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# The Sage-Grouse Habitat Mortgage: Effective Conifer Management in Space and Time☆

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ABSTRACT

Management of conservation-reliant species can be complicated by the need to manage ecosystem processes that operate at extended temporal horizons. One such process is the role of fire in regulating abundance of expanding conifers that disrupt sage-grouse habitat in the northern Great Basin of the United States. Removing conifers by cutting has a beneficial effect on sage-grouse habitat. However, effects may last only a few decades because conifer seedlings are not controlled and the seed bank is fully stocked. Fire treatment may be preferred because conifer control lasts longer than for mechanical treatments. The amount of conservation needed to control conifers at large temporal and spatial scales can be quantified by multiplying land area by the time needed for conifer abundance to progress to critical thresholds (i.e., "conservation volume"). The contribution of different treatments in arresting conifer succession can be calculated by dividing conservation volume by the duration of treatment effect. We estimate that fire has approximately twice the treatment life of cutting at time horizons approaching 100 yr, but, has high up-front conservation costs due to temporary loss of sagebrush. Cutting has less up-front conservation costs because sagebrush is unaffected, but it is more expensive over longer management time horizons because of decreased durability. Managing conifers within sage-grouse habitat is difficult because of the necessity to maintain the majority of the landscape in sagebrush habitat and because the threshold for negative conifer effects occurs fairly early in the successional process. The time needed for recovery of sagebrush creates limits to fire use in managing sage-grouse habitat. Utilizing a combination of fire and cutting treatments is most financially and ecologically sustainable over long time horizons involved in managing conifer-prone sage-grouse habitat.


## Introduction

In a previous paper (Boyd et al. 2014) we examined the contemporary challenges of managing conservation-reliant species within the context of regulatory frameworks such as the US Endangered Species Act (ESA). Such scenarios are complicated by the fact that managing the ecosystem processes necessary to maintain habitat for sensitive species may involve extended temporal horizons that are not consistent with the immediacy of regulatory imperatives. This is particularly true in disturbance-dependent ecosystems in which change over time is a reality, even in the absence of anthropogenic inputs. Part of the problem in managing these systems is the manner in which specific management practices have been previously monitored and evaluated. Such efforts are often couched in terms of implementation monitoring (e.g., documentation of spatial area treated) instead of effectiveness monitoring (i.e., biological effectiveness, or determining the success of management practices in influencing specific ecosystem processes or attributes) (Boyd and Svejcar 2009). When biological success of treatments is evaluated, authors of a recent comprehensive evaluation of rangeland conservation practices concluded that the spatial and temporal scale of existing research is often inadequate to be relevant to natural resources management (NRCS 2012).

In today's world, both conservation and research time lines are often based on administrative protocol or tradition (Boyd et al. 2014). From a research standpoint, grant cycles may encompass 2–5 yr. On rangeland managed by the Bureau of Land Management, management planning often takes place within the temporal boundaries of a Resource Management Plan (RMP), which is approximately 15–20 yr. Such time horizons can contrast with the timeframes over which ecological systems function or deliver desired values. For example, conifer woodland development in sagebrush steppe plant communities takes approximately

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100 yr depending on site conditions and year effects (Miller et al. 2005; Johnson and Miller 2006; Romme et al. 2009).

Spatial dimensions (vs. time) are more amenable to management planning efforts (e.g., see Chambers et al. 2014), in part because they are easily quantifiable at a given point in time and conceptualizing the boundaries of planned management actions is fairly straightforward. But space and time are not independent entities and ecological reality is defined by latitude, longitude, elevation, and time. These four dimensions define the management challenges that must be overcome to direct vegetation change along desired trajectories. Spatial dimensions are easily paired with project expenditures to determine cost outlay per unit area of space (e.g., cost per hectare) or for the total area within project boundaries. But what happens when the benefit of different management treatments varies in time? How do we value the spatial impact of different management options in an environment where treated plant communities experience succession to alternative states at treatment-dependent rates?

In this paper, we examine the interface between short-term and long-term habitat needs of greater sage-grouse *(Centrocercus urophasianus)* and conifer treatment options by developing a novel metric ("conservation volume") that integrates space and time to quantify the amount of conservation needed to meet management objectives over extended temporal and spatial horizons. We then provide conceptual guidance for designing management treatments to control conifer abundance and meet the habitat needs of sage-grouse in a financially and ecologically responsible manner. Importantly, this manuscript is not a review or synthesis paper and is, instead, the collective opinion of a group of researchers who work at the interface of science and management in sagebrush habitats. As such, we make no effort to comprehensively examine literature pertaining to all conifer treatment options and instead use simplified comparisons to highlight key management considerations that are relevant regardless of specific treatment techniques. For example, our discussion of mechanical methods of juniper control is purposefully limited to cutting, not because we are unaware of other mechanical methods, but because it is convenient to focus on a single tool in making larger conceptual arguments that we hope will stimulate discussion about making wise choices in management of conifer-prone sage-grouse habitat at extended temporal horizons.

While the emphasis of this paper is on sage-grouse, our work also relates more broadly to conservation of sagebrush ecosystems that provide habitat to a wide variety of sagebrush-dependent wildlife species (Davies et al. 2011; Chambers et al. 2014). Because of the variability in abiotic conditions and disturbance regimes present across the range of in piñon and juniper communities in the western United States (e.g., see Romme et al. 2009), we focus on conifer dynamics within the northern Great Basin. That said, concepts developed herein may have applicability to habitat management for other wildlife species in other ecosystems.

## Managing Conifer Prone Habitat for Greater Sage-Grouse

Fire return intervals in the mid to high elevations of the sagebrush steppe ecosystem have undergone significant change since European arrival (Miller and Wigand 1994; Miller and Rose 1999; Weisberg et al. 2007). Miller et al. (2000) reported historical mean fire return intervals (MFRIs) of < 30 yr; however, MFRIs have increased dramatically post European arrival in association with fine fuel removal via livestock grazing and later with improved fire suppression techniques (Pyne et al. 1996). In association with altered fire regimes, and perhaps changing climate, populations of fire-sensitive native conifers (primarily juniper [*Juniperus occidentalis* Hook., *J. osteosperma* Sarg.] and piñon pine [*Pinus monophylla* Torr. & Frén, *P. edulis* Engelm.]) have greatly expanded. Recent estimates suggest that conifer abundance in the northern Great Basin has increased from 0.3 to 3.5 million ha since the late 19th century (Miller et al. 2000; Azuma et al. 2005) and these species impact approximately 19 million ha in the western United States (Tausch et al. 1981; Johnson and Miller 2006; Miller et al. 2008).

Conifer woodland development can be conceptualized in three phases (Miller et al. 2005; Romme et al. 2009). Phase 1 is characterized by the presence of seedling and juvenile conifer plants at a site (Miller et al. 2005). In the absence of fire, these plants mature and become codominant with other understory perennial species over time (phase 2). Left unchecked, conifers eventually dominate the site (phase 3, or "woodland") and understory perennial herbaceous plants and shrubs can be dramatically reduced or eliminated and soil resources may be at greater risk for erosion (Miller et al. 2005; Pierson et al. 2007).

Both phase 2 and phase 3 conditions have the potential to impact not only understory plant conditions but also habitat quality for sagebrush (*Artemisia* spp.)—dependent wildlife species of critical concern including greater sage-grouse. Recently considered for listing under the ESA, sage-grouse populations have declined precipitously over the past 50 yr (Connelly and Braun 1997; Braun 1998; Connelly et al. 2004; USFWS 2013). At mid to high elevations, expansion of native conifer species into sagebrush steppe habitats is viewed as a major threat to sage-grouse populations (Connelly and Braun 1997; Braun 1998; USFWS 2013). Progression to conifer woodland conditions incrementally decreases quality of habitat as understory perennial plants are lost (Miller et al. 2000; Bates et al. 2005). Sage-grouse may avoid habitats when conifers are greater than about 1 m high, perhaps because of the potential for these trees to be used as perch sites for avian predators (Casazza et al. 2011). Moreover, these habitats may be of disproportionate value to sage-grouse as they provide late-season access to forbs that are critical to ensuring adequate body condition before winter onset (Drut et al. 1994a, 1994b).

Contemporary management of conifer populations in sage-grouse habitat relies heavily on mechanical treatments and these methods have yielded significant conservation benefit (Bates et al., 2005, 2014a, 2014b; Baruch-Mordo et al. 2013; Miller et al., 2014a, 2014b; Roundy et al. 2014). For example, the Sage Grouse Initiative (SGI), a program funded by the USDA — Natural Resources Conservation Service, has partnered with private landowners to mechanically treat > 100 000 ha of conifers in the western United States since program inception in 2010 (SGI 2015). However, such progress comes at a cost. At current prices for cutting of approximately $\$100-300 \cdot \mathrm{ha}^{-1}$ (Farzan et al. 2015), total cost of these treatments could be as high as \$30 million. With that in mind, a reasonable question to ask is "given the cost of mechanical treatments, how long can we afford to use these methods as our first line of defense against conifer expansion in sage-grouse habitat?"

That question is made even more relevant when we consider that sage-grouse were found to be "not warranted" for listing under the ESA (USFWS 2015). Before that finding, political pressures aligned to make such expenditures seem reasonable insofar as they helped demonstrate a good faith effort to restore habitat and potentially avoid a listing. Additionally, cutting is an interdictory treatment that temporarily alleviates the consequences of diminished fire presence, but the results of cutting may be short lasting in comparison with fire (Miller et al. 2005; O'Connor et al. 2013; Bates et al. 2014a) and current conifer management has not kept pace with woodland expansion (Miller et al. 2005). An alternative would be to simply restore the fire regime. However, fire comes with its own cost in the form of a temporary loss of sagebrush, which creates a spatially and temporally equivalent habitat deficit for sage-grouse (Connelly et al. 2000), although the effects of sagebrush loss on sage-grouse will vary in accordance with size and dispersion of burned areas over the landscape (Dahlgren et al. 2006; Boyd et al. 2011). Given the considerable area being affected by conifer expansion, widespread use of fire for conifer control could create a habitat deficit large enough to have serious negative consequences for sage-grouse populations, even though big sagebrush may recover in a matter of decades (Harniss and Murray 1973; Nelle et al. 2000; Lesica et al. 2007; Ziegenhagen and Miller 2009; Nelson et al. 2014). Seeding of sagebrush following fire in mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana* [Rydb.] Beetle) habitat would likely reduce shrub recovery time but would also increase the cost of treatment (Davies et al. 2014).

An alternative would be to combine cutting and fire into a conifer management scheme to simultaneously minimize costs while protecting critical habitats from the short-term negative effects of fire. Large-scale efforts to mechanically treat conifer populations (e.g., SGI) may make such an alternative possible by creating a baseline level of habitat necessary to buffer reduction in sagebrush habitat with fire and ultimately move beyond interdictory treatments and toward a long-term sustainable strategy. Partitioning management efforts in this manner is similar in concept to strategy associated with financial planning—maximizing long-term gain while being willing to consider reasonable short-term risks (Wells Fargo 2015). Productive allocation of mechanical and fire treatments will involve quantifying treatment rate of return over time for these practices within a landscape that is spatially variable and of temporally dynamic importance to sage-grouse.

## Integrating Space and Time

### *Calculating the "Volume" of Management Treatments*

One way to consider the value of conifer treatments over space and time would be to adopt analogous techniques from water rights adjudication. Water rights are often allocated in terms of "acre-feet," which refers to the volume of water to be dispersed over an area of known size. So, for example, a soybean (*Glycine max* [L]) farmer may have a water right to pump the equivalent of 4 f. of groundwater spread over an 80-acre field, which amounts to 320 acre-ft. Within a management timeframe (i.e., one growing season), a fraction of that water can be applied periodically to prevent undesired outcomes such as decreased crop productivity due to desiccation. For example, if all the water was applied during the first half of the growing season, plants may be vegetatively productive, but soybean yield would be low due to drought stress during the second half of the growing season. So the total amount of water is important, but equally important is the distribution of water application through time. This concept is also germane to how we evaluate and apply treatments.

Consider the following example for a 10 000-ha management unit composed of early phase 1 conifer habitat, in which our goal is to prevent conifer progression to phase 3 woodlands over a 100-yr period. To determine the amount of conservation needed to offset that change, we can multiply the spatial area of the management unit by the management time horizon:

$$\textit{Conservation volume} = S_a(T_m)$$

where:
$S_a$ = Spatial area (ha)
$T_m$ = Management time horizon (yr)

This is the "conservation volume" (CV) in ha-yr that would need to be applied to keep the management unit from progressing to woodland conditions (Fig. 1).

This concept can be used as the basis for determining the extent of the area that needs to be treated, within the management time horizon, to prevent progression to phase 3 conditions using different treatment options (i.e., "treatment allocation"):

$$\textit{Treatment allocation} = CV \div T_o^{-1}$$

where:
CV = Conservation volume (ha-yr)
$T_o^{-1}$ = number of years a treatment offsets an undesired vegetation change

As described earlier, two contrasting treatments for delaying conversion to conifer woodland are prescribed fire and cutting. Fire applied during the late growing season has the potential to remove all conifers from a plant community (Bates et al., 2013, 2014a, 2014b). So the treatment offset ($T_o$ in Fig. 1) for fire in this example is equal to the amount of time to progress from no conifers present postfire to woodland conditions (approximately 100 yr; Johnson and Miller 2006). Thus, the treatment allocation for fire is 10 000 ha (see Fig. 1). Put another way, burning the entire 10 000-ha management unit would generate a sufficient volume of conservation to offset transition to phase 3 conditions over the 100-yr management time horizon. The treatment offset for cutting may be less than for fire because small trees (< 0.5 m) are often missed during cutting and the seedbank is unaffected (Miller et al. 2005; Bates et al. 2014a). In this example we will use a treatment offset of 50 yr (i.e., plant communities will reach phase 3 conditions

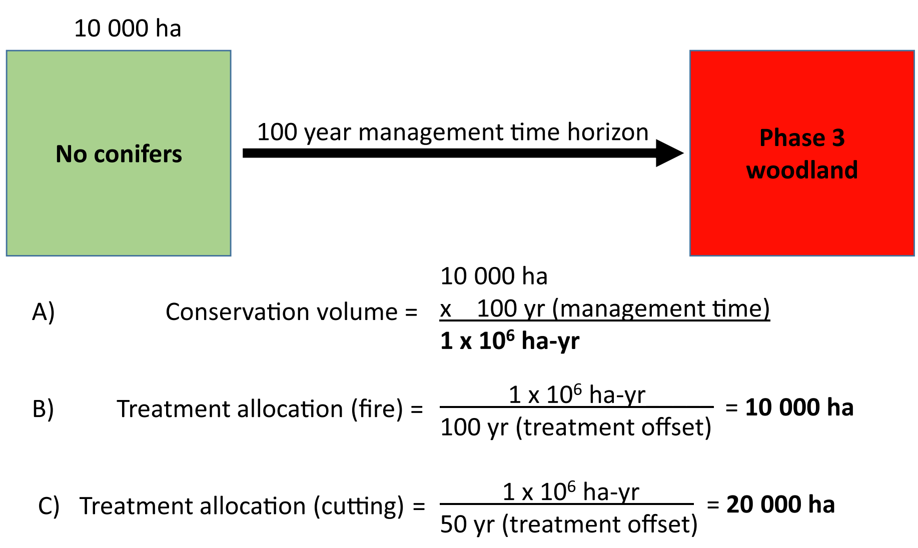


**Figure 1.** Schematic illustrating concept of conservation volume to integrate vegetation change over space and time with management treatment options in a conifer/sagebrush plant association. The management goal is to prevent transition to a phase 3 woodland condition for a 10 000-ha management area over 100 yr. **A,** A conservation volume of 1 x $10^6$ ha-yr would need to be applied to prevent transition from early phase 1 to a phase 3. **B,** Application of fire in yr 1 is sufficient to offset undesired change over the entire 10 000-ha management unit during the 100-yr management time. **C,** The treatment offset of cutting is only half the management time horizon, and thus cutting must be applied twice to each hectare in the management unit. With cutting we assume that some smaller trees/seedlings will be missed and that the conifer seed bank is unaffected by treatment.

approximately 50 yr from time of cutting). Calculating the treatment allocation for controlling conifers solely with cutting indicates that 20 000 ha would need to be cut within the management area over the 100-yr management time horizon to prevent progression to phase 3 conditions (see Fig. 1). Put another way, the entire management area would need to be cut twice within the 100-yr management time horizon.

*Sagebrush Loss as a Conservation "Cost" for Comparing Conifer Treatment Options*

Implementation of treatments can produce a measurable value, defined by the integrated spatial and temporal extent of those actions. We previously assumed that the treatment offset for cutting may be only half that of prescribed fire (see Fig. 1) because the time to woodland conversion following a single application of prescribed fire or cutting was 100 yr and 50 yr, respectively. Thus, fire has a higher value because it offsets undesired change for a longer period of time, whereas cutting would have to be applied twice within a 100-yr time frame to meet our objective; but the value of both treatments declines over time as conifer succession proceeds toward woodland conditions (Fig. 2A).

The inverse is also true; we can evaluate the "cost" of conservation actions in an integrated fashion to make better decisions, particularly when comparing actions that may produce different treatment volumes or have different costs associated with them. Conservation cost can be defined for any number of attributes, both economic (e.g., cost of implementation) and ecological (e.g., undesirable habitat changes). One notable conservation cost that differs between prescribed fire and cutting to prevent conversion of sagebrush habitat to woodland is the effect of these treatments on big sagebrush (*Artemisia tridentata* Nutt.). Burned big sagebrush typically experiences high or complete mortality, does not resprout, and recovers slowly (Bates et al. 2014a; Miller et al., 2014a, 2014b). In contrast, shrub cover is not directly affected by conifer cutting (Bates et al. 2014a; Miller et al. 2014a). The rate of postfire sagebrush recovery is variable, depending on site productivity, prefire plant community composition, and postfire weather conditions (Harniss and Murray 1973; Lesica et al. 2007; Ziegenhagen and Miller 2009; Nelson et al. 2014).

Applying the concept of sagebrush loss as a conservation cost to our hypothetical management scenario, we can also weigh its spatial and temporal implications within the 100-yr management timeframe. Assuming that postfire sagebrush recovery on more productive ecological sites prone to conifer woodland conversion requires 35 years (Ziegenhagen and Miller 2009; Nelson et al. 2014), "cost" of fire diminishes as sagebrush recovery is achieved (Fig. 2B). Because cutting typically does not reduce sagebrush cover, we can assume that its cost is effectively zero. Therefore, there is a significant initial conservation cost difference between fire and cutting, but this diminishes as sagebrush cover rebounds. Though we use a linear recovery in this simplistic example, land managers with more specific sagebrush objectives (e.g., critical thresholds of cover for wildlife species or sagebrush reproductive maturity) could apply their own cost estimates that reflect those objectives.

A useful analogy to articulate management trade-offs between cutting and fire is the decision regarding renting versus buying a home with a mortgage. Typically, high up-front expenses associated with a home purchase (e.g., down payment, closing costs) dictate that investment benefits are only realized over longer time frames as equity accumulates and/or home value rises, whereas renting is generally a more cost-effective option over the short term because it does not have significant up-front costs. A similar concept can be used to weigh the amount of conservation volume offset by different treatment options with varying costs and benefits.

If the management goal is to prevent woodland conversion, it is possible to integrate the conservation value (see Fig. 2A) of different management practices and their associated conservation costs (see Fig. 2B). If loss of sagebrush is the predominant cost and the prevention of woodland conversion is the primary value, examining the ratio of these two factors over the 100-yr management timeframe is informative (see Fig. 2C). Thus, cutting is clearly advantageous over fire for the first few decades following treatment because it doesn't incur the cost associated with sagebrush lost in fire (i.e., a short-term habitat rental). Fire only appears to be a viable option if the full management timeframe is considered (see Fig. 2C); fire prevents woodland conversion for a longer period, which offsets the upfront costs associated with lost sagebrush (i.e., habitat equity exceeding the down payment).

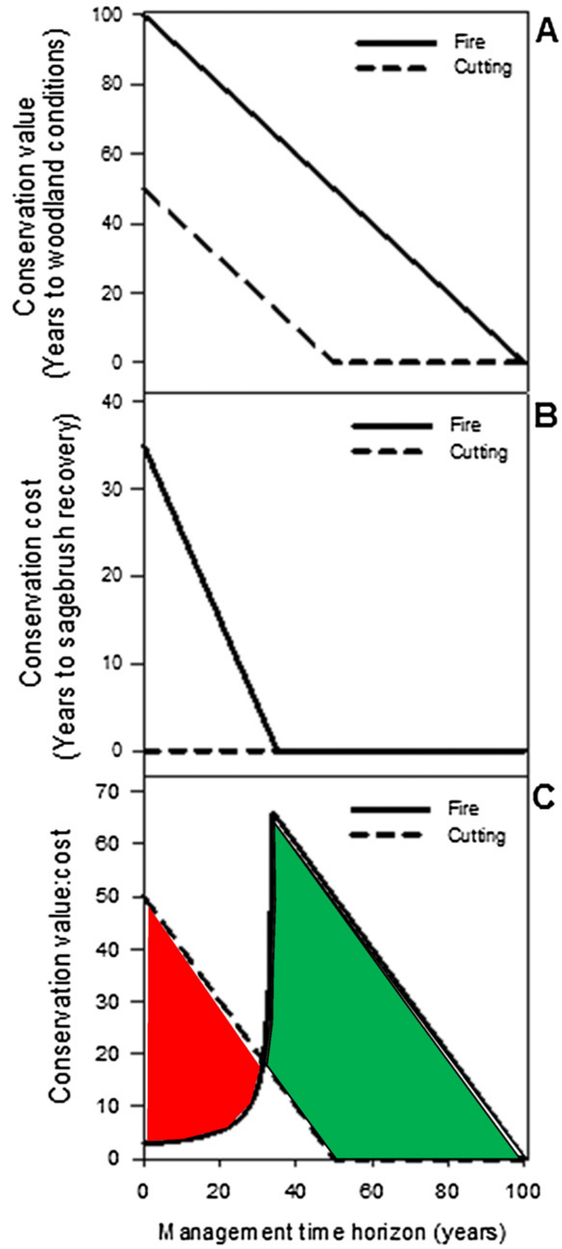


**Figure 2.** Conceptual relationships depicting relative conservation value and conservation cost to sagebrush conservation in the context of a single application of fire or cutting at time zero to prevent conifer progression to woodland conditions over a 100-yr time horizon. **A,** Fire has a longer treatment life. **B,** However, the initial high value of fire in controlling conifers is mitigated by the high upfront loss of sagebrush. The net benefit to sagebrush of using cutting to control conifer abundance is initially high but declines over time, while the value of fire is initially low but increases with sagebrush recovery and ultimately decreases as sagebrush is lost over time with increasing conifer abundance. **C,** We can compare benefits of different treatments by calculating the ratios of value-to-cost over the management lifetime. The conservation benefit of cutting is shaded with red and the conservation benefit of fire is shaded with green.

*But It's Not That Simple: Integrating Biological Thresholds*

Admittedly, our preceding management scenario used to articulate an approach for simultaneously weighing ecological values and costs is simplistic. Land managers must weigh numerous values and costs, often with incomplete knowledge of their attributes. Nonetheless, we contend there is value in using estimates to empirically compare short- and long-term costs and benefits of alternative treatments.

Though the previous examples suggest that one treatment, fire, has significant long-term advantage, it has short-term costs that may be untenable in some real-life scenarios. Sagebrush obligate species could be adversely impacted if short-term costs (i.e., loss of sagebrush) of treatment exceed their biological tolerance levels. Research has shown that for sage-grouse populations to have a high likelihood of persistence, the majority of the landscape needs to be in sagebrush habitat (Aldridge et al. 2008; Wisdom et al. 2011). For our purposes, we used a threshold of 70% of the landscape comprised of intact sagebrush habitat for sage-grouse persistence. If we establish a management objective of maintaining at least 70% of the 10 000-ha management unit in intact sagebrush habitat, then our perception of cost-to-benefit of fire and cutting in the previous example is modified by the management unit's proximity to that threshold. If the 10 000-ha management area has 100% landscape sagebrush cover, then tolerance for accepting some short-term costs (i.e., lost sagebrush cover) in order to realize the long-term favorable cost-to-benefit granted by fire may increase. However, if the landscape is at or near the 70% minimum, then the costs of fire would likely be unacceptably high and cutting, with its low conservation cost (i.e., no loss of existing sagebrush cover), is the more favorable alternative.

But managing a landscape for sage-grouse imposes the additional burden of sage-grouse avoidance of habitats that have crossed a fairly low threshold of conifer abundance. The literature suggests that sage-grouse may avoid habitats at approximately the point where conifer height begins to exceed that of the sagebrush canopy or when conifer cover reaches 4% (Atamian et al. 2010; Baruch-Mordo et al. 2013). For purposes of this paper, we consider anything beyond phase 1 (i.e., phase 2 or 3) to be nonhabitat. Thus, managing conifers for the benefit of sage-grouse becomes more stringent than the previous goal of preventing transition to phase 3 woodland.

Managing for biological thresholds will also interact with choice of conifer treatment. As noted previously, small trees (< 0.5 m) may be missed during cutting, and cutting does not directly diminish the seedbank (Miller et al. 2005; O'Connor et al. 2013; Bates et al. 2014a). Thus, following cutting, small trees do not need to reestablish for conifer succession to begin. Additionally, sagebrush plants (and perhaps other shrubs) remaining following cutting may serve as nurse plants that facilitate establishment success of additional juniper seedlings (Chambers 2001).

How long it takes for a cut community to reach phase 2 (i.e., nonhabitat conditions) is not well addressed in the literature and will likely vary strongly on the basis of site conditions including ecological site, aspect, the number of smaller trees left following cutting, and seed bank conditions. Based to some extent on the literature (Johnson and Miller 2006; Miller et al. 2008; Bates et al. 2014a), but also on our own field observations, we expect that a reasonable time estimate following cutting would be 10 to 30 yr for conifer seedlings to reach sagebrush canopy height and another 5 to 20 yr to reach phase 2 conditions (Fig. 3). Thus, total treatment lifetime (i.e., "treatment offset," see Fig. 1) for managing sage-grouse habitat with conifer cutting would be approximately 15 – 50 yr. For purposes of this paper, we will use a treatment offset period of 30 yr (see Fig. 3). Because fire is less likely to miss smaller trees (Miller et al. 2005; Bates et al. 2014a), some degree of conifer recruitment and reestablishment will likely have to take place post burn (Bates et al., 2013, 2014a, 2014b). For purposes of this paper, we estimate a postfire establishment period of 20 yr (see Fig. 3). Assuming the subcanopy and above-canopy growth periods would be similar to cutting, the treatment offset for fire in managing sage-grouse habitat is approximately 50 yr (see Fig. 3). Future climate change and atmospheric $CO_2$ enrichment have the potential to accelerate the rate of conifer increase due to the positive interaction between atmospheric $CO_2$ and conifer growth; this relationship may strengthen during drought years due to increased water use efficiency in high $CO_2$ environments (Knapp et al. 2001).

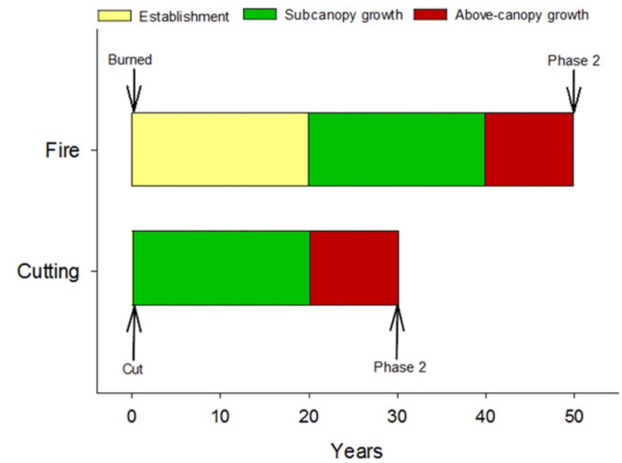


**Figure 3.** Conceptualization of progression to phase 2 conifer conditions following cutting and fire. For purposes of this figure, we assumed burning to be complete, or nearly so. Following fire conifers reestablish in the plant community, followed by a period of subcanopy seedling development, and ultimately above-canopy growth. Because smaller trees are often missed with cutting, succession following cutting involves growth of smaller trees already present on the site, so time from treatment to phase 2 conditions is shortened relative to fire.

Applying the above to our 10 000-ha management unit, the *management goal is now to manage the landscape for 70% in intact sagebrush habitat, with conifers limited to phase 1 within 7 000 ha, and to do so for the next 100 yr* (Fig. 4). Managing conifers within 7 000 ha of the landscape requires a conservation volume of $7 \times 10^5$ ha-yr (see Fig. 4). If we manage those conifers only with fire, we would need to treat a total of 14 000 ha over the 100-yr management time horizon, or approximately 14% of the landscape every decade (see Fig. 4). This is problematic, however, because if sagebrush takes 30 yr or more to recover (Ziegenhagen and Miller 2009; Nelson et al. 2014), we will begin to dip below the 70% landscape sagebrush threshold during the third decade of management. From a financial standpoint, at $160·ha (NRCS 2015), burning would cost about $224 000 per decade, or $2.24 x $10^6$ for a 100-yr management horizon (note: these figures and those later do not take inflation into account). If we manage only with cutting, we would need to treat just over 23 000 ha over the 100-yr management time horizon, or 23% of the landscape per decade (see Fig. 4). Unlike fire, since cutting does not kill sagebrush, cutting could be used exclusively to treat the management area. However, sustained (i.e., 100 yr) cutting of this quantity of conifers could be cost prohibitive. At $250·ha (Baruch-Mordo et al. 2013), cutting costs would run approximately $575 000 per decade, or $5.75 x $10^6$ for a 100-yr management horizon.

Arguably, neither cutting nor fire alone is an ideal treatment for managing conifer populations in sage-grouse habitat at extended temporal horizons. Land managers could use existing information to assess the current status of their land management units and design optimal balances of treatments that seek the highest cost-to-benefit possible while staying within critical bounds (e.g., at least 70% landscape sagebrush, no phase 2 or 3 conifer woodlands). Critical information to consider in allocating effort to cutting and fire will include, but not be limited to, the initial portion of the landscape in sagebrush habitat; the rate of post-treatment conifer recruitment, establishment, and expansion; financial and logistical capabilities of the management entity; and the probability of transition to non-native invasive species. These decisions can also be informed by the dispersion of conifer phases across a management area. For example, the use of fire (and subsequent

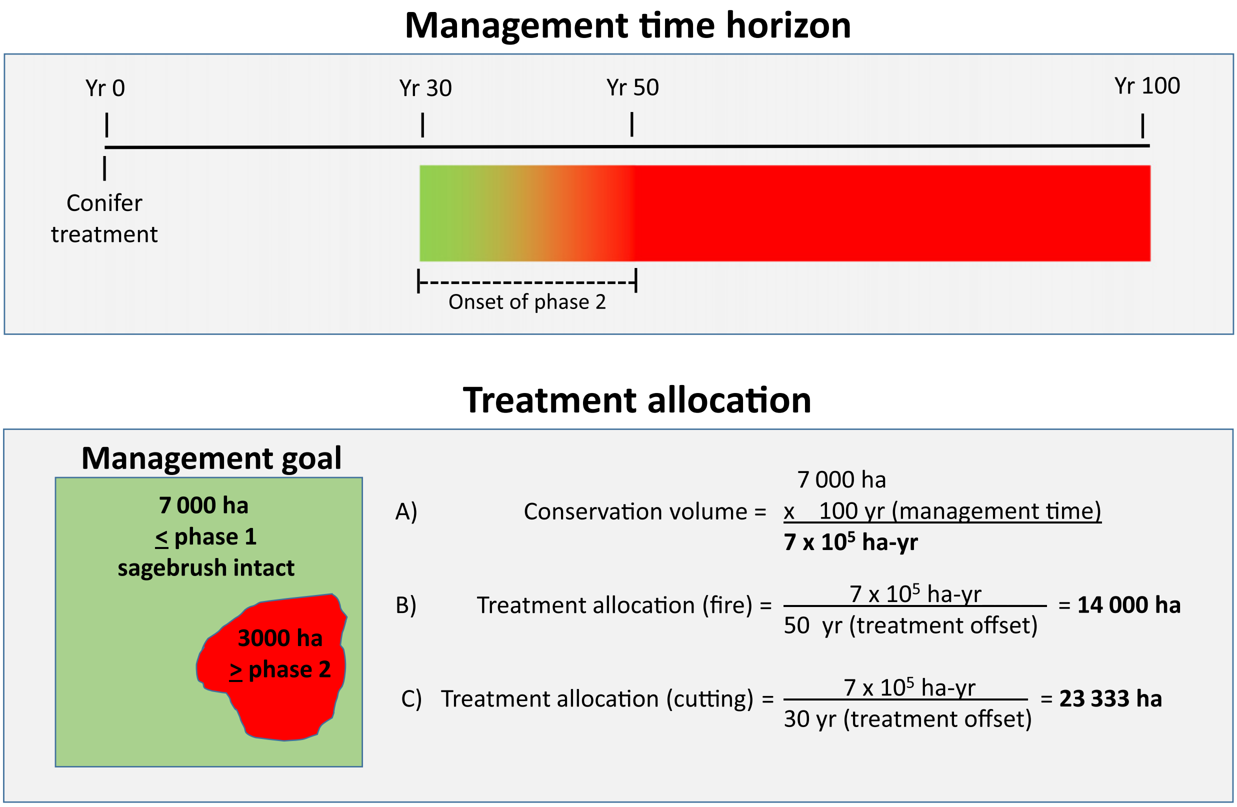


**Figure 4.** Hypothetical allocation of treatment effort for 10 000-ha management unit with the goal of maintaining 70% of the management unit in sagebrush habitat with no juniper beyond phase 1. Upper panel depicts management time horizon of 100 yr with onset of phase 2 conifer conditions occurring from 30 to 50 yr following cutting (30-yr) or fire (50-yr) treatment. Lower panel determines conservation volume and treatment allocation within the management time horizon using only fire or only cutting. Treatment allocation values indicate that some areas of the landscape will have to be treated multiple times within the management time horizon.

restoration practices) in habitats with advanced conifer progression (i.e., late phase 2 or phase 3) does little to decrease landscape sage-grouse habitat value because these areas have often lost understory vegetation necessary for sage-grouse habitat. Restoration of such areas would increase the base area of sagebrush habitat in the larger landscape, promoting increased latitude in future conifer management decisions.

## Management Implications

The purpose of this paper is not to criticize mechanical treatment of conifers as a management practice. In fact, the amount of conservation capitol generated and the associated amount of on-the-ground treatment, namely conifer cutting, over a short period of time preceding the 2015 ESA listing decision for greater sage-grouse is truly impressive. The focus on conifer cutting as a primary management tool was both logical and prudent given the tenuous status of sage-grouse. But as the immediacy of the sage-grouse decision fades, it will be necessary to transition from shorter timelines associated with opportunistic and often politically driven funding, to extended timelines governing ecological processes and plant succession in sage-grouse habitats. Our aim is not to promote one technique over another; in reality, all current juniper treatments are effectively temporary interventions meant to move plant community composition to a successional point in time that is consistent with societal expectations. However, the financial and logistical ramifications of using only cutting or other mechanical treatments to offset the "volume" of change in conifer-prone habitats, over extended temporal and spatial horizons, is daunting to say the least. The concept of conservation volume helps us to begin to quantify and discuss the amount of effort necessary to prevent undesired habitat changes over ecologically relevant time periods and at large spatial scales. Furthermore, as habitat calculators and conservation/mitigation banking approaches proliferate in sage-grouse habitat (e.g., Nevada Conservation Credit System 2014; Sage-Grouse Conservation Partnership 2015), the ability to quantitatively compare the durability, costs, risks, and benefits associated with different treatments becomes a necessity. Long-term management of sage-grouse habitat will involve balancing the habitat needs of sage-grouse with the financial, logistical, and ecological realities associated with relevant practices.

Throughout this paper we have made assumptions regarding post-treatment plant community change, and inaccuracies in these assumptions could strongly affect comparisons of plant community reassembly following conifer removal. For example, we assumed that burning will eliminate conifers, forcing reestablishment, whereas cutting will not completely remove conifers and will result in an abbreviated period of succession to phase 2 conditions (see Fig. 3). The reason for these assumptions was because there was insufficient information in the literature to quantify the long-term dynamics of plant successional processes following cutting versus fire. Thus, while we have ascribed fixed treatment lifetimes to cutting and fire and have generalized post-treatment successional processes, the reality is that these numbers and response of other vegetation functional groups will vary strongly on the basis of a host of factors including size of treated area, site productivity, resistance and resilience of the site, proximity of treated areas to a conifer seed source, efficacy of manually cutting small (< 0.5 m) trees, and fire mortality rates on all size classes of trees and seeds. This uncertainty is particularly relevant to the establishment period for conifer following fire. Because of the scarcity of empirical data, we were purposely conservative in our 20-yr estimate and prolonged post-fire establishment could markedly increase the conservation volume offset with fire relative to cutting (Campbell et al. 2012). Also, it is possible that sage-grouse occupy burned areas before full recovery of sagebrush cover or that cover meets minimum habitat needs earlier than our assumed 35-yr full recovery window (Connelly et al. 2000; Wambolt et al. 2001; Lesica et al. 2007; Dahlgren et al. 2015).

Managers need to consider that on warmer and drier sites associated with lower elevations or southern exposures, exotic annual grasses such as cheatgrass (*Bromus tectorum* L.) may increase or dominate post fire, leading to increased fuel continuity, increased risk of wildfire, and suppression of desired understory perennial vegetation (Chambers et al. 2014; Miller et al. 2014b). Postfire increases in exotic annuals are more likely on sites where prefire abundance of perennial bunchgrasses has been depleted or where tree dominance creates severe fire conditions (Condon et al. 2011; Bates et al. 2014b). That said, annual grasses may also increase following cutting on warmer and drier sites, particular if pretreatment understory perennials were lacking (Bates et al. 2005; Coultrap et al. 2008)

The Conservation Effects Assessment Project (NRCS 2012) made it clear that better information is needed for decision making in application of treatments and information gaps necessitating numerous assumptions are not unique to conifer management practices. One near-term way to produce evaluations of treatments over time would be to employ retroactive studies of past management at a variety of postmanagement timelines. Such studies would help to move management away from making assumptions regarding long-term effects of conifer management practices.

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