Received: 20 November 2023 | Revised: 27 February 2024 | Accepted: 8 March 2024

DOI: 10.1002/ecs2.4859

SYNTHESIS & INTEGRATION

ECOSPHERE
AN ESA OPEN ACCESS JOURNAL

Ecological benefits of strategically applied livestock grazing in sagebrush communities

Kirk W. Davies[1] | **Chad S. Boyd**[1] | **Jon D. Bates**[1] | **Lauren N. Svejcar**[1] | **Lauren M. Porensky**[2]

[1]United States Department of Agriculture – Agricultural Research Service, Burns, Oregon, USA

[2]United States Department of Agriculture – Agricultural Research Service, Fort Collins, Colorado, USA

Correspondence
Kirk W. Davies
Email: kirk.davies@usda.gov

Handling Editor: Robert R. Parmenter

Abstract

There are concerns about the negative consequences of non-native livestock grazing of sagebrush communities, especially since these communities are experiencing unpreceded threats from invasive annual grasses, altered fire regimes, and climate change. The narrative around grazing often focuses on the effects of heavy, repeated growing season use that were common historically but now are rare or localized (e.g., near water sources). At the same time, the potential for ecological benefits of strategically applied grazing is often overlooked, limiting management options that may promote desired outcomes. To improve management in the face of unprecedented threats, we synthesized the literature to investigate and identify potential ecological benefits of strategically applied livestock grazing in sagebrush communities. We found that grazing can be used to modify fine fuel characteristics in ways that decrease fire probability and severity in sagebrush communities. Pre-fire moderate grazing may be especially important because it decreases fire severity and, thereby, promotes biodiversity and reduces postfire annual grass invasion, fire-induced mortality of native bunchgrasses, and fire damage to soil biocrusts. Grazing can create and maintain fine fuel breaks to improve firefighter safety and fire suppression efficiency. Strategic grazing can also be used to promote desirable plant community composition. Grazing can be a valuable tool, that is currently underutilized, for achieving desired management outcomes in the sagebrush and likely other ecosystems. Improper grazing can generate severe negative consequences; therefore, successful application of grazing to achieve desired outcomes will require careful attention to plant community response and balancing management objectives with community constraints.

KEYWORDS
annual grasses, cattle, fire, fuel, herbivory, shrub restoration

INTRODUCTION

Domestic livestock grazing is the most prominent land use of sagebrush communities in western North America. Non-native livestock (sheep, cattle, and horses) were introduced in large numbers to these rangelands in the mid-to-late 1800s by Europeans (Oliphant, 1968). Early grazing practices were not ecologically sustainable and led to widespread overuse and degradation (e.g., loss of perennial grasses and forbs, reduced biodiversity, erosion, overabundant unpalatable species, and non-native plant invasions) (Box, 1990; Daubenmire, 1970; Griffiths, 1902). During this period, grazing regimes characterized by heavy stocking rates and repeated growing season use were pervasive because livestock producers did not know the grazing capacity of these rangelands, and on public lands, inadequate governance structures meant that if one producer did not use the forage, another producer would (Box, 1990; Hess & Holecheck, 1995). Grazing management practices improved as rangeland science developed, and with the creation of the Forest Service and Grazing Service (precursor to the Bureau of Land Management) which governed public land use (Box, 1990). Improvements in grazing management led to widespread recovery of native herbaceous understories in many rangeland plant communities (Box, 1990; Copeland et al., 2021; Young & Sparks, 1985). However, legacy effects and localized heavy grazing (e.g., near water sources) continue to be associated with losses of native perennial herbaceous plants and biocrusts, increases in invasive plants, and increased erosion potential in some areas (Reisner et al., 2013; Root et al., 2020; Williamson et al., 2020).

Consequentially, there has been concern about livestock grazing in sagebrush communities. Some have called for the removal of livestock grazing from public lands because of the effects of prior grazing practices and localized heavy grazing (e.g., Beschta et al., 2012; Kauffman et al., 2022; Meyer, 2011). However, grazing occurs at moderate (30%–50% utilization of available forage) to low (<30% utilization of available forage) intensities in many sagebrush rangelands, and these areas are comparable to ungrazed areas (Anderson & Holte, 1980; Copeland et al., 2021; Davies et al., 2018; Rice & Westoby, 1978; Veblen et al., 2015). Thus, it is unlikely that removing moderate or low intensity grazing will substantially improve sagebrush rangeland condition (e.g., increase native perennial forbs and grasses, limit invasive species, and decrease erosion potential) (Copeland et al., 2021; Davies et al., 2014; Thomas et al., 2022). There are also economic and social reasons to use sagebrush rangelands for livestock production, especially as world demand for food and fiber increases (Westcott & Trostle, 2012). Overlooking the ability to generate ecological benefits with livestock grazing may limit our ability to achieve desired outcomes in sagebrush plant communities.

It is well established that livestock grazing in other ecosystems can have ecological benefits. Livestock grazing promotes biodiversity in many different ecosystems around the world (Báldi et al., 2013; Marty, 2005; Mu et al., 2016; Papanikolaou et al., 2011; Porensky et al., 2013). Livestock grazing can be used as a tool for controlling invasive plant species (DiTomaso et al., 2008; Frost & Launchbaugh, 2003; Lym et al., 1997) and for fuel modification to reduce the probability of wildfires in some ecosystems (Freitag et al., 2021; Siegel et al., 2022). Another ecological benefit of grazing in some systems is that it can increase habitat diversity (Fuhlendorf et al., 2006; Öllerer et al., 2019; Vavra, 2005). Undoubtedly, grazing can be beneficial for some plant communities, but the idea that livestock grazing could be beneficial for sagebrush communities is often dismissed.

In the 62 million ha sagebrush ecosystem, particularly in the Great Basin, livestock grazing is considered outside of the historic disturbance regime by some people. This is based on the limited abundance of large herbivores in the recent evolutionary past and that most of the dominant herbaceous species in the sagebrush ecosystem lack clear grazing resilience traits (Adler et al., 2004; Díaz et al., 2007; Mack & Thompson, 1982). This, combined with the negative consequences of heavy, repeated growing season grazing (Box, 1990; Daubenmire, 1970; Griffiths, 1902; Laycock, 1967; Reisner et al., 2013), has led to a general assumption that sagebrush communities are likely to be negatively affected by any amount of grazing and that, at best, management can minimize those negative effects. However, large herbivores have been present at low densities for thousands of years in this ecosystem, and smaller herbivores are also common. Large ungulate herbivores were even more abundant in the distant past (>10,000 years ago) (Atwater & Davis, 2011; Grayson, 2016), and sagebrush communities have been around for at least 12 million years (Davis & Ellis, 2010). There are also some herbaceous species found in parts of the sagebrush ecosystem that have grazing resilience traits, such as western wheatgrass (*Agropyron smithii*) and blue grama (*Bouteloua gracilis*) (Benkobi et al., 2007; Kotanen & Bergelson, 2000), or grazing avoidance/tolerance traits, such as Sandberg bluegrass (*Poa secunda*) (McLean & Tisdale, 1972; Porensky et al., 2018). Sagebrush plant communities thus evolved in the context of some nonzero level of herbivory and may be resilient to grazing at moderate to low intensities or frequencies. Thus, it is possible that strategically applied livestock grazing could convey some ecological benefits in these communities.

There have been multiple terms used to define grazing to achieve desired outcomes, such as "prescribed," "targeted," or "strategic" livestock grazing (e.g., Bailey et al., 2019; Barnes & Howell, 2013; Frost & Launchbaugh, 2003; Rinella & Hileman, 2009). For the purpose of this manuscript, we use the term strategic grazing and define it as grazing purposefully applied to facilitate change to or maintain desired plant community characteristics. Our objectives were to synthesize the literature to investigate and identify potential ecological benefits of strategic livestock grazing in sagebrush communities and assess the ability of livestock management to achieve desired outcomes. Because more frequent and severe wildfires and undesirable plant community compositional changes (e.g., loss of native perennials, reduced biodiversity, and increases in invasive annual grasses) are two of the most pressing issues in sagebrush communities (Crist et al., 2023; Davies et al., 2011; Doherty et al., 2022), we focus our synthesis on investigating if strategically applied grazing can decrease fire probability and severity or can positively influence plant species composition. This includes identifying under what circumstances grazing can be beneficial and providing insight into how management can capitalize on its positive effects. We also suggest additional research avenues to increase opportunities to effectively manage livestock grazing to achieve desired outcomes in sagebrush plant communities.

GRAZING TO MODIFY FUELS AND FIRES

Fuels

Increased fire frequency, annual area burned, and incidents of mega-fires (Crist, 2023; Crist et al., 2023; NIFC, 2023) threaten the resilience and resistance of sagebrush communities prone to annual grass invasion (Chambers et al., 2007, 2014) as well as sagebrush-associated wildlife (USFWS, 2013). The cost of suppressing these wildfires and postfire restoration is exceedingly expensive with tens of millions of dollars expended per megafire (Crist et al., 2023; NIFC, 2023). Pre-suppression management of fuels could reduce the probability, size, and frequency of fires in sagebrush communities (Hulet et al., 2015); however, the extent of vast sagebrush rangelands makes fuel management challenging. Hence, grazing is one of the most economical and logistically feasible treatments that can be applied at the scale needed to manage fine fuels in sagebrush rangelands (Davies et al., 2015).

Strategic grazing can modify a wide suite of fine fuel characteristics (Figure 1). Moderate levels of grazing by cattle reduce fine fuel biomass, height, and continuity (Davies et al., 2010, 2015; Orr et al., 2023; Strand et al., 2014; Thomas & Davies, 2023). More intense grazing may also be used to reduce annual grass fine fuels in invasive annual grass-dominated sagebrush rangelands (Diamond et al., 2009, 2012; Porensky et al., 2018). Grazing also increases the moisture content of fine fuels by altering the live to dead ratio in subsequent years (Davies et al., 2015, 2017; Orr et al., 2023). By increasing fuel moisture content, moderate grazing truncates the period of time when fine fuels are dry enough to readily burn by ~2 months (Davies et al., 2015). Clearly grazing has substantial effects on fuel characteristics, but these effects vary according to grazing intensity (Orr et al., 2023), plant community composition (Thomas & Davies, 2023), and timing of grazing (Davies et al., 2017; Porensky et al., 2018). Hence, management of grazing must align with fuel management goals within the constraints of the plant communities.

Fuel breaks

Creating and maintaining fuel breaks with strategically applied grazing (Figure 2) may be a particularly productive use of livestock to protect ecosystem goods and services in sagebrush communities prone to annual grass invasion, especially when they limit fire spread from annual grass-invaded communities to intact sagebrush-bunchgrass communities. Fuel breaks are intended to provide firefighters "safe" locations from which to suppress wildfires and increase the effectiveness of suppression efforts. Recently a large network of fuel breaks has been implemented to assist in limiting the spread of fires in extensive sagebrush landscapes (BLM, 2020). Because of the vast nature of sagebrush rangelands, these fuel breaks can be costly to create and maintain (BLM, 2020; Shinneman et al., 2019). Grazing by livestock may be a cost-effective tool to create and maintain fine fuel breaks but presents logistical challenges, especially in regard to concentrating grazing in the fuel break. Traditional fencing can be used to focus grazing within the boundaries of fuel breaks but is expensive and may not be an option on public lands (Boyd et al., 2023; Clark et al., 2023). Supplementation placement when forage is not meeting livestock nutritional needs (Stephenson et al., 2023) and virtual fencing (Boyd et al., 2023) show promise for effectively focusing grazing within fuel breaks. In a 3-km long fuel break using virtual fence to control cattle distribution, utilization was 49% and 6% inside and outside of the fuel break, respectively (Boyd et al., 2023). Grazed fuel breaks in annual grass-dominated sagebrush rangelands substantially decreased wildfire flame lengths and rate of spread, thereby greatly improving suppression, preventing much

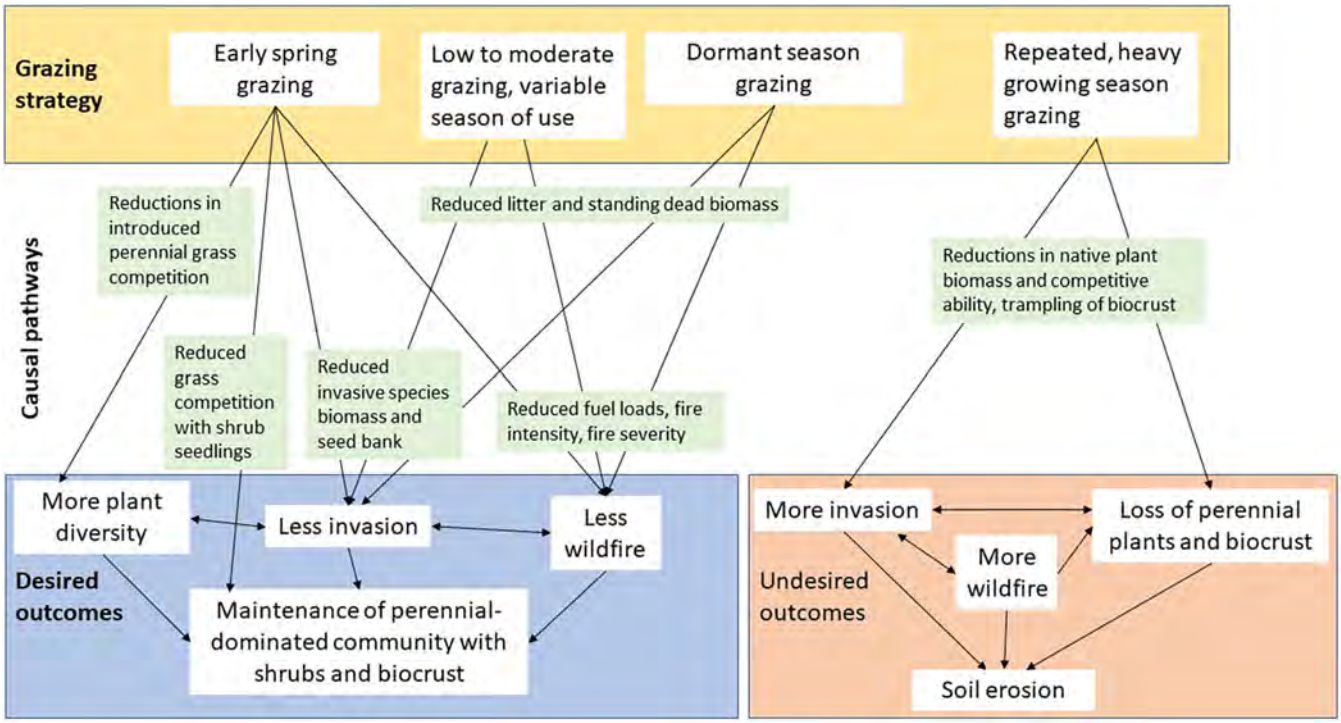

FIGURE 1 Conceptual diagram of the potential effects of different grazing strategies on plant communities in the sagebrush ecosystem. Grazing needs to be applied with careful attention to the duration, frequency, and intensity of use needed to meet desired outcomes.

larger fires, and protecting adjacent sage-grouse habitat from burning (Clark et al., 2023).

Fire probability

The aforementioned alterations to fuel characteristics through strategic grazing can subsequently reduce fire probability. Grazing prior to the wildfire season substantially reduced the likelihood of fire propagation (Davies et al., 2017; Diamond et al., 2009; Orr et al., 2023), though results vary by weather (Davies et al., 2017; Strand et al., 2014). Ignition of fuels is decreased with grazing as well as the spread of fire from the initial ignited fuel to other fuels (Davies et al., 2017; Orr et al., 2023). Without ignition and spread, wildfire cannot propagate. Grazing sagebrush-bunchgrass communities in the fall or spring prior to the summer wildfire season reduced the probability of fire propagation; however, spring grazing reduced it to a greater extent, especially during the hottest, driest part of the wildfire season (Davies et al., 2017). As grazing intensity increased the probability of fire decreased (Orr et al., 2023); however, substantial reduction of fire probability was achieved with moderate levels of grazing (Davies et al., 2017; Orr et al., 2023). Strategic grazing, especially if combined with the management of anthropogenic ignition sources, is likely a valuable tool to reduce the risk of fire propagation in sagebrush communities prone to annual grass invasion.

Fire behavior

Grazing, by altering fuel characteristics, can also modify fire characteristics. Moderately grazed compared with ungrazed sagebrush steppe had shorter flame lengths, slower rates of spread, and smaller burning fronts (Davies, Boyd, et al., 2016). Similarly, strategic grazing in annual grass-dominated rangelands reduced flame length and rate of spread (Diamond et al., 2009). These grazing-induced modifications to fire characteristics would result in safer and more effective fire suppression (Davies, Boyd, et al., 2016; Diamond et al., 2009). Another benefit of modified fire characteristics with grazing is a decrease in the area burned and a mosaic of burned and unburned patches (Davies, Boyd, et al., 2016; Orr et al., 2023; Strand et al., 2014). Unburned patches within a fire perimeter are important because they serve as a refuge for fire sensitive species and reduce the negative impacts of fire on wildlife (Henriques et al., 2000; Robinson et al., 2013; Watson et al., 2012). Grazing modifications to fire characteristics appear especially valuable for wildland firefighter safety, fire suppression efficiency, and fire sensitive species conservation.

FIGURE 2 Fuel break created with strategically applied grazing in an invasive annual grass-dominated sagebrush steppe in southeastern Oregon. Photo credit: Kirk Davies.

Fire severity

Grazing can also have ecological benefits in the event that sagebrush rangelands burn. Reduction of fine fuel and modification of fuel structure with grazing can decrease the severity of wildfires. Maximum fire temperature and heat loading (time with temperatures above 60°C) during a fire were reduced because moderate grazing decreases the total amount of highly flammable fine fuel (Davies, Boyd, et al., 2016). This reduction in fine fuel also decreases the engagement and combustion of shrubs during a fire, which decreases heat energy released during combustion, further limiting fire temperatures and heat loading (Davies, Boyd, et al., 2016). Moderate grazing in sagebrush communities decreases fuel loads near the meristematic tissue of native bunchgrasses and the incidences of dead centers in bunchgrasses (Davies et al., 2018) and, subsequently, reduces fire-induced mortality and damage to native bunchgrasses if these areas burn (Davies et al., 2009; Davies, Bates, et al., 2016; Davies, Bates, Boyd, et al., 2021). Reducing fire severity and the need for restoration, particularly when the loss of native perennial plants makes the plant community more vulnerable to annual grass invasion (Chambers et al., 2007; Davies et al., 2009; Davies, Bates, et al., 2016), can be an important ecological benefit of strategically applied grazing.

GRAZING TO INFLUENCE PLANT COMMUNITY COMPOSITION

Grazing to limit invasive annual grasses in the absence of fire

The largest threat to the integrity of the sagebrush ecosystem is invasive annual grasses (Davies et al., 2011; Davies, Leger, et al., 2021), with almost 200,000 ha of the Great Basin transitioning from perennial plant communities to invasive annual grasslands annually (Smith et al., 2022). Invasive annual grasses are highly competitive and often grow earlier and more rapidly than many native perennial species, thereby preempting resources and subsequently excluding native species (Figure 3; Humphrey & Schupp, 2004; Melgoza et al., 1990). Annual grasses can also negatively affect native perennial vegetation by increasing the amount and continuity of highly flammable fine fuels (Davies & Nafus, 2013; Knapp, 1995) and ultimately promoting more frequent fires (Brooks et al., 2004; D'Antonio & Vitousek, 1992). More frequent fire regimes exclude sagebrush and negatively affect most native perennial plants, favoring invasive annual grasses and often leading to the development of a positive biofeedback between annual grasses and fire (D'Antonio & Vitousek, 1992; Eiswerth et al., 2009; Ellsworth et al., 2020; Mahood & Balch, 2019).

The widespread nature of invasive annual grasses and minimal success in restoring annual grass-invaded communities limits the effectiveness of traditional "control and seed" restoration strategies (Davies, Leger, et al., 2021). The scope of the annual grass problem necessitates the use of treatments that can be applied at large spatial scales, which greatly limits treatment options. Livestock grazing is a treatment conducive for application at large spatial scales but would need to be applied strategically to limit invasive annual grasses, while avoiding unintended consequences. This is especially important

FIGURE 3 Invasive annual grass-dominated sagebrush steppe in northern Nevada. Native perennial species have largely been eliminated because of competition from annual grasses and increased fire frequency. Photo credit: Kirk Davies.

because heavy, repeated growing season grazing has substantially contributed to the annual grass problem (Laycock, 1967; Mack, 1981; Stewart & Hull, 1949). Clearly articulating how and by what mechanism livestock grazing may be able to limit invasive annual grasses would be crucial to its successful application.

Off-season (fall or fall–winter) grazing shows promise as a strategy for reducing invasive annual grasses and potentially increasing perennial vegetation in annual grass-invaded communities with residual perennial vegetation (Figure 1). In Nevada, fall grazing by cattle removed significant amounts of annual grass standing crop, thereby reducing its seedbank and productivity and increasing perennial plant standing crop, largely comprised of the introduced bunchgrass crested wheatgrass (*Agropyron cristatum*) (Perryman et al., 2020; Schmelzer et al., 2014). Similarly, moderate fall–winter grazing by cattle in sagebrush-bunchgrass dominated steppe (Davies et al., 2022) and after wildfire in annual grass-invaded sagebrush steppe (Davies, Bates, Perryman, et al., 2021) reduced invasive annuals and increased the native perennial bunchgrass, Sandberg bluegrass (*P. secunda*). Fall–winter grazing likely decreased invasive annual grasses by defoliating its early growth and reducing ground cover that favors annual grass emergence and early growth (Davies, Bates, Perryman, et al., 2021). Invasive annual grass abundance is often greater with ground cover from litter and herbaceous plants because it creates a microenvironment that is favorable for annual grass emergence and growth (Adair et al., 2008; Evans & Young, 1970; Facelli & Pickett, 1991; Newingham et al., 2007; Wolkovich et al., 2009). In contrast, litter on the soil surface can be a barrier to native bunchgrass establishment (Evans & Young, 1970). These studies suggest that off-season grazing may decrease the competitive advantage of invasive annual grasses over perennial grasses. However, off-season grazing can be difficult to apply successfully (e.g., Price et al., 2023).

Spring season grazing (Figure 4) may at times also limit invasive annual grasses and possibly open up safe

FIGURE 4 Cow grazing a sagebrush community with low levels of invasive annual grass invasion during the growing season in eastern Oregon. Photo credit: Kirk Davies.

sites for native plants. A single application of short duration early spring grazing reduced annual grass biomass and appeared to increase seeded species densities in certain seeding treatments compared with ungrazed treatments in northern Arizona (Porensky et al., 2021). Repeated spring grazing in an invasive annual grass-native bunchgrass co-dominated plant community reduced annual grass abundance and increased Sandberg bluegrass abundance (Davies et al., 2020). However, the authors cautioned against repeatedly applying spring grazing as it might negatively affect other native bunchgrasses. A decade of spring grazing of invasive annual grass-dominated communities also increased Sandberg bluegrass abundance (Thomas et al., 2022). Spring grazing reduces invasive annual grass seed production (Diamond et al., 2012), which might contribute to reducing annual grass abundance.

Other studies have found more generally that light to moderate grazing, regardless of season, may be able to reduce invasive annual grasses and favor some native species (Figure 1). In a sagebrush-grassland ecotone in northeast Wyoming, for example, long-term (>49 years) grazing exclosures had nearly three times more invasive annual grass cover and fewer native plant species than adjacent grazed areas, suggesting that light to moderate levels of livestock grazing may be necessary to maintain resistance to invasion in some sagebrush communities (Porensky et al., 2020). More litter cover and low biocrust cover in exclosures likely favored invasive annual grasses (Porensky et al., 2020). As mentioned before, litter favors annual grass establishment and growth (Evans & Young, 1970; Facelli & Pickett, 1991; Newingham et al., 2007; Wolkovich et al., 2009), while biocrusts can be a barrier to annual grass establishment (Root et al., 2020; Slate et al., 2019). Similarly, both heavy grazing and no grazing led to more abundant invasive annual grasses and more non-native plant species than moderate grazing in northern Arizona (Loeser et al., 2007). These results suggest that spring grazing of invasive annual grasses could favor native species as long as native species are not negatively impacted by the grazing treatment. Notably, this may require intensively managed grazing as many native plant species are the most sensitive to grazing when they are actively growing.

Grazing to reduce the effect of wildfire on community composition

There is growing evidence that prefire grazing can decrease postfire annual grass invasion. Long-term (+70 years) moderate growing season grazing with periodic rest from grazing compared with grazing exclusion prefire resulted in substantially less invasive annual grasses and about double the abundance of native bunchgrasses after fire (Davies et al., 2009; Davies, Bates, et al., 2016). Similarly, when compared with short-term (5 years) grazing exclusion, moderate off-season grazing before fire also reduced postfire invasive annual grass biomass and density and maintained plant community diversity (Davies, Bates, Boyd, et al., 2021). In northern Nevada, targeted applications of spring grazing for two years prefire also led to reductions in invasive annual grass biomass and densities measured two years postfire (Gornish et al., 2023). As mentioned in prior sections, the accumulation of dry fuels near the meristematic tissue in ungrazed communities likely increases the probability of fire-induced mortality of bunchgrasses (Davies et al., 2009, 2018). Prefire grazing can reduce the accumulation of these fine fuels, especially on the crowns of perennial bunchgrasses, leading to less severe fires, which in turn favors perennial bunchgrasses and limits invasive annuals (Davies et al., 2018; Davies, Bates, et al., 2016). This interaction between grazing and fire, both common in the sagebrush ecosystem, probably plays a critical role in plant community dynamics, particularly postfire invasion. Moderate grazing appears to be vital as it reduces fuel accumulations but does not negatively impact native perennial vegetation (Copeland et al., 2021; Davies et al., 2009, 2018).

Pre-fire, moderate grazing also reduced the negative impact of fire on soil biocrusts by reducing fire severity (Davies, Bates, et al., 2016; Davies, Boyd, et al., 2016). Biocrust cover was 2.3-fold greater postfire in areas that were moderately grazed compared with not grazed before fire (Davies, Bates, et al., 2016). Biocrusts are an important ecosystem component that captures soil resources, reduces erosion, and increases resistance to invasive annual grasses (Belnap et al., 2001; Harper & Belnap, 2001; Ponzetti et al., 2007; Root et al., 2020). In the absence of fire, activity associated with cattle grazing generally has a negative impact on biocrusts (Ponzetti & McCune, 2001; Root et al., 2020; Yeo, 2005). However, grazing may have an undervalued positive effect on biocrust because most sagebrush steppe plant communities will inevitably burn (Davies et al., 2012). The probability of these communities burning is also increasing as fire activity and the incidents of mega-fires in the sagebrush steppe have increased over the last several decades (Crist, 2023; Crist et al., 2023). Moderate grazing may also be benefiting biocrust by reducing the probability of wildfire (Davies et al., 2010, 2015, 2017; Orr et al., 2023) because fire is one of the most detrimental disturbances to biocrust (Brianne et al., 2020; Hilty et al., 2004; Root et al., 2017). Hence, moderate grazing can mediate the negative impacts of fire on biocrust by reducing fire severity and probability.

Shrub recovery

Shrub recovery after disturbances such as fire is critical to maintaining ecosystem goods and services provided by sagebrush communities. Strategic grazing can be used to promote recovery of shrubs (Figure 1). Although perennial herbaceous plants can resist invasion by annual grasses, they can also reduce shrub establishment (Porensky et al., 2014; Rinella et al., 2015). Grazing by cattle likely gives generally unpalatable shrubs, such as sagebrush, a competitive advantage over herbaceous vegetation. The removal of photosynthetic tissue places grazed plants at a competitive disadvantage with ungrazed plants (Briske & Richards, 1995; Caldwell et al., 1987; Wan et al., 2015). Moderate spring grazing of areas with sagebrush seedling transplants almost doubled sagebrush growth and reproductive efforts compared with ungrazed areas (Davies et al., 2020). Though not an ideal management strategy because of negative impacts to native herbaceous vegetation, heavy grazing in the spring increased sagebrush (Laycock, 1967). Grazing by cattle also promoted sagebrush recovery in grasslands comprised of highly competitive, introduced bunchgrasses (Angell, 1997; Nafus et al., 2016). Similarly, moderate grazing in the spring promoted the growth of young bitterbrush (*Purshia tridentata*), a wildlife-important native shrub, after fire in sagebrush rangelands compared with ungrazed and heavily grazed areas (Ganskop et al., 2004). Applied strategically across spatial and temporal scales, grazing appears to be a potential tool to alter competitive relationships between herbaceous vegetation and shrubs to promote recovery of shrubs.

Grazing to diversify introduced grasslands

Grazing can modify competitive relationships in introduced bunchgrass grasslands in the sagebrush ecosystem to achieve desired outcomes. Introduced bunchgrasses (crested wheatgrass and desert wheatgrass, *Agropyron desertorum*) are often seeded after disturbances to suppress invasive annual grasses, reduce erosion, and increase livestock forage (Arredondo et al., 1998; Dormaar et al., 1995; Dormaar & Smoliak, 1985). The competitiveness of these introduced bunchgrasses can result in near-monocultures and greatly reduce native species (Christian & Wilson, 1999; Heidinga & Wilson, 2002; Looman & Heinrichs, 1973). Reducing the competitiveness of introduced bunchgrasses by grazing them may open sites up for other species (Busso & Richards, 1995). In support of this, moderate grazing compared with grazing exclusion, increased the abundance of native perennial grasses, perennial forbs, sagebrush, and other native shrubs in introduced grasslands in the northern Great Basin (Nafus et al., 2016). Similarly, high stocking rates increased sagebrush seedling abundance in an introduced grassland in Oregon (Angell, 1997). Grazing to decrease the competitiveness of introduced bunchgrasses and encourage native species may be particularly valuable as other methods to increase native species in these grasslands have been largely unsuccessful (e.g., Fansler & Mangold, 2011; Hulet et al., 2010; McAdoo et al., 2017).

RESEARCH NEEDS

Understanding how prefire grazing modifies fire behavior across different fuel communities and variable fire weather is needed to improve fire management plans. Further research is also needed to better understand the effects of different types, intensities, and timings of growing and dormant season grazing on invasive annual grasses and native plants across plant community composition and environmental gradients and variable weather. Investigating integrating grazing with restoration efforts may prove quite fruitful. In particular, evaluating different grazing strategies to promote sagebrush recovery after fire may be valuable for restoring habitat for sagebrush-associated wildlife. Refinement of the timing, frequency, and intensity of grazing to promote different native species and functional groups in introduced grasslands would be invaluable. Investigating the effects of interactions between grazing and other treatments on native species recruitment in introduced grasslands is also needed. Research into effective and cost-efficient control of livestock distribution would also be valuable as it is essential to achieving desired outcomes.

CONCLUSIONS

Strategically applied grazing can modify fuels and plant community composition to achieve desired social-ecological outcomes such as reduced invasion, decreased fire probability and spread, reduced fire suppression cost, and prevention of ecological transformation postfire (Figure 1). This does not discount that heavy, repeated growing season grazing can have severe negative ecological consequences in sagebrush systems (Daubenmire, 1970; Griffiths, 1902; Mack, 1981; Stewart & Hull, 1949). However, strategic grazing, applied with careful attention to the timing, duration, frequency, and intensity of use needed to meet vegetation objectives, has the potential to limit the detrimental impacts of invasive annual grasses, promote native species in introduced grasslands, and encourage shrub recovery. Off-season grazing

may be particularly beneficial for managing invasive annual grasses and favoring perennial species, considering few other treatments can be effectively applied to the vast landscapes that have invasive annual grasses or are at risk of transitioning to invasive annual grasslands. Grazing can also be a valuable tool for fine fuel and fire management in the sagebrush ecosystem. Modification of fuel amounts, continuity, structure, and moisture content with grazing can decrease fire probability and severity. Fuel and fire management objectives will need to keep plant community constraints in mind to ensure negative ecological consequences do not develop. Creation and maintenance of fuel breaks with grazing can increase fire suppression effectiveness and firefighter safety. This can lead to a decrease in area burned and the protection of important ecological goods and services in sagebrush communities prone to annual grass invasion.

This synthesis highlights that there is a strong empirical foundation for characterizing benefits of strategic grazing in service of a wide variety of desired management outcomes. The ability of managers to actualize this knowledge for management benefit has increased dramatically in recent years with the advent of (1) geospatial technologies (e.g., the Rangeland Analysis Platform; RAP, 2023) that allow managers to characterize the spatial distribution of vegetation, environmental characteristics, and management challenges at very large spatial scales; and (2) precision agricultural technologies (e.g., virtual fencing; Boyd et al., 2022) that empower managers to influence grazing distribution in accordance with the geography and nature of those management challenges. With the near ubiquitous coverage of grazing within the sagebrush biome, this synthesis suggests the potential for substantial benefits from strategic grazing are high, but currently realized benefits are likely much less.

The positive effects of grazing in sagebrush ecosystems are often overlooked, possibly because heavy, repeated growing season grazing can clearly have severe negative impacts. Recognizing livestock grazing as a tool that can achieve desired outcomes instead of as an unnatural disturbance that needs to be limited could improve our ability to achieve meaningful management outcomes in sagebrush and likely other rangeland communities. Whether livestock grazing has positive, neutral, or negative effects on ecosystem goods and services depends on management of livestock use, including the timing, intensity, frequency, and duration of use (Copeland et al., 2023). Thus, outcomes are largely anthropogenically driven and constrained by logistical challenges. Strategically applying grazing to achieve specific outcomes will need to be tailored to fit within the ecological constraints of the plant community. Hence, investigating different timing, frequency, duration, and intensity of grazing to achieve desired outcomes in various plant communities, especially across large landscapes, is needed to further improve management. With the unprecedented threats (e.g., invasive annual grasses, climate change, and increased fire frequency) to sagebrush and other rangeland communities, strategic livestock grazing will be a vital management tool to achieving desired outcomes and limiting adverse disturbances.

ACKNOWLEDGMENTS

Mention of a proprietary product does not constitute a guarantee or warranty of the product by the USDA or the authors and does not imply its approval to the exclusion of other products. USDA is an equal opportunity provider and employer.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

No data were collected.

ORCID

Lauren N. Svejcar https://orcid.org/0000-0003-1121-3696
Lauren M. Porensky https://orcid.org/0000-0001-6883-2442

REFERENCES

Adair, E. C., I. C. Burke, and W. K. Lauenroth. 2008. "Contrasting Effect So of Resource Availability and Plant Mortality on Plant Community Invasion by *Bromus tectorum* L." *Plant and Soil* 304: 103–115.

Adler, P. B., D. G. Milchunas, W. K. Lauenroth, O. E. Sala, and I. C. Burke. 2004. "Functional Traits of Graminoids in Semi-Arid Steppes: A Test of Grazing Histories." *Journal of Applied Ecology* 41: 653–663.

Anderson, J. A., and K. E. Holte. 1980. "Vegetation Development over 25 Years without Grazing on Sagebrush-Dominated Rangeland in Southeastern Idaho." *Journal of Range Management* 34: 25–29.

Angell, R. F. 1997. "Crested Wheatgrass and Shrub Response to Continuous or Rotational Grazing." *Journal of Range Management* 50: 160–64.

Arredondo, J. T., T. A. Jones, and D. A. Johnson. 1998. "Seedling Growth of Intermountain Perennial and Weedy Annual Grasses." *Journal of Range Management* 51: 584–89.

Atwater, A. L., and D. B. Davis. 2011. "Topographic and Climate Change Differentially Drive Pliocene and Pleistocene Mammalian Beta Diversity of the Great Basing and Great Plains Provinces of North America." *Evolutionary Ecology Research* 13: 833–850.

Bailey, D. W., J. C. Mosley, R. E. Estell, A. F. Cibils, M. Horney, J. R. Hendrickson, J. W. Walker, K. L. Launchbaugh, and E. A. Burritt. 2019. "Targeted Livestock Grazing: Prescription

for Healthy Rangelands." *Rangeland Ecology & Management* 72: 865–877.

Báldi, A., P. Batáry, and D. Kleijn. 2013. "Effects of Grazing and Biogeographic Regions on Grassland Biodiversity in Hungary – Analysing Assemblages of 1200 Species." *Agricultura, Ecosystems & Environment* 166: 28–34.

Barnes, M., and J. Howell. 2013. "Multiple-Paddock Grazing Distributes Utilization across Heterogeneous Mountain Landscapes: A Case Study of Strategic Grazing Management." *Rangelands* 35: 52–61.

Belnap, J., R. Prasse, and K. T. Harper. 2001. "Influence of Biological Soil Crusts on Soil Environments and Vascular Plants." *Ecological Studies* 150: 281–300.

Benkobi, L., D. W. Uresk, and R. D. Child. 2007. "Ecological Classification and Monitoring Model for the Wyoming Big Sagebrush Shrubsteppe Habitat Type of Northeastern Wyoming." *Western North American Naturalist* 67: 347–358.

Beschta, R. L., D. L. Donahue, D. A. Dellasala, J. J. Rhodes, J. R. Karr, M. H. O'Brien, T. L. Fleischner, and C. D. Williams. 2012. "Adapting to Climate Change on Western Public Lands: Addressing the Ecological Effects of Domestic, Wild, and Feral Ungulates." *Environmental Management* 51: 1–18.

BLM. 2020. "Final Programmatic EIS for Fuel Breaks in the Great Basin." https://eplanning.blm.gov/eplanning-ui/project/71149/510.

Box, T. 1990. "Rangelands." In *Natural Resources for the 21st Century*, edited by R. Sampson and D. Hair, 101–120. Washington, DC: Island Press.

Boyd, C. S., R. O'Connor, J. Ranches, D. W. Bohnert, J. D. Bates, D. D. Johnson, K. W. Davies, T. Parker, and K. E. Doherty. 2022. "Virtual Fencing Effectively Excludes Cattle from Burned Sagebrush Steppe." *Rangeland Ecology & Management* 81: 55–56.

Boyd, C. S., R. C. O'Connor, J. Ranches, D. W. Bohnert, J. D. Bates, D. D. Johnson, K. W. Davies, T. Parker, and K. E. Doherty. 2023. "Using Virtual Fencing to Create Fuel Breaks in the Sagebrush Steppe." *Rangeland Ecology & Management* 89: 87–93.

Brianne, P., H. Rebecca, and L. David. 2020. "The Fate of Biological Soil Crusts after Fire: A Meta-Analysis." *Global Ecology and Conservation* 24: e01380.

Briske, D. D., and J. H. Richards. 1995. "Plant Responses to Defoliation: A Physiological, Morphological, and Demographic Evaluation." In *Wildland Plants: Physiological Ecology and Developmental Morphology*, edited by D. J. Bedunah and R. E. Sosebee, 635–710. Denver, CO: Society for Range Management.

Brooks, M. L., C. M. D'Antonio, D. M. Richardson, J. B. Grace, J. E. Keeley, J. M. DiTomaso, R. J. Hobbs, M. Pellant, and D. Pyke. 2004. "Effects of Invasive Alien Plants on Fire Regimes." *BioScience* 54: 677–688.

Busso, C. A., and J. H. Richards. 1995. "Drought and Clipping Effects on Tiller Demography and Growth of Two Tussock Grasses in Utah." *Journal of Arid Environments* 29: 239–251.

Caldwell, M. M., J. H. Richards, J. H. Manwaring, and D. M. Eissenstat. 1987. "Rapid Shifts in Phosphate Acquisition Show Direct Competition between Neighboring Plants." *Nature* 327: 615–16.

Chambers, J. C., B. A. Bradley, C. S. Brown, C. D'Antonio, M. J. Germino, J. B. Grace, S. P. Hardegree, R. F. Miller, and D. A. Pyke. 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.

Chambers, J. C., B. A. Roundy, R. R. Blank, S. E. Meyer, and A. Whittaker. 2007. "What Makes Great Basin Sagebrush Ecosystems Invasible by *Bromus tectorum*?" *Ecological Monographs* 77: 117–145.

Christian, J. M., and S. D. Wilson. 1999. "Long-Term Ecosystem Impacts of an Introduced Grass in the Northern Great Plains." *Ecology* 80: 2397–2407.

Clark, P. E., B. A. Porter, M. Pellant, K. Dyer, and T. P. Norton. 2023. "Evaluating the Efficacy of Targeted Cattle Grazing for Fuel Break Creation and Maintenance." *Rangeland Ecology & Management* 89: 69–86.

Copeland, S. M., K. W. Davies, C. S. Boyd, and J. D. Bates. 2021. "Recovery of the Herbaceous Component of Degraded Sagebrush Steppe Is Unimpeded by 75 Years of Moderate Cattle Grazing." *Ecosphere* 12: e03445.

Copeland, S. M., D. L. Hoover, D. J. Augustine, J. D. Bates, C. S. Boyd, K. W. Davies, J. D. Derner, M. C. Duniway, L. M. Porensky, and L. T. Vermeire. 2023. "Variable Effects of Long-Term Grazing across the Western US Suggest Diverse Approaches to Meet Global Change Challenges." *Applied Vegetation Science* 26: e12719.

Crist, M. R. 2023. "Rethinking the Focus on Forest Fires in Federal Wildland Fire Management: Landscape Patterns and Trends of Non-Forest and Forest Burned Area." *Journal of Environmental Management* 327: 116718.

Crist, M. R., R. Belger, K. W. Davies, D. M. Davis, J. R. Meldrum, D. J. Shinneman, T. E. Remington, J. Welty, and K. E. Mayer. 2023. "Trends, Impacts, and Cost of Catastrophic and Frequent Wildfires in the Sagebrush Biome." *Rangeland Ecology & Management* 89: 3–19.

D'Antonio, C. M., and P. M. Vitousek. 1992. "Biological Invasions by Exotic Grasses, the Grass/Fire Cycle, and Global Change." *Annual Review of Ecology and Systematics* 23: 63–87.

Daubenmire, R. 1970. *Steppe Vegetation of Washington*. Volume Technical Bulletin 62. Pullman, WA: Washington Agricultural Experiment Station.

Davies, K. W., J. D. Bates, and C. S. Boyd. 2020. "Response of Planted Sagebrush Seedlings to Cattle Grazing Applied to Reduce Fine Fuels to Decrease Fire Probability." *Rangeland Ecology & Management* 73: 629–635.

Davies, K. W., J. D. Bates, C. S. Boyd, S. M. Copeland, and R. O'Connor. 2021. "Dormant Season Grazing Pre-Fire Maintains Diversity and Reduces Exotic Grass Response Post-Fire in Imperiled *Artemisia* Steppe." *Rangeland Ecology & Management* 79: 91–99.

Davies, K. W., J. D. Bates, C. S. Boyd, and T. J. Svejcar. 2016. "Pre-Fire Grazing by Cattle Increases Post-Fire Resistance to Exotic Annual Grass (*Bromus tectorum*) Invasion and Dominance for Decades." *Ecology and Evolution* 6: 3356–66.

Davies, K. W., J. D. Bates, and A. M. Nafus. 2012. "Mowing Wyoming Big Sagebrush Communities with Degraded Herbaceous Understories: Has a Threshold Been Crossed?" *Rangeland Ecology & Management* 65: 498–505.

Davies, K. W., J. D. Bates, B. Perryman, and S. Arispe. 2021. "Fall-Winter Grazing after Fire in Annual Grass-Invaded Sagebrush Steppe Reduced Annuals and Increased a Native Bunchgrass." *Rangeland Ecology & Management* 77: 1–8.

Davies, K. W., J. D. Bates, T. J. Svejcar, and C. S. Boyd. 2010. "Effects of Long-Term Livestock Grazing on Fuel Characteristics in Rangelands: An Example from the Sagebrush Steppe." *Rangeland Ecology & Management* 63: 662–69.

Davies, K. W., C. S. Boyd, and J. D. Bates. 2018. "Eighty Years of Grazing by Cattle Modifies Sagebrush and Bunchgrass Structure." *Rangeland Ecology & Management* 71: 275–280.

Davies, K. W., C. S. Boyd, J. D. Bates, and A. Hulet. 2015. "Dormant-Season Grazing May Decrease Wildfire Probability by Increasing Fuel Moisture and Reducing Fuel Amount and Continuity." *International Journal of Wildland Fire* 24: 849–856.

Davies, K. W., C. S. Boyd, J. D. Bates, and A. Hulet. 2016. "Winter Grazing Can Reduce Wildfire Size, Intensity, and Behavior in a Shrub-Grassland." *International Journal of Wildland Fire* 25: 191–99.

Davies, K. W., C. S. Boyd, J. L. Beck, J. D. Bates, T. J. Svejcar, and M. A. Gregg. 2011. "Saving the Sagebrush Sea: An Ecosystem Conservation Plan for Big Sagebrush Plant Communities." *Biological Conservation* 144: 2573–84.

Davies, K. W., C. S. Boyd, S. M. Copeland, and J. D. Bates. 2022. "Moderate Grazing during the Off-Season (Fall-Winter) Reduces Exotic Annual Grasses in Sagebrush-Bunchgrass Steppe." *Rangeland Ecology & Management* 82: 51–57.

Davies, K. W., A. Gearhart, C. S. Boyd, and J. D. Bates. 2017. "Fall and Spring Grazing Influence Fire Ignitability and Initial Spread in Shrub Steppe Communities." *International Journal of Wildland Fire* 26: 485–490.

Davies, K. W., E. A. Leger, C. S. Boyd, and L. M. Hallett. 2021. "Living with Exotic Annual Grasses in the Sagebrush Ecosystem." *Journal of Environmental Management* 288: 112417.

Davies, K. W., and A. M. Nafus. 2013. "Exotic Annual Grass Invasion Alters Fuel Amounts, Continuity and Moisture Content." *International Journal of Wildland Fire* 22: 353–58.

Davies, K. W., T. J. Svejcar, and J. D. Bates. 2009. "Interaction of Historical and Nonhistorical Disturbances Maintains Native Plant Communities." *Ecological Applications* 19: 1536–45.

Davies, K. W., M. Vavra, B. Schultz, and N. Rimbey. 2014. "Implications of Longer Term Rest from Grazing in the Sagebrush Steppe." *Journal of Rangeland Applications* 1: 14–34.

Davis, O. K., and B. Ellis. 2010. "Early Occurrence of Sagebrush Steppe, Miocene (12 Ma) on the Snake River Plain." *Review of Palaeobotany and Palynology* 160: 172–180.

Diamond, J. M., C. A. Call, and N. Devoe. 2009. "Effects of Targeted Cattle Grazing on Fire Behavior of Cheatgrass-Dominated Rangeland in the Northern Great Basin, USA." *International Journal of Wildland Fire* 18: 944–950.

Diamond, J. M., C. A. Call, and N. Devoe. 2012. "Effects of Targeted Grazing and Prescribed Burning on Community and Seed Dynamics of Downy Brome (*Bromus tectorum*)-Dominated Landscape." *Invasive Plant Science and Management* 5: 259–269.

Díaz, S., S. Lavorel, S. McIntyre, V. Falczuk, F. Casanoves, D. G. Milchunas, C. Skarpe, et al. 2007. "Plant Trait Responses to Grazing – A Global Synthesis." *Global Change Biology* 13: 313–341.

DiTomaso, J. M., G. B. Kyser, M. R. George, M. P. Doran, and E. A. Laca. 2008. "Control of Medusahead (*Taeniatherum caput-medusae*) Using Timely Sheep Grazing." *Invasive Plant Science and Management* 1: 241–47.

Doherty, K., D. M. Theobald, J. B. Bradford, L. A. Wiechman, G. Bedrosian, C. S. Boyd, M. Cahill, et al. 2022. "A Sagebrush Conservation Design to Proactively Restore America's Sagebrush Biome: U.S. Geological Survey Open-File Report 2022-1081." 38 pp.

Dormaar, J. F., M. A. Naeth, W. D. Willms, and D. S. Chanasyk. 1995. "Effect of Native Prairie, Crested Wheatgrass (*Agropyron cristatum* [L.] Gaertn.) and Russian Wildrye (*Elymus junceus* Fisch.) on Soil Chemical Properties." *Journal of Range Management* 48: 258–263.

Dormaar, J. F., and S. Smoliak. 1985. "Recovery of Vegetative Cover and Soil Organic Matter during Revegetation of Abandoned Farmland in a Semiarid Climate." *Journal of Range Management* 38: 487–491.

Eiswerth, M. E., K. Krauter, S. R. Swanson, and M. Zielinski. 2009. "Post-Fire Seeding on Wyoming Big Sagebrush Ecological Sites: Regression Analyses of Seeded Nonnative and Native Species Densities." *Journal of Environmental Management* 90: 1320–25.

Ellsworth, L. M., J. B. Kauffman, S. A. Reis, D. Sapsis, and K. Moseley. 2020. "Repeated Fire Altered Succession and Increased Fire Behavior in Basin Big Sagebrush–Native Perennial Grasslands." *Ecosphere* 11: e03124.

Evans, R. A., and J. A. Young. 1970. "Plant Litter and Establishment of Alien Annual Weed Species in Rangeland Communities." *Weed Science* 18: 697–703.

Facelli, J. M., and S. T. A. Pickett. 1991. "Plant Litter: Its Dynamics and Effects on Plant Community Structure." *Botanical Review* 57: 1–32.

Fansler, V. A., and J. M. Mangold. 2011. "Restoring Native Plants to Crested Wheatgrass Stands." *Restoration Ecology* 19: 16–23.

Freitag, M., J. Kamp, A. Dara, T. Kuemmerle, T. V. Sidorova, I. A. Stirnemann, F. Velbert, and N. Hölzel. 2021. "Post-Soviet Shifts in Grazing and Fire Regimes Changed the Functional Plant Community Composition on the Eurasian Steppe." *Global Change Biology* 27: 388–401.

Frost, R. A., and K. L. Launchbaugh. 2003. "Prescription Grazing for Rangeland Weed Management." *Rangelands* 25: 43–47.

Fuhlendorf, S. D., W. C. Harrell, D. M. Engle, R. G. Hamilton, C. A. Davis, and D. M. Leslie. 2006. "Should Heterogeneity be the Basis for Conservation? Grassland Bird Response to Fire and Grazing." *Ecological Applications* 16: 1706–16.

Ganskop, D., T. Svejcar, F. Taylor, and J. Farstvedt. 2004. "Can Spring Cattle Grazing among Young Bitterbrush Stimulate Shrub Growth?" *Journal of Range Management* 57: 161–68.

Gornish, E. S., J. S. Guo, L. M. Porensky, B. L. Perryman, and E. A. Leger. 2023. "Pre-Fire Grazing and Herbicide Treatments Can Affect Post-Fire Vegetation in a Great Basin Rangeland." *Ecological Solutions and Evidence* 4: e12215.

Grayson, D. K. 2016. *Giant Sloths and Sabertooth Cats: Extinct Mammals and the Archaeology of the Ice Age Great Basin*. Salt Lake City, UT: University of Utah Press. 421 pp.

Griffiths, D. 1902. *Forage Conditions on the Northern Border of the Great Basin*. Bulletin 15. Washington, DC: Bureau of Plant Industry, USDA.

Harper, K. T., and J. Belnap. 2001. "The Influence of Biological Soil Crusts on Mineral Uptake by Associated Vascular Plants." *Journal of Arid Environments* 47: 347–357.

Heidinga, L., and S. D. Wilson. 2002. "The Impact of an Invading Alien Grass (*Agropyron cristatum*) on Species Turnover in Native Prairie." *Diversity and Distributions* 8: 249–258.

Henriques, R. P. B., M. X. A. Bizerril, and A. R. T. Plama. 2000. "Changes in Small Mammal Populations after Fire in a Patch of Unburned Cerrado in Central Brazil." *Mammalia* 64: 173–185.

Hess, K., and J. L. Holecheck. 1995. "Policy Roots of Land Degradation in the Arid Region of the United States: An Overview." *Environmental Monitoring and Assessment* 37: 123–141.

Hilty, J. H., D. J. Eldridge, R. Rosentreter, M. C. Wicklow-Howard, and M. Pellant. 2004. "Recovery of Biological Soil Crusts Following Wildfire in Idaho." *Journal of Range Management* 57: 89–96.

Hulet, A., C. S. Boyd, K. W. Davies, and T. J. Svejcar. 2015. "Prefire (Preemptive) Management to Decrease and Reduce Reliance on Postfire Seeding." *Rangeland Ecology & Management* 68: 437–444.

Hulet, A., B. A. Roundy, and B. Jessop. 2010. "Crested Wheatgrass Control and Native Plant Establishment in Utah." *Rangeland Ecology & Management* 63: 450–460.

Humphrey, L. D., and E. W. Schupp. 2004. "Competition as a Barrier to Establishment of a Native Perennial Grass (*Elmus elymoides*) in Alien Annual Grass (*Bromus tectorum*) Communities." *Journal of Arid Environments* 58: 405–422.

Kauffman, J. B., R. L. Beschta, P. M. Lacy, and M. Liverman. 2022. "Livestock Use on Public Lands in the Western USA Exacerbates Climate Change: Implications for Climate Change Mitigation and Adaptation." *Environmental Management* 69: 1137–52.

Knapp, P. A. 1995. "Intermountain West Lightning-Caused Fires: Climatic Predictors of Area Burned." *Journal of Range Management* 48: 85–91.

Kotanen, P. M., and J. Bergelson. 2000. "Effects of Simulated Grazing on Different Genotypes of *Bouteloua gracilis*: How Important Is Morphology?" *Oecologia* 123: 66–74.

Laycock, W. A. 1967. "How Heavy Grazing and Protection Affect Sagebrush-Grass Ranges." *Journal of Range Management* 20: 206–213.

Loeser, M. R. R., T. D. Sisk, and T. E. Crews. 2007. "Impact of Grazing Intensity during Drought in an Arizona Grassland." *Conservation Biology* 21: 87–97.

Looman, J., and D. H. Heinrichs. 1973. "Stability of Crested Wheatgrass Pastures under Long-Term Pasture Use." *Canadian Journal of Plant Science* 53: 501–6.

Lym, R. G., K. K. Sedivec, and D. R. Kirby. 1997. "Leafy Spurge Control with Angora Goats and Herbicides." *Journal of Range Management* 50: 123–28.

Mack, R. N. 1981. "Invasion of *Bromus tectorum* L. into Western North America: An Ecological Chronicle." *Agro-Ecosystems* 7: 145–165.

Mack, R. N., and J. N. Thompson. 1982. "Evolution in Steppe with Few Large, Hooved Mammals." *American Naturalist* 119: 757–773.

Mahood, A. L., and J. K. Balch. 2019. "Repeated Fires Reduce Plant Diversity in Low-Elevation Wyoming Big Sagebrush Ecosystems (1984–2014)." *Ecosphere* 10: e2591.

Marty, J. T. 2005. "Effects of Cattle Grazing on Diversity in Ephemeral Wetlands." *Conservation Biology* 19: 1626–32.

McAdoo, J. K., J. C. Swanson, P. J. Murphy, and N. L. Shaw. 2017. "Evaluating Strategies for Facilitating Native Plant Establishment in Northern Nevada Crested Wheatgrass Seedings." *Restoration Ecology* 25: 53–62.

McLean, A., and E. W. Tisdale. 1972. "Recovery Rate of Depleted Range Sites under Protection from Grazing." *Journal of Range Management* 25: 178–184.

Melgoza, G., R. S. Nowak, and R. J. Tausch. 1990. "Soil-Water Exploitation after Fire – Competition between *Bromus tectorum* (Cheatgrass) and 2 Native Species." *Oecologia* 83: 7–13.

Meyer, S. E. 2011. "Is Climate Change Mitigation the Best Use of Desert Shrublands?" *Natural Resources and Environmental Issues* 17: 13–22.

Mu, J., U. Zeng, Q. Wu, K. J. Niklas, and K. Niu. 2016. "Traditional Grazing Regimes Promote Biodiversity and Increase Nectar Production in Tibetan Alpine Meadows." *Agriculture, Ecosystems & Environment* 233: 336–342.

Nafus, A. M., T. J. Svejcar, and K. W. Davies. 2016. "Disturbance History, Management, and Seeding Year Precipitation Influences Vegetation Characteristics of Crested Wheatgrass Stands." *Rangeland Ecology & Management* 69: 248–256.

Newingham, B. A., P. Vidiella, and J. Belnap. 2007. "Do Soil Characteristics or Microhabitat Determine Field Emergence and Success of *Bromus tectorum*?" *Journal of Arid Environments* 70: 389–402.

NIFC. 2023. "Fire Information Statistics." https://www.nifc.gov/fire-information/statistics.

Oliphant, J. O. 1968. *On the Cattle Ranges of the Oregon Country*. Seattle, WA: University of Washington Press. 262 pp.

Öllerer, K., A. Varga, K. Kirby, L. Demeter, M. Biró, and J. Bölöni. 2019. "Beyond the Obvious Impact of Domestic Livestock Grazing on Temperate Forest Vegetation – A Global Review." *Biological Conservation* 237: 209–219.

Orr, D. A., J. D. Bates, and K. W. Davies. 2023. "Grazing Intensity Effects on Fire Ignition Risk and Spread in Sagebrush Steppe." *Rangeland Ecology & Management* 89: 51–60.

Papanikolaou, A. D., N. M. Fyllas, A. D. Mazaris, P. G. Dimitrakopoulos, A. S. Kallimanis, and J. D. Pantis. 2011. "Grazing Effects on Plant Functional Group Diversity in Mediterranean Shrublands." *Biodiversity and Conservation* 20: 2831–43.

Perryman, B. L., B. W. Schultz, M. Burrows, T. Shenkoru, and J. Wilker. 2020. "Fall-Grazing and Grazing-Exclusion Effects on Cheatgrass (*Bromus tectorum*) Seed Bank Assays in Nevada, United States." *Rangeland Ecology & Management* 73: 343–47.

Ponzetti, J. M., and B. McCune. 2001. "Biotic Soil Crusts of Oregon's Shrub Steppe: Community Composition in Relation

to Soil Chemistry, Climate, and Livestock Activity." *Bryologist* 104: 212–225.

Ponzetti, J. M., B. McCune, and D. Pyke. 2007. "Biotic Soil Crusts in Relation to Topography, Cheatgrass and Fire in the Columbia Basin, Washington." *Bryologist* 110: 706–722.

Porensky, L. M., O. Baughman, M. A. Williamson, B. L. Perryman, M. D. Madsen, and E. A. Leger. 2021. "Using Native Grass Seeding and Targeted Spring Grazing to Reduce Low-Level *Bromus tectorum* Invasion on the Colorado Plateau." *Biological Invasions* 23: 705–722.

Porensky, L. M., E. A. Leger, J. Davison, W. W. Miller, E. M. Goergen, E. K. Espeland, and E. M. Carroll-Moore. 2014. "Arid Old-Field Restoration: Native Perennial Grasses Suppress Weeds and Erosion, but Also Suppress Native Shrubs." *Agriculture, Ecosystems and Environment* 184: 135–144.

Porensky, L. M., R. McGee, and D. W. Pellatz. 2020. "Long-Term Grazing Removal Increased Invasion and Reduced Native Plant Abundance and Diversity in a Sagebrush Grassland." *Global Ecology and Conservation* 24: e01267.

Porensky, L. M., B. L. Perryman, M. A. Williamson, M. D. Madsen, and E. A. Leger. 2018. "Combining Targeted Grazing and Restoration Treatments to Reduce Invasive Species and Establish Native Plants in Invaded Ecosystems." *Ecology and Evolution* 8: 12533–46.

Porensky, L. M., S. E. Wittman, C. Riginos, and T. P. Young. 2013. "Herbivory and Drought Interact to Enhance Diversity and Spatial Patterning in a Savanna Understory." *Oecologia* 173: 591–602.

Price, W. J., A. Hulet, K. S. Jensen, E. K. Strand, C. S. Boyd, K. W. Davies, D. D. Johnson, B. L. Perryman, Y. Di, and S. A. Arispe. 2023. "Managing Medusahead Using Dormant Season Grazing in the Northern Great Basin." *Rangeland Ecology & Management* 90: 146–156.

RAP. 2023. "Rangeland Analysis Platform." https://rangelands.app/products/.

Reisner, M. D., J. B. Grace, D. A. Pyke, and P. S. Doescher. 2013. "Conditions Favouring *Bromus tectorum* Dominance of Endangered Sagebrush Steppe Ecosystems." *Journal of Applied Ecology* 50: 1039–49.

Rice, B., and M. Westoby. 1978. "Vegetation Responses of Some Great Basin Shrub Communities Protected against Jack Rabbits or Domestic Stock." *Journal of Range Management* 31: 28–34.

Rinella, M. J., D. H. Hammond, A. M. Bryant, and B. J. Kozar. 2015. "High Precipitation and Seeded Species Competition Reduce Seeded Shrub Establishment during Dryland Restoration." *Ecological Applications* 25: 1044–53.

Rinella, M. J., and B. J. Hileman. 2009. "Efficacy of Prescribed Grazing Depends on Timing Intensity and Frequency." *Journal of Applied Ecology* 46: 796–803.

Robinson, N. M., S. W. J. Leonard, E. G. Ritchie, M. Bassett, E. K. Chia, S. Buckingham, H. Gibb, A. F. Bennett, and M. F. Clarke. 2013. "Refuges for Fauna in Fire-Prone Landscapes: Their Ecological Function and Importance." *Journal of Applied Ecology* 50: 1321–29.

Root, H. T., J. C. Brinda, and E. K. Dodson. 2017. "Recovery of Biological Soil Crust Richness and Cover 12-16 Years after Wildfires in Idaho, USA." *Biogeosciences* 14: 3957–69.

Root, H. T., J. E. Miller, and R. Rosentreter. 2020. "Grazing Disturbance Promotes Exotic Annual Grasses by Degrading Soil Biocrust Communities." *Ecological Applications* 30: e02016.

Schmelzer, L., B. Perryman, B. Bruce, B. Schultz, K. McAdoo, G. McCuin, S. Swanson, J. Wilker, and K. Conley. 2014. "Case Study: Reducing Cheatgrass (*Bromus tectorum* L.) Fuel Loads Using Fall Cattle Grazing." *Professional Animal Scientist* 30: 270–78.

Shinneman, D. J., M. J. Germino, D. S. Pilliod, C. L. Aldridge, N. M. Vaillant, and P. S. Coates. 2019. "The Ecological Uncertainty of Wildfire Fuel Breaks: Examples from the Sagebrush Steppe." *Frontiers in Ecology and the Environment* 17: 279–288.

Siegel, K. J., L. Macaulay, M. Shapero, T. Becchetti, S. Larson, F. E. Mashiri, L. Waks, L. Larsen, and V. Butsic. 2022. "Impacts of Livestock Grazing on the Probability of Burning in Wildfires Vary by Region and Vegetation Type in California." *Journal of Environmental Management* 322: 116092.

Slate, M. L., R. M. Callaway, and D. E. Pearson. 2019. "Life in Interstitial Space: Biocrusts Inhibit Exotic but Not Native Plant Establishment in Semi-Arid Grasslands." *Journal of Ecology* 107: 1317–27.

Smith, J. T., B. W. Allred, C. S. Boyd, K. W. Davies, M. O. Jones, J. D. Maestas, S. L. Morford, and D. E. Naugle. 2022. "The Elevation Ascent and Spread of Exotic Annual Grasslands in the Great Basin, USA." *Diversity and Distributions* 28: 83–96.

Stephenson, M. B., B. L. Perryman, C. S. Boyd, B. W. Schultz, T. Svejcar, and K. W. Davies. 2023. "Strategic Supplementation to Manage Fine Fuels in Cheatgrass (*Bromus tectorum*) Invaded System." *Rangeland Ecology & Management* 89: 61–68.

Stewart, G., and A. C. Hull. 1949. "Cheatgrass (*Bromus tectorum* L.) – An Ecologic Intruder in Southern Idaho." *Ecology* 30: 58–74.

Strand, E. K., K. L. Lauchbaugh, R. Limb, and L. A. Torell. 2014. "Livestock Grazing Effects on Fuel Loads for Wildland Fire in Sagebrush Dominated Ecosystems." *Journal of Rangeland Applications* 1: 35–57.

Thomas, T., K. W. Davies, R. Mata-Gonzalez, L. N. Svejcar, and D. Clenet. 2022. "Effects of a Decade of Grazing Exclusion on Three Wyoming Big Sagebrush Community Types." *Global Ecology & Conservation* 40: e02338.

Thomas, T. W., and K. W. Davies. 2023. "Grazing Effects on Fuels Vary by Community State in Wyoming Big Sagebrush Steppe." *Rangeland Ecology & Management* 89: 42–50.

USFWS. 2013. *Sage-Grouse (Centrocercus urophasianus) Conservation Objectives: Final Report*. Denver, CO: U.S. Fish and Wildlife Service. 108 pp.

Vavra, M. 2005. "Livestock Grazing and Wildlife: Developing Compatibilities." *Rangeland Ecology & Management* 58: 128–134.

Veblen, K. E., K. C. Nehring, C. M. McGlone, and M. E. Richie. 2015. "Contrasting Effects of Different Mammalian Herbivores on Sagebrush Plant Communities." *PLoS One* 10: e0118016.

Wan, H., Y. Bai, D. U. Hooper, P. Schönbach, M. Gierus, A. Schiborra, and F. Taube. 2015. "Selective Grazing and Seasonal Precipitation Play Key Roles in Shaping Plant Community Structure in Semi-Arid Grasslands." *Landscape Ecology* 30: 1767–82.

Watson, S. J., R. S. Taylor, D. G. Nimmo, L. T. Kelly, M. F. Clarke, and A. F. Bennett. 2012. "The Influence of Unburnt Patches

and Distance to Refuges on Postfire Bird Communities." *Animal Conservation* 15: 499–507.

Westcott, P., and R. Trostle. 2012. *Long-Term Prospects for Agriculture Reflect Growing Demand for Food, Fiber, and Fuel*. Washington, DC: USDA – Economical Research Service. https://www.ers.usda.gov/amber-waves/2012/september/long-term-prospects-for-agriculture.

Williamson, M. A., E. Fleishman, R. C. MacNally, J. C. Chambers, B. A. Bradley, D. S. Dobkin, D. I. Board, et al. 2020. "Fire, Livestock Grazing, Topography, and Precipitation Affect Occurrence and Prevalence of Cheatgrass (*Bromus tectorum*) in the Central Great Basin, USA." *Biological Invasions* 22: 663–680.

Wolkovich, E. M., D. T. Bolger, and K. L. Cottingham. 2009. "Invasive Grass Litter Facilitates Native Shrubs through Abiotic Effects." *Journal of Vegetation Science* 20: 1121–32.

Yeo, J. J. 2005. "Effects of Grazing Exclusion on Rangeland Vegetation and Soils, East Central Idaho." *Western North American Naturalist* 65: 91–102.

Young, J. A., and B. A. Sparks. 1985. *Cattle in the Cold Desert*. Logan, UT: Utah State University Press. 333 pp.

How to cite this article: Davies, Kirk W., Chad S. Boyd, Jon D. Bates, Lauren N. Svejcar, and Lauren M. Porensky. 2024. "Ecological Benefits of Strategically Applied Livestock Grazing in Sagebrush Communities." *Ecosphere* 15(5): e4859. https://doi.org/10.1002/ecs2.4859