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RESEARCH ARTICLE

No evidence of three herbicides and one surfactant impacting biological soil crusts

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Land managers rely heavily on herbicides to mitigate exotic plant invasions but the nontarget effects of herbicides on treated plant, animal, and soil communities are often overlooked. Biological soil crusts (biocrusts) are important components of ecosystems yet the effects of different herbicides on biocrusts are rarely considered. We tested the impact of three widely used herbicides, indaziflam, imazapic, aminocyclopyrachlor, and chlorsulfuron, two of which were applied with or without a surfactant, on biocrusts dominated by mosses or lichens in intermountain grasslands. We found that neither the herbicides nor surfactant impacted biocrust moss or lichen cover within 2 years of their application.

Key words: aminocyclopyrachlor and chlorsulfuron, biocrusts, herbicide, imazapic, indaziflam, surfactant

Implications for Practice

- Aligning multiple management goals requires careful consideration of different methods and their nontarget effects. For example, managers interested in retaining the ecosystem services provided by biocrusts will want to minimize biocrust disturbance while effectively combating invasive weed encroachment.
- Herbicide impacts on biocrusts vary from positive to negative and depend on the specific herbicide used, the biocrusts present, and system context. Thus, controlling invasive weeds and maintaining the ecosystem services provided by biocrusts requires considering the nontarget effects of herbicide applications.
- We identify three herbicides that had no significant impacts on biocrust cover when applied with or without a surfactant in an intermountain grassland. These herbicides may prove effective for controlling invasive plants while minimizing effects on nontarget biocrusts.

Introduction

Exotic plant invasions have many negative impacts on ecosystems including loss of native species diversity (e.g., Sax & Gaines 2003; Hejda et al. 2009; Slate et al. 2020), disruption of ecological networks (e.g., Thijs et al. 2012; Fletcher et al. 2019; Aizen & Morales 2020), and changes in ecosystem function (e.g., Waller et al. 2020; McLeod et al. 2021). To combat these impacts, billions of dollars are allocated annually toward restoration efforts with a large portion of these funds being used on herbicide application (Pimentel et al. 2005). Land managers rely heavily on the use of herbicides to mitigate exotic plant invasions but the nontarget effects of herbicides within treated communities are often overlooked.

In addition to mitigating invasive plant establishment, herbicides can also have negative impacts on nontarget plants and soil biota (e.g., Crone et al. 2009; Zhao et al. 2013). An often-overlooked example of this is biological soil crusts (biocrusts hereafter). Biocrusts are complex communities of moss, lichen, and cyanobacteria that inhabit soil surfaces among grasses, forbs, and shrubs (Weber et al. 2022) and are in some cases negatively impacted by herbicides (e.g., Hällbom & Bergman 1979; Newmaster et al. 1999; Newmaster & Bell 2002). Biocrusts are critical components of ecosystems that stabilize soil (e.g., Belnap & Gardner 1993; Pointing & Belnap 2014), regulate soil surface hydrology (e.g., Concostrina-Zubiri et al. 2017; Faist et al. 2017), soil nutrient cycling (e.g., Chamizo et al. 2012; Concostrina-Zubiri et al. 2013; Barger et al. 2016; Tucker et al. 2017), buffer soil temperatures (e.g., Gornall et al. 2009; Couradeau et al. 2016; Concostrina-Zubiri et al. 2017), and differentially influence the establishment of vascular plants (e.g., Zhang et al. 2016; Havrilla et al. 2019). In some systems, biocrusts can

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favor native plant community dominance by suppressing the establishment of exotic invasive plant species (Eldridge & Simpson 2002; Hernandez & Sandquist 2011; Slate et al. 2019; Bowker et al. 2022). Although biocrusts can be resilient to disturbance, severe biocrust disturbance can lead to a loss of ecosystem function and in some cases, exotic invasive plant encroachment (Stohlgren et al. 2001; Hernandez & Sandquist 2011; Condon & Pyke 2018*a*, 2018*b*; Slate et al. 2019). Hence, when management goals include mitigating exotic plant establishment, minimizing biocrust disturbance should be prioritized (Bowker et al. 2022).

While reviewing the literature on herbicides and biocrusts, we found 10 studies that had tested the effects of herbicides on biocrusts in field settings (Table 1). Herbicide impacts were variable for the same herbicide among different biocrust organisms and across different study systems. For example, MCPA and fosamine ammonium were shown to have negative impacts on cyanobacteria but no impact on biocrust lichen (Hällbom & Bergman 1979). Likewise, glyphosate-based herbicides were found to have positive impacts on biocrust moss and lichen cover in semiarid grasslands (Youtie et al. 1999) but negative impacts on biocrust moss and lichen cover in boreal forests (Newmaster et al. 1999; Newmaster & Bell 2002). More research is needed to understand if this variation is due to differences in biocrust species, climate conditions, and/or methodological approaches. Furthermore, many herbicides are commonly applied with surfactants, yet we know very little about how surfactants impact biocrusts. Surfactants help herbicides spread, adhere, and penetrate leaf cuticles to improve herbicide absorbance and effectiveness. As both moss and lichen biocrusts absorb water and air directly through their surfaces (Brown 1982; Glime 1992), surfactants that create an oily film or coating could be expected to cause damage independent of herbicide effects but this question has not been addressed.

Here we focus on a specific semiarid study system, intermountain grasslands, not previously considered in this context. However, the system supports moss and lichen dominated biocrust communities similar to those previously studied in semiarid systems (Table 1). In our first field study, two widely used herbicides, imazapic and indaziflam, were sprayed onto mixed lichen-moss biocrust communities on two different dates and their effects on biocrust cover were monitored for 1 year. Results from this study were promising so we set up a large study over a much broader spatial area to test the effect of an additional herbicide (aminocyclopyrachlor and chlorsulfuron), crop oil concentrate (an oil-based surfactant), and herbicide-surfactant combinations on moss and lichen biocrust communities. Our expectation was that different herbicides would vary in their effect on biocrust cover, as has been shown in other semiarid communities (Hällbom & Bergman 1979; Newmaster et al. 1999; Newmaster & Bell 2002). We also expected to find that the addition of a surfactant would negatively impact biocrust cover.

Methods

Site Description

Our study site was in Western Montana's semiarid intermountain grasslands on MPG Ranch. MPG Ranch is a 6,677 ha property managed with a focus on conservation and restoration (46°40′48″N, 114°1′40″W; www.mpgranch.com). Mean annual precipitation in this region is 325 mm (www.ncdc.noaa.gov) with the majority of precipitation falling as rain or snow between November and March (Fig. S1). Biocrusts blanket soil surfaces of native grass, forb, and shrub interspaces throughout this region. Biocrust community composition varies across this landscape from being dominated by moss or lichen to being a mixture of bryophytes (mosses and liverworts) and lichens (Durham et al. 2018). The moss genus *Syntrichia* and lichen genus *Cladonia* have the highest representation within the biocrust community in terms of cover (63%), and at least 94 other lichen and bryophyte species are also present (Durham et al. 2018).

Small Field Study

Study plots were situated in an area with high biocrust cover (65–100%) composed of a mixture of lichens and mosses. Site elevation was 1,087 m and the slope was 10%. Ten fixed plots were marked within a 9-m^2 area. We selected locations for each fixed plot where vascular plant cover was minimal or absent to alleviate our concerns that herbicide impacts on the vascular plant canopy would alter biocrust growth conditions and confound our results by indirectly impacting biocrust cover. Within each fixed plot, nine microplots (7.5 cm × 7.5 cm) were established. We made a plexiglass frame with nine microplot sized openings to facilitate microplot relocation. Treatments were randomly assigned to microplots and included: control plots (equivalent amount of water only), indaziflam (Oct; 12 October 2016), indaziflam (Nov; 21 November 2016), imazapic (Oct; 12 October 2016), imazapic (Nov; 21 November 2016; $n = 9$ for each treatment; Table S1). Indaziflam (Esplanade 200 SC, Bayer CropScience; inhibits cellulose biosynthesis) is a pre-emergent successfully used to combat annual grasses such as cheatgrass while minimally impacting desired established perennial vegetation (e.g., Sebastian et al. 2017; Clark et al. 2020; Courkamp et al. 2022). Imazapic (Plateau, BASF Corporation; inhibits amino acid synthesis) is one of the most broadly applied herbicides in North America (Wagner et al. 2017) due to its ability to control annual and perennial grasses and some broadleaf weeds at pre- and post-emergent stages (Kyser et al. 2007; Mangold et al. 2013). Herbicides were applied under each manufacturer's labeled use requirements at rates recommended by practitioners based on a comparable management scenario (indaziflam 102 g ai/ha, imazapic 122 g ai/ha). Herbicides were delivered in 280 L/ha water with a manually pressured backpack sprayer (Solo Incorporated) after fall rains while biocrusts were hydrated. During herbicide application, microplots not assigned to the treatment being applied were covered with plastic to prevent cross contamination. Biocrust percent cover (mixed lichen-moss biocrust communities) was estimated visually pre-herbicide application (7 October 2016) and 1 year after herbicide application (19 October 2017). With the plexiglass frame in place, we also took annual photos of each microplot pre- and post-herbicide application when biocrusts were

Table 1. Previous studies that have experimentally evaluated herbicide effects on biocrusts in field settings.

Herbicide	*Mode of Action*	*Trade Names*	*Previous Findings*	*Study System*	*Citation*
2, 4-D-ester	Auxin mimic that causes disorganized plant growth		No impact on moss or lichen cover	Temperate scrubland	Peterson et al. (2020)
		Gullviks 2,4-D-ester	Lichen nitrogen (N) fixation not impacted but Nostoc N fixation decreased	Boreal forest	Hällbom and Bergman (1979)
Fosamine ammonium	Inhibits bud and leaf formation	Krenite	Lichen N fixation not impacted but nostoc N fixation decreased	Boreal forest	Hällbom and Bergman (1979)
Glyphosate	Inhibits plant enzyme synthesis	Vision	Negative impact on moss and lichen cover, richness, and diversity	Boreal forest	Newmaster and Bell (2002); Newmaster et al. (1999)
		Roundup	Positive effect on moss and lichen cover	Semiarid grassland	Youtie et al. (1999)
		Accord	Positive effect on moss and lichen cover	Semiarid grassland	Youtie et al. (1999)
		Pasture Kleen	No impact on moss or lichen cover	Temperate scrubland	Peterson et al. (2020)
Imazapic	Acetolactate synthase inhibition	Plateau	No impact on lichen or moss cover	Semiarid grass and shrublands	Condon and Gray (2020)
			Correlated with decrease in moss and lichen cover	Semiarid grass and shrublands	Pyke et al. (2014)
MCPA	Auxin mimic that causes disorganized plant growth	Gullviks MCPA-ester	Lichen N fixation not impacted but nostoc N fixation decreased	Boreal forest	Hällbom and Bergman (1979)
Simazine	Photosynthesis inhibition		Lowered ARA production in cyano/lichen biocrusts	Semiarid Mediterranean steppe	Cortina et al. (2010)
			Negative impact on moss cover	Negev Desert	Zaady et al. (2004)
Tebuthiuron	Photosystem II inhibition		No impact on lichen or moss cover	Semiarid grass and shrublands	Condon and Gray (2020)
			No impact on biocrust cover	Semiarid grass and shrublands	Wachocki et al. (2001)
Triclopyr	Auxin mimic that causes disorganized plant growth	Release	Negative impact on moss and lichen cover, richness, and diversity	Boreal forest	Newmaster and Bell (2002); Newmaster et al. (1999)
		Garlone 3A	Lichen N fixation not impacted but nostic N fixation decreased	Boreal forest	Hällbom and Bergman (1979)

completely hydrated (immediately following a rain event, same dates as above). To measure biocrust cover, we used the dimensions of the plexiglass frame openings to calibrate ("set scale" prompt) the open-source image processing software ImageJ (Schindelin et al. 2012), prior to tracing biocrust cover.

Large Field Study

We established 10 study sites across a large area spanning about 4 km with each site being at least 250 m apart. Five 10 cm × 10 cm plots were established for each type of biocrust (moss or lichen dominated biocrusts) in each study site. Within each site and for each type of biocrust, one plot was treated with: water (control), aminocyclopyrachlor and chlorsulfuron, a crop oil concentrate surfactant, aminocyclopyrachlor and chlorsulfuron with a crop oil concentrate surfactant, or imazapic with a crop oil concentrate surfactant (Table S1; $n = 10$ for each treatment per biocrust type across sites). Aminocyclopyrachlor and chlorsulfuron (Perspective, Bayer CropScience; inhibit auxin synthesis and acetolactate synthase, respectively) provide efficient pre- and post-emergent broadleaf control (Kyser & DiTomaso 2013; Greet et al. 2016). Note that while Perspective has since been discontinued, both active ingredients are available separately in other widely applied herbicides (i.e., Plainview SC, Method 240SL contain aminocyclopyrachlor, and Telar XP contains chlorsulfuron Bayer CropScience). We chose Perspective for this study because of its wide use in rangelands (at the time) and to consider the effect of an herbicide with two modes of action on biocrust cover. Crop oil concentrates (Superb HC; WinField United) are designed for use at the post-emergence stage. Herbicides and the surfactant were applied within the manufacturer's labeled rate (imazapic 122 g ai/ha, aminocyclopyrachlor 139 g ai/ha and chlorsulfuron 55 g ai/ha, crop oil concentrate surfactant 1.16 L/ha) with a backpack sprayer. All treatments were applied in late spring (5 June 2018) directly following a rain event so that biocrusts were hydrated. Plots were spaced far enough apart within each site that cross contamination among treatments was not an issue. Prior to photographing our fixed plots, we placed a 10 cm × 10 cm PVC quadrat around each plot. All plots were photographed before our treatments were applied and annually for the next 2 years (when biocrusts were completely hydrated; 5 June 2018, 23 May 2019, 29 June 2020). Lichen and moss biocrust cover was measured in each photo with ImageJ after calibrating the program with the known quadrat dimensions. During the course of this experiment, monthly precipitation means (snow and rainfall) were generally lower than average from November 2020–March 2021 (with the exception of February; Fig. S1).

Analyses

All analyses were performed in R Version 4.1.3 (R Core Team 2022). Figures were created using the "ggplot2" package (Wickham 2016). Plots that were noticeably damaged were excluded from our analyses. Most damage could be attributed to trampling from wild horses. No plots were excluded from the small field study, but 11 plots were excluded from the large field study leaving 6–10 replicates for each biocrust type x treatment combination. Diagnostics from the "DHARMa" package (Hartig 2022) were used to assess model normality and homoskedasticity in all cases. We compared the effects of our treatments on biocrust cover (%) with generalized linear mixed-effect models (GLMM) using the R package "glmmTMB" (Brooks et al. 2017) and the beta distribution to account for the type of data, repeated sampling, and differences in sample sizes. For the small field study, treatment, year, and their interaction were modeled as fixed effects with fixed plot included as a random factor for blocking. For the large field study, we ran separate GLMMs for moss and lichen biocrust cover to differentiate herbicide effects on each dominant biocrust organism. In each model, treatment, year, and their interaction were modeled as fixed effects, and site was modeled as a random effect for blocking with treatment nested within site.

$$\frac{(\text{cover post} - \text{treatment}) - (\text{cover pre} - \text{treatment})}{(\text{cover post} - \text{treatment}) + (\text{cover pre} - \text{treatment})} \quad (1)$$

We also calculated the effect size of each herbicide treatment on biocrust cover for both studies (Equation 1). Linear models for each study included herbicide treatment as a fixed effect. In addition, for the large field study, separate linear models were created for post-treatment year (2019 and 2020) and type of biocrust (moss or lichen; four models total).

Results

Biocrust cover in our small study did not vary among herbicide application treatments (see Table S1 for a description of treatments) or between pre- and post-treatment years (Table S2; Fig. 1). Likewise, the effect size of each treatment on biocrust cover was the same in the small study ($F = 1.363$, $p = 0.254$; Fig. S2).

Herbicide treatments also did not impact moss or lichen biocrust cover in our large field study (Table S3; Fig. 2). Moss and lichen biocrust cover generally decreased between 2019 and 2020 (Table S3), and this pattern was consistent across

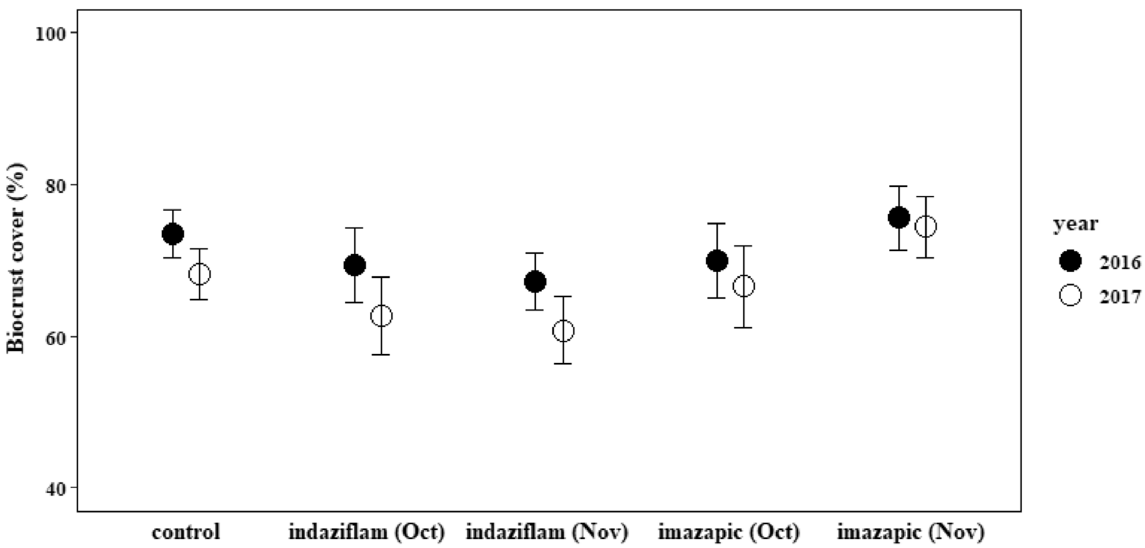

Figure 1. Biocrust percent cover before (2016) and 1 year after (2017) the addition of no herbicide (control), indaziflam (Oct), indaziflam (Nov), imazapic (Oct), or imazapic (Nov; small field study). Mean ±1 SE.

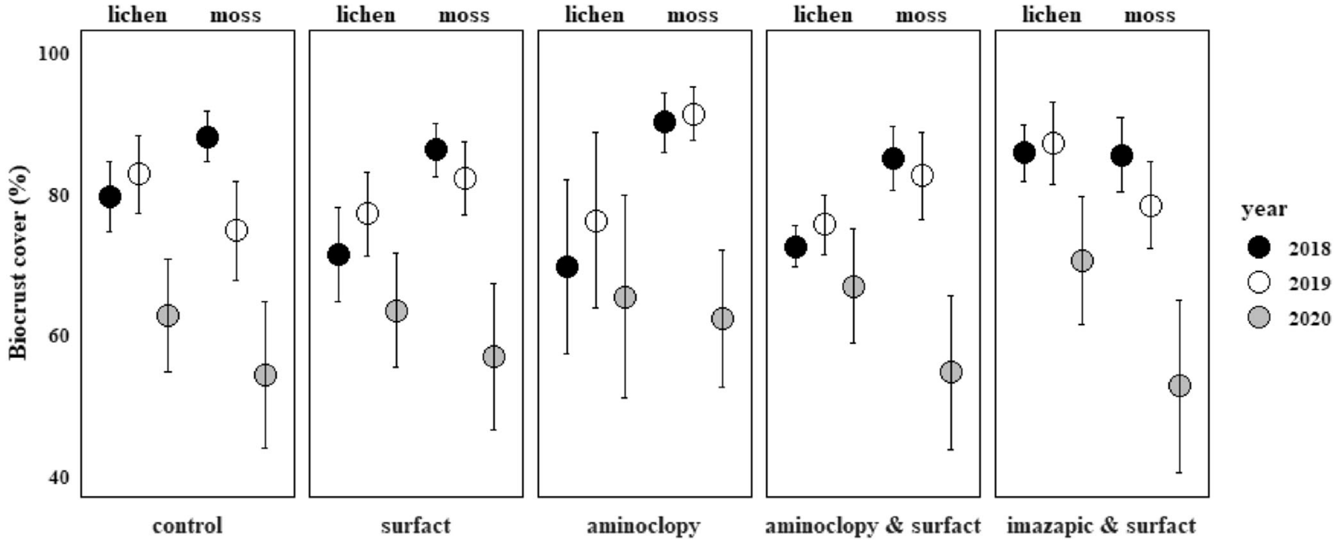

Figure 2. Biocrust lichen or moss percent cover before (2018), 1 year after (2019) or 2 years after (2020) the addition of no herbicide (control), an oil-based surfactant (surfact), aminocyclopyrachlor and chlorsulfuron (aminoclopy), aminocyclopyrachlor and chlorsulfuron with an oil-based surfactant (aminoclopy and surfact), or imazapic with oil-based surfactant (imazapic and surfact; large field study). Lichen and moss biocrust cover was not impacted by our treatments but did decrease across treatments between 2019 and 2020. Mean ±1 SE.

treatments. Similarly, the effect size of each treatment on moss or lichen biocrust cover did not vary in 2019 (moss: $F = 2.015$, $p = 0.110$; lichen: $F = 0.581$, $p = 0.679$) or 2020 (moss: $F = 0.100$, $p = 0.982$; lichen: $F = 0.268$, $p = 0.897$; Fig. S3).

Discussion

Herbicide application is one of the main tools used by land managers to combat exotic plant invasions. Previous research in boreal, temperate, and semiarid systems has reported a wide range of herbicide impacts on biocrusts that span from positive to negative. Hence, it is unclear which herbicides may be used for invasive plant control without incurring nontarget effects on biocrusts, particularly in semiarid systems. Our work helps address this understudied research topic by considering herbicide impacts on biocrusts in semiarid intermountain grasslands where biocrusts are known to inhibit the establishment of exotic invasive plants (Slate et al. 2019; Bowker et al. 2022). We found that the herbicides indaziflam, imazapic, and the combination of aminocyclopyrachlor and chlorsulfuron did not impact lichen or moss biocrust cover within 2 years of their application. In contrast to our predictions, these patterns held when herbicides were applied with or without a crop oil concentrate-based surfactant. A previous study that applied imazapic to moss and lichen biocrusts in the Great Basin also reported neutral effects (Condon & Gray 2020). The authors also found that the herbicide tebuthiuron had a positive impact on lichen biocrust cover (Condon & Gray 2020). Combined, these two studies suggest four herbicides and one surfactant that land managers from semiarid systems should consider when wishing to preserve the ecosystem services provided by biocrusts while managing exotic plant invasions.

In addition to mitigating invasive plant species, biocrust-safe herbicides could also facilitate biocrust restoration efforts. Biocrust organisms are often much slower to reestablish in degraded systems than vascular plants, and active restoration strategies can notably expedite their recovery (reviewed by Antoninka et al. 2020; but see Kidron et al. 2020). Land managers are becoming increasingly interested in restoring biocrust communities and their associated ecological services but mitigating invasive weed encroachment during biocrust reestablishment can be prohibitively time consuming for land managers and restoration practitioners. Given their lack of impact on biocrust communities, the herbicides and surfactant tested here and by Condon and Gray (2020) would be promising candidates to trial for their ability to inhibit exotic plant encroachment and not damage early successional restored biocrust communities.

Biocrust-safe herbicides are an important tool for land managers interested in minimizing disturbance on biocrust communities. Our review on this topic elucidated a few research priorities that would help extend this management tool even more broadly. Herbicides seem to have more negative impacts on biocrusts in boreal forests than in semiarid grasslands and temperate scrublands. However, including the work presented here, only 10 herbicides (five modes of action) and one surfactant have been evaluated in field situations, so one research priority should involve surveying additional types of herbicides and surfactants within these different study systems. We also found that studies based in arid systems and in grasslands dominated by annual grasses were particularly scarce and should be prioritized going forward. Next, most studies applied a single herbicide, and single herbicide application, while multiple herbicides are routinely applied, and applications can occur multiple times throughout a year. Thus, a third priority is to work with land managers to create more realistic experimental assessments that mimic land manager herbicide use strategies.

Biocrust cover decreased in our large field study between our 2019 and 2020 sampling dates by 12–24% for lichen biocrusts and 15–34% for moss biocrusts, and this was consistent across our treatments. While the temporal dynamics of biocrust communities are relatively understudied, biocrust moss and lichen cover can be highly variable in natural communities over months and years (e.g., Belnap et al. 2006; Dojani et al. 2011). For example, the dominant organism within a biocrust community can change as biocrusts mature (i.e., mosses may replace lichen; Belnap & Eldridge 2003), are disturbed (e.g., Deng et al. 2020), or compete for resources like light (Maestre et al. 2008; Bowker et al. 2010). Disturbance is unlikely to account for the differences in cover measured here since all visibly disturbed plots were removed from our analyses and we saw no evidence of disturbance in our remaining study plots. Biocrust cover can also increase or decrease rapidly in response to changes in precipitation (Karnieli et al. 2002; Belnap et al. 2006; Dojani et al. 2011). Monthly precipitation means (snow and rainfall) were generally lower from November 2020–March 2021 (except for February), the months during which this region receives the bulk of its precipitation. Hence, reduced precipitation may have driven this result. However, disentangling the effects of precipitation on biocrust cover is beyond the scope of the current study but this is a likely explanation for the decrease in biocrust cover measured here.

It is important to note that although we did not find negative impacts of herbicides on biocrusts, negative effects have been previously reported (Pyke et al. 2014), so it is necessary to consider why these divergent results may arise. Herbicides enter plants through the plant cuticle and are eventually transported through the vascular system. Biocrust organisms function very differently than vascular plants and do not have cuticles or vascular systems. These functional differences may contribute to the patterns found in the current study but do not explain results from previous work where herbicide effects were variable. For example, glyphosate-based herbicides can have negative, (Newmaster et al. 1999; Newmaster & Bell 2002), positive (Youtie et al. 1999), or neutral impacts (Peterson et al. 2020) on moss or lichen biocrust cover. Some of this variation may be related to differences in biocrust species, study systems, and/or timing of application but more research is needed to address these potential factors. Furthermore, in the current study, we measured biocrust cover and not function. Previous work has found that certain herbicides can inhibit nitrogen fixation in cyanobacteria and lichen biocrusts (Hällbom & Bergman 1979; Cortina et al. 2010) so biocrust function should also be evaluated before classifying these or other herbicides and surfactants as biocrust-safe.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Herbicide and surfactant treatments applied to biocrusts in 2016 (small field study) and 2018 (large field study).
Table S2. Results from a GLMM used to evaluate the impact of each treatment (see Table S1) and study year (pre- and post-herbicide application) on biocrust cover in our small field study.
Table S3. Results of two GLMMs used to evaluate the impact of each treatment (see Table S1) and study year (pre- and post-herbicide application) on biocrust cover for lichen or moss biocrusts evaluated in our large field study.
Figure S1. Monthly precipitation means (snow and rain) for the months between our 2019 and 2020 surveys of our large field study compared with the 30-year average (normal).
Figure S2. Effect size of the herbicides imazapic and indaziflam on biocrust cover one year after herbicide application compared with control plots (small field study).
Figure S3. Effect size of our no herbicide (control), an oil-based surfactant (surfact), aminocyclopyrachlor and chlorsulfuron (aminoclopy), aminocyclopyrachlor and chlorsulfuron with an oil-based surfactant (aminoclopy & surfact), imazapic with an oil-based surfactant, or on lichen or moss biocrusts one (2019; upper) or two (2020; lower) years after treatment application (large field study).

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