Prefire (Preemptive) Management to Decrease Fire-Induced Bunchgrass Mortality and Reduce Reliance on Postfire Seeding

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This page contains the abstract of the article, which discusses the importance of maintaining perennial bunchgrasses in rangelands to prevent exotic annual grass invasion. The article highlights the need for research that evaluates the interactions between biotic and abiotic factors to increase resilience and抵抗力 against exotic annual grasses. The abstract also mentions the potential for preemptive management strategies to decrease fire-induced bunchgrass mortality.
Managing plant communities for increased resilience and resistance using preemptive restoration techniques is not a new idea (Davies and Johnson, 2009; Pellant et al., 2004). Preemptive restoration practices that reduce fuel loads and potentially alter fire behavior have been recommended for both economic and ecological benefits across various ecosystems (Dale, 2009; Littell et al., 2009; Mercer et al., 2008). In the Great Basin, particularly in Wyoming big sagebrush plant communities, preemptive restoration practices may be reasonable (Davies et al., 2009; Landis, 2010; Taylor et al., 2013); however, supporting research is limited and preemptive restoration decisions are often based on experience and local expert knowledge alone.

In this paper, we present a fuel-based restoration model specific to Wyoming big sagebrush plant communities within the sagebrush steppe ecosystem. The basic concepts, however, could be applied to a wide range of ecosystems and disturbance regimes by identifying key plant species or functional groups, environmental factors (e.g., soil temperature, aspect), and ecological processes that control resistance and resilience. In addition to the fuel-based model, we identify potential gaps in current scientific knowledge and provide a framework within which research objectives can be linked to land management decisions.

**Identifying At-Risk Plant Communities**

At broad spatial scales, one approach to determining risk of annual grass expansion in the sagebrush biome involves assessing resilience and resistance of plant communities on the basis of soil temperature and precipitation regime (Chambers et al., 2014; Roundy et al., 2014). Generally speaking, resilience and resistance decrease among sites with increasing temperature and declining annual precipitation. Set within these evaluations, we can conceptually characterize vegetation potential on the basis of abiotic site attributes at more local scales and describe deviations or transition factors from vegetation potential on the basis of biotic and abiotic disturbances (plant composition model, Fig. 1A). Our alternative, or fuel-based, model (Fig. 1B) focuses on determining the probability of change to an annual grass-dominated plant community on the basis of biotic characteristics (expressed as fuel phases) and the interaction of these biotic characteristics with an abiotic disturbance (i.e., fire). An underlying assumption of the alternative, fuel-based model is that the probability of postfire change to an annual grass state is strongly linked to maintenance of perennial bunchgrasses.

Fuel phases described in Fig. 1B represent potential fuel phase gradients

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**Fig. 1.** Fire-based transition from Wyoming big sagebrush/perennial bunchgrass plant community to an annual grass-dominated state as depicted by the plant composition model (A) and an alternative fuel-based model (B). The fuel-based model suggests potentially variable postfire change probabilities with fire in accordance with fuel phases as defined by fuel loading.
found within Wyoming big sagebrush plant communities but are not in-clusive of all potential phases within the plant community.

The plant composition model (Fig. 1A) focuses on determining plant communities at risk of transition to annual grass dominance largely on the basis of plant species composition. Our alternative, fuel-based model (Fig. 1B) addresses changes in plant composition as being driven by the interaction between plant structure or fuel phase and abiotic disturbance (i.e., fire). The plant composition model helps illustrate management practices necessary for maintaining plant community composition resistant to annual grass invasion but fails to recognize the potentially important relationship between fuel attributes and fire severity (fire effects on vegetation and soil) in general and, specifically, perennial bunchgrass mortality. This relationship can produce emergent changes not predicted by plant composition alone. For example, Davies et al. (2009) reported that postfire annual grass invasion of large-ly intact, ungrazed Wyoming big sagebrush communities in the northern Great Basin was linked to prefire perennial grass fuel loading characteristics, but not preburn plant community composition, and suggested that high, fine-fuel loading resulted in increased fire-caused perennial grass mortality. In order to address exotic annual grass expansion in low to mid-elevation portions of the sagebrush biome, both compositional characteristics and fuel attributes (loading, structure, continuity, and packing ratio) are needed to develop robust management protocols.

The objective of the fuel-based model is to prevent change to an undesired plant community by 1) recognizing that plant community fuel phases may have starkly different probabilities of postfire change and 2) defining these probabilities relative to fire-based disturbance. To evaluate the potential use of this model in the management of sagebrush plant communities, research is needed to define fuel phases based on plant community structure (e.g., Fig. 2) and the associated probability of postfire change from a desired to undesired state following fire. A combination of both abiotic (e.g., fire weather conditions) and biotic (e.g., plant composition and structure) factors govern fire-induced bunchgrass mortality (Davies et al., 2009). However, biotic factors such as fuel loading and continuity can be influenced by management practices in the short term, whereas abiotic factors cannot. If modifications of biotic factors reduce fire severity to native perennial bunchgrasses, then land managers would have a powerful tool to preemptively manage sagebrush-bunchgrass communities, decreasing reliance on marginally successful postfire restoration practices.

Research Framework

The research framework (Fig. 3) provided in this paper emphasizes the need for research specific to managing fire-sensitive sagebrush steppe plant communities. With an increased understanding of factors that create fire conditions severe enough to kill bunchgrass plants, we can better determine effective prefire management strategies that increase plant community resilience to disturbance and resistance to annual grass invasion. Using the research framework as a guide, we will discuss three research scales where quantitative data is necessary to make informed preemptive restoration management decisions: 1) small plot or mechanistic research (individual plant scale to ~100 m²); 2) large plot research (~1000 m²); and 3) landscape research (km²). By evaluating multiple scales we can better understand the sensitivity of individual bunchgrass plants to fire, expand this knowledge to heterogeneous fuel environments, and select and prioritize Wyoming big sagebrush communities where preemptive restoration practices can be implemented to decrease the probability of transitioning from a desired to undesired state when wildfire occurs.

Small Plot, Mechanistic Research

Mechanistic knowledge is invaluable to guide large-plot research and ultimately design and select preemptive restoration practices to mitigate the negative effects of fire across a broad geographic area. Sagebrush plant community responses to fire have been described across a diverse array of ecological conditions (Conrad and Poulton, 1966; Davies et al., 2007, 2009; Ellsworth and Kauffman, 2010), and fire effects on individual bunchgrass species found within these plant communities have been briefly described (Britton et al., 1983; Defossé and Robberecht, 1996; Robberecht and Defossé, 1995; Wright, 1970, 1971; Wright and Klemmedson, 1965). However, little is known concerning the factors that influence heat dynamics during fire and thus the likelihood of fire-induced bunchgrass mortality. As follows, we suggest seven potential small-plot, mechanistic research objectives that are needed to identify biotic and abiotic thresholds that may influence bunchgrass mortality and briefly review factors that govern fire effects on bunchgrasses (Fig. 4). All objectives should be evaluated over the range of environmental and ecological conditions that exist for sagebrush plant communities.

Research Objectives 1 and 2. Evaluate the temperature tolerance of individual bunchgrass species under variable fire weather conditions. Determine the influence of plant morphology on fire-induced perennial bunchgrass mortality, and test similarities between species with comparable root crown structure. Fire-induced bunchgrass mortality is associated with the amount of heat received and the plant location exposed to lethal heat (Miller, 2000; Wright, 1970). The amount of heat received can be described in terms of heat load, which we define as the cumulative result of maximum fire temperature and duration of elevated temperature. Although multiple studies acknowledge that both of these factors are major determinants of fire-induced plant mortality (Bailey and Anderson, 1980; Conrad and Poulton, 1966), few have identified the temperature tolerance of individual plant species (Pelaez et al., 2001; Wright, 1970). Temperature tolerance of individual plant species is difficult to identify because of the exponential relationship between time and temperature. For example, Wright (1970) suggested that 215 minutes are required at a temperature interval between 51.7 and 57.2°C to kill needle-and-thread (Hesperostipa comata [Trin. & Rupr] Barkworth) plant tissue and only 1.6 minutes at 73.9–79.4°C. By acknowledging and more comprehensively defining this exponential
relationship, we can better relate mechanistic fire-induced bunchgrass mortality research to fire intensity measurements, or descriptions of fire behavior quantified by the temperature of, and heat released by the flaming front of a fire (Lentile et al., 2006) on large scales. Differences in temperature tolerance between individual species may also determine how plant communities are managed regarding plant composition and potentially influence restoration practices (e.g., reseeding with more fire tolerant bunchgrasses). Seed mortality in fire may also be important, but limiting the need for significant recruitment from seed is the focus of prefire management.

Growth patterns of individual bunchgrasses may influence mortality. Native perennial grasses may escape extreme heat damage during fire due to the location of meristematic tissue that can sprout after fire and create new tillers (Miller, 2000). The location exposed to lethal heat, however, is species dependent due to differing plant morphologies (Conrad and Poulton, 1966), thus contributing to a variety of plant responses that could ultimately influence post-fire plant community composition. Species with similar root crown structures may have similar responses to heat; however, further research is needed. Additionally, some native bunchgrass species experience “hollow crown phenomenon” (Briske, 1991); as bunchgrasses age, initial tiller generations die and decompose as they are not necessary for tiller recruitment due to tillers on the plant periphery. These hollow crown areas accumulate litter that can ignite and smolder, potentially killing most or all surrounding growing points (Miller, 2000).

Research Objectives 3 and 4. Determine the relationship between fire-induced perennial bunchgrass mortality and plant phenology or seasonal timing of fire. When annual grasses invade a sagebrush plant community, they often create a continuous fine-fuel condition, which increases the ignition potential and promotes rapid fire spread (Balch et al., 2013; Knapp, 1998; Link et al., 2006). Furthermore, in Wyoming big sagebrush communities where annual grasses constitute a significant portion of the herbaceous community, Davies and Nafus (2013) found that fuel moisture content was low enough to burn more than a month earlier than noninvaded communities, which may shift the seasonality of wildfire to earlier in the growing season and increase fire season duration (Littell et al., 2009; Westerling et al., 2006). Early-season wildfires can be particularly negative for perennial grasses because they are actively growing and often producing seed; however, susceptibility to damage may be species specific (Wright and Klemmedson, 1965). Fuel moisture in association with plant phenology and timing of fire can also influence plant response to fire. High fuel moisture acts as a heat sink that can increase the susceptibility of plants to fire but decreases fire spread; alternatively, low fuel moisture content acts as a heat source, which increases fire spread but is typically associated with plant dormancy during which time grasses may be less susceptible to fire (Sapsis, 1990; Wright and Bailey, 1982).

Research Objective 5. Evaluate the relationship between fire-induced perennial bunchgrass mortality and herbaceous fuel loading over a range of environmental and ecological conditions. Management actions (e.g., fire suppression, reduced herbivore pressure) and antecedent climate conditions can combine to increase fuel loading, or the amount of combustible fuel, and thus perennial grass vulnerability to fire. Herbaceous fine fuel loads, for example, are often associated with interannual climatic variability. Warm, wet springs promote plant biomass (both non-native and native) accumulation, and longer, dry summers increase the likelihood of more and longer-burning wildfires (Balch et al., 2013; Knapp, 1998; Littell et al., 2009; Westerling et al., 2003, 2006). Litter accumulation around and within the basal crown of native bunchgrasses due to an absence of disturbance (i.e., exclusion of grazing) has been shown to decrease a plant community’s tolerance of fire (Belsky and Blumenthal, 1997; Davies et al., 2009). This implies that preemptive management efforts to increase resilience to disturbance would need to be adjusted according to antecedent precipitation. Specific relationships between herbaceous fine fuel loading and fire severity are largely unknown in sagebrush plant communities. Fuel loading has been suggested as the primary driver of heat load (Bailey and Anderson, 1980; Morgan, 1999; Vermeire and Roth, 2011). Nevertheless, the net impact of fuel amount on heat load is highly influenced by fire weather conditions and fuel composition, structure, and continuity.

Research Objectives 6 and 7. Identify thresholds of shrub fuel loading beyond which there is increased probability for bunchgrass mortality. Evaluate the spatial distribution of heat loading produced in association with both shrub and herbaceous fuels. In addition to fine fuel loads, woody fuels influence the amount of heat transferred to perennial bunchgrasses. In general, woody fuels (e.g., shrubs) are more difficult to ignite but burn longer and hotter than fine fuels, especially at the center of the shrub, where there is a higher density of fuels (Bailey and Anderson, 1980; Strand et al., 2014). Preliminary data from our lab suggest that shrub fuel loading in Wyoming big sagebrush plant communities can increase heat loading and mortality of perennial bunchgrasses; however,
as the distance from the shrub canopy increases, bunchgrass mortality decreases in association with reduced heat (Fig. 5A; see also Boyd et al., 2015). Bunchgrasses within 50 cm of the shrub base during two prescribed fires in Wyoming big sagebrush (Artemisia tridentata ssp. wyomingensis Beetle & Young) plant communities had an average heat load three times greater than those farther than 50 cm away from the shrub base. For bunchgrasses within 50 cm of a shrub base, 48.8% were killed, whereas only 9.5% were killed beyond that distance. For Idaho fescue (Festuca idahoensis Elmer), 64.7% were killed while only 23.3% of bluebunch wheatgrass (Pseudoroegneria spicata [Pursh] Á. Löve) plants were killed. This suggests that the sensitivity of bunchgrasses to fire will vary by species and location within the plant community. Therefore the spatial arrangement of shrubs and bunchgrasses, in addition to fuel loads, will likely play an important role in fire-induced bunchgrass mortality. Fire-induced perennial bunchgrass mortality, than large plot research evaluating preemptive management treatments targeted to increase both resilience and resistance by altering woody fuel abundance or distribution would be the appropriate next step. One advantage to large plot versus landscape research is that a thorough description of fuel attributes, burn weather conditions, and fire intensity data can be collected before and during a fire. This scale provides an opportunity to evaluate four research objectives that 1) assess the relative

**Small Plot (Mechanistic) Research**

**Weather Conditions**
- Relative Humidity
- Ambient Temperature
- Wind
- Fuel Moisture

**Plant Phenology and Growth Patterns**
- Phenological Stage
- Packing Ratio
- Location of Meristematic Tissue

**Fuel Attributes**
- Loading (Biomass)
- Composition
- Structure
- Continuity
- Fuel Moisture

**Heat Characteristics**
- Maximum Temperature
- Duration of Elevated Temperature

**Individual Bunchgrass Mortality**

**Fig. 4.** Conceptual diagram describing potential factors that influence heat characteristics and subsequent individual bunchgrass mortality. The fuel-based model focuses on modifying fuel attributes (under various fire weather conditions) and associated heat stress for perennial bunchgrass species. Both abiotic and biotic factors strongly influence heat characteristics and therefore fire-induced bunchgrass mortality. Italicized words represent factors that can be managed using preemptive restoration strategies.

**Fig. 5.** (A) Heat load (y-axis) and distance (x-axis) from the center of the bunchgrass to the base of the nearest shrub for bluebunch wheatgrass (Pseudoroegneria spicata, PSSP; average total biomass (±SE): 26.2 ± 1.9 g), Idaho fescue (Festuca idahoensis, FEID; average total biomass (±SE): 36.4 ± 4.7 g), and Thurber’s needlegrass (Achnatherum thurberianum, ACTH; average total biomass (±SE): 19.1 ± 3.1 g) during two Wyoming big sagebrush (Artemisia tridentata ssp. wyomingensis) prescribed burns in September 2013; heat load is the cumulative result of maximum fire temperature and duration of elevated temperature above 60°C measured using high-temperature thermocouples placed in the center of each bunchgrass. (B) Heat load and duration of elevated temperature above 60°C (x-axis). (C) Heat load and maximum fire temperature (x-axis). Fire-induced bunchgrass mortality for each species is indicated in red.
effectiveness of preemptive management practices under various fire weather conditions and across environmental and ecological gradients of the sagebrush steppe ecosystem, 2) evaluate if quantitative characteristics used to describe fire intensity (e.g., fireline intensity) can be linked to fire-induced bunchgrass mortality, and 3) define the probability of postfire change on the basis of fuel phases.

**Research Objective 8.** Determine the effects of heat load relative to the spatial heterogeneity of fuel amount and type within sagebrush plant communities on bunchgrass mortality. On the basis of these results, use fuel attributes to describe distinct fuel phases within the context of environmental conditions (e.g., soil temperature, moisture regime). The purpose of preemptive management practices, such as shrub thinning and prescribed grazing, is to alter heat characteristics to create more fire-resilient plant communities by disrupting fuel continuity and altering fuel amount and composition. Perennial bunchgrasses in pristine sagebrush steppe communities are typically widely spaced, resulting in a discontinuous fuel bed that may not readily carry fire (Whisenant, 1990). Hence preemptive management practices should increase heterogeneity of fuel abundance within the plant community. In theory, this patchy fuel loading creates a discontinuous burn and spatially variable heat load patterns that may create safe zones for perennial bunchgrasses.

**Research Objective 9.** Determine the efficacy of using preemptive management practices (e.g., herbivory or shrub thinning) to alter fuel load characteristics, characterize subsequent heat load distribution during fire, and measure postfire plant community response across environmental gradients. Research that combines fuel management practices such as prescribed grazing and shrub thinning with fire is limited for Wyoming big sagebrush plant communities. Fence line contrasts (grazed vs. ungrazed) have been reported post wildfire (Launchbaugh et al., 2008) and may serve as a baseline for evaluating bunchgrass mortality relative to fuel loading; however, a more complete description of treatments is needed to accurately assess postfire transition probabilities. A concern when evaluating the feasibility of preemptive management practices is that some treatments initially only change fuel structure without altering fuel abundance (e.g., mechanical thinning of shrubs without removal or removal of live woody fuels with increased herbaceous annual fuels due to soil disturbance). Such treatments may act to homogenize fuel distribution, which could result in a more uniform distribution of high heat loading.

Prescribed herbivory has been shown to change the structure and spatial heterogeneity of vegetation by reducing fuel accumulations within perennial bunchgrasses and altering the likelihood for fire spread in a landscape (Davies et al., 2009; Launchbaugh and Walker, 2006; Taylor, 2006; Waldram et al., 2008). However, fire weather may largely influence treatment effectiveness in that regard. For example, Strand et al. (2014) suggest that grazing is most effective in reducing fire spread and intensity when sagebrush cover is low and fire weather severity is low (i.e., high fuel moisture, high relative humidity, low temperature, and low wind speed). When weather conditions become extreme, the role of grazing decreases. It should be noted, however, that fire intensity (e.g., Byram’s fire intensity; Byram, 1959) does not necessarily determine perennial bunchgrass mortality and hence the resiliency of the plant community to invasive annual grasses. Therefore prescribed herbivory may still be an effective treatment option for the maintenance of perennial bunchgrasses before the inevitable wildfire. Proper stock- ing intensity and timing should be adjusted for specific site characteristics to ensure that livestock grazing does not negatively impact the plant community in the long term (DiTomaso, 2000; Pierson et al., 2002; Thrope et al., 1988). Reisner (2010), for example, found that inappropriate cattle herbivory shifted bunchgrass composition and, perhaps more importantly, aggregated bunchgrasses beneath protective sagebrush canopies. If woody fuels are the primary driver in fire-induced bunchgrass mortality, this scenario would decrease the resilience of the plant community.

Thinning or mowing sagebrush may also be an option to enhance perennial bunchgrass survival after fire. If small plot research provides evidence that shrub fuel load in Wyoming big sagebrush plant communities correlates positively with heat loading and perennial bunchgrass mortality, then strategic reduction of shrub fuel loading and continuity will become a critical component for creating more fire-resilient communities. As with herbivory, potential positive and negative effects from shrub thinning should be evaluated before treatment on a site. In a recent study on relatively intact Wyoming big sagebrush plant communities across the Great Basin, Pyke et al. (2014) found that mowing reduced sagebrush biomass and cover immediately after treatment and increased perennial grass cover 3 years post treatment. However, they also found that mowing favored cheatgrass (Bromus tectorum L.) and annual forbs, although they never became significantly greater than controls. In a degraded Wyoming big sagebrush plant community in Oregon, Davies et al. (2012) did not find an increase in native perennial herbaceous vegetation following mowing but did have a significant increase of exotic annuals. When sagebrush were removed in two studies conducted in Idaho, available soil moisture increased, which subsequently increased bunchgrass cover, as well as cheatgrass (Prevey et al., 2010a) and exotic forb (Prevey et al., 2010b) cover. These examples illustrate the importance of strategically implementing preemptive restoration treatments only in locations with adequate perennial bunchgrass cover, minimal exotic annuals, and moderate to high resilience to disturbance.

**Research Objective 10.** Link quantitative measurements of fire intensity (including factors that determine fire intensity such as live fuel moisture) to the ecological response and environmental factors of the plant community. The relationship between fire intensity and plant community response to fire is limited. Common descriptors of fire intensity may not always provide adequate information for gauging fire effects on vegetation and soil. For example, Keeley (2009) states that fire intensity is a real-time burning measurement that may not relate to the heat released by fuels that continue to burn after the flame front has passed. Preliminary data from our lab suggest that a duration of at least 30 minutes above 60°C needs to occur to kill 51.6% of the individual bunchgrass species studied (Fig. 5B), versus the 21.2% that experience fire-induced mortality with less than 30 minutes of elevated temperatures. Conditions where more than 50% mortality occurred were typically within 50 cm of a shrub base (Fig. 5A). Maximum temperatures, which likely occur as the flame front passes and/or during flaming combustion, also contribute to fire-induced mortality. Our data suggest that a maximum temperature of at least 250°C needs to occur for 48.6% of bunchgrasses to be killed versus 20.7% that were killed with lower maximum temperatures (Fig. 5C). Hence less extreme fire intensity (e.g., slow-moving fire) may increase the duration of elevated heat for individual bunchgrasses more than when fire intensity is “extreme” relative to fire behavior measures. However, extreme fire intensity may still provide the heat necessary for fire-induced mortality to occur in a short, intense burn. Furthermore, the relationship between fire intensity and fuel-reduction treatments is limited (Diamond et al., 2009; Ingram et al., 2013; Stephens and Moghaddas, 2005; Stratton, 2004), especially for arid rangelands, and warrants further research.

**Research Objective 11.** Use large-plot prescribed burns and measurement of postfire plant community dynamics to model the probability of postfire change for fuel phases. In order to define the probability of postfire change from a desired to an undesired plant community on the basis of fuel attributes, a solid understanding of both mechanisms that influence bunchgrass mortality and a description of fuel phases as described earlier will be necessary. Following these steps, postfire change probabilities can then be determined under various fire weather and environmental conditions by implementing large-plot prescribed fires. By
identifying postfire change probabilities, we can potentially avoid long-term conversion to an annual grass-dominated state by implementing preemptive restoration practices where appropriate.

**Landscape Applications**

Land managers are responsible for the management and conservation of large landscapes across variable environmental and ecological conditions. Plant communities continually transition between fuel phases over time, and weather conditions will vary within and between burning seasons. Thus there is a need to rapidly identify and quantify fuel attributes (i.e., spatial distribution, structure, and composition) over a heterogeneous fuel environment to prioritize preemptive management strategies. Fig. 6 provides a hypothetical decision support tool developed from small- and large-plot research findings that could be used as a temporally dynamic model to predict plant community resistance and resilience on a landscape scale based on the plant communities’ potential for fire-induced perennial bunchgrass mortality. After an initial assessment of the environmental and ecological conditions of the landscape (such as is conceptualized with the hypothetical relationships in Fig. 6), we could then use Fig. 6 to evaluate the probability of postfire change to an annual grass community on the basis of the likelihood for perennial bunchgrass mortality post fire relative to fuel loads and weather conditions. For example, a plant community with a high shrub-to-grass ratio (x-axis) that burns under relatively low humidity (y-axis) may be less resistant to postfire weed invasion than a community with a low shrub-to-grass ratio due to the large amounts of woody fuels, which, theoretically, produce higher heat loads and subsequently higher perennial bunchgrass mortality.

In addition to fuel ratios, the spatial distribution of woody fuels may result in vastly different fire effects on bunchgrass mortality at the landscape scale. Geospatial technologies such as remote sensing and geographic information systems may be an efficient solution for prioritizing landscape treatments. Although limitations associated with remote sensing have been noted (Arroyo et al., 2008), the use of high-resolution imagery and object-based image analysis techniques show promise in identifying fuel composition and continuity (Hulet et al., 2014; Laliberte et al., 2004). When geospatial technologies are combined with resistance and resilience information (Fig. 6), land managers can better prioritize preemptive management practices that will address long-term restoration objectives.

**Implications**

Successfully minimizing invasive annual grass species in sagebrush plant communities is impacted by management decisions made before, during, and after a fire event. To date, we have placed disproportionate effort on decisions occurring during and after wildfire, with less regard for prefire action. Although preemptive management practices cannot guarantee a reduction in fire severity, we believe they have strong potential to enhance resilience and resistance of sagebrush/bunchgrass plant communities. The tradeoff between costs of preemptive management practices and fire suppression/rehabilitation efforts will likely vary depending on weather (Peterson et al., 2004) and ecological health before wildfire (Taylor et al., 2013). However, by investing in healthy rangelands where ecological processes and functions can be maintained (i.e., have a desirable response to preemptive management practices) before wildfire occurs, we can minimize our reliance on postfire restoration efforts. Recent research concerning sage-grouse habitat has demonstrated that successful postwildfire restoration of Wyoming big sagebrush sites is only likely under a relatively narrow range of climate and environmental conditions; therefore the protection of critical habitat may be the best opportunity for conservation (Arkle et al., 2014).

For the fuel-based model to be effective in guiding land management practices to prioritize conservation efforts, research is needed to define phases on the basis of fuel attributes and the associated probability of postfire change from a desired to undesired plant community following fire. Both short-term (small-plot mechanistic research) and long-term (large-plot and landscape application) research will be necessary to define fuel phases and associated probabilities of change and will involve a more thorough examination of the interaction between abiotic and biotic factors that influence fire-induced bunchgrass mortality. Fire and fire effects are naturally variable and heterogeneous, which complicates identifying mechanisms that influence fire patterns over space and time. However, an increased understanding of basic relationships among fuel attributes, fire weather, and fire tolerance of individual bunchgrass species will directly assist land managers in modifying fuel loads to minimize the threat of postfire weed invasion, increase plant community resilience to inevitable wildfire, and help prioritize where postfire restoration practices are needed on the basis of both prefire compositional characteristics and fuel attributes.

**Acknowledgements**

We thank Erik Hamerlynck and Brenda Smith for their comments on earlier versions of this manuscript and appreciate the reviews by the anonymous reviewers and Associate Editor.

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**Fig. 6.** A hypothetical decision support tool for Wyoming big sagebrush plant communities that combines small- and large-plot research findings to 1) define plant community resilience to fire and resistance to exotic annual grasses based on a plant community’s potential for fire-induced bunchgrass mortality and 2) prioritize areas annually where preemptive management strategies would be more effective. The y-axis represents a particular weather condition (relative humidity, RH) that likely influences fire-induced bunchgrass mortality. The x-axis represents fuel attributes that could potentially be modified using preemptive management strategies.

**Fig. 6.** A hypothetical decision support tool for Wyoming big sagebrush plant communities that combines small- and large-plot research findings to 1) define plant community resilience to fire and resistance to exotic annual grasses based on a plant community’s potential for fire-induced bunchgrass mortality and 2) prioritize areas annually where preemptive management strategies would be more effective. The y-axis represents a particular weather condition (relative humidity, RH) that likely influences fire-induced bunchgrass mortality. The x-axis represents fuel attributes that could potentially be modified using preemptive management strategies.


