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Received: 10 July 2019 | Revised: 25 November 2019 | Accepted: 9 December 2019
DOI: 10.1002/ldr.3516

RESEARCH ARTICLE

WILEY

# Not all fuel-reduction treatments degrade biocrusts: Herbicides cause mostly neutral to positive effects on cover of biocrusts

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**Funding information**
Great Northern Landscape Conservation Cooperative; National Interagency Fire Center; US Bureau of Land Management; US Joint Fire Science Program

## Abstract

In response to increasing fire, fuel-reduction treatments are being used to minimize large fire risk. Although biocrusts are associated with reduced cover of fire-promoting, invasive grasses, the impact of fuel-reduction treatments on biocrusts is poorly understood. We use data from a long-term experiment, the Sagebrush Steppe Treatment Evaluation Project, testing the following fuel-reduction treatments: mowing, prescribed fire, and the use of two herbicides: one commonly used to reduce shrub cover, tebuthiuron, and one commonly used to combat cheatgrass, imazapic. Looking at sites with high cover of biocrusts prior to treatments, we demonstrate positive effects of the herbicide, tebuthiuron on lichens with an increase in cover of 10% and trending towards slightly negative effects on moss cover. Across plots, imazapic trended towards a decrease in lichen and moss cover without being statistically significant. Mowing and prescribed fire reduced cover of mosses, with the latter leading to greater declines across sites (declines of 18% vs. 32%). Reductions in moss cover mirrored gains in cover of bare soil, which is associated with increased risk of invasion by grasses responsible for increasing fire risk. We demonstrate that the use of herbicides simultaneously reduces fuels and maintains greater cover of lichens and mosses compared with other fuel-reduction treatments, possibly reducing risk of invasion by annual grasses that are responsible for increasing fire risk.

KEYWORDS
biocrusts, Great Basin, lichen, moss, sagebrush ecosystem

## 1 | INTRODUCTION

In the sagebrush steppe, wildfires have become increasingly severe and more frequent as early Euro-American settlement, grazing, and fire suppression have altered vegetation and land use patterns (Knick, 1999). Fuel-reduction treatments are becoming more important for use by land managers to combat invasion by the annual exotic, cheatgrass (*Bromus tectorum* L.), to reduce the disturbance severity from fire, and to retain native perennial bunchgrasses and forbs in the understory. Resilience to disturbance and resistance to exotic annual plant invasion is supported by maintenance of the native biotic community: both vascular plants and biological soil crusts (biocrusts) in sagebrush steppe ecosystems (Chambers, Roundy, Blank, Meyer, & Whittaker, 2007; Condon & Pyke, 2018a; Condon, Weisberg, & Chambers, 2011; Reisner, Grace, Pyke, & Doescher, 2013). Biological soil crusts (biocrusts) are a living, mostly photoautotrophic soil surface community composed of moss, lichen, cyanobacteria, algae, and fungi. Biocrusts hold soil together, reduce erosion, contribute to carbon and nitrogen cycling, and increase water retention in soils, prolonging hydration periods for surrounding plants (Canton, Sole-Benet, & Domingo, 2003;

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Eldridge, 1998; Harper & Belnap, 2001). Lichens, mosses, and algae including cyanobacteria vary in their susceptibility to disturbances such as high-temperature wildfires, trampling by livestock or humans, compression by vehicle tires, and changing precipitation patterns induced by climate change (Condon & Pyke, 2018a, 2018b; Ponzetti, McCune, & Pyke, 2007; Weber, Budel, & Belnap, 2016).

As compounding factors degrade sagebrush steppe habitats, including biocrusts, understanding how the components that make up biocrusts are affected by land management actions has repercussions on the resistance and resilience of managed lands.

The Sagebrush Steppe Treatment Evaluation Project (SageSTEP) was designed to monitor the long-term response of sagebrush steppe habitat to prescribed fire and fire-surrogate treatments to better inform land managers of best practices and considerations for managing sagebrush lands. Although many studies of the sagebrush steppe serve as case studies that address single locations, SageSTEP is unique because it provides a long-term, region-wide assessment of ecological responses to fuel-reduction treatments that were applied over comparable study sites (Pyke et al., 2014). The SageSTEP study looked at three common land management techniques employed by land management agencies: prescribed fire, mowing, and herbicide application. All of these treatments were intended to reduce fuels and release native herbaceous vegetation from competition with woody vegetation (i.e., sagebrush). Tebuthiuron is the herbicide that was used to reduce sagebrush. It is a photosystem II inhibitor that is transported through the xylem (http://herbicidesymptoms.ipm.ucanr.edu/MOA/Photosystem_II_Inhibitors/, accessed October 21, 2019). Additionally, SageSTEP evaluated the effectiveness of using a cheatgrass-inhibiting, postemergent herbicide with a surfactant (imazapic) in conjunction with the fuel-reduction treatments to promote further infilling of native herbaceous vegetation. Imazapic is transported through the xylem and phloem. It is an acetolactate synthase inhibitor, which is a key enzyme in the biosynthesis of some amino acids (http://herbicidesymptoms.ipm.ucanr.edu/MOA/ALS_or_AHAS_inhibitors/, accessed October 21, 2019). Data on cover of biocrusts were collected and provided the opportunity to examine the effects on these commonly used land management treatments on biocrust components. We ask two main questions: (a) what is the posttreatment response of biocrusts (as assessed by cover) to prescribed fire, mowing, and herbicide and (b) how do the two recorded biocrust components (cover of lichens and mosses) and soil differ in their response to the fuel-reduction treatments? We ask both questions across sites and at sites that were selected as having high cover of biocrusts prior to treatment. Findings from this study will provide managers with documented effects of fuel-reduction treatments on biocrusts.

## 2 | METHODS

### 2.1 | Experimental area and design

Our research focused on six study locations within the SageSTEP network (Table 1; Miller et al., 2014). A seventh location (Roberts) was removed from analysis due to an initial poor burn in the fire treatment followed by a wildfire that burned much of the site during the fourth year of the study. All sites were characterized as having loam soils, dominated by Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) and experiencing varying degrees of invasion by cheatgrass. Estimated mean ranges of cheatgrass cover across subplots was between 0.11% and 20.36% prior to treatment. Elevations ranged from 270 m in the Columbia Plateau in Washington to 1,800 m in the Great Salt Lake area in Utah. Sites were in Nevada, Oregon, Utah, and Washington and were representative of five major land resource areas (Columbia Basin, Columbia Plateau, Malheur High Plateau, Owyhee High Plateau, and Great Salt Lake; United States Department of Agriculture, Natural Resources Conservation Service, 2006). The data used are publicly available (Condon and Gray 2019).

The sites were selected for a perennial native plant understory that would be susceptible to cheatgrass invasion if disturbed and also exhibit some level of resilience to disturbance. Fire had not occurred on the sites in the past 50 years, and grazing was discontinued on sites at least 1 year prior to treatment implementation; Rock Creek and Gray Butte stopped grazing on site in 1993 when the Hart Mountain National Antelope Refuge was established. Due to random chance, total moss and lichen cover pretreatment was higher in non-imazapic treatments compared with imazapic treatments (Pyke et al., 2014). Subplots that did not receive imazapic had lichen cover between 0.44% and 53.78% and moss cover between 0.83% and 40.06% prior to treatment. Subplots that received imazapic treatment had lichen cover between 0.33% and 50.52% and moss cover between 0.93% and 39.39% prior to treatment. This difference in cover was generally true when comparing each treatment: prescribed fire and mowing as well as the control.

The study was designed as a randomized, split-plot block design. The six sites are plots. Sites are split into subplots, which are our unit of replication. Each site has a control and three sagebrush-reduction treatments (fire, mow, and herbicide), which are further split into cheatgrass-suppression treatments (imazapic or no imazapic). The prescribed fire treatments were designed to eliminate all shrubs and woody debris, whereas the mowing and herbicide treatments were intended to reduce the shrub cover by 50%. Mowing was done using a rotary deck mower (set at a height of 30.5 to 38.1 cm) pulled behind a wheel-driven tractor. Tebuthiuron, a commonly used herbicide for woody plant reduction, was applied using either fixed-wing aircraft or helicopters. Due to limited opportunities to implement the prescribed fire treatment in late fall, the mow and herbicide treatments were implemented after the prescribed fire but before initiation of plant growth the following spring.

The number of subplots varied between sites. At a given site, each treatment had the same number of subplots (e.g., four sites had 18 subplots per treatment, whereas the other two had 24 subplots). Half of these treatment subplots (either 9 or 12) were randomly selected for treatment with imazapic to control cheatgrass. Subplots are $30 \times 33$-m rectangles. Two 30-m baselines were run along the 30-m sides of the plot, whereas transects were run perpendicular to the baselines with 1.5-m buffer zones on either end (totaling 33-m length). Five of the transects were placed at the 2-, 7-, 15-, 23-, and

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**TABLE 1** Site locations and descriptions taken from Pyke et al. (2014)

| 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 | | | | | | |
| Latitude: 42°43′17″N Longitude: 119°29′32″W | 1,515 | 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. (R024XY0170R) |
| Gray Butte | | | | | | |
| Latitude: 42°42′45″N Longitude: 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. (R024XY0170R) |
| Moses Coulee | | | | | | |
| Latitude: 47°37′17″N Longitude: 119°40′51″W | 520 | Columbia Plateau | Columbia Plateau | Loamy skeletal to coarse loamy over sand | 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 | | | | | | |
| Latitude: 46°44′32″N Longitude: 119°20′29″W | 270 | Columbia Basin | Columbia Plateau | Coarse silty | Warden very fine sandy loam (0–5%; mesic: xeric) | Loamy 6–9 P.Z. (R007XY102WA) |
| Onaqui | | | | | | |
| Latitude: 40°12′4″N Longitude: 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 | | | | | | |
| Latitude: 41°23′16″N Longitude: 116°52′54″W | 1,725 | 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) |

Abbreviation: MLRA, Major Land Resource Area.

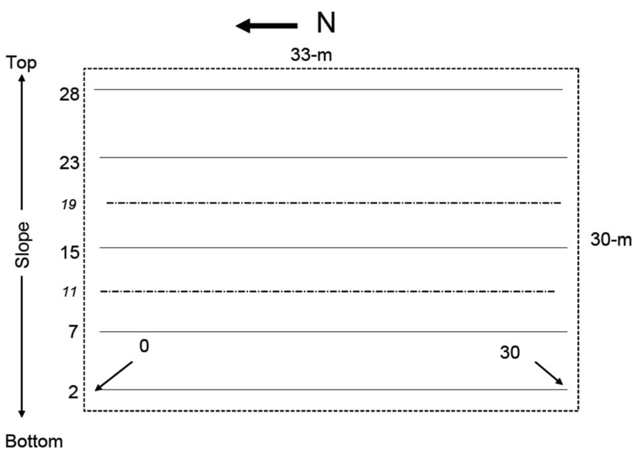


**FIGURE 1** Schematic representation of a subplot setup with vegetation monitoring transects. Subplots are 33-m long, with the slope, and 30-m wide perpendicular to the slope. Solid lines represent transects that are used for vegetative sampling. Dashed lines represent transects that are used for destructive sampling of herbaceous biomass. Transects originating at 11 and 19m are used in alternating years

28-m points for vegetative sampling, whereas a sixth transect alternated each year between 11- and 19-m points for destructive sampling of herbaceous biomass (Figure 1).

## 2.2 | Data collection

Pretreatment vegetation data were collected for at least 1 year prior to treatment implementation, then monitored posttreatment for 10 years to observe ecosystem responses. Biocrust cover data were obtained from line-point intercept records collected at every half-meter point on all five transects at every subplot (300 data points per subplot) for the six study sites. Functional groups were limited to designations of 'lichen crust' or 'moss'; cyanobacteria and other biocrust classifications were not included in the protocols to simplify data collection while still capturing basic trends of biocrust response to the treatments.

## 2.3 | Statistical analyses

Data were analyzed with linear mixed effects models, allowing for repeated sampling at subplots, blocked by site (random effects). Mixed effects models also allow for unbalanced designs. Analyses were performed in R Version 3.4.0 and R Studio Version 1.0.143 (R Core Team, 2017). Mixed effects models were run with the package NLME (Pinheiro, Bates, DebRoy, Sarkar, & Core Team, 2017). Separate models were used to evaluate the effects of treatments on cover of lichens, mosses, and soil using first all six sites and second using two

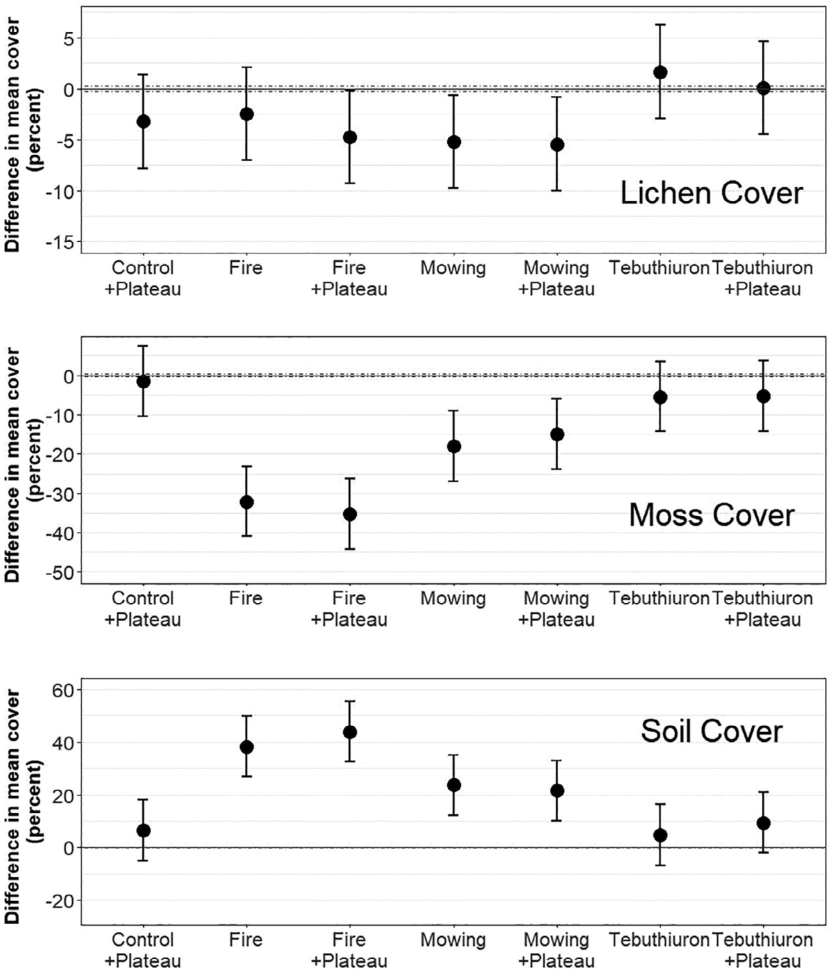


**FIGURE 2** Differences in mean cover of lichen, moss, and soil between treatments and control subplots across sites. Error bars represent 99% confidence interval. Plateau is a trade name for imazapic

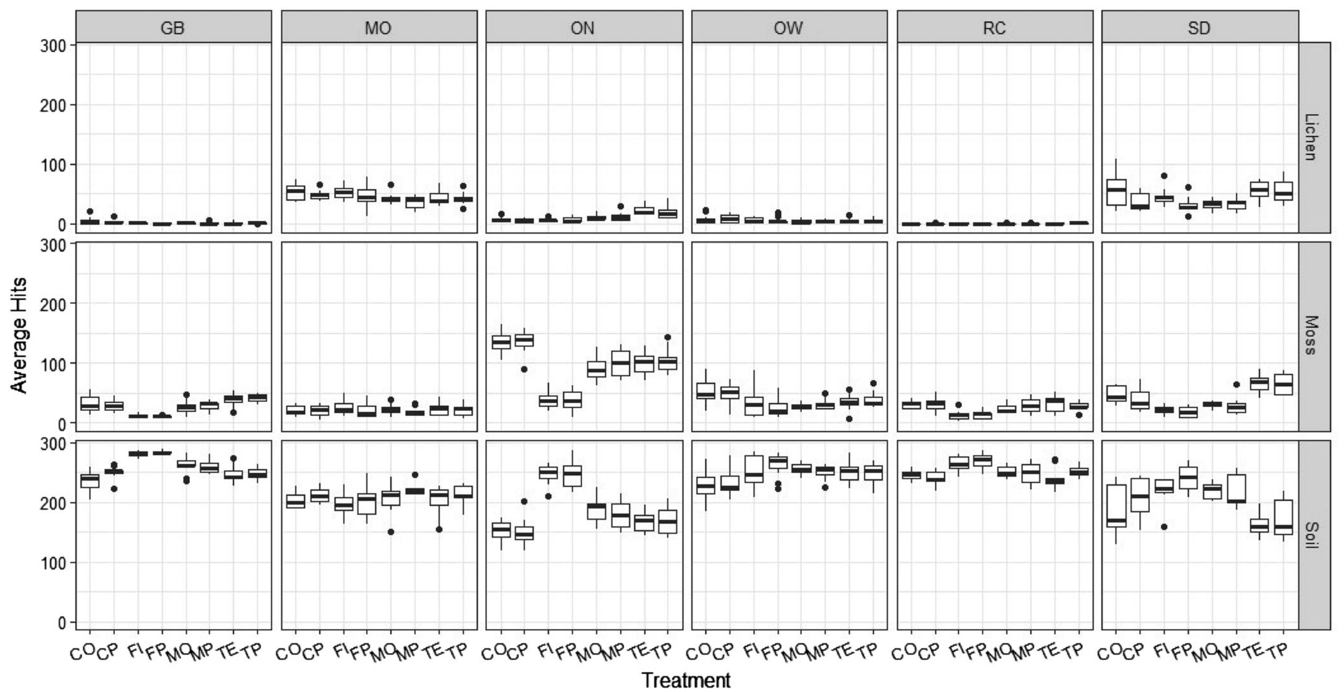


**FIGURE 3** Boxplots of the average number of line point intercept hits, in a subplot, by site and treatment. Boxplots show the median and the interquartile range. Whiskers show values within 1.5 times the interquartile range, the distance between the first and third quartiles. Data beyond this range are plotted as individual points. Abbreviations are as follows for sites: GB, Gray Butte; MO, Moses Coulee; ON, Onaqui; OW, Owyhee; RC, Rock Creek; SD, Saddle Mountain, and for treatments: CO, control; CP, control + Plateau; FI, fire; FP, fire + Plateau; MO, mowing; MP, mowing + Plateau; TE, tebuthiuron; TP, tebuthiuron + Plateau. Plateau is a trade name for imazapic

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of the six sites, one selected as having the highest recorded lichen cover prior to treatments and one selected as having the highest recorded moss cover prior to treatment. Model residuals were evaluated to meet assumptions of normality and symmetry, and we did not detect a reason to transform the data. Due to the number of comparisons being made, Bonferroni adjustments were made to reported confidence intervals, and so, we report 99% confidence intervals.

## 3 | RESULTS

Across sites, models demonstrated significant effects of treatments on cover of lichens, $F(7, 471) = 4.73$, $p < .0001$, mosses, $F(7, 471) = 31.42$, $p \le .0001$, and soil, $F(7, 471) = 26.42$, $p \le .0001$. The statistically significant effects of treatments ($p \le .05$) differed with the biocrust component being examined. Mean lichen cover was 5% lower on subplots that were burned or mowed and received imazapic or only mowed compared with control subplots that received no treatment (Figure 2). Statistically significant differences in moss cover compared with control subplots were also seen on burn subplots and burn subplots with imazapic application where moss cover was reduced by 32% and 35%, respectively (Figure 2). Losses in mean moss cover were not as dramatic following mowing treatments or treatments of mowing with imazapic, 18% and 15% respectively. Increases in mean soil cover mirrored losses in lichen and moss cover. Mean soil cover increased by 38% and 44% in burn subplots and burn subplots with imazapic applications (Figure 2). Mean soil cover also increased by 24% and 21% in mowed subplots and mowed subplots with imazapic applications (Figure 2). Fire and mowing treatments led to significant declines in cover of mosses and lichens that mirrored increases in soil cover (Figure 2). Site differences appeared to be related to the cover of lichens and mosses that were present onsite before the study began (i.e., control subplots, Figure 3).

Models of treatment effects on lichen, moss, and soil cover at sites that demonstrated high cover of lichens (Saddle Mountain) and mosses (Onaqui) prior to treatment demonstrated significant treatment effects on mean cover of lichens, $F(7, 159) = 7.61$, $p \le .0001$, mosses, $F(7, 159) = 33.0$, $p \le .0001$, and soil, $F(7, 159) = 27.4$, $p \le .0001$. The direction of treatment effects did not change when examining these sites, but the magnitude of effects did. Mean lichen cover was 8% lower on subplots that were treated with imazapic compared with control subplots that received no treatment, but subplots treated with tebuthiuron or a combination of tebuthiuron and imazapic experienced increases in cover of 10% and 8%, respectively (Figure 4). Mowing alone and prescribed fire in combination with imazapic resulted in decreases in mean lichen cover of 7% and 10%,

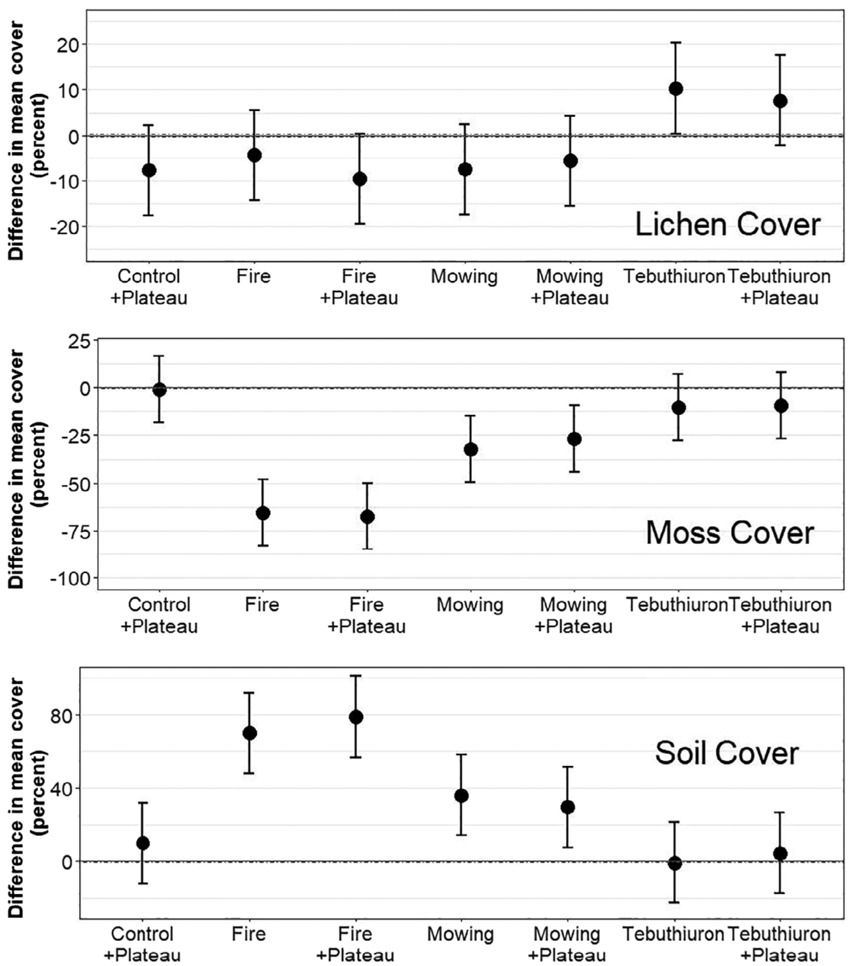


**FIGURE 4** Differences in mean cover of lichen, moss, and soil between treatments and control subplots on sites with high cover of lichen and moss prior to treatments (Saddle Mountain and Onaqui). Error bars represent 99% confidence interval. Plateau is a trade name for imazapic

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respectively (Figure 4). Mean moss cover declined dramatically following prescribed fire and fire in combination with imazapic, by 65% and 67%, respectively (Figure 4). Mean moss cover also declined following mowing and mowing in combination with imazapic, by 32% and 27%, respectively (Figure 4). Losses in mean cover of biocrusts mirrored increases in soil. Mean soil cover increased by 70% and 79% following prescribed fire and prescribed fire in combination with imazapic application (Figure 4). Mean soil cover increased by 36% and 29% following mowing and mowing in combination with imazapic application (Figure 4).

## 4 | DISCUSSION

Herbicides demonstrated positive effects on cover of biocrusts when they were significant. We found a positive effect of tebuthiuron on lichen cover (Figure 4). Tebuthiuron has previously been shown to not be detrimental to soil crust components corroborating the positive to mostly neutral effects we observed (Wachocki, Sondossi, Sanderson, Webb, & McArthur, 2001). Although imazapic has been associated with a decline in moss cover (von Reis, 2015), we did not observe this effect. However, we did observe a negative effect of imazapic on lichen cover when examining sites that had high cover of lichens and mosses prior to treatment. The magnitude of the effects of imazapic on lichens and mosses may have been more positive had the subplots, with and without treatment, had more equal covers of lichen and moss prior to treatment. We speculate that the mostly positive effects of herbicides on moss and lichen cover that we observed could be due to the fact that herbicides are transported through the vascular structure of vascular plants. Mosses and lichens do not have the same anatomy as vascular plants.

Fuel-reduction treatments that were mechanical or prescribed fire had profoundly different effects on lichens versus mosses, which was expected given the differences in sensitivity to disturbance of these groups (Condon & Pyke, 2018b; Eldridge & Rosentreter, 1999; Ponzetti & McCune, 2001). We expected to see a negative effect of fire on lichen cover observed by Condon and Pyke (2018a), which was only partially corroborated by this study. Negative effects of burning on lichen cover were only seen when prescribed fire was followed by imazapic applications. These results suggest that fire alone does not lead to substantial decreases in lichen cover. Warren et al. (2015) demonstrated similar observations of fire not being highly detrimental to lichen cover in a pinyon-juniper woodland. If maintaining lichen cover is a management objective, and the use of tebuthiuron is not an option, prescribed fire without the application of imazapic may be a preferred fuel-reduction management treatment. However, this comes with the caveat that prescribed fire is likely to have different effects on vegetation in different plant communities (Chambers et al., 2014). Although moss cover decreased in response to mowing and fire, reductions in cover seen following mowing were less than reductions seen following burning (Figure 2). This suggests that if the maintenance of the moss component is a goal in fuel-reduction treatments, and tebuthiuron is not an option, mowing may be a preferred method.

This study highlights the utility of differentiating biocrusts at the level of moss versus lichen when evaluating fuel-reduction treatments. Others have examined the effects of chaining, mowing, and prescribed fire on the cover of biocrusts with mixed effects (Bates, O'Conner, & Davies, 2014; Pyke et al., 2014; Redmond, Cobb, Miller, & Barger, 2013). Our results show that these different responses might be due to the dominant biocrust component being examined as well as the amount of cover of mosses and lichens prior to treatment.

Increases in soil cover were observed in all treatments. A common practice in the sagebrush steppe is to increase the biotic community to minimize bare soil and reduce the opportunity for non-native invasive grasses to establish (Chambers et al., 2007; Condon et al., 2011; Condon & Pyke, 2018a; Davies, Bates, Boyd, & Svejcar, 2016; Knutson et al., 2014). We demonstrate that common fuel-reduction treatments affect the cover of biocrusts and often, but not always, lead to increases in bare soil.

Fire season is beginning earlier and extending later, increasing the likelihood of fire (Abatzglou & Kolden, 2011; Westerling, Hidalgo, Cayan, & Swetnam, 2006). In response to increasing likelihood of fire, fuel-reduction treatments are currently being implemented at landscape and regional scales in the sagebrush steppe with an acknowledged need for more information on how these treatments affect plant communities (Shinneman et al., 2018). The positive response of biocrusts to herbicide and the negative response to mowing add to our knowledge of the potential ecological effects of fuel-reduction treatments on this critical component of plant communities. The response of burning was dependent on whether lichens or mosses were being examined with the former appearing to be less susceptible. Future work calls for the need to examine relationships between biocrusts and other herbicides, as few herbicides have been examined for their effects on biocrusts (Youtie, Ponzetti, & Salzer, 1999; Zaady, Levacov, & Shachak, 2004) as well as relationships between biocrusts and fuel-reduction treatments in other plant communities, especially given variation in the composition of biocrusts by plant community (Condon, Pietrasiak, Rosentreter, & Pyke, 2019; Condon & Pyke, 2020).

## 5 | CONCLUSIONS

We examined the effects of common fuel-reduction treatments on the cover of moss and lichen components of biocrusts. Our results demonstrate that the use of herbicides (imazapic and tebuthiuron) has neutral to positive effects on both lichen and moss cover but that mowing and prescribed fire have negative effects on the moss cover, which were directly mirrored by increases in bare soil. Bare soil is associated with increased invasion by annual invasive grasses that are responsible for increasing fire risk. Our findings provide justification for the inclusion of biocrusts when deciding upon appropriate fuel-reduction treatments, suggesting that surveying for biocrusts prior to treatment could inform which treatment is most likely to maintain cover of biocrusts in addition to vascular plants.

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## ACKNOWLEDGMENTS

We thank the multiple field crews who have dedicated many seasons collecting the data. We also thank the land management agencies who worked diligently to acquire the necessary funding and site permissions to implement the various treatments. Many thanks to the primary investigators who made this study a reality and who provided invaluable input for establishing the data collection protocols. The manuscript was improved by Don Major, Anne Halford, and two anonymous reviewers. Rachel Bomberger provided information related to herbicides and modes of action. This is Contribution Number (136) of the Sagebrush Steppe Treatment Evaluation Project (SageSTEP), funded by the US Joint Fire Science Program, the US Bureau of Land Management, the National Interagency Fire Center, and the Great Northern Landscape Conservation Cooperative. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

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**How to cite this article:** Condon LA, Gray ML. Not all fuel-reduction treatments degrade biocrusts: Herbicides cause mostly neutral to positive effects on cover of biocrusts. *Land Degrad Dev*. 2020;31:1727–1734. https://doi.org/10.1002/ldr.3516

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