JOURNAL OF RANGELAND APPLICATIONS

Volume 1, 2014
pp. 35-57
ISSN: 2331-5512

Livestock Grazing Effects on Fuel Loads for Wildland Fire in Sagebrush Dominated Ecosystems

Eva K. Strand[1], Karen L. Launchbaugh[2], Ryan Limb[3], L. Allen Torell[4]

Keywords: annual grasses, wildlife fire, prescribed grazing, sagebrush, fuel treatments
AGROVOC Terms: fire ecology, herbivory, invasive species, grazing, grazing management, sagebrush

Abstract

Herbivory and fire are natural interacting forces contributing to the maintenance of rangeland ecosystems. Wildfires in the sagebrush dominated ecosystems of the Great Basin are becoming larger and more frequent, and may dramatically alter plant communities and habitat. This synthesis describes what is currently known about the cumulative impacts of historic livestock grazing patterns and short-term effects of livestock grazing on fuels and fire in sagebrush ecosystems. Over years and decades grazing can alter fuel characteristics of ecosystems. On a yearly basis, grazing can reduce the amount and alter the continuity of fine fuels, potentially changing wildlife fire spread and intensity. However, how grazing-induced fuel alterations affect wildland fire depends on weather conditions and plant community characteristics. As weather conditions become extreme, the influence of grazing on fire behavior is limited, especially in communities dominated by woody plants.

[1] *Eva Strand (evas@uidaho.edu) - Assistant Professor of Landscape Disturbance Ecology, Department of Forest, Rangeland, and Fire Sciences, University of Idaho, 875 Perimeter Drive- MS 1135, Moscow, ID 83844-1135.*

[2] *Karen Launchbaugh - Professor of Rangeland Ecology, Department of Forest, Rangeland, and Fire Sciences, University of Idaho, 875 Perimeter Drive- MS 1135, Moscow, ID 83844-1135.*

[3] *Ryan Limb - Assistant Professor of Rangeland Fire Ecology, School of Natural Resource Sciences, Dept. 7680, North Dakota State University, PO Box 6050, Fargo, ND 58108.*

[4] *Allen Torell - Professor of Agricultural Economics, Department of Agricultural Economics, New Mexico State University, Box 30003, MSC 3169, Las Cruces, NM 88003.*

Contents

Key Points

- *Cover and biomass of perennial herbaceous plants in sagebrush communities can be reduced by heavy (or severe) grazing repeatedly in the spring before the perennial grasses initiate bolting.*
- *High severity grazing (i.e. >50% utilization), especially in the spring during initiation of bolting of perennial grasses, can suppress competition from native herbaceous plants and cause soil disturbance that can favor annual invasive grasses including cheatgrass.*
- *Livestock grazing at low/moderate severity (i.e., < 50% utilization) generally has little influence on the cover of perennial grasses and forbs.*
- *Areas grazed by livestock can have more, less, or the same density and cover of sagebrush compared to non-grazed areas. Determining factors include the season and intensity of grazing, species of livestock, ecological site, and site conditions at the time of grazing.*
- *A window of opportunity may exist for targeted grazing to reduce annual grasses before perennial grasses initiate bolting or during dormancy of perennial grasses.*
- *Targeted grazing with sheep or goats can reduce the fuel load of shrublands in the short term by reducing woody fuels.*
- *Livestock grazing can reduce the standing crop of perennial and annual grasses to levels that can reduce fuel loads, fire ignition potential, and spread.*

- *Grazing after perennial grasses produce seed and enter a dormant state can reduce the residual biomass left on the site, thereby decreasing the fire hazard the following spring and summer.*
- *Grazing can reduce the continuity of fuels, including the amount of herbaceous biomass between shrubs, in sagebrush ecosystems.*
- *Economic analyses reveal that fuel treatments in sagebrush ecosystems have the highest benefit/cost ratio when the perennial grasses comprise the dominant vegetation, i.e. prior to annual grass invasion and shrub dominance.*
- *Extreme fire weather conditions, characterized by low fuel moisture and relative humidity, and high temperature and wind speed, affect wildland fires more than do fuel characteristics, and the potential role of grazing to alter fire behavior is limited.*

Introduction

Sagebrush steppe and semi-desert ecosystems cover vast areas in western North America and dominate landscapes of the Great Basin and Colorado Plateau (Miller et al., 1994). In this review we focus on the sagebrush steppe and semi-desert ecosystems within the Great Basin. Despite their immense extent, several forces threaten the persistence and distribution of these ecosystems. Climatic conditions, grazing, exotic plant invasion, habitat fragmentation, and fire all can alter the extent and composition of sagebrush-dominated landscapes (Miller et al., 1994; Miller & Eddleman, 2000; Davies et al., 2011). A significant concern in recent years is increasingly large and severe wildfires occurring across the arid regions in the west; these fires remove sagebrush and favor more tolerant annual and perennial grasses (Knick & Rotenberry, 1997). Invasive early-curing annual grasses such as cheatgrass, red brome, and medusahead are filling the interspaces between shrubs on many arid sites, or are becoming the ecologically dominant species after a fire. Both situations create a continuous fuel bed, allowing fire to spread more readily across the landscape (Stewart & Hull, 1949; D'Antonio & Vitousek, 1992). A warming climate with earlier snowmelts contributes to a prolonged fire season with larger and more severe fires (Chambers and Pellant, 2008).

Weather, fuel characteristics, and landscape features all affect fire spread, severity, and intensity (Figure 1). Efforts to reduce the risk of extensive fires in sagebrush-dominated ecosystems have focused considerable attention on how livestock grazing affects fuels, fire behavior and fire effects. Livestock grazing influences factors related to fuel characteristics, including the proportions of herbaceous and woody fuel, amount of herbaceous biomass, live/dead fuel mix, and continuity of fuel at a patch and landscape scale (Figure 1). Fire behavior and effects are also influenced by weather and

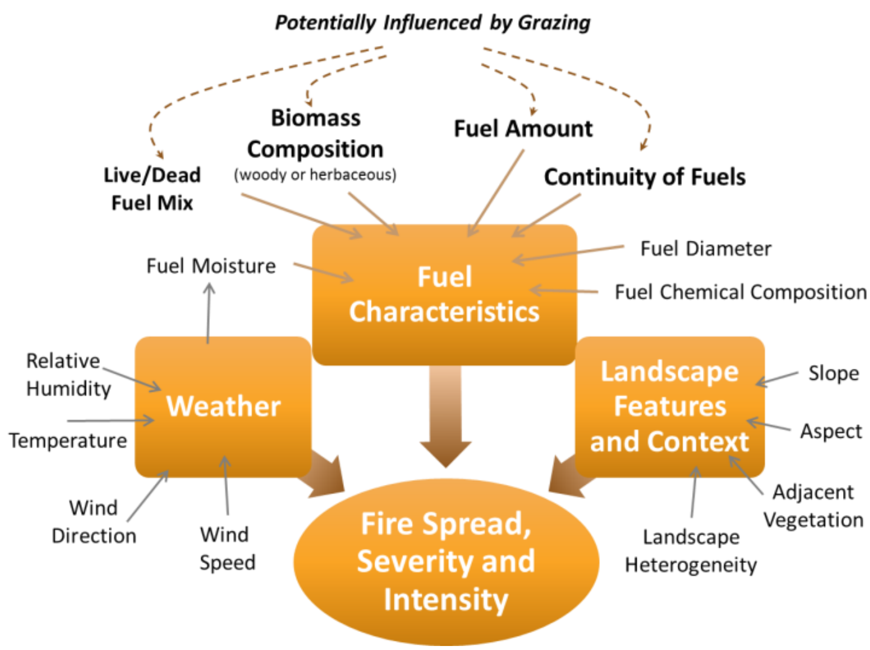

Figure 1. Factors that affect rate of spread, intensity, and severity of wildland fires can be separated into factors related to weather, fuel characteristics, and landscape features and context. Grazing can potentially influence factors related to fuel characteristics.

landscape features that are independent from grazing (Figure 1). This paper provides a comprehensive overview and scientific synthesis of published research on: 1) how livestock grazing can modify plant community composition and alter fuel characteristics of sagebrush-dominated plant communities; 2) how yearly grazing patterns affect fuel loads and wildland fire behavior; and, 3) the comparative economics of grazing as a fuel reduction treatment.

Historic Livestock Grazing Patterns

The introduction of domestic livestock to the Great Basin in the 1860s initiated an era of broad-scale ranching and significant changes in rangeland ecosystems (Miller et al., 1994). Early grazing practices during settlement and homesteading were by all accounts ill-informed and poorly managed (Belsky & Blumenthal, 1997; Miller & Eddleman, 2000). After several decades of heavy stocking and season-long use, the perennial grass and forb understory was considerably depleted across much of the sagebrush steppe and semi-desert (Vale, 1974). One of the greatest effects of this excessive grazing pressure was a reduction of the fine fuels that had previously carried wildfires (Miller et al., 1994; Miller & Eddleman, 2000). Concomitant with excessive grazing pressures was the reduction and relocation of Native American populations which reduced the presence of rangeland fire in sagebrush systems (McAdoo et al. 2013).

With a reduced frequency of wildfires, the woody plant cover increased, and shrublands and woodlands expanded (Miller et al., 1994; Miller & Eddleman, 2000). Livestock grazing also promoted woody plant growth by suppressing competition from herbaceous plants through preferential grazing of grasses and forbs (Miller et al., 1994; Wilcox et al., 2012).

Grazing management programs designed to improve native perennial grass communities were first implemented in the 1940s. Managed grazing, including periods of rest, seasonal deferment, and reduced stocking rates was widely implemented in the latter half of the 20th century (Krueger et al., 2002). As grazing management practices were implemented, herbaceous fuel loads generally increased, and wildfires became more common. This reduced the abundance of non-sprouting shrubs, including most sagebrush species, across vast areas (Young & Blank, 1995; Davies et al., 2009).

Introduction of Exotic Annuals Grasses

Cheatgrass, an invasive annual grass introduced to North America in the 18th century (Mack, 1981), has vastly changed the fire regimes across the Great Basin and western North America (Brooks et al., 2004). Medusahead is another annual grass, introduced from the Mediterranean region in the late 1800s and spread rapidly across the Great Basin (DiTomaso et al., 2008). These and other invasive annual grasses, including red brome, have changed fuel characteristics and fire regimes of the ecosystems they invaded (D'Antonio & Vitousek, 1992; Brooks et al., 2004). These fine-textured, flammable, and early maturing grasses have lengthened the annual fire season and shortened the return interval of wildfires across the Great Basin (Hull & Pechanec, 1947; Stewart & Hull, 1949; Davison, 1996; Bradford & Lauenroth, 2006; Balch et al., 2013). Their rapid spread was exacerbated by excessive stocking rates and inappropriate grazing practices (Knapp, 1996; Young & Sparks, 2002; Chambers et al., 2007). Thus a discussion of the effects grazing has on fire patterns in sagebrush-dominated ecosystems necessitates a discussion of how grazing affects annual grass abundance.

Fire is a widespread disturbance type in sagebrush ecosystems, but when cheatgrass and other annual grasses become established, they change fuel characteristics and shorten the fire return interval in these ecosystems (Stewart & Hull, 1949; Brooks et al., 2004; Balch et al., 2013). Fires can occur more frequently because it only takes a few years post-fire (i.e., three to six) to develop a sufficient fuel continuity to facilitate another fire (Peters & Bunting, 1994). The abundance of cheatgrass also increases the likelihood of fire ignition and spread (Bunting et al., 1987; Link et al., 2006; Balch et al., 2013). For example, the estimated fire ignition risk more than doubled (i.e., from 46% to 100%) in bunchgrass communities in southwestern Washington when the cover of cheatgrass increased from 12% to 45% (Link et al., 2006). The continuity and flammability of cheatgrass contribute to a highly connected fuel bed which facilitates rapid spread across the landscape (Figure 2). The fire return interval can be halved and the fire size greatly increased on rangelands dominated by cheatgrass as compared to fires in vegetation communities without cheatgrass (Balch et al., 2013). As wildfires become more frequent, perennial grasses and native shrubs are generally lost from the plant community (Peters & Bunting 1994). With repeated fires, the seedbank of perennial herbaceous species eventually becomes depleted, permanently altering vegetation composition in sagebrush communities (Knapp, 1996; Humphrey & Schupp, 2001).

How Grazing Alters Plant Community Composition in Sagebrush Ecosystems

How grazing affects the plant composition of sagebrush ecosystems depends on several factors: precipitation is key, followed by soil characteristics, season and intensity of grazing, and species of grazing herbivore. Plant community composition also has important implications for fire regimes and potential fire behavior. Different types of plants exhibit very different fuel characteristics that affect fire ignition, fire behavior, and fire effects (Figure 2). Fine herbaceous fuels cure over the summer, rapidly equilibrate with the ambient relative humidity, and facilitate easy ignition in the summer and early fall. Fire spread through these fuels is usually low intensity because of the lower amount of biomass per unit area (Scott & Burgan, 2005).

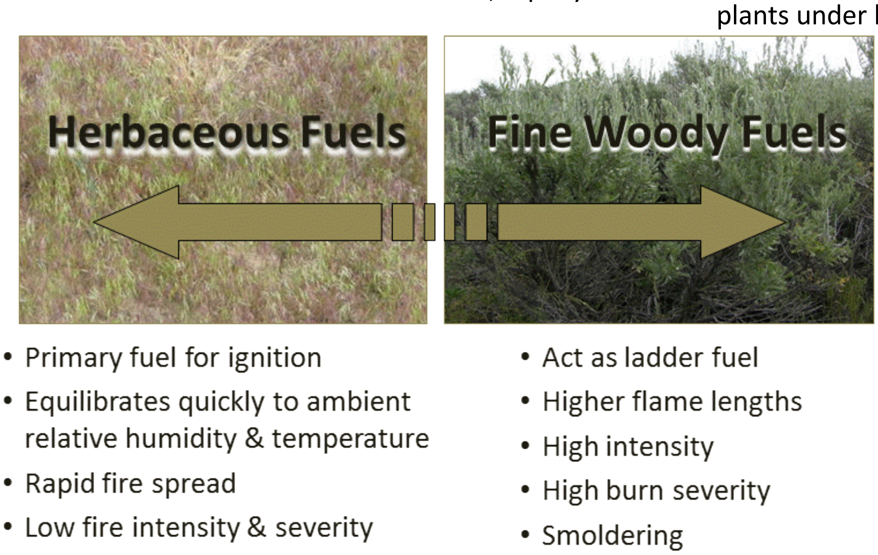

Figure 2. The fuels of sagebrush-dominated ecosystems can be categorized and described as herbaceous (i.e., grasses and forbs) and fine woody fuels (i.e., < 7.6 cm [3.0 inches] diameter woody stems). The fuels vary in how they contribute to fire behavior and effects.

Sagebrush-dominated ecosystems support an overstory of shrubs composed of fine woody fuels (i.e., less than 7.6 cm [3.0 inches] diameter). Fine woody fuels are more difficult to ignite but typically burn longer and hotter than the herbaceous grass and forb fuels in the understory. Fine woody vegetation increases flame length and fire intensity. Increasingly greater shrub biomass and fuel loads lead to more severe fire effects, e.g. plant mortality, smoke emissions, soil heating, and biomass consumption (Sikkink et al., 2009). Woody plants such as sagebrush can also contain volatile oils that can create highly flammable fuel loads and increase both flame lengths and fire spread (Buttkus & Bose, 1977).

Livestock grazing effects on shrub cover/densities

An examination of a variety of grazing studies and comparisons reveals no clear and consistent effect of grazing on cover, density, or biomass production of shrubs. For example, researchers in eastern Oregon recorded increased density of juvenile sagebrush plants under high stocking rates (1.2 AUM/ha or .48 AUM/ac) compared to no grazing or a low stocking rate (0.6 AUM/ha or 0.24 AUM/ac) in Wyoming big sagebrush with a crested wheatgrass understory (Angell, 1997). Likewise, sagebrush density increased in response to early season grazing, before perennial grasses flower and set seed, in a threetip sagebrush community (Laycock, 1967; Bork et al., 1998).

The variable effect of grazing on shrubs can also be assessed by comparing the plant community in areas where grazing has been excluded to adjacent similar areas where grazing has continued. We examined eleven exclosure studies in sagebrush ecosystems where grazing had been excluded for ten years or more. In these comparison studies, sagebrush and other shrubs' response to the removal of grazing varied depending on the species of shrub, soil type, community condition at the time of exclosure, species of herbivore, and season and intensity of grazing. In seven of the eleven studies; there was no consistent or discernible difference in shrub cover or density between grazed and ungrazed sites (Rice & Westoby, 1978; Daddy at al., 1988; Courtois et al., 2004; Yeo, 2005; Davies et al., 2010). For example, Davies et al. (2010) found no difference in Wyoming big sagebrush cover in areas grazed at moderate intensity (30-50% utilization and a deferred rotation grazing system) over the past 70+ years compared to areas that had been excluded from grazing in Wyoming big sagebrush steppe. A similar comparison of rangeland vegetation in fourteen grazing exclosures with mountain and Wyoming big sagebrush in southeastern Idaho revealed no difference in shrub cover inside and outside the exclosures in areas available for grazing by wildlife and livestock (primarily cattle) under a variety of grazing systems. (Yeo, 2005).

Several exclosure studies revealed that grazing affected shrub cover or density, but the effect was not consistent. Laycock (1967) described greater production of threetip sagebrush in areas grazed (at levels describe as "heavy") in the spring by sheep compared to those areas excluded from grazing (for 25 years) or areas grazed in the fall. Holechek and Stephenson (1983) similarly showed greater cover of basin big sagebrush on grazed lowland sites in an exclosure study in northern New Mexico. However, on upland sites Holechek and Stephenson (1983) reported greater cover of sagebrush in the exclosure compared to the adjacent grazed area with 30 to 50% utilization levels. Manier and Hobbs (2006) showed greater cover of mountain big sagebrush in exclosures than on adjacent grazed areas at 17 exclosure sites in western Colorado. Similarly, Whisenant and Wagstaff (1991) reported greater relative cover of bud sage in exclosures without grazing for 53 years compared to adjacent grazed areas. Exclosure studies may be valuable in discerning the effects of the recent grazing regimes on specific areas. However, exclosure studies, collectively, do not reveal global trends due to grazing. The results of these studies suggest that the effects of grazing on shrub cover and production are site-specific, and depend on the site conditions; the historic grazing regimes; plant community composition at the time the exclosures were constructed; and, the specific grazing regime after the exclosures were established.

Several researchers also attributed plant community change to the removal or reduction of grazing by comparing observations before and after changes in a grazing regime. For example, Yorks et al. (1992) found an increase in basin big sagebrush cover (0.5% to 13% from 1933 to 1989) along a 37-km (30-mile) transect in sagebrush semi-desert in Utah. During this 56-year period, grazing pressure was reduced as a result of the Taylor Grazing Act of 1934; however, a general increase in annual average precipitation may have had a greater influence on shrub cover than did the reduction in grazing. Similarly, Wyoming big sagebrush cover on a site in south-central Idaho increased from 18% in 1950 to 25% in 1975 after the removal of grazing (Anderson & Holte, 1981). In this study, the increase can be attributed to succession and adequate precipitation. In a subsequent study on the same site, sagebrush cover declined from 25% in 1975 to 13% in 1995 because of wide-spread die off of sagebrush likely related to drought, insect and rodent damage, and/or fungal pathogens (Anderson & Inouye, 2001). Increased shrub cover was also observed ten to fifteen years after removal of grazing by free-roaming horses in sagebrush ecosystems across the Great Basin (Beever et al., 2008). On the other hand, big sagebrush cover decreased on a site in northern Utah eleven years after livestock grazing was removed (Austin & Urness, 1998). This decrease was largely attributed to increased grazing pressure by mule deer and more competition with sagebrush from perennial grasses that were not grazed after the removal of cattle.

Livestock grazing effects on perennial grass cover

The effects of grazing on perennial grass cover in sagebrush communities depends on factors similar to those affecting sagebrush cover, including precipitation, soil characteristics, season of grazing, grazing intensity, and type of herbivore. Severe grazing that occurs repeatedly in the spring, before plants produce seeds, has been shown to reduce the cover of perennial grasses and forbs (Vale, 1974; Bork et al., 1998); the effect of light to moderate intensity livestock grazing on vegetation is more obscure.

It is difficult to discern grazing effects from other biotic effects and abiotic environmental conditions (Miller et al., 1994, Holechek et al., 2006). When grazing was removed from a Wyoming big sagebrush site, increases in perennial grass cover occurred sometimes (Robertson, 1971), but not always (Rice & Westoby, 1978; West et al., 1984). Yorks et al. (1992) observed a ten-fold increase in perennial grass cover from 1933 to 1989 in Utah semi-desert where grazing pressure by livestock was reduced. On the other hand, Davies et al. (2010) found no difference in current year's herbaceous production when comparing long-term (i.e., 70 years) moderately grazed rangeland (30-50% utilization) with areas excluded from grazing in Wyoming sagebrush steppe communities in eastern Oregon.

Livestock grazing effects on annual grass abundance

Livestock grazing and annual grasses are interacting factors that affect fuel characteristics and wildland fire occurrence and behavior throughout sagebrush ecosystems. Intense (high stocking rate), severe (high utilization levels), and repeated (multiple defoliation events in the same season) grazing can suppress competition from native plants and cause soil disturbance that can favor annual invasive grasses including cheatgrass (Klemmedson & Smith, 1964; Mack, 1981; D'Antonio & Vitousek, 1992; Knapp, 1996; Bradford & Lauenroth, 2006; Chambers et al., 2007; Loeser et al. 2007). Perennial grasses are strong competitors with cheatgrass (Booth et al., 2003; Chambers et al., 2007; Blank & Morgan, 2012), so grazing that adversely affects perennial grasses can actually increase annual grasses.

Exclusion of livestock does not necessarily slow invasion or reduce abundance of annual grasses (Cottam & Evans, 1945; West et al., 1984; Young & Allen, 1997; Anderson & Inouye, 2001; Courtois et al., 2004; Young & Sparks, 2002). A comparison of grazed and ungrazed canyon vegetation in Utah showed that cheatgrass was 1.5 times more frequent in an ungrazed than a grazed canyon (Cottam & Evans, 1945). Substantial invasion by cheatgrass and other exotic annual grasses can also occur on sites that have never been grazed by livestock but where there is a seed source (Daubenmire, 1940; Tisdale et al., 1965; Svejcar & Tausch, 1991; Goodwin et al., 1999). However, caution should be applied to site comparisons aimed at ascertaining the effects of grazing because the spread of cheatgrass across an area depends on the level of site degradation when the annual grasses were introduced (Young & Sparks, 2002), frequency of wildfire (Cottam and Evans, 1945) and on the relative resistance of different ecological sites to cheatgrass invasion (Chambers et al., 2007).

Though severe and poorly timed grazing can promote annual grasses, in some situations livestock grazing can suppress annual grasses, including cheatgrass (Daubenmire, 1940; Mosley, 1994; Vallentine & Stevens, 1994; Mosley & Roselle, 2006; Loeser et al., 2007) and medusahead (DiTomaso et al., 2008). The intensity of grazing can influence whether annual grasses are suppressed or promoted. For example, in northern Arizona high elevation semi-arid grasslands, sites with moderate grazing intensity (about 50% utilization) in the summer grazing season had lower cheatgrass abundance than either intensely grazed (stocked to accomplish high utilization >70% in a 12-hour grazing period) or ungrazed treatments (Loeser et al., 2007). In southeastern Washington bluebunch wheatgrass communities, high-intensity sheep grazing pressure during winter dormancy and the spring grazing season eliminated cheatgrass from a site within a few years. However, a reduction in perennial grasses also occurred and the rapid reinvasion by annual grasses was observed after cessation of grazing (Daubenmire, 1940).

The impact of grazing on invasive annual grasses is highly variable and site specific, which gives rise to opposing research and field observations that either implicate grazing in the spread and abundance of annual grasses, or describe the suppression of annual grasses by livestock grazing. Important factors contributing to these conflicting results include resistance to cheatgrass as determined by soil temperature, the timing and amount of available soil moisture, the relative abundance of perennial herbaceous species, and the season and intensity of grazing (Chambers et al., 2013).

The timing and amount of precipitation and winter or spring temperatures strongly affect the germination, survival and growth of annual grasses such as cheatgrass (Mack & Pyke, 1983; Chambers et al., 2007). Cheatgrass also is favored after fire or other disturbances when the community of perennial herbaceous plants has been depleted (Chambers et al., 2007; Hoover & Germino, 2012). Precipitation timing and amount are immensely important factors determining the response of cheatgrass to grazing (Young et al., 1987). Because cheatgrass responds quickly to early season rains, grazed cheatgrass plants may exceed the growth of ungrazed plants if moisture is available following spring grazing (Vallentine & Stevens, 1994).

However, grazing can also increase annual grass abundance in dry years. A study in a high-elevation, Great Basin grassland in Arizona revealed similar levels of cheatgrass in high-intensity cattle grazing with high stocking rates compared to ungrazed pastures until a drought year occurred (Loeser et al., 2007). In the two years after the drought year, the high-intensity grazing treatment resulted in an 80% increase of cheatgrass cover and a frequency of occurrence of nearly 100% compared to about 40% on ungrazed sites (Loeser et al., 2007).

The effects of grazing on annual grass abundance also varies by season in which grazing occurs. There appears to be a window of opportunity for grazing to reduce annual grasses if grazing occurs when annuals begin to produce seeds but before native perennial grasses initiate bolting (Figure 3; Mosley, 1994; Vallentine & Stevens, 1994; Mosley & Roselle, 2006; Smith et al., 2012). Cheatgrass is very palatable to livestock and has high nutritional value in the vegetative stage and is preferentially selected over many perennial grasses in early spring throughout the Great Basin (Young & Clements, 2007). Early and late spring clipping that simulated grazing reduced the biomass of cheatgrass compared to an unclipped control, though density of cheatgrass was unaffected (Tausch et al., 1994). A similar clipping study found no effect of clipping on cheatgrass seed density except when plants were clipped in the boot stage and then clipped again two weeks later, resulting in reduced seed density (Hempy-Mayer & Pyke, 2008).

The timing of grazing is critical because annual grasses may flourish if perennial plants are grazed preferentially at times when the perennial grasses are sensitive to damage by grazing (Pyke, 1986; Ganskopp, 1988). If bunchgrasses are routinely heavily grazed (exceeding 50% utilization) in the period from bolting through seed-set, and particularly if multiple defoliation events in the same season occur, the competitive advantage can be shifted toward cheatgrass (Daubenmire, 1940; Young et al., 1987). Late season grazing, after perennial grasses have produced seed and begin to senesce, has minimal

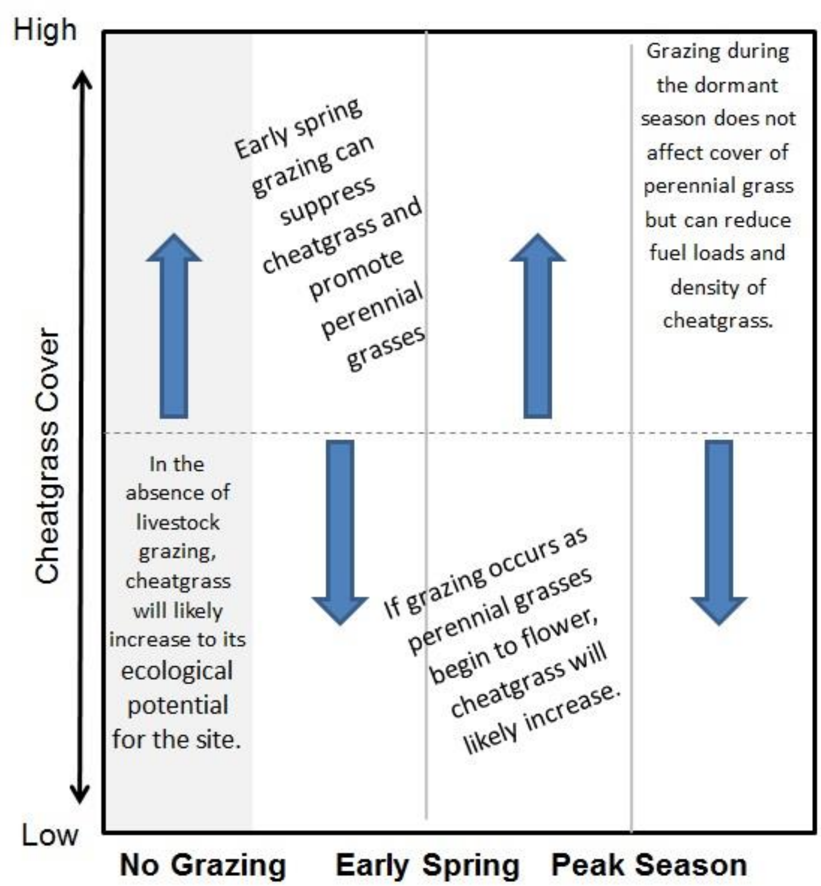

Figure 3. Conceptual depiction of how livestock grazing can influence cheatgrass abundance in sagebrush-dominated ecosystems with a significant component of perennial grasses. Grazing can suppress or promote cheatgrass depending primarily on the season of grazing. Grazing suppresses cheatgrass when applied in early spring when annuals begin to produce seeds and before native perennial grasses initiate bolting; and when applied during the dormant season.

impact on these grasses (Ganskopp, 1988; Hempy-Mayer & Pyke, 2008). Several years of fall grazing by cattle on semi-desert (27 cm [10.6 inches] annual precipitation) sites in Nevada dominated by Wyoming big sagebrush and salt desert shrub plant communities has been shown to reduce cheatgrass density and cover and increase cover of perennial grasses compared to sites without fall or winter grazing (Schmelzer et al., in press).

Well-timed and closely managed spring grazing can be an effective tool to suppress annual grasses including cheatgrass and medusahead (Mosley, 1994; Vallentine & Stevens, 1994; Mosley & Roselle, 2006; DiTomaso et al., 2008; Smith et al., 2012). One of the best opportunities to reduce the abundance and cover of cheatgrass is before most perennial grasses begin active growth (Vallentine & Stevens, 1994; Young & Allen, 1997; Mosley & Roselle, 2006; Smith et al., 2012). The challenge is to remove livestock before perennial plants begin active growth in order to avoid reduced vigor in the perennial grasses (Laycock, 1967; Miller et al., 1994; Loeser et al., 2007). Regardless, perennial grasses with similar phenologies as annual grasses, like bottlebrush squirreltail, may be reduced (Booth et al., 2003). On cheatgrass-dominated sites, high grazing intensity and annual use must be maintained or annual grasses will quickly re-invade and dominate an area (Daubenmire, 1940; Klemmedson & Smith, 1964; Pyke, 1986).

How Livestock Grazing Can Modify Fuel Loads

Management practices can greatly affect a landscape's fuel amount and distribution. Fuel load, or biomass, is one of the most influential and easily manipulated fuel variables affecting fire intensity (Figure 4). Fuel load is the portion of the biomass that will actually burn in a wildfire or prescribed fire, and is closely related to vegetation biomass. Fuel loads are the primary drivers of heat, and all measures of heat increase with increasing fuel loads (Vermeire & Roth, 2011). The likelihood of fire-induced bunchgrass mortality depends upon the amount of heat received and the type of plant tissue exposed to lethal heat (Miller, 2000; Wright, 1971). Livestock grazing is one management technique that has been shown to decrease fine fuel loading and subsequent wildfire severity (Archibald et al., 2005; Davies et al., 2010).

Fuel management objectives aimed at reducing flame lengths and fire spread in grassland and shrubland ecosystems could be accomplished by altering the fuel bed depth, fine fuel loading, cover, and continuity such that the flame length never reaches 1.2 meters (3.9 feet; Nader et al., 2007). Livestock (i.e., cattle horses, sheep and goats) grazing primarily impacts small diameter fuels (< 0.51 cm [0.2 inch] diameter), including grass and small woody stems that equilibrate with the ambient humidity and temperature within 1 hour (i.e., the 1-hour time lag

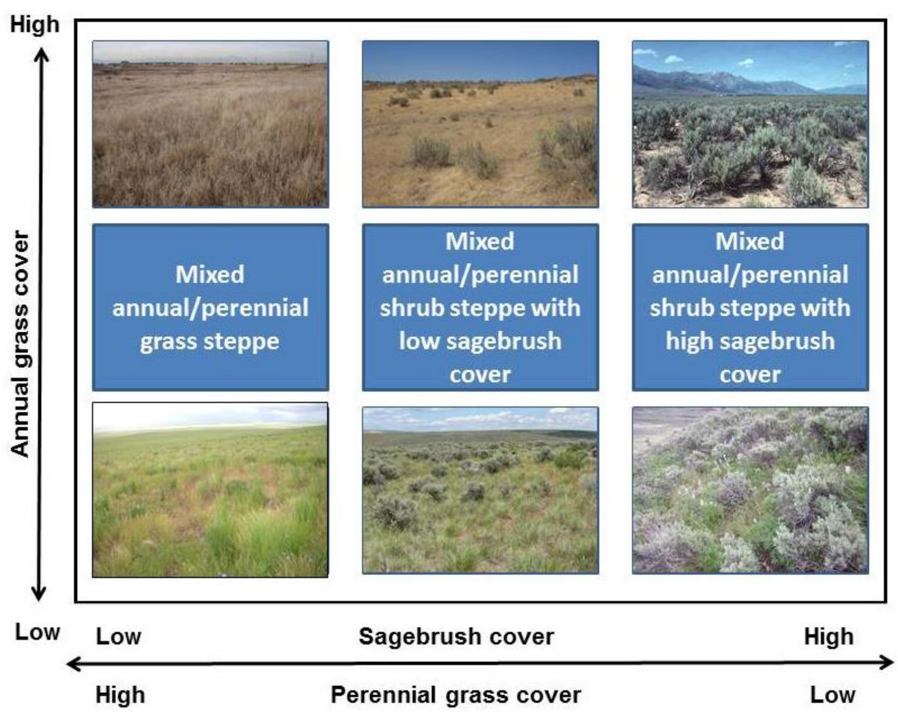

Figure 4. The plant composition in sagebrush-dominated ecosystems is variable across the landscape; this has important implications for fire behavior because different types of plants exhibit different fuel characteristics affecting fire ignition, behavior, and effects. Fire spreads quickly through cured grass usually at low intensity because of the low amount of biomass per unit area. Fine woody vegetation increases flame length and fire intensity. Higher shrub loads lead to more severe fire effects when the area burns. The continuity and flammability of cheatgrass contributes to fire connectivity and spread.

[htl] fuels). Livestock can also impact larger fuels (0.51-2.54 cm [0.2 -1 inch] diameter or 10-htl fuels) through browsing and trampling as suggested in a review by Davison (1996). Hence, grazing could be a useful management tool for reduction of grass and shrub biomass (1-htl and 10-htl fuels).

Shrub fuel loads

Targeted grazing can be applied to reduce the fuel load of shrublands through "brush-clearing" strategies (Nader et al., 2007). Strategies to reduce shrub abundance generally rely on goats or sheep because these species generally consume greater quantities of shrubs than cattle (Taylor, 2006; Papanastasis, 2009). Grazing by cattle would not be expected to affect sagebrush cover through direct consumption of sagebrush.

Perennial grass fuel loads

The effect of grazing on fire behavior and extent is predictably less pronounced on sites dominated by woody plants compared to those with more herbaceous biomass. However, reduced fire frequency and spread in grazed shrublands and forests have been observed because the herbivores remove the fine herbaceous fuels that are most likely to ignite and initiate fire spread (Zimmerman & Neuenschwander, 1984; Hobbs, 1996).

Grazing with the goal of reducing herbaceous fuel loads generally is more effective if it occurs right before the season of greatest fire risk, which generally coincides with peak biomass and the initiation of dormancy (Taylor, 2006). If grazing occurs early in the growing season, grasses can regrow and biomass can be reestablished to levels similar to ungrazed areas (Anderson & Frank, 2003). Grazing or mowing after plants have initiated seed formation and reached peak biomass can reduce biomass levels below those of ungrazed plants and paddocks (Miller et al., 1990; Anderson & Frank, 2003). Grazing late in the growing season (after seed set) and in the dormant season can thereby reduce the residual biomass carried over to the following spring and summer (Launchbaugh et al., 2008). Furthermore, grazing after seed production has lower impact on plant vigor and survival than grazing before floral initiation (Adler et al., 2001).

Ungulate grazing reduces the standing herbaceous plant material available for burning; this in turn can potentially reduce the frequency, extent and intensity of fires in grass, shrub, and forest understory fuel types (Vale, 1974; Zimmerman & Neuenschwander, 1984; Tausch et al., 1994; Hobbs, 1996; Belsky & Blumenthal, 1997; Blackmore & Vitousek, 2000). In relatively moist Wyoming big sagebrush steppe (30 cm [11.8 inches] annual precipitation), Davies et al. (2010) found that grazing reduced the amount of herbaceous fuel. The fine flammable grassy fuel load, including dead standing crop, was two-fold greater in plots that had not been grazed for 70 years compared to adjacent areas that had been grazed long-term at moderate grazing intensity (30-50% utilization). In grasslands without shrubs, fire intensity is inversely related to standing crop biomass (Stronach & McNaughton, 1989; Hobbs, 1996), and grazed patches burn less completely and intensely than ungrazed patches (Hobbs et al., 1991); however, these relationships have not been well researched in shrubland systems of the Great Basin.

Beyond the amount of residual fuel remaining after grazing, the proportion of live versus dead herbaceous biomass may be an important factor affecting a fire's ability to spread in grasslands. Grazing can in some instances increase the propensity for fire to spread because herbivores selectively remove green biomass and thereby increase the proportion of dead to live biomass (Leonard et al., 2010). Though alteration of the live-dead ratio of herbaceous biomass is possible through grazing, it is unlikely to be important in late season wildfires in the Great Basin when most vegetation is dormant.

Annual grass fuel loads

The effects of livestock grazing on fuel characteristics of communities with significant amounts of annual grasses can be viewed in two ways. First, as noted, grazing can promote or suppress annual grasses over years or decades. Second, livestock grazing can reduce the standing biomass of annual grasses within a year to reduce fuel loads and alter fuel continuity. Only a few studies have addressed the potential effect of livestock grazing on fuel loads in annual grasslands. Diamond et al. (2009) examined the effect of grazing by cattle on fire behavior on a cheatgrass-dominated site in Nevada. Targeted grazing when cheatgrass was in the boot stage was applied to reduce 80 to 90% of the herbaceous biomass. This treatment resulted in reduced flame length and rate of fire spread in a prescribed burn conducted in October: fuel characteristics were so greatly reduced that the fire would not spread across the grazed plots (Diamond et al., 2009). Note, however, this study was conducted in a confined area that may not be easily replicated on landscape scales.

Cheatgrass is most palatable and nutritious before the seeds mature and plants turn purple (Hull & Pechanec, 1947; Young & Allen, 1997). However, livestock will eat cheatgrass throughout the season and it has been considered by some as important winter forage in the Great Basin (Emmerich et al., 1993; Vallentine & Stevens, 1994). This may create an opportunity to graze cheatgrass almost year-round to manage fuel loads. Research in Nevada examined the potential value of winter grazing by cattle to reduce cheatgrass fuel loads (Schmelzer et al., in press). In this study, cheatgrass fuel loads were reduced 70 to 80% by winter cattle grazing. The cattle favored cheatgrass over perennial grasses, and with a protein supplement were able to maintain their weight. This study suggests that winter livestock grazing could be accomplished on landscape scales as a part of regular grazing practices to manage fuel loads of cheatgrass. Winter (dormant season) grazing reduces fuel carryover to the next summer (Figure 5), can reduce the thick litter layer known to facilitate the germination of medusahead and cheatgrass seed, may decrease the size of the annual grass seedbank, and has few if any adverse effects on the dormant, desired perennial grasses.

Figure 5. Sagebrush steppe where cheatgrass dominates the herbaceous vegetation. Winter grazing has been applied in the image to the left while the image to the right has been excluded from grazing for the past 20 years. Both photos were taken in late May in neighboring pastures.

A significant challenge to managing fuel loads of annual grasses with livestock grazing is the highly variable biomass production related to rainfall patterns (Young et al., 1987). One study in southern Idaho showed that cheatgrass biomass varied ten-fold depending on annual precipitation; from 404 to 3879 kg/hectare [452 to 4344 lbs/acre] in a dry compared to a wet year (Hull & Pechanec, 1947). Thus, a program using livestock grazing to manage fuel loads created by annual grasses will need to be flexible, and responsive to annual moisture regimes that will alter plant growth and biomass. Winter grazing of cheatgrass has one distinct advantage for livestock production: the amount of potential forage is known months in advance, so the livestock numbers needed to achieve desired utilization levels can be easily determined. For spring grazing of cheatgrass, biomass production can fluctuate dramatically in a short period due to sudden and unpredictable changes in precipitation and temperature. Matching livestock numbers with that forage base is much more difficult.

Continuity of fuels

Fuel continuity describes the spatial arrangement or distribution of fuel and is a major factor affecting the spread of fire across a landscape (Cheney & Sullivan, 2008). Greater fuel continuity leads to faster rates of spread, and spread with lower fireline intensity (NWCG, 1994). Horizontal continuity is the relationship of the horizontal distance between fuel particles and is related to percent cover of vegetation. Management actions that alter vegetation species composition and abundance can strongly affect the fuel continuity (Brooks et al., 2004). Fuel continuity generally increases as fuel load increases. However, if major shifts in vegetation composition occur, then fuel load can decrease while fuel continuity increases. Invasion of the sagebrush ecosystem by annual grasses is a classic example of this phenomenon: bunchgrasses and shrubs, with abundant open space between plants, are being replaced with smaller-statured grasses with less space between individual plants. A major factor of larger wildfires in recent years is the increased fuel continuity across the landscape (Davison, 1996).

Livestock grazing can alter the spatial pattern of vegetation which in turn can have important consequences for fire occurrence and spread (Adler et al., 2001). Grazing can increase or decrease the spatial heterogeneity of vegetation depending on the existing plant community's grazing animal distribution, and the scale of observation (Adler et al., 2001). Typically, grazing increases patchiness when the grazing pattern is stronger than the vegetation pattern and when grazing increases the contrast among vegetation types. In grassland systems, grazed patches may be more likely to be re-grazed in subsequent years because they typically contain a greater proportion of new growth (Hobbs et al., 1991).

In grasslands, landscape mosaics created by variable grazing intensity can provide "firebreaks" and prevent fires from becoming larger (McNaughton, 1992). However, these relationships may not apply to shrublands because fire can be carried by the shrubs. Davies et al. (2010) observed larger fuel gaps in moderately grazed areas compared to ungrazed areas in a Wyoming big sagebrush community, and the continuous perennial grass patches were larger in ungrazed areas. Furthermore, herbaceous fuel between shrubs in sagebrush ecosystems may be effectively reduced by livestock grazing. France and colleagues (2008) documented grazing by cattle in Wyoming big sagebrush ecosystems was focused on bunchgrasses in interspaces between shrubs with only negligible removal of grasses under shrub canopies at moderate (i.e., 40%) utilization levels. A case study in sagebrush steppe in northern Nevada demonstrated success keeping landscape scale fire at a minimum using livestock to reduce fuels and implementing range improvement projects, such as flanking existing roads with green-strip seedings, managing brush, seeding projects, and improving riparian areas to function as green-strips (Freese et al., 2013).

Although high-intensity grazing can reduce biomass and fine fuel loads, light grazing can produce patchy burn patterns in continuous sagebrush steppe fuels (Bunting et al., 1987). Low- to moderate-intensity grazing can remove sufficient fuel and break up fuel continuity to significantly reduce fire spread (Bunting et al., 1987). Patchy burn patterns are particularly important in sagebrush regions where maintenance of sagebrush cover (e.g., for wildlife habitat) is a management objective. Patchy burns leave islands of unburned sagebrush, thereby creating a seed source for reestablishment of sagebrush plants across the affected area (Colket, 2003).

Much of the evidence on fire behavior in herbaceous fuels is extrapolated from grassland ecosystems in both North America and Africa. However, because fire itself is a physical process driven by fuel, it is largely unaffected by the specific plant species, but rather the amount and structure of the fuel source. For example, one classification for wildland fuels is the time required for dead fuel to equilibrate to changes in relative humidity (largely a function of fuel diameter). Additionally, fuel loading and fuel continuity are used in fire spread models, whereas vegetation species is generally not included (Scott and Burgan, 2005). This allows for comparisons of fire behavior among ecosystems with similar fuel classes, but completely different species composition.

Grazing to Manage Fuels Depends On Weather, Topography, and Vegetation Composition

Carefully targeted grazing can be used as a tool to reduce fine fuel loads, the rate of spread and final extent of fires, and ultimately fire frequency, in sagebrush-dominated ecosystems. However, the level to which grazing affects fire behavior depends on a number of physical and environmental conditions, such as ambient temperature, wind speed, humidity, fuel composition, fine-scale continuity (tuft-scale), spatial distribution, and topography (Figure 1). Fuel loading and fuel moisture directly affect the fire behavior and consumption rates in sagebrush ecosystems under most environmental conditions. In the absence of sagebrush cover, if fine fuel loading is less than 560 to 650 kg/hectare (627 to 728 lbs/acre), fires will sustain only under environmental conditions characterized by less than 15% relative humidity, temperatures exceeding 29°C (84.2 °F), dead fuel moisture less than 12%, and wind speeds greater than 16 km/hour (9.9 miles/hour (Britton et al., 1981; Bunting et al., 1987; Launchbaugh et al., 2008). However, when fine fuel loading is above 1700 kg/hectare (1904 lbs/acre), fire will spread under a wide array of environmental conditions (Bunting et al., 1987). Given these estimates, based on models, livestock grazing could remove sufficient fine fuel to reduce the risk for fire ignition and spread throughout most of the year. Consequently, areas that are selected for a prescribed fire should not be grazed the season before the planned fire to allow fine fuel accumulation (Bunting et al., 1987).

In sagebrush steppe and semi-desert, the shrub component adds vertical structure to an understory of herbaceous forbs and grasses. Brown (1982) suggested that at 20% sagebrush canopy cover, a cured herbaceous fuel load of at least 340 kg/hectare (381 lbs/acre) would be required to sustain a fire with a 16 km/hour (9.9 mile/hour) wind. Areas with greater sagebrush cover may burn at lower herbaceous fuel loads. Lower fuel moistures, typical in the fall, increase the rate of spread, flame lengths and fire intensity when compared to spring burns (Sapsis & Kauffman, 1991). Consumption rate of 10-htl and 100-htl woody fuel also increases with lower fuel moisture content (Sapsis & Kauffman, 1991). In addition to fuel moisture and weather, topography also affects fire behavior. At 30% slope the fire rate of spread is two to three times greater than a flat area, while at 50% slope the rate of spread increases four to seven times (Brown, 1982). Thus, fuel reduction by grazing will have the most pronounced effects and potential to benefit suppression activities on more level parts of the landscape.

Reducing levels of fine fuels, as could be accomplished with livestock grazing, reduced the modeled surface rate of spread and fire intensity in simulated shrub and grassland communities (Launchbaugh et al., 2008). Model assumptions using Behave Plus software include uniform fuel continuity, weather, and slope (Andrews, 2008). In addition, the model does not include potential spotting to advance the fire ahead of the containment line. The effects of reduced fuel load on fire behavior were more pronounced at low wind speeds and high fuel moisture. When burning conditions became extreme, changes in the amount of herbaceous fuels (1-htl fuel classes) had little effect on fire behavior variables. Under less extreme fire weather conditions, livestock grazing to reduce herbaceous fuel loads could influence fire behavior, making fire in these sagebrush communities easier to contain.

A similar study with similar fire model assumptions and results was conducted at study sites near Las Cruces, New Mexico and Tucson, Arizona (Varelas, 2012). This study confirmed that with moderate fuel moisture and light winds the reduction of fine fuels by grazing could reduce flame lengths below a 1.2-meter (4-feet) level, permitting direct attack by hand crews. However, the grazing treatments were not effective under more extreme burning conditions and the cattle grazing treatment had limited potential to alter fire behavior when a significant shrub component was present.

Important factors driving the behavior and effects of fire in sagebrush steppe and semi-desert systems are fuel characteristics and fire weather (Figure 6). Livestock grazing has the highest potential to reduce fire spread and intensity in areas dominated by herbaceous fuels with low sagebrush cover under moderate or better weather conditions, (i.e., conditions represented in the upper left region of Figure 6). Grazing by cattle is generally focused on grasses and other herbaceous forage, therefore cattle grazing would have limited potential to alter fire behavior that is driven primarily by sagebrush cover (i.e., conditions represented in the lower left region of Figure 6). However, under moist and cool conditions, grazing can influence fires that move through sagebrush communities by slowing the movement of fire along the herbaceous understory between shrubs. Under extreme burning conditions, characterized by low fuel moisture and relative humidity, and high temperature and wind speed, wildland fires are driven more by weather conditions than by fuel characteristics. Therefore, as fire weather conditions become extreme, the potential role of grazing on fire behavior decreases and may

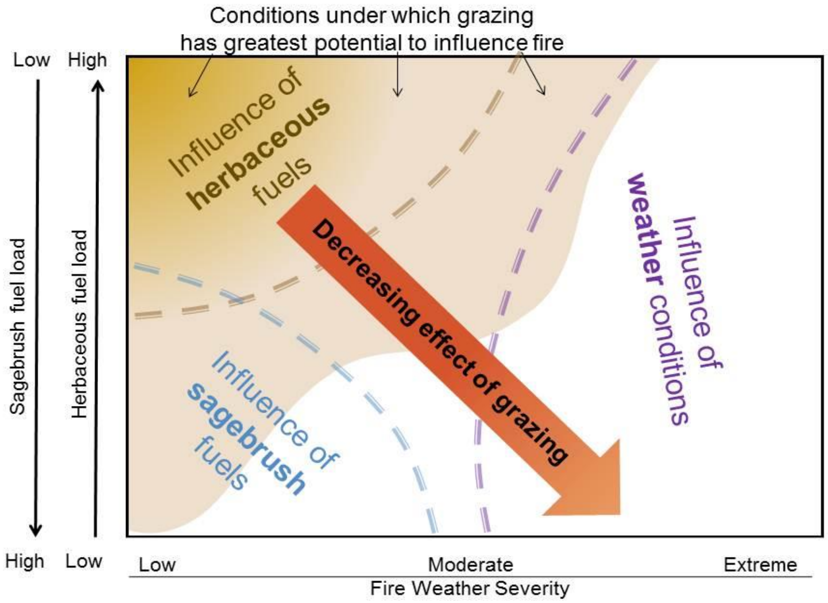

Figure 6. The potential for grazing to influence fire behavior occurs along continuums of fuel and weather conditions. In this conceptual model, fuel composition is displayed on the y-axis and fire weather condition is displayed on the x-axis. Low fire weather severity is characterized by high fuel moistures, high relative humidity, low temperature, and low wind speeds, while extreme fire weather is characterized by the opposite conditions. The potential for grazing to be effective in reducing the risk of fire initiation and spread is greatest when the sagebrush cover is low and the fire weather severity is low to moderate.

become meaningless (e.g., conditions represented on the right side of Figure 6).

Economics of Fuel Treatments

Fuel treatments are designed to alter fuel conditions so that wildfire is easier to control and less destructive (Reinhardt et al., 2008). As noted above, cattle grazing primarily alters fuel conditions by reducing the amount of herbaceous fine fuels, whereas goat and sheep grazing can potentially also reduce the shrub component. Other fuel treatments that can be used to accomplish these same objectives include, herbicides, mechanical treatments such as mowing, prescribed/controlled fires, or a combination of these treatments (Nadar et al., 2007; Diamond et al., 2009).

The costs of fuel treatments vary widely, yet the relative costs and success of alternative treatments is an obvious concern and must be considered when evaluating fuel management options. Several studies review and describe the many factors affecting fuel treatment costs on forested areas where management of the woody overstory is of key concern (Cleaves et al., 2000; Hesseln, 2000; Kline, 2004) similar cost estimates on rangelands are limited. Least cost fuel treatments will vary with conditions and objectives, but grazing alternatives appear to be cost-competitive especially if the objective is reduced fine fuel loads where mowing or a prescribed burn are potential alternatives.

As described by Mercer et al. (2007) and Kline (2004), expanding beyond costs to consider net economic benefits of fuel treatments is a complex analysis. The most important unanswered economic question is whether the resource expended to reduce wildfire risk and damages result in net economic gains. Tradeoffs also exist between increased expenditures on fire suppression versus fuels management (Mercer et al., 2007). The benefit/cost (B/C) assessment requires definition of a wildfire production function that defines the relationship between size and intensity of wildfires as it relates to alternative fuel management treatments, climate variables, and site-specific characteristics. Potential benefits of fuel treatments such as reduced wildfire risk, reduced fire suppression costs, and reduced structural losses will be site-specific. Thus, the site-specific analysis must account for the cumulative cost of fuel treatments, the likelihood of wildfire events with and without treatments, the effects and costs of fire suppression and post-fire restoration, and the effect of management actions and wildfires on resource conditions, structural damages, and saleable products over time (Kline, 2004). Given these complexities, only a few studies have estimated net economic benefits of fuel treatments in forested areas (Mercer et al., 2007; Prestemon et al., 2012), and only one recent study considered net economic benefits of fuel treatments on rangelands (Taylor et al. 2013).

Table 1. Estimated costs for alternative fuel management options on rangeland. a/Personal communication, Feb. 4, 2013, Dan Macon, Flying Mule Farm (http://flyingmulefarm.com/), custom land and vegetation services

Treatment	Source	Location	Description	Cost $/acre
Herbicide	Wolcott et al. 2007	Florida	Grass/Shrub/Tree Intermix	$68-$1,000+
	Torell et al. 2005	New Mexico	Closed canopy of sagebrush, treat with tebuthiuron, aerial	$21
	Taylor et al. 2013	Utah	Closed canopy of sagebrush, treat with tebuthiuron, aerial	$31
	Taylor et al. 2013	Utah	Closed canopy of sagebrush, treat with tebuthiuron, ground application	$52
	Nader et al. 2007	California	Grass/Shrub	$25-$250
Hand Crews	Dan Macon[a]	California	Brush removal	$350 - $600
Mechanical	Nader et al. 2007	California	Mowing on grassland	$25-$40
	Wolcott et al. 2007		Mowing on grass/shrubland	$35-$500
Prescribed Fire	Nader et al. 2007	California	Brush, range, and grassland burns	<$150
	Cleaves et al. 2000		Brush, range, and grassland burns	$57
	Mercer et al. 2007		Southeast U.S.	$11- $344
	Taylor et al. 2013	Utah	Healthy Sagebrush, perennial understory	$20
	Taylor et al. 2013	Utah	Pinyon-Juniper with mature shrubs	$46
Combined Treatments	Taylor et al. 2013	Utah	Closed-canopy pinyon-juniper; brush management, herbicide, and reseeding	$205
	Taylor et al. 2013	Utah	Annual grass dominated; prescribed fire, herbicide, and reseeding	$165
Targeted Grazing	Nader et al. 2007	California	Targeted grazing with goats	$60-$70
	Dan Macon[a]	California	California sheep and goat grazing contractor	
			< 20 acres	$300
			> 20 acres	$150 - $200
	Varelas (2012)	New Mexico	Targeted cattle grazing	$45-$65

The net economic benefits of selected fuel treatments in the sagebrush ecosystems of the Great Basin were estimated in a study by Taylor et al. (2013). State-and-transition models were used to define vegetative characteristic changes expected to occur based on natural succession and disturbance interactions for sites dominated by Wyoming big sagebrush and mountain big sagebrush. The analysis was a probabilistic benefit/cost assessment where the benefit of the treatment was considered to be fire suppression costs averted over the next two hundred years because alternative fuel management treatments were undertaken. The success of fuel treatments (movement to a state with less shrubs and invasive annual grasses) was considered to be uncertain with re-treatment required when the simulation projected a treatment failure.

Because healthier ecological states with relatively high perennial grass cover and without an overgrown sagebrush canopy (sagebrush present but not ecologically dominant) were considered to be resilient and responsive to treatment, and with a marked reduction in fire frequency following relatively low-cost fuel treatments, these healthy areas were found to be more economical to treat than were mature sagebrush areas with a depleted perennial herbaceous understory or areas invaded with annual grasses. The estimated B/C ratio ranged from a high of 13.3 for productive Wyoming sagebrush steppe sites (a relatively low-cost controlled burn treatment) to less than one (i.e., not economically efficient) for high shrub densities and levels of annual grass invasion (requiring expensive and often unsuccessful treatments). Similarly, the estimated B/C ratio for mountain big sagebrush sites decreased with a rise in brush canopy and annual grass invasion. The implication is that the desired time for fuel treatments is before a decadent shrub canopy (one with considerable dead standing biomass) occupies the area and annual grass invasion occurs.

No known studies have quantified the net economic benefits of grazing treatments for fuels management. The analysis would be quite different from that of Taylor et al. (2013) because the effects of grazing treatments would generally only last one or two years: the herbaceous understory regrows and the treatment must be reapplied. However, several broad conclusions might be drawn. First, grazing treatments would potentially be an economical alternative to the prescribed burn treatment suggested by Taylor et al. (2013) specifically for areas with relatively low shrub cover where perennial grasses dominate. Areas where sagebrush fuel loads are low and herbaceous fuel loads are high are the conditions most favorable for grazing treatments (Figure 6). Second, given the relatively short benefit period for the grazing treatment, unless the brush canopy is significantly altered, the cost of the treatment must remain relatively low. The harvested forage would contribute an additional grazing benefit to livestock production if previously unused forage were harvested.

Negative potential ecological impacts from grazing treatments are of concern, as are treatment costs (Table 1). Varelas (2012) estimated the cost of targeted cattle grazing treatments increased by about $18/hectare ($7.30/acre) for each 89 kg/hectare (100 lbs/acre) of herbaceous material removed by grazing animals. Targeted cattle grazing treatments using herding and low moisture blocks to hold cattle on targeted areas were found to be effective and cost competitive ($123/hectare [$50/acre]) when the standing herbaceous materials were reduced by about 45% (from 1,161 kg/hectare [1,300 lbs/acre] to about 536 kg/hectare [600 lbs/acre]).

Summary and Remaining Knowledge Gaps

The legacy of early post-settlement livestock grazing has played an important role in shaping vegetation dynamics in sagebrush ecosystems. High intensity and severe grazing in the late 1800s contributed to a dramatic reduction in both fine herbaceous fuels and fire frequency, and provided a competitive advantage for, and consequent increase in, woody plants. The introduction of exotic annual grasses in the late 1800s to early 1900s radically altered the fuel characteristics of many sites in the Great Basin. Over the last several decades, reduced grazing pressure, increased cover of flammable exotic annuals, increased human activity, and more recently, a longer climate-induced fire season (Chambers & Pellant, 2008), have all led to the current situation in the Great Basin where fires are larger and more frequent than 25+ years ago. Wildfires burn frequently enough to prevent establishment of sagebrush and cause a change in vegetation types across this vast region.

There are several ways contemporary livestock grazing practices can affect the extent and behavior of fires in sagebrush-dominated ecosystems. These include cumulative effects that occur on decadal time scales and that alter plant community composition (i.e., woody versus herbaceous) and those influenced annually through changes in fuel loads. Over decades, livestock grazing can change the relative proportions of shrubs, perennial grasses, and annual grasses, altering the fuel composition. On an annual basis, grazing can reduce the amount of herbaceous fine fuels, including cheatgrass, forbs and small twigs of woody plants. Grazing can reduce fire spread and intensity by removing understory vegetation, reducing the amount of fuel, and accelerating the decay of litter through trampling. This altering of fuels continuity can create patchy burns that result in unburned islands of vegetation providing seed sources for re-establishment of plants after the burn.

The effects of grazing could result in fires that burn at lower intensity, increased patchiness, decreased rate of spread, and increased subsequent survival of plants after fire. The specific outcome will depend on the fire weather conditions and the structural composition of the plant community when a fire occurs. As fire weather conditions become extreme, the potential role of grazing on fire behavior is limited.

Fuels management programs that incorporate grazing treatments must consider the long-term effects of such treatments on both desired and undesired plant species, with desirability defined by site-specific management goals and objectives. Grazing practices can alter plant communities such that shrub density increases, perennial grasses decrease, and exotic annual grasses and other invasive species gain a foothold, an outcome that would decrease resistance to and resilience from fire. Sound grazing practices and targeted grazing efforts aimed at wildland fuel reduction, however, have a strong potential to decrease undesirable fire behavior. Reductions of fine fuels and the desirable alterations to wildfire behavior are often overlooked benefits from including sound grazing practices on the landscape.

We identified four main research gaps in understanding how grazing influences fire behavior in sagebrush ecosystems and the related fuel treatment economics. First, research and observations clearly support the statement that grazing can influence wildland fuels and thereby fire behavior. However, residual herbaceous biomass level thresholds required to stop or carry the spread of fire under various weather conditions are largely unknown. Second, it is not known how shrub properties (cover, height, structure, etc.) influence the probability that an area will burn under different weather conditions. Third, further research is needed to discern the effects of landscape scale grazing patterns on fire behavior. Fence-line contrasts suggest that uneven utilization or spatial variation in grazing systems at the pasture scale can contribute to stopping or carrying fires, thereby reducing the area burned. However, this hypothesis has not been tested at meaningful scales. Fourth, an important economic question is whether the resources expended to reduce wildfire risk result in net economic gains.

From an ecological point of view, many questions remain unanswered. Sagebrush ecosystems evolved with fire. However, invasive annual grasses have altered the nature and impact of fire in these systems. Fire will always play an important role in sagebrush steppe and semi-desert, with effects ranging from rejuvenation to destruction. Grazing is one of the tools rangeland managers can apply to moderate these effects.

Acknowledgements

The authors would like to thank Dr. Stephen Bunting, the Bureau of Land Management, Owyhee Initiative (http://www.owyheeinitiative.org/), and Great Basin Fire Science Delivery Project (http://www.gbfiresci.org/) for support to gather this information and for providing valuable review in the development of this synthesis. The research was also supported by Agricultural Experiment Stations at Idaho, Oregon, and New Mexico.

Common and Scientific Names of Plants Listed in Text According to the USDA PLANTS Database (http://www.plants.usda.gov/).

Common Name	Scientific Name
Basin big sagebrush	*Artemisia tridentate Nutt. ssp. tridentata*
Bluebunch wheatgrass	*Pseudoroegneria spicata* (Pursh) Á. Löve
Bottlebrush squirreltail	*Elymus elymoides* (Raf.) Swezey
Cheatgrass	*Bromus tectorum* L.
Crested wheatgrass	*Agropyron cristatum* (L.) Gaertn.
Medusahead	*Taeniatherum caput-medusae* (L.) Nevski
Mountain big sagebrush	*Artemisia tridentata* Nutt. ssp*. vaseyana* (Rydb.) Beetle
Red brome	*Bromus rubens* L.
Sagebrush	*Artemisia* spp.
Threetip sagebrush	*Artemisia tripartita* Rydb.
Wyoming big sagebrush	*Artemisia tridentate Nutt. ssp. wyomingensis* Beetle & Young

Common and Scientific Names of Animals Listed in Text According to the Integrated Taxonomic Information System (www.itis.gov).

Common Name	Scientific Name
Goat	*Capra hircus*
Horses	*Equus caballus*
Sheep	*Ovis aries*

Literature Cited

Adler, P., Raff, D., & Lauenroth, W. (2001). The effect of grazing on the spatial heterogeneity of vegetation. *Oecologia*, *128*(4), 465–479. doi:10.1007/s004420100737

Anderson, J.E., & Holte, K.E. (1981). Vegetation development over 25 years without grazing on sagebrush-dominated rangeland in southeastern Idaho. *Journal of Range Management*, *34*(1), 25–29. doi:10.2307/3898446

Anderson, J.E., & Inouye, R.S. (2001). Landscape-scale changes in plant species abundance and biodiversity of a sagebrush steppe over 45 years. *Ecological Monographs*, *71*(4), 531–556. doi:10.1890/0012-9615(2001)071[0531:LSCIPS]2.0.CO;2

Anderson, M.T., & Frank, D.A. (2003). Defoliation effects on reproductive biomass: Importance of scale and timing. *Journal of Range Management*, *56*(5), 501–516. doi:10.2307/4003843

Andrews P.L. (2008). *BehavePlus fire modeling system, version 5.0: Variables* (General Technical Report No. 213WWW). Fort Collins, CO, USA: US Department of Agriculture, US Forest Service, Rocky Mountain Research Station.

Angell, R.F. (1997). Crested wheatgrass and shrub response to continuous or rotational grazing. *Journal of Range Management*, *50*(2), 160–164. doi:10.2307/4002374

Archibald, S., Bond, W.J., Stock, W.D., & Fairbanks, D.H.K. (2005). Shaping the landscape: Fire-grazer interactions in an African savanna. *Ecological Applications*, *15*(1), 96-109. doi:10.1890/03-5210

Austin, D.D., & Urness, P.J. (1998). Vegetal change on a northern Utah foothill range in the absences of livestock grazing between 1948 and 1982. *Western North American Naturalist, 58*(2), 181-191.

Balch, J.K., Bradley, B.A., D'Antonio, C.M., & Gómez-Dans, J. (2013). Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Global Change Biology*, *19*(1), 173–183. doi:10.1111/gcb.12046

Beever, E.A., Tausch, R.J., & Thogmartin, W.E. (2008). Multi-scale responses of vegetation to removal of horse grazing from Great Basin (USA) mountain ranges. *Plant Ecology*, *196*(2), 163–184. doi:10.1007/s11258-007-9342-5

Belsky, A.J., & Blumenthal, D.M. (1997). Effects of livestock grazing on stand dynamics and soils in upland forests of the Interior West. *Conservation Biology*, *11*(2), 315–327. doi:10.1046/j.1523-1739.1997.95405.x

Blackmore, M., & Vitousek, P.M. (2000). Cattle grazing, forest loss, and fuel loading in a dry forest ecosystem at Pu'u Wa'aWa'a ranch, Hawaii. *Biotropica*, *32*(4a), 625–632. doi:10.1111/j.1744-7429.2000.tb00509.x

Blank, R.R., & Morgan, T. (2012). Mineral nitrogen in a crested wheatgrass stand: Implications for suppression of cheatgrass. *Rangeland Ecology & Management*, *65*(1), 101–104. doi:10.2111/REM-D-10-00142.1

Booth, M.S., Caldwell, M.M., & Stark, J.M. (2003). Overlapping resource use in three Great Basin species: Implications for community invasibility and vegetation dynamics. *Journal of Ecology, 91*(1), 36-48. doi:10.1046/j.1365-2745.2003.00739.x

Bork, E.W., West, N.E., & Walker, J.W. (1998). Cover components on long-term seasonal sheep grazing treatments in three-tip sagebrush steppe. *Journal of Range Management*, *51*(3), 293–300. doi:10.2307/4003414

Bradford, J.B., & Lauenroth, W.K. (2006). Controls over invasion of *Bromus tectorum*: The importance of climate, soil, disturbance and seed availability. *Journal of Vegetation Science*, *17*(6), 693–704. doi:10.1111/j.1654-1103.2006.tb02493.x

Britton, C.M., Clark, R.G., & Sneva, F.A. (1981). Will your sagebrush range burn? *Rangelands*, *3*(5), 207–208.

Brooks, M.L., D'Antonio, C.M., Richardson, D.M., Grace, J.B., Keeley, J.E., DiTomaso, J.M., Hobbes, R.J. Pellant, M., & Pyke, D. (2004). Effects of invasive alien plants on fire regimes. *BioScience*, *54*(7), 677–688. doi:10.1641/0006-3568(2004)054[0677:EOIAPO]2.0.CO;2

Brown, J.K. (1982). *Fuel and fire behavior prediction in big sagebrush* (Report No. 290). Ogden, UT, USA: US Department of Agriculture, US Forest Service, Intermountain Research Station.

Bunting, S.C., Kilgore, B.M., & Bushey, C.L. (1987). *Guidelines for prescribed burning sagebrush-grass rangelands in the northern Great Basin* (Report No. 231). Ogden, UT, USA: US Department of Agriculture, US Forest Service, Intermountain Research Station.

Buttkus, H., & Bose, R.J. (1977). Characterization of a monoterpenoid ether from the essential oil of sagebrush (*Artemisia tridentata*). *Journal of the American Oil Chemists' Society*, *54*(5), 212–214. doi:10.1007/BF02676278.

Chambers, J.C., & Pellant M. (2008). Climate change impacts on northwestern and intermountain United States rangelands. *Rangelands*, *30*(3), 29-33. doi:10.2111/1551-501X(2008)30%5B29:CCIONA%5D2.0.CO;2

Chambers, J.C., Roundy, B.A., Blank, R.R., Meyer, S.E., & Whittaker, A. (2007). What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? *Ecological Monographs*, *77*(1), 117–145. doi:10.1890/05-1991

Chambers, J.C., Bradley, B.A., Brown, C.S., D'Antonio, C., Germino, M.J., Grace, J.B., Hardegree, S.P., Miller, R.F., & Pyke, D.A. (2013). Resilience to stress and disturbance and resistance to *Bromus tectorum* invasion in cold desert shrublands of western North America. *Ecosystems*. doi:10.1007/s10021-013-9725-5. Available online: http://link.springer.com/search?query=cheatgrass&search-within=Journal&facet-publication-title=Ecosystems#page-1

Cheney, P., & Sullivan, A. (Eds.). (2008). *Grassfires: Fuel, weather and fire behaviour*. Collingwood, Victoria, Australia: Csiro Publishing.

Cleaves, D.A., Martinez, J., & Haines, T.K. (2000). *Influences on prescribed burning activity and costs in the National Forest System* (General Technical Report No. 37). Asheville, NC, USA: US Department of Agriculture, US Forest Service, Southern Research Station.

Colket, E. (2003). *Long-term vegetation dynamics and post-fire establishment of sagebrush steppe* (Master's Thesis). University of Idaho, Moscow, ID, USA.

Cottam, W.P., & Evans, F.R. (1945). A comparative study of the vegetation of grazed and ungrazed canyons of the Wasatch Range, Utah. *Ecology*, *26*(2), 171–181. doi:10.2307/1930822

Courtois, D.R., Perryman, B.L., & Hussein, H.S. (2004). Vegetation change after 65 years of grazing and grazing exclusion. *Journal of Range Management, 57*(6), 574–582. doi:10.2307/4004011

D'Antonio, C.M., & Vitousek, P.M. (1992). Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics*, *23*, 63–87. doi:10.1146/annurev.es.23.110192.000431

Daddy, F., Trlica, M.J., & Bonham, C.D. (1988). Vegetation and soil water differences among big sagebrush communities with different grazing histories. *The Southwestern Naturalist, 33*(4), 413-424. doi:10.2307/3672209

Daubenmire, R.F. (1940). Plant succession due to overgrazing in the *Agropyron* bunchgrass prairie of southeastern Washington. *Ecology*, *21*(1), 55–64. doi:10.2307/1930618

Davies, K.W., Svejcar, T.J., & Bates, J.D. (2009). Interaction of historical and nonhistorical disturbances maintains native plant communities. *Ecological Applications*, *19*(6), 1536–1545. doi:10.1890/09-0111.1

Davies, K.W., Bates, J.D., Svejcar, T.J., & Boyd, C.S. (2010). Effects of long-term livestock grazing on fuel characteristics in rangelands: An example from the sagebrush steppe. *Rangeland Ecology and Management*, *63*(6), 662–669. doi:10.2111/REM-D-10-00006.1

Davies, K.W., Boyd, C.S., Beck, J.L., Bates, J.D., Svejcar, T.J., & Gregg, M.A. (2011). Saving the sagebrush sea: An ecosystem conservation plan for big sagebrush plant communities. *Biological Conservation*, *144*(11), 2573–2584. doi:10.1016/j.biocon.2011.07.016

Davison, J. (1996). Livestock grazing in wildland fuel management programs. *Rangelands*, *18*(6), 242–245.

Diamond, J.M., Call, C.A., & Devoe, N. (2009). Effects of targeted cattle grazing on fire behavior of cheatgrass-dominated rangeland in the northern Great Basin, USA. *International Journal of Wildland Fire*, *18*(8), 944–950. doi:10.1071/WF08075

DiTomaso, J.M., Kyser, G.B., George, M.R., Doran, M.P., & Laca, E.A. (2008). Control of medusahead (*Taeniatherum caput-medusae*) using timely sheep grazing. *Invasive Plant Science and Management*, *1*(3), 241–247. doi:10.1614/IPSM-07-031.1

Emmerich, F.L., Tipton, F.H., & Young, J.A. (1993). Cheatgrass: Changing perspectives and management strategies. *Rangelands*, *15*(1), 37–40.

France, K.A., Ganskopp, D.C., & Boyd, C.S. (2008). Interspace/undercanopy foraging patterns of beef cattle in sagebrush habitats. *Rangeland Ecology & Management*, *61*(4), 389–393. doi:10.2111/06-072.1

Freese, E., Stringham, T., Simonds, G., & Sant, E. (2013). Grazing for fuels management and sage grouse habitat maintenance and recovery: A case study from Squaw Valley Ranch. *Rangelands,* 35(4), 13–17. doi: 10.2111/RANGELANDS-D-13-00008.1

Ganskopp, D. (1988). Defoliation of Thurber needlegrass: Herbage and root responses. *Journal of Range Management*, *41*(6), 472–476. doi:10.2307/3899519

Goodwin, J.R., Doescher, P.S., Eddleman, L.E., & Zobel, D.B. (1999). Persistence of Idaho fescue on degraded sagebrush-steppe. *Journal of Range Management*, *52*(2), 187–198. doi:10.2307/4003515

Hempy-Mayer, K., & Pyke, D.A. (2008). Defoliation effects on *Bromus tectorum* seed production: Implications for grazing. *Rangeland Ecology and Management*, *61*(1), 116–123. doi:10.2111/07-018.1

Hesseln, H. (2000). The economics of prescribed burning: A research review. *Forest Science*, *46*(3), 322-334.

Hobbs, N.T. (1996). Modification of ecosystems by ungulates. *The Journal of Wildlife Management*, *60*(4), 695–713. doi:10.2307/3802368

Hobbs, N.T., Schimel, D.S., Owensby, C.E., & Ojima, D.S. (1991). Fire and grazing in the tallgrass prairie: Contingent effects on nitrogen budgets. *Ecology*, *72*(4), 1374–1382. doi:10.2307/1941109

Holechek, J.L., & Stephenson, T. (1983). Comparison of big sagebrush vegetation in northcentral New Mexico under moderately grazed and grazing excluded conditions *Artemisia tridentata*. *Journal of Range Management, 36*(4), 455-456. doi:10.2307/3897939

Holechek, J.L., Baker, T.T., Boren, J.C., & Galt, D. (2006). Grazing impacts on rangeland vegetation: What we have learned. *Rangelands*, *28*(1), 7–13. doi:10.2111/1551-501X(2006)28.1[7:GIORVW]2.0.CO;2

Hoover, A.N., & Germino, M.J. (2012). A common-garden study of resource-island effects on a native and an exotic, annual grass after fire. *Rangeland Ecology & Management, 65*(2), 160-170. doi:10.2111/REM-D-11-00026.1

Hull, A.C., & Pechanec, J.F. (1947). Cheatgrass–A challenge to range research. *Journal of Forestry*, *45*(8), 555–564.

Humphrey, L.D., & Schupp, E.W. (2001). Seed banks of *Bromus tectorum*-dominated communities in the Great Basin. *Western North American Naturalist*, *61*(1), 85–92.

Klemmedson, J.O., & Smith, J.G. (1964). Cheatgrass (*Bromus tectorum* L.). *The Botanical Review*, *30*(2), 226–262. doi:10.1007/BF02858603

Kline, J.D. (2004*). Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the Nation's forests* (Research Note No. 542). Portland, OR, USA: US Department of Agriculture, US Forest Service, Pacific Northwest Research Station.

Knapp, P.A. (1996). Cheatgrass (*Bromus tectorum* L) dominance in the Great Basin desert: History, persistence, and influences to human activities. *Global Environmental Change*, *6*(1), 37–52. doi:10.1016/0959-3780(95)00112-3

Knick, S.T., & Rotenberry, J.T. (1997). Landscape characteristics of disturbed shrubsteppe habitats in southwestern Idaho (USA). *Landscape Ecology, 12*(5), 287–297. doi:10.1023/A:1007915408590

Krueger, W.C., Sanderson, M.A., Cropper, J.B., Miller-Goodman, M., Kelley, C.E., Pieper, R.D., Shaver, P. L., & Trlica, M.J. (2002). *Environmental impacts of livestock on U.S. grazing lands*. Ames, IA, USA: Council for Agricultural Science and Technology.

Launchbaugh, K., Brammer, B., Brooks, M., Bunting, S., Clark, P., Davison, J., Fleming, M., Kay, R., Pellant, M., Dyke, D.A., & Wylie, B. (2008). *Interactions among livestock grazing, vegetation type, and fire behavior in the Murphy Wildland Fire Complex, July 2007* (Report No. 1214). Washington, D.C.: US Department of the Interior, United States Geological Survey.

Laycock, W.A. (1967). How heavy grazing and protection affect sagebrush-grass ranges. *Journal of Range Management*, *20*(4), 206–213. doi:10.2307/3896253

Leonard, S., Kirkpatrick, J., & Marsden-Smedley, J. (2010). Variation in the effects of vertebrate grazing on fire potential between grassland structural types. *Journal of Applied Ecology*, *47*(4), 876–883. doi:j.1365-2664.2010.01840.x

Link, S.O., Keeler, C.W., Hill, R.W., & Hagen, E. (2006). *Bromus tectorum* cover mapping and fire risk. *International Journal of Wildland Fire*, *15*(1), 113–119. doi:10.1071/WF05001

Loeser, M.R.R., Sisk, T.D., & Crews, T.E. (2007). Impact of grazing intensity during drought in an Arizona grassland. *Conservation Biology*, *21*(1), 87–97. doi:j.1523-1739.2006.00606.x

Mack, R.N. (1981). Invasion of *Bromus tectorum* L. into Western North America: An ecological chronicle. *Agro-ecosystems*, *7*(2), 145–165. doi:10.1016/0304-3746(81)90027-5

Mack, R.N., & Pyke, D.A. (1983). The demography of *Bromus tectorum*: Variation in time and space. *The Journal of Ecology*, *71*(1), 69–93. doi:10.2307/2259964

Manier, D.J., & Hobbs, T.N. (2006). Large herbivores influence the composition and diversity of shrub-steppe communities in the Rocky Mountains, USA. *Oecologia*, *146*(4), 641–651. doi:10.1007/s00442-005-0065-9

McAdoo, J.K., Schultz, B.W., & Swanson, S.R. (2013). Aboriginal precedent for active management of sagebrush perennial grass communities in the Great Basin. *Rangeland Ecology and Management*, *66*(3), 241-253. doi:10.2111/REM-D-11-00231.1

McNaughton, S.J. (1992). The propagation of disturbance in savannas through food webs. *Journal of Vegetation Science*, *3*(3), 301–314. doi:10.2307/3235755

Mercer, D.E., Prestemon, J.P., Butry, D.T., & Pye, J.M. (2007). Evaluating alternative prescribed burning policies to reduce net economic damages from wildfire. *American Journal of Agricultural Economics*, *89*(1), 63-77. doi:10.1111/j.1467-8276.2007.00963.x

Miller, M. (2000). Fire Autecology. In J.K. Brown & J.K. Smith (Eds.), *Wildland fire in ecosystems: Effects of fire on flora* (General Technical Report No. 42, vol. 2, pp. 9-34). Ogden, UT, USA: US Department of Agriculture, US Forest Service, Rocky Mountain Research Station.

Miller, R.F., & Eddleman, L. (2000). *Spatial and temporal changes of sage grouse habitat in the sagebrush biome* (Technical Bulletin No. 151). Corvallis, OR, USA: Oregon State University, Agricultural Experiment Station.

Miller, R.F., Haferkamp, M.R., & Angell, R.F. (1990). Clipping date effects on soil water and regrowth in crested wheat grass. *Journal of Range Management, 43*(3), 253-257. doi:10.2307/3898684

Miller, R.F., Svejcar, T.J., & West, N.E. (1994). Implications of livestock grazing in the Intermountain sagebrush region: Plant composition. In M. Vavra, W.A. Laycock, and R.D. Pieper (Eds.), *Ecological implications of herbivory in the west* (pp. 101–146). Denver, CO, USA: Society for Range Management.

Mosley, J.C. (1994). Prescribed sheep grazing to suppress cheatgrass: A review. *Sheep Research Journal*, *12*(2), 79–91.

Mosley, J.C., & Roselle, L. (2006). Targeted livestock grazing to suppress invasive annual grasses. In K. L. Launchbaugh & J. W. Walker (Eds.), *Targeted grazing: A natural approach to vegetation management and landscape enhancement* (pp. 67–76). Centennial, CO, USA: American Sheep Industry Association.

Nader, G., Henkin, Z., Smith, E., Ingram, R., & Narvaez, N. (2007). Planned herbivory in the management of wildfire fuels. *Rangelands, 29*(5), 18–24. doi:10.2111/1551-501X(2007)29[18:PHITMO]2.0.CO;2

(NWCG) National Wildfire Coordinating Group. (2012). *Glossary of wildland fire terminology*. PMS 205. Boise, Idaho: National Interagency Fire Center. Retrieved from http://www.nwcg.gov/pms/pubs/glossary/

Papanastasis, V.P. (2009). Restoration of degraded grazing lands through grazing management: Can it work? *Restoration Ecology*, *17*(4), 441–445. doi:10.1111/j.1526-100X.2009.00567.x

Peters, E.F., & Bunting, S.C. (1994). Fire conditions pre- and post occurrence of annual grasses on the Snake River Plain. In S. B. Monsen & S. G. Kitchen (Eds.), *Proceedings: Ecology and management of annual rangelands* (General Technical Report No. 313, pp. 31–36). Ogden, UT, USA: US Department of Agriculture, US Forest Service, Intermountain Research Station.

Prestemon, J.P., Abt, K.L., & Barbour, R.J. (2012). Quantifying the net economic benefits of mechanical wildfire hazard treatments on timberlands of the western United States. *Forest Policy & Economics*, *21*, 44-53. doi:10.1016/j.forpol.2012.02.006

Pyke, D.A. (1986). Demographic responses of *Bromus tectorum* and seedlings of *Agropyron spicatum* to grazing by small mammals: Occurrence and severity of grazing. *The Journal of Ecology*, *74*(3), 739–754.

Reinhardt, E.D., Keane, R.E., Calkin, D.E., & Cohen, J.D. (2008). Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *Forest Ecology and Management*, *256*(12), 1997-2006. doi:10.1016/j.foreco.2008.09.016

Rice, B., & Westoby, M. (1978). Vegetative responses of some Great Basin shrub communities protected against jackrabbits or domestic stock. *Journal of Range Management*, *31*(1), 28–34. doi:10.2307/3897627

Robertson, J.H. (1971). Changes on a sagebrush-grass range in Nevada ungrazed for 30 years. *Journal of Range Management*, *25*(5), 397–400. doi:10.2307/3896614

Sapsis, D.B., & Kauffman, J.B. (1991). Fuel consumption and fire behavior associated with prescribed fires in sagebrush ecosystems. *Northwest Science*, *65*(4), 173–179.

Schmelzer, L., B. Perryman, B. Bruce, B. Chultz, K. McAdoo, G. McCuin, S. Swanson, J. Wilder, & K. Conley. *In press.* Reducing cheatgrass (*Bromus tectorum L.*) fuel loads using fall cattle grazing: a case study. Professional Animal Scientist.

Scott, J.H., & Burgan, R.E. (2005). *Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model* (General Technical Report No. 153). Fort Collins, CO, USA: US Department of Agriculture, US Forest Service, Rocky Mountain Research Station

Sikkink, P.G., Lutes, D.C., & Keane, R.E. (2009). *Field guide for identifying fuel loading models* (General Technical Report No. 225). Fort Collins, CO, USA: US Department of Agriculture, US Forest Service, Rocky Mountain Research Station.

Smith, B., Sheley, R., & Svejcar, T.J. (2012). *Grazing Invasive annual grasses: The green and brown guide*. Burns, OR, USA: US Department of Agriculture, Agricultural Research Service.

Stewart, G., & Hull, A.C. (1949). Cheatgrass (*Bromus tectorum* L.) – An ecologic intruder in southern Idaho. *Ecology*, *30*(1), 58–74. doi:10.2307/1932277

Stronach, N.R.H., & McNaughton, S.J. (1989). Grassland fire dynamics in the Serengeti ecosystem, and a potential method of retrospectively estimating fire energy. *Journal of Applied Ecology*, *26*(3), 1025–1033. doi:10.2307/2403709

Svejcar, T., & Tausch, R. (1991). Anaho Island, Nevada: A relict area dominated by annual invader species. *Rangelands*, *13*(5), 233–236.

Tausch, R.J., Nowak, R.S., Bruner, A.D., & Smithson, J. (1994). Effects of simulated fall and early spring grazing on cheatgrass and perennial grass in western Nevada. In S.B. Monsen & S. G. Ketchen (Eds.) *Proceedings—Ecology and Management of Annual Rangelands* (General Technical Report No. 313), (pp. 113-119). Ogden, UT, USA: US Department of Agriculture, US Forest Service, Intermountain Research Station.

Taylor, C.A. (2006). Targeted grazing to manage fire risk. In K. Launchbaugh& J. Walker (Eds.), *Targeted grazing: A natural approach to vegetation management and landscape enhancement* (pp. 107–112). Englewood, CO, USA: American Sheep Industry Association.

Taylor, M.H., Rollins, K., Kobayashi, M., & Tausch, R.J. (2013). The economics of fuel management: Wildfire, invasive plants, and the dynamics of sagebrush rangelands in the western United States. *Journal of Environmental Management, 126*, 157-173. doi:10.1016/j.jenvman.2013.03.044

Tisdale, E.W., Hironaka, M., & Fosberg, M.A. (1965). An area of pristine vegetation in Craters of the Moon National Monument, Idaho. *Ecology*, *46*(3), 349–352. doi:10.2307/1936343

Torell, L.A., McDaniel, K.C., & Ochoa, C.G. (2005). Economics and optimal frequency of Wyoming big sagebrush control with tebuthiuron. *Rangeland Ecology & Management*, *58*(1), 77-84. doi:10.2111/1551-5028(2005)58<77:EAOFOW>2.0.CO;2

Vale, T.R. (1974). Sagebrush conversion projects: An element of contemporary environmental change in the western United States. *Biological Conservation*, *6*(4), 274–284. doi:10.1016/0006-3207(74)90006-8

Vallentine, J.F., & Stevens, A.R. (1994). Use of livestock to control cheatgrass: A review. In S.B. Monsen, & S.G. Ketchen (Eds.), *Proceedings—Ecology and management of* *annual rangelands* (General Technical Report No. 313). Ogden, UT, USA: US Department of Agriculture, US Forest Service, Intermountain Research Station.

Varelas, L.A. (2012). *Effectiveness and costs of using targeted grazing to alter fire behavior* (Master's Thesis). New Mexico State University, Las Cruces, NM, USA.

Vermeire, L.T., & Roth, A.D. (2011). Plains prickly pear response to fire: Effects of fuel load, heat, fire weather, and donor site soil. *Rangeland Ecology & Management*, *64*(4), 404-413. doi:10.2111/REM-D-10-00172.1

West, N.E., Provenza, F.D., Johnson, P.S., & Owens, M.K. (1984). Vegetation change after 13 years of livestock grazing exclusion on sagebrush semidesert in west central Utah. *Journal of Range Management*, *37*(3), 262–264. doi:10.2307/3899152

Whisenant, S.G., & Wagstaff, F.J. (1991). Successional trajectories of grazed salt desert shrubland. *Vegetatio, 94*(2), 133-140. doi:10.1007/BF00032627

Wilcox, B.P., Sorice, M. G., Angerer, J., & Wright, C.L. (2012). Historical changes in stocking densities on Texas rangelands. *Rangeland Ecology & Management*, *65*(3), 313-317. doi:10.2111/REM-D-11-00119.1

Wolcott, L., O'Brien, J.J., & Mordecai, K. (2007). A survey of land managers on wildland hazardous fuels issues in Florida: A technical note. *Southern Journal of Applied Forestry*, *31*(3), 148-150.

Wright, H.A. (1971). Why squirreltail is more tolerant to burning than needle-and-thread. *Journal of Range Management*, *24*(4), 277-284. doi:10.2307/3896943

Yeo, J.J. (2005). Effects of grazing exclusions on rangeland vegetation and soils, east central Idaho. *Western North American Naturalist*, *65*(1), 91–102.

Yorks, T.P., West, N.E., & Capels, K.M. (1992). Vegetation differences in desert shrublands of western Utah's Pine Valley between 1933 and 1989. *Journal of Range Management, 45*(6), 569–578. doi:10.2307/4002574

Young, J.A., & Allen, F.L. (1997). Cheatgrass and range science: 1930-1950. *Journal of Range Management, 50*(5), 530–535. doi:10.2307/4003709

Young, J.A., & Blank, R.R. (1995). Cheatgrass and wildfires in the Intermountain West. In J. Lovich, J. Randall, & M. Kelly, (Eds.), *California exotic pest plant council symposium proceedings* (pp. 1–3). Sacramento, CA, USA: California Exotic Pest Plant Council.

Young, J.A., & Clements, C.D. (2007). Cheatgrass and grazing rangelands. *Rangelands, 29*(6), 15–20. doi:10.2111/1551-501X(2007)29[15:CAGR]2.0.CO;2

Young, J.A., & Sparks, B.A. (2002). *Cattle in the cold desert*. Reno, NV, USA: University of Nevada Press.

Young, J.A., Evans, R.A., Eckert Jr, R. E., & Kay, B. L. (1987). Cheatgrass. *Rangelands, 9*(6), 266–270.

Zimmerman, G.T., & Neuenschwander, L.F. (1984). Livestock grazing influences on community structure, fire intensity, and fire frequency within the Douglas-fir/ninebark habitat type. *Journal of Range Management, 37*(2), 104–110. doi:10.2307/3898893