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Dormant season grazing may decrease wildfire probability by increasing fuel moisture and reducing fuel amount and continuity

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Abstract. Mega-fires and unprecedented expenditures on fire suppression over the past decade have resulted in a renewed focus on presuppression management. Dormant season grazing may be a treatment to reduce fuels in rangeland, but its effects have not been evaluated. In the present study, we evaluated the effect of dormant season grazing (winter grazing in this ecosystem) by cattle on fuel characteristics in sagebrush (*Artemisia* L.) communities at five sites in south-eastern Oregon. Winter grazing reduced herbaceous fuel cover, continuity, height and biomass without increasing exotic annual grass biomass or reducing bunchgrass basal area or production. Fuel moisture in winter-grazed areas was high enough that burning was unlikely until late August; in contrast, fuels in ungrazed areas were dry enough to burn in late June. Fuel biomass on perennial bunchgrasses was decreased by 60% with winter grazing, which may reduce the potential for fire-induced mortality. The cumulative effect of winter grazing from altering multiple fuel characteristics may reduce the likelihood of fire and the potential severity in sagebrush communities with an understorey dominated by herbaceous perennials. Dormant season grazing has the potential to reduce wildfire suppression expenditures in many rangelands where herbaceous fuels are an issue; however, increasing woody vegetation and extreme fire weather may limit its influence.

Additional keywords: fuel management, sagebrush, sage-grouse habitat, wildfire suppression, winter grazing.

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Introduction

The general increase in the number of wildfires and the incidence of large-scale, destructive wildfires is a global issue (Krawchuk *et al.* 2009; Adams 2013). Extreme wildfire seasons in the past decade have resulted in unprecedented expenditures on wildland firefighting (Calkin *et al.* 2005; National Interagency Fire Center (NIFC) 2013). In the US, federal firefighting costs for suppression have been approximately US$1 billion or more since 2000, with several recent years (2006, 2007, 2008, 2011 and 2012) approaching US$2 billion (NIFC 2013). This has increased pressure for presuppression actions to manage fuels (Daugherty and Snider 2003; Snider *et al.* 2006). The need for and benefits of presuppression fuel management are well known (Snider *et al.* 2006). However, most efforts have been developed for forested lands, and presuppression efforts on rangelands have received considerably less attention (Davies *et al.* 2009).

The need for effective presuppression fuel management on rangelands will likely increase because the risk of larger and more frequent wildfires is expected to escalate with global climate change and elevated CO_2 levels. Almost all models of wildfire occurrence suggest that fires will become more frequent in the future (Fulé 2008). Warmer and earlier springs have already increased wildfire activity in the western US (Westerling *et al.* 2006). Yue *et al.* (2013) estimated that the length of the wildfire season will increase by more than 3 weeks and the area burned would likely double for much of the western US by mid-century (2046–65) compared with the present day (1981–2000). Increases in atmospheric CO_2 levels can increase plant production and fuel retention because of decreased decomposition due to increased cellulose and lignin, further increasing fuel biomass (Ziska *et al.* 2005). Thus, there is an urgent need for management action, but management of fuels in rangelands has been constrained by a lack of information regarding the effects of potential treatments.

Mechanically established fuel breaks, green stripping and grazing have been proposed to reduce fuels to help manage wildfires (Omi 1979; Pellant 1994; Diamond *et al.* 2009). We speculate that grazing is likely the most financially and logistically feasible treatment at the scales needed to effectively address this issue across the vast geographic regions dominated by rangelands, although other methods are undoubtedly invaluable in some locations. Strategic placement of fuel breaks or green strips could potentially provide opportunities to limit the scope of a wildfire and provide an area to stage suppression efforts (Pellant 1994; Agee *et al.* 2000), but these methods do not prevent the ignition of the fire or alter the burn severity across most of the landscape. Grazing, however, can damage plants if not done properly (Daubenmire 1940; Mack and Thompson 1982), especially during the growing season. Improper grazing during the growing season can promote exotic annual grass invasion (Daubenmire 1970; Mack 1981; Knapp 1996), which increases the risk of large, frequent wildfires (D'Antonio and Vitousek 1992; Balch *et al.* 2013). Livestock distribution can also be limited by water sources in many arid and semi-arid rangelands (Ganskopp 2001), thus reducing its effectiveness as a landscape treatment. Grazing when plants are dormant (winter grazing in our study area) may decrease the potential for damage to grazed plants. Winter grazing may also reduce the effects of limited water sources on livestock distribution. Ephemeral water sources that are often dry during the normal grazing period may hold water during the winter, especially in areas where most of the precipitation occurs during the winter and summers are relatively dry. Livestock water demands are also less during cooler winter weather (Winchester and Morris 1956). Therefore, winter grazing may be a sustainable and effective landscape-scale treatment to reduce herbaceous fuels in rangelands in some regions.

Livestock grazing may alter fuel characteristics (biomass, height, continuity etc.) and this may subsequently influence the likelihood of burning and fire behaviour. Davies *et al.* (2010) demonstrated that long-term moderate grazing during the growing season decreased fuel biomass, height and continuity compared with long-term livestock exclusion in sagebrush (*Artemisia* L.) communities. Burn severity (i.e. mortality of perennial vegetation) was also decreased with moderate grazing and this reduced the post-fire invasion of exotic annuals compared with long-term ungrazed areas (Davies *et al.* 2009). Therefore, winter grazing is likely to influence fuel biomass, height and continuity, but it has not been experimentally tested. However, the potential for livestock grazing to affect fire behaviour decreases with extreme fire weather, especially where woody plants dominate (Strand *et al.* 2014).

In addition, winter grazing by livestock may have different effects than traditional growing season grazing. One of the potential sources for variation between traditional and winter grazing is that the forage base during the dormant season is often inadequate to meet the nutritional needs of livestock (Coppock *et al.* 1986; Ganskopp and Bohnert 2001) and thus livestock are often fed supplements high in protein. Alfalfa (*Medicago sativa* L.) hay is a commonly used protein supplement for cattle wintering on rangelands (Vanzant and Cochran 1994) and this could potentially alter fuel biomass and continuity. Unconsumed hay (litter) may result in an increase in fuels or high protein hay may have a fertilisation effect and increase herbaceous production. Thus, assumptions that winter grazing will reduce herbaceous fuels are largely based on speculation and anecdotal evidence.

The effect of winter grazing on fuel moisture is relatively unknown. Understanding the effect of winter grazing on fuel moisture is important because fuel moisture is a major determinant of the susceptibility of plant communities to burning (Rothermel 1972; Flannigan and Wotton 1991; Chuvieco *et al.* 2004; Manzello *et al.* 2006). Fire ignition and potential area burned decreases with increasing fuel moisture (Chuvieco *et al.* 2009). Winter grazing in areas with a higher proportion of herbaceous cover compared with shrub cover and understoreys dominated by perennial herbaceous vegetation could increase fuel moisture by preventing the accumulation of dry herbaceous fuel from previous years (i.e. increase the live : dead fuel ratio), which may truncate the wildfire season and thereby greatly decrease the risk of wildfire. Conversely, winter grazing may only increase fuel moisture early in the growing season and climatic conditions during the mid- and late growing season, when most wildfires occur, may override any effects of grazing on fuel moisture. In contrast, if grazing encourages the invasion of exotic annual grasses (Daubenmire 1970; Mack 1981; Knapp 1996) that dry out earlier than native vegetation, then the wildfire season may actually be lengthened (Davies and Nafus 2013). Fuel moisture effects are not limited to just the probability of fire ignition and propagation, but also fire behaviour during a burn. The rate of spread decreases as fuel moisture increases because more energy is required to heat fuels to combustion (Rothermel 1972; Thonicke *et al.* 2001).

To investigate the effects of dormant season grazing, we evaluated the effect of grazing during the winter on fuel biomass, cover, continuity, height and moisture content in Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle and A. Young) plant communities. Wyoming big sagebrush plant communities and the wildlife that depend upon them are threatened by large, frequent wildfires that promote exotic annual grass invasion (Chambers *et al.* 2007; Davies *et al.* 2011). However, using a grazing treatment has some potential risk in these plant communities and so the effects of winter grazing should be evaluated before it is applied as a fuel management treatment. The purpose of the present study was to evaluate the effects of winter grazing on fuel biomass, cover, continuity, height and moisture content, as well as native vegetation in sagebrush communities that still have an understorey dominated by native herbaceous perennials. We hypothesised that winter grazing would increase herbaceous (live and dead) fuel moisture and decrease herbaceous fuel biomass, cover, continuity and height. We did not expect that winter grazing would increase exotic annual grasses because grazing occurred during the dormant season.

Methods

Study area

The present study was conducted in south-eastern Oregon, USA, near the Diamond Craters (43°04′N, 118°40′W). Study sites receive, on average, 250–280 mm precipitation annually (Natural Resource Conservation Service (NRCS) 2013). Crop year (October–September) precipitation was 74% of the 30-year long-term average in 2012–13 (Eastern Oregon Agricultural Research Center, unpubl. data). Most precipitation occurs in the cool season. Summers are hot and dry and the wildfire season generally spans from early summer to mid-September (Davies and Nafus 2013), varying with annual climatic conditions. Study sites occurred on Sandy Loam 10–12 PZ (R023XY213OR) and Droughty Loam 11–13 PZ (R023XY316OR) ecological sites (NRCS 2013). Elevation was approximately 1450 m above sea level and topography was relatively flat at the study sites. Wyoming big sagebrush was the dominant shrub at all study sites. Thurber's needlegrass (*Achnatherum thurberianum* [Piper] Barkworth) was the dominant perennial bunchgrass or co-dominant with bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] A. Löve) depending on study site. Other common bunchgrasses included Sandberg bluegrass (*Poa secunda* J. Presl), squirreltail (*Elymus elymoides* [Raf.] Swezey) and Indian ricegrass (*Achnatherum hymenoides* [Roem. and Schult.] Barkworth). Cheatgrass (*Bromus tectroum* L.) a naturalised exotic annual grass, was present in low abundance (6.6 ± 3.0 plants m^{-2}) across the study area at the start of the study. Historical fire return intervals for these sagebrush plant communities are estimated to be 50–100+ years (Wright and Bailey 1982; Mensing *et al.* 2006).

Experimental design

We used a randomised complete block design with five blocks and two treatments (winter-grazed and ungrazed). Treatments were applied at five different locations (blocks) and randomly assigned to plots at each block. Ungrazed treatments were livestock grazing exclosures built in the autumn of 2009. Native herbivores were not excluded from the ungrazed treatment. Vegetation data collected in 2009 revealed no difference in vegetation and fuel characteristics between treatments. Exclosures were established in large (~800–1000 ha) grazing pastures. Winter grazing by cattle was applied at the operation level, not the individual plot, to ensure that results were applicable to actual management scenarios. Grazing occurred between November and early April, with cattle rotated through the pastures. The order of rotation among pastures varied among years. Consumption of available forage was between 40% and 60% based on biomass following the method described in Anderson and Curreir (1973). Cattle were fed 2.7–4.5 kg alfalfa hay per individual every other day as a protein supplement. The location of the supplementation was dispersed across each pasture. The winter grazing treatment was applied for 4 consecutive years prior to measurements.

Measurements

Fuel characteristics were measured from June through to late August 2013. Each treatment in each block was sampled with a 50×80 m plot. The 50×80 m area adjacent to the exclosure was considered the grazed plot, although grazing was applied at the pasture level. Four, 45-m transects spaced at 10-m intervals were established in each plot. Data collected along the four transects were averaged for each plot. Fuel cover type and fuel gaps were measured along each transect using the line-intercept method (Canfield 1941). Cover types included herbaceous vegetation, shrubs and litter. Fuel gaps were areas lacking fuels (i.e. bare ground and rocks). Herbaceous vegetation included current and previous years' standing growth. Fuel continuity by fuel type was the average length of uninterrupted patches of herbaceous, shrub and litter. Community herbaceous biomass was estimated by clipping 15 randomly placed 1-m^2 quadrats in each treatment within each block. Biomass was separated by functional group, oven dried and then weighed. Functional groups included: Sandberg bluegrass, perennial bunchgrasses, annual grasses, perennial forbs and annual forbs. The annual grass functional group was comprised solely of exotic annual grasses. Other functional groups were predominantly native species. Sandberg bluegrass was treated as a separate functional group from the other perennial bunchgrasses because it is much smaller and completes is annual growth cycle much earlier (James *et al.* 2008). Other fuel characteristics of perennial bunchgrasses were measured by randomly selecting 30 individuals per plot. Tallest current and previous years' growth and the basal diameter of selected bunchgrasses were measured. After height and basal measurements were collected, the perennial bunchgrasses were harvested to ground level, oven dried, separated into current and previous years' growth and weighed. Fuel moisture was determined by harvesting herbaceous (live and dead) fuels in five 0.2-m^2 quadrats in each plot approximately every 2 weeks during the summer. Harvested biomass was weighed, oven-dried at 50°C for 72 h and weighed again to determine moisture content. Fuel moisture was then calculated as a percentage of dry weight.

Statistical analysis

Analysis of variance (ANOVA) was used to determine the effect of winter grazing on fuel characteristics that were not measured repeatedly (TIBCO Spotfire S+ v. 8.2; TIBCO Software, Palo Alto, CA, USA[1]). The five sites were treated as blocks in the analysis. Fuel cover and continuity were analysed based on fuel groups: herbaceous vegetation, shrubs, litter and gaps. Fuel biomass was analysed by functional group. Repeated-measures ANOVA using the mixed-models procedure (Proc Mixed SAS v. 9.1; SAS Institute, Cary, NC, USA) was used to compare fuel moisture during the summer between treatments. Fixed-effect variables were treatment, sampling date and their interaction. Random-effect variables were block and the block by treatment interaction. Akaike's Information Criterion (Littell *et al.* 1996) was use to select the appropriate covariance structure (compound symmetry) for repeated-measures ANOVA. Because there was an interaction between treatment and sampling date, treatment effects were also analysed individually at each sampling date using ANOVA. Data that did not meet assumptions of normality were log transformed. All figures show original, non-transformed data. Differences between mean values were considered significant at $P \leq 0.05$ (two-sided). Data are reported as the mean ± s.e.

Results

Winter livestock grazing reduced the average continuity of herbaceous fuels and total herbaceous foliar cover ($P = 0.02$ and <0.01 respectively; Fig. 1). Herbaceous fuel continuity and cover were approximately 1.4-fold greater in the ungrazed than winter-grazed treatment, largely from the biomass of previous years' growth. Winter grazing did not affect shrub continuity or cover ($P = 0.56$ and 0.22 respectively). Litter continuity was reduced with winter grazing ($P = 0.01$; Fig. 1*a*), but litter ground cover was not influenced by treatment ($P = 0.80$; Fig. 1*b*). The

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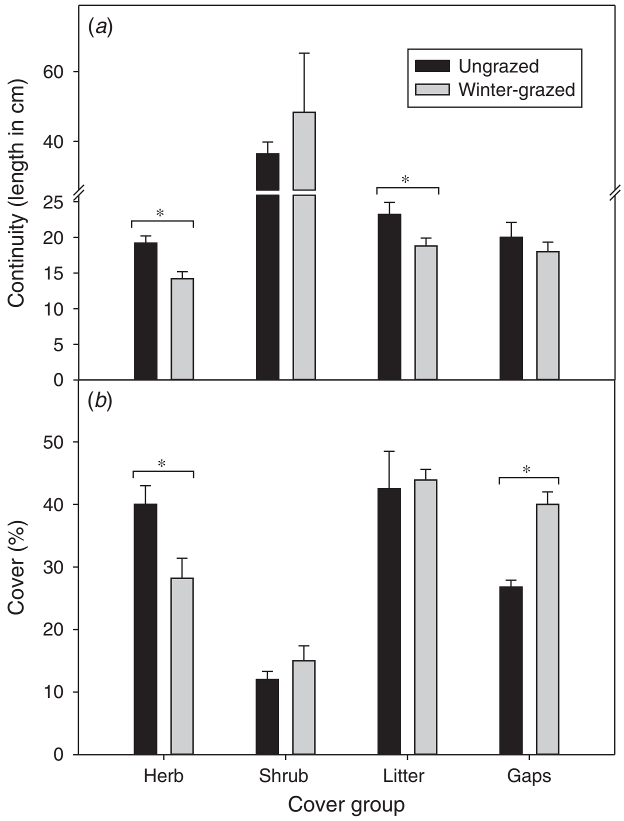

Fig. 1. (*a*) Average length of continuous cover segments and (*b*) percentage cover by cover group in winter-grazed and ungrazed treatments. Vegetation cover measurements included live and dead standing cover. Herb, herbaceous vegetation; Shrub, shrub (predominantly *Artemisia*); Litter, ground litter; Gaps, fuel gaps. Data are the mean ± s.e. $*P < 0.05$.

average size of fuel gaps was not affected by winter grazing ($P = 0.20$; Fig. 1*a*). Gaps in fuel covered 1.5-fold more of the ground in the winter-grazed than ungrazed treatments ($P < 0.01$; Fig. 1*b*).

Fuel biomass response to winter grazing varied among the functional groups (Fig. 2). Perennial bunchgrass (previous and current years' growth) biomass was 2.4-fold greater in the ungrazed compared with winter-grazed treatments ($P = 0.03$). In contrast, current year's growth of perennial bunchgrass did not differ between the winter-grazed and ungrazed treatments ($P = 0.25$). Sandberg bluegrass biomass was 2.8-fold greater in the ungrazed compared with winter-grazed treatment ($P < 0.01$). Annual grass, annual forb and perennial forb biomass did not differ between winter-grazed and ungrazed treatments ($P = 0.50$, 0.57 and 0.20 respectively). Winter grazing reduced total herbaceous (live and dead) fuel biomass by 58% compared with the ungrazed treatment ($P = 0.02$).

Winter grazing influenced other fuel characteristics of perennial bunchgrasses (Figs 3, 4). The height of perennial bunchgrass current year's growth and previous years' growth was 1.4- and 1.6-fold greater in the ungrazed compared with winter-grazed treatment ($P = 0.03$ and 0.02 respectively; Fig. 3). The basal diameter of perennial bunchgrasses was not affected by winter grazing ($P = 0.84$; Fig. 4*a*). Fuel biomass on

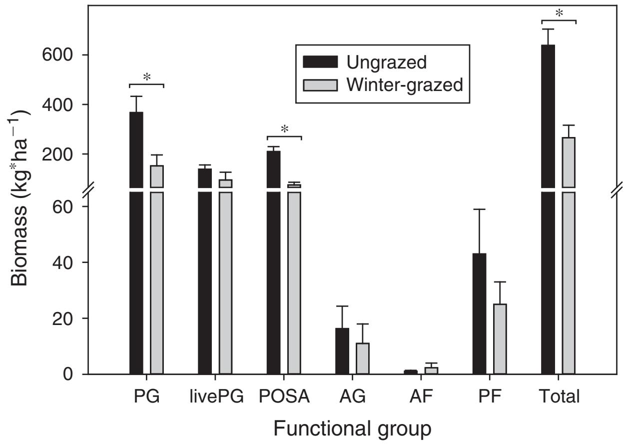

Fig. 2. Fuel biomass of functional group in winter-grazed and ungrazed treatments. PG, perennial bunchgrasses; livePG, perennial bunchgrass current year's production; POSA, Sandberg bluegrass; AG, exotic annual grasses; AF, annual forbs; PF, perennial forbs; Total, total herbaceous vegetation. Data are the mean ± s.e. $*P < 0.05$.

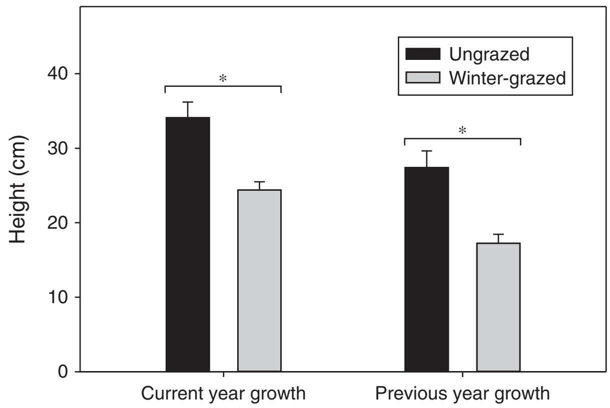

Fig. 3. Fuel heights of perennial bunchgrass in winter-grazed and ungrazed treatments. Data are the mean ± s.e. $*P < 0.05$.

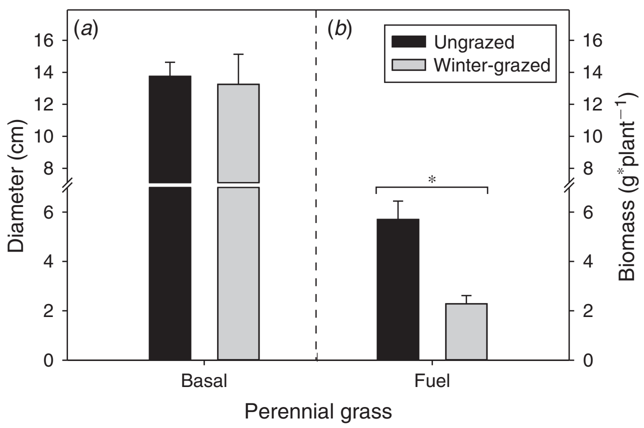

Fig. 4. (*a*) Basal diameter and (*b*) fuel biomass of perennial bunchgrass in winter-grazed and ungrazed treatments. Data are the mean ± s.e. $*P < 0.05$.

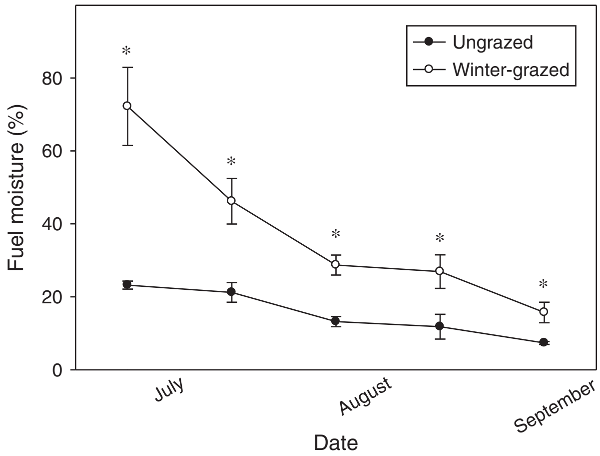

Fig. 5. Herbaceous (live and dead) fuel moisture content in winter-grazed and ungrazed treatments. Moisture content was calculated as a percentage of dry weight. Data are the mean ± s.e. *$P < 0.05$ winter-grazed treatment compared with ungrazed treatment on the same date.

perennial bunchgrasses was 2.5-fold greater in the ungrazed compared with winter-grazed treatment ($P = 0.03$; Fig. 4*b*).

Herbaceous (live and dead) fuel moisture response to treatment varied by sampling date ($P < 0.01$). The magnitude of difference between the winter-grazed and ungrazed treatment decreased from the first sampling date in mid-June to later sampling dates (Fig. 5). Fuel moisture content was 3.1-fold greater in the winter-grazed compared with ungrazed treatment at the first sampling date ($P < 0.01$). At all other sampling dates, the winter-grazed treatment had 2.1- to 2.3-fold greater herbaceous fuel moisture content than the ungrazed treatment ($P < 0.05$).

Discussion

Dormant season grazing may be a herbaceous fuel treatment that can reduce the likelihood of a wildfire and decrease fire severity in grass–shrub steppe communities where herbaceous fuels play an important role in fire behaviour. Ungrazed compared with winter-grazed Wyoming big sagebrush plant communities in the present study had vastly different fuel characteristics. The multiple fuel characteristics (fuel moisture, height, biomass, cover and continuity) that were concurrently influenced by winter grazing suggest that it likely reduces wildfires behaviour.

Greater fuel moisture with winter grazing is likely the result of an increased ratio of live to dead herbaceous fuels, which decreases the likelihood of fire ignition and potential spread and severity of wildfires in shrub–grasslands (Chuvieco *et al.* 2009, 2014). Most notably in the present study, winter grazing truncated the period when herbaceous (live and dead) fuels would readily burn by approximately 2 months. In grasslands, the fuel moisture of extinction (i.e. fuel moisture above which fuels do not readily combust) generally ranges between 20% and 24% (Cheney *et al.* 1998). Based on this estimate, herbaceous (previous and current years' growth) fuels in winter-grazed areas in the present study were unlikely to burn until the end of August, whereas the ungrazed areas were dry enough to burn in mid-June to early July. Thus, the duration of the wildfire season was likely reduced from approximately 3 months to approximately 1 month with winter grazing. The effect of winter grazing on wildfire seasonality could have significant impacts on the response of the native plant community to fire. Winter grazing reduced the likelihood of early season wildfires, which can be detrimental to native vegetation. Native bunchgrasses are more susceptible to fire-induced mortality early in the season when they are at a critical stage of phenological development (Wright and Klemmedson 1965; Britton *et al.* 1990). Even when the winter-grazed areas were dry enough to burn, they appear less likely to ignite because of higher fuel moisture content compared with the ungrazed areas. More energy is required for ignition with higher fuel moisture among similar sized fuels (Thonicke *et al.* 2001; Chuvieco *et al.* 2004) and the probability of fire ignition decreases with increasing fuel moisture (Chuvieco *et al.* 2009).

The decrease in herbaceous fuels with winter grazing reduces the probability of an ignition source making contact with fuels, because less area is covered by herbaceous fuels. Well-managed livestock grazing during the spring and summer compared with long-term livestock exclusion resulted in similar reductions in herbaceous fuels (Davies *et al.* 2010). Blackmore and Vitousek (2000) and Briggs *et al.* (2002) also measured decreased herbaceous fuel biomass with grazing. Greater fuel biomass and heights increase flame length, which promotes fire spread, especially across fuel gaps (Bradstock and Gill 1993; Blackmore and Vitousek 2000). The increase in fuel moisture with winter grazing may further reduce the rate of spread (Rothermel 1972). A decrease in the rate of spread and shorter flame lengths may increase the probability of a patchy (mosaic) burn (K. W. Davies, unpubl. data), thus increasing landscape heterogeneity. Unburned patches can provide refuge for fire-sensitive species. Because fire intensity is related to fuel abundance (Byram 1959) and reduced flame lengths and rates of spread increase the effectiveness of fire suppression efforts (Fried *et al.* 2004; Moghaddas and Craggs 2007), fire suppression efforts may be more effective and less costly in winter-grazed areas. Although fuel characteristics are generally more important than climatic conditions in determining fire spread and severity in drier ecosystems (Schoennagel *et al.* 2004), extreme fire weather conditions may override fuel characteristics (Gedalof *et al.* 2005). The effects of grazing on fire behaviour are limited with extreme fire weather, especially with high amounts of woody vegetation (Strand *et al.* 2014).

Decreased fuel biomass with winter grazing may decrease the potential severity of a fire if a plant community burns. Most notable is the reduction in the fuel biomass on perennial bunchgrasses. Ungrazed perennial bunchgrasses had approximately 2.5-fold more biomass than winter-grazed bunchgrasses. This was not a result of the effects of grazing on basal area, because basal diameter did not differ between winter-grazed and ungrazed bunchgrasses. Growing season grazing results in a similar decline in fuels on the crown of perennial bunchgrasses (Davies *et al.* 2010). The increased fuel biomass on the top of perennial grass plants may affect their risk of fire-induced mortality (Davies *et al.* 2009). In Wyoming big sagebrush plant communities, perennial bunchgrasses are the most important plant functional group for limiting invasion by exotic annual grasses (Davies 2008; James *et al.* 2008). Thus, fire-induced mortality of perennial bunchgrasses from increased fuel biomass increases the chances of exotic plant invasion (Davies *et al.* 2009). Our results suggest that winter grazing may be an effective tool to decrease the risk of fire-induced mortality in perennial grasses and thereby promote post-fire recovery of the native plant community.

One of the concerns with using livestock grazing as a fuel treatment is the risk of promoting exotic plant invasions. The results of the present study suggest that winter grazing can be applied without promoting exotic plants. No difference in exotic annual grass biomass was detected between winter-grazed and ungrazed areas (Fig. 2). After 4 years of winter grazing, perennial bunchgrass production and basal diameter were similar between winter-grazed and ungrazed treatments, suggesting that winter grazing was not adversely affecting native herbaceous plants. However, we caution that winter grazing may negatively impact native perennial herbaceous vegetation and subsequently promote exotic plant invasion if plants are grazed too severely (Holechek *et al.*1998). The lack of a difference in native shrubs between treatments further suggests that winter grazing can be used to reduce herbaceous fuels without adversely impacting the native plant community.

In the sagebrush ecosystem in the US, sage-grouse (*Centrocercus urophasianus*) are a species of critical conservation concern because they occupy only approximately 54% of their historic range (Schroeder *et al.* 2004) and their populations have been declining by approximately 2% a year since the 1960s (Connelly and Braun 1997; Connelly *et al.* 2004). Fire has been identified as the primary threat to sage-grouse habitat in Wyoming big sagebrush communities because of the loss of sagebrush (which is killed by fire) and the potential for post-fire exotic annual grass invasion (Davies *et al.* 2011; US Fish and Wildlife Service (USFWS) 2013). Our results suggest winter grazing has the potential to reduce the risk of sage-grouse habitat loss to wildfire by modifying fuel characteristics. Considering this research and that of Davies *et al.* (2009, 2010), there is a growing body of literature suggesting that properly managed livestock grazing can protect both sagebrush rangelands and the fauna that depend upon them. Although grazing needs to be managed to ensure a diversity of habitats (i.e. areas with high and low residual vegetation cover) is provided, this research suggests winter grazing can be used to protect habitat used by sage-grouse and other sagebrush-associated wildlife species.

Previous research has suggested that livestock introduction in areas that historically had few large herbivores greatly reduced fire frequency by decreasing herbaceous fuels (Burkhardt and Tisdale 1976; Miller *et al.* 1994). Our research supports this thesis and further suggests that livestock grazing probably substantially alters fuel moisture and may thereby truncate the wildfire season. This suggests that the effect of livestock introduction on fire regimes in areas with historically few large herbivores has probably been underestimated. This also suggests that estimates of historical fire regimes based on current fire frequencies without accounting for the widespread influence of livestock (e.g. Baker 2006) may be overly conservative. A more complete understanding of historical and current effects of livestock on wildfires requires additional research on different grazing patterns and fuel characteristics across varying ecosystems.

Conclusions

Our research suggests that winter livestock grazing may be used as a fuel treatment in some Wyoming big sagebrush rangelands to reduce the likelihood of fire and potentially reduce wildfire severity. Winter grazing will most likely be most useful at reducing the probability of wildfires and fire severity in areas with a greater abundance of herbaceous vegetation, because the potential for grazing to influence fire behaviour decreases as the dominance of woody plants increases (Strand *et al.* 2014). Considering grazing can be applied across vast areas and at minimal net cost, dormant season grazing has the potential to be an efficient fuel treatment in shrub–grasslands and grasslands. However, winter grazing should not be attempted in areas that can receive heavy snow fall because forage can be buried and access to livestock can become limited. With climate change likely increasing the area burned by wildfires (Fulé 2008; Westerling *et al.* 2006; Yue *et al.* 2013), the need for effective and efficient management of fuels will only become more important. Dormant season grazing has the potential to reduce wildfire suppression expenditures in many rangelands where herbaceous fuel accumulation is an issue and thus warrants further evaluation and refinement to maximise benefits and limit negative impacts across a wide array of ecosystems.

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