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

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ABSTRACT

Western rangelands are currently under severe threat from exotic annual grasses. To successfully manage rangelands that are either infested with or susceptible to exotic annual grasses, we must focus on increasing resilience to disturbance and resistance to exotic annual grass invasion. Here, we present a fuel-based model and research framework for Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young) rangelands that focuses on increasing resilience to fire and resistance to exotic annual grasses through the maintenance of perennial bunchgrasses. By maintaining perennial bunchgrass, exotic annual grasses have limited resources, thus decreasing the invasibility of the site. In order for the fuel-based model to be effective in guiding land management practices, research that evaluates the interactions between biotic and abiotic factors that influence fire-induced bunchgrass mortality is needed. Hence, we propose a research framework to identify and fill potential gaps in current scientific knowledge. We also suggest potential research objectives that are necessary to make informed management decisions before wildfire, with a goal to ultimately decreasing our reliance on marginally successful postfire restoration practices through preemptive management strategies.

Introduction

The sagebrush *(Artemisia)* steppe is one of the largest remaining rangeland biomes in the United States but is currently under severe threat from exotic annual grass invasion (Davies et al., 2011; Meinke et al., 2009; Pellant et al., 2004), particularly at low elevations. As exotic annual grasses become dominant in sagebrush rangeland, wildfire risk and extent increase (Link et al., 2006) and alter the regional fire regime (Balch et al., 2013). These factors work to decrease or eliminate native perennial vegetation including sagebrush and make reestablishment exceedingly difficult (Brooks et al., 2004; Kauffman et al., 2006; Pellant et al., 2004). The effects of exotic annual grasses are of concern for a myriad of ecosystem services, not the least of which is their impact on greater sage-grouse *(Centrocercus urophasianus)* habitat (USFWS, 2013). Greater sage-grouse are currently being considered for listing by the U.S. Fish and Wildlife Service under provisions of the Endangered Species Act, a listing that could impact management of both private and public lands in 11 western states.

Recent research has demonstrated that maintenance of native perennial bunchgrasses is key to preventing exotic annual grass invasion into relatively intact sagebrush plant communities; by maintaining perennial bunchgrasses, exotic annual grasses have limited resources, thus decreasing the invasibility of the site (Chambers et al., 2007; Davies et al., 2008; James et al., 2008). When perennial grass mortality is high following disturbance, invading species have more access to available resources, increasing the vulnerability of a community to invasion (Davis et al., 2000). Environmental factors such as soil temperature and moisture regime are also critical components in determining the invasibility of a site (Chambers et al., 2007, 2014; Miller et al., 2013). For example, Chambers et al. (2007) found that cold soil temperatures limited annual grass growth and reproduction, therefore increasing the plant community's resistance to invasion.

At present, most of the effort to contain the spread of exotic annual grasses in sagebrush steppe rangelands has focused on postfire restoration of perennial bunchgrasses. Nevertheless, in low to mid-elevation Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*) plant communities with significant presence of annual grasses, postfire efforts to reestablish perennial grasses generally fail despite massive capital investment (e.g., $60 million in 2007, Knutson et al., 2009). Given the low success rate for postfire restoration of low-elevation plant communities, preventing degradation of remaining largely intact communities is of critical importance. Preventing annual grass expansion into relatively intact plant communities will involve managing these communities for increased resilience (ability to recover from stresses and disturbances) to fire and resistance (capacity to retain structure, processes, and function despite disturbance, stress, or invasive species; Folke et al., 2004) to annual grass invasion.

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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

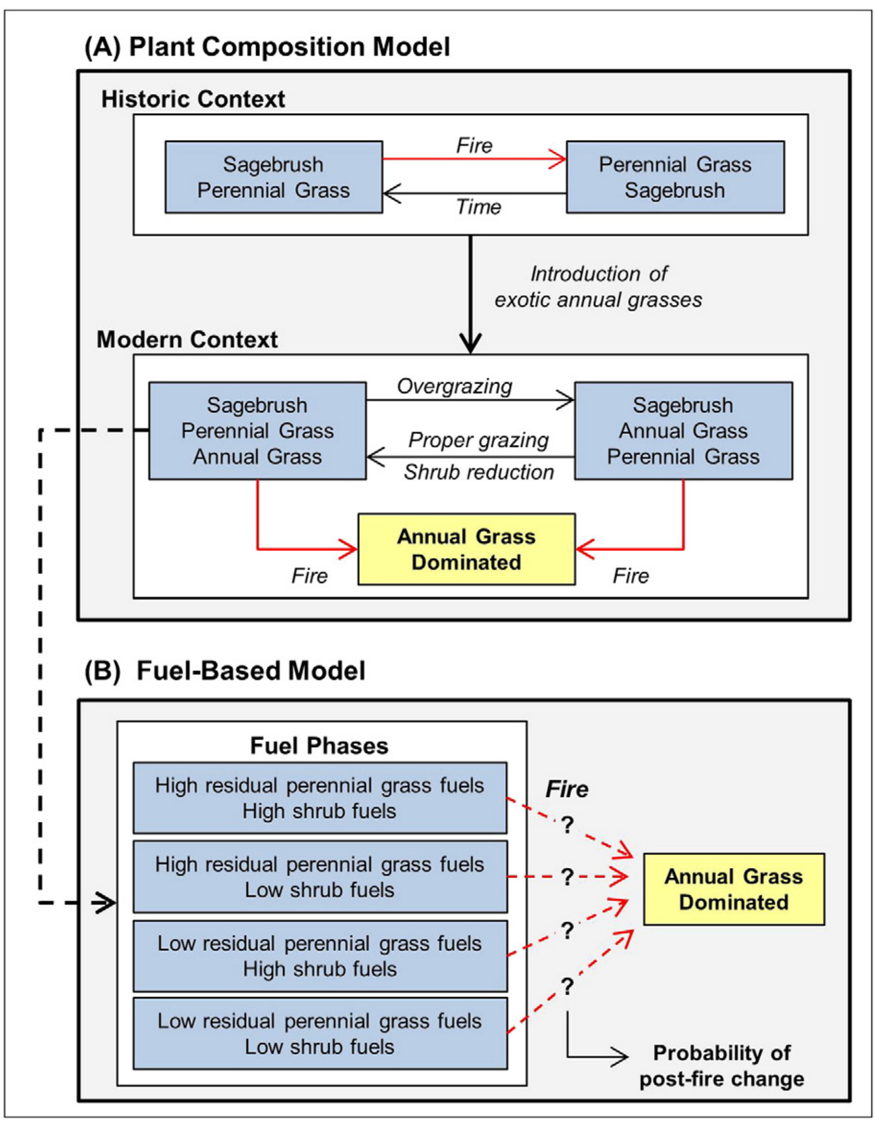

Fig. 1. Fire-based transition from Wyoming big sagebrush/perennial bunchgrass plant community to an annual grass-dominated state as depicted by the plant composition model **(A)** and an alternative fuel-based model **(B)**. The fuel-based model suggests potentially variable postfire change probabilities with fire in accordance with fuel phases as defined by fuel loading.

found within Wyoming big sagebrush plant communities but are not inclusive 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 largely 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.

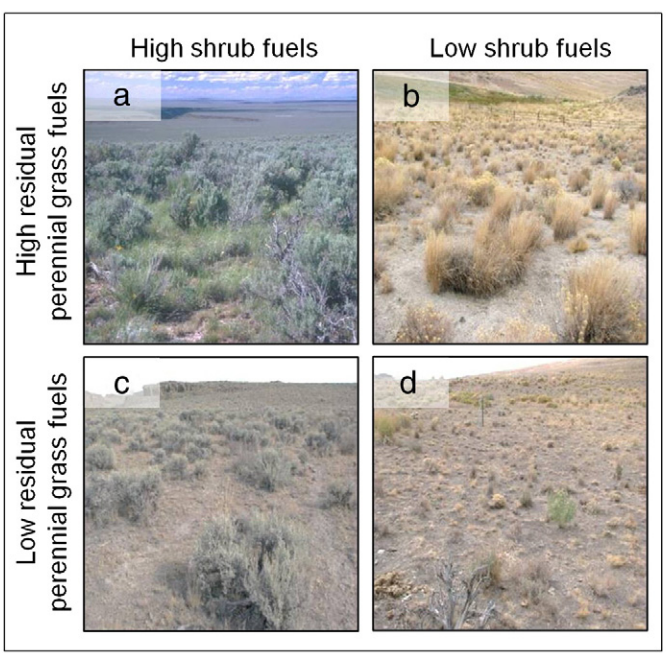

Fig. 2. Photographs showing Wyoming big sagebrush plant community fuel phases described in the fuel-based model; clockwise from upper left: (a) high residual perennial grass fuels, high shrub fuels; (b) high residual perennial grass fuels, low shrub fuels; (d) low residual perennial grass fuels, low shrub fuels; and (c) low residual perennial grass fuels, high shrub fuels. Fuel phases described are not inclusive but represent potential gradients within Wyoming big sagebrush plant communities.

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 m^2); 2) large plot research (~1000 m^2); and 3) landscape research (km^2). 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 comate* [Trin. & Rupr] Barkworth) plant tissue and only 1.6 minutes at 73.9–79.4°C. By acknowledging and more comprehensively defining this exponential

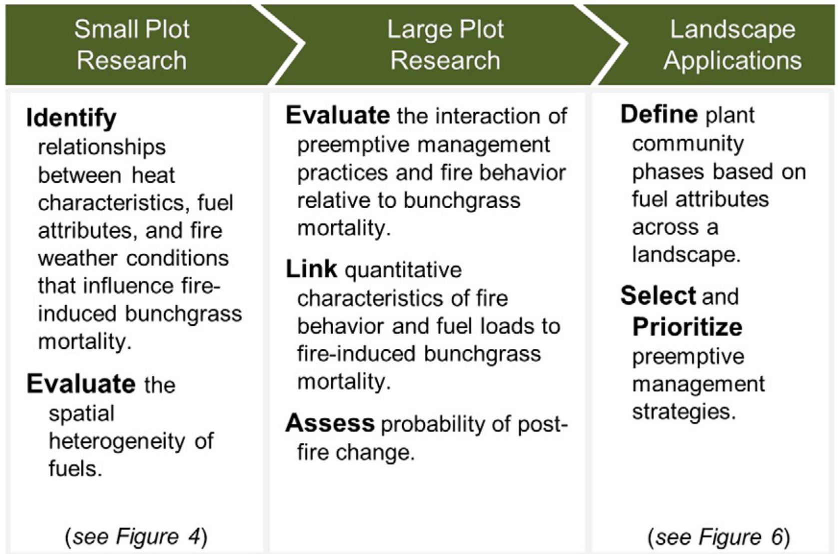

Fig. 3. Research framework describing small-plot (individual plant research to ~100 m^2), large-plot (~1000 m^2), and landscape (km^2) research where quantitative data are necessary to make informed preemptive restoration management decisions.

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 nonnative 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,

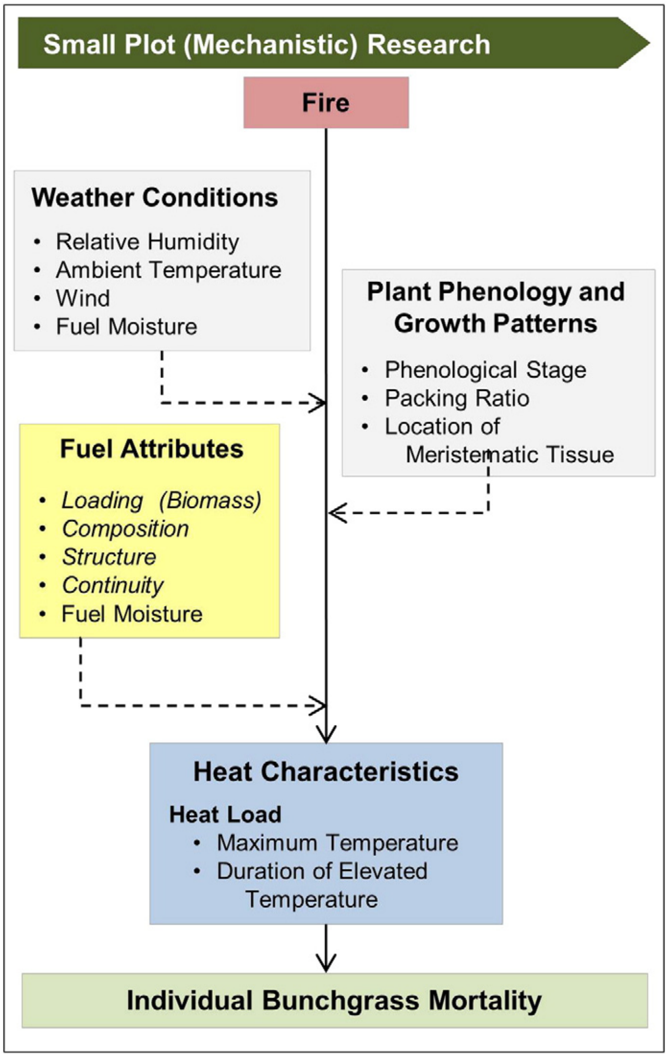

Fig. 4. Conceptual diagram describing potential factors that influence heat characteristics and subsequent individual bunchgrass mortality. The fuel-based model focuses on modifying fuel attributes (under various fire weather conditions) and associated heat stress for perennial bunchgrass species. Both 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.

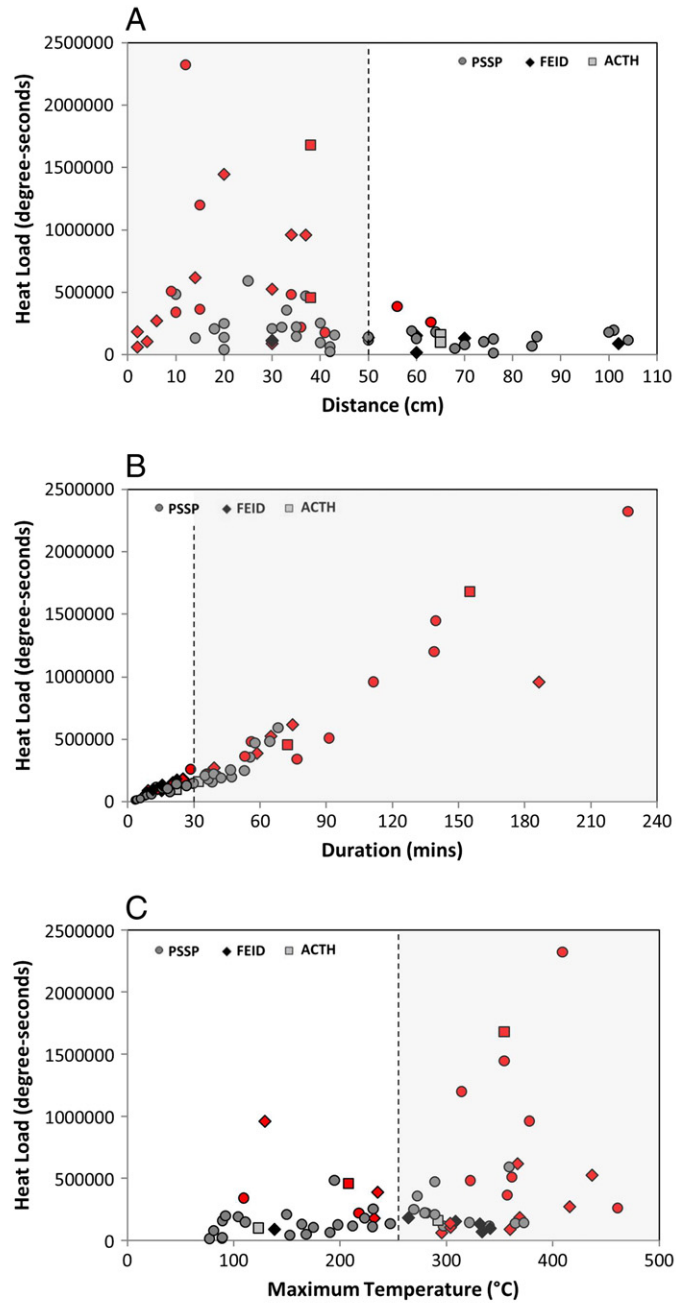

Fig. 5. (A) Heat load (y-axis) and distance (x-axis) from the center of the bunchgrass to the base of the nearest shrub for bluebunch wheatgrass (*Pseudoroegneria spicata*, PSSP; average total biomass (±SE): 26.2 ± 1.9 g), Idaho fescue (*Festuca idahoensis*, FEID; average total biomass (±SE): 36.4 ± 4.7 g), and Thurber's needlegrass (*Achnatherum thurberianum*, ACTH; average total biomass (±SE): 19.1 ± 3.1g) 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.

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.

Large Plot Research

A mechanistic understanding of biotic and abiotic factors that influence heat characteristics and subsequent bunchgrass mortality serves as a platform for designing fuel management treatments for large plot research (Fig. 3). For example, if woody fuel loads are closely tied to 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 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 necessary 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 stocking 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; Thurow 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.

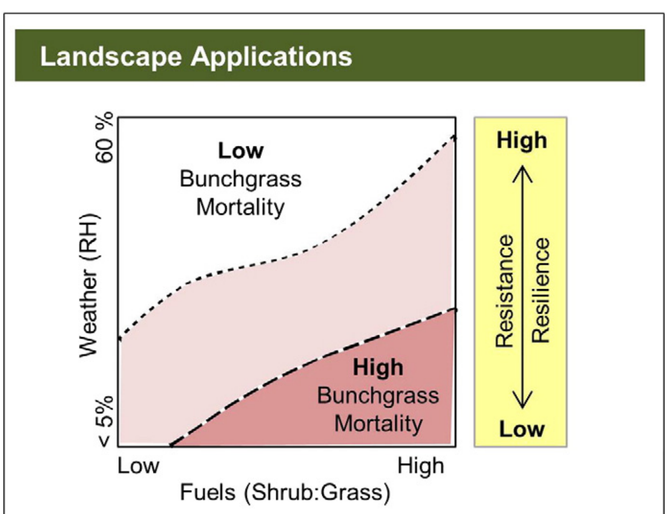

Fig. 6. A hypothetical decision support tool for Wyoming big sagebrush plant communities that combines small- and large-plot research findings to 1) define plant community resilience to fire and resistance to exotic annual grasses based on a plant community's potential for fire-induced bunchgrass mortality 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.

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.

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References

Arkle, R.S., Pilliod, D.S., Hanser, S.E., Brooks, M.L., Chambers, J.C., Grace, J.B., Knutson, K.C., Pyke, D.A., Welty, J.L., 2014. Quantifying restoration effectiveness using multi-scale habitat models: implications for sage-grouse in the Great Basin. Ecosphere http://dx.doi.org/10.1890/es13-00278.1.

Arroyo, L.A., Pascual, C., Manzanera, J.A., 2008. Fire models and methods to map fuel types: the role of remote sensing. For. Ecol. Manag. 256, 1239–1252.

Bailey, A.W., Anderson, M.L., 1980. Fire temperatures in grass, shrub and aspen forest communities of Central Alberta. J. Range Manag. 33, 37–40.

Balch, J.K., Bradley, B.A., D'Antonio, C.M., Gomez-Dans, J., 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). Glob. Chang. Biol. 19, 173–183.

Belsky, A.J., Blumenthal, D.M., 1997. Effects of livestock grazing on stand dynamics and soils in upland forests of the interior west. Conserv. Biol. 11, 315–327.

Boyd, C.S., Davies, K.W., Hulet, A., 2015. Predicting fire-based perennial bunchgrass mortality in big sagebrush plant communities. Int. J. Wildland Fire http://dx.doi.org/10.1071/WF14132.

Briske, D.D., 1991. Developmental morphology and physiology of grasses. In: Heitschmidt, R.K., Stuth, J.W. (Eds.), Grazing management: an ecological perspective. Timber Press, Portland, OR, USA, pp. 85–108.

Britton, C.M., Clark, R.G., Sneva, F.A., 1983. Effects of soil moisture on burned and clipped Idaho fescue. J. Range Manag. 36, 708–710.
Brooks, M.L., D'Antonio, C.M., Richardson, D.M., Grace, J.B., Kelley, J.E., DiTomaso, J.M., Hobbs, R.J., Pellant, M., Pyke, D., 2004. Effects of invasive alien plants on fire regimes. Bioscience 54, 677–688.
Byram, G.M., 1959. Combustion of forest fuels. In: Davis, K.P. (Ed.), Forest fire: control and use. McGraw Hill, New York, NY, USA, pp. 61–89.
Chambers, J.C., Roundy, B.A., Blank, R.R., Meyer, S.E., Whittaker, A., 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? Ecol. Monogr. 77, 117–145.
Chambers, J.C., Bradley, B.A., Brown, C.S., D'Antonio, C., Germino, M.J., Grace, J.B., Hardegree, S.P., Miller, R.F., Pyke, D.A., 2014. Resilience to stress and disturbance, and resistance to *Bromus tectorum L.* invasion in cold desert shrublands of western North America. Ecosystems 17, 360–375.
Conrad, C.E., Poulton, C.E., 1966. Effect of a wildfire on Idaho fescue and bluebunch wheatgrass. J. Range Manag. 19, 138–141.
Dale, L., 2009. The true cost of wildfire in the Western U.S. Western Forestry Leadership Coalition, Lakewood, CO, USA, pp. 1–16.
Davies, K.W., Johnson, D.D., 2009. Prevention: a proactive approach to the control of invasive plants in wildlands. In: Wilcox, C.P., Turpin, R.B. (Eds.), Invasive species: detection, impacts and control. Nova Science publishers, Inc, Hauppauge, NY, USA, pp. 81–96.
Davies, K.W., Nafus, A.M., 2013. Exotic annual grass invasion alters fuel amounts, continuity and moisture content. Int. J. Wildland Fire 22, 353–358.
Davies, K.W., Bates, J.D., Miller, R.F., 2007. Short-term effects of burning Wyoming big sagebrush steppe in Southeast Oregon. Rangel. Ecol. Manag. 60, 515–522.
Davies, K.W., Sheley, R.L., Bates, J.D., 2008. Does fall prescribed burning *Artemisia tridentata* steppe promote invasion or resistance to invasion after a recovery period? J. Arid Environ. 72, 1076–1085.
Davies, K.W., Svejcar, T.J., Bates, J.D., 2009. Interaction of historical and nonhistorical disturbances maintains native plant communities. Ecol. Appl. 19, 1536–1545.
Davies, K.W., Boyd, C.S., Beck, J.L., Bates, J.D., Svejcar, T.J., Gregg, M.A., 2011. Saving the sagebrush sea: an ecosystem conservation plan for big sagebrush plant communities. Biol. Conserv. 144, 2573–2584.
Davies, K.W., Bates, J.D., Nafus, A.M., 2012. Mowing Wyoming big sagebrush communities with degraded herbaceous understories: has a threshold been crossed? Rangel. Ecol. Manage. 65, 498–505.
Davis, M.A., Grime, J.P., Thompson, K., 2000. Fluctuating resources in plant communities: a general theory of invisibility. J. Ecol. 88, 528–534.
Defossé, G.E., Robberecht, R., 1996. Effects of competition on the postfire recovery of 2 bunchgrass species. J. Range Manag. 49, 137–142.
Diamond, J.M., Call, C.A., Devoe, N., 2009. Effects of targeted cattle grazing on fire behavior of cheatgrass-dominated rangeland in the northern Great Basin, USA. Int. J. Wildland Fire 18, 944–950.
DiTomaso, J.M., 2000. Invasive weeds in rangelands: species, impacts, and management. Weed Sci. 48, 255–265.
Ellsworth, L.M., Kauffman, J.B., 2010. Native bunchgrass response to prescribed fire in ungrazed mountain big sagebrush ecosystems. Fire Ecol. 6, 86–95.
Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C.S., 2004. Regime shifts, resilience, and biodiversity in ecosystem management. Annu. Rev. Ecol. Evol. Syst. 35, 557–581.
Hulet, A., Roundy, B.A., Petersen, S.L., Jensen, R.R., Bunting, S.C., 2014. An object-based image analysis of pinyon and juniper woodlands treated to reduce fuels. Environ. Manag. 53, 660–671.
Ingram, R.S., Doran, M.P., Nader, G., 2013. Planned herbivory in the management of wildfire fuels. In: Barros, B., Fernandes, M.E.B. (Eds.), Herbivory http://dx.doi.org/10.5772/48673.
James, J.J., Davies, K.W., Sheley, R.L., Aanderud, Z.T., 2008. Linking nitrogen partitioning and species abundance to invasion resistance in the Great Basin. Oecologia 156, 637–648.
Kauffman, J.B., Larson, D., Wills, R., Augustine, A., Wilson, J., Ellsworth, L., 2006. Interactions of burn season and ecological condition on ecosystem response to fire in mountain big sagebrush communities: information necessary for restoration and postfire rehabilitation. Joint Fire Sciences Program Final Report 82 pp.
Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. Int. J. Wildland Fire 18, 116–126.
Knapp, P.A., 1998. Spatio-temporal patterns of large grassland fires in the Intermountain West, U.S.A. Glob. Ecol. Biogeogr. Lett. 7, 259–273.
Knutson, K.C., Pyke, D.A., Wirth, T.A., Pilliod, D.S., Brooks, M.L., Chambers, J.C., 2009. A chronosequence feasibility assessment of emergency fire rehabilitation records within the Intermountain Western United States. Joint Fire Sciences Program Final Report. Project 08-S-08:U.S Geological Survey Open-File Report 2009–1099 20 pp.
Laliberte, A.S., Rango, A., Havstad, K.M., Paris, J.F., Beck, R.F., McNeely, R., Fonzalez, A.L., 2004. Object-based image analysis for mapping shrub encroachment from 1937–2003 in southern New Mexico. Remote Sens. Environ. 93, 198–210.
Landis, M.T., 2010. The effect of invasive annual plants on wildfire suppression costs thesis, University of Nevada Reno, Reno, NV, USA 78 pp.
Launchbaugh, K., Walker, J., 2006. Targeted grazing—a new paradigm for livestock management. In: Launchbaugh, K., Walker, J.W., Daines, R.J. (Eds.), Targeted grazing: a natural approach to vegetation management and landscape enhancement. American Sheep Industry Association, Centennial, CO, USA, pp. 2–8.
Launchbaugh, K., Brammer, B., Brooks, M.L., Bunting, S., Clark, P., Davison, J., Fleming, M., Kay, R., Pellant, M., Pyke, D.A., Wylie, B., 2008. Interactions among livestock grazing, vegetation type, and fire behavior in the Murphy Wildland Fire Complex in Idaho and Nevada, July 2007. U.S. Geological Survey Open-File Report 2008–1214 42 pp.
Lentile, L.B., Holden, Z.A., Smith, A.M.S., Falkowski, M.J., Hudak, A.T., Morgan, P., Lewis, S.A., Gessler, P.E., Benson, N.C., 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. Int. J. Wildland Fire 15, 319–345.
Link, S.O., Keeler, C.W., Hill, R.W., Hagen, E., 2006. *Bromus tectorum* cover mapping and fire risk. Int. J. Wildland Fire 15, 113–119.
Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L., 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecol. Appl. 19, 1003–1021.
Meinke, C.A., Knick, S.T., Pyke, D.A., 2009. A spatial model to prioritize sagebrush landscapes in the Intermountain West (USA) for restoration. Restor. Ecol. 17, 652–659.
Mercer, D.E., Haight, R.G., Prestemon, J.P., 2008. Analyzing trade-offs between fuels management, suppression, and damages from wildfire. In: Holmes, T.P., Prestemon, J.P., Abt, K.L. (Eds.), The economics of forest disturbances. Springer, The Netherlands, pp. 247–272.
Miller, M., 2000. Fire autecology. In: Brown, J.K., Smith, J.K. (Eds.), Wildland fire in ecosystems—effects of fire on floraForest Service, RMRS-GTR-42 vol. 2. US Department of Agriculture, Ogden, UT, USA, pp. 9–34.
Miller, R.F., Chambers, J.C., Pyke, D.A., Pierson, F.B., Williams, J.C., 2013. A review of fire effects on vegetation and soils in the Great Basin region: response and site characteristics. Forest Service, RMRS-GTR-308. US Department of Agriculture, Fort Collins, CO, USA, p. 136.
Morgan, J.W., 1999. Defining grassland fire events and the response of perennial plants to annual fire in temperate grasslands of south-eastern Australia. Plant Ecol. 144, 127–144.
Pelaez, D.V., Boo, R.M., Mayor, M.D., Elia, O.R., 2001. Effect of fire on perennial grasses in central semiarid Argentina. J. Range Manag. 54, 617–621.
Pellant, M., Abbey, B., Karl, S., 2004. Restoring the Great Basin desert, U.S.A.: integrating science, management, and people. Environ. Monit. Assess. 99, 169–179.
Peterson, D., Finney, M., Skinner, C., Kaufmann, M., Johnson, M., Shepperd, W., Harrington, M., Keane, R., McKenzie, D., Reinhardt, E., Ryan, K., 2004. Science basis for changing forest structure to modify wildfire behavior and severity. In: Graham, R.T., McCaffrey, S., Jain, T.B. (Eds.), Forest Service, RMRS-GTR-120. US Department of Agriculture, Fort Collins, CO, USA, pp. 1–43.
Pierson, F.B., Spaeth, K.E., Weltz, M.A., Carlson, D.H., 2002. Hydrologic response of diverse western rangelands. J. Range Manage. 55, 558–570.
Prevey, J.S., Germino, M.J., Huntly, N.J., Inouye, R.S., 2010a. Exotic plants increase and native plants decrease with loss of foundation species in sagebrush steppe. Plant Ecol. 207, 39–51.
Prevey, J.S., Germino, M.J., Huntly, N.J., 2010b. Loss of foundation species increases population growth of exotic forbs in sagebrush steppe. Ecol. Appl. 20, 1890–1902.
Pyke, D.A., Shaff, S.E., Lindgren, A.I., Schupp, E.W., Doescher, P.S., Chambers, J.C., Burnham, J.S., Huso, M.M., 2014. Region-wide ecological response of arid Wyoming big sagebrush communities to fuel treatments. Rangel. Ecol. Manag. 67, 455–467.
Reisner, M.D., 2010. Drivers of plant community dynamics in sagebrush steppe ecosystems: cattle grazing, heat and water stress. Dissertation Oregon State University, Corvallis, OR, USA, p. 286.
Robberecht, R., Defossé, G.E., 1995. The relative sensitivity of two bunchgrass species to fire. Int. J. Wildland Fire 5, 127–134.
Roundy, B.A., Young, K., Cline, N., Hulet, A., Miller, R.F., Tausch, R.J., Chambers, J.C., Rau, B., 2014. Pinon-juniper reduction effects on soil temperature and water availability of the resource growth pool. Rangel. Ecol. Manag. 67, 495–505.
Sapsis, D.B., 1990. Ecological effects of spring and fall prescribed burning on basin big sagebrush/Idaho fescue-bluebunch wheatgrass communities thesis Oregon State University, Corvallis, OR, USA, p. 106.
Stephens, S.L., Moghaddas, J.J., 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. For. Ecol. Manag. 215, 21–36.
Strand, E.K., Launchbaugh, K.L., Limb, R., Torell, L.A., 2014. Livestock grazing effects on fuel loads for wildland fire in sagebrush dominated ecosystems. J. Rangel. Appl. 1, 35–57.
Stratton, R.D., 2004. Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. J. For. 102, 32–40.
Taylor Jr., C.A., 2006. Targeted grazing to manage fire risk. In: Launchbaugh, K., Walker, J.W., Daines, R.J. (Eds.), Targeted grazing: a natural approach to vegetation management and landscape enhancement. American Sheep Industry Association, Centennial, CO, USA, pp. 107–114.
Taylor, M., Rollins, K., Kobayashi, M., Tausch, R., 2013. The economics of fuel management: wildfire, invasive plants, and the evolution of sagebrush rangelands in the western United States. J. Environ. Monit. 126, 157–173.
Thurow, T.L., Blackburn, W.H., Taylor Jr., C.A., 1988. Infiltration and interrill erosion responses to selected livestock grazing strategies, Edwards Plateau, Texas. J. Range Manag. 41, 296–302.
U.S. Fish and Wildlife Service, 2013. Greater sage-grouse *(Centrocercus urophasianus)* conservation objectives: final report. US Fish and Wildlife Service, Denver, CO, USA 92 pp.
Vermeire, L.T., Roth, A.D., 2011. Plains prickly pear response to fire: effects of fuel load, heat, fire weather, and donor site soil. Rangel. Ecol. Manag. 64, 404–413.
Waldram, M.S., Bond, W.J., Stock, W.D., 2008. Ecological engineering by a mega-grazer: white rhino impacts on a South African Savanna. Ecosystems 11, 101–112.
Westerling, A.L., Gershunov, A., Brown, T.J., Cayan, D.R., Dettinger, M.D., 2003. Climate and wildfire in the western United States. Bull. Am. Meteorol. Soc. 84, 595–604.
Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313, 940–943.
Whisenant, S.G., 1990. Changing fire frequencies on Idaho's Snake River Plains: ecological and management implications. In: McArthur, D.E., Romney, E.M., Smith, S.D., Tueller, P.T. (Eds.), Proceedings-symposium on cheatgrass invasion, shrub die-off and other aspects of shrub biology and management. 5–7 April 1989; Las Vegas, NV, USA. US Department of Agriculture. Forest Service, INT-GTR-276, Ogden, UT, USA, pp. 4–10.
Wright, H.A., 1970. A method to determine heat-caused mortality in bunchgrasses. Ecology 51, 582–587.
Wright, H.A., 1971. Why squirreltail is more tolerant to burning than needle-and-thread. J. Range Manag. 24, 277–284.
Wright, H.A., Bailey, A.W., 1982. Fire ecology: United States and southern Canada. John Wiley & Sons, New York, NY, USA 528 pp.
Wright, H.A., Klemmedson, J.O., 1965. Effect of fire on bunchgrasses of the sagebrush-grass region in Southern Idaho. Ecology 46, 680–688.