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## Potential for post-fire recovery of Greater Sage-grouse habitat

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**Abstract.** In the western United States, fire has become a significant concern in the management of big sagebrush (*Artemisia tridentata* Nutt.) ecosystems. This is due to large-scale increases in cover of the fire-prone invasive annual cheatgrass (*Bromus tectorum* L.) and, concurrently, concerns about declining quantity and quality of habitat for Greater Sage-grouse (*Centrocercus urophasianus*). The prevailing paradigm is that fire results in a loss of sage-grouse habitat on timescales relevant to conservation planning (i.e., 1–20 yr), since sagebrush cover can take many more years to recover post-fire. However, fire can have effects that improve sage-grouse habitat, including stimulating perennial grass and forb production. The conditions under which fire results in the permanent loss or enhancement of sage-grouse habitat are not well understood. We used long-term data from the Utah Division of Wildlife Resources Range Trend Project to assess short-term (1–4 yr post-treatment) and long-term (6–10 yr post-treatment) effects of fire on vegetation cover at 16 sites relative to sage-grouse habitat vegetation guidelines. Sagebrush cover remained low post-fire at sites considered historically unsuitable for sage-grouse (<10% initial sagebrush cover). In contrast, at sites that had higher (>10%) pre-fire sagebrush cover, sagebrush cover decreased to <10% in the short-term post-fire, but by 6–10 yr after fire, most of these sites exhibited a recovering trajectory and two sites had recovered to >10% cover. Post-fire sagebrush cover was positively related to elevation. Across all sites, perennial grasses and forbs increased in cover to approximately meet the habitat vegetation guidelines for sage-grouse. Cheatgrass cover did not change in response to fire, and increased perennial grass cover appears to have played an important role in suppressing cheatgrass. Our results indicate that, while fire poses a potential risk for sage-grouse habitat loss and degradation, burned sites do not necessarily need to be considered permanently altered, especially if they are located at higher elevation, have high sagebrush cover pre-fire, and are reseeded with perennial grasses and forbs post-fire. However, our results confirm that fire at more degraded sites, for example, those with <10% sagebrush cover, can result in cheatgrass-dominated landscapes and sagebrush loss at these sites should be avoided.

**Key words:** *Artemisia tridentata*; *Bromus tectorum* L.; *Centrocercus urophasianus*; cheatgrass; perennial grass; resilience; wildfire.

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### INTRODUCTION

Over the past several decades, significant attention has turned to understanding how best to manage big sagebrush (*Artemisia tridentata* Nutt.) ecosystems of the western United States (Wisdom and Chambers 2009, Davies et al. 2011, McIver and Brunson 2014, Chambers et al.

2017a). Land managers are now challenged with managing widespread and rapid change in these ecosystems and supporting declining populations of the Greater Sage-grouse (*Centrocercus urophasianus*, sage-grouse), a sagebrush obligate (Connelly et al. 2011). Changes in the condition of sagebrush ecosystems have occurred due to a variety of factors, including non-native species invasions, inappropriate livestock management, land development, and changes in fire regimes (Connelly et al. 2004, Crawford et al. 2004).

Fire is a critical management concern for sage-grouse because it has become more frequent and widespread in sagebrush systems (Connelly et al. 2004). Fire risks have increased in part due to large-scale increases in the fire-prone invasive annual cheatgrass (*Bromus tectorum*, downy brome; Balch et al. 2013, Chambers et al. 2014). Compounding this risk is the fact that sagebrush cover can take decades to recover to pre-fire levels (Baker 2006, Lesica et al. 2007).

The current prevailing wisdom is that wildfire and prescribed burns that result in the loss of sage-grouse habitat on timescales relevant to management should be avoided (Nelle et al. 2000, Rhodes et al. 2010, Beck et al. 2012, Hess and Beck 2012, U.S. Fish and Wildlife Service 2013, Coates et al. 2015). Based on 30-yr projections of wildfires and recovery rates, Coates et al. (2015) predicted steady and substantial long-term declines in sage-grouse populations across the Great Basin. As an example of policy set for managing fire in sage-grouse habitat, the Conservation Plan for Greater Sage-grouse in Utah (Utah Public Land Policy Coordinating Office [PLPCO] 2018) states that any ground or vegetation disturbance, such as wildfire, with impacts that last longer than five years is considered a permanent loss of sage-grouse habitat.

However, the effects of fire on big sagebrush communities, which provide sage-grouse habitat, can be somewhat nuanced (Davies et al. 2011, 2014). Sage-grouse habitat requirements vary seasonally and geographically, but in general, sage-grouse prefer areas with moderate-to-heavy sagebrush cover (10–30% canopy cover), perennial grass cover exceeding 10%, and perennial forb cover exceeding 5% (Connelly et al. 2000, 2011, D. Dahlgren et al., *unpublished manuscript*). One of the primary concerns about fire is that sagebrush cover is estimated to take 30–100 or

more years to recover in more mesic mountain big sagebrush (*A. tridentata* subsp. *vaseyana*) communities and 50–120 or more years to recover in more xeric Wyoming big sagebrush (*A. tridentata* subsp. *wyomingensis*) communities (Baker 2006, Lesica et al. 2007). However, sagebrush recovery rates are recognized to be variable from site to site depending on temperature and moisture regimes and land-use history (Morris et al. 2011, Chambers et al. 2014, Morris and Rowe 2014). Moreover, in many areas, high pre-fire sagebrush cover can competitively suppress production of perennial grasses and forbs, and removal of sagebrush by fire, chemical, or mechanical means can result in an increase in grasses and forbs (Crawford et al. 2004, Dahlgren et al. 2006, Thacker 2010, Swanson et al. 2016, Monaco et al. 2017, Riginos et al. 2019). Forbs and grasses make up key components of sage-grouse diets during pre-nesting, early brooding, and late brooding in spring and summer and are also critical food resources for a variety of insects that are themselves important components of sage-grouse diets (Connelly et al. 2011, Dahlgren et al. 2015). Thus, depending on the rate at which sagebrush cover recovers post-fire, the longevity of any increases in grass and forb production, and pre-fire site conditions such as native perennial versus invasive annual cover, the effects of fire on sage-grouse habitat quality may not all be negative on the scale of 10–20 yr (after the initial several years post-fire, when sagebrush cover is expected to be very low).

Fire can also promote the spread of invasive annual grasses, especially cheatgrass, in big sagebrush ecosystems (D'Antonio and Vitousek 1992, Chambers et al. 2007). However, site-to-site variation in this response can also be high, with vulnerability to cheatgrass invasion thought to be greatest in lower-elevation, Wyoming big sagebrush communities with warm–dry soil temperature and moisture regimes and lowest in higher-elevation, mountain big sagebrush communities with cool–moist soil temperature and moisture regimes (Chambers et al. 2007, 2014). Further, if sites have high pre-fire perennial grass cover and/or are successfully reseeded with perennial grasses post-fire, and if fire stimulates production of perennial grasses, this may suppress annual grasses (Reisner et al. 2013, Chambers et al. 2014, Rau et al. 2014). Thus, depending on

the pre-fire conditions and post-fire response of the plant community, fire may not necessarily degrade habitat quality by promoting annual grass cover.

Understanding the potential for sites to recover after fire, the conditions under which recovery can occur and the timeline for recovery are all important for effective management of sage-grouse habitat. Much of the research that has been done on post-fire recovery of sagebrush ecosystems has focused on lower-elevation, more xeric, and more degraded sites and short-term time frames post-fire; few long-term studies have focused on sites at higher elevation and in relatively good condition pre-fire (Davies et al. 2014, Ellsworth et al. 2016). We examined the short- and long-term post-fire plant community responses at 16 sagebrush-dominated sites with variable elevation and annual precipitation relative to sage-grouse habitat vegetation guidelines. We ask the following questions: (1) Does vegetation show the potential to meet sage-grouse habitat guidelines within 10 yr post-fire? And if so (2) how did pre-fire site conditions affect recovery potentials?

## METHODS

### Data source

All data came from project sites associated with the Utah's Watershed Restoration Initiative (WRI; <https://wri.utah.gov/wri/>) and monitored by the Utah Division of Wildlife Resources, Range Trend Project. The WRI is a public-private partnership program aimed at improving watersheds through pro-active restoration and post-fire rehabilitation in Utah, USA. Each project is planned, reviewed, ranked, and executed at the local level.

We identified 16 big sagebrush-dominated WRI sites that had burned and for which both short-term (1–4 yr) and long-term (6–10 yr) post-fire data existed. Fourteen of these burned by wildfire and two by prescribed fire. Eight sites were seeded post-fire, and eight were not. The decision to seed or not was based on site conditions and did not depend on whether the fire was prescribed or not. Sites that were seeded had significantly lower cover of perennial grasses and perennial forbs than unseeded sites (Riginos et al. 2019). Seeds were aerially broadcast and

consisted of a mix of perennial forbs, grasses, and sagebrush; the exact species composition was custom-mixed for each project site (see Wilder et al. 2019 for more details).

Sites were dominated by either Wyoming big sagebrush (*A. tridentata* subsp. Nutt. *wyomingensis* Beetle & Young;  $n = 7$ ) or mountain big sagebrush (*A. tridentata* subsp. *vaseyana* [Rydb.] Beetle;  $n = 9$ ) communities (Table 1). Sites ranged in elevation from 1432 to 2560 m and in mean annual precipitation from 254 to 711 mm, as calculated using PRISM climate data (<http://www.prism.oregonstate.edu>) between 1981 and 2010. Sites ranged from 1% to 21% slope, with the majority <10% slope. We deliberately excluded from our analysis sites that had slope >25%. This was based on observations that sage-grouse generally use sites with 0–25% slope (Holloran et al. 2005; but note that habitat has been characterized as 0–10% slope for winter and breeding habitat (Doherty et al. 2008) and 0–44% for nesting habitat (Yost et al. 2008). Sites varied in ecological site and temperature-moisture regime (Table 1).

We compiled a database that included vegetation and ground cover characteristics at each site before and after fire. Sites were monitored between 1999 and 2013 by the Utah Division of Wildlife Resources Range Trend Studies Project (<https://wildlife.utah.gov/range-trend.html>) every three to five years on a rotating monitoring schedule, regardless of the date the treatment was applied. To accommodate this variable schedule, we classified each monitoring event as pre-fire, short-term post-fire (1–4 yr), or long-term post-fire (6–10 yr).

Plant cover characteristics were measured at each site along five parallel 30 m long transects variably spaced perpendicular to a 152-m baseline. For the purposes of cross-site comparison, we grouped cover into the following broad functional categories: sagebrush, perennial grass, perennial forb, and annual grass (which was predominantly cheatgrass). Canopy cover was measured using a modified Daubenmire (1959) method; 0.25-m<sup>2</sup> quadrats were placed every 1.5 m along each transect ( $n = 20$  along each transect,  $n = 100$ /site), and cover was determined using an ocular estimation of cover in seven cover classes: (1) 0.01–1%, (2) 1.1–5%, (3) 5.1–25%, (4) 25.1–50%, (5) 50.1–75%, (6) 75.1–95%, and (7) 95.1–100%. For analysis, cover for each quadrat

Table 1. Sagebrush community, ecological site description, and temperature–moisture regime for each of the 16 sites.

| Site name         | Sagebrush community | Ecological site description                            | Moisture–temperature regime |
|-------------------|---------------------|--|-----------------------------|
| Big Cedar Cove    | Wyoming             | Upland Gravelly Loam (Wyoming big sagebrush)           | Frigid–xeric                |
| Buckskin 1        | Wyoming             | Upland Shallow Loam (Cliffrose)                        | Mesic–ustic                 |
| Coldwater 1       | Wyoming             | Semidesert Gravelly Loam (Wyoming big sagebrush) North | Mesic–aridic                |
| Doubleup Hollow   | Mountain            | Upland Loam (mountain big sagebrush)                   | Frigid–xeric                |
| Flat Top Mountain | Mountain            | Mountain Gravelly Loam (Oak)                           | Frigid–ustic                |
| Hereford 1        | Wyoming             | Semidesert Loam (Wyoming big sagebrush)                | Mesic–aridic                |
| Hoovers Hollow    | Mountain            | Mountain Shallow Loam (mountain big sagebrush)         | Frigid–xeric                |
| Muley Point       | Wyoming             | Semidesert Loam (Wyoming big sagebrush)                | Mesic–xeric                 |
| Pahcoon Flat      | Wyoming             | NA   | NA                          |
| Saddle Horse      | Mountain            | Mountain Stony Loam (Browse)                           | Frigid–ustic                |
| Sidhill Spring    | Mountain            | Upland Loam (mountain big sagebrush)                   | NA                          |
| Smith Canyon      | Mountain            | Mountain Loam (mountain big sagebrush)                 | Mesic–xeric                 |
| South Spring      | Mountain            | Mountain Loam (mountain big sagebrush)                 | Frigid–aridic               |
| Tobin Bench       | Mountain            | NA   | NA                          |
| West Goslin       | Wyoming             | Mountain Loam (mountain big sagebrush)                 | Frigid–ustic                |
| Wooden Shoe       | Mountain            | NA   | Mesic–aridic                |

was treated as the midpoint of the observed cover class value; these values were averaged across all quadrats to obtain an overall site value.

Starting in 2002, sagebrush cover was also measured using the line-intercept method along each 30-m transect (U.S. Department of the Interior Bureau of Land Management 1999). There were six sites for which there was no line-intercept cover data for sagebrush cover pre-fire because they were initially measured prior to 2002; for these, we used the strong correlation ( $R^2 = 0.93$ ,  $P < 0.0001$ ) between the Daubenmire cover and line-intercept cover in a larger set of 84 WRI sites (see Riginos et al. 2019 for details) for which there was both Daubenmire and line-intercept data to interpolate line-intercept cover values pre-fire. This enabled us to use line-intercept cover values for assessing whether sagebrush cover at sites met sage-grouse habitat standards, since line intercept is the shrub cover method that has been used in developing sage-grouse habitat vegetation guidelines (Stiver et al. 2015).

### Analyses

For both mountain and Wyoming big sagebrush community sites, we compared sites pre- and post-fire in order to assess the impact of treatments on sites' ability to meet sage-grouse habitat vegetation guidelines. We considered

whether sites met sage-grouse habitat vegetation guidelines in terms of sagebrush cover (10–30%), perennial grass cover (>10%), and perennial forb cover (>5%) and also assessed patterns of annual grass cover, for which no guidelines exist. These guidelines were obtained from the Utah Greater Sage-Grouse Approved Resource Management Plan (Bureau of Land Management 2015) and range-wide habitat vegetation guidelines (Connelly et al. 2000). We recognize that sagebrush shrub height and perennial grass and forb height are also important aspects of sage-grouse habitat quality; however, these data were not available for our study sites.

We used R (version 3.3.1) for all analyses. For each vegetation category (sagebrush, perennial grass, perennial forb, and annual grass cover), we used repeated-measures ANOVAs with the *corAr1* covariance structure and Tukey's tests to compare mean values before fire, 1–4 yr after fire, and 6–10 yr after fire (time period) and test for any effects of sagebrush community. Site was the unit of replication and was treated as a random effect in the repeated-measures models. The sagebrush community for each site was determined based on the dominant sagebrush subspecies present: Wyoming big sagebrush, *A. t. subsp. wyomingensis* or mountain big sagebrush *A. t. subsp. vaseyana*. We did not consider the effect of seeding in statistical models



because seeding was not independent from cover of perennial grasses and forbs pre-fire.

In addition, we plotted the mean cover values within each site at each time period in order to highlight the trajectory of sites' changes post-fire. For the purposes of analyzing sagebrush recovery post-fire, we divided sites into those with <10% sagebrush cover before the fire ( $n = 8$ ), and those with >10% sagebrush cover ( $n = 8$ ). We made this distinction because sites with <10% sagebrush cover pre-fire may not have had the potential to achieve the 10% minimum sagebrush cover necessary to be considered sage-grouse habitat. Response variables were natural-log-transformed to meet assumptions of normality.

Finally, we used bivariate regressions to explore some of the potential influences of site environmental factors on observed vegetation responses as well as relationships between vegetation cover response variables. We regressed each cover response variable (sagebrush, perennial grass, perennial forb, and annual grass cover) from the pre-fire and long-term post-fire data collection events on site elevation, precipitation, and slope. Site precipitation and elevation were strongly correlated with each other; therefore, we present results only for elevation, which was more strongly predictive of a broader set of variables. We further regressed cover response variables against each other to understand the extent to which major functional groups' responses to fire were coupled or decoupled.

## RESULTS

Big sagebrush cover showed different responses to fire depending on whether pre-fire cover was <10% or >10%. Pre-fire sagebrush cover was not related to sagebrush community (Wyoming versus mountain big sagebrush:  $t = -0.013$ ,  $P = 0.99$ ), enabling us to consider the effect of community independently of time since fire. Where pre-fire sagebrush cover was <10%, there was no significant difference among pre-fire cover and post-fire cover in the short or long term (Table 2), and long-term post-fire sagebrush cover was well below the 10% threshold proposed in the sage-grouse habitat vegetation guidelines for the majority of sites (Fig. 1a). Where pre-fire sagebrush cover was >10%, there were significant differences among pre-fire,

Table 2. Results of ANOVAs on cover responses to fire at 16 locations in Utah.

| Parameter             | df | F      | P      |
|-----------------------|----|--------|--------|
| Sagebrush cover > 10% |    |        |        |
| Time period           | 1  | 25.65  | 0.0002 |
| Community             | 1  | 0.82   | 0.40   |
| Time × community      | 1  | 0.45   | 0.51   |
| Sagebrush cover < 10% |    |        |        |
| Time period           | 1  | 2.94   | 0.11   |
| Community             | 1  | 2.27   | 0.18   |
| Time × community      | 1  | 0.0009 | 0.97   |
| Perennial grasses     |    |        |        |
| Time period           | 1  | 5.87   | 0.02   |
| Community             | 1  | 0.004  | 0.95   |
| Time × community      | 1  | 1.25   | 0.27   |
| Perennial forbs       |    |        |        |
| Time period           | 1  | 3.96   | 0.06   |
| Community             | 1  | 2.05   | 0.17   |
| Time × community      | 1  | 0.76   | 0.39   |
| Annual grasses        |    |        |        |
| Time period           | 1  | 0.55   | 0.46   |
| Community             | 1  | 0.29   | 0.59   |
| Time × community      | 1  | 1.03   | 0.34   |

*Note:* Time period consists of pre-fire, short-term (1–4 yr) post-fire, and long-term (6–10 yr) post-fire, and community refers to sites dominated by either Wyoming big sagebrush or mountain big sagebrush.

short-term post-fire, and long-term post-fire cover (Table 2). In this case, both short-term post-fire sagebrush cover and long-term post-fire sagebrush cover were reduced compared to pre-fire cover, but average long-term post-fire sagebrush cover was approaching the 10% threshold to meet sage-grouse habitat vegetation guidelines and most individual sites showed a trajectory of increasing sagebrush cover (Fig. 1b). Two of these sites exceeded the 10% threshold by 6–10 yr post-fire. Sagebrush community was not a significant predictor of sagebrush response to fire in either situation of pre-fire cover being <10% or >10% (Table 2).

Perennial grass cover was higher in the long-term post-fire than pre-fire or in the short-term post-fire (Table 2) and, on average, exceeded the 10% threshold of cover necessary to meet sage-grouse habitat vegetation guidelines (Fig. 2a). The effect of time period on perennial forb cover was marginally significant (Table 2), and forb cover was slightly higher post-fire (both short-term and long-term) than pre-fire, averaging just short of the 5% threshold necessary to meet sage-grouse habitat vegetation guidelines (Fig. 2b).

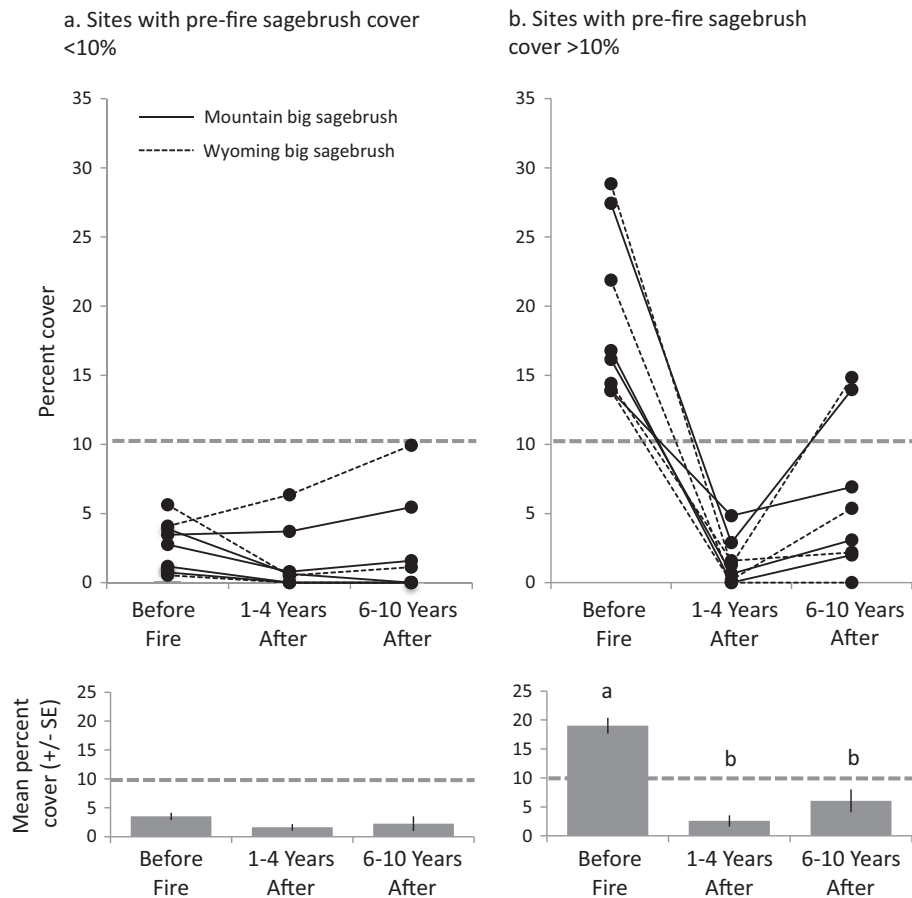


Fig. 1. Percent sagebrush cover at (a) sites that had pre-fire sagebrush cover of <10% and (b) sites that had pre-fire sagebrush cover of >10%. Top panels show individual site cover values over time, and bottom panels show mean cover values across all sites. Dashed gray lines indicate the 10% minimum sagebrush cover value recommended for sage-grouse habitat. Letters indicate significant differences among groups using Tukey's HSD test.

There was no significant difference among time periods for annual grass cover (Table 2), and although annual grass cover was reduced in the short-term post-fire compared to pre-fire, in the long-term it had increased back to a comparable cover as pre-fire (Fig. 3a). Perennial grass, perennial forb, and annual grass cover responses to treatments did not depend on sagebrush community type (Table 2).

Sagebrush and perennial grass cover were positively related to elevation pre-fire (sagebrush:  $R^2 = 0.29$ ,  $P = 0.03$ ; perennial grass:  $R^2 = 0.23$ ,  $P = 0.05$ ), and annual grass cover was negatively related to elevation pre-fire ( $R^2 = 0.18$ ,  $P = 0.04$ ). However, in the long-term post-fire, only sagebrush cover showed a significant positive

relationship with elevation ( $R^2 = 0.37$ ,  $P = 0.01$ ), whereas annual and perennial grass had no relationship with elevation. None of the cover responses was related to slope before or after fire. Pre-fire, perennial grass, and sagebrush cover were weakly and positively related, but this pattern did not hold in the long-term post-fire. Conversely, in the long-term post-fire, annual grass cover was negatively related to perennial grass cover (Fig. 3b), whereas these cover variables were not related to each other pre-fire.

## DISCUSSION

The consequences of fire for sage-grouse and their habitats are generally considered to be



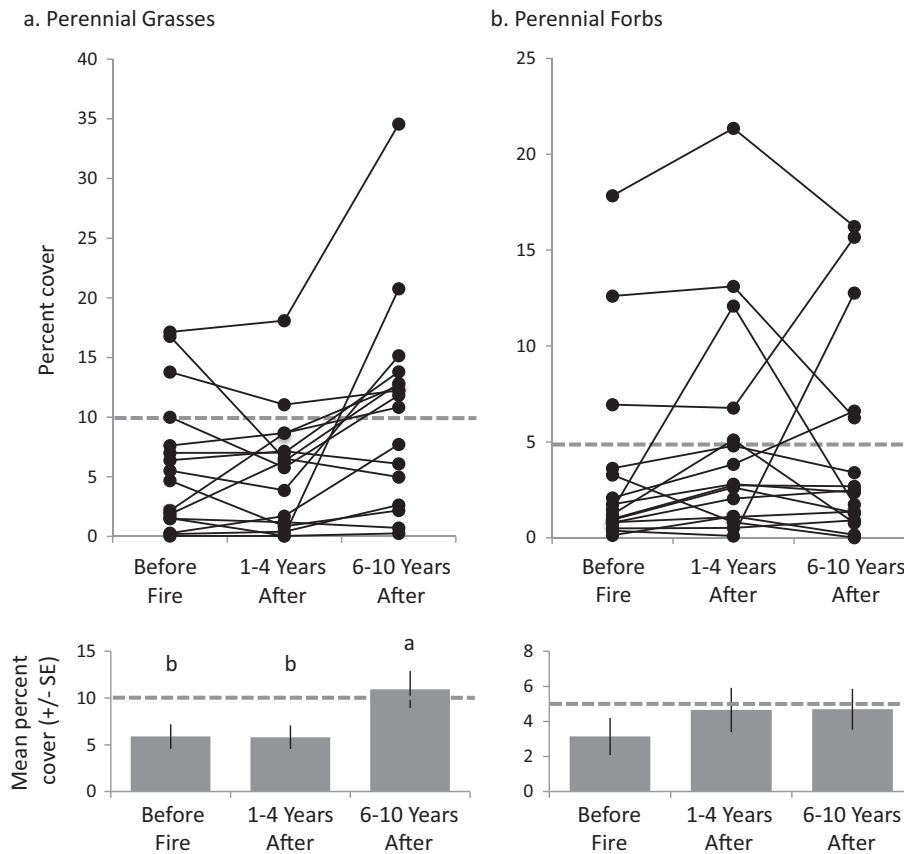


Fig. 2. Percent cover of (a) perennial grasses and (b) perennial forbs, pre-fire, 1–4 yr after fire, and 6–10 yr after fire. Top panels show individual site cover values over time, and bottom panels show mean cover values across all sites. Dashed gray lines indicate the 10% and 5% minimum perennial grass and forb cover values, respectively, that are recommended for sage-grouse habitat. Letters indicate significant differences among groups using Tukey's HSD test.

negative or highly risky, especially in breeding habitats (Coates et al. 2015). Recent recommendations have focused on avoiding the use of prescribed fire in big sagebrush ecosystems because of concerns that fire will suppress sagebrush cover for decades to come and that fire increases the risk of cheatgrass spread (Nelle et al. 2000, Wambolt et al. 2001, Rhodes et al. 2010, Condon et al. 2011, Davies et al. 2011, Beck et al. 2012, Hess and Beck 2012, U.S. Fish and Wildlife Service 2013, Utah PLPCO 2018). Our analysis of 16 burned sites shows a more nuanced picture. We found that sites with pre-fire sagebrush cover greater than the minimum 10% necessary to meet sage-grouse habitat standards showed a trajectory of recovery post-fire. In contrast, at sites with pre-fire sagebrush cover <10%, post-fire sagebrush

cover remained low, despite seeding at most of these sites. Across all sites, average perennial grass cover increased from pre-fire to post-fire to exceed the 10% cover necessary for sage-grouse habitat. Perennial forb cover also increased slightly across all sites, to an average just below the 5% recommended cover. Increases in herbaceous cover, especially forb cover, may benefit sage-grouse brooding habitat both directly as a food source and indirectly by increasing the arthropod abundance for chick diets (Dahlgren et al. 2015). Average annual grass cover, which was almost exclusively cheatgrass and was <25% pre-fire at all but one of these sites, did not change following fire (although some individual sites did show substantial increases in annual grass cover post-fire). Taken together, these results indicate

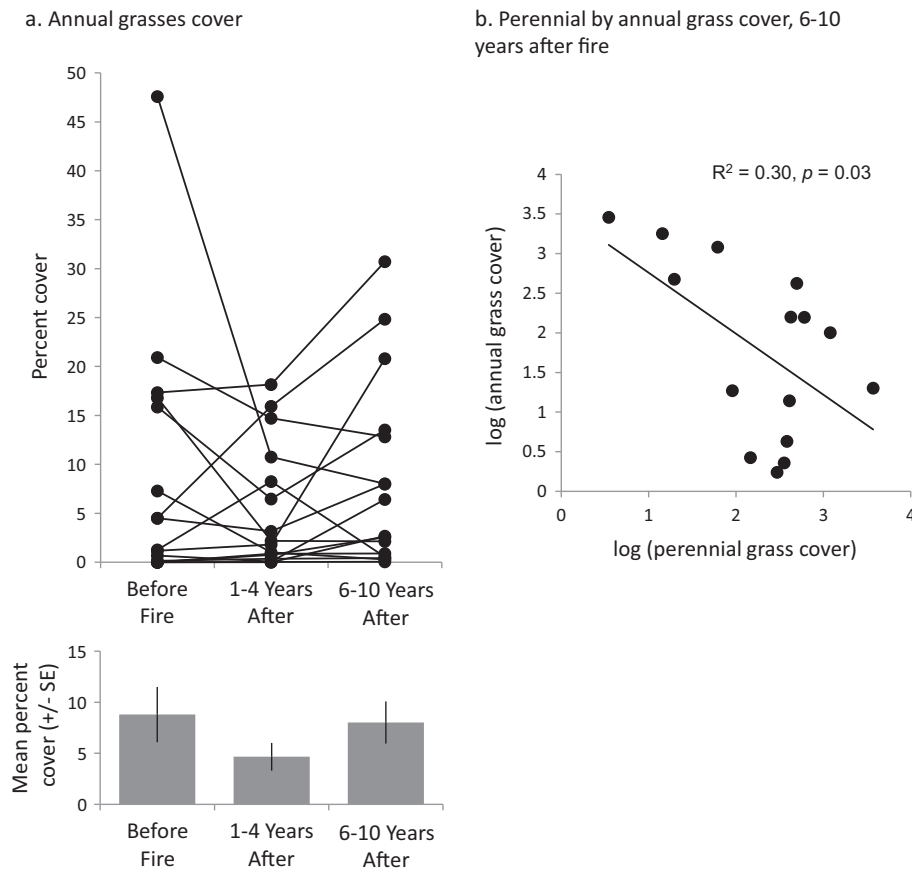


Fig. 3. (a) Percent cover of annual grasses pre-fire, 1–4 yr after fire, and 6–10 yr after fire. Top panel shows individual site cover values over time, and bottom panel shows mean cover values across all sites. (b) Percent cover of annual grasses 6–10 yr post-fire as a function of percent cover of perennial grasses.

that sites with >10% pre-fire sagebrush cover were on a trajectory to recover to meet sage-grouse habitat standards, with reduced sagebrush cover but enhanced perennial grass and forb cover and no change in average annual grass cover relative to pre-fire conditions.

Pre-fire sagebrush cover and post-fire sagebrush cover were both higher at higher elevations (sites ~2000–2600 m asl, as compared to sites ~1400–2000 m asl), consistent with observations of positive relationships between elevation and sagebrush cover and resilience following disturbance (Wisdom and Chambers 2009, Chambers et al. 2017b). Although Wyoming big sagebrush communities generally occur at lower-elevation, drier sites and are considered to have lower resilience than mountain big sagebrush communities, we found no significant difference

in post-fire sagebrush cover between sites dominated by these two communities. It is possible that this is due to low replication, as the sites with the highest post-fire sagebrush cover values were all dominated by mountain big sagebrush. In a 17-yr study of fire effects on Wyoming big sagebrush at sites ~1500 m asl and in good pre-fire condition, Ellsworth et al. (2016) also found evidence of post-fire community resilience and recovery toward meeting sage-grouse standards, while Beck et al. (2009) found little recovery of sagebrush cover 14 yr post-fire at a similar elevation and community type. At comparable elevations, we saw generally low post-fire sagebrush cover values (<3%), whereas cover was more consistently higher (4–15%) above 2000 m. Together, these results suggest that the impacts of fire on sage-grouse habitat are less likely to be

negative at higher-elevation, higher precipitation sites with pre-fire sagebrush cover >10%.

Annual grass cover pre-fire was negatively related to elevation, also consistent with prior observations of higher susceptibility to cheatgrass invasion at lower elevations (Chambers et al. 2007, 2013). However, post-fire annual grass cover was not correlated with elevation, but was instead negatively related to perennial grass cover, suggesting that competitive dynamics between these guilds was as, or more, important than the effects of elevation. These results support a number of other findings that the effects of fire on annual grass cover depend strongly on perennial grass recovery (Chambers et al. 2007, Condon et al. 2011, Rau et al. 2014) and underscore the importance of seeding burned sites with perennial grasses, especially if pre-fire perennial grass cover is low (Riginos et al. 2019).

Although site recovery to meet sage-grouse habitat vegetation guidelines after fire may take more than ten years, our results indicate that burned sites need not necessarily be considered permanently altered, especially if they are located at higher-elevation sites with high sagebrush cover pre-fire and are seeded with perennial grasses and forbs post-fire to suppress annual grasses. This has implications for policy. For example, conservation plans for sage-grouse in Utah consider fire a permanent ground disturbance if sagebrush recovery to the 10% threshold has not occurred after five years (State of Utah 2013, Utah Public Land Policy Coordinating Office [PLPCO] 2018). Our results indicate that five years may be too soon post-fire to determine the site's full potential to recover to meet sage-grouse habitat vegetation guidelines. Further, a rigid classification of burned areas as lost sage-grouse habitat overlooks the possibility that a mosaic of burned patches within a larger unburned landscape may have benefits for sage-grouse and other species through promoting a diversity of habitat and diet resources (Davies et al. 2014). Carefully managed, prescribed fire may even be an effective strategy for limiting the spread of invasive annuals and preventing more intense wildfires, especially at higher-elevation sites (McAdoo et al. 2013, Swanson et al. 2018).

It is important to note, however, that fire may have additional undesirable impacts that are not

adequately captured by evaluating sage-grouse habitat standards alone. For example, the impacts of fire on insect productivity and abundance are unclear; while Davies et al. (2014) found increased insect abundance following fire, others have reported neutral to negative effects of fire on insects (Rhodes et al. 2010, Beck et al. 2012). Since insects are a key component of sage-grouse diet, any negative effects of fire on insects could adversely affect sage-grouse and other wildlife. Fire can also decrease the amount of litter and biological crusts protecting the soil surface from erosion (Pyke et al. 2014, Riginos et al. 2019) and suppressing cheatgrass invasion (Reisner et al. 2013). Further, as the climate becomes warmer, fire may promote annual grass invasions to a greater degree than it does now (Abatzoglou and Kolden 2011). It is also important to note that this study focused on small-scale habitat components relative to the habitat needs of sage-grouse. The need to ensure the recovery of a full suite of ecosystem processes, at relevant spatial scales, post-fire is an important consideration in any decisions around prescribed burns or post-wildfire management.

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