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Predicting fire-based perennial bunchgrass mortality in big sagebrush plant communities

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Abstract. Maintenance and post-fire rehabilitation of perennial bunchgrasses is important for reducing the spread of exotic annual grass species in big sagebrush plant communities. Post-fire rehabilitation decisions are hampered by a lack of tools for determining extent of fire-induced perennial grass mortality. Our objective was to correlate post-fire characteristics with perennial bunchgrass mortality at the plant and plant community scales. We recorded basal area, percent char, depth of burn and soil colour for 174 bunchgrasses across four ecological sites after a 65 000 ha wildfire in south-east Oregon and assessed plant mortality. Mortality was correlated with post-fire soil colour and ecological site; soil colours (black and grey) associated with pre-fire shrub presence had up to five-fold higher mortality than brown soils typical of interspace locations. Models incorporating depth of burn and soil colour correctly predicted mortality for 90% of individual plants; cover of brown soil explained 88% of the variation in bunchgrass mortality at the plant community scale. Our results indicate that soil colour and depth of burn are accurate predictors of bunchgrass mortality at individual plant and plant community scales and could be used to spatially allocate post-fire bunchgrass rehabilitation resources.

Additional keywords: annual grass, fire severity, post-fire rehabilitation, sagebrush, wildfire.

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Introduction

Exotic annual grasses such as cheatgrass (*Bromus tectorum* L.) and medusahead (*Taeniatherum caput-medusae* (L.) Nevski) have invaded millions of hectares of rangeland in the western US (Meinke *et al.* 2009). Affected areas experience loss or dramatic reductions in the abundance of native perennial plant species due to increased fire frequency associated with annual grass fuel accumulations and post-fire competition for perennial seedlings (Chambers *et al.* 2007; Davies 2011). Transformation to exotic annual grass dominance is affecting not only native plant species, but also human safety in the wildland–urban interface (due to increased fire frequency) and production of ecosystem services such as forage production and carbon sequestration (Davies *et al.* 2011). Bradley *et al.* (2006) estimated that aboveground carbon storage decreases 3- to 30-fold with conversion of sagebrush plant communities to exotic annual grass dominance. Also at stake is the welfare of a variety of sagebrush (*Artemisia* spp.) obligate and facultative wildlife species that utilise these plant communities as habitat. Sage-grouse (*Centrocercus urophasianus*) populations decrease with annual grass expansion and upcoming decisions for this species under the US Endangered Species Act have potential to influence rangeland use and management across 11 western states (USFWS 2010).

In sagebrush communities, maintenance of established perennial bunchgrasses has been shown to play an important role in limiting annual grass expansion (Chambers *et al.* 2007; Davies 2008). Large-scale efforts unfold every year to restore perennial grasses following fire, particularly on low-elevation sites typified by Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis* Beetle & Young) plant communities. Recent US Department of Interior budgets for these expenditures have been US$14–90 million annually, and total annual wildland fire appropriations (including suppression and fuels management) are measured in billions of dollars (USDI 2012). These figures are poised to increase as annual grasses continue to expand, especially as almost all models of wildfire occurrence predict that under future climate scenarios of drier and warmer conditions, fires will become more frequent (Fulé 2008).

Efficacy and success of post-fire restoration programmes will be greatest if funds are allocated in accordance with ecologically based needs. Logically, post-fire restoration of perennial grasses will be most critical in sites that either had low pre-fire abundance of these species, or sites where fire-associated mortality of these species was high. At present there are limited data describing the extent of perennial bunchgrass mortality during fires in sagebrush plant communities (Conrad and Poulton 1966). Our ability to estimate fire severity in an

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accurate and timely manner for sagebrush plant communities is limited, despite the fact that important decisions regarding restoration planning and funding allocation must often be made within weeks after fire containment (Boyd and Davies 2012*a*). Given the spatial heterogeneity of fuel loading in Wyoming big sagebrush plant communities (Davies *et al.* 2009), fire heat characteristics and severity will vary across the landscape and may be highest for bunchgrasses located in the immediate vicinity of sagebrush plants due to greater fuel density (Bailey and Anderson 1980; Boyd and Davies 2010, 2012*b*; Strand and Launchbaugh 2013). In previous work, Boyd and Davies (2010, 2012*b*) demonstrated differential post-fire soil colouring for interspace *v.* under the shrub canopy (i.e. 'under canopy') locations, suggesting that post-fire soil colour may be a useful predictor of shrub location, and by extension, the thermal environment to which perennial bunchgrasses were exposed during fire.

Our objectives were to use a case study approach to (1) quantify the amount of perennial grass mortality in a large wildfire that burned basin big sagebrush [*A.t.* Nuttal ssp. *tridentata* = synonym *A.t.* Nutt. var. *tridentata* (Beetle & Young) Welsh] and Wyoming big sagebrush plant communities, and to (2) evaluate the potential for using plant location and other post-burn physical characteristics to predict perennial grass mortality at the individual plant and plant community scales. We hypothesised that (1) fire-induced mortality of perennial grasses would be higher under the canopy than in interspace locations (as determined by post-fire soil colour), and (2) perennial grass mortality at the plant community scale would correlate with post-fire soil colour.

Methods

Study area

Our study was located in the 65 000-ha Miller Homestead Fire ~75 km south of Burns, OR (42°49′N 118°53′W). This fire was active during a 16-day period in July 2012 and burned under extreme fire weather conditions with relative humidity values in the single digits, temperatures nearing 40°C and winds gusting to 58 km h^{-1} (BLM 2013). Within our study sites, burns were complete (i.e. there was no unburned vegetation). The climate is characterised by cold and wet winters and cool summers; the majority of the annual precipitation in the area (~270 mm) falls during the winter and spring months, and the frost-free period is 50–100 days (Eastern Oregon Agricultural Research Center data file; NRCS 1997). Precipitation in the water year (October–September) preceding data collection (2012) was 80% of average and was 96% of average during the year of data collection (2013) (Western Regional Climate Center 2014). The fire occurred during a dry period in which precipitation in the 2 months preceding the fire was only 50% of the long-term average.

Study sites and experimental design

Within the burned area we selected two 20 × 20-m study sites in each of four different ecological sites (*sensu* NRCS 1997) ranging from 1400 to 1475 m elevation with slopes <2%. Ecological Sites included Sandy Loam 10–12 (SANDY LOAM), Loamy 10–12 (LOAM), Clayey 10–12 (CLAYEY), and Swale 10–12 (SWALE). Pre-burn plant composition was unknown; however, abundant sagebrush stumps at all sites post-fire indicate pre-fire sagebrush presence. Ecological site descriptions suggest that basin big sagebrush would have dominated the SWALE sites and Wyoming big sagebrush would have been the dominant sagebrush species on the remaining ecological sites (NRCS 1997). Pre-fire dominant perennial grass species likely included Thurber's needlegrass (*Achnatherum thurberianum* (Piper) Barkworth) and bluebunch wheatgrass (*Pseduoroegneria spicata* (Pursh) A. Löve) on the LOAM sites, bluebunch wheatgrass on the CLAYEY sites, needle and thread (*Hesperostipa comata* (Trin. & Rupr.) Barkworth) and Thurber's needlegrass on the SANDY LOAM sites and basin wildrye (*Leymus cinereus* (Scribn. & Merr.) A. Love) on the SWALE sites (NRCS 1997). Based on previous field observations, Sandberg bluegrass (*Poa secunda* J. Presl) was likely present at all sites.

At each site, we randomly chose 25 points in October 2012 (3 months post-fire) and noted the soil colour as brown, black or grey at each point. These colours were assumed to characterise pre-fire interspace (brown) and under shrub canopy (black and grey) locations as per Boyd and Davies (2010, 2012*b*; Fig. 1). Brown soils represented the 'natural' colour of uncharred soils. Burned shrub stumps were found near the centre of black and grey soil patches. At each point, we selected the nearest perennial bunchgrass located on the same colour soil and marked it using metal stakes and numbered metal tags. All perennial bunchgrasses were burned to some extent. For each grass plant we measured or recorded basal area, percentage of the plant that was charred, minimum height of remaining tillers and presence of regrowth. When minimum remaining height was below ground level (i.e. some portion or the entire plant crown was burned to below ground level) we recorded the plant as being 'burned below ground'. We evaluated mortality of marked bunchgrasses in July 2013 and determined species identity for surviving plants. Those plants without living above ground tissue at this time were considered dead and species identity could not be obtained.

Statistical analyses

We used SAS (v 9.1; SAS Institute Inc., Cary, NC) for all statistical analyses. Data from one of the SANDY LOAM sites were excluded due to soil colour being altered by rainfall occurring at the time of data collection in 2012. Of the remaining 175 marked plants we were able to re-locate and record mortality data for 174. Percentage ground cover of soil colours was calculated for each study site by dividing the number of sample points for each colour by the total number of sample points. To characterise the magnitude of bunchgrass mortality at each study site, we divided the surviving number of marked grasses in July 2013 by the total number of re-located plants and expressed this number in percentage form. The influence of soil colour and ecological site on bunchgrass mortality was determined using mixed-model analysis of variance (PROC MIXED) with site as a random factor. When significant ($P \leq 0.05$) main or interactive effects were found we used the LS MEANS procedure to determine differences between means ($\alpha = 0.05$). The relationship between bunchgrass mortality and measured bunchgrass post-burn characteristics and soil colour was evaluated using

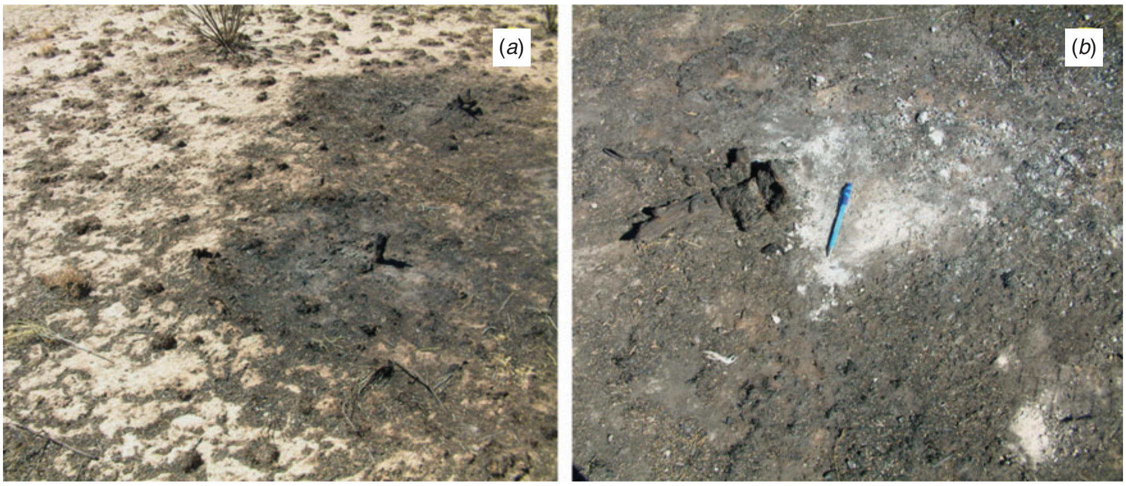

Fig. 1. Soil colours used to characterise study sites included brown, black and grey. Brown soils were assumed to be representative of interspace locations whereas black and grey soils were assumed to represent areas that were under shrub canopy before burning. Grey soils are associated with ash in the immediate vicinity of a shrub base. In image (*a*), an area of black soil on the right of the image is bordered by brown soil to the left. In image (*b*), an area of grey soil is surrounded by black soil.

Table 1. Percentage ground cover of brown, black and grey soil colour post-wildfire for plots in south-east Oregon
Values represent composition within Ecological Site Description (ESD)

ESD	% of total					
	Brown	Standard error	Black	Standard error	Grey	Standard error
LOAM	59.3	3.3	20.5	4.5	20.3	7.8
CLAYEY	40.0	12.0	34.0	10.0	26.0	2.0
SANDY LOAM	28.0	n/a	36.0	n/a	36.0	n/a
SWALE	78.0	2.0	22.0	2.0	0.0	0.0

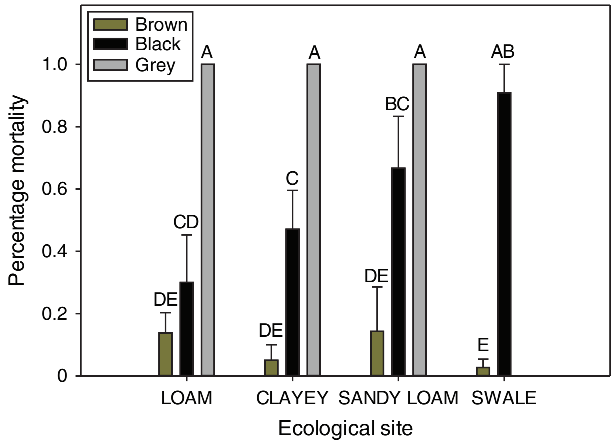

Fig. 2. Mortality of perennial grasses 1 year post-wildfire as a function of soil colour surrounding the plants and Ecological Site in south-east Oregon. Surrounding soils were classified post-fire as brown, black or grey. Black and grey soils are assumed to represent under shrub canopy locations before fire, whereas brown soils are assumed to represent interspace locations between shrubs (Boyd and Davies 2012*b*). Means without a common letter are different ($\alpha = 0.05$).

stepwise logistic regression (PROC LOGISTIC). This analysis was conducted using forward selection with an α level of 0.15 for variable entry into the model. Data were combined across study sites and ecological sites for this analysis. For the final model we generated predicted probabilities of mortality for all unique combinations of independent variables in the model. To determine the relationship between soil colour and plant mortality at the plant community scale we regressed (PROC REG) the percentage of each site ($n = 7$) occupied by each of the three soil colours against percentage bunchgrass mortality for the site (i.e. one regression model for each soil colour). Means are reported with their associated standard errors.

Results

Cover of brown soils ranged from 40 to 78% across ecological sites. Black soil cover varied from 20 to 36%. Grey soils did not occur on SWALE sites and cover varied from 20 to 36% across remaining ecological sites (Table 1). Percentage plant mortality was 33.3 (+/−6.9), 44.0 (+/−7.1), 64.0 (+/−6.1) and 22.9% (+/−6.1) for LOAM, CLAYEY, SANDY LOAM and SWALE ecological sites. Analysis of variance results indicated that mortality varied by soil colour ($P < 0.001$) and its interaction with ecological site ($P < 0.001$). Mortality was lowest for brown soils and was consistently less than 20% across ecological sites (Fig. 2). Bunchgrass mortality on black soils ranged from ~30 to 90% across sites and was higher on SWALE sites than LOAM or CLAYEY sites. Mortality was higher on black soils than brown soils at all sites (Fig. 2), except on LOAM sites where mortality did not differ between black and brown soils. On grey soils mortality was 100% for the three ecological sites on which they occurred. Of the 105 bunchgrasses that survived (out of 174 total), 80 were Thurber's needlegrass, 20 were Sandberg bluegrass, 4 were squirreltail (*Elymus elymoides* (Raf.) Swezey) and 1 was needle and thread.

Table 2. Continuous and discrete variables used to predict 1 year post-fire bunchgrass mortality in south-east Oregon using logistic regression

Variable	*n*	Description	Mean	Standard error	Minimum	Maximum
Basal area	174	Elliptical crown area (cm^2)	102.5	7.5	13.0	595.8
Percent char	174	Percentage of plant crown charred as viewed from above	80.9	1.7	5.0	100.00
Burned below ground	174	1 = yes, 0 = no	0.45	0.04	0.0	1.0
Soil colour	174	Brown, black or grey	n/a	n/a	n/a	n/a
Ecological site	n/a	Loam, sandy loam, claypan, clayey	n/a	n/a	n/a	n/a

Table 3. Predicted and actual probability of mortality for perennial bunchgrasses 1 year post-wildfire as a function of surrounding soil colour and burn depth in south-east Oregon

Predicted values were generated using logistic regression ($P < 0.001$). Post-fire soils were classified as brown ($n = 93$), black ($n = 47$) or grey ($n = 31$). Black and grey soils are assumed to represent under shrub canopy locations before fire, whereas brown soils are assumed to represent interspace locations between shrubs (Boyd and Davies 2012*b*;). 'Burned below ground' score of 1 indicates that the plant was incinerated to a depth below the surrounding ground level

Burned below ground	Soil colour	*n*	Predicted mortality	Actual mortality
0	brown	76	0.038	0.026
1	brown	17	0.242	0.294
0	black	16	0.258	0.313
1	black	31	0.738	0.710
0	grey	1	1.000	1.000
1	grey	30	1.000	1.000

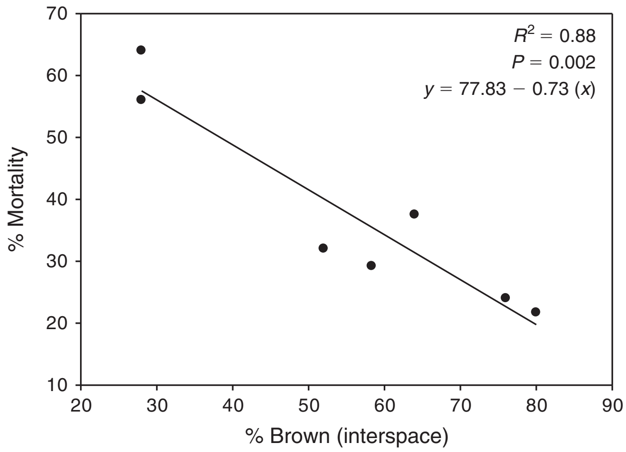

Fig. 3. Regression of perennial grass mortality 1 year post-wildfire as a function of percentage of a site covered by brown soils. Brown soils are assumed to represent interspace locations between shrubs (Boyd and Davies 2012*b*).

Variables used to predict bunchgrass mortality with logistic regression analysis are included in Table 2. Only soil colour ($P < 0.001$) and burned below ground ($P < 0.001$) met the critical chi-square P-value (≤ 0.15) for inclusion in the model. The regression equation correctly predicted mortality for 90.3% of plants. At the 0.50 probability level, model sensitivity was 81.5% and specificity was 91.5%. Percentage false positive and negative predictions were 14.5 and 11.0%. Predicted probability of bunchgrass mortality increased from brown to black to grey soils, and for bunchgrasses burned below ground (Table 3). Actual mortality values more than doubled from brown to black soils for plants burned below ground and increased over 10-fold from brown to black soils for bunchgrasses not burned below ground. Both predicted and actual values indicate 100% mortality for bunchgrasses on grey soils, regardless of burning depth.

At the plant community scale, soil colour was strongly related to measured bunchgrass mortality values. Percentage black and grey soil explained 74.7 and 64.2% of the variation in bunchgrass mortality ($P = 0.012$ and 0.030). Brown soils were the best predictor of bunchgrass mortality and explained 87.8% of the variation in mortality at the community scale (Fig. 3; $P = 0.002$). The slope coefficient indicated that for every 1-unit increase in percentage ground cover of brown soils, there was a corresponding 0.73 (+/−0.12) unit decrease in percent mortality.

Discussion

In the past 15 years, 7 of the 11 western US states have experienced their largest wildfires since European settlement (NOAA 2012). Increases in wildfire size and continued expansion of invasive annual grasses have heightened the importance of post-fire restoration programs in the western US. This is particularly true on sites within the big sagebrush alliance receiving <30 cm of annual precipitation; where perennial grasses are key to minimising invasion of exotic annual grasses (Davies *et al.* 2011). Few empirical studies have quantified perennial grass mortality during wildfires within the sagebrush biome. Our data indicate that fire-associated perennial bunchgrass mortality can be substantial; up to 64%, depending on ecological site, which is in agreement with previous work (Conrad and Poulton 1966). Our estimates should be considered conservative given that high heat loading in the vicinity of shrubs (Boyd and Davies 2012*b*) could have led to complete combustion of above ground understorey perennial grasses, making these plants impossible to identify in the field. Perennial grass losses of the magnitude measured in our study could significantly decrease the resistance of sagebrush plant communities to annual grass invasion and suggest that practices to restore perennial grass species or minimise fire-caused mortality of these species are appropriate (Chambers *et al.* 2007; Davies 2008).

Limited seed availability combined with budgetary and logistic constraints suggest that effective allocation of post-fire restoration and rehabilitation efforts is critical. Effective allocation involves finding a balance between conducting such activities where they are most likely to succeed and where they are most needed. Other authors have developed frameworks and provided technical information necessary to assess the relative likelihood of restoration success across sagebrush plant communities based on temperature, precipitation and other environmental factors (Boyd and Davies 2012*a*; Chambers *et al.* 2014*a*, 2014*b*). Determining where restoration is most needed has received comparatively less attention and under existing federal protocols decisions about how restoration activities will be arrayed over space must often be made within weeks of fire containment (USDI 2004). Our data suggest that post-fire soil colour and burning depth can be used to accurately characterise bunchgrass mortality across a variety of ecological sites and support the hypothesis that mortality will be greatest under shrub canopies. Additionally, we found strong support for the hypothesis that post-fire soil colour, specifically cover of brown (interspace) soil, can be used to explain most of the variation in bunchgrass mortality at the plant community scale. Thus, our data indicate that soil colour could play a key role in post-fire rehabilitation decisions in sagebrush plant communities by determining those areas most likely to have experienced significant perennial grass mortality during fire.

Soil colour in the post-burn environment has been shown to be a good predictor of interspace *v.* under shrub canopy location. Boyd and Davies (2012*b*) reported measurably darker soils under burned Wyoming big sagebrush as compared with interspace locations and that these differences could be distinguished in a field environment (Boyd and Davies 2010). Darker soils under burned shrubs may be caused by localised high concentrations of fuels associated with shrub biomass, as well as greater pre-fire soil organic matter and carbon content of under canopy soils (Vetaas 1992; Davies *et al.* 2007). In the present work we segregated brown (interspace), black (under shrub canopy) and grey soils; the latter being associated with areas of ash-covered soil in the vicinity of burned shrub stumps. We suspect that higher bunchgrass mortality on black and grey soils as compared with brown soils may relate to elevated fire temperatures in the vicinity of shrubs. Boyd and Davies (2012*b*) found that bunchgrasses under shrub canopies burned more than 40% hotter than interspace counterparts and other authors have reported similar findings (Korfmacher *et al.* 2003; Rau *et al.* 2007). Additionally, duration of elevated temperature can be significantly higher with denser woody fuels (Odion and Davis 2000) as compared with herbaceous fuels in the interspace, suggesting that total heat exposure (i.e. integral of temperature and time) may be higher for bunchgrasses under shrub canopies *v.* interspace locations.

In the present study, black and grey soils generally had much greater levels of bunchgrass mortality than brown soils and we assume based on previous research that black and grey soil colours are associated with under shrub canopy locations. The implication of these relationships is that biomass and density of shrubs before fire may be positively related to the amount of bunchgrass mortality experienced during a fire (see Fig. 3). This strongly supports additional research to determine if pre-emptive fuel treatments focussed on shrubs could reduce fire-associated perennial bunchgrass mortality. Reduced bunchgrass mortality would presumably impart a higher degree of resistance to exotic annual grass invasion in low-elevation big sagebrush communities. However, we recognise that the ecological relationship between shrubs and bunchgrasses is more complicated than can be appreciated by examining in isolation direct effects during fire, and involves elements of both competition and facilitation. For example, evidence suggests that sagebrush can limit recovery of perennial bunchgrasses following their selective removal from unburned sagebrush plant communities (Boyd and Svejcar 2011). Conversely, Boyd and Davies (2010, 2012*b*) noted increased abundance of post-fire seeded perennial grasses in burned shrub canopy locations (*v.* in interspaces) in association with more favourable soil temperature regimes and increased soil nutrients. The preceding suggests that characterising the long-term effect of shrubs on perennial grass populations should include consideration of inter-species dynamics before, during and after a fire.

Existing methods for estimating fire severity, whether ground based or remotely sensed, largely focus on forested or chaparral ecosystems (e.g. van Wagtendonk *et al.* 2004; Lentile *et al.* 2006) and often present generalisations of post-fire conditions that may or may not relate specifically to bunchgrass mortality (e.g. Parson *et al.* 2010). At present there is an absence of published work linking specific post-burn environmental attributes with mortality of perennial bunchgrasses in sagebrush plant communities. Results from our research indicate that post-fire soil colour has strong utility for estimating fire severity based on its demonstrated quantitative relationship with perennial bunchgrass mortality. In the field, determining post-fire ground cover of different soil colour classes at the site scale can be accomplished with minimal logistical outlay and training. At larger scales, our data provide conceptual support for the use of remotely sensed imagery for determining post-fire distribution of soil colour based on reflectance values (e.g. van Wagtendonk *et al.* 2004). However, access to satellite imagery, processing requirements, cost, and in some cases limited resolution may limit application of these technologies. It is possible that combining emerging un-manned aerial vehicle technology with soil colour classification could be an efficient means to characterise potential bunchgrass mortality at larger scales (Ambrosia *et al.* 2003). Given the expanding footprint of wildfires on the western US landscape, airborne surveys (by remote- or pilot-controlled vehicles) would represent a fundamental increase in the utility of soil colour-based estimates of fire severity.

Several limitations associated with the current study are worthy of discussion. First, our study included data from a single wildfire. This fire encompassed a large and ecologically diverse area and burned under variable weather conditions over a 2-week period (BLM 2013); however, additional research is needed to determine if soil colour is a robust estimator of perennial bunchgrass mortality across a larger population of sagebrush steppe wildfires. Second, accurate determination of post-fire soil colour is hampered under wet soil conditions. As noted previously, one of our study sites was dropped due to difficulties in determining soil colour under wet soil conditions. Lastly, our initial data were collected ~3 months post-fire, suggesting that characterisation of post-fire soil colour does not have to take place in the immediate aftermath of a wildfire. However, the size of the post-fire data collection time window is unknown and will likely vary strongly in accordance with precipitation and wind conditions. Areas of ash in the vicinity of the shrub base (i.e. 'grey' soils) may be particularly susceptible to redistribution by wind.

Composition of surviving perennial bunchgrasses was heavily skewed towards Thurber's needlegrass across all study sites. This was somewhat surprising given that Ecological Site Descriptions predicted bluebunch wheatgrass would dominate on CLAYEY sites and that basin wildrye would dominate on SWALE sites. Post-fire bunchgrass composition is a product of pre-fire composition as modified by potentially species-specific mortality rates during fire. In this case, we suspect inaccuracies in Ecological Site Descriptions and that CLAYEY and SWALE ecological sites were actually dominated by Thurber's needlegrass pre-fire, given that this species is relatively susceptible to fire mortality (Britton *et al.* 1990).

Conclusions

Maintenance of perennial grass populations in big sagebrush plant communities is critical to reducing the spread of exotic annual grasses. In recent years, maintaining these species has been made more difficult by the increasing frequency of large wildfires (NOAA 2012). When large wildfires occur, land managers must often make decisions regarding restorative practices within a short time frame, and with little empirical guidance for how to gauge fire effects on perennial grass populations. Our data indicate that post-fire soil colour and burning depth can be useful for estimating fire-based mortality of perennial bunchgrasses. Accurate estimates of perennial grass mortality would help managers to differentiate areas where natural recovery of perennial grasses may be possible from locations where active restoration practices (e.g. seeding, herbicide application followed by seeding) may be required. Black or grey soils are associated with under shrub canopy locations that may be exposed to increased heat loading during fire, and subsequent elevated levels of perennial bunchgrass mortality. Brown soils are more typical of interspace environments that may experience relatively less thermal stress during fire and reduced perennial bunchgrass mortality. Determining coverage of post-fire soil colours in the field is straightforward and logistically non-taxing and could be combined with remote sensing technology for use at large scales. Additional research is needed to determine correlations between post-fire soil colour and perennial grass mortality across a larger population of wildfires and variable weather conditions during and after the fire.

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