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ABSTRACT

Many of the tools available for managing forested ecosystems lie within the disciplines of silviculture and fire management. These two sets of management practices, in fact, are commonly used in concert. Understanding the relationships between these two disciplines, therefore, can contribute to more intelligent ecosystem management. Silvicultural techniques mimic to varying degrees some of the disturbance functions—such as facilitating establishment of regeneration and influencing forest structure and composition—performed naturally by fire. This chapter provides a brief overview of some of these relationships for a range of stand structures and fire regimes. Effects of partial cuttings on fire hazard also are discussed. Research is needed to clarify basic relationships between fire regimes and the dynamics and structures of stands and landscapes. Adaptive management experiments also should be undertaken to determine the practicability and long-term ecological consequences of a range of silvicultural and fire treatments.

INTRODUCTION

Before Euro-American settlement, relatively frequent fires strongly influenced the composition, structure, and dynamics of most forest ecosystems in the Sierra Nevada, in concert with other disturbance factors (Ferrell 1996; Skinner and Chang 1996). These fires, mostly low to moderate in severity, caused changes by damaging or killing plants and setting the stage for regeneration (including sprouting of top-killed plants) and vegetation succession. They maintained surface fuels at fairly low levels, and in most areas kept forest understories relatively free of trees and other vegetation. In addition, fires influenced many processes in the soil and forest floor, including the organisms therein, by consuming organic matter, affecting nutrient cycling, and inducing other thermal and chemical changes (Agee 1993; Chang 1996). These fire effects in turn resulted in a wide array of effects on other ecosystem components and processes, including wildlife communities and watershed properties.

Human activities since the mid-1800s have greatly changed the occurrence, nature, and effects of fire in the Sierra Nevada (Husari and McKelvey 1996; McKelvey and Johnston 1992; Skinner and Chang 1996; Weatherspoon et al. 1992). Organized fire suppression, which began early in the twentieth century, has been extremely effective in limiting the area burned by wildfires (Husari and McKelvey 1996; McKelvey and Busse 1996). The resulting virtual exclusion of low- and moderate-severity fire has profoundly affected the structure and composition of most Sierra Nevada vegetation, especially in low- to middle-elevation forests. Conifer stands have become denser, mainly in small and medium size classes of shade-tolerant and fire-sensitive tree species. Stands have also become more complex when viewed vertically, but less complex and more homogeneous in terms of areal arrangement (Weatherspoon et al. 1992). "Selective" cutting of large overstory trees (McKelvey and Johnston 1992) and the relatively warm and moist climate that has characterized most of the twentieth century (Graumlich 1993) have probably reinforced these trends. Excessively dense stands have led to drought stress and bark beetle outbreaks, resulting in widespread mortality of trees in many areas and the potential for extensive additional mortality (Ferrell 1996). One consequence of

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these changes has been a large increase in the amount and continuity of both live and dead forest fuels, resulting in a substantial increase in the probability of large, severe wildfires (Weatherspoon and Skinner 1996). In many areas, ecosystem diversity and sustainability appear jeopardized by these changes, even without the threat of severe fires.

The necessity of restoring and sustaining these at-risk ecosystems is emerging as a major challenge confronting those responsible for managing Sierra Nevada forests. The means to accomplish these goals is the subject of some controversy. Some would advocate a hands-off philosophy of forest management, one of "letting nature take its course." Such a philosophy may well be appropriate for some upper montane and subalpine forests that have been affected relatively little by past management activities and in which wilderness values and/or restoration of natural processes are primary management emphases, especially if lightning fires are permitted to resume their natural role. This approach, however, is very unlikely to be successful in most lower- and middle-elevation Sierran forests, whose presettlement disturbance regimes were dominated by frequent low- to moderate-severity fires (Skinner and Chang 1996). Given the excessive quantities of fuels present in most of these forests, continued fire suppression (which certainly is not a hands-off approach) at a minimum will be required to avoid wildfire losses that are completely unacceptable ecologically and socially. Suppression alone, however, will only exacerbate the growing problems of overly-dense stands and excessive fuels. In addition to fire suppression, therefore, some form of active management, designed to replace critical missing elements of the largely defunct historic disturbance regimes, is probably essential to begin to reverse these problems and to ensure the diversity and sustainable productivity of these forests into the future.

Many of the tools available for managing forested ecosystems, and thereby mimicking to various degrees the functions of historic fire regimes (Skinner and Chang 1996) or other disturbance processes, lie within the disciplines of silviculture and fire management. These two sets of management practices are commonly used in concert, and in fact the line between silviculture and fire management can be quite blurry. For example, cuttings can be effective in breaking up the horizontal and vertical continuity of live fuels in lower canopy layers or in pretreating a stand to facilitate the introduction of prescribed fire. Alternatively, cuttings can add fuels and otherwise increase wildfire hazard. Prescribed fire and other techniques are often used for the dual purpose of reducing hazardous fuels and preparing a site for successful establishment of tree regeneration. Silvicultural techniques are used to emulate some of the historic effects of fire on forest structure. In fact, prescribed fire itself is considered by some to be a silvicultural technique.

The many ecosystem functions of frequent low- to moderate-severity fire can be restored fully only through the use of fire. Silvicultural cuttings and other fire "surrogates" can substitute only partially for fire. As is described in the following section, silvicultural techniques can mimic to varying degrees some of the functions performed naturally by fire, including facilitating the establishment of regeneration and influencing forest structure and composition. A wide array of thermal and chemical effects of fire (Agee 1993; Kilgore 1973; Chang 1996), however, are not mimicked by other methods. Fire and fire "surrogates" also differ markedly in terms of other factors, including potential for soil compaction and components of biomass removed from a site (i.e., fire tends to consume greater proportions of smaller size classes of biomass, whereas larger size classes typically are removed by cuttings). Accordingly, it seems desirable for low- to moderate-severity fire—both prescribed fire and "managed wildfire" (Husari and McKelvey 1996; Weatherspoon and Skinner 1996)—to assume a considerably expanded role in the management of Sierra Nevada forests. In those areas from which such fire continues to be excluded, for whatever reasons, managers should recognize that some ecosystem components and processes will depart significantly from their historical ranges of variability (Manley et al. 1995), with mostly unknown consequences for long-term ecosystem viability.

Nevertheless, it is important to understand that the reintroduction of fire alone cannot restore millions of acres of degraded Sierra Nevada forests. Silvicultural techniques are needed in addition to or in lieu of fire in many areas to move conditions away from dense forests dominated by small trees and containing excessive fuels toward more open forests dominated by large trees. Given the realities of modern civilization, it is inconceivable that fire in its presettlement extent, frequencies, and severities could be restored fully to the Sierra Nevada. Even at a reduced scale, a number of factors constrain the use of both management-ignited prescribed fires and prescribed natural (lightning) fires (Husari and McKelvey 1996; Weatherspoon and Skinner 1996). Furthermore, like nonfire methods, prescribed fire cannot fully mimic the ecosystem functions of presettlement fire, at least in the short term. The effects of newly reintroduced fire are likely to be quite different from those of presettlement fires because the forests (including fuels) have changed so greatly. If fire alone were used, several sequential entries with prescribed fire would probably be necessary, especially in densely stocked stands with heavy fuel concentrations, before the desired forest conditions would be approached. Early prescribed burns in such stands would tend to be expensive and have a relatively high risk both of escapes and of undesirable fire effects. In contrast, where feasible and compatible with management objectives, appropriate silvicultural cuttings preceding prescribed burns may significantly speed the movement toward desired forest structure and composition and in turn could hasten the use of prescribed fire in a way that more nearly mimics the natural ecosystem functions of frequent low- to moderate-severity fire. Of course, cuttings also provide opportunities to meet human needs for jobs and utilization of wood fiber.

Understanding the relationships between silviculture and fire can contribute to more intelligent ecosystem management. This chapter provides a brief overview of some of these relationships, discussed in two general categories: (1) silvicultural cutting methods as approximations of stand and landscape structural effects of fire in different fire regimes, and the compatibility of fuel-management techniques with these cutting methods; and (2) effects of partial cuttings on wildfire hazard. Although even-aged cutting methods are discussed briefly, this chapter emphasizes methods other than even-aged ones because (1) they more closely mimic the natural disturbance regimes prevailing in most Sierra Nevada forests, and (2) any landscape-level needs for large, even-aged stands are likely to be met by severe wildfires and subsequent plantation establishment for the foreseeable future.

SILVICULTURE, FIRE REGIMES, AND FUEL-MANAGEMENT TECHNIQUES

Silviculture was originally developed to produce timber efficiently and sustainably (Smith 1962), and in fact timber production has been the principal focus of the discipline during most of its existence. In the minds of many, silviculture is still the handmaiden of timber management. Over the years, however, silviculturists and others have come to recognize that silviculture employs a powerful and flexible set of techniques for meeting a wide array of resource management objectives and desired values (Daniel et al. 1979; Helms and Tappeiner 1996). These techniques need to be used with intelligence and discrimination. In prescribing and implementing management treatments, the silviculturist should consider site capabilities, species requirements, and key ecological processes, including the natural disturbance (mainly fire) regimes that prevailed in the area. The extent to which these factors, especially fire regimes, have been considered in the past has varied considerably.

One key function that both silviculture and natural disturbance have in common is facilitating the establishment of regeneration. The long-term sustainability of any desired forest condition in the Sierra Nevada depends in part on adequate establishment of regeneration at suitable intervals. Silvicultural systems are designed to promote the establishment of regeneration and in fact are classified by the methods they use to achieve this goal and the types of structures they create (Ford-Robertson 1971). In most Sierran forest types, fire historically was the primary agent that set the stage for regeneration of conifers and many other plants. Fires typically produced at least two conditions that promoted conifer regeneration: they provided the mineral soil seedbed favored by many species for seed germination and seedling survival, and they created openings ranging from a fraction of an acre to perhaps hundreds of acres—needed for survival and subsequent growth of shade-intolerant species. Other effects of fire that often influenced regeneration establishment included increased nutrient availability, reduced density of potentially competing vegetation, and reduced populations of soil microorganisms pathogenic to tree seedlings.

In many cases, regeneration was not established after a fire of low to moderate intensity burned through the understory. Such fires, however, influenced stand structure and species composition in other ways. A disproportionate percentage of smaller trees were killed by fire, thereby tending to keep the understory relatively open. In addition, fire discriminated against thin-barked or otherwise fire-sensitive species. Silvicultural counterparts exist for these nonregeneration functions of fire: thinning from below (removing smaller trees and leaving larger trees) and thinning to modify species composition. In fact, the short- to medium-term need most apparent in many Sierran forests is not the establishment of new regeneration but rather the removal, or thinning, of excessive numbers of small understory trees. This is a high priority, both to reduce the hazard of severe wildfire and to begin to restore forests to a healthier, more sustainable condition (Weatherspoon and Skinner 1996).

A Range of Fire Regimes and Their Associated Stand Structures

Fire as a disturbance event, and the variability in the way fire functions as reflected in various fire regimes, is largely responsible for the range of natural stand structures found in forests of the western United States. Stephenson and colleagues (1991, 322–23) defined five “fire types” representing points along a continuum of increasing dominance by intense fire (and decreasing survival by main canopy trees), in order to account for the patchy nature of fires:

> (1) uniform low intensity, in which all or most canopy trees survive; (2) low intensity with patchy high intensity . . . in which groups of canopy trees are killed locally within a matrix of surviving trees; (3) mixed intensity, in which roughly equal areas of canopy trees are killed and survive, with neither obviously predominating; (4) high intensity with patchy low intensity, in which groups of canopy trees survive within a matrix of killed trees; and (5) uniform high intensity, in which all or most canopy trees are killed.

These fire types provide useful reference points in the sections that follow.

The natural fire regime of most Sierra Nevada forests is generally characterized as one of comparatively frequent fires of low to moderate severity, with small patches of high severity (Skinner and Chang 1996). This fire regime, which corresponds to fire type 2 (Stephenson et al. 1991), prevailed historically in most ponderosa pine and mixed conifer forests both west and east of the Sierran crest and in portions of the upper montane forests as well. Greater variability in fire regimes occurred in more mesic sites within the mixed conifer forest type, especially those dominated by white fir, and in significant portions of the red fir and other upper montane types (Skinner and Chang 1996). This greater variability in fire regimes probably translated to greater variability in fire types as well, so that significant, albeit probably small, proportions of these cooler and/or more mesic types may have been characterized by fire types 3, 4, or 5 (Stephenson et al. 1991).

It is noteworthy that the extensive changes in Sierran forests brought about largely by fire suppression and other human activities over the past 150 years have included a virtual reversal of fire types (Stephenson et al. 1991). Fire type 2, historically the dominant fire type in Sierra Nevada forests, has now been virtually eliminated. Conversely, fire types 4 and 5, relatively rare historically, now account for a large proportion of wildfire acreage in the Sierra Nevada.

As was noted earlier, fire type 2 (Stephenson et al. 1991) corresponds to the presettlement fire regime that evidently dominated most Sierra Nevada forests, especially those low- to middle-elevation forests now in greatest need of restorative management. The corresponding stand structure type (a mosaic of small, even-sized groups) and its silvicultural counterpart (the group selection cutting method) are therefore of special interest in the discussion that follows. Three additional basic stand structures are discussed, however, in the interest of providing information on a more complete range of silvicultural and fire techniques to accommodate varied current stand conditions and to help meet management objectives for achieving structural diversity across the landscape. The extent to which it is desirable to mimic with management the kinds of stand and landscape structures associated with presettlement fire regimes (as best we can reconstruct those structures) is a subject of debate. At a minimum, however, we need to recognize and understand those historic structures as a frame of reference, so we know what we are departing from and can better assess the significance and sustainability of such departures.

The sections that follow contrast even-aged stands with three other basic types of stand structures that may be found in more of our managed forests in the future. These are simplified representations of stand structure; the real world is more complex. Nevertheless, they should provide useful reference points for illustrating silvicultural alternatives. One could probably approximate any realistic stand structure by varying the arrangement and stocking of particular canopy levels, using one of these four structures as a starting point. A desired stand structure could also be viewed as a point on the multidimensional continuum connecting the four basic types of structures. For example, as the structure created by the retention shelterwood cutting method becomes clumpier, it begins to approximate the structure created by the group selection cutting method; as openings created by group selection cuttings become larger, they grade into small clear-cuts; as the openings become smaller, the structure approximates that created by the individual tree selection cutting method. Stand components other than live trees—such as snags, downed logs, and nontree vegetation—are also important parts of stand structure for many purposes, and within limits they can be manipulated silviculturally. For simplicity, however, the live tree component is emphasized here.

The discussion that follows, which is adapted in part from McKelvey and Weatherspoon 1992, deals with generalized stand structures and associated management practices primarily at the stand level. Just as numerous stand-level variations in structure are possible, as was indicated earlier, it is important to emphasize that great flexibility also exists for distributing variations and combinations of these structures across the landscape and through time. This provides opportunities to arrange landscape-level vegetation structures to meet varying management objectives.

The sections that follow are organized around stand structures associated with different regeneration cutting methods. For each of these structures, however, nonregeneration, or intermediate, cutting methods such as thinnings are integral components of the overall silvicultural system, and, like regeneration cutting methods, mimic natural disturbance functions to various degrees.

Standard silvicultural terminology is used (Daniel et al. 1979; Ford-Robertson 1971; Smith 1962). As was indicated earlier, these silvicultural systems and the associated terminology were developed in the context of timber management. The terms, however, are descriptive of cuttings that result in a broad range of stand conditions—clearly of interest to many resource areas—and are widely used and recognized.

A short consideration of fuel-treatment options relevant to each of the basic stand structures is included. It is assumed that, to the extent practicable, fuels are removed from the site to promote utilization as well as to reduce wildfire hazard. In the case of partial cuttings (cuttings other than clear-cuts), this includes the removal of small understory trees that form hazardous fuel ladders. Historically, effective fuel management has not always been a strong emphasis, due largely to short-term economic considerations. However, it is becoming an increasingly important concern in treatments prescribed today.

With all of the cutting methods, the use of tractors or other ground-based machines for yarding logs or for piling or otherwise manipulating harvest residues is limited to relatively moderate slopes. Treatment options are much more limited on steep slopes.

Even-Aged Stands

In an even-aged stand, the ages of all of the trees in the stand are similar. Natural even-aged stands originate mostly from high-severity fires that kill the great majority of trees in the stand (fire type 5) (Stephenson et al. 1991). With natural fire regimes, such fires in coniferous forests normally are separated by fairly long intervals (usually more than 100 years) and typically occur in forest types found in moist or cold regions.

Even-aged forest stands in the Sierra Nevada were probably relatively uncommon in the presettlement era. Such stands may have been represented best in portions of the upper montane forests—for example, in some red fir areas—and in widely-scattered stands of knobcone pine (Skinner and Chang 1996). In contrast, fire type 5 characterizes a large proportion of current wildfire acreage in the Sierra Nevada because of increased fuel quantities and continuity.

Silvicultural regeneration cutting methods that produce even-aged stands include clear-cutting, seed-tree, and shelterwood cutting. In a complete cycle of practices in the even-aged silvicultural system, such a regeneration cutting would normally be followed by establishment of a plantation or natural regeneration, removal of seed trees or shelterwood trees (retained initially to provide seed and/or protection for regeneration) where present, appropriate tending of the young stand, a series of intermediate cuttings (precommercial and commercial thinnings and possible "improvement" cuttings), and, at rotation age, another regeneration cutting to begin the cycle again. Either broadcast burning or machine piling and burning is commonly used to prepare the site for regeneration (including reducing competing vegetation and physical obstacles to planting) following the regeneration cutting. Underburning or other fuel treatments may take place at subsequent times during the life of the stand, especially after any intermediate cuttings. Prescribed burning is relatively straightforward in even-aged stands except when the trees are very young.

Even-aged stands resulting from even-aged silvicultural systems and from infrequent severe fires may be similar in terms of the general structure and arrangement of live trees. Other stand components, however, including large woody material such as snags and downed logs, and their ecological functions in the new stand, can be quite different in the two kinds of stands.

Two-Storied Stands

As the name suggests, two-storied stands consist of trees of two quite different ages and sizes. These stands are, in a sense, intermediate in structure between even-aged and uneven-aged stands. Natural two-storied stands tend to be associated with a moderate- to high-severity fire regime, in which only scattered live trees or clumps of trees (generally the larger trees and those of fire-resistant species) survive a fire within a matrix of killed trees (fire type 4) (Stephenson et al. 1991). The fire also promotes the establishment of a new age class of trees in the understory. Climates tend to be fairly moist but somewhat drier than those of the high-severity, long-interval fire regimes.

The presettlement occurrence of fire type 4 and two-storied stands in the Sierra Nevada was probably somewhat more frequent than fire type 5 and even-aged stands, although direct evidence of this is very limited. Some upper montane forests, along with the more mesic mixed conifer sites, such as those dominated by Douglas fir or white fir, may have accounted for much of this stand structure type (Skinner and Chang 1996).

The silvicultural technique associated with this kind of stand structure is retention shelterwood (also sometimes called irregular shelterwood or shelterwood without removal). Typically beginning with a shelterwood seed cutting, shelterwood trees (and trees reserved for other reasons) are left in place after regeneration has become established, instead of being removed. These trees may remain in the stand through much or all of the following rotation. Some will become snags, and some may be removed at the end of the next rotation (at which time a new set of overstory shelterwood trees will be selected for retention).

Other conditions could be used as starting points for creating a two-storied stand structure. Understocked stands, traditionally a high priority for clear-cutting, could instead be underplanted, leaving most of the overstory in place. This kind of structure could also be initiated in an older plantation by having a heavy commercial thinning double as a shelterwood-type regeneration cutting. The cut could be followed by site preparation/fuel treatment and underplanting with the desired mix of species. Throughout the "rotation" of such a stand, thinnings could be conducted as needed to maintain desired size classes and species. These should be followed by prescribed burning or other fuel treatments such as mastication or chipping. Snags could be created as needed. Once created, the stand would never be devoid of large trees: each regeneration cutting would be accompanied by the retention of some overstory trees.

Fuel treatments, including prescribed burning, should not be particularly difficult for a two-storied stand. Initial site preparation/fuel treatment before establishment of the understory would be the same as for a shelterwood cut. Subsequent treatments would be comparable to those for an even-aged plantation. Separation of canopy layers would normally be sufficient to keep wildfires from torching into overstory crowns.

Uneven-Aged Stands Consisting of a Mosaic of Small, Even-Aged or Even-Sized Groups

In an uneven-aged stand of small, even-aged or even-sized groups, each of several age or size classes occurs in a number of small (mostly from 1/4 acre to about 2 acres in size) groups or aggregations distributed throughout the stand. For the most part, age or size classes are separated horizontally rather than vertically. Natural stand structures of this type originate primarily in fire regimes in which fires burn relatively frequently but generally at low to moderate severity. Most areas are underburned, with many small trees being killed but most large trees surviving. Scattered individuals and groups of main canopy trees, however, are killed where the fire locally flares up or burns more severely (or groups of trees previously killed by other agents such as bark beetles are consumed to varying degrees by the fire), leaving scattered small openings within a matrix of surviving trees (fire type 2) (Stephenson et al. 1991). The locally intense fire exposes mineral soil (a favorable substrate for seedling establishment) and temporarily reduces competing vegetation (including reserves of dormant seeds stored in duff and soil). Given good cone crops and favorable soil moisture and other conditions, tree seedlings become established. Seedlings in an opening may be even-aged—originating from a single cone crop—or they may become established over a number of years. This fire regime and this stand structure were common during the presettlement era in the Sierra Nevada, especially in the ponderosa pine and mixed conifer forest types (Skinner and Chang 1996).

Silviculturally this kind of stand structure is approximated with the group selection cutting method. Group sizes should be large enough to permit successful regeneration of shade-intolerant tree species. In a sense, each group can be regarded as a small even-aged stand, which can be carried through the full cycle of regeneration cutting, regeneration establishment and tending, intermediate cuttings, and regeneration cutting once again. So within a stand that contains many of these small, even-aged groups, the group (regeneration) cuttings can be accompanied by concurrent intermediate cuttings in the other groups within the stand (mimicking small, high-severity burn areas within a matrix of low- to moderate-severity fire). Keeping track of numerous small openings and groups for management purposes, long considered a major obstacle to the use of group selection, should be significantly easier with the advent of geographic information systems and satellite-based global positioning systems.

In groups to be regenerated, all trees could be removed, or, especially in larger groups, scattered live trees and/or snags could be retained. To facilitate fuel treatment and reduce damage to the surrounding stand, cut trees should be felled as much as possible into the newly created opening.

Openings could be regenerated, either naturally or artificially and with or without vegetation management (reduction of competing vegetation). Even with planting and vegetation management, growth of tree seedlings would be less in an opening typical of group selection than in a large opening because of competition for site resources from large trees surrounding the opening. (The degree of competition will depend on the density or stocking level of the surrounding stand as well as the distance from the edge of the opening.) Without planting and some control of nonconifer vegetation, however, the development of conifers could be delayed for several decades. Under such conditions, fuel treatment would be complicated as well.

The development of a mosaic of small groups could be initiated in a wide range of stand conditions—for example, in an older plantation, an uneven-aged young-mature stand, or an old stand with patchy, uneven distributions of size classes or species.

Harvesting and other treatments are more difficult and expensive in an uneven-aged stand with a mosaic of even-aged or even-sized groups than in an even-aged stand. Implementing group selection cuttings on steep slopes, however, is especially problematical. Helicopters can be used but are very expensive. This area is ripe for some good logging engineering research and development. Hopefully, practical and economically viable methods will be developed for using skyline systems to yard group selection cuttings while keeping damage to the residual stand within acceptable limits. This could also provide opportunities for cable yarding of residues or for the use of other means of reducing fuel loads, such as removing tree tops (which contain considerable potential fuel) together with adjacent merchantable logs.

Fuels should be treated not only in the regeneration openings but also in the rest of the stand. On machine-operable slopes, the whole range of mechanical fuel-management techniques would be available. These could include tractor piling and burning of slash in regeneration openings, mastication, and removal (with or without utilization). Residual stand damage and soil impacts, however, must be kept within acceptable levels. Machine size and capabilities and operator skill are all critical factors.

Prescribed understory burning is an option on steep as well as moderate slopes. Prescribed burning would be more difficult than in even-aged or two-storied stands, simply because a variety of conditions and tree sizes occur within the stand. However, the fact that these size or age classes are separated horizontally rather than vertically, if combined with proper temporal spacing of treatments (McKelvey and Weatherspoon 1992), should alleviate many of the potential problems. Two-stage burning (sequential burns under different conditions) or jackpot burning (burning of residue concentrations under conditions that impede fire spread into adjacent areas) may be applicable in some situations. One could broadcast-burn regeneration cut areas after harvest, and then underburn the rest of the stand at the same time or perhaps at a later stage, when understory fuels have dried a little more. Depending on stand conditions, some preburn treatment may be necessary prior to the first fire entry to reduce fuel ladders and overall flammability to acceptable levels. This could be expensive and might include biomass harvest, cutting and hand piling, or other methods. If litter from ponderosa pine is available, prescribed burns can be conducted under moister conditions and therefore in more difficult situations. Again depending on stand conditions, a first burn might create substantial additional fuel by scorching or killing (mostly small) trees, necessitating a second and possibly a third burn to get the fire hazard down to an acceptable level.

Uneven-Aged Stands Consisting of a Fine Mosaic of Individual Trees

In an uneven-aged stand containing a fine mosaic of individual trees, three or more sizes and ages of all tree species present are distributed more or less uniformly throughout the stand. Openings are very small, the size of individual large trees. This occurs in nature (at least in a sustainable mode) only in forest types composed entirely of shade-tolerant species and in fire regimes having very long fire-return intervals. It develops long after a stand-replacement fire, as the overstory begins to break up and a full range of understory canopy layers has had a chance to develop. This stand type is incompatible with frequent periodic fires. (Some observers have considered certain open-growing ponderosa pine stands with short fire-return intervals to have this kind of stand structure. In such cases, the distinction between stands of uneven-aged individual trees and stands of uneven-aged groups of trees becomes largely one of semantics.)

This stand condition is produced and maintained silviculturally using the individual-tree selection cutting method. Unless a definition of individual-tree selection is used that includes openings up to 1/4 acre or so (or involves very open stands), this method will not allow for adequate regeneration and development of shade-intolerant species on most sites. If the stand does not already consist of shade-tolerant conifers, it will move in that direction under this cutting method as long as such species are present in the area. Retention of the smallest size classes of trees well distributed through the stand—a necessity for sustaining this stand structure through time—creates dangerous fuel ladders and makes prescribed understory burning essentially impracticable.

On gentle terrain, various machine treatment methods are available, at least theoretically, for accomplishing individual-tree selection cuttings. Residues remaining after harvesting could be machine piled, chipped, or masticated. But skillful operators and tight controls over fuel-treatment activities would be necessary to avoid unacceptable damage to the residual stand.

Other alternatives include jackpot burning of slash concentrations and the much more costly option of hand piling and burning—either applied preferably at a time when surrounding fuels are too moist to carry fire. Both of these methods would also be available on steep slopes. Implementation of individual-tree selection on steep slopes may be feasible only with expensive helicopter logging systems.

At higher elevations or other mesic sites where the probability of severe wildfire is not great, some combination of lopping, bucking, and scattering of slash, or no fuel treatment at all, may be acceptable. If individual-tree selection is to be used at all, it will be on such mesic sites that it probably makes the most sense anyway because it is more nearly compatible with presettlement fire regimes and stand and landscape structures.

EFFECTS OF PARTIAL CUTTINGS ON WILDFIRE HAZARD

The effects of partial cuttings on wildfire hazard in the residual stand result from combinations and interactions of two general factors: effects on fuels, and effects on microclimate.

Effects of Partial Cuttings on Fuels

Thinnings, insect sanitation and salvage cuts, and other partial cuttings add slash, or activity-generated fuels, to the stand unless all parts of the tree above the stump are removed from the forest. Small trees damaged by harvest activities but not removed from the forest often add to the fuel load. To the extent that it is not treated adequately, this component of the total fuel complex tends to increase the probability of a more intense, more damaging, and perhaps more extensive wildfire.

Foliage and small branches of live forest vegetation also contribute to the total amount of available fuel. The position and continuity of these fuels are important. Dense understory trees, for example, can provide both the horizontal and the vertical continuity of live fuels needed to move a fire from the surface into the main forest canopy and sustain it as a crown fire. This kind of stand condition is currently widespread in Sierra Nevada forests. Cutting and removing a large proportion of such a dense understory, thus interrupting much of the live fuel continuity, can substantially reduce the probability of a crown fire.

Partial cuttings also have longer-term, more indirect effects on fuels. Thinning or not thinning overly dense stands, for example, influences overall levels of competition for limiting resources (water, nutrients, and sunlight) in the stand and consequent levels of stress-induced mortality (including but not limited to that caused by insects). Dead trees obviously add to the total dead fuel load and may increase both the severity of a future wildfire and its spread rate via spotting. Thinning also influences the subsequent regeneration and development of understory vegetation—trees, shrubs, and herbs—which becomes part of the live fuel component.

Effects of Partial Cuttings on Microclimate

A related but separate kind of concern has to do with changes in microclimate brought about by stand opening. Thinning or otherwise opening a stand allows more solar radiation and wind to reach the forest floor. The net effect, at least during periods of significant fire danger, is usually reduced fuel moisture and increased flammability (Countryman 1955). The greater the stand opening, the more pronounced the change in microclimate is likely to be.

Interactions of Changed Fuels and Microclimate

The ways in which changes in these two sets of factors—fuels and microclimate—as a result of a management activity interact to affect wildfire hazard can be quite complex. The net effect, in terms of the direction of change in hazard, may be obvious in many cases, however. For example, removing most of the large trees from a stand, leaving most of the understory in place, and doing little or no slash treatment—a situation all too familiar in the past—will certainly increase the overall hazard and expected damage to the stand in the event of a wildfire. Everything points in the same direction: removing most of the fire-tolerant large trees; retaining most of the easily damaged small trees; increasing the loading (quantity) and depth of the surface fuel bed; and creating a warmer, drier, windier environment near the forest floor during times of significant fire danger. In contrast, heavily thinning an overstocked stand from below and using whole-tree removal (or chipping and spreading the limbs and tops), followed by a prescribed understory burn to reduce natural fuels, will almost certainly reduce the wildfire hazard of the stand. Computer simulations of the effects of such treatments on fire behavior (van Wagtendonk 1996), along with anecdotal reports of how such stands have fared during a wildfire in comparison with surrounding untreated stands, provide strong support for this conclusion. In this case, the "negative" effects on microclimate of opening the stand are outweighed by the reduction in live and dead fuel loading and continuity. Past cuttings in the Sierra Nevada (Helms and Tappeiner 1996) have spanned the range represented by these two contrasting situations but have tended generally, like the first situation, to create a net increase in fire hazard.

An example of a more complex relationship was reported by Weatherspoon and Skinner (1995) as part of a large retrospective study of factors—including prior management activities—that affected the degree of tree damage resulting from the extensive 1987 wildfires in northern California. Among three categories of uncut or partial-cut stands, they found that uncut stands (with no treatment of natural fuels) suffered the least fire damage, followed by partial-cut stands with some fuel treatment; partial-cut stands with no treatment had the most damage. The fact that partial-cut stands with no fuel treatment experienced more damage than partial-cut stands with some fuel treatment is no surprise. One might wonder, however, why the uncut stands experienced less damage than the partial-cut and treated stands. The explanation probably lies in a combination of the following factors:

- The partial cuttings created a warmer, drier microclimate compared with that of the uncut stands—an inevitable effect of cuttings, as was explained earlier.
- The partial cuttings were typical of many past cuttings that removed big trees and left small ones. The more readily scorched small trees thus constituted a higher percentage of the residual stand. Furthermore, the live fuel ladder component of fire hazard in the uncut stand was not reduced in the partial-cut stand.
- Fuel treatments may have been only partially effective. Two types of fuel treatments—lop and scatter and underburning—were combined in the analysis (their separate effects on fire damage were indistinguishable). Lop-and-scatter treatments reduced slash depth (and so presumably reduced flammability compared with no treatment) but did not change the fact that total downed dead fuel loading in those partial-cut stands (consisting of natural plus activity-generated fuels) was greater than downed dead fuel loading in uncut stands (consisting of natural fuels only). The underburns were not planned treatments but rather were burns that were allowed to creep around between clear-cut units that had been broadcast-burned or to move away from burned roadside piles. Thus, fuel consumption may have been spotty in these areas. More intensive treatment of surface fuels might well have reduced fire damage further.
- When only the management compartments containing fuel-treated stands (a small subset of the total number of compartments in the study) were analyzed separately, differences in fire damage between uncut and partial-cut and treated stands virtually disappeared. Evidently, lower average levels of damage in uncut stands in the remaining compartments changed the relationship in the overall analysis.

CONCLUSIONS AND RESEARCH NEEDS

Restoration and maintenance of Sierra Nevada forests in productive, sustainable conditions will almost certainly require combinations of silvicultural and fire-management techniques. Understanding the ecological and operational linkages between these two disciplines will facilitate this task.

It is generally recognized that recurring fires historically played a key role in influencing the species composition, stand structure, and landscape mosaic of most forest types in the Sierra Nevada as well as elsewhere in western North America. But the basic relationships between fire regimes and stand and landscape dynamics are poorly understood for many forest types, including those in the Sierra Nevada. Clarifying these relationships through research should help managers as they seek to define desired forest conditions and processes.

We also have little information about the long-term consequences of various forest conditions on a range of ecosystem components. The long-term nature of these questions and the need to find answers on a landscape scale means that the necessary studies will need to be done in the context of adaptive management, an organized process of learning by doing (Everett et al. 1994; Walters and Holling 1990). Managers and scientists should cooperate in long-term adaptive management experiments to (1) devise silvicultural and fire treatments that mimic historical or other desired conditions in certain key respects; (2) define treatments representing reasonable management alternatives that "bracket" those conditions; and (3) incorporate these treatments into long-term, interdisciplinary studies of the consequences of alternative management strategies in terms of ecosystem productivity, diversity, and sustainability. Because of the key role of fire historically and the broad range of fire effects on forest ecosystems, it is important that the suite of treatments include comparable stand structures produced and maintained by prescribed fire alone (requiring multiple burns), through silvicultural cuttings and mechanical fuel treatments alone (i.e., without fire), and through combinations of cuttings, mechanical fuel treatments, and prescribed fire. Only in this way will it be possible to determine which ecosystem functions of fire can be emulated satisfactorily by other means, which may be irreplaceable, and the implications of these findings for management.

Although the basic theory of silvicultural systems has been well established, actual application of systems other than even-aged ones in California is quite limited. Practical methods for implementing such treatments, especially on steep ground and in conjunction with a variety of fuel-treatment methods, will require considerable applied research as part of the adaptive management efforts discussed previously.

At least in the short to medium term, much of the needed silviculture in Sierran forests will involve thinning of small trees. To make such operations economically sustainable, cooperative research and development efforts are needed to develop more efficient technology for harvesting and processing of small material and new markets for utilizing it (Lambert 1994).

While we have much to learn, it is important to note that we do not have to have all the answers before beginning needed restoration work. We know enough at this point to recognize that current conditions in most low- to middle-elevation forests of the Sierra Nevada are unacceptable in terms of wildfire hazard, diversity, and sustainability. Regardless of the extent to which presettlement conditions are used as a guide to desired conditions, most informed people would agree that these forests generally should be less dense, have less fuels, and have more large trees. Even if we have not precisely identified target conditions, we certainly know the direction in which we should begin moving. That beginning alone will require a large measure of commitment and hard work. We can adjust along the way as we learn more and become better able to define desired conditions for Sierran forests.

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