennial vegetation to be resistant to cheatgrass dominance and to be resilient to fuel treatments based on perennial plant cover and spatial arrangements (Chambers et al. 2007; Condon et al. 2011; Reisner et al. 2013). All locations and subplots contained Wyoming big sagebrush, and at least 81% of subplots contained cheatgrass. Cheatgrass was initially a subordinate in cover to shrubs and perennial grasses. All locations had at least some subplots with Sandberg bluegrass (*Poa secunda* J. Presl.), squirreltail (*Elymus elymoides* [Raf.] Swezey), and green rabbitbrush (*Chrysothamnus vicidiflorus* [Hook.] Nutt.) (Table 2).

Experimental Design and Measurements

The experiment was a randomized block split plot with repeated measures. The six locations were blocks. These blocks consisted of four woody fuel treatment whole plots (fire, mowing, tebuthiuron, and untreated) that were split into two annual plant fuel treatments (imazapic and no imazapic) where measurements were conducted either 1 yr pretreatment or for 3 yr posttreatment (year was repeated-measure factor). This yielded 46 experimental units pretreatment (some missing) (six sites * four treatments [one site with 3] * two split treatments; Appendix III, analysis of variance [ANOVA] pretreatment, available online at http://dx.doi.org/10.2111/REM-D-13-00090.s1) and 138 experimental units (six sites * four treatments [one site with three] * two split treatments = 46 experimental units per year * 3 yr; Appendix III ANOVA posttreatment, available online at http://dx.doi.org/10.2111/REM-D-13-00090.s1).

Locations ranged from roughly 120 ha to 325 ha, depending on the willingness of land managers to remove sagebrush given that they are currently trying to maintain as much as possible. In addition, some managers were reluctant to treat large areas

Table 2. Species constancy (% of measurement subplots with species present) among sites. Structural/functional groups were AG indicates annual grass; PSG, perennial short grass; PTG, perennial tall grass; and S, shrub.

Species (structure/functional group)	Owyhee	Onaqui	Gray Butte	Rock Creek	Saddle Mountain	Moses Coulee
Achnatherum hymenoides (PTG)	49	39	36	24	0	7
Achnatherum thurberiana (PTG)	16	0	35	92	71	1
Bromus tectorum (AG)	81	94	100	97	100	100
Chrysothamnus vicidiflorus (S)	22	31	47	28	8	19
Elymus elymoides (PTG)	100	99	99	100	14	17
Poa secunda (PSG)	100	100	43	100	100	100
Artemisia tridentata wyomingensis (S)	100	100	100	100	100	100

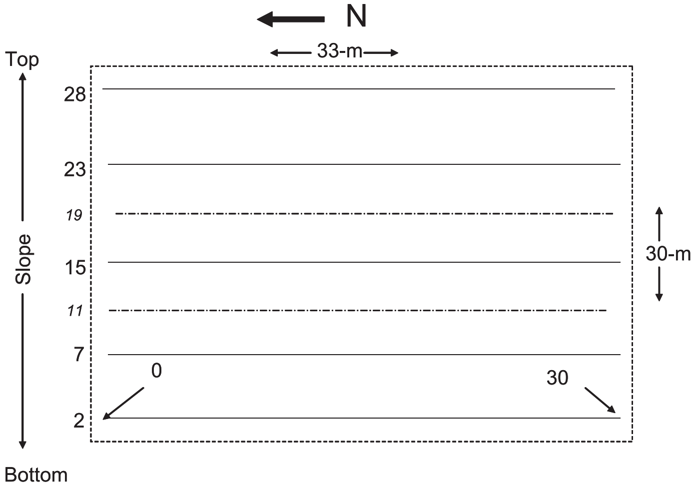

Figure 1. Measurement subplots were oriented with the short axis (baseline) extending parallel to the slope, unless there was no slope in which they faced east to west. Cover (solid lines) and biomass transects (dashed lines) were 30 m long and ran perpendicular to the baseline and were interior of a 1.5-m buffer.

because of the risk of cheatgrass increasing on their lands. Each location was divided into four equal-sized woody fuel treatment whole plots that ranged from 20 ha to 81 ha each. These were arranged to provide similar soils that supported the same ecological site across all treatments in a block (location) (Natural Resources Conservation Service, https://esis.sc.egov.usda.gov/ESIS/About.aspx; accessed 29 April 2013).

Responses were measured in either 9 or 12 measurement subplots (Fig. 1) within an experimental unit. These subplot response measurements were averaged before analysis. To ensure that we captured the natural variation of perennial grass cover among measurement subplots within each treatment (woody fuel treatment by annual plant treatment experimental unit), we conducted a rapid assessment early in the growing season. An initial 100 randomly selected subplots (30 m × 33 m) in each woody fuel treatment plot were arranged ordinally based on visual estimates of perennial grass cover and then divided into roughly three equal-sized groups based on this estimated cover. Then equal numbers (six at four sites and eight at two sites) were selected randomly from each group to give 18 or 24 subplots within each woody fuel treatment, of which half (three or four per group, yielding 9 or 12 subplots) were assigned to the annual plant fuel treatment within each woody fuel treatment (Appendix I, available online at http://dx.doi.org/10.2111/REM-D-13-00090.s1). This stratified sampling scheme was imposed to produce a balanced sample (sensu Stevens and Olsen 2004) with respect to perennial grass cover with equal probability of inclusion among subplots.

Eight fuel treatments were applied at each location. Four woody fuel treatments (prescribed fire, mowing, tebuthiuron application, and an untreated control) per location were assigned to whole plots and two annual plant fuel treatments (imazapic and no imazapic applications) were split plots within each whole plot. This combined woody fuel and annual plant fuel treatment was our experimental unit for the study ($n=7$). Fire management officers who conducted prescribed fires chose whole plots assigned to fire treatments based on their safety needs. The other three treatments were assigned randomly to remaining plots. Prescribed fires were conducted in late summer through early autumn (late August through October) and were intended to eliminate shrubs and woody debris totally. Fire subplots that did not receive a complete burn of all shrubs with the initial fire immediately received spot fires of individual shrubs to blacken leaves and stems of all shrubs. Mowing (height of 30.5 cm to 38.1 cm) of plants was done with a power take-off rotary deck mower (3.7-m diameter) pulled by a wheel-driven tractor. Tebuthiuron at 1.68 $kg \cdot ha^{-1}$ (Spike 20P®) was applied aerially by either fixed-wing aircraft or helicopters. Both mowing and tebuthiuron were intended to change fuel structure by reducing woody plant cover by approximately 50%.

Half of the subplots (9 out of 18 or 12 out of 24, depending on the location) within a woody fuel treatment received an additional imazapic (Plateau®; 22.2% acid equivalent) herbicide treatment (split-plot) within about 1 mo of the fire treatment, with the goal of temporarily reducing fine fuels and annual plant competition (mostly cheatgrass). Methylated seed oil was added as a surfactant (rates determined by licensed applicators) to impact any germinated cheatgrass. Imazapic application rates varied by fuel treatment depending on the level of litter on the soil surface after the fuel treatment was applied (105 $g \cdot ha^{-1}$ for fire, 123 $g \cdot ha^{-1}$ for tebuthiuron and control, and 140 $g \cdot ha^{-1}$ for mow).

Because location was our blocking factor, all fuel treatments within a location were implemented within the same year. Because of logistics and a small window of opportunity to complete the prescribed fire in autumn, implementation of all other treatments occurred postfire (after October), but before initiation of growth (early spring, before March). The exception was the fire at Moses Coulee. Legal and logistical problems did not allow the fire to be done in the same growing year as the other fuel treatments. Therefore the fire treatment only had five replicates and created an unbalanced design.

All whole plots and subplots were marked permanently and relocated annually. All measurements were taken within subplots (Fig. 1) near to peak growth immediately before treatments (year 0) and after treatments (years 1, 2, and 3). Cover and interperennial gap measurements were taken along five 30-m transects that were located perpendicular to the baseline at 2, 7, 15, 23, and 28 m from the northwest corner of each subplot. Plant and soil surface cover (%) were measured with the use of the line-point intercept method with 60 points per transect (one point per 0.5 m) for a total of 300 points per subplot. Interperennial plant gap distances were measured with the use of basal-gap intercept distances (cm) between bases of perennial plants intercepting the transect (Herrick et al. 2005). Cover measurements were recorded by individual species. Wyoming big sagebrush, cheatgrass, and Sandberg bluegrass were retained as individual species, and the remaining species were grouped into tall perennial bunchgrasses (all perennial bunchgrasses except Sandberg bluegrass), annual grasses, annual forbs, and perennial forbs.

Densities of mature tall perennial bunchgrasses, Sandberg bluegrass, nonrhizomatous perennial forbs, and shrub seedlings were counted in 45, 0.25-m^2 quadrats placed at 2-m intervals along transects perpendicular to the baseline at 7, 15, and 23 m and converted to $counts \cdot m^{-2}$. Density of live shrubs (all live

Table 3. Significant pretreatment response variables and their corresponding effects, mixed-model ANOVA (*F* and *P* values) with a brief explanation of the direction and amount of response.

Response variable	Effect variable	*F* (numerator df, denominator df)	$P > F$	Response direction and amount
Cheatgrass cover	Imazapic	5.14 (1, 19)	0.04	Imazapic 36% > no imazapic
Sandberg bluegrass cover	Woody fuel treatment by Imazapic	3.70 (3, 19)	0.03	Varied among fuel treatments and imazapic
Annual forbs cover	Imazapic	6.07 (1, 19)	0.02	Imazapic 26% > no imazapic
Perennial forbs cover	Imazapic	10.05 (1, 19)	< 0.01	Imazapic 37% > no imazapic
Lichen and moss cover	Woody fuel treatment by Imazapic	4.20 (3, 19)	0.02	No imazapic 34% > imazapic in fire and control treatments
Soil cover	Imazapic	4.23 (1, 19)	0.05	Imazapic 4% > no imazapic

shrubs by species in two height classes [5–15 cm and > 15 cm]) and of dead shrubs taller than 5 cm were counted within three, 2×30 m belt transects located perpendicular to the baseline at 7, 15, and 23 m.

Shrub biomass ($kg \bullet ha^{-1}$) was estimated from allometric relationships of shrub canopy height, greatest width, and greatest perpendicular width to the first width of all major shrub species, provided the shrub was > 15 cm tall and had at least 10% of the canopy alive. One of six nested circular frames (0.5–3 m radius, increasing by 0.5 m) were placed every 6 m along the transect beginning at 3 m to obtain five frames. Observers selected the smallest size of circular frame to measure approximately 15 individuals across all five circular frames. Shrub allometric measurements were converted to biomass by developing regressions from similarly measured, destructively harvested individuals located outside of subplots (Appendix II, available online at http://dx.doi.org/10.2111/REM-D-13-00090.s1).

We collected herbaceous live, standing dead, and litter biomass ($kg \cdot ha^{-1}$) separately within 8, 0.25-m^2 quadrats. Biomass quadrats were placed at 2-m intervals rotating annually among the 11- and 19-m transects running perpendicular to the baseline. The starting position was advanced in 1-m increments every 2 yr starting at the 0-m position. Biomass collections were dried at 70°C until a constant mass was achieved and then weighed.

Analytical Methods

For analyses, measurements were averaged across subplots receiving the same imazapic treatment within each woody fuel treatment. The equal stratum weights (1/3 of total) and equal sampling fraction within each stratum resulted in a stratified sample mean that was equivalent to a random sample mean (Cochran 1977). Pre- and posttreatment response parameters (hereafter called responses) were analyzed as univariate responses in three stages: 1) all potential gap measures (mean gap length, number of gaps, and percentage of the transect lines with gaps greater than 2 m) were analyzed pretreatment (year 0) to assure no confounding of potential covariates with treatment; 2) all responses were analyzed pretreatment (year 0) to assure no initial bias in the random assignment of treatments (because of a change in the sampling protocol, Wyoming big sagebrush biomass measurements in year 0 were deleted from one site, Onaqui, for analysis); and 3) all responses were analyzed posttreatment as repeated measures (3 yr). We evaluated distributions of residuals from models and considered $\log_e$ transformations when necessary to satisfy model assumptions of normality and homogeneity of variance. Results were backtransformed for presentation. We evaluated the potential inclusion of a gap measure as a covariate with the use of AICc to compare a null model (full design with no covariate) against three models, each with a different representation of the gap covariate with the use of PROC MIXED with AICc model selection (SAS 2007). We modeled 1) six vascular plant cover responses (percent cover of Wyoming big sagebrush, cheatgrass, native perennial tall grasses, Sandberg bluegrass, annual forbs, and perennial forbs), 2) cover of total (regardless of vegetation or litter above) and exposed (first contact) lichens and mosses, 3) cover of total and exposed soil, 4) density of native perennial tall grasses and Sandberg bluegrass, and 5) biomass of shrubs and herbaceous plants. Lower-order significant interactions or main effects were presented only if higher-order interactions were not significant ($P \leq 0.05$). ANOVA designs and tables of results are available online (Appendix III, available online at http://dx.doi.org/10.2111/REM-D-13-00090.s1). If year was a significant interacting effect in the posttreatment analysis, then we implemented the Slice statement in PROC MIXED on year to conduct an analysis of simple effects on each year to determine which years had interacting treatment effects. We report the sizes of the differences and ls means for responses by year along with their 95% confidence interval (CI), but do not determine which treatments differed significantly within those years.

RESULTS

Pretreatment Initial Differences in Responses and Potential Covariates

Seven response variables had significant pretreatment differences relating to the imazapic treatments because of initial chance selection of subplots (Table 3). Four of the variables (cheatgrass cover, annual forb cover, perennial forb cover, and soil) had greater cover in imazapic than no-imazapic subplots by chance. Total lichen or moss had more cover in no-imazapic than imazapic treatments. Two of the variables had significant woody fuel treatment by imazapic interactions. Cover of exposed lichens and mosses (first-contact lichens and mosses) was greater in no-imazapic than imazapic treatments within the untreated and fire woody fuel treatments only. Sandberg bluegrass cover varied among the woody fuel by imazapic treatment combinations. There was no consistent pattern among imazapic treatments, but the fire treatment tended to have lower cover of Sandberg bluegrass than other woody fuel treatments.

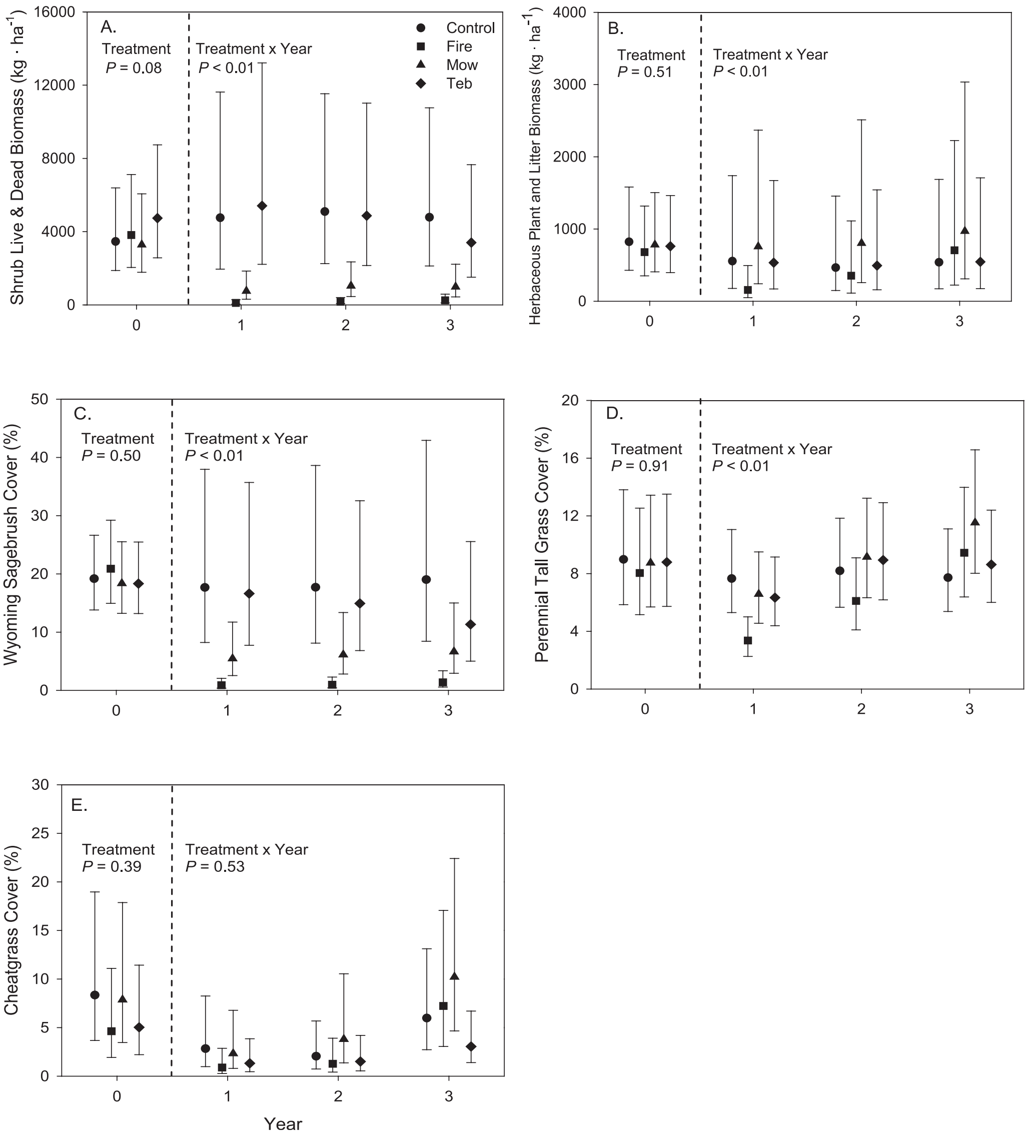

Figure 2. Pretreatment differences and posttreatment woody fuel treatment by year interactions illustrating responses of variables. **A,** Total shrub biomass. **B,** Total herbaceous (live and standing) and litter biomass. **C,** Wyoming big sagebrush (*Artemesia tridentata* subsp. *wyomingensis*) cover. **D,** Perennial tall grass cover. **E,** Cheatgrass (*Bromus tectorum*) cover. Vertical dashed line indicates time of treatment initiation. Symbols represent maximum-likelihood mean estimates from best-fit models with bars representing 95% confidence intervals around means.

In addition, we did not find that any of our response variables had any gap measures (mean, density, or proportion of gaps >2 m) as significant covariates pretreatment or posttreatment.

Woody and Herbaceous Biomass Response

The main fuel reduction treatments were applied to reduce or redistribute woody biomass (largely sagebrush). Overall shrub biomass was reduced with fire to between 1% and 6% of the control and with mowing to between 61% and 93% of the controls ($\pm$ $CI_{95\%}$ hereafter CI; Fig. 2A). These treatment-induced reductions remained through the third year. However, woody biomass in the tebuthiuron treatment required 3 yr to attain a CI between 35% and 145% of control levels (Fig. 2A).

Fire removed herbaceous live, dead, and litter mass (fine fuels) in the first year posttreatment (CI of difference=59–80% reduction; Fig. 2B), but these fuels recovered to untreated levels by Year 2. Imazapic reduced herbaceous mass more in the fire treatment than the other fuel treatments, as indicated by the significant imazapic by woody fuel treatment interaction ($P=0.03$; Appendix IV available online at http://dx.doi.org/10.2111/REM-D-13-00090.s1). The fire plus imazapic combination had about one-third less mass than the fire with no imazapic (CI of the difference=17–47%), about one-half the untreated with and without imazapic (CI of the difference=29–58%), and one-half the tebuthiuron with and without imazapic (CI of the difference=51–54%). Regardless of imazapic, herbaceous mass in the mow treatment (CI= 246–2 859 kg) was nearly 60% greater than mass in untreated or tebuthiuron with or without imazapic (CI of differences 120–213%) and nearly twice the mass of the fire imazapic treatment (CI differences 151–404%).

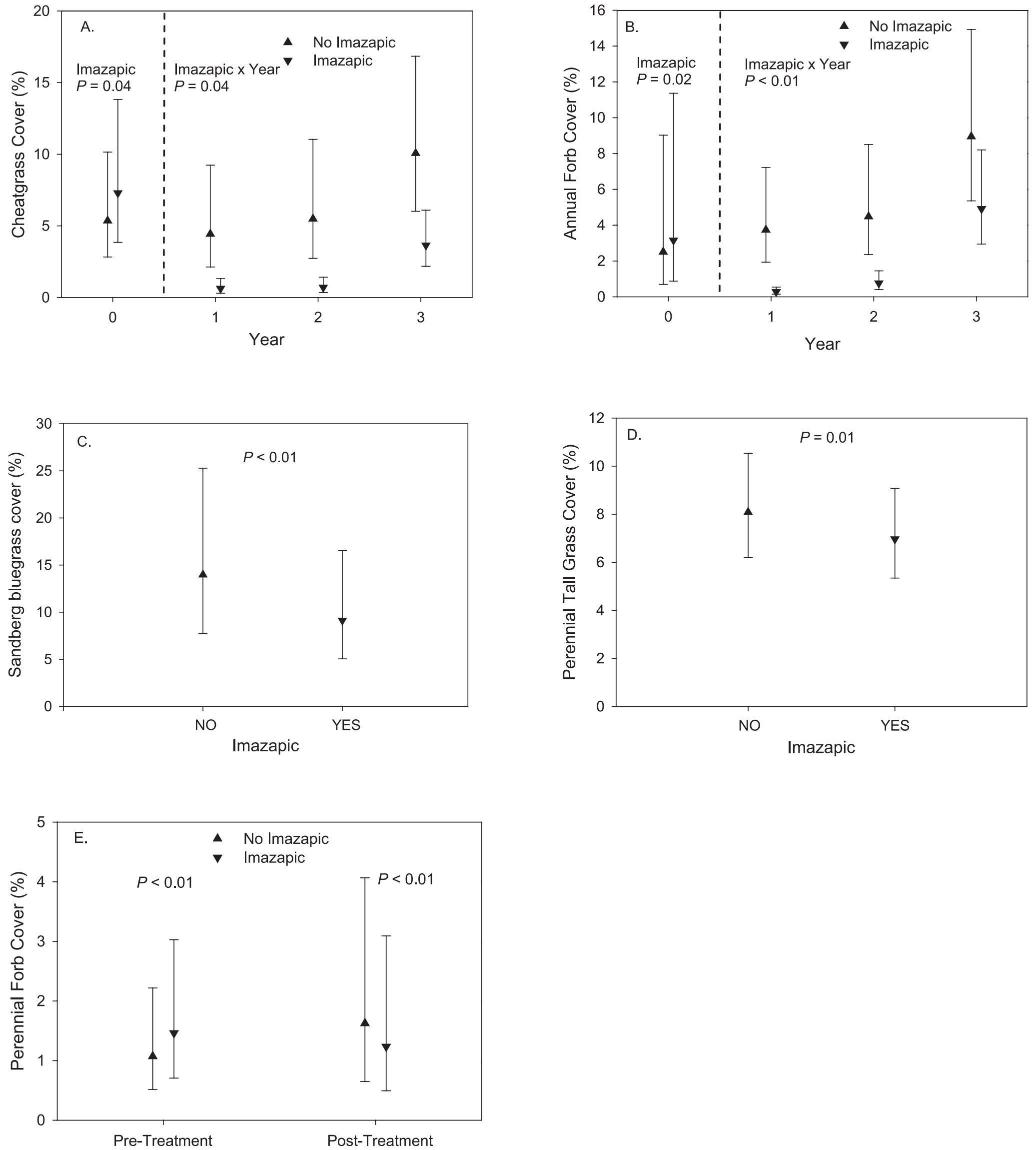

Figure 3. Responses of vegetation cover or soil to imazapic herbicide applications. **A**, Cheatgrass (*Bromus tectorum*) cover. **B**, Annual forb cover. **C**, Sandberg bluegrass cover. **D**, Perennial tall grass cover. **E**, Perennial forb cover. Vertical dashed lines in **A** and **B** indicates time of imazapic initiation and separates the test for pretreatment imazapic effects from the imazapic by year interactions, whereas other panels had no interaction with year and display imazapic main effects posttreatment averaged over years and pretreatment for **E**. Symbols represent maximum-likelihood mean estimates from best-fit models with bars representing 95% confidence intervals around means.

Vegetation Cover

Similar to shrub biomass, the fire treatment achieved the objective of near-complete removal of Wyoming big sagebrush cover (CI 2–24% of control cover) in all 3 posttreatment years, and shrub cover in the mow treatment was within the 50% reduction objective (CI 11–89% of the control). Shrub cover in the tebuthiuron treatment approached 50% reduction by year 3, although it did not significantly differ from shrub cover in the control (CI 19–182% of control; Fig. 2C).

Woody fuel treatments had minor short-term impacts on herbaceous plant cover. Only cover of perennial tall grasses experienced any significant impact, and this only occurred in the first year after the fire (CI=28–70% of the control; Fig. 2D). In the second and third year posttreatment, there were no differences in perennial tall grass cover between fire and control. Sandberg bluegrass (CI=6–20%), perennial forb (CI=0.5–4.0%), and annual forb cover (CI=2–15%) were not significantly impacted by any woody fuel treatments in any year. In addition, there was no significant effect of woody fuel treatments on cheatgrass cover among the three posttreatment years (CI=2–16%; Fig. 2E). Cheatgrass cover increased in the third year, but it increased in all treatments.

Imazapic resulted in significant declines of cheatgrass cover that was maintained over 3 yr (Fig. 3A). Although cover of cheatgrass was significantly greater by chance in the imazapic treatment than in the no-imazapic treatment at the pretreatment stage, this response was reversed after treatment. Imazapic significantly reduced cheatgrass cover the greatest in the first year (CI 2–36% of no imazapic), with that amount declining to the third year (CI 21–62% of no imazapic). Similar

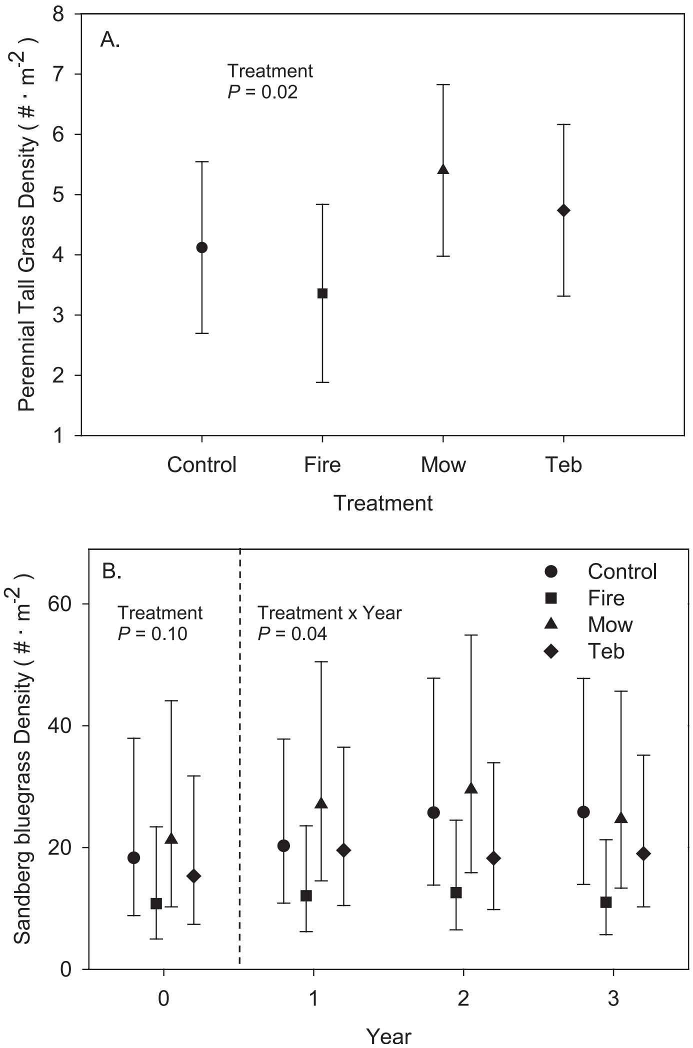

Figure 4. A, Posttreatment woody fuel removal effect on perennial tall grass density averaged over 3 yr. **B,** Pretreatment test of fuel treatment effect and posttreatment woody fuel treatment-by-year interactions on Sandberg bluegrass density with the vertical dashed line indicating time of treatment. Symbols represent maximum-likelihood mean estimates from best-fit models with bars representing 95% confidence intervals around means.

to cheatgrass, annual forb cover by chance was higher in imazapic treatments than no imazapic before treatment, but this response was reversed after treatment and it varied by year (Fig. 3B). Annual forb cover with imazapic in the first year was between 3% and 16% (CI) of the no-imazapic treatment and that difference declined to between 33% and 91% of the no-imazapic treatment (Fig. 3B).

Perennial plant cover was also reduced significantly by imazapic, but this reduction was maintained across all treatments and years (no significant interactions between fuel treatment and years with imazapic). Although Sandberg bluegrass cover varied among woody fuel and imazapic treatments at the pretreatment stage, imazapic reduced Sandberg bluegrass cover to between 56% and 76% (CI) of the no-imazapic treatment (Fig. 3C). Imazapic also reduced perennial tall grass cover to between 76% and 96% of the no-imazapic treatment (Fig. 3D). Imazapic applications yielded perennial forb cover between 64% and 91% of the no-imazapic treatment, but these percent reductions due to imazapic would be even greater (nearly half) if we compared results to the initial pretreatment values that were significantly higher in imazapic relative to no-imazapic plots (Fig. 3E).

Plant Density

Pretreatment, there were no statistically significant differences in perennial tall grass density among treatments ($P=0.31$, data not shown); however, perennial tall grass density diverged after treatments (Fig. 4A). The mowing treatment increased densities of perennial tall grasses, and fire reduced densities slightly relative to mowing and tebuthiuron, but not relative to controls. No significant year-by-treatment interaction was found. Similarly, Sandberg bluegrass had lower densities after fires. By year 3 densities in fire treatments were significantly lower than in controls or mowing, and mowing, tebuthiuron, and controls had similar densities (Fig. 4B).

Soil Surface Cover Components

Total lichen/moss soil crusts occurred both under plants and in their interspaces and accounted for roughly between 10% and 47% cover of the soil surface before treatments and in untreated locations for the 3 yr posttreatment, but fire essentially eliminated crust cover (CI=0.0–16.3%), and those levels of cover were maintained through the 3 yr after treatments (Fig. 5A). If no fuel treatment was applied, lichen/moss cover in areas not protected by vegetation or litter was between 2% and 12% (CI; Fig. 5B), but similar to the total lichen/moss cover, the reduction by fire was immediate and was maintained for 3 yr, whereas mowing reductions did not diverge until the third year.

The amount of mineral soil cover that is unprotected appears to increase with many fuel treatments. Before fuel treatments were applied, cover of total bare soil regardless of the overstory protection was between 48% and 77% (CI). After treatments, fire increased and maintained mineral soil cover to between 82% and 103% (CI; Fig. 5C). In addition, there is an increase in exposed mineral soil (first contact soil) cover with imazapic, but this increase does not appear until the second year after treatment (Fig. 5D). Exposed mineral soil cover was between 8% and 34% (CI) before treatments and in controls for 3 yr posttreatment (Fig. 5E). Fire resulted in the only consistent 3-yr increase in exposed mineral soil, although the difference between fire and control decreased over the 3 posttreatment yr.

The proportion of interperennial plant gaps that were >2 m before treatments remained constant between 26% and 78% (Fig. 5F). After treatment, fire immediately increased this proportion by nearly 20% (CI=48–92%), with only a slight recovery by year 3 posttreatment. The proportion of interperennial plant gaps >2 m in the other two fuel treatments remained similar to control levels.

DISCUSSION

Our study is the first comprehensive and replicated study across the region of plant community responses, including cheatgrass responses, to disturbances associated with fuel reduction

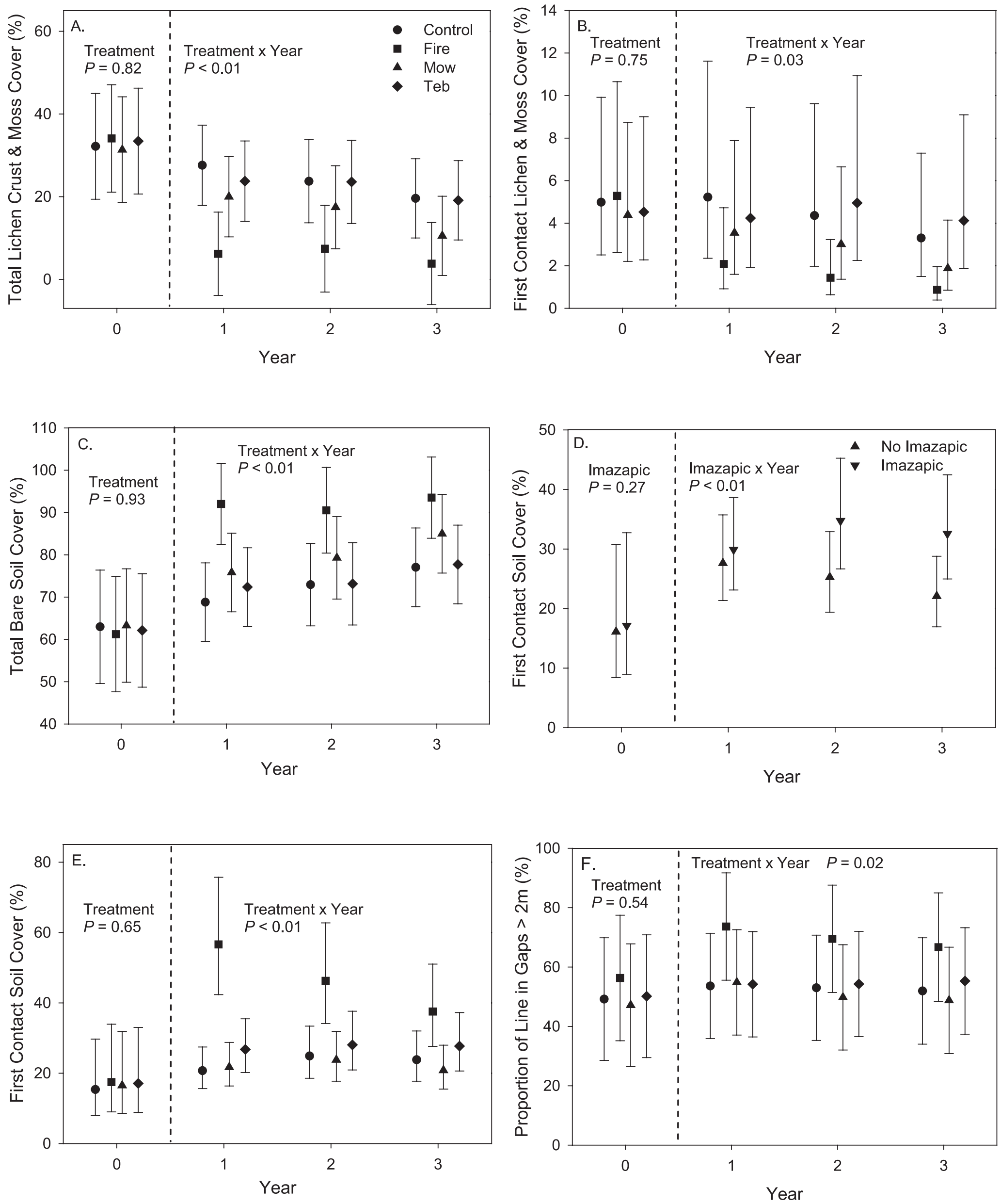

Figure 5. Pretreatment differences and posttreatment woody fuel treatment by year interactions illustrating responses of variables. **A,** Total (regardless of vegetation or litter overhanging the location) lichen and moss cover. **B,** First contact (exposed) lichen and moss cover. **C,** Total soil cover. **D,** First contact bare soil cover as a response to the interaction of imazapic and year. **E,** First contact (exposed) soil cover. **F,** Proportion of interperennial plant gaps greater than 2 m. Vertical dashed line indicates time of treatment initiation. Symbols represent maximum-likelihood mean estimates from best-fit models with bars representing 95% confidence intervals around means.

treatments on warm and dry Wyoming big sagebrush ecosystems (Miller et al. 2013). Our locations represent common Wyoming big sagebrush and bunchgrass ecological sites (152–381 mm precipitation) with minor amounts of cheatgrass. Based on soil temperature and moisture regimes, these sites should be moderately to highly susceptible to cheatgrass dominance (Miller et al. 2013). These locations were chosen intentionally because, in our professional opinions and those of the local land managers, these communities contained sufficient perennial herbaceous cover to resist cheatgrass or were resilient enough to recover from fuel treatments and re-establish dominant perennial plant communities even if cheatgrass became temporarily dominant. This allowed us to test the hypothesis that spatial arrangements of perennial plants before disturbances control the resilience of these communities and aid us in identifying early warning indicators for communities approaching a transition to alternative stable state dominated by cheatgrass (Reisner et al. 2013).

Woody Plant Responses and Fuel Treatments

Fire and mowing equally reduced Wyoming big sagebrush biomass and cover (the main woody plant fuel of these ecosystems) immediately after their treatments. Declines associated with fire and to some degree with mowing are obvious, because Wyoming big sagebrush dominated the woody plant components of these communities and it does not tolerate disturbances that kill the current year's growth on the plant (Bilbrough and Richards 1993). Tebuthiuron's effect showed a similar, but less severe decline that was not readily apparent until the third year. This delay is typical of low application rates of tebuthiuron (Olson and Whitson 2002). This herbicide results in leaf drop that leaves the woody plant skeleton standing, resulting in minimal short-term changes in fuel structure.

Once Wyoming big sagebrush is eliminated from a community, recovery may take in excess of 40 yr (Miller et al. 2011) and is dependent on seeds surviving the disturbance and establishing. This scenario is difficult to attain because most sagebrush seeds are killed by fire (Allen et al. 2008) and those that survive are relatively short lived (1–3 yr) (Wijayratne and Pyke 2012) with germination and establishment requiring seeds at the soil surface (Chambers 2000, Miller et al. 2013). However, depending on the size and shape of the disturbance, the small wind-dispersed seeds of sagebrush may arrive in adequate numbers from nearby unburned areas to allow establishment in favorable years, but most seeds fall within 1 m of the mother plant (Meyer 1994). This indicates that fires with unburned patches and fuel treatments that leave sagebrush seed sources have the best odds of promoting sagebrush establishment after treatment.

Mowing would allow continued Wyoming big sagebrush reproduction from some plants after treatment and would allow for quicker recovery through continued growth of surviving branches and through potential seedling emergence, leading to increased density. However, we did not detect significant increases in sagebrush density in the short term. In the tebuthiuron treatment, surviving sagebrush may contribute fewer seeds if they are partially impacted by the herbicide, which is a photosynthesis inhibitor and may reduce a plant's vigor. However, those shrubs that survive might be able to contribute to long-term recovery through reproduction, but recovery via seedlings is often delayed for several years (McDaniel et al. 2005).

Herbaceous mass that included litter and standing dead vegetation, mostly cheatgrass and annual forbs, appears to be favored by mowing treatments regardless of imazapic applications, because these produced between 60% and 100% more mass than any other treatments. The application of imazapic only reduced herbaceous mass when combined with fire. The lack of imazapic applications reducing herbaceous mass in other treatments could indicate that our rate of imazapic was too light in treatments with litter remaining on the soil surface; however, note the impacts of imazapic on cover of many plant groups listed later.

Native Herbaceous Plant Responses

Fuel treatments that kill or reduce sagebrush dominance potentially leave resources available for growth and reproduction of tolerant species that survive the disturbance (Roundy et al. 2014). Relative to the Wyoming big sagebrush reductions, herbaceous plants are generally more tolerant of woody fuel treatments. Herbaceous plant tolerance to these treatments should allow them to respond positively to resources that are released by the loss of woody plants (Roundy et al. 2014).

In the short term, these fuel treatments appear to have only slight, but nonsignificant, impacts on perennial herbaceous cover, with the noted exception of the immediate postfire decline of perennial tall grasses followed by their recovery 1 yr later. Based on long-term effects of shrub-reduction treatments, similar to those we imposed, we anticipate future increases in perennial grass abundances, but these increases are not readily apparent at this early stage (Davies et al. 2011; Miller et al. 2013). Relatively high cover of cheatgrass and annual forbs on mesic (warmer) sites, especially during high precipitation years favorable for establishment, may impede increases in perennial grasses into the future (Chambers et al. 2014). Frigid (cooler) sites that are less climatically suited for exotic annuals may have a higher probability of increases in herbaceous perennials over time (Chambers et al. 2014; Miller et al. 2013)

We anticipated that when these woody fuel treatments were combined with imazapic, annual forbs would be reduced because of their similar life cycle to cheatgrass. The impact of imazapic on perennials was not expected at the time the experiment began, but recent studies corroborate this finding when imazapic is applied on native plant communities (Baker et al. 2009; Elseroad and Rudd 2011). The use of a surfactant may have contributed to the impact on perennial plants because it would cause imazapic to stick to live plants and increase imazapic's impact on existing perennial plants on application sites. Some functional groups may be extremely important even though they only represent a small portion of the overall plant community. For example, perennial forbs only represented a few percent of the overall plant cover, but even a loss of 1% could represent a 50% reduction in a group that is an important life form for pollinators and the sensitive greater sage-grouse (Connelly et al. 2000). We did not examine the impact to individual species, so this negative effect may not be equal among all perennial forbs. More detailed analyses of the impact of imazapic on perennial forbs are therefore needed.

Cheatgrass Responses

Initial reductions of cheatgrass during the first growing season after fire have been commonly reported and are thought to relate to one or more of the following factors: reduced microrelief, reduced litter cover, or reduced seed availability (Miller et al. 2013). On similar warm and dry sites to those in our study, West and York (2002) noted increases in cheatgrass cover in years 2 and 3 after a fire. They found that cheatgrass composition (relative cover) began to decline in year 4 as perennial grass cover increased. Our data show a similar increase in cheatgrass and perennial tall grass cover through posttreatment year 3, but cheatgrass cover never became significantly greater than control levels in these 3 yr after the fire.

Mowing tended to increase cheatgrass and perennial grass cover over the 3 posttreatment years, but cheatgrass cover never became significantly greater than controls. Davies et al. (2011) and Davies and Bates (2014) showed significant increases in cheatgrass, but in contrast they found little benefit for perennial grasses. One difference was that our study areas had nearly twice the cover of perennial grasses before treatment than their 8% cover (Davies et al. 2011). There is increasing evidence that initial cover of perennials is an important factor in determining resilience to disturbances and resistance to cheatgrass dominance (West and York 2002; Chambers et al. 2007, 2013; Miller et al. 2013), and Chambers et al. (2014) show a strong relationship between cover of perennial herbaceous species and cover of cheatgrass on these sites.

Consistent with other studies, applications of imazapic, especially after a fire, can greatly reduce cheatgrass cover for multiple years (Shinn and Thill 2002; Davidson and Smith 2007; Morris et al. 2009; Owen et al. 2011), but as noted above, this may have unintended consequences on non-target plants.

Cheatgrass cover is highly variable among years, simply because of differences in weather (West and Yorks 2002; Chambers et al. 2014), and can fluctuate for years before showing a trend that is clearly attributable to a management treatment. Weather-related fluctuations in cheatgrass can create interannual swings in cheatgrass cover and biomass (Stewart and Hull 1949). Autumn rainfall with continued precipitation occurring throughout the growing season can provide high populations and biomass of cheatgrass (Mack and Pyke 1984). Similarly, seasonal droughts can produce cohorts of cheatgrass that emerge and die, resulting in low production (Mack and Pyke 1984). Chambers et al. (2014), with the use of a subset of subplots, were able to detect a significant increase by the fourth year. Weather models estimated that our sites had above-average rainfall in nearly all months in the third year posttreatment with normal to below-normal temperatures (Appendix V, available online at http://dx.doi.org/10.2111/REM-D-13-00090.s1), which may have contributed to this increase.

Blumenthal et al. (2006), based on a study in a Wyoming sagebrush site near Lander, WY, USA, questioned whether tebuthiuron applications to thin sagebrush might lead to elevated cover of cheatgrass. Cheatgrass cover was higher in nontreated than treated tebuthiuron plots 2 and 4 yr posttreatment (Olson and Whitson 2002), but these patterns were reversed 11 yr posttreatment (Blumenthal et al. 2006). However, cheatgrass cover was still less than 4% on their sites. We found no reduction in cheatgrass due to tebuthiuron applications alone, but because significant declines have taken 3 yr, responses may still be developing.

Spatial and Soil Indicators of Potential Cheatgrass Increases

Other indicators, however, point to a potential future increase of cheatgrass. Recent studies indicate the importance of close spatial distances among native perennials in keeping cheatgrass cover, biomass, and reproduction low (Reisner et al. 2013; Rayburn et al. 2014). In addition, Reisner et al. (2013) demonstrated that the strongest direct predictors of cheatgrass cover in order of importance were as follows: 1) the proportion of interperennial plant distances that were >2 m (positive relationship); 2) the percentage of cover of exposed mineral soil (positive relationship); and 3) the percentage of cover of lichen/moss soil crusts (negative relationship). We examined if interperennial plant gap was related to cheatgrass cover before treatment, but those analyses failed to find a relationship. If these indicators reflect longer-term responses to disturbance, then they may reflect early warning indicators of future cheatgrass increases.

Our findings suggest that 1) fire will increase the proportion of large (>2 m) interperennial plant gaps, 2) fire and mowing will increase the amount of exposed soil, and 3) fire and mowing will decrease biological soil crusts (Fig. 5). These are all indicators that cheatgrass cover will likely increase with time and that it would likely be more severe within prescribed fire than mowing. Cheatgrass cover appears to be trending in this direction for fire and mowing treatments relative to controls, but not significantly at the end of 3 yr (Fig. 2E); however, with a subset of these subplots, Chambers et al. (2014) found significantly higher cheatgrass in the fourth year posttreatment.

Before treatments, 94% of subplots had greater perennial plant cover than cheatgrass cover. By 3 yr postfire, average cheatgrass and perennial grass cover were equal (cheatgrass 16%; perennial tall grass 10%; Sandberg bluegrass 6%). Although cheatgrass represented nearly 50% of the relative cover, it is not clear from our data whether perennial grasses or cheatgrass will ultimately dominate these sites. Three years, the length of most manipulative studies, is clearly insufficient to draw long-term conclusions regarding resilience of these ecosystems, but during this initial period cheatgrass has not increased significantly above levels of controls.

Research on plant community responses to disturbances needs to focus on identifying indicators and risks that managers can use in deciding if the probabilities for positive responses will outweigh the potential of negative responses. Long-term research that focuses on measuring a wide range of environmental and biological attributes is required to make these predictions and provide decision support models. It is rare to have an opportunity such as SageSTEP, with sites distributed across a range of ecoregions, as opposed to individual case studies. Inferences of our current and future results are broader than most studies. Our design used locations throughout the region as replicates, allowing a broader inference that will be useful for predicting responses to management-imposed disturbances over both the short and long term throughout the region. These initial results are an important first step in understanding resilience of Wyoming big sagebrush ecosystems in the Intermountain West, and should provide long-term insights necessary for creating predictive decision support tools for managers.

IMPLICATIONS

Since the initiation of this study, fuel managers have tended to restrict direct treatments of Wyoming big sagebrush unless treatments can produce fuel breaks to aid fire suppression efforts (D. Havelina, BLM, Division of Fire Planning and Fuels Management, National Interagency Fire Center, Boise, ID, USA, pers. comm.). However, fuel treatments of other woody species, such as juniper or piñon pine, may also include treatments that can impact Wyoming big sagebrush. Fuel managers of arid Wyoming big sagebrush communities can immediately achieve goals of reduced woody plant fuels with fire or mowing and can reduce herbaceous fuels with imazapic applications. Fuel managers might consider a concomitant goal of creating communities of herbaceous perennials with discontinuous fuels. Our early results yield concerns that cheatgrass may continue to increase based on the list of early-warning indicators that are related to higher cheatgrass cover. Fire was the only method that increased large interperennial plant gaps, increased exposed mineral soil, and decreased biological soil crusts, all of which are associated with potential increases of cheatgrass. Poor mowing practices that disturb the soil surface or uproot perennial plants may have the same impacts. An increase in cheatgrass is a major fuel management concern in Wyoming big sagebrush ecosystems, and one that has proven to change the fire regime if cheatgrass creates a continuous fuel source.

The use of imazapic to reduce cheatgrass has been proposed and was effective in reducing cheatgrass cover over the 3 yr of this study. Not only will imazapic reduce cheatgrass, but at least at the rates that we used and with the surfactant, it can reduce desirable plants (perennial and annual herbaceous plants) during this same period, and thus potentially defeat the purpose of providing perennial plants with a release from competition from cheatgrass. The long-term impacts of imazapic are only now being determined; therefore, long-term management implications are unknown. Managers that elect to use this herbicide, especially on locations with desirable perennial herbaceous plants, might consider the elimination of the surfactant so that imazapic is more likely to act as a pre-emergent herbicide than as both a contact and a pre-emergent herbicide. Managers might contribute to our long-term understanding by invoking monitoring techniques that track cheatgrass and nontarget plants.

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