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An Ecosystem Management Strategy for Sierran Mixed-Conifer Forests

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and Scott Stephens

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Cover photos, clockwise from top: Lodgepole and white pine forest on the Lee Lake Trail, by Malcolm North; fisher, by Bill Zielinski; Aspen Valley mixed conifer, by Malcolm North; prescribed fire, by Malcolm North; and heavy fuel load, by Eric Knapp.

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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 guide 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 than 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.

Addendum

After reading the first printing of this general technical report (GTR), forest managers have raised a number of issues that could use clarification and further detail. A second printing of the paper allows us to include this addendum addressing some of these issues, clarifying the paper's intent, and adding some relevant recent publications.

A central concern has been that some of the concepts presented in the GTR would constrain a manager's ability to design and implement forest management plans and practices based on local conditions. Our paper is not intended as a "standards and guides" that prescriptively dictates forest management. Prescriptive guidelines applied to the entire Sierra Nevada often frustrate best management practices, which need flexibility to respond to regional and local differences in climate, topography, soils, and forest conditions. We realize that managers already face many constraints when designing landscape-level treatments, some of which can be overcome more easily than others (Collins et al., in press). Rather than being prescriptive, the GTR's intent is to provide a conceptual approach for managing Sierran forests, against which proposed management plans and practices can be evaluated. Managers already use many of concepts presented in the GTR, but it has been difficult to communicate how variable forest conditions are created without a research-based conceptual framework for landscape management.

The GTR's principal intent is to summarize the latest science on how land managers can treat forests to concurrently provide for fuels reduction, ecosystem restoration, and wildlife habitat. Varying treatments in response to site conditions and existing forest structure can often create such variability. For example, some areas do not have enough topographic relief to be categorized into different aspects, slope positions, or slope steepness. These conditions, however, need not frustrate efforts to apply the concepts presented in the GTR. The paper's intent is offer alternatives to manage for different structural and fuel conditions while retaining extant habitat structures (i.e., hardwoods, large snags, groups of large trees). Keying off of these structures, the forest can be treated to provide both clusters of high canopy cover for wildlife and more open restoration conditions that favor rapid pine growth (Bigelow et al. 2009), better resilience to insects and pathogens, and with lower fire hazards. The GTR's concepts might provide challenges but also present opportunities to design and implement new prescriptions and management practices.

Several specific issues have been repeatedly raised:

1. **What are the silvicultural prescriptions that can be used to implement the concepts presented in the GTR?** We have not developed specific prescriptions as the GTR presents concepts merely to guide resource specialists who best know their local forest conditions. The GTR's concepts neither require nor preclude the use of any particular silvicultural prescription. Marking guidelines based on leaf area index have not yet been developed for the Sierra Nevada, but in the future may offer greater flexibility for designing silvicultural prescriptions grounded in more direct measures of physiological and ecological processes.

2. **In designing treatments to increase heterogeneity, what is the size of tree groups that should be retained and gaps that should be created in treated stands?** Local stand conditions will often determine what size tree groups and gaps can be created. High canopy cover areas are usually defined by groups of larger trees, which at the smallest scale are generally less than 10 individuals. This scale of tree clustering has been found both in unmanaged mixed conifer (E. Knapp unpublished data, North et al. 2004) and giant sequoia/mixed-conifer (Piirto and Rogers 2002) forests. Tree groups also occur at larger sizes such that several small-scale clusters are nested within a larger group. However, if a contiguous group of trees becomes too large, forest conditions can add to potential fire intensity. After a wildfire these large groups may no longer provide the high canopy cover habitat preferred by some sensitive species. Gaps impede fire spread (Agee and Skinner 2005) and therefore may reduce fire severity in forests where high canopy cover groups are retained. Stand structure reconstructions in mixed-conifer/giant sequoia stands suggest a wide range of gap sizes with most less than 0.5 ac (Piirto and Rogers 2002). Locating gaps in areas with thinner soils or lower productivity may be logical to foster lower canopy cover since these areas historically supported lower tree densities and fuel loads (Meyer et al. 2007b). In the forest matrix between tree groups and gaps, frequent-fire forests generally consisted of widely spaced, large trees, most of which were pines. The relative proportion of these conditions (i.e., low density, dispersed large trees, and large and small gaps and tree groups) and their composition could be varied depending on existing forest conditions and topographic position.

3. **How should social and economic issues be addressed in applying the concepts presented in the GTR?** The GTR does not address social or economic issues. We recognize that providing socioeconomic benefits, including the provision of a sustainable supply of timber, is part of the mandate of the USDA Forest Service. We also recognize that the economic viability of a project can affect whether the project will be implemented. We have not attempted to address these issues that are best resolved in the public arena. National forest staff, including interdisciplinary teams, which typically prepare National Environmental Policy Act (NEPA) documents for projects, are better qualified to address these issues.

4. **How should the concepts presented in the GTR be applied to the management of plantations?** Some of the general principles outlined in the GTR can be applied to stand-level plantations, especially the ideas of increasing spatial heterogeneity. The high uniformity of plantations (both spatially and temporally) makes them vulnerable to catastrophic change from fire, insects, and disease (single-species plantations are the most vulnerable). Both precommercially thinned and unthinned plantations can experience high mortality in most wildfire conditions (Stephens and Moghaddas 2005b, Kobziar et al. 2009). Modifying plantation tree density will not reduce the probability of mortality unless surface fuel loads are reduced and height to the base of the live crown is increased. Once a plantation reaches the stem-exclusion phase (Oliver and Larson 1996), silvicultural activities that produce gaps, increase the height to live crown (i.e. pruning, mastication, prescribed fire), and reduce surface fuels will increase plantation resiliency and resistance to fire.

5. **Are there situations where thinning intermediate-size pine trees would have ecological benefits for Sierra Nevada mixed-conifer forests?** Yes. We overstated the need to avoid thinning pine trees, particularly larger pines (p. 24 "Thinned intermediate-size trees should only be fire-sensitive, shade-tolerant species…"; p. 31 "silvicultural prescriptions would only remove intermediate-size trees when they are shade-tolerants on mid or upper slope sites."). In general, leaving pine and thinning white fir, Douglas-fir, and incense-cedar will help restore historical species composition and increase the forest's fire resilience. There are forests, however, where removing pine can reduce fuels, decrease the risk of drought or insect induced mortality, and accelerate the growth of the residual pine trees. We encourage thinning prescriptions that can be adaptable to existing stand structures and site conditions.

6. **What characterizes a "defect" tree that can provide wildlife habitat?** Although the importance of "defect" trees for wildlife habitat is widely acknowledged amongst managers, these trees are still marked for removal in many of the stands we've seen. Some silviculture technician classes may still be teaching thinning marks based on stand improvement with an emphasis on removing "defective trees." Unfortunately, we are not aware of any quantitative or visual guide to identify tree sizes and defects associated with wildlife use (i.e., platforms, mistletoe brooms, forked tops and cavities) for the Sierra Nevada. Research is needed to determine the size and number of "defect" trees that may be required to maintain or improve wildlife habitat. We plan to develop such a guide shortly. In the interim, managers may wish to examine the Bull et al. (1997) guide to identifying important wildlife trees in the interior of the Columbia River basin.

7. **How is ecological restoration defined in the GTR?** In the face of changing climate conditions, our focus is on increasing ecosystem resiliency. This focus is consistent with that described in USDA Forest Service Manual 2020.5, which defines ecological restoration as: "The process of assisting the recovery of resilience and adaptive capacity of ecosystems that have been degraded, damaged, or destroyed. Restoration focuses on establishing the composition, structure, pattern, and ecological processes necessary to make terrestrial and aquatic ecosystems sustainable, resilient, and healthy under current and future conditions."

8. **In the face of changing climate conditions, how can managers improve forest resiliency?** One measure of resilience is that disturbance produces mortality patterns consistent with the dynamics under which the forest evolved. Mixed-conifer resilience might be best ensured by (1) reducing fuels such that if the forest burned, the fire would most likely be a low-severity surface fire (Hurteau et al. 2009, Stephens et al. 2009b) and (2) producing a forest structure that keeps insect and pathogen mortality at low, chronic levels. In some fire-suppressed forests, mortality from bark beetles has shifted to large-scale, episodic occurrences (Fettig et al. 2008). One method of changing this pattern is to reduce tree moisture stress and subsequent bark beetle activity by reducing stand density with mechanical thinning and prescribed fire (Negron et al. 2009). Evidence suggests tree die-offs may be increasing in some forests (Breshears et al. 2009, Lutz et al. 2009, van Mantgem et al. 2009). The mechanisms behind such die-offs are complex,

but in fire-dependent forests often there is a cascade of effects linking water stress and bark beetle attacks (Ferrell and Hall 1975, Ferrell et al. 1994, McDowell et al. 2008, Stephens and Fule 2005). Drought can produce prolonged periods of stomata closure preventing carbon dioxide absorption needed for growth, or "carbon starvation" (McDowell et al. 2008). Carbon-starved trees may not be able to mount sufficient defenses to ward off insects (Breshears et al. 2005, Gower et al. 1995). In dense, fire-suppressed stands, thinning can significantly reduce the amount of transpiring leaf area often leading to decreased transpiration and increases in soil water content (Ma et al., in press, Zou et al. 2008). Even when no difference is detected in soil water content between thinned and control stands, it is common to detect improved water uptake and metabolic function of the remaining trees. This may be due to increased per-tree water availability (Brodribb and Cochard 2009). Fuels reduction thinning has reduced water stress, as measured by predawn water potential, in many ponderosa and Jeffrey pine stands (McDowell et al. 2003, Sala et al. 2005, Simonin et al. 2006, Walker et al. 2006). The thinning intensity needed to reduce moisture stress and the associated risk of bark beetle infestations will differ based on local site, soil, and stand conditions (Meyer et al. 2007b).

Prescribed fire can also reduce tree density, but some studies have found an immediate, short-term (1 or 2 years) increase in bark beetle damage and tree mortality following fire (Fettig et al. 2008, Youngblood et al. 2009). After that initial mortality increase, however, surviving tree growth rates can be higher than in untreated stands (Fajardo et al. 2007). Prescribed burning has also been found to increase soil moisture (Zald et al. 2008, Soung-Ryoul et al. 2009), although the increase may not be detected until several years after treatment (Feeney et al. 1998; Wallin et al. 2008).

Mixed-conifer forests have persisted in the Sierra Nevada through more severe droughts (Cook and Krusic 2004) than they are currently experiencing. These forests, however, are not adapted to the high densities and fuel loads now commonly found in many stands. Much is unknown about the potential long-term effects of a warming and/or drying climate. In the near term, however, reducing surface fuels and the densities of small-diameter stems may be the best means of creating more resilient forests.

9. **When is cutting 20- to 30-inch diameter at breast height (dbh) trees ecologically appropriate?** The ecological benefits of and rationale for cutting 20- to 30-in dbh trees depend on site-specific conditions. In many locations, there may be no benefit to cutting such trees because most ecological restoration will result from treating surface fuels and smaller diameter trees. In other locations, removing such trees may genuinely serve an ecological goal. For example, in some locations, where intermediate-size trees are abundant, they may present a fire and fuels risk, especially when live crowns are continuous to the forest floor. Typically overstory fuels are a small component of the fire hazards in mixed-conifer forests (Stephens and Moghaddas 2005b), however removal of trees in larger size classes can improve firefighter safety in some instances (Moghaddas and Craggs 2007). In other locations, intermediate-size trees contribute to overly dense stands that are moisture stressed and at risk of bark beetle attacks. And in yet other locations, intermediate-size conifers may be invading stands of at-risk species, like aspen, jeopardizing restoration efforts. These are just a few stand examples of situations where the removal of intermediate-size trees may be warranted from a strictly ecological perspective. Given the overall deficit of large trees in the Sierra Nevada, however, the removal of trees in the 20- to 30-in dbh class needs to be balanced against the desired development of more large trees and the future recruitment of large snags.

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Contents

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.

Over the dozen years since publication of the last science summary, the Sierra Nevada Ecosystem Project, project findings 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 forest health unclear as an objective (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.

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

Although 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 will benefit water production and quality for downstream users.

Recent Scientific Information

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.

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). 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 restraints.

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 stresses 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 listing 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.

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 and Skinner 2005, Agee et al. 2000, 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).

Mixed-conifer forests were highly clustered with groups of trees separated by sparsely treed or open gap conditions.

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

Figure 1—Regular spacing of "leave" trees in a defensible fuel profile zone.

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. 2008). 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.

Carl Skinner

Figure 2—An example of the clumped tree distribution and canopy gaps produced by an active fire regime. The photograph is an aerial view of the Beaver Creek Pinery, which has experienced very little fire suppression.

Fire is both a viable fuel-treatment tool and an important jumpstart for many ecosystem processes stalled by accumulating surface fuels and the absence of frequent burning

1996, Stephens et 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. 2009) 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. 2009, Stephens et al. 2009).

Some forests cannot be prescription 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.

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?

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. 2009). 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.

Species will not simply shift up in elevation or latitude in response to warming conditions.

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, Fettig et al. 2007, Maloney et al. 2008, Smith et al. 2005).

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. Historical 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 that 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 that 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 2009), 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.

As climate changes, managing the process or behavior of fire 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. 2009) 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).

Managing for owl and fisher viability needs to account for 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 cover (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).

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.

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

Figure 3—Pacific fisher resting on a limb of a large black oak. Although this picture is from the Klamath Mountains, it is typical of the stand conditions associated with fisher resting locations.

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 that 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[2] suggest shrub cover in active-fire conditions might have been much higher than in current forests, mostly owing to large 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. (2008) 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,

[2] Eric Knapp. 2008. Personal communication. Research ecologist, USDA Forest Service, Silviculture Laboratory, 3644 Avtech Parkway, Redding, CA. 96002.

Robert Dunning

Figure 4—Photograph taken in 1929 of mixed-conifer forest before thinning and approximately 40 years after the last fire, near Pinecrest, California. Note the extensive cover of understory shrubs, particularly under the canopy gap in the foreground.

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 might consider incorporating a means of preserving what remains and 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 that 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 [3] (Seglund 1995, Zielinski et al. 2004a) suggest that 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).

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[3] Katherine Purcell. 2008. Personal communication. Research wildlife biologist, USDA Forest Service, Forestry Sciences Laboratory, 2081 E Sierra Ave., Fresno, CA 93710.

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 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 that 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[4] suggest that low-intensity prescribed fire can reduce fuels while maintaining high canopy cover and large logs if fuels have high moisture content.

We suggest that riparian corridors be treated with prescribed fire in spring or late fall (after rains) to help reduce surface fuels.

Importance of Heterogeneity

A 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.

[4] Dave McCandliss, 2008. Personal communication. Fire management officer, USDA Forest Service, Sierra National Forest, 1600 Tollhouse Road, Clovis, CA 93611.

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.

Drawing courtesy of Robert van Pelt.

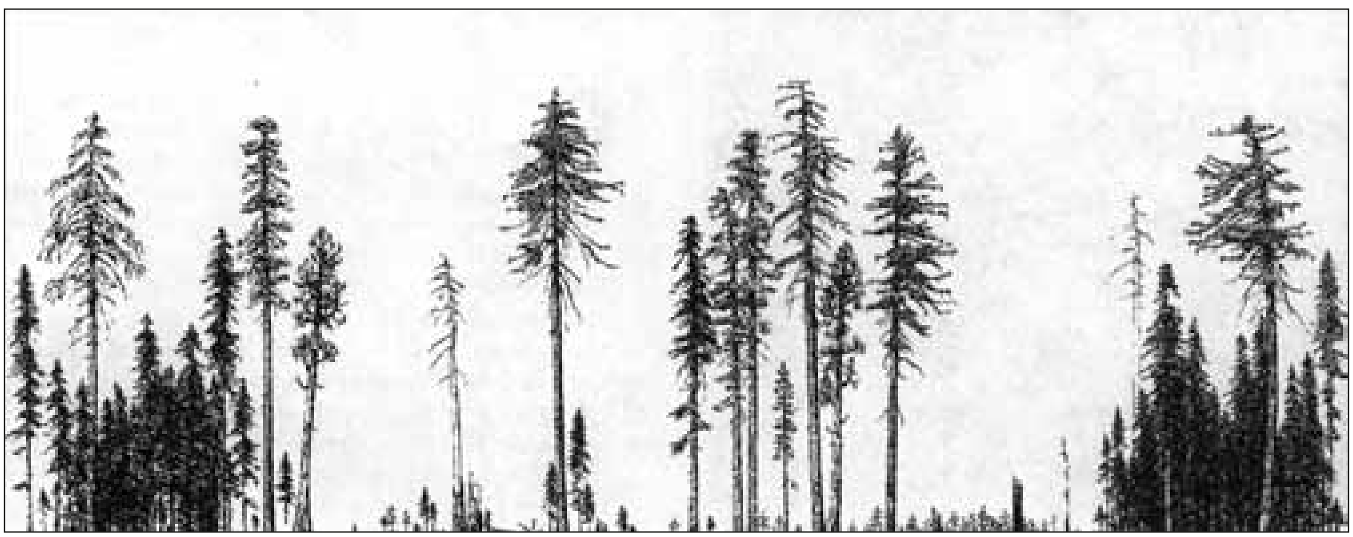
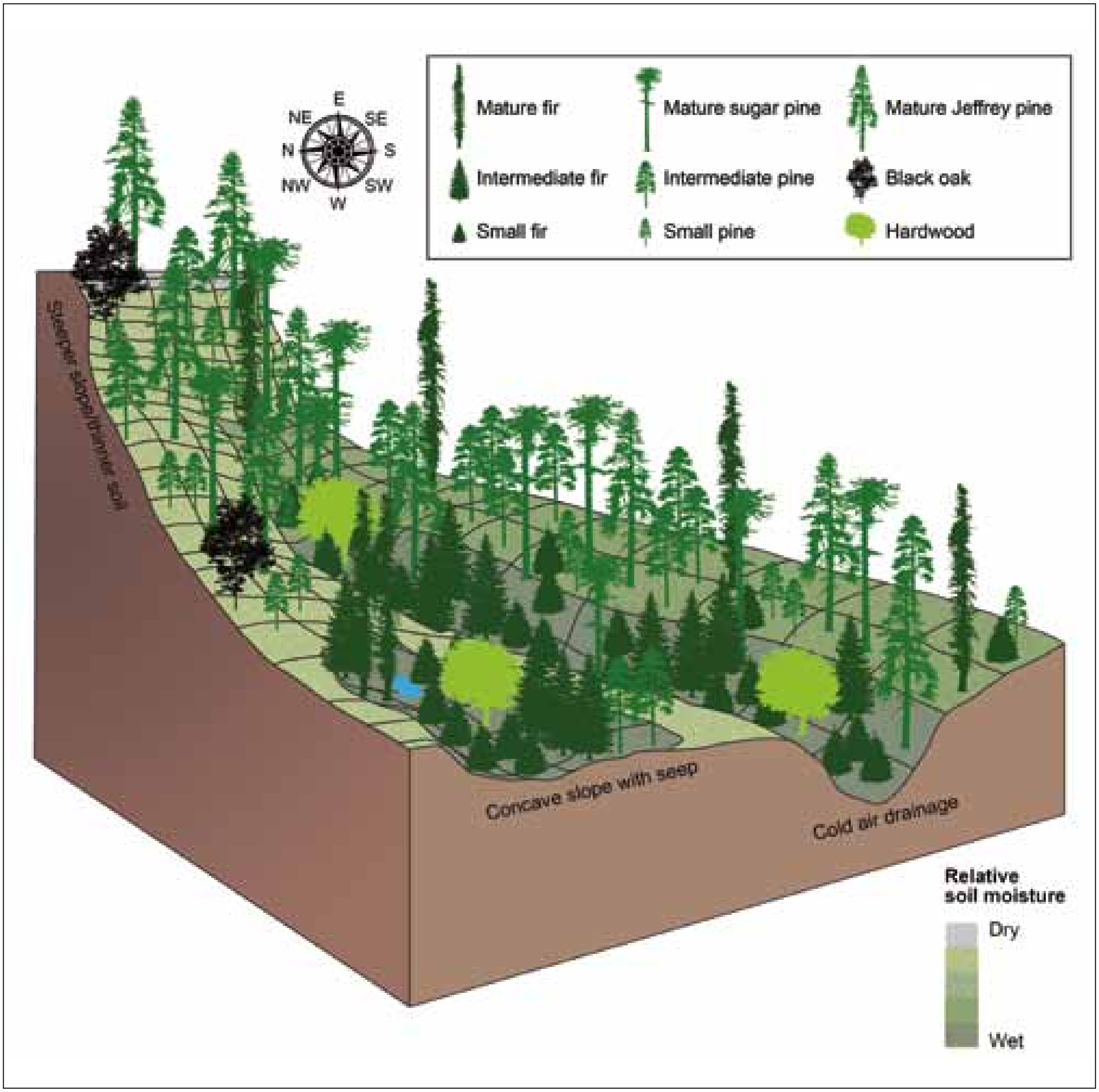


Figure 5—Transect of a mixed-conifer forest in Yosemite National Park’s Aspen Valley, which has experienced three understory burns within the last 50 years. Note that the stand has vertical heterogeneity but that trees in different canopy strata tend to be spatially separated.

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). Limiting thinning to ladder fuels in these areas is suggested because with their potentially higher productivity and cooler microclimate, they 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.



Mature tree drawings courtesy of Robert van Pelt

Figure 6—Stand-level schematic of how forest structure and composition would vary by small-scale topography after treatment. Cold air drainages and concave areas would have high stem densities, more fir and hardwoods. With increasing slope, stem density decreases and species composition becomes dominated by pines and black oak.

Malcolm North

Figure 7—Mixed-conifer stand structure at Aspen Valley, Yosemite National Park, produced by frequent, low-intensity fire. Note the higher stem density and hardwoods in the seep drainage in the background.

Within a stand, varying stem density according to potential fire intensity effects on stand structure would create horizontal heterogeneity.

In contrast, upslope areas, where soils may be shallower and drier and where fire can burn with greater intensity, historically 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.

Malcolm North

Figure 8—Upslope stand conditions where thinner soils and rock outcrops are often associated with drier conditions, and lower density forests, which burned frequently.

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 that forest landscapes varied depending on what structural conditions would be produced by topography's influence on fire frequency and intensity.

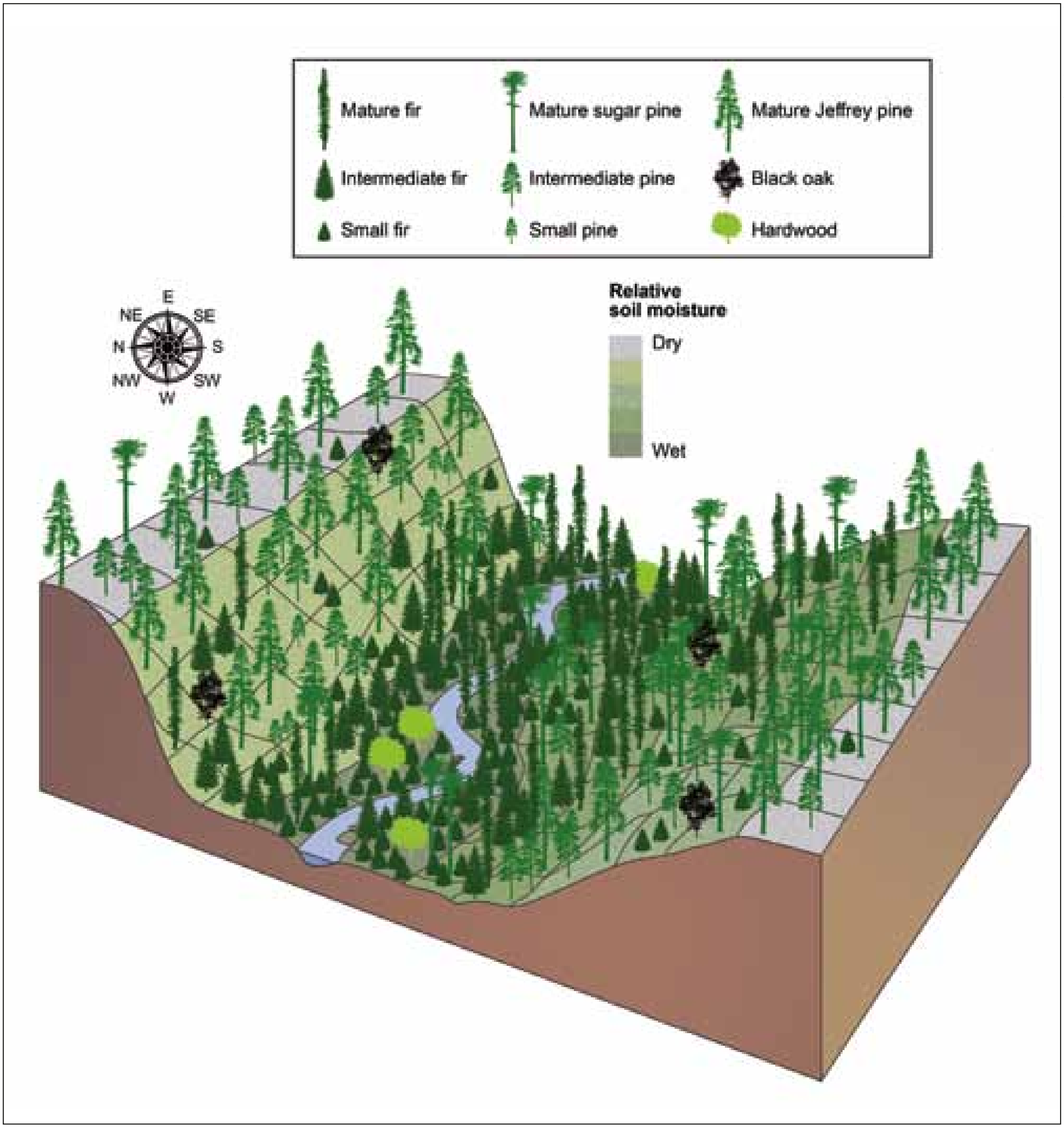
These studies suggest that forest landscapes varied depending on what structural conditions would be produced by topography's influence on fire frequency and intensity.

Eric Knapp

Figure 9—Landscape variation in burn intensity on the Moonlight Fire (2007), Plumas National Forest.

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.

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 midslope 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.



Mature tree drawing courtesy of Robert van Pelt

Figure 10—Landscape schematic of variable forest conditions produced by management treatments that differ by topographic factors such as slope, aspect, and slope position. Ridgetops have the lowest stem density and highest percentage of pine in contrast to riparian areas. Midslope forest density and composition varies with aspect: density and fir composition increase on more northern aspects and flatter slope angles.

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 large trees with multiple tops, rot, cavities, etc., managers may want to retain them 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. Disease incidence does not necessarily indicate that a tree is genetically more susceptible and therefore should be "culled" (Tainter and Baker 1996). 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 historical 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).

Research suggests that fire-prone forests rarely had reverse-J diameter distributions.

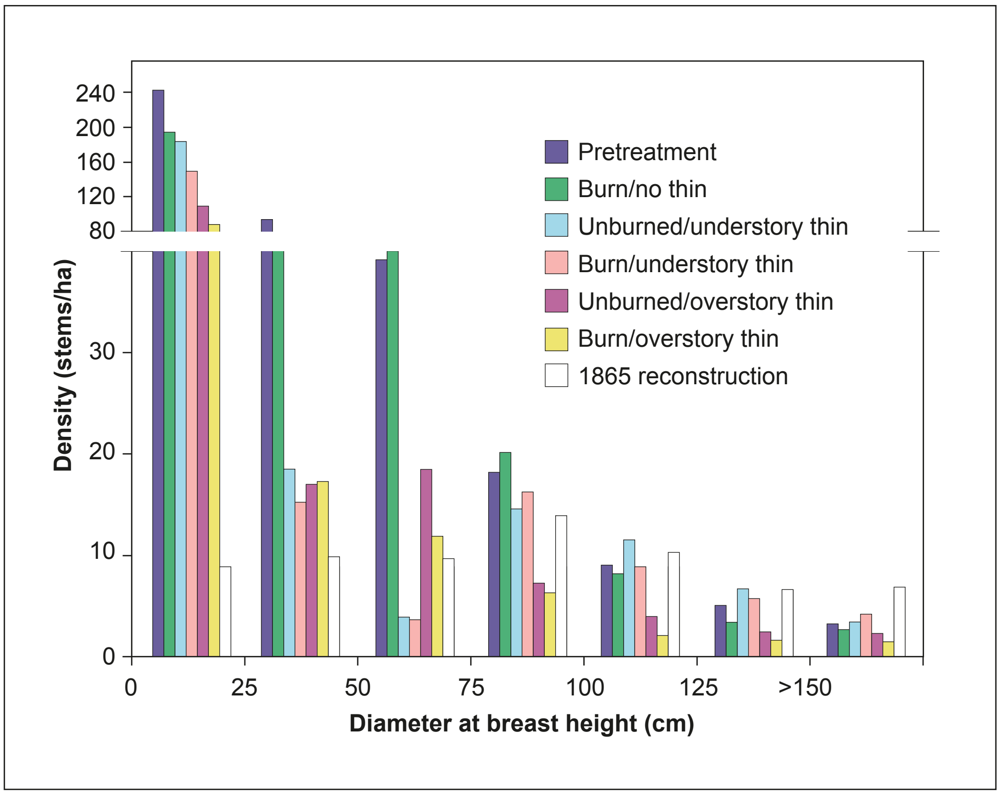


Figure 11—Density of live trees (stems per hectare) in seven size classes for seven conditions in the Teakettle Experiment. The five fuel-reduction treatments (prescribed burn only, understory thin, understory thin and burn, overstory thin, and overstory thin and burn) retain the same reverse-J-shaped diameter distribution as the pretreatment (fire-suppressed old growth) and do not approximate the reconstruction of the diameter distribution in 1865 active-fire conditions. Reconstruction methods probably underestimate the number of small stems in 1865 active-fire conditions, but even a three- to fourfold increase would not produce a reverse-J distribution (reprinted from North et al. 2007).

Groups of Large Trees

Clusters of intermediate to large trees (i.e., >20 inches 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.

If trees larger than 10 to 16 inches in d.b.h. are thinned, it is important to provide reasons other than for ladder-fuel treatment.

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. 2009). 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 ladder-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, Skov 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 intermediate trees be thinned?

Under what conditions could intermediate 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.) Lindl. ex Hildbr.), 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).

Malcolm North

Figure 12—Fire suppressed stand in the Teakettle Experimental Forest with white fir (*Abies concolor*) 20- to 30-in d.b.h. with ladder fuel potential.

Allocation of Growing Space

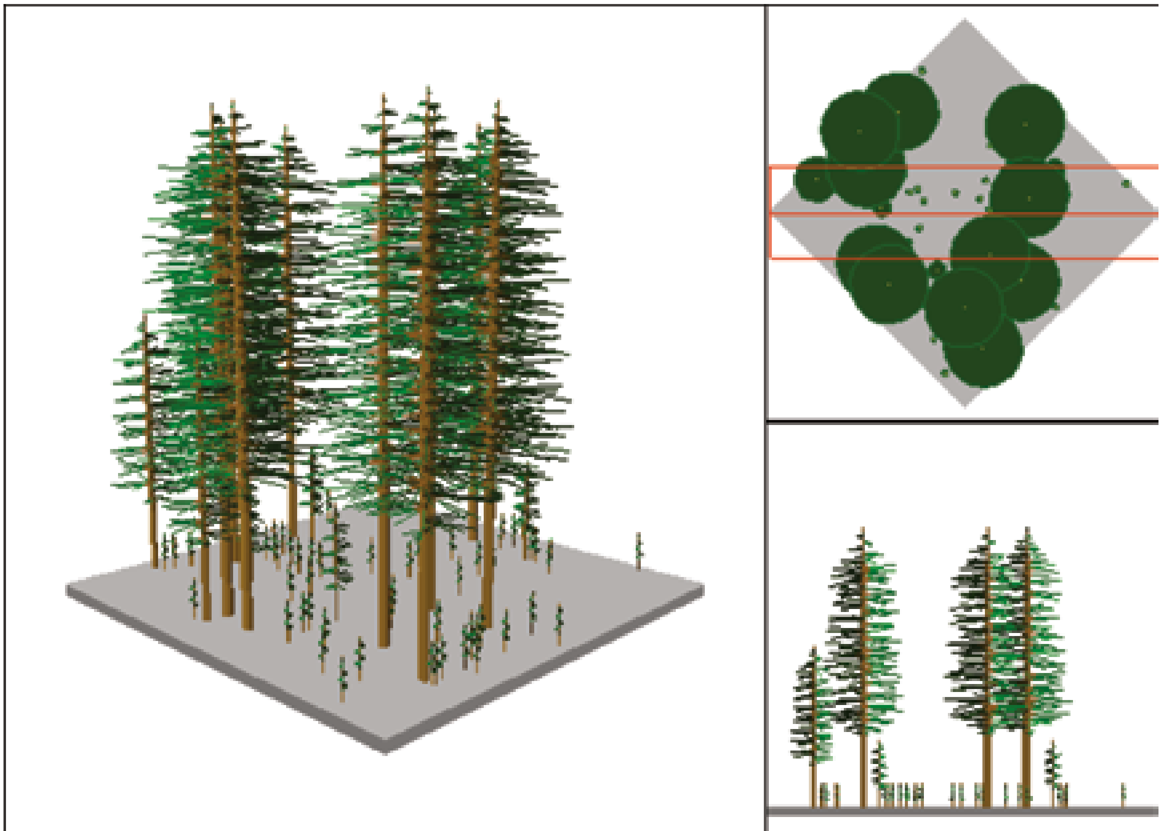
We propose a form of multiaged silviculture for Sierra mixed-conifer forest that is flexible to meet diverse forest objectives, that would retain existing large trees and promote recruitment of more large structures, and that provides for sustainability. The silvicultural system is based on leaf area 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.

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.

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. Many of the ideas contained within this ecosystem management strategy are not new, but their implementation will require some innovations, and they may provide a greater range of management options than do current practices. Our scientific understanding of mixed-conifer



Ponderosa pine MASAM — OREGON					
	User-Specified Variables				
TOTAL Leaf area index (LAI)	6				
	Cohort 1	Cohort 2	Cohort 3	Cohort 4	TOTAL
Number of trees/cohort/acre	25	40	55		120
Percent of LAI/cohort	50	35	15		100
	Diagnostic Information				
	Cohort 1	Cohort 2	Cohort 3	Cohort 4	TOTAL
Leaf area index/cohort ECC	3.0	2.1	0.9	0	6.0
Leaf area index/cohort BCC	1.3	0.7	0	0	2.0
Leaf area/tree (ft^2) ECC	5,227.2	2,286.9	712.8	0	—
BA/cohort (ft^2/ac) ECC	72.5	47.6	19.8	0	139.8
BA/cohort (ft^2/ac) BCC	29.7	14.4	0	0	44.1
Average volume increment/tree (ft^3/yr) ECC	1.02	0.64	0.18	0	—
Average volume increment/CC (ft^3/ac/yr)	20.7	16.3	5.0	0	42.0
Quadratic mean DBH/cohort (in) ECC	23.1	14.8	8.1	0	—
Tree vigor (in^3/ft^2/yr)	0.408	0.460	0.440	0	—
Stand density index ECC	95.2	74.6	39.4	0	209.2
Stand density index BCC	46.6	28.7	0	0	75.3

Figure 13—MultiAged Stocking Assessment model of a three-strata (or three-cohort) Oregon ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stand. Growing space can be allocated in a variety of patterns providing flexibility in stand structure design (from O’Hara et al. 2003). (— = not calculated.)

In bringing together authors representing different key disciplines affecting Sierran forests, we did not know whether they would provide contrasting or complementary management concepts; however, each discipline's research findings coalesced around the importance of variable forest structure and fuels conditions.

ecosystems is rudimentary, and, therefore, it is important to continue learning from these strategies as they are applied. We have tried to 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 as 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.

Summary Findings

Sierra Nevada mixed-conifer forests could benefit from a new management strategy that goes beyond short-term fuel treatment objectives and incorporates long-term ecological restoration and habitat improvement into forestry practices. This strategy is compatible with current landscape fuel treatments (i.e., SPLATs, DFPZs, and WUI defense zones), but strives to incorporate ecological restoration and wildlife habitat needs that have not been explicitly addressed. This strategy can be implemented using a multiage silvicultural system to meet fuel reduction, ecosystem restoration, and wildlife habitat objectives. Important facets of the strategy include:

- **Mechanical fuels management:** When stands cannot be burned, reducing fuels to moderate fire behavior is still a key priority because wildfire is likely to burn the area eventually. A few of the ecological benefits of fire are achieved with mechanical fuel reduction, but thinning is not an effective substitute for fire in affecting ecosystem processes. Reducing surface fuels is as important as reducing ladder fuels.

- **Limit use of crown separation in fuel treatments:** Sparingly apply canopy bulk density reduction and increased tree crown separation only in key strategic zones. More research is needed, but current models suggest its effects on reducing crown fire spread are limited, and the regular leave-tree spacing does not mimic tree patterns in active-fire-regime forests.
- **The ecological importance of fire:** Prescribed fire can help reduce surface fuels and restore some of the ecological processes with which mixed-conifer forests have evolved.
- **Treatments focused on affecting fire behavior:** Efforts to restore pre-European forest conditions are likely to fail in the face of climate change and also do not provide flexible prescriptions that adapt to different site conditions. Focus treatments on affecting potential fire behavior by manipulating fuel conditions, thereby allowing forests to equilibrate to fire under modern conditions and increasing forest heterogeneity.
- **Retention of suitable structures for wildlife nest, den, and rest sites:** Trees providing suitable structure for wildlife include large trees and trees with broken tops, cavities, platforms, and other formations that create structure for nests and dens. These structures typically occur in the oldest trees. Develop and adopt a process for identifying, and thus protecting, such trees for use by inventory and prescription-marking crews.
- **Stand-level treatments for sensitive wildlife:** Areas of dense forest and relatively high canopy cover are required by California spotted owls, fishers, and other species. Identify and manage areas where, historically, fire would have burned less frequently or at lower severity owing to cooler microclimate and moister soil and fuel conditions for the higher stem and canopy densities that they can support.
- **Large trees and snags:** Given their current deficit in mixed-conifer forest and the time necessary for their renewal, protect most large trees and snags from harvest and inadvertent loss owing to prescribed fire.
- **Landscape-level treatments for prey of sensitive wildlife:** In the absence of better information, habitat for the prey of owls and fishers may best be met by mimicking the variable forest conditions that would be produced by frequent fire. Reductions in stem density and canopy cover would emulate the stand structure produced by local potential fire behavior, varying by a site’s slope, aspect, and slope position.

- **Retain hardwoods and defect trees and promote shrub patches:** Hardwoods (particularly black oak) and defect trees (i.e., those with cavities, broken tops, etc.) are valued wildlife habitat and should be protected whenever possible. Increasing understory light for shrub patch development, can increase habitat for some small mammals and birds.
- **Riparian forest fuel reduction:** Prescribed burning of riparian forest will help reduce fuels in these corridors that are also important wildlife habitat.
- **Spatial dispersion of treatments:** Trees within a stratum (i.e., canopy layers or age cohorts) would often be clumped, but different strata would usually be spatially separated for fuel reasons. Give particular attention to providing horizontal heterogeneity to promote diverse habitat conditions.
- **Spatial variation in forest structure:** "Average" stand conditions were rare in active-fire forests because the interaction of fuels and stochastic fire behavior produced highly heterogeneous forest conditions. Creating "average" stand characteristics replicated hundreds of times over a watershed will not produce a resilient forest, nor one that provides for biodiversity. Managers could strive to produce different forest conditions and use topography as a guide for varying treatments. Within stands, important stand topographic features include concave sinks, cold air drainages, and moist microsites. Landscape topographic features include slope, aspect, and slope position.
- **Stand density and habitat conditions vary by topographic features:** Basic topographic features (i.e., slope, aspect, and slope position) result in fundamental differences in vegetation composition and density producing variable forest conditions across the Sierra landscape. Drainage bottoms, flat slopes, and northeast-facing slopes generally have higher site capacity, and thus treatments retain greater tree densities and basal areas.
- **Tree-species-specific prescriptions:** Hardwoods and pines, with much lower densities in current forests compared with historical conditions, would rarely be thinned. Thinning would be focused on firs and incense-cedar. Address pine plantations separately.
- **Silvicultural model and strategy:** Tree diameter distributions in active-fire forests vary but often have nearly equal numbers in all diameter size classes because of periodic episodes of fire-induced mortality and subsequent recruitment. Stand treatments that significantly reduce the proportion of small trees and increase the proportion of large trees compared to current stand conditions will improve forest resilience.

- **Treatment of intermediate-size trees:** In most cases, thinning 20- to 30-in d.b.h. trees will not affect fire severity, and, therefore, other objectives for their removal should be provided. Where those objectives are identified, silvicultural prescriptions would only remove intermediate-size trees when they are shade-tolerants on mid or upper slope sites.
- **Field implementation of silvicultural strategy:** Modify marking rules to ones based on species and crown strata or size and structure cohorts (a proxy for age cohorts) rather than uniform diameter limits applied to all species.
- **Allocation of growing space:** A large proportion of the growing space would be allocated to the largest tree stratum.
- **Assessment of treatment effects:** Emphasis is on what is left in a treated stand rather than what is removed.

Research Needs

Some of our management recommendations are currently based on inferences from studies in other forest types. There are many aspects of Sierra Nevada ecosystems that are still poorly understood. The list below is focused on research needed to investigate and refine some of the suggested management practices. These studies and implementing the suggested strategy will undoubtedly raise new questions. Working together, forest managers and researchers can exchange information and identify unknowns as they develop.

1. Quantify the leaf area and growth relationships needed to develop stocking control relationships for Sierra Nevada mixed-conifer forest. This will allow completion of a Sierra Nevada MASAM for the Kings River Project (KRP) area or any other area in the Sierra where this approach could be implemented. This tool will allow the design and assessment of a variety of multiaged-stand structures that include, among others, older residual trees, development of resilient structures, and accommodation of prescribed burning regimes.
2. Develop and implement an adaptive monitoring strategy to assess the efficacy of a multiaged strategy at both the stand and landscape scales. This information will include both on-the-ground monitoring of treated stands and simulations using Sierra Nevada MASAM. This input will be used to refine the strategy over time and make large-scale assessments of landscape patterns for wildlife habitat, potential fire behavior, and general diversity of

vegetation patterns. A multiaged strategy would be adjusted pending results of monitoring efforts to accommodate other resource objectives such as wildlife, fire, or forest restoration.

3. Assess the potential outcomes of this proposed silvicultural approach on vegetation response and wildlife habitat features of interest. This could be combined with a comparison to other possible silvicultural strategies to evaluate the similarities and differences of approaches. Research would also assess the effects of any treatment on predicted fisher resting habitat using either a predictive microhabitat model (Zielinski et al. 2004b) or a habitat model based on Forest Inventory and Analysis (FIA) protocols (Zielinski et al. 2006).

4. More closely examine the distribution of tree size and canopy density characteristics within female fisher home ranges to establish the means and variances of tree number/density by size class, for both conifers and hardwoods. This would require overlaying the boundaries of female fisher home ranges, which have been estimated on the Sierra and Sequoia National Forests (Mazzoni 2002, Zielinski et al. 2004a), and then using both remotely sensed and ground-based methods to described the vegetation within these areas. Once we have estimates of the average number of, say, white fir between 20 and 30 in d.b.h. per acre within the average female home range, we will be able to compare this and other characteristics with the average number of this species and size class predicted to occur as **residuals** after proposed treatments. If the selected tree size or density characteristic, when measured after treatment, is significantly **lower** than what occurs in female home ranges, then the proposed management activity would not be consistent with fisher conservation.

5. Determine fire histories of riparian areas to identify fire frequency, intensity, and extent. How far does the riparian influence for dampening fire extend away from the stream? What stream characteristics (i.e., bank slope, stream size, etc.) affect the size of the riparian influence zone? What were historical fuel loads in these forests? How can riparian systems be managed to reduce adverse fire effects while maintaining wildlife habitat? In current wildfires, are riparian forests typically experiencing high-intensity crown fires, or are moister fuels and microclimate still dampening fire behavior?

6. Determine how forest structure and composition varied by topographic feature under an active-fire regime in the Sierra Nevada. There have been studies in the Klamath Mountains and eastern Washington, but no information is available for California forests. The research would identify which topographic features matter, and stand structure and fuels loads associated with different physiographic areas.

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Metric Equivalents

When you know:	Multiply by:	To find:
Acres (ac)	0.405	Hectares
Inches (in)	2.54	Centimeters
Feet (ft)	.305	Meters

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