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Communication

Winter grazing decreases the probability of fire-induced mortality of bunchgrasses and may reduce wildfire size: a response to Smith *et al.* (this issue)

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Abstract. A recent commentary by Smith *et al.* (2016) argues that our study (Davies *et al.* 2016) contained methodological errors and lacked data necessary to support our conclusions, in particular that winter grazing may reduce the probability of fire-induced mortality of bunchgrasses. Carefully reading Davies *et al.* (2016) and relevant literature provides strong evidence that the comments of Smith *et al.* are unfounded. Most notably, Smith *et al.* (2016) state that thermocouples placed in the air have no correlation to temperatures experienced by vegetation. However, in our study, thermocouples were placed inside the centre of meristematic crowns of bunchgrasses, as was clearly stated in the methods. Nowhere in the manuscript does it say that thermocouples were placed in the air. Duration of elevated temperatures has been repeatedly linked to an increased risk of fire-induced mortality of vegetation in the literature, contrary to claims by Smith *et al.* (2016) that no evidence of a relationship exists. The conclusion that winter grazing may decrease the likelihood of perennial bunchgrass mortality was not based solely on data collected in this experiment, but also Davies *et al.* (2009), where post-fire bunchgrass density and production in ungrazed areas were less than half those of grazed areas.

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Introduction

Since 1997, seven of the eleven western states have experienced their largest wildfire in recorded history (NOAA 2012) and the occurrence of very large wildfires is projected to increase with changing climate conditions (Barbero *et al.* 2015). This increased presence of fire on the landscape has been associated with loss of native perennial vegetation that provides resistance to annual grass invasion and expansion, loss of shrub communities important to sage-grouse and other sagebrush obligates, and impairment or loss of a multitude of ecosystem services (Davies *et al.* 2011). Fire behaviour is governed by weather, topography, and fuel composition and loading. Of these variables, only fuels can be manipulated by management. However, in low- to mid-elevation sagebrush plant communities, there is a critical shortage of empirical data to guide fuel management decisions and policy. Therefore, Davies *et al.* (2016) is an important and forward-thinking contribution to management of fire-prone sagebrush plant communities in the western United States. The critique of Smith *et al.* concludes that our study is not a valid contribution to management of fire-prone sagebrush communities; however, their argument is flawed owing to a misunderstanding of the methodology we employed, as well as overlooking relevant literature.

Concerns over methodology

Smith *et al.* (2016) argue that heat load and maximum temperature as we measured them have no relationship to fire-induced mortality of vegetation, primarily based on the assumption our thermocouples were placed in the air and therefore have no relationship to temperatures experienced by vegetation during a burn. As stated in our methods, however, thermocouples were placed into the centre of meristematic crowns of bunchgrasses so that measured temperatures would serve as an index of the thermal environment of meristematic tissue during a fire. It was not our intent to measure the heat transfer into plants as suggested by Smith *et al.* (2016). Using the same approach as our study, Hulet *et al.* (2015) demonstrated that fire-induced mortality of bunchgrasses increases with greater heat loads measured at the meristematic crowns. They also determined that mortality increased by 48% when maximum temperature in the meristematic crown of a perennial bunchgrass during a burn was above 250°C and 80% when temperatures were greater than 350°C. Duration of temperatures greater than 60°C during a fire (the method for determining heat load in our study) was the best predictor of fire-induced mortality in plains prickly pear (*Opuntia polyacantha* Haw.) (Vermeire and Roth 2011). The latter authors also found that maximum temperature during burns was correlated positively with prickly pear mortality. Peak fire temperatures in the Mojave Desert were most affected by fuel and directly affected annual plant mortality (Brooks 2002). Our thermocouple measurements fall within the range of surface temperatures found in multiple publications directly related to sagebrush steppe ecosystems (Wright and Bailey 1982; Allen *et al.* 2008), woody-encroached grasslands (Stinson and Wright 1969) and grasslands in south-eastern Australia (Morgan 1999). Variation in surface temperatures between and within fires is expected as temperatures are influenced by ambient temperature, relative humidity and wind speed (Pyne *et al.* 1996). This body of literature suggests our methodology was sound, and that there is a clear relationship between heat load and fire-induced plant mortality.

Smith *et al.* (2016) state that data precision cannot be determined without further discussion of how data were averaged. This misses the point that the treatment differences we describe were relative as well as statistically and biological significant. Regardless of the limitations of thermocouples (Iverson *et al.* 2004), the measurement procedures for each treatment were identical, and hence provide a quantitative index to determine relative differences between treatments. We agree with Smith *et al.* (2016) that rigorously quantifying heat flux would be a valuable metric in assessing thermally induced plant mortality. However, the purpose of our study was not to quantify heat flux, but to determine the difference between treatments and establish the degree of treatment effect. Although many factors (fire weather, fuel moisture content, etc.) influence duration of elevated heat and maximum temperature during a fire, our objective was to determine if winter grazing influenced duration of elevated heat and maximum temperature during a fire, and our results demonstrate that it did.

Smith *et al.* (2016) state that there is no evidence that our prescribed fires were ignited within the range of wildfire growth conditions in this region. However, table 1 in Davies *et al.* (2016) shows fire weather conditions during the burns. We also reported fine-fuel moisture content in the text of the article. The assertion of Smith *et al.* (2016) that prescribed fires must be ignited under wildfire conditions is not practical. Owing to legal and liability issues with burning during the wildfire season, most prescribed-burning studies occur well outside the wildfire season. That we were able to conduct burns within days of wildfire growth and while wildfires were still being mopped up is a rarity. Our prescribed burns occurred across a broad array of fire weather conditions and thus demonstrated that winter grazing can affect fire behaviour and severity across a range of meteorological conditions.

We cite mechanistic studies such as Wright and Klemmedson (1965), Wright (1970), Odion and Davis (2000) and Pelaez *et al.* (2001) to emphasise that time and duration of elevated temperatures are important factors when considering both individual plant mortality and community response to fire. Smith *et al.* (2016) state that, 'Wright and Klemmedson (1965) did not generally observe any significant differences in mortality 1 year post-fire between using the 93° and 240°C (soil temperature) treatment'. We find this statement misleading, as Wright and Klemmedson (1965) did find significant mortality in both *Stipa comata* and *Stipa thurbariana* bunchgrasses and reported that 'the June treatments killed all of the small and 90% of the large [*Stipa comata*] plants'. For *Stipa thurberiana*, Wright and Klemmedson (1965) reported, 'The large plants burned at 400°F in June were the only *Stipa thurberiana* plants to differ significantly in mortality from the check plants'. Wright and Klemmedson (1965) also found high mortality of *Stipa thurberiana* following wildfire and concluded that higher temperatures created by sagebrush fuels contributed to the high mortality they observed. One of the criticisms from Smith *et al.* (2016) is that two of the works cited above (Odion and Davis 2000 and Pelaez *et al.* 2001) are from 'different ecosystems', yet they cite work from Africa (McNaughton *et al.* 1998; Smith *et al.* 2005) and a dry eucalypt forest (Wotton *et al.* 2012) to suggest the expected diffusion flame temperature range for the sagebrush steppe ecosystem. In any case, this is irrelevant because flame temperature was not mentioned in Davies *et al.* (2016).

Smith *et al.* (2016) also criticised Davies *et al.* (2016) for not providing greater details on how flame heights, rate of spread and flame depth were measured. We could have exhaustedly detailed how each variable was measured; however, these are standard fire behaviour measurements (i.e. most fire ecologists would find the level of detail sufficient to replicate this study), and once again this overlooks that the purpose of our study was to ascertain the relative differences between treatments – not the exact flame height, rate of spread or flame depth, as all of these variables will also vary with fire weather and other factors. Other authors have reported a similar level of detail when describing their methods used to measure fire behaviour (e.g. Sapsis and Kauffman 1991; Sparks *et al.* 2002; Diamond *et al.* 2009).

Data and literature support conclusions

Increased risk of fire-induced mortality

Our conclusion that the greater duration of elevated temperatures at the meristematic tissue of perennial bunchgrasses in ungrazed than in grazed areas suggests that these plants have a greater likelihood of fire-induced mortality is supported by the literature (Vermeire and Roth 2011; Hulet *et al.* 2015; see prior discussion in *Concerns over methodology*). Smith *et al.* (2016) think it is important to know the exact rate of heat transfer, which would vary across and within wildfires. Our principal result was a clear demonstration that the likelihood of fire-induced mortality is greater in ungrazed compared with winter-grazed areas; however, we acknowledge that this will also vary with other factors influencing fire severity. It has already been established that grazing can reduce the likelihood of fire-induced mortality in bunchgrasses (Davies *et al.* 2009). Ungrazed compared with moderately grazed areas, with the same bunchgrass and annual grass densities prefire, had fewer bunchgrasses and increased exotic annual grasses post-fire (Davies *et al.* 2009). Thus, the current study is expanding on this research and investigating potential mechanisms for this effect. We are also collecting post-fire plant community response over the next several years in winter-grazed and ungrazed treatments to provide additional information on this topic.

Extrapolation beyond the scale of the research

Smith *et al.* (2016) are correct that we did not present any data to support our statement 'Shrubs in ungrazed areas were more engaged by the fire; thus they burned more completely…' Shrub biomass was similar between treatments before fire (Davies *et al.* 2016). We measured but did not report post-fire shrub biomass, which was greater in winter-grazed (2610 ± 899 kg ha^{-1}) than in ungrazed areas (1427 ± 466 kg ha^{-1}) ($P = 0.003$). This supports our statement that more shrub fuel was consumed during the burns in ungrazed areas. Other literature suggests a positive linkage between pre-fire cover or loading of herbaceous vegetation and proportion of an area burned in big sagebrush-dominated systems (Britton *et al.* 1981; Wright 2013).

Although we agree with Smith *et al.* (2016) that large fires in this region are often wind-driven for a significant portion of their duration, these fires can also burn under meteorological conditions similar to those recorded for our prescribed burns (InciWeb 2015; Weather Underground 2015). Therefore, winter grazing would likely provide opportunities where suppression would be more effective and safer because of reduced fire behaviour. Smith *et al.* (2016) cited Lauchbaugh *et al.* (2008) as an example where grazing had little impact on fire spread during the Murphy Complex fire. However, Lauchbaugh *et al.* (2008) did report that some areas did not burn because they had been grazed before the fire. Because Lauchbaugh *et al.* (2008) was a post-hoc case study, it is difficult to determine if rate of spread was different between grazed and ungrazed areas as other factors that influence rate of spread were simultaneously varying temporally and spatially. Another significant issue not mentioned by Smith *et al.* (2016) is that large-fire years in the sagebrush steppe ecosystem usually occur after a year or two of above-average plant production resulting in an accumulation of fine fuels (Knapp 1998; Westerling *et al.* 2003; Littel *et al.* 2009). Therefore, large-fire years in sagebrush ecosystems can be driven by fine fuels and winter grazing would likely be a valuable tool to decrease the risk and severity of wildfires in years following fuel accumulation because it decreases fine-fuel loads and because it can extended the period when fine-fuel moisture content is too high to burn for 1 month or more compared with ungrazed areas (Davies *et al.* 2015).

Discussion of grazing effects

Smith *et al.* (2016) suggest that our article (this issue) should have included a thorough discussion of the effects of livestock grazing on these communities. This was already included in our prior paper on winter grazing (Davies *et al.* 2015), which was based on data from the same study as Davies *et al.* (2016). However, we did note that winter grazing must be carefully applied, as overuse may negatively impact native vegetation and decrease plant community resilience (Davies *et al.* 2016). Smith *et al.* (2016) also argue that our conclusion (Davies *et al.* 2016) that winter grazing may reduce the likelihood of developing an annual grass–fire cycle is not supported. This argument is likely based on a presumption of overgrazing, something we specifically caution against in Davies *et al.* (2016). Overgrazing has been clearly demonstrated to promote exotic annual grass invasion (Mack 1981; Young and Allen 1997; Reisner *et al.* 2013); however, areas with well-managed grazing have similar vegetation characteristics to ungrazed areas, including minimal exotic annual grass abundance (West *et al.* 1984; Rickard 1985; Courtois *et al.* 2004; Mainer and Hobbs 2006; Davies *et al.* 2014). In addition, Davies *et al.* (2015) found no difference in exotic annual grass production between winter grazing and ungrazed areas prefire. In fact, reduction of fine-fuel accumulation with moderate grazing in sagebrush plant communities reduced post-fire exotic annual grass dominance (biomass, cover and density) compared with ungrazed areas (Davies *et al.* 2009). Ungrazed areas had only half the native large bunchgrass density and biomass of grazed areas post-fire, likely owing to increased fire-induced mortality associated with fuel accumulations on bunchgrasses (Davies *et al.* 2009). Therefore, it is logical to assume that properly applied winter grazing can decrease the potential for fire-induced mortality of bunchgrasses and post-fire invasion of exotic annual grasses.

Smith *et al.* (2016) also mistakenly claim that Davies *et al.* (2016) suggested that winter grazing would break the exotic annual grass–fire cycle, and then concluded there is no evidence in the wider literature to support this claim. To the contrary, we agree that studies assessing the efficacy of winter grazing to break the feedback between fire and exotic annual grass spread are lacking, and urge the implementation of rigorously controlled field experiments to address this issue. Our current study was conducted in intact, undegraded sagebrush–bunchgrass steppe communities that had not been severely impacted by annual grasses. Our results suggest that well-managed winter grazing could provide a valuable management tool to promote and sustain extensive perennial bunchgrass populations, which has been found to be the most effective method to limit exotic annual grasses (Chambers *et al.* 2007; Davies *et al.* 2011).

Smith *et al.* (2016) disagree with our statement (Davies *et al.* 2016) that winter grazing needs to be applied strategically in order to maintain a diversity of habitats, most notably to maintain enough residual vegetation for sage-grouse. Nest success of sage-grouse is positively correlated with perennial herbaceous screening cover (Gregg *et al.* 1994; Connelly *et al.* 2000). Therefore, we suggested that it would be prudent to apply winter grazing in such a way as to maintain habitat elements for sage-grouse (Davies *et al.* 2016), which may include not winter-grazing some areas or applying winter grazing to only a portion of a given pasture.

Conclusions

We stand by our conclusions that winter grazing can reduce the severity of fire behaviour and subsequently may increase post-fire resistance to exotic annual grass invasion as these conclusions are well supported by the literature and our data. We are not suggesting that all ungrazed areas would suffer high bunchgrass mortality during a fire. Nonetheless, our data indicate a positive correlation between fuel reduction associated with grazing and a reduction in thermal extremes experienced by bunchgrasses during fire. The likelihood of fire-induced mortality increases with increasing fuel loads on bunchgrasses in ungrazed compared with well-managed grazed areas (Davies *et al.* 2009, 2010; 2015, 2016). Smith *et al.* (2016) made several errors in interpreting Davies *et al.* (2016). Most evident was mistakenly reporting that our thermocouples were placed in the air even though the methods clearly state that thermocouples were placed in meristematic crowns of bunchgrasses. They then argue that there is no correlation between heat load and bunchgrass mortality. However, other research (Hulet *et al.* 2015) clearly demonstrated that fire-induced mortality of bunchgrasses was positively associated with increasing heat load in sagebrush communities. Smith *et al.* (2016) also argue that more information regarding methods was needed; however, this does not change the fact that fire behaviour and other response variables were vastly different between winter-grazed and ungrazed areas. Furthermore, these methods are standard fire behaviour measurements that most fire ecologists could replicate with the level of detail provided. One valuable effect of Smith *et al.* (2016) was to echo our call (Davies *et al.* 2015, 2016) for additional research to address costs and benefits of winter grazing as a conservation and restoration tool in sagebrush steppe ecosystem.

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