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Wildlife Responses to Brush Management: A Contemporary Evaluation☆

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ABSTRACT

Wildlife-associated recreation and biodiversity are important management considerations on public and private rangelands, making it imperative that rangeland professionals explicitly take wildlife conservation into account in vegetation management planning and implementation. Here, we synthesize the literature reporting effects of brush management on wildlife and make recommendations for applying brush management to accomplish wildlife conservation objectives. Key observations arising from our synthesis are that habitat-related terminology is often misused in brush management literature. Recommending brush management as a "wildlife habitat improvement" tool is a non sequitur because habitat is species specific and brush management has different consequences for different species of wildlife and plants. Communication between resource managers and stakeholders can be improved by making it clear that habitat is species specific and then identifying what constitutes a benefit of brush management. Changes in resources resulting from brush management may not benefit targeted wildlife species unless these changes overcome some limiting factor or factors. Wildlife responses to brush management treatments are too complex to make broad generalizations because they are mediated by environmental factors and depend on the plant community, size and configuration of the area manipulated, type of treatment applied, and time since application. Prescriptions aimed at improving habitat for wildlife generalists may have relatively modest positive effects on that group but have potentially detrimental effects on specialists. Given this potential trade-off, an idea to consider is that it may be best to err on the side of using brush management as a tool to manage habitat for specialists. Brush management plans and recommendations should take into account trade-offs such as benefiting grassland wildlife at the expense of woodland species. Taking a broader "systems" perspective that balances needs of wildlife in conjunction with other ecosystem services affected by woody plant encroachment and brush management should be a goal of natural resource managers.

Introduction

One of the most striking land cover changes over the past 150 yr on rangelands worldwide has been the proliferation of trees and shrubs, often in conjunction with the loss of herbaceous vegetation and a fundamental alteration of ecosystem processes (Archer et al., 2017). In some cases, native woody plants are increasing in stature and density within their historic geographic distributions; in others, non-native woody plants are becoming dominant. Brush management, defined as the removal, reduction, or manipulation of nonherbaceous plants (Hamilton et al., 2004), is an integral component of rangeland management. However, this practice has historically been criticized, especially when broad-scale programs have narrowly focused on needs of livestock and have failed to consider impacts on wildlife (e.g., Klebenow, 1969; Belsky, 1996).

Rangelands provide biotic and abiotic resources for diverse assemblages of wildlife. Multiple-use mandates on federal lands and the revenue to landowners generated from hunting and ecotourism underscore the value of rangeland wildlife to society. Regarding the latter, in Texas, the potential of rangeland for wildlife-related recreation adds more to real estate values than agricultural production potential (Baen, 1997). About 33% of the private land in the United States is either leased or owned for wildlife-related recreation (Macaulay, 2016). Accordingly, leasing private land for wildlife recreation is an important source of income for landowners. Nationwide in the United States >$900 million is spent annually to lease private land for hunting with another $279.6 million spent for wildlife watching (Macaulay, 2016). The economic significance of wildlife recreation and the fact that returns from wildlife may exceed returns from livestock underscore the importance of accounting for wildlife needs when implementing brush management.

Decisions pertaining to the mixture of herbaceous and woody plants on managed landscapes are challenging because of variation among wildlife species in the kinds, structure, and amount of vegetation cover they require. Increases in woody plants have had mixed effects

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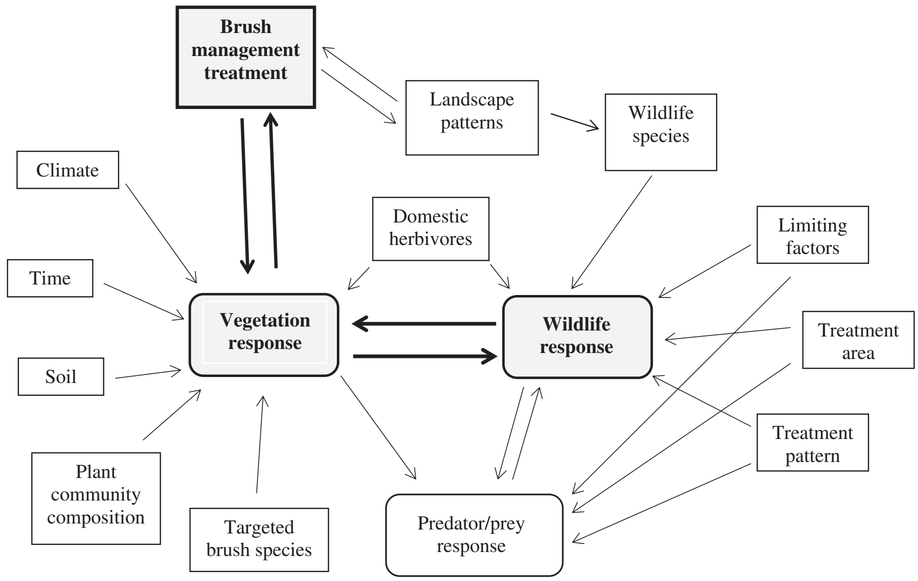

Figure 1. Wildlife response to brush management varies with time since treatment and is determined by a variety of interacting factors. For simplicity, only select feedbacks are shown.

on wildlife. For example, while woody plant proliferation on rangelands is considered among the primary causes of the continent-wide decline in the abundance of North American grassland birds (Brennan and Kuvlesky, 2005; Scholtz et al., 2017), it can benefit wildlife adapted to woody plant communities. Proliferation of non-native saltcedar (*Tamarix* spp.) is widely decried, and the plant has been targeted for reduction via brush management. Saltcedar, however, can perform important ecological roles, including providing habitat for the endangered southwestern willow flycatcher *(Empidonax traillii)* and other avifauna and wildlife taxa (Cohn, 2005; Shafroth et al., 2005). Removal of saltcedar could therefore spawn unintended problems that may need to be addressed in post-treatment restoration activities.

Our primary goal here is to provide a contemporary evaluation of how brush management, when applied as a conservation/restoration tool, affects wildlife and to present recommendations to help natural resource professionals improve planning, communication to stakeholders, and execution of brush management programs to accomplish wildlife conservation objectives. Information transfer from natural resource professionals to the public through scientific publications, technical bulletins, and other forms of communication has been hampered by overgeneralizing the expected benefits of brush management for wildlife. In our evaluation of how brush management affects wildlife, we highlight why such generalizations are often inappropriate. We also emphasize factors that should be accounted for when specifying how brush management may influence wildlife including 1) the effects of biotic factors that influence species- or functional group—specific responses to brush management with respect to gender, season of the year, foraging niche, population status, herbicide toxicity, and trophic level (e.g., predators vs. prey), 2) initial vegetation characteristics and the scale and pattern of brush management, and 3) how local brush management influences on wildlife are mediated by climate (temporal variability) and soils (spatial variability) (Fig. 1). Finally, during our evaluation of the literature we encountered frequent misuse of terminology pertaining to habitat and we make recommendations for improving communication by using appropriate terminology (Text Box 1).

Text Box 1
Definitions of terminology as used in this manuscript.

Cumulative effects—Cumulative effects refer to events, including brush management, that individually may be innocuous but that, over time, accumulate and act collectively to produce substantial and potentially deleterious impacts on wildlife and ecosystems (Odum, 1982; Krausman and Harris, 2011).
Functional group—collection of species that process resources to provide a specific ecosystem service or function (Blondel, 2003).
Edge species—species occurring in greatest abundance where two or more plant communities come together.
Grassland—ecosystems dominated by herbaceous graminoids.
Heterogeneous—temporally and spatially variable structure and composition of physical or biological components.
Homogeneous—little temporal or spatial variation in structure and composition of physical or biological components.
Interior species—species that occupy a certain plant community and avoid areas where plant communities meet and intermingle.
Landscape—a heterogeneous area of land sufficiently large to contain interacting ecosystems.
Landscape level or landscape scale—at a broad scale that encompasses the interacting components of a landscape; > 5 km^2 in size.
Legacy effects—modifications of the environment caused by abiotic or biotic factors that persist for a long time after the factor causing the modification has ceased activity or is no longer present (Cuddington, 2011).
Mosaic—a mixture of patches on the landscape.
Patch—an area with vegetation, soils, or other properties differing from its surroundings
Patch scale—a small scale that includes only an individual patch.
Savanna—shrubs or trees scattered throughout a grassy matrix
Shrubland—ecosystems characterized by short-statured, multistemmed woody plants.
Woodland—open-canopy, arboreal ecosystems.

Species, Gender, and Seasonal Requirements

Rangeland management literature and guidelines often contain statements such as "brush management is applied to maintain or enhance wildlife habitat." Broad statements such as these ignore the fact that habitat is species- or functional group-specific and create the false impression that reducing woody vegetation benefits all wildlife species (Hall et al., 1997; Krausman, 2002; Krausman and Morrison, 2016). Wildlife functional groups (see Text Box 1; Blondel, 2003) and species vary widely in their habitat requirements, ranging from grassland obligates to generalists to woodland obligates.

Brush removal may benefit grassland obligates while adversely impacting shrub- or woodland-adapted species (Coffman et al., 2014). Clearing a large tract of sagebrush (*Artemisia* spp.), for example, may benefit grassland birds (Reinkensmeyer et al., 2007). Conversely, management programs focused on reducing Wyoming big sagebrush could cause a decline in populations of sagebrush-obligate wildlife (Klebenow, 1969; Martin, 1970; Green and Flinders, 1980; Beck et al., 2012). Examination of the response of one sagebrush obligate, greater sage-grouse *(Centrocercus urophasianus)*, to brush management provides a poignant example of why generalizations that brush management has either a positive or a negative impact on wildlife are broad oversimplifications of a complex issue, even when only considering a single species.

Treatments removing sagebrush can negatively impact sage-grouse habitat by degrading hiding cover and food (Connelly et al., 2000; Crawford et al., 2004). Accordingly, fire is generally assumed to negatively impact sage-grouse habitat (Connelly et al., 2000). However, in higher-elevation sagebrush communities where sagebrush recovers relatively quickly compared with lower elevations, fire limits conifer encroachment. Thus, while fire may locally reduce sage-grouse habitat in the short term, long-term benefits accrue when sagebrush recovers (Boyd et al., 2017). Treatments that reduce sagebrush over extensive areas negatively impact sage-grouse (Connelly et al., 2000), whereas local, small-scale treatments, especially those that thin sagebrush, improve brood-rearing habitat in some situations (Cohn, 2005; Dahlgren et al., 2006).

Spatial variation in shrub community responses to brush management can be subtle but important. Mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana*) occurs on cooler, moister sites than Wyoming big sagebrush (*A. tridentata* Nutt. ssp. *wyomingensis*), and these communities differ in their response to brush management. Treating mountain big sagebrush can increase sage-grouse food sources (e.g., Dahlgren et al., 2006; Davies et al., 2012b), whereas treating Wyoming big sagebrush communities may increase exotic annual grass abundance without increasing sage-grouse food sources (Rhodes et al., 2010; Beck et al., 2012; Davies et al., 2012a).

Regulation of tree cover in shrublands can also be an important component of brush management for wildlife habitat. Greater sage-grouse habitat use declines with as little as 4% conifer (*Pinus* and *Juniperus* species) cover (Baruch-Mordo et al., 2013). Declines in sagebrush abundance with additional conifer proliferation (Reinkensmeyer et al., 2007; Miller et al., 2017) further diminish habitat quality (Miller et al., 2000). Accordingly, brush management targeting encroaching conifers would be expected to improve sagebrush communities for sage-grouse (e.g., Sandford et al., 2017).

Targeting conifer removal as a method of improving sagebrush communities for other wildlife has trade-offs and may not necessarily produce assumed outcomes. Treatments aimed at thinning pinyon-juniper, for example, can be detrimental to gray vireos *(Vireo vicinior)* while benefitting Brewer's sparrow *(Spizella breweri)* and bushtits *(Psaltriparius minimus)* (Crow and van Ripper, 2010). A review of the effects of reducing pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) abundance on wildlife found that 69% of animal species demonstrated little response to juniper reduction and that mule deer *(Odocoileus hemionus)* and elk *(Cervus elaphus)* responded positively to mechanical removal or thinning in < 10% and 20%, respectively, of the studies conducted (Bombaci and Pejchar, 2016).

General statements about brush management that ignore differences among wildlife subspecies may also have unintended consequences. Grassland is important for northern scaled quail *(Callipepla squamata pallida)* in Arizona, and it has been recommended that woody canopy cover be maintained at < 6% (Bristow and Ockenfels, 2006). Accordingly, brush management has been recommended to improve scaled quail habitat in areas dominated by woody plants (Campbell et al., 1973; Germano et al., 1983; Cantu et al., 2006). In contrast, Chestnut-bellied scaled quail *(C. s. catanogastris)* in southern Texas use areas with dense woody cover (Bridges et al., 2002). This subspecies selects species-rich woody plant communities that have not been disturbed by brush management and avoid cleared areas dominated by non-native grasses (Kline, 2015). Therefore, while brush management may benefit northern scaled quail when woody plant cover exceeds some maximum threshold, it is apparently detrimental to chestnut-bellied scaled quail.

Broad generalizations about wildlife responses to brush management gloss over the fact that brush management may affect sexes of the same wildlife species differently (Leslie et al., 1996; Stewart et al., 2003). Male and female white-tailed deer *(Odocoileus virginianus)* in Oklahoma, for example, used different herbicide and fire treatments (Leslie et al., 1996). Anticipated conservation benefits should, therefore, be stated on the basis of the species or functional group plant community preferences (grassland, shrubland, woodland); their trophic niche (granivores, insectivores, browsers, grazers, etc.); and differential gender responses, if any.

Brush management may also affect the same species differently depending on their seasonal use of the area treated. For example, thinning dense stands of mountain big sagebrush can benefit sage-grouse *(Centrocercus urophasianus)* during brood-rearing (Dahlgren et al., 2006) but may decrease its habitat value in Wyoming big sagebrush communities in the winter for sage-grouse and other wildlife species (Davies et al., 2009). Small-scale treatments that reduce dense stands of sagebrush can improve habitat for brood rearing when they increase forbs (Dahlgren et al., 2006). However, those same reductions, especially in Wyoming big sagebrush communities, can reduce winter habitat quality (Davies et al., 2009; Beck et al., 2012) when diets are almost solely composed of sagebrush (Wallestad and Eng, 1975; Crawford et al., 2004). Management that improves vegetation for a species in one season may therefore have negative consequences if it reduces value of the vegetation during a different season. Decisions regarding the type and timing of brush management should also take into account direct adverse impacts and seek to minimize them. For example, mechanical brush clearing during periods of active nesting would destroy eggs and kill nestlings, and prescribed burning may cause mortality if applied when individuals of the species of concern are not mobile enough to escape the fire.

Foraging Niche

Brush management may temporarily improve food accessibility, quality, and quantity for some wildlife species or functional groups (e.g., grazers) but reduce it for others (e.g., browsers, frugivores). A key word literature search yielded 53 published papers addressing 64 cases of effects of brush management treatments or combinations of treatments (e.g., fire and herbicides) on wildlife food plants. Effects on food plants ranged from positive (48%) to neutral (31% with no or short-term [<3 yr] increases) to negative (20%). In most cases, negative responses occurred where brush management reduced key shrub-associated foods (e.g., mistletoe [*Phoradendron* spp.], a parasitic plant on honey mesquite [*Prosopis glandulosa* Torr.] eaten by deer; Quinton et al., 1979); reduced browse plants (Fulbright and Beasom, 1987; Ruthven et al., 1993); or increased thorns or secondary compounds in shrub regrowth (Schindler and Fulbright, 2003; Schindler et al., 2003).

Chemical, mechanical, and pyric brush management methods vary in their specific impacts on food for wildlife. Chemical treatments, for example, tend to temporarily reduce forbs, whereas fire may stimulate growth and abundance of early successional forbs beneficial to many species of animals (Beasom and Scifres, 1977; Bozzo et al., 1992b). Among woody plants capable of vegetative regeneration, fire or mechanical treatments can encourage production of basal sprouts that are more palatable and more accessible than shoots on untreated shrubs (e.g., Schindler et al., 2004b).

Endangered Species

Brush management potentially reduces critical habitat components for endangered species that depend on woody plant communities but may benefit grassland species. An example of a species dependent on woody plant communities is the ocelot *(Felis pardalis)*, which needs >97% woody canopy cover (Harveson et al., 2004). Conversely, reduction of brush cover potentially could benefit grassland-adapted species, such as Attwater's prairie chicken (*Tympanuchus cupido attwateri*.; Morrow et al., 2004) and Sonoran pronghorn *(Antilocapra Americana sonoriensis)*. Documentation of the effects of brush management on species listed as threatened or endangered in the United States is generally lacking, however. Consideration of the conservation status of broader suites of species (e.g., threatened, sensitive) should also factor into the development of brush management plans.

Herbicide Toxicity

Generalizations about the effects of brush management often do not take into account possible effects of herbicides on nontarget organisms. Acute effects of the herbicide 2,4-D have been documented, especially with regard to its magnification through food chains. This herbicide is toxic to cutthroat trout *(Salmon clarkia)* (Woodward, 1982) and led to declines in pocket gopher *(Thamomys talpoidis)* populations in Colorado (Keith et al., 1959). However, the herbicides used in contemporary rangeland brush management are less toxic, are usually not applied in concentrations harmful to wildlife, and dissipate following the growing season they are applied (Scifres, 1977; Freemark and Boutin, 1995; Guynn et al., 2004). Herbicides are generally not acutely toxic to soil organisms (Freemark and Boutin, 1995; Liu et al., 2016) but may harm insects.

Herbicides may indirectly affect wildlife via their impacts on insects, which are an important food source for many classes of wildlife (O'Leske et al., 1997). Most herbicides used in rangeland applications have low toxicity for insects (DiTomaso et al., 2010); however, rangeland herbicides may reduce pollinator insects through indirect toxic effects such as insects feeding on treated plants (Bohnenblust et al., 2013) and by killing plants important to insects (Black et al., 2011). The decline of monarch butterflies *(Danaus plexippus)* in North America, for example, has resulted from loss of milkweeds because of widespread use of glyphosate (Pleasants and Oberhauser, 2013). More empirical research on effects of rangeland herbicides on invertebrates is needed to develop a better understanding of their direct and indirect effects on wildlife. Potential effects of surfactants and inert ingredients, as well as possible synergistic effects of multiple chemicals applied simultaneously on invertebrates, are unknown (Guynn et al., 2004). These knowledge gaps are of concern, as rangelands serve as a reservoir of pollinator and predator insects important to not only wildlife but also the local ecology and crop production in nearby cultivated areas (Freemark and Boutin, 1995). Information on direct and indirect effects of herbicides on reptiles and amphibians is also lacking (Freemark and Boutin, 1995; Guynn et al., 2004).

Predators

Brush management alters habitat components important to predators and may influence behavioral responses of prey. Ungulates, for example, may preferentially use cleared patches within woodland or shrubland because of enhanced forage production and quality but also because of the greater ability to visually detect predators (Bozzo et al., 1992a; Wiemers et al., 2014). Predators, however, are also attracted to cleared areas where prey species congregate. Florida panthers *(Felis concolor coryi)*, for example, are attracted to burns < 1 yr old because structural changes in the vegetation increase availability of white-tailed deer and other prey species (Dees et al., 2001). Landscape-scale reductions of woody plants decrease the availability of hunting perches for raptors, potentially impairing their ability to obtain prey (Renwald, 1978). Ostensibly seeking to minimize predation risk, greater sage-grouse hens select brood-rearing locations where there are fewer perches for raptors (Dinkins et al., 2014).

Prey population densities may also change in response to brush management. Effects of mechanical brush management on mortality of small mammals and less mobile wildlife species at the time of treatment are largely unknown. However, vegetation changes following treatment may favor increased densities of some prey species. Cotton rat *(Sigmodon hispidus)* densities, for example, were six times greater on root-plowed rangeland in Texas than in untreated rangeland (Guthery et al., 1979).

Brush management can also affect visual cues used by predators to locate prey. For example, the efficiency of predation by martens *(Martes americana)* is greatest in uncut timber stands where levels of coarse woody debris are greater than in regenerating forest (Andruskiw et al., 2008). High levels of coarse woody debris provide sensory cues that enhance hunting success. We speculate that brush management practices (e.g., mechanical, chemical, pyric) may, in a similar manner, vary in their effects on predator efficiency depending on how they influence structural attributes and amount of woody debris. This might account for why herbicide application—where standing woody material remains after treatment—has little influence on habitat use by coyotes *(Canis latrans)* and bobcats *(Felis rufus)* (Bradley and Fagre, 1988). Mechanical treatments such as roller chopping, by contrast, might have a more pronounced impact on predator efficiency because of the greater abundance of downed woody debris.

Patterned applications of brush management that create mosaics of woody- and herbaceous-dominated vegetation patches may also affect hunting efficiency of predators that rely on smell to detect prey. Turbulence and updrafts occur when wind moves across herbaceous vegetation into taller woody vegetation and can reduce the distance scent travels. Accordingly, predators relying on scent hunt less efficiently along edges where air flow is more turbulent than in patch interiors where air flow is relatively less so (Conover, 2007).

Treatment Longevity

Potential benefits of brush management for wildlife are transient. Duration of brush management treatment effects varies greatly, but woody plants typically reestablish in areas where they have been treated (Hamilton et al., 2004; Archer et al., 2011). Brush management may benefit a wildlife species initially, but as the woody plant community reestablishes, those benefits diminish. The temporary nature of treatments and the need for follow-up treatments (e.g. Hamilton et al., 2004; Paynter and Flanagan, 2004; Noble and Walker, 2006) must therefore be explicitly considered in long-term wildlife conservation and management plans and in communicating potential benefits to the public.

Single applications with no follow-up may have adverse legacy effects (see Text Box 1). For example, density of browse species palatable to white-tailed deer may be lower in the plant communities that reestablish following root plowing than in untreated communities (Fulbright and Beasom, 1987). Density of woody legumes such as honey mesquite and huisache (*Acacia farnesiana* [L.] Willd.) developing on root plowed areas can be greater than those on untreated areas (Fulbright and Beasom, 1987; Ruthven et al., 1993). Furthermore, woody plants regenerating following brush management may have longer and more numerous spines than undisturbed plants, which could reduce browser bite rates (Schindler and Fulbright, 2003; Schindler et al., 2004a).

Scale and Pattern

Effects of brush management on wildlife may vary dramatically depending on scale and pattern of application. Many grassland-adapted species respond in a positive fashion to broad-scale conversion of woodland to grassland (Fitzgerald and Tanner, 1992; Smythe and Haukos, 2008). Conversely, broad-scale conversions from shrubland to grassland reduce species that are more shrubland dependent such as northern bobwhites and Texas tortoises (*Gopherus berlandieri* Kazmaier et al., 2001; Ransom et al., 2008). Reductions in brush cover >60% reduce landscape use by white-tailed deer (Rollins et al., 1988; Reynolds et al., 1992). In contrast to game birds such as sage-grouse, large areas of conifer-encroached sagebrush provide habitat for many nongame bird species adapted to interior woodland environments. Brush management in these areas should be limited in scope if conservation of this wildlife group is a priority (Fulbright and Guthery, 1996).

Traditional rangeland management actions promoting vegetation uniformity rather than heterogeneity have been rightly questioned (Fuhlendorf and Engle, 2004), with the latter being more desirable for many wildlife species. Diversity and richness of birds, for example, is greatest in plant communities with structural heterogeneity (Reinkensmeyer et al., 2007). Accordingly, landscapes composed of mosaics of closed-canopy oak forest and open pastures derived from forest promote breeding songbird species richness in Oklahoma (Schulz et al., 1992). Many wildlife species reach maximum diversity or density in heterogeneous landscapes, such as those containing a mosaic of shrub- and herbaceous-dominated communities (Roth, 1976; Tews et al., 2004).

Spatial landscape heterogeneity may benefit herbivores nutritionally. A mosaic of woody plant and herbaceous patches should, in theory, benefit the nutritional status of white-tailed deer with the former providing browse and mast during summer and early autumn and the latter producing cool-season forbs in late winter and spring (Folks et al., 2014). Changes in forage composition and production and patch structure accompanying clearing of pinyon-juniper resulted in greater lean tissue and body fat reserves in mule deer in a study done in New Mexico (Bender et al., 2013). Interspersion of treated areas within untreated areas was beneficial because cleared areas received the most use when located within 200 m of undisturbed pinyon-juniper woodland. Consequently, Bender et al., (2013) recommended using brush management to create a mosaic of pinyon-juniper cover classes with > 60% in at least 25% of mule deer home ranges and thinned stands of 10–30% cover. Population models for bison *(Bison bison)* and elk suggest habitat spatial heterogeneity relaxes density-dependence (Wang et al., 2006). Accordingly, the capacity for herbivore diversity and abundance on heterogeneous landscapes is likely to exceed that of homogeneous landscapes (Searle et al., 2010).

Projections of brush management effects should take into account the extent to which vegetation heterogeneity is important for a wildlife species and for wildlife species diversity (Fulbright, 1996; Kie et al., 2002; Tews et al., 2004). Brush management done in strips or other patterns to create mosaics of woody plant communities interspersed with communities dominated by herbaceous plants can benefit species that need herbaceous-dominated patches for foraging and woody cover for loafing, relieving heat stress, or hiding (Fulbright, 1996; Fulbright and Ortega-Santos, 2013). Brush sculpting, another mosaic approach to brush management (Fulbright, 1997; McGinty and Ueckert, 2001), refers to selective removal of shrubs to accomplish multiple-use objectives such as improving vegetation structure and composition for white-tailed deer or northern bobwhites and increasing forage for livestock (Ansley et al., 2003). Use of these spatially explicit approaches to brush management requires that rangeland managers take into account the importance of landscape heterogeneity for the wildlife species of interest. Creating mosaics that are the most beneficial to a species, however, requires more than simply recognizing their importance. An understanding of the seasonal habitat requirements of the wildlife species is critical to decisions regarding the size, configuration, connectivity, and distribution of management-induced vegetation patterns.

Patch size and configuration requirements vary among wildlife species. Grassland birds, for example, may require patches > 50 ha (Helzer and Jelinski, 1999). Response to brush management may depend on the size of areas treated. Clearing woody vegetation to increase early-successional vegetation in Oklahoma, for example, did not result in occupancy by northern bobwhites because the areas treated were too small to induce colonization (Crosby et al., 2013).

The ratio of patch perimeter to area is also important. Among grassland birds, species richness within patches is greatest when patches have large interiors and edge-effects are minimized. For grassland birds, vegetation structure may interact with patch size such that larger core areas may be more important in landscapes with a mixture of grassland and woodland communities than in landscapes composed of treeless communities (Winter et al., 2006). Interactions among factors such as vegetation structure and patch size should be taken into account in brush management planning.

Edge and interior wildlife species are more sensitive to patch size than are generalist species (Bender et al., 1998). Mosaics consisting of few, large patches with little perimeter are likely to support fewer edge species. Conversely, mosaics of numerous small patches result in a large amount of edge relative to interior and thereby may reduce habitat quality for interior species. A possible reason that presence of a large amount of edge is detrimental to woodland-adapted birds is that nest parasitism and nest predation tend to increase with increasing edge, although this relationship has been questioned (Paton, 1994; Lahti, 2001).

Although the idea of creating mosaics through brush management has been around for some time (Scifres et al., 1988, Fulbright, 1996), the use of brush management as a tool to achieve an "optimum" patch size and configuration has not been widely practiced. This may reflect the fact that the preponderance of studies has focused on edge-adapted or generalist game species that show little response to variation in patch size. Northern bobwhites, for example, appear to be adapted to a wide range of patch configurations (Guthery, 1999). Given that edge-adapted generalists are relatively robust in their response to vegetation patterns and that requirements for many wildlife species are not well-known, it could be argued that management should focus on designs that are most likely to benefit specialist species, with the expectation that generalists will be minimally affected. Conversely, prescriptions aimed at improving habitat for generalists may have relatively modest positive effects on that group but have serious and potentially detrimental effects on specialists. Given this potential trade-off, an idea for resource managers to consider is that it may be best to err on the side of managing for specialists. Doing so might have the most positive net effect on biological diversity.

Habitat patches should be linked by corridors that facilitate movements across and between landscapes (Bennett, 2003). Lack of connectivity to source populations, for example, slowed colonization of banner-tailed kangaroo rats *(Dipodomys spectabilis)* by a decade or more into areas treated with herbicides to reduce creosote bush cover (Cosentino et al., 2014). Absence of kangaroo rats, a keystone species, in turn slowed recovery of lizards in the treated sites, demonstrating the importance of recolonization of keystone species on recovery of biodiversity after brush management (Cosentino et al., 2013). Consideration should, therefore, be given to applying brush management in a configuration that enhances connectivity and reduces fragmentation. However, configurations enhancing connectivity for grassland-adapted species may simultaneously fragment habitat of shrubland or woodland adapted species. Recognition of such trade-offs is a key first step when setting and evaluating brush management goals and objectives for wildlife.

Climate and Soils Mediate Outcomes

Abiotic variables may mediate or override effects of disturbances such as brush management in highly stochastic environments (Fig. 2). Variation in precipitation can be a stronger driver of change in animal populations than brush management. For example, abundance of small mammals and herpetofauna varied with precipitation in southern Texas during 2001–2004; however, abundance was similar on control sites and sites root plowed 36–39 yr earlier despite substantial structural differences in vegetation (Fulbright et al., 2013). Similarly, northern bobwhite populations in South Texas responded more strongly to annual variation in precipitation than to brush management treatments (Cooper et al., 2009).

Brush management effects on wildlife food and cover are also mediated by soil properties (Fulbright et al., 2008). Root plowing on well-drained, coarse-textured upland soils may result in long-term loss of shrubs important as browse for white-tailed deer, whereas lowland with fine-textured soils supported shrub communities similar in species composition and diversity to control sites > 3 decades after root plowing (Fulbright and Beasom, 1987). Rainfall inputs on topographically low landscape elements are supplemented by runoff from uplands, and this, in conjunction with their higher nutrient and water retention capacity, enable them to support more productive and resilient shrub communities (Wu and Archer, 2005). A possible explanation for the different responses of upland and lowland communities to brush management is that growing conditions in lowland landscape locations are more favorable for reestablishment of woody plants than those in uplands.

Non-Native Vegetation: Game Changers

Invasion of non-native plants may make the response of vegetation and wildlife to brush management more difficult to predict. Vegetation change following disturbance is often nondirectional (Westoby et al., 1989; Briske et al., 2005) and influenced by what is occurring in neighboring landscapes (Bestelmeyer et al., 2011). Disturbance by brush management may lead to a different, but relatively stable, plant community that may or may not provide better conditions for specific wildlife species. This often occurs when brush management creates opportunities for the establishment and spread of non-native vegetation. Once established, non-native plants may create “ecological traps” wherein cues that trigger habitat selection by wildlife can be decoupled from the resources linked evolutionarily to that cue (Steidl et al., 2013). Non-native annual grass invasion in sagebrush communities decreases value for sagebrush-obligate and other wildlife species that use sagebrush communities (Davies and Svejcar, 2008), and brush management may create opportunities for their spread (Evans and Young, 1985; Young and Allen, 1997). Buffelgrass (*Pennisetum ciliare* [L.] Link), a non-native perennial grass, often increases following root plowing or disking in southern Texas (Gonzalez and Dodd, 1979; Johnson and Fulbright, 2008) with adverse effects on bobwhites (Sands et al., 2012). Thus, the potential for and probability of undesirable shifts in plant communities following brush management must be carefully considered before implementing treatments aimed at wildlife conservation.

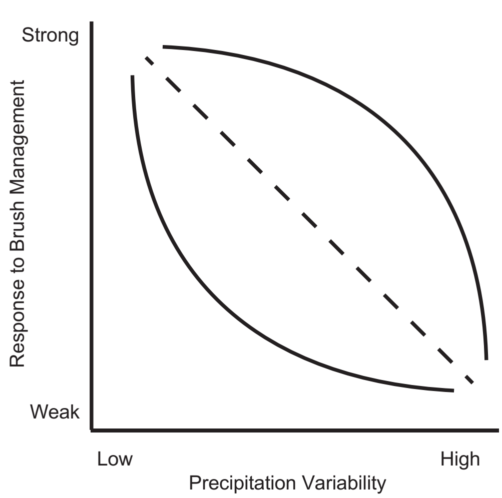

Figure 2. Hypothetical relationships between wildlife responses to brush management and precipitation variability. Wildlife and vegetation may respond more strongly to precipitation than to effects of brush management in environments with highly variable seasonal and annual precipitation. Lines represent various wildlife species or functional groups.

Misuse of Terminology

Generalizations about the effects of brush management on “wildlife habitat” are inappropriate since the term *habitat* is species specific (Hall et al., 1997). Statements should reflect how brush management is anticipated to affect individual species or functional groups. In the brush management literature, the term “habitat” is frequently incorrectly used as a synonym for vegetation (e.g., creating a “mosaic of habitats” by clearing patches of brush rather than “creating a mosaic of vegetation”). This is also an inappropriate use of the term since “habitat” includes all of the conditions and resources in an area that enable occupancy by an organism, not just vegetation (Krausman and Morrison, 2016).

Increases in food or cover resulting from brush management are often referred to as “habitat improvement” in the literature. However, because “habitat” includes more than vegetation, metrics related to vegetation are insufficient by themselves to make inferences about habitat improvement or habitat quality (Guthery, 1997). A change in vegetation may intuitively seem like it should benefit a wildlife species, but unless the demographic characteristics or productivity of the target wildlife species are quantified, this is only an assumption (Van Horne, 1983). Conversely, a brush management practice that is detrimental to a vegetation species used by an organism would intuitively seem like it would reduce habitat quality for that species. This is not necessarily the case, however. Northern bobwhites *(Colinus virginianus)* in central Texas, for example, preferentially nest in prickly pear (*Opuntia* spp.), and a logical assumption would be that reducing prickly pear abundance would reduce nesting success. However, this is not necessarily the case (Hernandez et al., 2003).

Changes in a specific habitat characteristic or component may have little positive effect on a species. Increasing the amount of some habitat component would only constitute a benefit to a species or functional group if that component is limiting. Thus, while rangeland disking may increase abundance of seed-producing forbs, this may be of little consequence to northern bobwhites if seed availability in untreated areas is sufficient to support their populations (Guthery, 1997). In fact, one could envision a potential scenario where increased seed abundance could increase granivorous rodent populations that might then attract predators that would, in turn, reduce quail populations. Numerous confounding factors exist in natural ecosystems, and an increase in food and cover alone may not benefit a wildlife species if some other factor, such as nesting cover, is limiting or co-limiting. Where multiple limiting factors occur, overcoming one limitation may be necessary, but by itself not sufficient, to constitute an improvement in habitat. Although it is impossible to grasp all of the complexities of natural systems, healthy respect for this complexity will help managers avoid making simplistic assumptions about treatment outcomes when potential limiting factors are unclear.

“Enhancing habitat” is another phrase that assumes habitat attributes are “improved” for a species or functional group by brush management. Ideally, improvements in quality of habitat for a species should directly link to increased survival and reproduction in addition to increased population densities and availability of key habitat components (Van Horne, 1983; Hall et al., 1997). This is because density alone is a misleading indicator of habitat quality and habitat quality should be defined in terms of survival and production characteristics (Van Horne, 1983). Increased organism densities in response to a brush management, therefore, are not sufficient evidence of improvement. For example, clearing woody vegetation in a 300-ha pasture and increasing the abundance of forbs may make more food available to deer, but is this an improvement in habitat quality? Deer from adjacent pastures dominated by woody plants may congregate in the cleared pasture during morning, evening, and night foraging periods, resulting in increased deer densities in the treated pasture. Clearing may have altered space use, but the treatment did not actually “improve” the area for deer if their survival and reproduction are concomitantly not increased. In addition, tall woody vegetation is a key component of white-tailed deer habitat because of its importance for thermal cover (Steuter and Wright, 1980; Deperno et al., 2003; Wiemers et al., 2014). Increasing forbs by clearing woody vegetation may not benefit deer populations if it occurs at the expense of another key habitat component such as thermal cover.

Demographic characteristics of wildlife populations are more difficult, expensive, and time consuming to quantify than are habitat traits such as food production. As a result, comparisons of survival and reproduction of wildlife on sites with and without brush management are limited (Text Box 2). Until such information becomes available, we must acknowledge that interpretations of brush management effects on various habitat properties must be made with caution and caveats.

Wildlife and Ecosystem Services

We recognize that in managing brush to increase forage for livestock, there may be a trade-off between livestock production and manipulating plant communities to meet wildlife objectives. Our focus is on wildlife responses to brush management without taking forage production for livestock and potential trade-offs into consideration. Perspectives on woody plants in rangelands vary widely depending on cultural traditions and land-use goals and objectives. Wildlife are an important component of a broader portfolio of ecosystem services affected by woody plant encroachment and brush management (Archer and Predick, 2014). Despite considerable investments accompanying the application of brush management practices (Briske et al., 2011), the recovery of key ecosystem services may be short-lived or absent (Archer et al., 2011). This makes brush management difficult to justify from the traditional emphasis on enhancing forage production for livestock or improving stream flow and ground water recharge. However, in the absence of brush management, the persistence of grassland and savanna ecosystem types and the wildlife and plants endemic to them will be threatened. Including wildlife biodiversity and other ecosystem services in cost-effectiveness assessments may therefore help determine whether or not brush management is a viable tool in ecosystem conservation and restoration. Rangeland ecologists are challenged with generating objective, robust information regarding the response of various ecosystem services to shrub encroachment and brush management. Such information is essential to position land managers and policymakers to make objective, evidence-based decisions that take into account the many trade-offs and competing objectives at play in the conservation and dynamic management of grasslands and savannas. Shrub encroachment and brush management impacts on wildlife should therefore be considered in the context of a diverse portfolio of ecosystem services.

Implications

Brush management has evolved from a largely production agriculture focus in the mid-20th century to a more comprehensive view that encompasses manipulation of vegetation to benefit wildlife, increase biodiversity, and conserve grasslands and the plant and animal species that occupy them (Fuhlendorf et al., 2012). Taking an approach to brush management that maintains the integrity of natural ecosystems and wildlife populations yet encompasses traditional needs such as livestock production and watershed management will improve the public’s perception of brush management while advancing the conservation of wildlife and other natural resources (Archer and Predick, 2014).

We have summarized what we know about how brush management influences wildlife. Our key findings form the groundwork for a more contemporary approach that avoids excessive generalization and considers the variation in responses of different wildlife species and functional groups to brush management. On the basis of our review, we offer the following recommendations to help natural resource professionals improve the manner by which wildlife conservation objectives are developed, communicated to stakeholders, and carried out in brush management programs:

- Managing brush for one species and simultaneously benefitting all other sympatric species is impossible. Identify wildlife species that will benefit *and* those that may be adversely affected to make stakeholders aware of potential trade-offs.
- Take into consideration the complexity of wildlife/biodiversity responses to brush management, including variation in species,

Text Box 2
Knowledge gaps: knowing what we don’t know.

We identified the following knowledge gaps regarding the response of wildlife to brush management:

- Brush management effects on wildlife have mainly focused on game species with nongame species including predators, passerines, small mammals, and reptiles being largely neglected. Habitat requirements of many nongame species are not well understood, making it challenging to even speculate about effects of brush management (Rottler et al., 2015).
- The extent to which brush management-induced changes in habitat attributes in an area translate into improvements in animal birth rates and longevity or attributes such as nutritional status and body mass are largely unknown.
- More broad-scale studies of the responses of wildlife to brush management are needed. For example, more than half of the studies of the responses of wildlife to pinyon-juniper removal reviewed by Bombaci and Pejchar (2016) were conducted using experimental units < 100 ha in size.
- Our understanding of the response of wildlife to brush management is also limited by the short duration of most studies. In the literature on responses of wildlife to pinyon juniper removal reviewed by Bombaci and Pejchar (2016), 86% of studies were < 10 yr in duration.
- Information on the effects of biological brush management on wildlife and wildlife habitat is noticeably lacking in the literature.
- Importance of the interaction between vegetation patches and the surrounding landscape emphasizes the importance of considering landscape composition and context in studies of the response of wildlife to brush management.
- Our understanding of wildlife responses to brush management can be improved by accounting for legacy effects of previous land management practices and increasing our knowledge of cumulative effects (see Text Box 1) of brush management and other range management practices.

functional group, gender, seasonal use, potential changes in predator-prey relationships, and invertebrate responses.

- Time brush management applications to accommodate critical life-cycle phases of wildlife. This may not be possible for all species; however, efforts should be made to minimize effects of brush management on biodiversity.
- Consider potential effects of herbicide application on pollinator and predator insects and how changes in their abundance may influence crop production in nearby cultivated areas.
- Consider temporal and spatial scale in management planning, recognizing needs of different wildlife species in regard to patch attributes (size, shape, distribution, connectivity), core area and home range size, and minimum areas needed for species persistence.
- Recognize that 1) reductions of woody plant cover will be temporary and follow-up treatments will be necessary (e.g., Noble and Walker, 2006); 2) long-term effects such as loss of woody plant diversity and changes in plant morphology may occur; 3) interannual climate variability and soil properties will alter brush management outcomes; and 4) heterogeneity promotes biological diversity.
- Avoid use of brush management when it might facilitate invasion of non-native plants that are potentially detrimental to wildlife and overall biodiversity. Where weeds or non-native plants are a risk, mitigation plans should be in place.
- Standardize terminology regarding the effects of brush management on habitat of wildlife species and functional groups to improve communication in technical and lay venues. Articulate wildlife species- or functional group-specific responses in brush management plans and state the assumptions underlying those expectations.
- Inferences pertaining to brush management effects on wildlife based on visual and empirical observations of vegetation change should be applied cautiously. Demographic and productivity responses of a species are the most direct and reliable measures of whether brush management "improved" or "enhanced" overall habitat quality for a species.
- Conservation of grasslands and savannas as ecosystem types and the persistence of the plants and animals endemic to them should be a high priority (Samson and Knopf, 1994; Noss et al., 1995; Hoekstra et al., 2005). Accordingly, brush management may play an important role in conserving grassland wildlife and landscapes.
- Evaluate shrub encroachment and brush management impacts on wildlife in the context of a diverse portfolio of ecosystem services.
- Simplistic generalizations and prescriptions that ignore the dynamics, complexities, and knowledge gaps we identify have not served us well and have caused their own sets of problems. Taking a broader "systems perspective" that allows for interactions and feedbacks and that incorporates new information as it becomes available is the way forward.

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