An Ecosystem Management Strategy for Sierran Mixed-Conifer Forests

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Abstract

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Current Sierra Nevada forest management is often focused on strategically reducing fuels without an explicit strategy for ecological restoration across the landscape matrix. Summarizing recent scientific literature, we suggest managers produce different stand structures and densities across the landscape using topographic variables (i.e., slope shape, aspect, and slope position) as a template for varying treatments. Local cool or moist areas, where historically fire would have burned less frequently or at lower severity, would have higher density and canopy cover, providing habitat for sensitive species. In contrast upper, southern aspect slopes would have low densities of large fire-resistant trees. For thinning, marking rules would be based on crown strata or age cohorts and species, rather uniform diameter limits. Collectively, our management recommendations emphasize the ecological role of fire, changing climate conditions, sensitive wildlife habitat, and the importance of forest structure heterogeneity.

Keywords: Climate change, ecosystem restoration, forest heterogeneity, forest resilience, topographic variability, wildfire.

Introduction

In recent years, there has been substantial debate over Sierra Nevada forest management. All perspectives on this debate inevitably cite "sound science" as a necessary foundation for any management practice. Over the dozen years since publication of the last science summary, the Sierra Nevada Ecosystem Project (SNEP 1996), many relevant research projects have published findings in dozens of scientific journals, yet these have not been synthesized or presented in a form that directly addresses current land management challenges.

Current management usually cites a "healthy forest"[1] as a primary objective. It is difficult, however, to define forest "health," and, as a broad concept, "a healthy forest" provides few specifics to guide management or assess forest practices. Various constituencies have different ideas of forest health (i.e., sustainable timber production, fire resilience, biodiversity, etc.) making its objective unclear (Kolb et al. 1994). A premise of silviculture is that forest prescriptions can be tailored to fit a wide variety of land management objectives, once those objectives are defined. We attempt to define some of the key management objectives on National Forest system lands in the Sierra Nevada and how they might be approached through particular silvicultural prescriptions.

In this paper, we focus on summarizing forest research completed at different scales and integrating those findings into suggestions for managing forest landscapes. Although many experiments and forest treatments still occur at the stand level, ecological research and recent public input have emphasized the need to address cumulative impacts and coordinate management across the forest landscape. We believe our synthesis has some novel and highly applicable management implications. This paper, however, is not intended to produce new research findings for the academic community; rather it is an effort to provide managers of Sierran forests with a summary of "the best available science." Some of the suggestions in this paper are already used in different Forest Service management practices.

There are several aspects of forest management that this paper does not address, but we would like to particularly note two omissions. The USDA Forest Service is charged with multiple-use management, which can include more objectives (e.g., socioeconomic impacts) than our focus on ecological restoration of Sierran forests. Restoration practices need both public and economic support to be socially and financially viable. Also, we do not specifically address the issues of water yield and quality in this paper, although water is one of the Sierra's most important resources. While our focus is on forest conditions, the suggested management practices may also make forests more resilient to disturbances including climate change. Management practices that help restore the forest headwaters of Sierran watersheds should benefit water production and quality for downstream users.

Recent Scientific Information

Current Sierra Nevada forest management is often focused on landscape strategies intended to achieve immediate fuel reduction (e.g., strategically placed area treatments [SPLATs] [Finney 2001], defensible fuel profile zones [DFPZs], and defense zones) (SNFPA 2004) and stem

[1] See definition in http://www.whitehouse.gov/infocus/healthyforests/Healthy_Forests_v2.pdf

density reduction. Fire scientists have developed effective models for the strategic placement of these fuel treatments across forest landscapes accounting for practical limitations of how much area can actually be treated in the coming decades (Finney 2001, Finney et al. 2007). These models have been particularly valuable for optimizing and prioritizing fuel treatment locations, and comparing likely fire behavior between treated and untreated landscapes (Ager et al. 2007, Bahro et al. 2007, Finney et al. 2007, Stratton 2006). Although these models have assisted managers in the strategic placement of fuel treatments, they don't have the capacity to evaluate ecosystem responses to treatments. Treatments often rely upon various diameter limits for mechanical tree removal and treat only a portion of the landscape, roughly 20 to 30 percent, relegating most of the forest matrix to continued degradation from the effects of fire suppression. With a focus on evaluating fire intensity and spread, these fuel strategies do not explicitly address how forests might be ecologically restored or wildlife habitat enhanced. Without addressing these issues, treatments often face legal challenges resulting in fuel-treated acres falling far behind Forest Service goals (e.g., approximately 120,000 ac/yr in the Sierra Nevada [Stephens and Ruth 2005]).

We have learned much in recent years that can contribute to how forests are managed within strategically placed fuel treatments and throughout the landscape matrix. The Forest Service is already using many ideas in this paper. In other instances, litigation, limited funding, and regulations have fostered practices such as thinning to a diameter limit or limited use of prescribed fire that no one is happy with. We hope this science summary contributes to revising and removing some of these constraints.

In this paper, we first summarize recent science findings on fuel dynamics that might improve current fuel treatment practices. Even with these changes, however, Sierra Nevada forest management still lacks an explicit strategy for enhancing forest resilience and wildlife habitat, or managing the majority of the forested landscape outside fuel-treated areas. To incorporate these goals into current management, we then examine recent research on the ecological role of fire, forest resilience under changing climate conditions, and habitat requirements of sensitive wildlife. Research in all of these areas suggests the ecological importance of forest heterogeneity. Knowing the restoration importance of fire, we determined the pattern and stand structures for implementing this heterogeneity based on how fuel and fire dynamics varied topographically. We discuss how these variable forest conditions could be implemented with revised silvicultural practices. Finally we summarize the paper's content in short bullet points, distilling the applied management implications and list research needed to improve and modify implementation.

Fuel Dynamics and Current Management Practices

Forest fuels are usually assessed in three general categories; surface, ladder, and canopy bulk density (Agee et al. 2000). Fuel treatments often focus on ladder fuels (generally defined to be variably sized understory trees that provide vertical continuity of fuels from the forest floor to the crowns of overstory trees [Keyes and O'Hara, 2002, Menning and Stephens 2007]). Some studies and models, however, suggest a crown fire entering a stand is rarely sustained (i.e., sustained only under extreme weather conditions) if understory fuels are too sparse to generate sufficient radiant and convective heat (Agee and Skinner 2005, Stephens and Moghaddas 2005).

Surface fuels merit as much attention as ladder fuels when stands are treated. Prescribed fire is generally the most effective tool for reducing surface fuels.

One approach to developing fuel prescriptions, similar to current Forest Service procedures, is using modeling software to understand how the load of different fuel sizes and weather conditions affect predicted fire intensity. For example, Stephens and Moghaddas (2005) have modeled fire behavior and weather using Fuels Management Analysis (FMA) (Carlton 2004) and Fire Family Plus software (Main et al. 1990), respectively. The FMA uses two modules, Dead and Down Woody Inventory (data supplied by the Brown 1974 fuel inventory) and Crown Mass (data supplied by inventories of trees by species, size, height and crown ratio), to model a stand's crowning and torching indices (the windspeed needed to produce an active and passive crown fire, respectively), scorch height, and tree mortality. All four outputs can be controlled by changing surface and ladder fuels, giving managers an opportunity to interactively develop target fuel conditions for a desired fire behavior. Fuels can be reduced until the crowning and torching indices are higher than conditions that are likely to occur even under extreme weather events (e.g., Stephens and Moghaddas 2005).

In addition to ladder and surface fuels, managers have been concerned with reducing canopy bulk density in DFPZs and the defense zone of wildland urban interaces (WUI). Overstory trees are commonly removed, and residual trees are evenly spaced to increase crown separation. The efficacy of canopy bulk density reduction in modifying fire behavior is largely a function of weather conditions. Research has suggested there is often limited reduction in crown fire potential through overstory thinning alone, without also treating surface fuels (Agee 2007, Agee et al. 2000, Agee and Skinner 2005, Stephens and Moghaddas 2005). However, some field observations (JoAnn Fites Kaufmann, Forest Service Enterprise Team, Steve Eubanks, Tahoe National Forest) suggest that under severe weather conditions (e.g., sustained high winds) or on steep slopes, crown separation may reduce the risk of crown fire spread. Fire behavior under extreme conditions is still difficult to model, and, furthermore, what constitutes "extreme" (because many wildfires occur under hot, windy conditions) has not been defined (for the Southwest see Crimmins 2006). In forests adjacent to homes or key strategic points, managers may want to reduce canopy bulk density to reduce potential fire severity under all possible weather scenarios. Outside of those cases, the value of crown separation in preventing crown fire spread may be limited (Agee et al. 2000, Stephens and Moghaddas 2005).

A concern with the widespread use of canopy bulk density thinning in defensible fuel profile and defense zones is the ecological effects of the regular tree spacing (fig. 1). In the Sierra Nevada, historical data (Bouldin 1999, Lieberg 1902), narratives (Muir 1911), and reconstruction studies (Barbour et al. 2002, Bonnicksen and Stone 1982, Minnich et al. 1995, North et al. 2007, Taylor 2004) indicate mixed-conifer forests were highly clustered with groups of trees separated by sparsely treed or open gap conditions. This clustering can be important for regenerating shade-intolerant pine (Gray et al. 2005, North et al. 2004, York and Battles 2008, York et al. 2003), increasing plant diversity and shrub cover (North et al. 2005b), moderating surface and canopy microclimate conditions within the tree cluster (North et al. 2002, Rambo and North 2009), and providing a variety of microhabitat conditions for birds (Purcell and Stephens 2006) and small mammals (Innes et al. 2007, Meyer et al. 2007a). Studies in Baja's Sierra San Pedro del Martir (SSPM) forests also indicate forest structures (live trees, snags, logs,

and regeneration) are highly clustered (Stephens 2004, Stephens and Fry 2005, Stephens and Gill 2005, Stephens et al. 2007a). This forest in Mexico shares many characteristics of mixed-conifer forests found in the Sierra Nevada but has had little fire suppression and has not been harvested. Although these Baja forests have a different weather pattern than California's Sierra Nevada (Evett et al. 2007), they can provide some insight into the structure and ecological dynamics of a mixed-conifer forest with an active fire regime. A recent study of stressed SSPM Jeffrey pine/mixed-conifer forests where a 2003 wildfire was preceded by a 4-year drought, found spatial heterogeneity was a key feature in forest resiliency (Stephens et al. In press a). A clumped tree distribution, where groups are separated by gaps, might also slow crown fire spread (fig. 2), but we do not know of any studies that have examined this idea. Studies in other mixed-conifer forests (e.g., Klamath Mountains and eastern Washington) imply this heterogeneity may be an important characteristic of frequent fire's effect on mixed-conifer forests (Hessburg et al. 2005, 2007, Taylor and Skinner 2004). Fuel treatments that produce uniform leave tree spacing reduce this ecologically important spatial heterogeneity.

Managing surface fuels and reducing the use of regular leave-tree spacing can improve current fuel treatments. These changes, however, have not addressed a fundamental public concern, that current forest management lacks explicit strategies for ecological restoration and provision of wildlife habitat.

Ecological Restoration Using Fire

Fire plays a pivotal role in reshaping and maintaining mixed-conifer ecosystems. Fire was once very common in most of the Sierra Nevada and has been a primary force shaping the structure, composition, and function of mixed-conifer forests (Fites-Kaufman et al. 2007, Franklin and Fites-Kaufman 1996, McKelvey et al. 1996, Stephens at al. 2007b). Management strategies need to recognize that, in many situations, fire is both a viable fuel-treatment tool (Agee and Skinner 2005, Stephens et al. In press b) and an important jumpstart for many ecosystem processes stalled by accumulating surface fuels and the absence of frequent burning (North 2006). The main effect of low-intensity fire is its reduction of natural and activity (i.e., resulting from management activities) fuels, litter, shrub cover, and small trees. These reductions open growing space, provide a flush of soil nutrients, and increase the diversity of plants and invertebrates (Apigian et al. 2006, Knapp et al. 2007, Moghaddas and Stephens 2007, Murphy et al. 2006, Wayman and North 2007). By reducing canopy cover, fire also increases habitat and microclimate heterogeneity at site, stand, and landscape levels (Chen et al. 1999, Collins et al. 2007, Concilio et al. 2006, Falk et al. 2007, Hessburg et al 2007, Miller and Urban 1999). Fire is an indispensable management tool, capable of doing much of the work to restore ecological processes (Bond and van Wilgen 1996, Covington et al. 1997, North 2006, Stephenson 1999, Sugihara et al. 2006).

By itself, prescribed fire will be difficult to apply in some forests owing to fuel accumulations, changes in stand structure, and operational limitations on its use. Mechanical treatments can be effective tools to modify stand structure and influence subsequent fire severity and extent (Agee et al. 2000, Agee and Skinner 2005) and are often a required first treatment in forests containing excessive fuel loads. Prescribed fire is generally implemented very carefully, killing only the smaller size class trees (Kobziar et al. 2006). In some cases, it is ineffective for restoring resilience, at least in the first pass (Ritchie and Skinner 2007). For example, prescribed

fire may not kill many of the larger ladder-fuel or co-dominant true fir trees that have grown in with fire suppression (Knapp and Keeley 2006, North et al. 2007). In many stands, mechanical thinning followed by prescribed fire may be necessary to achieve forest resilience much faster than with prescribed fire alone (Schwilk et al. in press, Stephens et al. In press b).

Some forests cannot be prescribe burned, at least as an initial treatment, because of air quality regulations, increasing wildland home construction, and limited budgets. Yet restoration of these forests still depends on modifying fuels because it reduces wildfire intensity when a fire does occur (Agee and Skinner 2005) and can produce stand conditions that simulate **some** of fire's ecological effects (Innes et al. 2006, Stephens and Moghaddas 2005, Wayman and North 2007). Mechanical control of fuels allows fire, both wildland fire and prescribed fire, to be more frequently used as a management tool.

Climate Change

Forest restoration has often examined past conditions, such as the pre-European period, as a basis for developing management targets. With climate change, however, is restoring forests to these conditions even an appropriate goal? Returning to a pre-European condition, is unlikely to be feasible, because in addition to climate, livestock grazing and Native American ignitions have changed (Millar and Woolfenden 1999, Millar et al. 2007). Rather than strive for restoration of a fixed presettlement condition, managers could increase tree, stand, and landscape resiliency.

Research suggests global mean minimum temperatures may have already begun to rise (Easterling et al. 1997). One effect of this change for western forests would be earlier spring melt of mountain snowpacks. An analysis of Western U.S. fire season length over the last 50 years suggests that during the last two decades, fires begin earlier in the spring and occur later in the fall possibly owing to this trend in elevated nighttime minimum temperatures (Westerling et al. 2006). An analysis of fire severity and size in California has found an increase in both, along with a regional rise in temperature (Miller et al. in press). Climate change effects on precipitation have been more difficult to predict with models suggesting regional differences. For example, some models predict an increase in precipitation for northern California, some predict a decrease, and others suggest little change (Hayhoe et al. 2004, Lenihan et al. 2003). Most models predict the southern Sierra will receive less precipitation, with a higher percentage of it occurring as rain rather than snow (Miller et al. 2003). Climate models suggest there will be more frequent and stronger shifts between El Niño and La Niña events making changes in average precipitation difficult to predict. Perhaps one point of consensus is that most modelers agree the climate will become more extreme, suggesting oscillations between wet and drought conditions will be more common.

The potential effects of these changes on vegetation, fire, and wildlife are largely speculative (Field et al. 1999, Skinner 2007). Studies of past vegetation communities under a range of climates show unique plant assemblages without modern analogs (Millar et al. 2007, Williams and Jackson 2007). This suggests species will not simply shift up in elevation or latitude in response to warming conditions. Some general predictions that grouped species by functional categories have predicted an increase in broad-leaved over needle-leaved species, a

general increase in ecosystem productivity (i.e., total biomass), and a decrease in forest and an increase in shrub and grasslands (Lenihan et al. 2003). Changes in forest understory may vary depending on existing vegetation and the synergistic effects of increasing nitrogen enrichment from pollution and increased herbaceous fuels affecting burn intensity and frequency (Hurteau and North 2008). If Sierra precipitation decreases or experiences more frequent, intense La Niña events, forests are likely to become more drought stressed. One study examining several decades of mixed-conifer demography trends (van Mantgem and Stephenson 2007) suggests a recent increase in mortality may be related to increased drought stress from a warming climate. This drought stress would make current, high-density, Sierra forests more susceptible to pest and pathogen mortality, particularly from bark beetles (Ferrell 1996, Smith et al. 2005, Fettig et al. 2007, Maloney et al. 2008).

Managing forests under these conditions will be challenging. In the face of uncertainty, Millar et al. (2007) have suggested managers consider adaptive strategies focused on three responses: resistance (forestall impacts and protect highly valued resources), resilience (improve the capacity of ecosystems to return to desired conditions after disturbance), and response (facilitate transition of ecosystems from current to new conditions). All of these strategies acknowledge the influence of climate change and suggest management may fail if focused on re-creating past stand conditions using strict structural targets.

Although historical forest conditions may not provide numerical guidelines, the past still has lessons for managing Sierran forests. Historic forests can provide a better understanding of the ecological processes that have shaped mixed-conifer forest and the habitat conditions to which wildlife have adapted (Falk 1990, Society for Ecological Restoration 1993). All reconstruction studies, old forest survey data sets, and 19th-century photographs (Gruell 2001, McKelvey and Johnson 1992) suggest frequently burned forests had very low tree densities. For example, in the early 20th century, Lieberg (1902) estimated that stem density in the northern California forests he surveyed was only 35 percent of its potential because of mortality from frequent fire. Studies reconstructing pre-European conditions all indicate forests had a greater percentage of pine, a clustered pattern with highly variable canopy cover, and a high percentage of the growing stock in more fire-resistant, large-diameter classes. These past conditions give general guidance but should not be taken as strict numerical targets for density or diameter distribution in silvicultural prescriptions. What these reconstructions do provide is inference about the cumulative process effects of fire, insects, pathogens, wind, and forest dynamics on stand structure and composition, producing forests resilient to most disturbances including wildfire. A modeling comparison of different stand structures grown over 100 years, including those produced by fuel treatments (Hurteau and North in press), found a low-density forest dominated by large pines was most resilient to wildfire, sequestered the most carbon, and had the lowest carbon dioxide (CO_2) emissions and thus contributed less to global warming. An analysis of carbon emissions and storage from different fuel treatments, found understory thinning followed by prescribed fire produced the greatest reduction in potential wildfire severity without severely reducing carbon stocks (North et al. in press). As climate changes, managing the process or behavior of fire (i.e., manipulating fuels to influence burn intensity) may produce more resistant and resilient forests than managing for a desired number and size of trees.

An important benefit of forest management focused on affecting fire behavior is that in areas of wildland fire and prescribed burning, forest structure and composition are allowed to reestablish to modern dynamic equilibrium by adapting to fire that occurs under current climate and ignition conditions (Falk 2006, Stephenson 1999). A recent analysis of fire severity data by 10-yr periods in Yosemite's mixed-conifer forest (Collins et al. in press) revealed a fair degree of stability in the proportion of area burned among fire severity classes (i.e., unchanged, low, moderate, high). This suggests that free-burning fires, over time, can regulate fire-induced effects across the landscape.

Sensitive Wildlife

A strategy for mixed-conifer ecological restoration will conserve wildlife and minimize habitat impacts for both the broader animal community as well as the specific needs for a subset of species of concern. For over 15 years, Sierran forest management devoted significant effort to meeting the needs of old-forest-associated species, particularly the California spotted owl (*Strix occidentalis occidentalis)* (Verner et al. 1992) and the Pacific fisher (*Martes pennanti*). Sound wildlife management strategies balance species needs (both sensitive and common) at a variety of spatial (microsite to foraging landscape) and temporal (immediate to long-term population viability) scales (Noss et al. 1997).

A few shared characteristics of these top tropic species, including territoriality, large home range size, strong associations with late-seral forest structures, and long-distance travel for foraging contribute to improved owl and fisher viability. Both species are strongly associated with Sierran forest stands characterized by large trees and dense canopy closure (Verner et al. 1992, Zielinski et al. 2004b). These features are consistently selected by spotted owls for nesting (North et al. 2000), and by fishers for denning and resting sites in the Sierra Nevada (Mazzoni 2002, Zielinski et al. 2004a, 2004b) and elsewhere. Fishers use cavities in living and dead conifers and hardwoods (particularly California black oak [*Quercus kellogii* Newb.]) as daily refuges, and tend to select the largest individual trees in dense canopy stands (fig. 3). Individual trees are rarely reused as rest structures, at least consistently from night to night (Zielinski 2004b), so many different large trees are required. This behavior makes provision of resting habitat critical to fisher conservation (Zielinski 2004b). Spotted owls also use many different large trees within their home range for roosting (Verner et al. 1992). Large decadent trees are less common in the Sierra Nevada than they once were (Bouldin 1999), and providing for this structure requires protecting existing large trees, managing for their future development, and reducing major threats (i.e., high severity fire and pest mortality).

Foraging habitat, unlike resting habitat, is much easier to provide for spotted owls and fishers. The fisher's diet is very diverse and includes a variety of small mammals, birds, reptiles, fruits, and insects (Zielinski et al. 1999). Owls have a somewhat more specialized diet. In most locations they tend to prey on woodrats (*Neotoma* spp.*)*, northern flying squirrels (*Glaucomys sabrinus*), and deer mice (*Peromyscus maniculatus*), at least during nesting season (Forsman et al. 2004, Williams et al. 1992). Although our current knowledge of fisher and owl foraging habitats is fairly limited, we do know that their array of prey species are associated with a variety of forest conditions suggesting that habitat heterogeneity at different spatial scales across the landscape may be desirable for sustaining adequate food supplies (Carey 2003, Coppeto et al.

2006, Innes et al. 2007, Meyer et al. 2005). A cautious strategy would be emulating patterns created by natural disturbance to provide a heterogeneous mix of forest habitat across a managed landscape (Lindenmayer and Franklin 2002, North and Keeton 2008).

Management of Large Structures

Much of the public apprehension over forest management practices stems from possible impacts to old-forest associated species such as the Pacific fisher, California spotted owl, and northern goshawk (*Accipiter gentilis*). All three of these sensitive species depend on a forest structure usually dominated by large trees, snags, and downed logs, which provide suitable substrate for nesting, denning, and resting sites. Retaining these large snags and logs may increase fire hazard in these favorable habitat microsites, particularly in warming climate conditions. In some stands that have been depleted of larger trees, the best available structures may be intermediate-sized trees, generally defined as the 20- to 30-inch size class for conifers. In these stands, retaining conifers of this size is important not only for immediate wildlife needs, but also because they will become the next generation of large trees, (and eventually) snags and logs. Fisher rest structures include live trees (e.g., cavities, broken tops), snags (e.g., cavities, broken tops, stumps), platforms (nests, mistletoe growths, witches' brooms), logs, and ground cavities (Zielinski et al. 2004b). We do not yet have a good understanding of how best to distribute potential rest sites or how many are needed.

Other Key Structures and Habitats

Other forest features that may be important to sensitive species as well as the broader wildlife community include hardwoods, shrubs, "defect" trees, and riparian corridors. Hardwoods, particularly black oak, are increasingly regarded as an important species for providing food and cavities. Many small and large mammals and birds use acorns as a food source (McShea 2000), particularly in large masting years (Airola and Barrett 1985, Morrison et al. 1987, Tevis 1952). Oaks often have broken tops and large cavities from branch breakage, and are frequently used for resting and nesting sites by small mammals (Innes et al. 2007), forest carnivores (Zielinski et al. 2004b), and raptors (North et al. 2000, Richter 2005). In many areas, hardwoods are in decline because they have become overtopped and shaded by conifers. The larger oaks likely germinated and had much of their early growth in more open forest than exists today (Zald et al. 2008). Provisions are needed to create open areas within stands to facilitate hardwood recruitment. Thinning around large oaks, which are prolific seed producers, creates open conditions that favor oak regeneration. However, thinning around large, cavitary oaks that are currently shaded is a difficult decision. It is important to balance thinning to prolong the life of the oak against the possibility that reducing the canopy around the oak will decrease the overall habitat value of the rest structure. Managers might consider thinning around some, but not all cavitary oaks if several are present within a stand.

In fire-suppressed forests, shrubs are often shaded out (Nagel and Taylor 2005, North et al. 2005b) reducing their size, abundance, and fruit and seed production in low-light forest understories. Anecdotal narratives (Lieberg 1902, Muir 1911), a forest reconstruction (Taylor 2004), and a few early plot maps (Eric Knapp[2], pers. communication) suggest shrub cover in active-fire conditions might have been much higher than in current forests, mostly owing to large

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shrub patches that occupied some of the gaps between tree clusters (fig. 4). In SSPM's active-fire Jeffrey pine/mixed-conifer forests, Stephens et al. (In press a) found shrub cover was highly spatially variable, and often occurred in high-density patches. Some birds (Robinson and Alexander 2002) and small mammals, including spotted owl prey such as the woodrat (Coppeto et al. 2006, Innes et al. 2007), are associated with these habitat patches. We also know that species of *Ceanothus* are an important source of available nitrogen (Erickson et al. 2005, Johnson et al. 2005, Oakley et al. 2006) that persists even after the shrubs have been removed by fire (Oakley et al. 2003). In forests where shrubs are currently rare, it is important for managers to consider protecting what shrubs remain and increasing understory light conditions for shrub establishment and patch expansion. Patch size and configuration of such habitat should vary (see discussion on habitat heterogeneity in the next section).

Forest management practices have sometimes removed decadent, broken-topped, or malformed trees that are actually some of the most important features of habitat for many wildlife species (Mazurek and Zielinski 2004, North et al. 2000, Thomas et al. 1976, Zielinski et al. 2004b). These "defect" trees are some of the rarest structures in current forest conditions, often rarer than large trees. Successful management strategies incorporate means for preserving what remains and consider adding more of these features across the landscape. The Green Diamond Resource Company developed a guide for identifying and ranking the potential habitat quality of these forest structures in the Klamath Mountains. Developing a similar guide for Sierra forests would be extremely useful.

Connecting habitat within a landscape using corridors has been extensively studied, but results often indicate suitable forest conditions within the corridor and the optimal distribution of corridors, differs by species (Hess and Fischer 2001). In the Sierra Nevada, with its extended summer drought, riparian forests may be particularly important habitat and movement corridors for many species. Owing to greater soil development and moisture retention, these corridors usually provide more vegetative cover, have greater plant and fungal abundance and diversity (Meyer and North 2005), and a moderated microclimate (Rambo and North 2008). Many small mammals are found in greater abundance in riparian areas (Graber 1996, Kattelmann and Embury 1996, Meyer et al. 2007a), and some of these species are selected prey of old-forest-associated species. Initial observations of fisher (Katherine Purcell[3] pers comm.; Seglund 1995; Zielinski et al. 2004a) suggest riparian areas may be preferred movement corridors. Riparian corridor width would be better defined by overstory and understory vegetation than the set distances of 150 and 300 feet that are specified in the Sierra Nevada Forest Plan Amendment (SNFPA 2004).

Riparian forests are less moisture limited than upland areas, are highly productive, and now have some of the heaviest ladder and surface fuel loads of any Sierran forest communities (Bisson et al. 2003, Stephens et al. 2004). Recent Western U.S. research suggests that although reduced, fire is still a significant influence on riparian forest structure, composition, and function in forests with historically frequent, low-intensity fire regimes (Dwire and Kauffman 2003, Everett et al. 2003, Olson 2000, Pettit and Naiman 2007, Skinner 2003). Although fire in Sierran riparian areas was probably less frequent than in surrounding uplands, we do not yet know what

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its historical frequency, intensity, and extent was in stream corridors. When inevitable wildfires burn these corridors, they are likely to be high-severity crown fires that can denude riparian areas of vegetation (Benda et al. 2003). Any management activity in riparian areas, including no action, has risks. We suggest riparian corridors be treated with prescribed fire in spring or late fall (after rains) to help reduce surface fuels (Beche et al. 2005). In moist conditions, some observations (Dave McCandliss[4], Sierra N.F.) suggest that low-intensity prescribed fire can reduce fuels while maintaining high canopy cover and large logs if fuels have high moisture content.

Importance of Heterogeneity

A revised ecosystem management strategy that includes methods for increasing forest heterogeneity at multiple scales will improve habitat quality and landscape connectivity.

Creating vertical and horizontal heterogeneity in forests with frequent fire, however, has been a challenge. Multilayered canopies, often associated with Pacific Northwest old-growth forests (Spies and Franklin 1988), are not the best model for Sierran mixed-conifer forests because when adjacent trees are multilayered, the continuity of vertical fuels can provide a ladder for surface fire into the overstory canopy. Horizontal heterogeneity, however, used to be relatively common in Sierran mixed-conifer forests (Franklin and van Pelt 2004, Knight 1997, Stephens and Gill 2005). All of the Sierran reconstruction studies (Barbour et al. 2002, Bonnicksen and Stone 1982, Minnich et al. 1995, North et al. 2007, Taylor 2004) suggest mixed-conifer forests, under an active fire regime, had a naturally clumped distribution containing a variety of size and age classes.

Within Stand Variability

At the stand level, vertical heterogeneity can still be provided by separating groups of trees by their canopy strata (fig. 5). For example, a group of intermediate-size trees that could serve as ladder fuels might be thinned or removed if they are growing under large overstory trees. The same size trees in a discrete group, however, might be lightly thinned to accelerate residual tree growth or left alone if the group does not present a ladder fuel hazard for large, overstory trees. These decisions could be made using the revised silvicultural markings proposed (see "Allocation of Growing Space" section), where growing space is allocated by leaf area index among trees in different height strata. This strategy would produce within-stand vertical heterogeneity, albeit in discrete tree clusters, which will contribute to horizontal heterogeneity.

To increase horizontal heterogeneity, we suggest using microtopography as a template (Sherlock 2007) (fig. 6). Wetter areas, such as seeps, concave pockets, and cold air drainages, may have burned less frequently or at lower intensity (fig. 7). Thinning limited to ladder fuels in these areas is suggested because with their potentially higher productivity and cooler microclimate can support greater stem densities, higher canopy cover, and reduced fire effects. A concern with current uniform fuel reduction is that these microsite habitats associated with sensitive species would be eliminated. Surface fuel loads at these microsites should still be reduced to lower their vulnerability to high-intensity fire.

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In contrast, upslope areas, where soils may be shallower and drier, and where fire can burn with greater intensity, historically probably had lower stem densities and canopy cover (Agee and Skinner 2005) (fig. 8). On these sites, thinning might reduce the density of small or, where appropriate, intermediate trees and ladder and surface fuels toward a more open condition. In some circumstances this thinning may reduce water stress, accelerating the development of large residual trees (Kolb et al. 2007, Latham and Tappenier 2002, McDowell et al. 2003, Ritchie et al. 2008). Within a stand, varying stem density according to potential fire intensity effects on stand structure would create horizontal heterogeneity.

Landscape-Level Forest Heterogeneity

Landscapes with an active fire regime are highly heterogeneous. In Baja's active-fire Jeffrey pine/mixed-conifer forests, Stephens et al. (2007a) found that "average" stand characteristics such as snag density, large woody debris, tree density, basal area, and surface fuel loads were rare (approximately 15 to 20 percent of the sampled stands) and varied by an order of magnitude among localized (0.25-ac) plots. Studies in the Sierra Nevada (Fites-Kaufman 1997, Urban et al. 2000) and Klamath Mountains (Beaty and Taylor 2001, Taylor and Skinner 2004) found that mixed-conifer structure and composition varied by fire patterns that were controlled by landscape physiographic features (fig. 9). Fire intensity, and consequently a more open forest condition, increased with higher slope positions and more southwesterly aspects. In eastern Washington mixed-conifer forests, Hessburg et al. (2005, 2007) also found a heterogeneous historical forest landscape shaped by topographic influences on fire behavior. Cumulatively these studies suggest forest landscapes varied depending on what structural conditions would be produced by topography's influence on fire frequency and intensity.

We suggest creating landscape heterogeneity in the Sierra Nevada by mimicking the forest conditions that would be created by the fire behavior and return interval associated with differences in slope position, aspect, and slope steepness (Sherlock 2007). In general, stem density and canopy cover would be highest in drainages and riparian areas, and then decrease over the mid slope and become lowest near and on ridgetops (fig. 10). Stem density and canopy cover in all three areas would be higher on northeast aspects compared to southwest. Stand density would also vary with slope becoming more open as slopes steepen.

Revising Silvicultural Prescriptions

A new silviculture for Sierran mixed-conifer forest that balances ecological restoration and wildlife habitat with fuel reduction can meet multiple forest objectives. By necessity, recent Sierran silviculture has first been focused on reducing fire severity through fuel reduction. For many reasons, including maintaining or restoring resilient forests, public safety, and property loss, fuel reduction remains a priority. We suggest that, with some modification, wildlife and ecological objectives can also be met.

Importance of Tree Species

Diameter-limit prescriptions applied equally to all species will not remedy the significant deficit of hardwoods and pines in current forests (Franklin and Fites-Kaufmann 1996, SNFPA 2004). Prescriptions that differ by species can retain hardwoods, which are important for wildlife, and favor pines that can increase the forest's fire resilience. Given their current scarcity in many locations, there are few instances that warrant cutting either hardwoods or pines in mixed-conifer forests.

Retention of "Defect" Trees

Given the wildlife habitat value of trees with multiple tops, rot, cavities, etc., they should be retained whenever possible. These growth forms often result from disease or injury (e.g., from lightning, wind breakage, and being struck by adjacent falling tree), and are important structural features for many wildlife species. Modern Sierran forests have a significant shortage of these "decadent" but essential habitat structures (McKelvey and Johnson 1992).

Revising the Desired Diameter Distribution

The proposed silvicultural approach is a multiaged-stand strategy driven by the need for wildlife habitat, fire-resistant stand structures, and restoration of stand and landscape patterns similar to active-fire conditions in mixed-conifer forests. Although we use the term multiage, we are most interested in size and structure, and their associated ecological attributes. Multiaged stands are a flexible means of including variable stand structures with two or more age classes and integrating existing stand structures into silvicultural prescriptions. More traditional forms of uneven-age silviculture were heavily reliant on achieving a reverse-J diameter distribution that reduced large tree retention (O'Hara 1998). Past silviculture has often changed the slope of this line (i.e., adjusting the q-factor [Smith et al. 1996]) in response to different forest types and stand conditions, but has not fundamentally changed the shape of the curve or its allocation of growing space. The reverse-J diameter distribution prescribes a stand structure with a surplus of small trees and limited space for large trees. Such a distribution is inconsistent with historic Sierran mixed-conifer forests where fire reduced small-tree abundance while retaining fire-resistant, large-diameter trees (North et al. 2005a, 2007) (fig. 11). Research suggests that fire-prone forests rarely had reverse-J diameter distributions (Bouldin 1999, O'Hara 1996, 1998, Parker and Peet 1984).

Groups of Large Trees

Clusters of intermediate to large trees (i.e., >20 in. [diameter at breast height] [d.b.h.]) are sometimes marked for thinning with the belief that they are overstocked and thinning would reduce moisture stress. Some evidence, however, suggests these groups of large trees may not be moisture stressed by within-group competition because they have deep roots that can access more reliable water sources including fissures in granitic bedrock (Arkley 1981, Hubbert et al. 2001, Hurteau et al. 2007, Plamboeck et al. 2008). Reconstructions of Sierran forests with active fire regimes (Barbour et al. 2002, Bonnicksen and Stone 1982, Minnich et al. 1995, North et al. 2007, Taylor 2004) have consistently found large trees in groups. These groups, however, can be at risk if intermediate and small trees grow within the large tree groups. Thinning these small and intermediate trees will reduce fire laddering.

Managing the Intermediate Size Class

Many studies have documented the importance of large tree structures in forests for many ecological processes and their value for wildlife habitat (see summaries in Kohm and Franklin 1997, Lindenmayer and Franklin 2002). However, "large" varies with forest type and site productivity, and there is no set size at which a tree takes on these attributes. We only address this question of 20- to 30-in d.b.h. trees because it is so pivotal in the current management strategies for Sierran forests and is driving much of the discussion around fuel treatment thinnings.

What is achieved by thinning intermediate sized 20- to 30-in d.b.h. trees? Some research suggests that for managing fuels, most of the reduction in fire severity is achieved by reducing surface fuels and thinning smaller ladder-fuel trees (see summaries in Agee et al. 2000, Agee and Skinner 2005, Stephens et al. In press b). What is considered a ladder fuel differs from stand to stand, but typically these are trees in the 10- to 16-in d.b.h. classes. If trees larger than this are thinned, it is important to provide reasons other than for fuel treatment. These may include additional fuel reduction such as thinning canopy bulk density in strategic locations. Or it could be other ecological objectives such as restoration of an active-fire stand structure, managing for open habitat that includes shrubs, or accelerating the development of large leave trees. Although large trees are often old, studies have found diameter growth increases significantly when high densities of adjacent small stems are removed (Das et al. 2008, Latham and Tappeiner 2002, McDowell et al. 2003, Ritchie et al. 2008, Shov et al. 2004). There may be socioeconomic purposes for harvesting intermediate-sized trees such as generating revenue to help pay for fuel treatment or providing merchantable wood for local sawmills (Hartsough et al. 2008). Clear statement of the objectives for thinning intermediate-sized trees will help clarify management intentions.

Under what conditions, could larger trees be thinned? We suggest the following criteria but stress that these criteria are based on working hypotheses. The first selection criteria is species. Thinned intermediate-size trees should only be fire-sensitive, shade-tolerant species such as white fir (*Abies concolor* (Gord. & Glend.) Lind.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and incense-cedar (*Calocedrus decurrens* (Torr.) Florin). In mixed-conifer forest, attempt to keep intermediate-size pines and hardwoods because of their relative scarcity and importance to wildlife and fire resilience. A second criterion would be tree growth form. Some intermediate-size trees can still function as ladder fuel, particularly those that were initially grown in more open conditions (fig. 12). These trees can have live and dead limbs that extend down close to the forest floor providing a continuous fuel ladder. A third condition is middle to upper slope topographic position. In these slope positions some thinning of intermediate-size trees may help accelerate the development of large "leave" trees. We suggest, however, that these criteria not be applied to riparian areas, moist microsites often associated with deeper soils, concave topography, or drainage bottoms because these areas may have supported higher tree densities and probably greater numbers of intermediate-size trees (Meyer et al. 2007b).

Allocation of Growing Space

We propose a form of multiaged silviculture for Sierra mixed-conifer forest that is flexible to meet diverse forest objectives, that would retain existing large trees and promote recruitment of more large structures, and that provides for sustainability. The silvicultural system is based leaf area representing the occupied growing space of trees and stands. By segmenting stand-level leaf area index among canopy strata, we can develop tools to allocate growing space and provide flexibility for creating heterogeneous stand structures and meet ecological objectives (fig. 13) (O'Hara 1996, O'Hara and Valappil 1999). For example, leaf area could be allocated primarily to larger trees in one stand where these large trees are present and important structural components. In other stands, large trees may be absent and leaf area is allocated to developing cohorts to expedite development of large structural features. Trees are harvested and timber is an output, but the silvicultural system's focus is on retained stand structures, not what is removed for harvest. On the ground, this system provides for a diverse stand structure with both vertical (in discrete groups) and horizontal heterogeneity. It is

prescribed one stand at a time and creates landscape-level heterogeneity by varying the stocking regime. Treatments are intended to create a mixture of structures sustained throughout the period between active management entries.

The proposed silvicultural system recognizes canopy strata as the primary unit for allocation of growing space. Within these strata, space is allocated to species or species groups. A resulting stocking matrix might consist of three canopy strata and three species groups (e.g., pines, white fir and incense-cedar, and others) providing for a stocking matrix with nine cells. This approach generally simplifies the marking of trees and also can modify species composition (O'Hara et al. 2003). This silvicultural revision will, however, require a new research project to adapt the MultiAge Stocking Assessment Model (MASAM) to Sierra Nevada mixed-conifer forests.

Conclusion

A central premise of this paper is that the risks of carefully considered active forest management are lower than the risks of inaction and continued fire suppression in the Sierras' fire-prone forest types. We recognize the need to address specific management priorities (e.g., sensitive species) while developing practical and ecologically sound silvicultural guidelines. While many of the ideas contained within this ecosystem management strategy are not new, their implementation will require some innovations, but may provide a greater range of management options than do current practices. Our scientific understanding of mixed-conifer ecosystems remains incomplete, and therefore, it is important to continue learning from these strategies as they are applied. We have tried identify information that is supported by many studies, that is suggested by fewer but often recent studies, and that we can only infer from lines of evidence or observation but do not yet know with any degree of certainty. In the "Research Needs" section below, we identify some of the topics raised in this paper that need further investigation, although management will also be improved by trying some of the proposed strategies and learning what works and what fails.

This project began at the invitation of Forest Service Pacific Southwest Region managers who asked if we could develop a summary of current research to inform mixed-conifer management. In bringing together authors representing different key disciplines affecting Sierran forests, we did not know whether recent fire science, forest ecology, and wildlife biology research would provide contrasting or complementary management concepts or whether the concepts could be translated into silviculture practices. It was soon clear that each discipline's research findings coalesced around the importance of variable forest structure and fuels conditions for ecological restoration, forest resilience, and resulting diversity of wildlife habitat. We know that fire was the most important process influencing these ecosystems and that fire behavior was influenced by topography. This suggests managers could use localized site conditions and landscape position a guide for varying forest treatments. The various treatments can be based on flexible thinning guidelines using tree species and canopy position to vary retention by site conditions. In sum, our management strategy is based on emulating forest conditions that would have been created by low-intensity, frequent fire throughout the forest matrix.