**NATHAN L. STEPHENSON**
National Biological Service
Sequoia and Kings Canyon National Parks
Three Rivers, California

55

# Ecology and Management of Giant Sequoia Groves


## ABSTRACT

As a result of recent changes in U.S. Forest Service (USFS) policy, the two public agencies that collectively manage most giant sequoia groves—the USFS and the National Park Service—now share remarkably similar sequoia management goals: to protect, restore, and conserve giant sequoia ecosystems for their non-commodity values. The goal of greatest immediate importance is to protect sequoia groves from unusually severe wildfires; the hazard of such fires has increased with the accumulation of forest fuels during a century of fire exclusion. By reducing surface fuels, tree density, and the vertical continuity of aerial fuels, restoration of pre-Euroamerican grove conditions automatically confers a good deal of protection from extreme wildfires. Managers wishing to restore pre-Euroamerican grove conditions face at least four complex issues: (1) defining specific restoration goals (e.g. is the goal simply to restore low- to moderate-intensity fire as a natural process, letting it determine forest structure, or to mechanically restore a particular forest structure before reintroducing fire?), (2) describing the physical targets for restoration (what was the range of pre-Euroamerican grove conditions?), (3) evaluating the practicality and possibility of re-creating the target grove conditions (can we restore past conditions, given the limitations imposed by present grove conditions?), and (4) choosing specific restoration tools and approaches (what are the trade-offs among using prescribed fire, saws, or both as restoration tools?).

Once groves have been protected and restored a conservative approach to assuring their long-term sustainability is to maintain the processes that sustained them in the past, especially frequent low- to moderate-intensity surface fires. Undisturbed hydrology is also important, thus special management attention should focus on the local watershed above and adjacent to groves. There is no evidence that the long-term sustainability of giant sequoia ecosystems as a whole depends on adding to the public land base. Continuing and future threats to sequoia ecosystems include air pollution, unnatural effects of pathogens, and anthropogenic climatic change.

Present conditions in many sequoia groves demand immediate attention—particularly the ongoing failure of giant sequoia regeneration and the accumulation of hazardous fuels. Yet our present understanding of grove restoration and conservation is imperfect, meaning that management must move forward in spite of uncertainties. Success therefore depends on managers practicing adaptive management, which formalizes the common-sense process of trying something, seeing what happens, learning from the experience, then trying something new. Successful adaptive management depends on monitoring the results of different management actions, a step that is often ignored. Within certain bounds, there is no single clearly correct approach to grove restoration and conservation; thus, the different sequoia management agencies are likely to apply a variety of different management approaches. Knowledge will grow most rapidly if the various agencies cooperate in comparing the consequences of their different management approaches.

For the agencies managing giant sequoias, meeting obligations to protect, restore, and conserve sequoia ecosystems will be difficult, time-consuming, and expensive. Efforts seem sure to fail unless there is strong institutional support at all levels, including significant permanent base funding.


## INTRODUCTION

The charge of the Sierra Nevada Ecosystem Project (SNEP) included conducting "[a]n examination of the Mediated Settlement Agreement [U.S. Forest Service 1990], Section B, Sequoia Groves for the Sequoia National Forest and recommendations for scientifically based mapping and management of Sequoia groves" (SNEP 1994). This chapter is limited to addressing the last part of this charge: providing an assessment for scientifically-based management of sequoia groves, with some

Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources, 1996.



Back to CD-ROM Table of Contents

attention given to scientifically-based grove mapping. The remainder of the SNEP charge relating to giant sequoias (i.e., examining the Mediated Settlement Agreement between Sequoia National Forest and various appellants, and related institutional issues) is addressed by Elliott-Fisk et al. (1996).

To a large degree, this chapter is shaped by three premises. The first is that sequoia management policy, at its broadest, is an ethical decision reflecting human values (Croft 1994); the role of science is to inform and support the expression of those values. This chapter accepts as a given that the management goal for the majority of naturally-occurring sequoia groves, as determined by decades of public and political discourse, is to protect, restore, and conserve the natural character of the groves (see "Broad Goals of Sequoia Management," below). Science's most important role in sequoia management is to suggest different means to achieve this end, and to evaluate their possible consequences. This chapter therefore musters the best available scientific information to support a critical review and analysis of the complex policy, scientific, and practical issues related to the protection, restoration, and conservation of giant sequoia ecosystems for their amenity values. A handful of sequoia groves, both public and private, currently are managed for commodity production in addition to amenity values (e.g. see Dulitz 1986; Rueger 1994); however, a review of issues related to commodity production is beyond the scope of this chapter.

The second premise is that forest managers, policy-makers, and the public will best be served by a chapter that focuses on broad principles of sequoia ecology and management, not on site-specific management prescriptions or in-depth discussions of the mechanics of specific management tools. During my sixteen years of interactions with sequoia managers and the interested public, I have come to conclude that meaningful debate about sequoia management has been most hindered by people's differing assumptions as to the fundamental nature and dynamics of sequoia ecosystems. By focusing on general principles, then, this chapter helps lay a necessary foundation for informed discussion among scientists, policy-makers, managers, and the public. The critical review of principles will also help managers set justifiable, site-specific goals and objectives, and implement sequoia management practices that are based on sound science and consistent with policy. Additionally, by focusing on principles the chapter becomes relevant to sequoia grove management in general, not just the management of groves in the Sequoia National Forest (as emphasized in the SNEP charge).

The third underlying premise, consistent with the policies of the major sequoia land management agencies, is that the overarching goal of sequoia management is to restore and sustain the health of whole, functioning giant sequoia ecosystems. Sequoia ecosystems include the physical environment and all living organisms found where giant sequoias grow, including everything from bacteria to mice to the giant sequoias themselves. At times, approaches to managing whole sequoia ecosystems have seemed in conflict with the tremendous social value placed on individual large sequoias, such as when prescribed fire has charred the trunks of some sequoias (Croft 1994; Parsons 1994; Tweed 1994). However, managing whole sequoia ecosystems and managing selected individual sequoias as objects of great social importance are not mutually exclusive, and the analysis I present here should not be taken to preclude the special status of selected big trees. Rather, managing whole sequoia ecosystems should be viewed as a conservative approach to maintaining the sequoias themselves, assuring their perpetuation for the enjoyment and benefit of future generations.

Even though the overarching goal of sequoia grove management is to sustain all the pieces of giant sequoia ecosystems, this chapter focuses almost exclusively on trees. This is because (1) social values are such that most past management conflicts have centered on trees, (2) trees are the components of sequoia ecosystems for which the best available scientific information is available, and (3) through their dominant influence on habitat structure, microclimate, and soil properties, trees exert tremendous influence on most other organisms within sequoia ecosystems.

The remainder of the chapter is divided into six sections. The first summarizes present conditions in giant sequoia groves throughout the Sierra Nevada, and is followed by a brief section summarizing the new, broad sequoia management goals adopted by the USFS. The next three sections sequentially assess sequoia grove protection, restoration, and conservation. By far most attention is given to the complex and difficult task of defining specific grove restoration goals and describing targets for restoration; of necessity, new syntheses of available scientific information are presented to support this analysis. The final section offers some general conclusions and summarizes some of the alternatives for implementing giant sequoia management.

## PRESENT GROVE CONDITIONS

Giant sequoias are the largest trees on the planet and are among the oldest, sometimes living for 3,200 years or more. They often occur in stately groups which some people have likened to living cathedrals (figure 55.1). Few organisms on the planet, plant or animal, have inspired as much human admiration.

Sequoia groves are portions of Sierra Nevada mixed conifer forest that contain giant sequoias. Groves contain a mix of tree species in which sequoia is a numerically minor, but visually striking, component. Numerically, most groves are overwhelmingly dominated by white fir, with sugar pine commonly being the next most abundant species, followed by giant sequoia (Rundel 1971). Black oak, ponderosa pine, incense-cedar, Jeffrey pine, and red fir are often additional grove components.

**FIGURE 55.1**

Generations of Americans, as well as people from all over the world, have been awed and inspired by giant sequoias. Sequoias are the largest trees on the planet and are among the oldest, sometimes living for 3200 years or more. (Photograph by George Grant, courtesy of the National Park Service.)

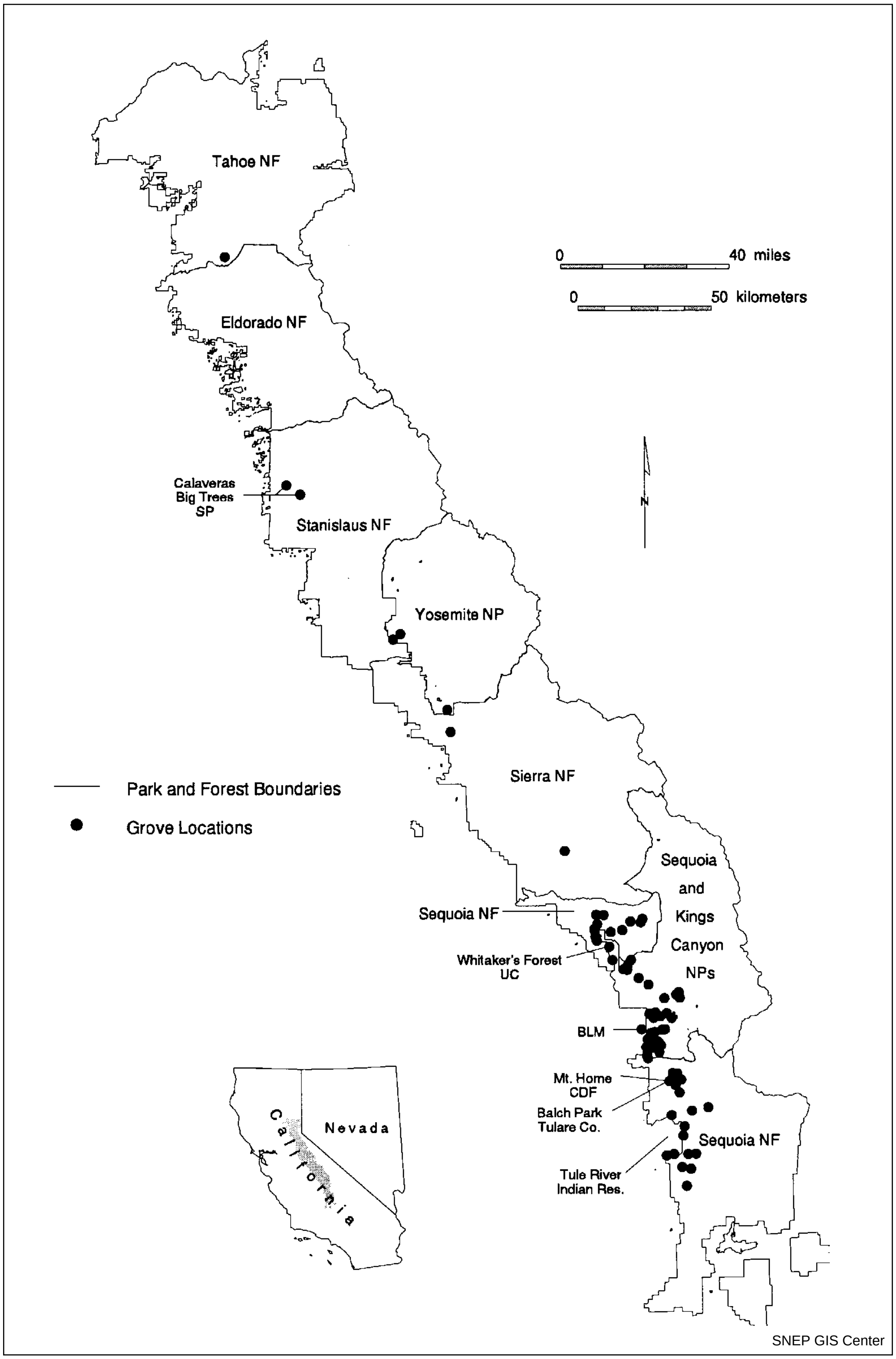


**FIGURE 55.2**

The 75 naturally-occurring sequoia groves in the Sierra Nevada (indicated by dots) are small and scattered. Most are found south of the Kings River (which separates the Sierra and Sequoia National Forests) and are on national forest, national park, or other public land. Roughly 8% of all grove area is privately owned. (SNEP map by John Aubert.)

Most of the 75 naturally-occurring sequoia groves occur in the southern Sierra Nevada, south of the Kings River (Rundel 1972a; figure 55.2), collectively occupying about 14,600 ha (36,000 acres).[1] Most are under federal jurisdiction; about 49% of all grove area in the Sierra Nevada is managed by the U.S. Forest Service (USFS), about 28% by the National Park Service (NPS), and less than one percent by the Bureau of Land Management.[2] (Percentages are of total Sierra Nevada grove area, not number of groves.) Other public ownership includes 11% of all grove area, variously managed by the California Department of Forestry and Fire Protection, California Department of Parks and Recreation, the University of California, and Tulare County. About 4% is managed by the Tule River Indian Reservation. The remaining approximately 8% of grove area in the Sierra Nevada is privately owned.

Grove areas can be classified simplistically into four broad categories according to past management, which strongly shapes future management objectives and possibilities: (1) grove areas which have been continuously protected from both fire and logging (presently about 53% of all grove area in the Sierra Nevada), (2) grove areas which have been protpected from logging, but treated with prescribed fire (about 18% of all grove area), (3) grove areas which were logged, by whatever method, before 1980 (i.e. before the most recent round of logging on the Sequoia National Forest—about 23% of all grove area), and (4) grove areas which were logged since 1980 (about 6% of all grove area). The latter two categories fail to distinguish between grove areas that have been logged more or less continuously over several decades (such as Mountain Home Grove and some private lands) from those that were logged, usually intensely, over a very short period (most other logged areas). The former represents only a relatively small portion of all grove area.

The following brief overviews describe current ecological conditions of groves in each of the four categories. However, it is important to recognize that broad variability in grove conditions occurs within each of these categories. Other sources of information on current grove conditions can be found in Hartesveldt et al. (1975), Harvey et al. (1980), Weatherspoon et al. (1986), Aune (1994), and Willard (1994b).

## Grove Areas Protected from Both Fire and Logging (About 53% of All Grove Area)

For at least the two or three millennia preceding Euroamerican settlement, predominantly low- to moderate-intensity surface fires burned within individual sequoia groves on the order of every 2 to 10 years (Kilgore and Taylor 1979; Swetnam et al. 1992; Swetnam 1993). Because of the loss of Native American ignitions and suppression of lightning ignitions that followed Euroamerican settlement, most groves areas today have experienced a 100- to 130-year period without significant fire (figure 55.3)—a fire-free period that is unprecedented over at least the last two millennia (Swetnam et al. 1992). This lack of fire has resulted in important changes in grove conditions. Soil characteristics in unburned groves are more homogeneous than in burned groves (Gebauer 1992). Giant sequoia reproduction, which in the past depended on frequent fires, has effectively ceased in groves protected from fire and logging, and reproduction of other shade-intolerant species has been reduced (Harvey et al. 1980; Stephenson 1994 and in preparation). Today more area is dominated by dense intermediate-aged forest patches, and less by young patches, than in the past (Bonnicksen and Stone 1978, 1982a; Stephenson 1987). Forest conditions have become more closed in many areas (figure 55.4), and shrubs and herbaceous plants are probably less abundant than in the past (Kilgore and Biswell 1971; Harvey et al. 1980). Perhaps most significantly, dead material has accumulated, causing an unprecedented buildup of surface fuels (Agee et al. 1978; van Wagtendonk 1985; see figure 55.5). Additionally, "ladder fuels" capable of conducting fire into the crowns of mature trees have increased (Kilgore and Sando 1975; Parsons and DeBenedetti 1979; see figure 55.4).

One of the most immediate consequences of increased fuels is an increased hazard of wildfires sweeping through groves with a severity rarely encountered before Euroamerican settlement (cf. Stephens 1995; Chang 1996; McKelvey and Busse 1996; Skinner and Chang 1996; Weatherspoon and Skinner 1996; van Wagtendonk 1996). High-severity fires are those that kill many or most mature forest trees, sometimes even monarch sequoias. Though pre-Euroamerican fires usually consisted of small (on the order of 0.1 ha) patches of high-severity fire within a matrix of low-severity surface fire (Harvey et al. 1980; Stephenson et al. 1991), fires of more uniformly high severity occasionally burned large portions of individual groves (Swetnam et al. 1992; Caprio et al. 1994). Fuel conditions today are such that these formerly relatively rare, high-severity fires could become more common.

## Grove Areas Treated with Prescribed Fire (About 18% of All Grove Area)

Prescribed fires for both fuels management and ecosystem management were first introduced in sequoia groves on a large scale in the late 1960s, mostly in Sequoia and Kings Canyon National Parks. Though prescribed fire has caused immediate and dramatic reductions of surface fuels (forest litter, duff, and all downed woody debris; figure 55.5), fuel re-accumulation has been relatively rapid. In Redwood Mountain Grove, Parsons (1978; see also Kilgore 1973a; Agee et al. 1978; Gebauer 1992) found that prescribed fires of the late 1960s to mid-1970s reduced the average surface fuel load to about 8% of its pre-burn value of 190 tonnes / ha (85 tons / acre). Within seven years of the fires, however, fuels had accumulated to 53% of pre-burn levels. In contrast, prescribed fires of the 1980s and 1990s, generally burning in other groves and under somewhat moister and cooler conditions, reduced the average fuel load to about 33% of its pre-burn value of 126 tonnes / ha (56 tons / acre) (Keifer 1995 and personal communication). After ten years, surface fuels within the older of these burns had nearly reached pre-burn values. Compared to pre-burn fuels, however, post-burn fuel accumulation was more heavily dominated by woody debris. Much of the rapid re-accumulation of fuel is due to fire-caused death of small trees in the abnormally dense thickets which have become established in the absence of frequent fires (Parsons 1978). It is therefore evident that a sustained reduction of fuel accumulation rates to their probable pre-Euroamerican levels will require at least two prescribed fires, the second of which removes the small


**FIGURE 55.3**

The dates of past fires are revealed by scars in the growth rings of this ponderosa pine from the edge of the Big Stump Grove, Kings Canyon National Park. Between 1722 and 1896, 20 fires burned at the base of this particular tree at intervals ranging from 4 to 16 years, averaging one fire every 8.7 years. In most groves, pre-Euroamerican fires were predominantly low- to moderate-intensity surface fires. Fire scarring in most groves ceased abruptly in the 1860s or 1870s, due to the loss of ignitions by Native Americans, suppression of lightning ignitions, and perhaps due to reduction of fine fuels by grazing. The last two fires revealed in this cross-section (1885 and 1896) were almost certainly related to logging activities in the heavily-logged Big Stump Grove (see figure 55.6). The recent 100- to 130-year fire-free interval in most sequoia groves is unprecedented during at least the last 2000 to 3000 years. (Photograph courtesy of C. Baisan, T. Swetnam, and M. Wilkenson, University of Arizona.)

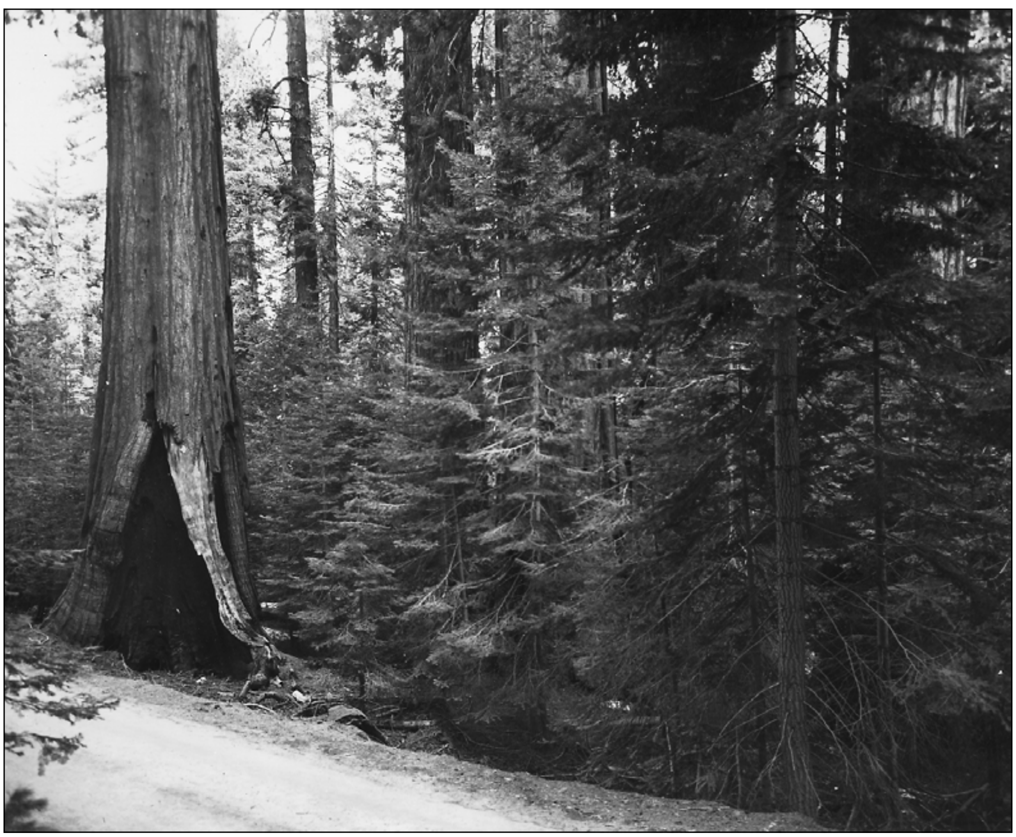

**FIGURE 55.4**

*Top*: The Confederate Group of giant sequoias in Mariposa Grove, Yosemite National Park, was nearly free of understory trees in about 1890.
*Bottom*: By 1970, in the absence of frequent surface fires, a dense thicket of white firs grew at the base of the sequoias. Such thickets provide fuels that could conduct fire high into the sequoias. (Photographs courtesy of Bruce M. Kilgore, National Park Service.)

**FIGURE 55.5**

*Top:* Lack of frequent surface fires has led to heavy build-up of surface fuels, such as shown in this photo taken within the Redwood Mountain Grove, Kings Canyon National Park. Such fuels increase the hazard of wildfires that are generally more severe than those of pre-Euroamerican times. *Bottom:* Low- to moderate-intensity prescribed fires can greatly reduce hazardous fuels, as in this view of the same spot in Redwood Mountain Grove following a prescribed fire. (Photographs by Dan Taylor, courtesy of Bruce M. Kilgore, National Park Service.)

trees killed by the first. Importantly, the death of small understory trees and the lower branches of larger trees has reduced “ladder fuels” otherwise capable of conducting wildfires into the crowns of the largest trees (Kilgore and Sando 1975).

Tree density is reduced in burned groves. After a prescribed fire in Redwood Mountain Grove, Kilgore (1973a) found that total tree density was reduced by 81%. Almost all of the dead trees were firs and pines less than 30 cm diameter, and especially less than 15 cm diameter; these small trees occurred in abnormally dense thickets which had become established during a century of fire exclusion. In a more extensive sample of 29 plots in several groves, small trees were less common in the pre-burn forest and average tree density was reduced by only 36% one year following prescribed fires, again with greatest mortality in the smallest trees (Keifer 1995 and personal communication; see also Keifer and Stanzler 1995). Because almost no sequoias of any size were killed by fire in these plots, the relative density of sequoia increased at the expense of white fir. (This is partly because most sequoias in modern groves are large and relatively fire-resistant.) The absolute density of sequoias greater than 1.4 m tall doubled within 10 years of the fires and is likely to keep increasing, due to the rapid ingrowth of seedlings following the fires. There has not yet been a corresponding increase in the density of firs greater than 1.4 m tall. In a separate study which followed the fate of 1135 giant sequoias for 23 years, Lambert and Stohlgren (1988) found that the death rate (not the proportion dying) of sequoias less than 30 cm in diameter increased by 65% in areas that had been burned. Their data also suggested that death rates increased for sequoias larger than 30 cm in diameter, but death rates of large sequoias in both the presence and absence of fire were so low as to be statistically indistinguishable.

Tree death following prescribed fires is spatially clumped (Kilgore 1973a, 1973b; Harvey et al. 1980; Stephenson et al. 1991; Demetry 1995; Demetry and Duriscoe 1996). Demetry (1995) found that 18 forest gaps created by prescribed fires in Giant Forest were of variable size (the author’s non-random sample included gaps of 0.067 to 1.17 ha), with 0.1 ha being the approximate (to the nearest order of magnitude) modal gap size for a large portion of Giant Forest (A. Demetry, personal communication). These fire-created forest gaps are the site of abundant sequoia seedling establishment and rapid growth, and appear to be essential for successful sequoia regeneration in the absence of other gap-creating disturbances (Harvey et al. 1980; Stephenson et al. 1991; Mutch 1994; Stephenson 1994).

Shrubs, particularly Ceanothus and Ribes, are much more abundant in burned groves than in unburned and otherwise undisturbed groves (Kilgore and Biswell 1971; Harvey et al. 1980). Herbaceous cover also is greater in burned groves, though it generally begins to decline a few years following a fire (Harvey et al. 1980).

## Grove Areas Logged before 1980 (About 23% of All Grove Area)

The heaviest logging of sequoia groves occurred south of the Kings River between about 1880 and 1920 (figure 55.6). Nearly all pines and many firs were removed from several groves, though trees of lesser value (particularly small trees) often were left, providing a seed source for regeneration. In many areas (particularly the groves in or near Converse Basin), nearly all old-growth sequoias were removed.

Today, these logged groves have regenerated as complex mosaics of forest patches of differing structures (tree diameter, height, and density) and species compositions (R. Rogers, personal communication). Some patches are densely stocked with nearly pure, century-old giant sequoias; this regeneration now typically ranges from 0.3 to 1 m (1 to 3 ft) in diameter and 30 to 50 m (100 to 150 ft) tall. There are few understory trees or shrubs in these dense patches. Other patches have similar structure but contain additional species, particularly white fir and sugar pine. In still other patches, trees are sparse and the once-forested lands are dominated by shrubs (on dry sites) or grasses, sedges, and forbs (on wetter sites), with scattered large sequoia stumps standing as reminders of past conditions. In some regenerating patches, fuels (and therefore fire danger) are generally high and are steadily increasing. Some heavily-logged sites have been re-disturbed more recently, such as by the 1955 McGee wildfire; many of these sites are now dominated by young-growth white fir and planted ponderosa pine rather than giant sequoia.

In the heavily-logged Big Stump Grove (figure 55.6), Stohlgren (1992) found that patches of regeneration that are presently dominated by sequoias do not necessarily grow in the same places within the grove that were dominated by sequoias in pre-Euroamerican times. Locations of slash burning and other factors may have influenced this spatial redistribution of sequoia dominance. Because some sequoia seedlings became established beyond the original grove boundary, there was a small net increase in grove area following logging. Stohlgren reported that in some respects the grove seemed resilient to heavy logging; 85 years after logging, it had already recovered nearly half of its pre-logging sequoia basal area. However, as Stohlgren noted, after 85 years the sequoia stumps he used to estimate pre-logging basal area had probably lost most of their bark and sapwood, meaning that he underestimated pre-logging sequoia basal area for the grove. If estimates of lost sapwood and bark thicknesses are added to the pre-logging basal area calculations (Stephenson, unpublished data), the grove seems somewhat less resilient; a revised estimate is that after 85 years the grove had recovered about one third of its pre-logging sequoia basal area. Much of this regeneration is dense and would have been thinned by recurring fires, had they not been excluded.

FIGURE 55.6

In the heavily-logged Big Stump Grove, a photographer captured that last moments of the Mark Twain Tree as it was felled in 1891 to provide cross-sections for museum exhibits. For scale, note the people standing on the edge of, and to the right of, the Twain Tree's 7 m (24 ft) diameter stump. About one-fourth of all naturally occurring sequoia grove area was logged between 1880 and 1980, mostly early in that period. The logging often including most or all of the largest sequoias. Most of these heavily-logged grove areas have regenerated and often are now dominated by dense growth of young trees or brush. Fuels have re-accumulated to the point that many logged areas are now at risk of unusually severe wildfires. (Negative 42130, courtesy of the Department of Library Services, American Museum of Natural History.)

A few larger sequoias, on the order of 200 or 300 years old, are scattered throughout areas that were heavily logged near the turn of the century. These sequoias are just beginning to show the rounded crowns characteristic of old growth sequoias; their crowns contrast sharply with the extremely pointed crowns of sequoias that became established since logging. These older and larger sequoias will help restore old-growth character to once-devastated groves.

## Grove Areas Logged since 1980 (About 6% of All Grove Area)

Logging in USFS sequoia groves during the 1980s helped spur the events leading to the Mediated Settlement Agreement (MSA) between Sequoia National Forest and various appellants. Overall, about 490 ha (1,200 acres) of sequoia groves, mostly on the Sequoia National Forest, were logged (R. Rogers, personal communication). About one third of this area was selectively logged, with only occasional trees being cut; no large

**FIGURE 55.7**

These recently-logged blocks in the Black Mountain Grove, Sequoia National Forest, illustrate some of the effects of logging during the 1980s. Though large sequoias were not cut, logging such as this helped spark the controversies that ultimately led to the Mediated Settlement Agreement between Sequoia National Forest and various appellants. (Photograph by Nathan L. Stephenson, National Biological Service.)

sequoias were cut. There is presently little visual difference in forest structure between these areas and the surrounding uncut forest matrix (R. Rogers, personal communication).

The other two thirds of logged grove area was logged in distinct 2 to 10 ha (5 to 25 acre) patches within an otherwise intact grove matrix (figure 55.7). The patches presently are open stands occupied by scattered large sequoias (again, no large sequoias were cut) and occasionally other mixed-conifer trees left as seed sources or along riparian corridors. This approach to logging was described as “modified clear-cutting” by critics (Cloer 1994), and helped spark the chain of events that led to changes in USFS policy regarding sequoia groves. Most of the logged forest openings today are dominated by shrubs and planted or naturally-seeded trees. Most gap area was planted with mixed ponderosa pine and giant sequoia, either in equal numbers or with ponderosa pine dominating. In some areas, sugar pine and white fir were also planted. Shrubs presently are about 0.5 to 1.2 m (2 to 4 ft) tall, with tree seedlings somewhat taller, though conditions are variable from place to place. There is little surface fuel accumulation, as these sites were cleared before planting.

## BROAD GOALS OF SEQUOIA MANAGEMENT

The Mediated Settlement Agreement (MSA) (U.S. Forest Service 1990), President Bush's Presidential Proclamation (Bush 1992), and Regional Forester Stewart's policy directive (Stewart 1992) collectively provide a uniform suite of policy and management direction for all naturally-occurring sequoia groves in national forests. All USFS grove areas containing old-growth giant sequoias are to be managed in such a way that will "... protect, preserve, and restore the Groves for the benefit and enjoyment of present and future generations" (U.S. Forest Service 1990).[3] Additionally, "... groves shall be protected as natural areas with minimal development. ... [A]ny proposed development shall provide for aesthetic, recreational, ecological, and scientific value" (Bush 1992). Regional Forester Stewart (1992) further defined the new policy direction: "Naturally occurring groves, including an appropriate ecological 'buffer', shall be withdrawn from the land base considered suitable for the long term sustained (regulated) production of timber. Groves shall also be withdrawn from other forms of consumptive entry such as mineral and geothermal developments." These policy and management directions chart a new course for USFS management of the groves, and raise a broad spectrum of challenging issues.

As explained in more detail later, I interpret the intent of the policy statements and management goals expressed in the documents cited above to be:

- To protect sequoia ecosystems from commodity-driven uses (such as logging and associated road construction) and from other major disturbances (such severe wildfires) which could preempt future management and use options,
- To restore sequoia ecosystems to the range of conditions that existed before Euroamerican settlement
- To conserve sequoia ecosystems, assuring their long-term sustainability in the face of changes resulting from Euroamerican settlement and potential future threats such as air pollution, unnatural effects of pathogens, and anthropogenic climatic change.

These goals are remarkably similar to the sequoia management goals of the NPS (see Parsons 1994). Therefore the following assessments of the policy and practical issues surrounding protection, restoration, and conservation draw heavily on decades of NPS experience managing giant sequoia ecosystems.

## GROVE PROTECTION

The term protection has had several different meanings with reference to sequoia groves. In the MSA (U.S. Forest Service 1990), Presidential Proclamation (Bush 1992), and Regional Forester's policy directive (Stewart 1992), grove protection mostly refers to protection from mechanical human disturbances (such as road construction and logging for commodity production) that are inconsistent with the amenity values of groves. As a consequence of the recent changes in USFS policy (Stewart 1992), this form of grove protection currently is in place for USFS groves (as it has been for decades in NPS groves).

For much of the history of sequoia management by Euroamericans, protection has also meant exclusion of all fire. This form of protection has allowed both surface and aerial fuels to accumulate within and surrounding groves, thereby increasing the hazard of unusually severe wildfires (cf. Stephens 1995; Chang 1996; McKelvey and Busse 1996; Skinner and Chang 1996; Weatherspoon and Skinner 1996; van Wagtendonk 1996). In the last 50 years, four groves (Case Mountain, Cherry Gap, Converse Basin, and Redwood Mountain) have been burned at least partly by large wildfires. Some areas within these groves were burned severely, particularly areas that had been logged before the fires but that had not been subjected to subsequent fuel reductions. The hazard of similar or more severe fires occurring in other groves is steadily increasing. Unlike protection from logging, groves cannot be protected from severe wildfires simply by a change in written policy.

Thus, the foremost immediate concern of all giant sequoia managers is to assure that future management and use options are not preempted by unusually severe wildfires; this is the form of grove protection that will receive the greatest attention in this chapter. Groves can be protected from wildfire by altering fuel conditions inside of groves, altering fuel conditions outside of groves, or both. Methods for altering fuel conditions are discussed elsewhere (Stephens 1995; van Wagtendonk 1996; Weatherspoon 1996; Weatherspoon and Skinner 1996). The effectiveness of grove protection conferred by fuels management within groves has been demonstrated twice within the last decade. In August of 1987, a lightning-ignited wildfire swept into the Redwood Mountain Grove (Sequoia National Forest and Kings Canyon National Park). The fire grew quickly in size and severity, in some places completely scorching or consuming the crowns of huge pines, firs, and even monarch giant sequoias, killing the trees (Stephenson et al. 1991). Fire crews were successful in containing the blaze only after it died down upon entering the portion of the grove that had been prescribed burned by NPS managers a few years before (Nichols 1989). In October of 1988, a wildfire caused by a carelessly discarded cigarette raced upslope through heavy chaparral toward the famous Giant Forest grove in Sequoia National Park. To contain the blaze and protect the grove, fire crews began to ignite backfires along the edge of Giant Forest. Recent prescribed burns had been so effective in reducing fuels that the fire crews could barely get their backfires to burn. This freed some firefighting resources to be focused elsewhere, and created a no-panic situation in which fire control efforts could go forward more deliberately. The fire was easily contained upon reaching the grove.

A fundamental premise of this chapter is that restoration of sequoia groves to pre-Euroamerican conditions automatically confers a large measure of protection from extreme wildfires (Fullmer et al. in press; Weatherspoon and Skinner 1996). As discussed elsewhere in this chapter, pre-Euroamerican sequoia groves were less dense, had lower average fuel loads, and had less continuous vertical fuels than typical unlogged and otherwise undisturbed groves today. Consequently, pre-Euroamerican groves supported fires of predominantly low to moderate severity (i.e., spatially variable fires that killed many seedlings and saplings and some subcanopy trees, with occasional patches of high severity which locally killed many or most trees of all ages; Stephenson et al. 1991). (There were a few notable exceptions, such as the predominantly high-severity fire that swept through Mountain Home Grove in A.D. 1297; Swetnam et al. 1992; Caprio et al. 1994.) It stands to reason that once grove structure (which broadly includes the spatial arrangement and sizes of forest patches and the diameters, heights, and densities of trees in the patches) and fuel characteristics are restored to pre-Euroamerican conditions, pre-Euroamerican fire behavior will follow, and groves will thus be less susceptible to severe wildfires (Weatherspoon and Skinner 1996).

This line of reasoning suggests that restoration and protection can proceed simultaneously, as a single action. In fact, this may be the only reasonable approach to grove management, since changes in grove structure automatically accompany fuel manipulations designed to protect groves from unusually severe wildfires. For these reasons many of the issues surrounding protection are addressed below, in the section on restoration.

## GROVE RESTORATION

The MSA (U.S. Forest Service 1990) does not clearly define the term restore. It states that "[t]he objectives of regenerating cutover Giant Sequoia Groves will be to restore these areas, as nearly as possible, to the former natural forest condition" (p. 27). Unfortunately, it is unclear whether the "former natural forest condition" means what occurred immediately before logging (which might have been quite different from pre-Euroamerican conditions), or what occurred "naturally" in pre-Euroamerican times. Another statement hints at the latter: "The objective of fuel load reduction plans shall be to preserve, protect, restore, and regenerate the Giant Sequoia Groves ..." (pp. 10–11). The use of the term restore in this context implies that present conditions in many undisturbed groves, which often include unusually heavy fuel loads, are not the desired "natural forest condition." Regional Forester Stewart's 1992 sequoia management policy directive offers a specific interpretation of the intent of the MSA. Stewart directed that sequoia management activities "... shall generally be designed to recreate and maintain stand structure, including the long term recruitment of 'specimen' giant sequoia trees and understory vegetation, that would have occurred naturally prior to the settlement of California by European immigrants." This USFS policy statement, which is meant to comply with the intent of the MSA, declares that pre-Euroamerican grove structure is to be restored and maintained. NPS policy implies similar goals for restoration.

The goal of recreating pre-Euroamerican grove conditions is logical and defensible. As described earlier, groves returned to pre-Euroamerican conditions will be protected, to a large degree, from unusually severe wildfires because of reduced surface and aerial fuels (Weatherspoon and Skinner 1996). Additionally, re-creating the conditions that sustained the groves for millennia is the most conservative approach to assuring their continued long-term sustainability (Fullmer et al. in press).

Managers wishing to restore groves to pre-Euroamerican conditions face at least four complex issues:

1. Defining specific restoration goals consistent with the overall goals and policies of the agencies or individuals managing the groves. A specific restoration goal discussed in detail later, for example, is to restore grove structure, species composition, and function to the usual range of conditions that existed in the 1,000 years preceding Euroamerican settlement.

2. Describing the targets for restoration. For the preceding example, this would entail explicitly describing the range of grove conditions that occurred in the 1,000 years preceding Euroamerican settlement.

3. Evaluating the practicality (and possibility) of meeting restoration objectives. Having determined the range of grove conditions that existed in the 1,000 years preceding Euroamerican settlement, can we realistically expect to restore groves to this range, given that present grove structure and composition limit the possible changes we can make?

4. Choosing restoration tools and approach. Choice of restoration tools and approach depends on various trade-offs and on the starting grove structure.

As in past analyses of issues surrounding grove restoration, the following analysis focuses most strongly on unlogged, unburned groves—the most abundant grove type in the Sierra Nevada and among the most vulnerable to unusually severe wildfires. However, attention is also given to specific issues surrounding restoration of logged groves.

## Defining Restoration Goals

### Structural versus Process Restoration

The most lively and instructive debate over appropriate grove restoration goals has been between "structural restorationists" and "process restorationists" (Vale 1987). Simply stated, structural restorationists have argued that grove structure (the spatial arrangement and sizes of forest patches and the diameters, heights, and densities of trees in the patches) and species composition must be restored, by whatever means possible, before natural processes (particularly fire) are allowed to run a more natural course in determining grove dynamics (Bonnicksen and Stone 1978, 1982b, 1985). In contrast, process restorationists have argued that initial grove structure is unimportant; the goal of restoration is to restore the major processes (particularly fire) that shaped sequoia ecosystems in pre-Euroamerican times in such a way that "the interaction of those processes with other ecosystem elements ... [is] ... similar to that which would have occurred had modern humans not intervened" (Parsons et al. 1986; Parsons 1990a). The debate has largely centered on NPS grove management; the details of the debate therefore have been colored by the assumption (following NPS policy) that at some point during or after grove restoration, fire becomes the tool of choice in determining future grove structure and composition. Broadly, however, the debate is equally relevant to management approaches in which mechanical manipulation, not fire, is the management tool of choice.

Some of the disagreements between structural restorationists and process restorationists have hinged upon differing interpretations of NPS legislation, goals, and policies. No attempt is made here to assess or reconcile differences among these interpretations; excellent summaries can be found elsewhere (Bonnicksen and Stone 1978, 1982b; Bancroft et al. 1985; Parsons et al. 1986; Lemons 1987; Parsons 1990a). Instead, this section summarizes the philosophical and practical issues that have driven the debate—those issues most relevant to managers and policy makers establishing future restoration goals for sequoia groves.

Both the structural and process restoration viewpoints recognize the dynamic nature of forests and share a similar goal of restoring "natural" forest conditions lost during a century of fire exclusion (Vale 1987). However, the viewpoints differ in several important respects. According to Vale (1987), the structural restorationist viewpoint is characterized by (1) reestablishing a precise forest structure, (2) calibrating initial restoration to a particular point in time, (3) focusing only on the effects of fire suppression on forest trees, (4) emphasizing the vegetation structure needed to reestablish natural process (fire), and (5) believing that vegetation change is not easily reversible. In contrast, the process restorationist viewpoint is characterized by (1) reintroducing a general forest process (fire), (2) calibrating restoration to a general period, not a precise point in time, (3) recognizing multiple causes of vegetation and ecosystem change, (4) believing that reestablishing process (fire) will eventually allow the forest to reestablish its natural structure, and (5) believing that vegetation change is easily reversible. Lemons (1987) has persuasively argued that many of these differences in viewpoints are based not on science, but on largely unarticulated human values.

Championing the structural restorationist viewpoint, Bonnicksen and Stone (1978, 1982b) argued for the necessity of structural restoration preceding the reintroduction of fire, largely based on their contention that fire suppression had led to more uniform fuel and vegetation conditions within sequoia groves, thus blurring the boundaries between formerly distinct forest patches of different ages and structures. This increased uniformity in forest conditions, they argued, would be perpetuated even after fire was reintroduced, thereby erasing the original character of the forest mosaic. As part of their analysis, Bonnicksen and Stone (1978, 1982b) evaluated the practicality and desirability of several potential vegetation restoration goals that at some point have been considered by land managers: (1) maintaining vegetation exactly as it is today, (2) restoring vegetation to its pre-Euroamerican state, then maintaining it exactly in that condition, (3) restoring pre-Euroamerican conditions, then allowing fire to determine future conditions, (4) reintroducing fire in the present vegetation without first restoring pre-Euroamerican structure, and (5) restoring conditions as they would be today, had Euroamericans never arrived, then reintroducing fire. Bonnicksen and Stone recognized that the first two goals are impossible to achieve; vegetation is dynamic and cannot be frozen in time. Of the latter three goals, they felt that the last would most closely fit NPS legislation and policies. They also recognized that the last goal could never be met perfectly due to physical limitations imposed by present grove conditions (see below).

There is much appeal to the structural restorationists' preferred goal of restoring conditions as they would be today, had Euroamericans never arrived, followed by allowing natural processes (especially fire) to play a major role in determining future forest conditions. However, some sequoia managers have argued that the goal is impractical. Expanding on Vale's (1987) summary, some of the reasons that NPS sequoia managers have adopted process rather than structural restoration goals are listed below. No attempt has been made to assure consistency among the reasons. As will be discussed later, the following reasons do not preclude the possibility of setting some broad structural goals.

It is difficult or impossible to quantitatively define precise structural targets for grove restoration. There are strong limitations on the accuracy and precision with which we can determine grove characteristics in the past, much less hypothetical grove conditions that would exist today if Euroamericans had never arrived.

Even if they could be quantified, it is impossible to approach some structural goals in less than several centuries (if ever). As elaborated later, this fact is a practical, not philosophical impediment.

The urgent need to protect groves from wildfire eliminates the option of waiting until quantitative structural goals can be defined and implemented with confidence.

At least within national parks (where policy generally prohibits timber sales), structural restoration by mechanical means is prohibitively expensive for all but small areas. A possible rebuttal to this argument is that prescribed fire is less expensive than mechanical manipulation, and can be used as a tool to restore at least some aspects of grove structure (see the next subsection). Outside of national parks, sale of trees removed during restoration might partially offset costs.

A large proportion of grove area is legally-defined wilderness, where mechanical tools for restoration are generally prohibited. Again, structural restoration by prescribed fire may be an option.

It is difficult to justify expending scarce funds on fine-tuning forest structure when other threats may unravel the restoration efforts. The interacting effects of air pollution, introduced diseases (such as white pine blister rust), and potential anthropogenic climatic change collectively threaten to force large changes on sequoia ecosystems; such changes could overwhelm efforts to restore forest structure altered by fire suppression. Of course, structural restoration (specifically, reduction in tree density within groves) could increase grove vigor by reducing competitive stresses, and therefore could diminish the effects of the other threats (Ferrell 1996).

The informed opinion of some managers is that the pre-Euroamerican range of variation in forest conditions will be restored if process (fire) is restored. At least one model of landscape change suggests that this belief may be true in at least some forest types (Baker 1994). However, the possibility has yet to be convincingly demonstrated for all aspects of sequoia grove structure (see the next subsection).

Some managers have suggested that present forest structure and composition may already fall within the pre-Euroamerican range of variability, therefore there is no need for structural restoration. The fossil pollen record (Anderson 1994; Anderson and Smith 1994) shows that large compositional changes (and presumably structural changes) occurred in sequoia groves over the last 10,000 years, sometimes including combinations of tree species that no longer exist (such as sequoia growing with lodgepole pine). Some managers have suggested that at some point during these wide variations in grove conditions, forest structure may have been similar to today's (which is partly a consequence of fire exclusion). However, if we limit ourselves to considering only past forest structures that existed under climatic conditions relatively similar to today's, this argument is unpersuasive.

Given how little we know about sequoia ecosystems (which include much more than just the trees focused on by structural restorationists), a conservative management approach is to (1) avoid introducing new processes (such as mechanical restoration and its accompanying soil disturbance) which have unknown immediate or long-term effects on many ecosystem components, and (2) restore and maintain those processes that sustained the grove ecosystems in the past. To paraphrase Aldo Leopold, a wise tinkerer keeps all the pieces, including fire, and avoids adding new pieces.

### Reconciling Structural and Process Restoration Goals

Nearly a decade of renewed sequoia ecosystem research, mostly funded by the NPS and the National Biological Service (Parsons 1990b; Stephenson and Parsons 1993), has provided a rich background of new findings to support a reassessment of the debate between structural and process restorationists. Partly in response to the results of this new research, NPS managers have begun cautiously to step back from pure process restoration and to also consider structural goals (Parsons 1995). Here I attempt to close the formerly enormous gap between the structural and process restorationist viewpoints by finding a balance between the idealistic view of structural restorationists, which recognizes that grove structure and process are inextricably intertwined, and the pragmatic view of process restorationists, which recognizes physical limitations to structural restoration. To reach this end, I muster the available scientific information to demonstrate that (1) process restoration alone, without a preceding mechanical treatment, can restore and sustain at least some aspects of pre-Euroamerican grove structure, and (2) broad structural restoration goals can be defined which bracket a wide range of possible outcomes, consistent with our limited knowledge of past grove conditions, physical limitations to grove restoration, and the intrinsic variability of giant sequoia ecosystems.

In support of their contention that reintroduction of fire without a preceding structural restoration would perpetuate unnatural grove changes, Bonnicksen and Stone (1981) cited spatial data from a single 80 m x 80 m plot established in a recently-burned portion of Redwood Mountain Grove. Bonnicksen and Stone found that trees 41 to 60 years old (i.e., a cohort that became established since fire suppression became effective) within the recently-burned plot were clumped in a hierarchical pattern. Since two separate unburned plots in the same grove showed similar hierarchical clumping within the same tree age class, they concluded that "the prescribed burn did not significantly alter the pattern for this age class." They additionally concluded that "[s]ince this [hierarchical] pattern was not characteristic of most older age classes [in the same three plots] it was probably not characteristic of the presettlement giant sequoia - mixed conifer forest community." By Bonnicksen and Stone's reasoning, these findings demonstrated that fire perpetuated a Euroamerican-induced change in the forest mosaic. They suggested that similar changes existed in, and would be perpetuated in, other sequoia groves in which prescribed fire is reintroduced without a preceding structural restoration (Bonnicksen and Stone 1978, 1981, 1982b).

For several reasons Bonnicksen and Stone's arguments are unpersuasive. First, their analysis was based on only a single burned plot. Second, they did not actually measure changes in forest pattern resulting from a fire; they inferred changes by comparison with two different unburned plots. Third, though they concluded that the present clumping of 41- to 60-year-old trees was unnatural because it differed from that of older trees, it has long been known that tree spatial pattern changes fundamentally with age (e.g. Laessle 1965). Finally, and most important, direct evidence from the studies outlined below demonstrates that high spatial heterogeneity in present-day fuels, prescribed fire behavior, and consequent forest response continue to result in a forest mosaic that, at least in gap and patch sizes, is similar to that of pre-Euroamerican times.

After a century of fire exclusion, average surface fuel loads (forest litter, duff, and all downed woody debris) within unlogged groves are high (128 tonnes / ha [57 tons / acre]; Keifer 1995 and personal communication) but are also highly variable. (Data are not available for logged groves.) Kilgore (1973a) found extreme fuel variability at scales of a few meters. Variability is high even at larger spatial scales; averaged fuel loads within each of 26 approximately 0.1 ha plots within several sequoia groves (stratified random sampling) ranged from 42 tonnes / ha (19 tons / acre) to 301 tonnes / ha (134 tons / acre), a seven-fold difference (Keifer 1995 and personal communication). This variability in fuels accentuates variability in prescribed fire behavior, which is already high due to differences in local topography and changes in daily and seasonal weather and fuel moisture (Kilgore 1973b; Harvey et al. 1980). Kilgore (1973a) found that total energy released during a prescribed fire in the Redwood Mountain Grove varied by several orders of magnitude over a distance of a few meters. During two prescribed fires in other groves, flame length (a measure related to fire intensity) at predesignated monitoring points varied from 0 (smoldering combustion) to more than 1 m (M. Keifer, personal communication). In a pocket of extremely heavy fuels during another prescribed fire, flame lengths were more than 12 m (Nichols 1977).

Such variability in fire behavior and intensity, in turn, contributes to variability in fire effects and forest response. For example, Gebauer (1992) showed that spatial heterogeneity in four of seven soil characteristics was significantly greater in recently-burned areas of Giant Forest than in areas that had not burned for more than a century (there was no significant trend in the remaining three soil characteristics). Kilgore (1973a) showed that in a study plot in the Redwood Mountain Grove (different from the plots studied by Bonnicksen and Stone), non-uniform fuels and fire behavior broke a uniform thicket of young white fir into a distinct gap (greater than 0.05 ha) and two smaller remaining thickets. Demetry (1995) found that 18 forest gaps created by a number of prescribed fires burning under different conditions in Giant Forest were of variable size (the author's non-random sample included gaps of 0.067 to 1.17 ha). (Gap size depends on how gaps are defined; Demetry defined gaps using a slight modification of the methods used by Spies et al. 1990.) The approximate modal gap size (to the nearest order of magnitude) was 0.1 ha for a large portion of Giant Forest (A. Demetry, personal communication). These gap sizes correspond to pre-Euroamerican gap sizes inferred from sequoia age structure analysis (Stephenson 1994); they also roughly correspond to the modern-day 0.0135 to 0.16 ha forest patch sizes found in Redwood Mountain Grove by Bonnicksen and Stone (1981, 1982a). Demetry additionally found that composition and structure of tree and shrub regeneration varied with gap size (Demetry 1995; Demetry and Duriscoe 1996).

Collectively, these data suggest that process restoration alone can restore or sustain at least one component of pre-Euroamerican forest structure: the relative abundances of different sizes of forest gaps and, presumably, resulting forest patches. We do not yet know, however, whether other aspects of grove structure ultimately will be restored, such as the relative proportions of forest patches in different age classes or with particular species compositions. However, it is worth examining the results of a landscape dynamics model developed by Baker (1994), which simulated the effects of different fire regimes on eight measures of forest mosaic pattern in the Boundary Waters Canoe Area, Minnesota. Baker's simulations suggested that by simply restoring the pre-Euroamerican fire regime to a forest that had been altered by 82 years of fire suppression, the forest mosaic would be restored to its pre-Euroamerican range of variability. Restoration of some aspects of the simulated forest mosaic occurred within 50 to 75 years; all eight measures of forest pattern were restored within 125 to 250 years after fire reintroduction. While Baker's results apply to a forest type that differs in many ways from sequoia groves, they suggest that it is not unreasonable to believe that grove structure might be restored by process reintroduction alone. The possibility should be tested more thoroughly with the aid of linked fire and forest models tailored specifically to sequoia groves, and by better monitoring of prescribed fire effects.

I now turn to evidence supporting part of the structural restorationists' viewpoint—that it is possible to define broad structural restoration goals that reflect practical limitations. As described in later subsections, physical constraints limit our ability to quantitatively describe grove conditions at a specific point in time, and especially grove conditions that would exist today if Euroamericans had never arrived. Even if we could describe these conditions, physical constraints limit our ability to recreate them. Of necessity, then, a reasonable goal for structural restoration must bracket a range of possible outcomes (often called "natural range of variability," or NRV; Manley et al. 1995). Conversation among sequoia managers and scientists has centered on two slightly different structural restoration goals that meet the latter criterion: (1) restore grove structure and composition within the range of variation that occurred during pre-Euroamerican periods in which the climate was similar to today's, or (2) restore structure and composition within the range of variation that occurred over a long but relatively recent pre-Euroamerican period. Describing targets appropriate to these goals is still an enormous challenge (see the next subsection), but is more realistic than calibrating restoration to a specific point in time.

Paleoecological records from pollen sediments and tree rings help set limits on what pre-Euroamerican time periods might provide appropriate targets for the two goals. Pollen records from meadow sediments demonstrate that within present grove boundaries, sequoias began to increase dramatically in importance relative to pines about 4,500 years ago, coincident with a slight global cooling (Anderson 1994; Anderson and Smith 1994). Though the pollen records suggest that changes in the relative proportions of tree species in groves have continued up to the present, most of the changes were completed by about 1,000 years ago. Even though climate and fire regimes have varied within groves during the last 1,000 years (Hughes and Brown 1992; Graumlich 1993; Swetnam 1993; Caprio et al. 1994), the variation has been relatively non-directional and the combined effect on giant sequoia demography at centennial time scales has been moderate; by far the largest deviation from equilibrium conditions (stationary age distribution) in giant sequoia populations over the last two to three millennia is due to the effects of fire suppression during the last century (Stephenson in preparation). The millennium preceding Euroamerican settlement therefore seems to be a good period for calibrating goals for structural restoration.

However, it seems unnecessarily restrictive and perhaps philosophically difficult to defend calibrating structural restoration only to those climatic periods during the last millennium that were similar to the present. Sequoia groves in the millennium preceding Euroamerican settlement experienced only a few brief periods of climate comparable to the warm, wet conditions of the last few decades (Graumlich 1993). Additionally, the natural tendency for vegetational change to lag behind climatic change ("vegetational inertia"; Cole 1985) suggests that forest structure and composition during these brief periods was to a large degree a legacy of preceding annual-, decadal-, and centennial-scale shifts in climate and fire regimes, not the climate of the moment. It therefore seems reasonable to conclude that a variety of different grove structures, not a single predictable grove structure, probably occurred during periods that shared similar climates. On the other hand, this does not imply that it is appropriate to calibrate restoration to any arbitrary time period. As described earlier, large directional changes in grove composition coincided with a general climatic cooling from about 4,500 to 1,000 years ago. I suggest that only the millennium preceding Euroamerican settlement is an appropriate period for calibration, because changes in the relative proportions of tree species slowed during this period, and grove composition was more similar to today's than at any time period for which we have pollen or other fossil records. Climatic changes during the last millennium have tended to be relatively non-directional when compared to the preceding several thousand years.

The preceding arguments lead me to suggest that a reasonable structural restoration goal is to come as close as is practical to restoring grove structure and composition to the usual range of conditions that existed during the 1,000 years preceding Euroamerican settlement. The term "usual range of conditions" is meant to exclude rare extremes that may have occurred over the last millennium, such as the large expanses of trees that were likely killed by the widespread, severe fire of A.D. 1297 in Mountain Home Grove (Swetnam et al. 1992; Caprio et al. 1994). While such extremes fall within the "natural" (pre-Euroamerican) range of variability, their deliberate creation is not likely to be tolerated by many managers or the public (though it is reassuring to know that, on the scale of centuries, groves seem resilient to such extremes).

The structural goal described above allows managers to step back from the unrealistic limitations imposed by trying to determine and replicate conditions calibrated to a specific year or other narrow time period. I now turn the discussion to an enormous challenge: describing structural restoration targets by determining the range of grove conditions that occurred in the millennium preceding Euroamerican settlement.

## Describing Restoration Targets

Given the high quality and great length of paleoecological records of climatic and fire regimes in sequoia groves (Hughes and Brown 1992; Swetnam et al. 1992; Graumlich 1993; Swetnam 1993), explicit process restoration targets are relatively easy to describe. Discussion of several issues surrounding restoring fire is deferred to the section on grove conservation.

### Tools for Describing Past Grove Structure

In contrast, describing targets for structural restoration (i.e., descriptions of the desired spatial arrangement and sizes of forest patches and the diameters, heights, and densities of trees in the patches) has proven difficult. Many constraints limit our ability to precisely and confidently determine pre-Euroamerican grove structure. Thus, before describing our best current understanding of past grove conditions, I present a brief overview of the capabilities and limitations of the various tools and approaches used to describe those conditions. Though conclusions drawn from any one tool or approach may be suspect, they can be powerful in combination.

Old written accounts (see especially the summaries in Bonnicksen 1975; Bonnicksen and Stone 1978). Old written accounts supply qualitative descriptions of conditions surrounding (and sometimes within) sequoia groves in the late 1800s and early 1900s. There is some disagreement among the written accounts and their interpretations (e.g., contrast the summaries in Otter [1963], who believed grove conditions of the late 1800s were artifacts of shepherds' fires, with those in Bonnicksen [1975] and Bonnicksen and Stone [1978]). Many written accounts were probably biased toward scenes that were particularly memorable to the chroniclers.

Reconstruction from repeat photography (e.g. Vankat 1969, 1970; Kilgore 1972; Vankat and Major 1978; Kauper et al. 1980). Photographs are one of the best windows on past grove conditions, sometimes showing dramatic changes (see figure 55.4). So far, photographic analyses of past grove conditions have been limited and qualitative. Some photographs undoubtedly were biased by photographers seeking attractive (but not necessarily representative) scenes. Most early photographs from sequoia groves date from the late 1800s, usually one or more decades after Euroamerican arrival.

Biological inference based on tree life-history traits and responses to fire (e.g. Harvey et al. 1980). (This might also be called the modern analog approach.) Modern studies of the shade tolerance, seed dispersal, and seedling germination and establishment traits of the various Sierran conifers, coupled with our understanding of the present effects of fires in groves and our knowledge that fires burned frequently through groves in pre-Euroamerican times, allow us to qualitatively infer past grove conditions relative to today. By themselves, they do not allow us to define a precise forest structure and composition for a specific location or time in the past.

Analysis of forest age structure (e.g. Vankat and Major 1978; Kilgore and Taylor 1979; Parsons and DeBenedetti 1979). Forest age structure alone is difficult to interpret. For example, without further information one cannot determine whether finding many more young trees than old—the usual condition in forests worldwide—indicates an increasing, steady-state, or declining tree population. However, obviously multi-modal age distributions reveal periods of high and low success in tree recruitment, thereby extending our ability to qualitatively infer conditions in centuries past.

Analysis of forest age structure coupled with demographic models (e.g. Stephenson in preparation). Age structure data coupled with demographic models gives clues as to forest trends (increasing, steady-state, decreasing, or fluctuating tree populations) over the last several hundred years (or thousands of years, in the case of giant sequoia). Such analysis can help define general, but not precise forest structures at a specific time in the past.

Forest dynamics models (e.g. Kercher and Axelrod 1984; Miller 1994; Miller and Urban in preparation; Urban et al. in preparation). Though the potential exists, no gap-phase forest dynamics model has yet been explicitly applied to estimate grove conditions at a specific time or time period in the past (but see the related approach listed in the next paragraph). Forest dynamics models depend heavily on the empirical data that drive them, and in many cases the data are weak, meaning that broad, untested assumptions sometimes must be made. However, this approach deserves more serious attention, especially in conjunction with the other approaches listed here.

Analysis of the physical legacies of past forest conditions (e.g. Bonnicksen and Stone 1978, 1982a, 1982b). Through analysis of logs, snags, and the sizes and ages of living trees, past forest conditions can be estimated by backward projection from present conditions. Unfortunately, white fir logs rot quite rapidly in the Sierra Nevada, having a half-life of only 14 years (Harmon et al. 1987). Thus, some of the material needed to accurately determine pre-Euroamerican conditions may be missing. Accurate reconstructions may therefore be limited to the postsettlement era (see Stephenson 1987). With consideration given to this caveat, this approach can still be used to help set limits on possible past grove conditions.

Analysis of old plot data (e.g. the data presented by Sudworth 1900, and summarized by Stephens 1995). The earliest available plot data from sequoia groves—Sudworth's 1900 data—are probably biased. His size structure data for every species are modal in the middle size classes, not the smallest size classes. This strongly suggests that his sampling was biased toward older forest patches, that he ignored small trees, or both. However, his data might help us understand conditions specifically in old-growth patches 30 to 40 years after Euroamerican settlement.

Inferring forest composition and structure from pollen records and macrofossils (e.g. Anderson 1994; Anderson and Smith 1994). Pollen and macrofossils from meadow or lake sediment can reveal changes in the relative abundances of different tree species over periods of 10,000 years or more. General forest aspect—open or closed—can be inferred from the relative abundances of pollen from shade-intolerant trees and understory plants. Pollen cannot reveal other aspects of forest structure, such as gap and patch sizes, relative proportions of trees in different age classes, and so on.

Thus, descriptions of past grove conditions often are limited in three ways: (1) most descriptions should be considered qualitative, not quantitative, (2) information is skewed toward describing grove conditions in the late 1800s or early 1900s, not earlier periods, and (3) results are usually specific to only a few locations.

### Current Best Estimates of Past Grove Conditions

With consideration given to the preceding cautions, I provide a qualitative best estimate of average grove conditions in the late 1800s, followed by a best estimate of conditions in the millennium preceding the late 1800s. The descriptions are based on a synthesis of available studies and, when reasonable, assume that results apply to sequoia groves in general; however, potentially large within- and between-grove variation may be obscured. As discussed later, local research can be used to derive better descriptions for individual groves or portions of groves.

The description of grove conditions in the late 1800s is presented as a list of twenty-one brief statements supported by references. The references are not meant to be exhaustive; they were selected as being the most recent, most relevant, unique, or offering an entry into the broader literature (also see Harvey et al. 1980; Weatherspoon 1990; and Aune 1994 for other entries into the literature). Differences in past grove conditions are described relative to modern groves that have never been disturbed by logging, and have not burned since the late 1800s.

1. The dominant tree species in groves of the late 1800s were the same as today; no tree species has been lost or gained, though there have been some shifts in density and age structure (Bonnicksen and Stone 1978, 1982a; Stephens 1995).

2. Groves of the late 1800s (as well as today) could be described as a mosaic of generally small forest patches of differing ages, vegetation structures, and species composition (Bonnicksen and Stone 1981, 1982a; see figure 55.8).

3. These forest patches generally originated in forest gaps created or modified by locally severe fire; recently-created forest gaps were an integral part of the grove landscape (Bonnicksen and Stone 1978, 1982a; Stephenson et al. 1991; Stephenson 1994).

4. The gaps and patches comprising the forest mosaic often were characterized by diffuse boundaries, grading together without sharp edges; scattered trees (particularly large sequoias) often survived in gap interiors (Demetry and Duriscoe 1996; Stephenson unpublished data).

5. Gap sizes were variable, ranging from single tree gaps to gaps of several hectares; the modal (most common) gap size may have been near 0.1 ha, to the nearest order of magnitude (Stephenson et al. 1991; Stephenson 1994).

6. Rarely, large gaps of more than ten hectares were created by avalanches or single or repeated fires dominated by high intensities (Fry 1933; Stephenson et al. 1991; Caprio et al. 1994).

7. Forest patches of more-or-less uniform structure and composition were probably generally smaller than the gaps in which they became established, due to non-uniform regeneration within gaps (Demetry 1995; Demetry and Duriscoe 1996).

8. The structure and composition of forest regeneration partly depended on gap size (Demetry 1995; Demetry and Duriscoe 1996).

9. Virtually all successful sequoia regeneration occurred within recently-created forest gaps (Stephenson et al. 1991; Stephenson 1994; figure 55.9).

10. Giant sequoia seedlings often were by far the most abundant tree seedlings within gaps (Demetry 1995; Demetry and Duriscoe 1996), though they would not necessarily maintain their dominance as the new forest patch matured.

11. The largest sequoia seedlings in a given cohort (and presumably those most likely to survive to maturity; Harvey and Shellhammer 1991; Demetry 1995) occurred toward the center of gaps larger than about 0.1 ha (Demetry 1995; Demetry and Duriscoe 1996).

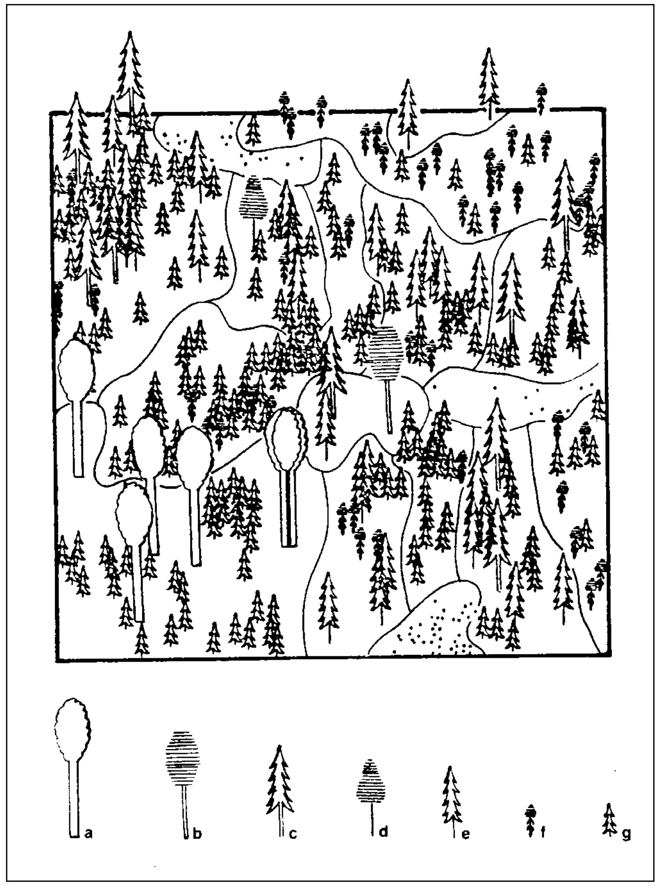


**FIGURE 55.8**

Sequoia grove structure and dynamics can be understood in terms of a mosaic of forest gaps and patches. This schematic diagram shows the locations of trees in a 50 m x 50 m (164 ft x 164 ft) section of the Redwood Mountain Grove, unburned for about a century. Lines are meant to accentuate the forest mosaic by delimiting patches of relatively uniform forest structure and composition, though it is clear that patch boundaries are not always distinct and their designation can be somewhat arbitrary. The tree symbols represent *a,* giant sequoias greater than 35 m (115 ft) tall, *b,* sugar pines greater than 35 m tall, *c,* white firs greater than 35 m tall, *d,* sugar pines 10 to 35 m (33 to 115 ft) tall, *e,* white firs 10 to 35 m tall, *f,* sugar pines 3 to 10 m (10 to 33 ft) tall, and *g,* white firs 3 to 10 m tall. For clarity, the tree symbols are reduced in size relative to the plot, lending a somewhat open appearance to the stand. (Reproduced from Bonnicksen and Stone [1982a], with permission of the Ecological Society of America.)

12. Young sequoias (1 to 100 years old) were orders of magnitude more abundant in the late 1800s than today (Stephenson 1994 and in preparation).

13. For trees less than about 30 cm diameter, the overall proportion of pine, oak, and sequoia relative to fir was greater than today (Kilgore 1973a, 1973b).

**FIGURE 55.9**

Sequoia is a pioneer species, requiring forest gaps for successful regeneration. This vigorous sequoia reproduction is in a forest gap created by locally intense fire during a prescribed burn in the Redwood Mountain Grove, Kings Canyon National Park. The white firs and incense-cedars in the background were killed by the fire, whereas the large sequoia at right was not. Most forest gaps created by fire in pre-Euroamerican groves were relatively small, probably covering fractions of hectares (a hectare is about 2.5 acres). Modern wildfires burning through heavy fuel accumulations are likely to be more severe, killing more trees and creating unusually large gaps. (Photograph by Nathan L. Stephenson, National Biological Service.)

14. Relative to today, more area was occupied by conifers less than about 10 m tall, and correspondingly less area was occupied by conifers 10 to 35 m tall; that is, more area was occupied by young forest patches than today (Bonnicksen and Stone 1978, 1982a).

15. More total area was occupied by young forest patches than old (Bonnicksen and Stone 1978, 1982a; Stephenson 1987).

16. More area was dominated by shrubs (particularly Arctostaphylos, Ceanothus, and Prunus) or open ground (depending on time since last fire) than today (Bonnicksen and Stone 1978, 1982a).

17. More area was dominated by mature Quercus kelloggii (California black oak) than today (Bonnicksen and Stone 1978, 1982a).

18. Understory trees (and perhaps to a lesser extent overstory trees) within forest patches were generally more sparse than today, although thickets still existed (Kilgore 1973a).

19. Vertical fuels were less continuous than today; fires removed the lower branches of trees (Kilgore and Sando 1975).

20. The crowns of monarch giant sequoias and other trees were sometimes much more sparse than today (when comparing the same individual trees); local high-severity fires scorched some trees high into their crowns (photos in Vankat 1969, 1970).

21. Average surface fuel loads were much lower than today, with fuels distributed in a patchy mosaic ranging from light or absent to locally heavy (Kilgore 1973b; Bonnicksen 1975; van Wagtendonk 1985).

Some authors have suggested that grove conditions in the late 1800s were an artifact of abnormally frequent and severe wildfires ignited by shepherds and cattle ranchers (see especially Otter 1963). This is probably not the case; reconstructed fire histories suggest that fires of the 1800s were of the normal range of intensities, with a marked decline in fire frequency beginning soon after the arrival of shepherds and ranchers in the 1860s (Swetnam et al. 1992; Swetnam 1993; Caprio and Swetnam 1995). For the most part, then, the description of grove conditions given above is based on information from groves that had been fire-free for one to a few decades. This falls within the range of fire-free intervals recorded over the preceding two millennia (Swetnam et al. 1992), suggesting that any grove structural changes that had taken place between the arrival of Euroamericans in the 1860s and the photographs and descriptions of the 1870s, 1880s, and 1890s were within the normal range of variability, and were probably far too small to affect the broad, qualitative description of grove conditions listed above.

Interpreting their finding that more total grove area was occupied by young forest patches than old in the late 1800s, Bonnicksen and Stone (1978, 1982b) concluded that grove structure in the late 1800s, at least in the Redwood Mountain Grove, was far from equilibrium (stationary age distribution). It would logically follow that conditions in the late 1800s were not representative of earlier periods in the same century. However, Stephenson (1987) reevaluated Bonnicksen and Stone's conclusions using well-established demographic models, demonstrating that the presence of more forest area in young patches than old qualitatively fits what is expected for groves near (but probably fluctuating around) equilibrium. (This same conclusion was reached by Van Wagner [1978] for other forest types.) If conditions in the Redwood Mountain Grove were indeed fluctuating near equilibrium in the late 1800s, it follows that they were probably near equilibrium in the early 1800s, given the multi-century life spans of the mixed conifer tree species. We do not know whether this conclusion would apply to sequoia groves in general; however, it lends support to the notion that the qualitative description of grove conditions in the late 1800s (listed above) is broad enough to apply also to the early 1800s.

As described in the preceding subsection, even though climate and fire regimes have varied within sequoia groves during the last 1,000 years (Hughes and Brown 1992; Graumlich 1993; Swetnam 1993), their combined effect on giant sequoia demographics at centennial time scales has been moderate. By far the largest deviation from equilibrium conditions (stationary age distribution) in giant sequoia populations over the last two to three millennia is due to the effects of fire suppression during the last century (Stephenson 1994 and in preparation). Additionally, the pollen record indicates no major changes in species composition over the last millennium (Anderson 1994; Anderson and Smith 1994). Collectively, these data suggest that our broad, qualitative description of grove conditions in the 1800s may also apply to other portions of the millennium preceding Euroamerican settlement.

Tree-ring reconstructions of fire history and sequoia population age structure suggest that grove conditions during the millennium preceding Euroamerican settlement experienced some local (and perhaps sometimes widespread) deviations from grove conditions found in the late 1800s. In A.D. 1297, during a severe drought, Mountain Home Grove experienced a widespread, severe fire which probably killed many mature trees, including some large sequoias (Swetnam et al. 1992; Caprio et al. 1994). This fire apparently induced the establishment of a large cohort of new sequoia regeneration in the grove. Big Stump Grove may have experienced a similar event at about the same time; Huntington's (1914) sequoia age determinations demonstrate that a large cohort of sequoias became established at Big Stump (he called it "Comstock") in about the early 1300s.

Linked fire and forest dynamics computer models show good promise of helping us more precisely infer the possible range of past grove conditions. Such modeling efforts are presently being made by the National Biological Service's Sierra Nevada Global Change Research Program (Stephenson and Parsons 1993; Miller 1994; Miller and Urban in preparation; Urban et al. in preparation). The models will be driven with climatic and fire regimes reconstructed from tree rings for the millennium preceding Euroamerican settlement; model output will be spatially-explicit patterns of grove structure and composition through time.

### Describing Structural Restoration Targets for Specific Groves

In pre-Euroamerican times, forest structure and composition undoubtedly varied from grove to grove in response to chance, local cultural practices of Native Americans, and local environmental conditions (elevation, slope aspect, slope steepness, soil characteristics, soil moisture, surrounding vegetation types, local ignitions and fire regime, and so on). It follows that managers should, to the extent possible, recognize the unique environment and history of each grove by setting grove-specific targets for restoration. Ideally, the targets would be set by using as many as possible of the tools and approaches listed earlier to determine past grove conditions in each grove. However, at least four problems interfere with our ability to define precise structural restoration targets for individual groves. I will first present the problems, then possible solutions.

First, some groves lack the information needed to directly determine past conditions. For example, many heavily logged groves have lost all signatures of their past structure, except for large sequoia stumps. If such groves also lack photographic and written records, there is no reliable direct way to determine their past structure and composition. Second, even if the needed information on past conditions could be gathered and analyzed, it may be too expensive and time consuming to attempt to describe past conditions unique to each grove unless significant new funds are made available. This is especially true during the present period of shrinking federal and state budgets. Third, even if both the funds and needed information are available, grove-specific descriptions of past conditions may still be so qualitative as to be nearly indistinguishable from the generic target listed earlier. For individual groves, targets will usually be quite broad, such as "reduce the area occupied by pole-sized white firs by 10 to 50%," leaving much room for overlap in target structures among groves. Finally, for reasons listed earlier, individual grove targets will usually be defined only by conditions near the turn of the century, which in some cases may have been extreme relative to local conditions in the preceding millennium. For example, if there is good evidence that a particular grove in the late 1800s experienced a predominantly high-severity fire which killed much of the forest (such as portions of the Redwood Meadow Grove, as indicated by present grove structure and the photographs and commentary by Sudworth [1900]), managers would probably be hard-pressed to justify re-creating such conditions, no matter how "natural" they might have been.

There are at least three ways of partly overcoming these obstacles to describing restoration targets for individual groves. First, the best available target might be defined by the pre-Euroamerican conditions of other groves found in similar environments (assuming that such analog groves exist, and that their past conditions can be determined). Second, linked fire and forest dynamics computer models using local environmental variables might be used to simulate the possible range of past grove conditions unique to a particular grove (see the preceding subsection). Finally, if all else fails, perhaps the only reasonable option would be to move forward with restoration using as a target the generic, qualitative description of past grove conditions listed in the preceding subsection.

Uncertainties are inevitable and are no reason to halt restoration. We do know many things with certainty, such as the existence of a continuing and unprecedented failure of sequoia regeneration (which is relatively easily reversed) in groves protected from fire and logging. Most uncertainty surrounds the details of restoration, not the big picture. Having considered issues related to describing targets for structural restoration, I now move the discussion to the step that managers must take after defining targets: evaluating the practicality of reaching restoration objectives.

## Evaluating the Practicality of Reaching Restoration Objectives

Once restoration targets have been described, managers must determine how precisely and how quickly they can be reached. The fidelity with which restored grove structure matches target structure will depend both on the pre-restoration grove structure and the target structure. Today, pre-restoration structure varies widely among four broad categories of groves (as described earlier): (1) groves that have been protected from both fire and logging, (2) groves that have been treated with prescribed fires, (3) groves that were logged near the turn of the century, and (4) groves that were logged more recently.

Our ability to rapidly achieve structural restoration goals is severely limited by a simple fact: it is possible to remove trees of any size, but not to plant trees of any size. For example, research has demonstrated that groves protected from logging and fire during the last century have orders of magnitude fewer 20- to 100-year-old sequoias than they would if fires had not been excluded (Stephenson 1994 and in preparation). This is well outside of the range of pre-Euroamerican conditions. Even if enough sequoias in this age class could be found in plantations around the world (which is doubtful), it would be impossible to transplant them successfully into groves (not to mention that such an operation would be prohibitively expensive and would compromise the genetic integrity of groves). Realistically, only small sequoia seedlings can be planted. Broadly speaking, then, selective removal of trees and selective encouragement of seedling establishment (either by planting or natural seeding) can be used to relatively quickly bring grove structure closer, but not exactly, to a specific target.

Agee (1995) has suggested the possibility of thinning and even fertilization aimed at increasing the sizes, and therefore apparent ages, of younger trees in selected forest stands, thereby creating large trees to "replace" a missing cohort. Even with this admittedly labor-intensive approach, it may take centuries (the time it takes for seedlings to become mature trees) of ongoing, hands-on management to increase the precision of structural restoration. Those grove areas recently logged of all but large sequoias will take longest to regain old-growth character. (On the other hand, in some ways the latter areas presently come close to mimicking the structural effects of rare but particularly severe fires of the past.)

It seems inevitable that, for centuries to come, most groves will bear at least some imprint of twentieth century fire suppression and logging. Managers must accept that even when they have a well-defined structural target, they may not be able to reach it. The best option may be to put in motion the structure and dynamics that someday may result in a structure that falls within the range of pre-Euroamerican variability.

## Choosing Restoration Tools and Approach

Simplistically, structural restoration can been seen as consisting of two parts: taking things out (removing trees) and putting things in (sowing seeds or planting seedlings). Two major tools can be used to remove trees: fire and saws. In many people's minds fire is associated with process restoration, but fire can be (and is) used also as a tool for structural restoration (figure 55.10). Fire intensity and effects can be controlled with moderate precision by judiciously locating fire lines, burning under selected weather and fuel conditions, and using different ignition techniques. This gives managers moderate control over which trees are killed and which are not, conferring moderate control over final forest structure.

Managers seeking to restore grove structure must consider potential tradeoffs between the two major tools for removing trees (table 55.1). Of course, the tools are not mutually exclusive; either or both can be used, depending on objectives and practical considerations. For example, saws can be used to girdle or fall trees selected for removal, then fire used to consume them. By whatever means selected trees are removed, the resulting release from competition results in dramatic increases in the height and especially diameter growth of mature sequoias (Dulitz 1986; Gasser 1994; Mutch 1994; Mutch and Swetnam 1995).

By whatever means it is accomplished, opening the forest canopy and clearing litter and duff from the forest floor also creates conditions favorable to sequoia seedling establishment, growth, and survival (Harvey et al. 1980; Harvey and Shellhammer 1991). However, there are large differences in sequoia seed release (and therefore seedling establishment) after fire and cutting. Stephens (1995) found more than one million sequoia seedlings per hectare in forest gaps created by fire, compared to a maximum of 90 seedlings per hectare in gaps of similar sizes created by cutting, even if slash fires had burned in the cut gaps. Benson (1986) found greater, but still low, sequoia seedling establishment after logging (820 seedlings / ha), with the number of seedlings dropping off rapidly in the following years. Insignificant sequoia seed release in cut

**FIGURE 55.10**

This prescribed fire is burning in a century's worth of accumulated fuels in the Giant Forest sequoia grove, Sequoia National Park. Prescribed fire can be used both as a tool for fuel reduction (grove protection) and as a tool for restoring aspects of grove structure to pre-Euroamerican conditions, while simultaneously maintaining the ecosystem processes of the past (such as soil sterilization and nutrient cycling). (Photograph by Betty Knight, courtesy of the National Park Service.)

gaps is due to the absence of a large, cone-opening heat pulse delivered to the crowns of the mature sequoias within and surrounding the gaps. Simple demographic models show that, due both to the high natural death rates of sequoia seedlings and to centuries of compounding of low death rates in sapling and mature sequoias (Harvey and Shellhammer 1991, Lambert and Stohlgren 1988), 90 to 820 seedlings per hectare is simply not enough to ensure recruitment of old-growth sequoias at pre-Euroamerican rates (Stephenson in preparation). Thus, sequoia regeneration in forest gaps created by cutting must be encouraged by one or more of three possible ways: (1) carefully-positioned slash fires deliver a heat pulse to the crowns of some nearby mature sequoias, (2) sequoia seeds are collected from manually-harvested cones, then scattered in the gaps, or (3) nursery-raised sequoia seedlings are planted. In either of the latter two cases, maintenance of the genetic integrity of local sequoia populations depends on the use of only local seed stock (Libby 1986).

The mechanics of restoration will be influenced heavily by individual grove histories (that is, initial grove structures). Currently, some unlogged grove areas that have been prescribed burned two or more times are probably closer to pre-Euroamerican conditions than any other grove areas. Among the other grove areas, those presently unlogged and unburned, with their dense mixture of trees in a broad spectrum of age classes, generally have the most potential for being restored to something approaching pre-Euroamerican conditions. The next greatest potential for restoration is in groves that were logged near the turn of the century, which now are often dominated by dense regeneration of all species. Where appropriate, dense stands can be thinned and new gaps created in the forest—a first step toward re-creating a forest mosaic of stands of many different ages (Weatherspoon 1996).

The most difficult grove areas in which to make rapid, significant progress in restoration are those that were logged of all trees except large sequoias in the 1980s. These 2 to 10 ha (5 to 25 acre) grove areas now lack intermediate ages classes, being dominated only by scattered old sequoias and relatively uniform expanses of seedlings of mixed species (figure 55.7). On the other hand, these forest gaps individually may resemble gaps created by uncommon, extremely severe fires of the past millennium. Thus, natural regeneration patterns in large fire-caused gaps could serve as a guiding analog for restoration of the cut gaps (see Demetry 1995; Demetry and Duriscoe 1996). Immediate attention should be given to restoring the species composition of tree seedlings in the gaps created by logging in the 1980s, most of which were planted with only ponderosa pine and giant sequoia. The findings of Demetry (1995) and Demetry and Duriscoe (1996), coupled with site-specific knowledge of forest composition around the gaps, will provide guidance for restoring the composition and spatial arrangement of tree seedlings within these gaps.

The mechanics of restoration will also be heavily influenced by the details of the desired target structures, such as the relative proportions of gaps and patches of different sizes, and their spatial relationships. Collectively, uncertainties about both the past structure of individual groves (and of groves in general) will make it difficult for managers to specify precise restoration actions on the ground. For example, if managers are confronted with ten white fir thickets and, to meet a broad objective of reducing white fire thickets by 10 to 50%, decide to mechanically remove some of the thickets, how do they choose precisely how many of the ten to remove? How do they choose which to remove? Should they remove only part of a given thicket or all of it? Should they expand the resulting gap into adjacent forest patches? Should a few trees be left standing in the newly-created gap? How many, and where? Should the boundary of the gap be relatively sharp, or should there be a slow transition of increasing tree density into the intact forest matrix?

Such uncertainty need not halt restoration; managers confronted with broad structural restoration objectives but lacking the information needed to prescribe the details of the restoration still have reasonable options for moving forward. First, managers might use fire as the main tool for achieving broad structural objectives. (Earlier I presented evidence that fire is a reasonable tool for restoring at least some aspects of pre-Euroamerican grove structure.) Managers using fire can achieve at least some of their broad structural objectives by controlling the season of burns, fire line locations, and ignition patterns, while allowing the details of the structural restoration to be determined by the same process that shaped the forest in the past—fire. This approach presumes that fire can do a better job of restoring the details of pre-Euroamerican forest structure than humans with saws, who lack complete information on past fire effects and therefore must make some arbitrary choices. However, it remains to be seen whether fire alone can meet all broad structural objectives. For example, it may be difficult to reduce the abnormally large cohort of large firs that has grown since fire suppression became effective (Bonnicksen and Stone 1978, 1982a). However, Kilgore (1973a) reports success in using fire to reduce this cohort. The use of fire in restoration should err on the conservative; once a tree is killed, it cannot be brought back.

If fire is not used as the primary tool for meeting broad restoration targets, managers must then precisely define, on the ground, which trees are to be removed by cutting. Given that structural targets are likely to be very broad, choosing the details of the reconstruction will be somewhat arbitrary. In this case, the best approach is conservative, because once a tree is removed, it cannot be put back. Restoration using saws will proceed in ways unlike standard silvicultural treatments (though it will most closely resemble the group selection cutting method; Weatherspoon 1996). Restoration targets will be

**TABLE 55.1**

Some tradeoffs between the two major tools for tree removal.

| Fire | Saws |
|---|---|
| Structural objectives achieved with moderate precision. | Structural objectives achieved with excellent precision. |
| Conservative: maintains the processes that sustained groves in the past, such as nutrient cycling and soil sterilization. | More likely to have unknown or unexpected short- and long-term ecosystem consequences. |
| No soil compaction, usually low erosion. | Potential for soil compaction and greater erosion, depending on approach. |
| Policy allows use in many designated wildernesses. | Would require special exemption for use in designated wildernesses. |
| Low or no potential for commodity production as an incidental byproduct of restoration. | High potential for commodity production as an incidental byproduct of restoration. |
| Smoke production and a chance of fire escape. | No smoke or chance of fire escape unless debris is removed by burning. |
| High potential for scarring trees, providing possible entry points for pathogens. | Lower potential for scarring trees, but high chance of entry of root pathogens through cut stumps. |
| Adequate natural seed release following treatment. | Some species (particularly sequoia) will require manual seeding or planting. |
| Relatively inexpensive to apply over large areas. | May be very expensive if costs are not partially offset by commodity production. |

based on ecological principles aimed at restoring variable pre-Euroamerican conditions, not on commodity values, maximization of site production, or ease of silvicultural treatment. (Commodity production, however, still could be an incidental byproduct of restoration.) Restored groves will include suppressed trees, insects and pathogens, snags, logs, brush patches, small forest gaps of different sizes, and different levels of forest thinning which grade into one another—sometimes gradually, sometimes more abruptly. Some of the different cutting treatments that have been used, sometimes for decades, in different groves and plantations (e.g. Mountain Home Demonstration State Forest, Calaveras Big Trees State Park, the Tule River Indian Reservation, the University of California's Whitaker's Forest and Blodgett Forest Research Station, and on private lands) may help illustrate the consequences of different approaches (Benson 1986; Dulitz 1986; Harrison 1986; Heald 1986; Gasser 1994; Rueger 1994; Stephens 1995).

Prescribing sizes and spatial arrangement of forest gaps and patches may be difficult. I have emphasized that the modal gap size in pre-Euroamerican sequoia groves may have been near 0.1 ha, but was also highly variable. To complicate matters, patterns of clumping in trees are hierarchical, spanning scales from a few meters to whole groves, and can vary among groves (Bonnicksen and Stone 1981; Stohlgren 1993). To replicate the hierarchical clumping of pre-Euroamerican times will require thoughtful consideration of the spatial arrangement of newly-created gaps of different sizes.

A related problem is determining at which spatial scales restoration success is to be judged. Individual forest stands can deviate widely from the general pre-Euroamerican grove conditions listed earlier, yet collectively they might re-create the conditions. Clearly, criteria for judging restoration success need to be defined differently at different spatial scales: individual trees, stands, groves, and the whole population of naturally-occurring groves.

## Restoration of Areas Affected by Roads and Foot Traffic

The preceding subsections were devoted to issues relevant to restoration of the structure and dynamics of grove vegetation altered by fire exclusion or logging. In contrast, some of the earliest and most urgent calls for grove restoration centered on counteracting the effects of roads and tourist foot traffic on the rooting zones of sequoias (Meinecke 1926; Hartesveldt 1962). These earlier concerns bear reexamination.

In contrast to Meinecke's (1926) expectation that sequoias would be harmed by foot traffic and by the placement of road fill and pavement over their rooting zones, Hartesveldt (1962, 1965) found that most mature sequoias actually showed a distinct increase in growth rate after these disturbances. Pavement over a sequoia's rooting zone eliminates competition for moisture and nutrients by other plants, reduces losses of soil moisture to evaporation, and causes substantial soil warming. At 30 cm (1 ft) beneath pavement in the summertime, Hartesveldt (1965) found soils to be 14°C (25°F) warmer than nearby soils not covered with pavement. These warm, moist soils result in accelerated growth and longer growing seasons for the affected sequoias. Similarly, soils compacted by foot traffic often retain more soil moisture than uncompacted soils. Consequently, mature sequoias with compacted rooting zones also tend to grow faster than sequoias in undisturbed areas (Hartesveldt 1965).

In no way do these findings mean that paving or trampling of sequoia rooting zones is desirable. First, it is possible that warmer and wetter soils also provide a better environment for root pathogens, potentially leading to accelerated toppling of infected sequoias (Hartesveldt 1962). While there is presently no evidence of increased failure rates among sequoias with paved or trampled rooting zones, such an effect, if it existed, could be subtle and could take decades or more to become evident. Second, heavy foot traffic around sequoias can result in erosion that exposes sequoia roots (Hartesveldt 1962), possibly opening corridors to root pathogens. Third, heavy trampling eliminates other plant species native to sequoia ecosystems, while compacting soils to the point that plant reestablishment is inhibited long after trampling ceases. Finally, many (if not most) people find trampled areas esthetically less pleasing than untrampled areas.

Hartesveldt (1962, 1965) found that the primary negative effect of roads on mature sequoia growth rates was from roots being cut during road construction. Some sequoias with cut roots showed signs of growth recovery over a period of decades. Hartesveldt further proposed that improper road drainage could damage sequoias and other species through the direct effects of accelerated erosion, which might undermine and topple trees, or by the indirect effects of extreme erosion or deposition that raises or lowers local water tables (Hartesveldt 1966).

Because roads and foot traffic tend to be localized, and because their negative effects on most mature sequoias seem to be small to insignificant, restoration of such areas seems less urgent than reducing fuel loads within groves. However, some restoration actions can be taken relatively easily. First, the most conservative approach to grove management would avoid new road construction and would minimize areas of concentrated off-trail foot traffic. Second, foot, stock, and off-highway vehicle trails showing signs of significant soil loss or exposure of roots might be moved away from the rooting zones of sequoias, which, to the best of our knowledge, generally extend 30 m (100 ft) or more from the bases of sequoias (Hartesveldt et al. 1975). Dirt roads experiencing or inducing significant erosion should be repaired, or closed and rehabilitated. Third, areas that were formerly heavily trampled might be re-planted with native plants and lightly mulched with forest litter and duff to encourage site recovery. In extreme cases of topsoil loss (see Hartesveldt 1962), a layer of topsoil taken from adjacent mixed-conifer forest might be added. Attempts to reduce soil compaction by tilling should probably be avoided; tilling might encourage pathogen entry through root wounds. Fourth, various efforts can be taken to help stabilize trees obviously weakened by road cuts or accelerated erosion. Finally, original drainage patterns could be restored in those apparently few areas where water tables have been significantly raised or lowered by erosion, deposition, or other causes.

## GROVE CONSERVATION

Active management cannot end with protection and restoration; once protected and restored, groves must be maintained. Here I address the following pertinent issues: What approach or approaches should be taken to assure long-term grove sustainability? How much protected land adjacent to groves is needed, and how should it be managed? What are likely future threats to the long-term sustainability of sequoia ecosystems?

### Maintaining Restored Groves

As is the case for restoration, groves can be sustained through the judicious use of fire, saws, or both. The most conservative approach to assuring the long-term sustainability of sequoia ecosystems is to maintain the processes that sustained them in the past. Specifically, prescribed fire is the most conservative tool for sustaining sequoia ecosystems. Some important ecosystem functions of fire which cannot be mimicked by other means are mobilization of nutrients locked in litter, duff, and woody fuels; killing of pathogens in the upper soil layers; changing soil structure and wettability without causing soil compaction; and inducing seed release from serotinous cones (Kilgore 1973b; Harvey et al. 1980; Chang 1996; Weatherspoon 1996). To paraphrase J. B. S. Haldane, sequoia ecosystems are not only more complex than we suppose, but more complex than we can suppose. Given this complexity, fire probably plays other important roles of which we are not yet aware, and may never be aware. To permanently remove fire from its former role would put sequoia ecosystems on a new, unknown track (Weatherspoon 1996).

It is clear that for a number of purposes Native Americans lit fires extensively in the foothills and mixed conifer forest of the Sierra Nevada (Reynolds 1959; Lewis 1973; Anderson and Moratto 1996). (Interestingly, one of the primary purposes of these generally low-intensity fires was to reduce fuels that could lead to catastrophic fires [Anderson and Moratto 1996]). A non-trivial policy question therefore accompanies the restoration of fire: should the restored fire regime mimic the pre-Euroamerican fire regime (which included fires ignited by Native Americans), or mimic a lightning-only fire regime appropriate to the present climate? (An additional non-trivial question is whether rare high-severity fires, even if natural, should be allowed to burn.) This choice between Native American and lightning-only fire regimes is partly philosophical, driven by conflicting definitions of "natural" and by ethical choices as to the proper role of humans in ecosystems. For discussions of the philosophical aspects of the dilemma, I refer readers to other articles (e.g. Kilgore 1985, Graber 1985, 1995).

It is possible that the choice between Native American and lightning-only fire regimes is of little material importance. First, some fire ecologists intimately familiar with the Sierra Nevada have examined patterns of lightning fire ignitions and think that, in contrast to Kilgore and Taylor's (1979) conclusions, in some places fire frequency may have been limited mostly by weather, fuel quantity, and fuel quality—not by availability of ignitions (Swetnam et al. 1992; J. van Wagtendonk personal communication). This possibility should be examined with the aid of computer simulations by linked forest and fire dynamics models specifically tailored to sequoia ecosystems (e.g. Miller 1994; Finney 1995; Miller and Urban in preparation). Second, if differences exist between Native American and lightning-only fire regimes, they might not be large enough to have a major effect on grove structure and composition. Again, this possibility should be examined with the aid of computer simulations. However, until convincing evidence exists that the choice of fire regimes makes little difference, managers' choices should be based on clearly articulated policy justifying one approach or the other.

If the managers' choice is to mimic the Native American fire regime (which includes fires started by lightning), they should burn so as to mimic the size, frequency, season, and usual range of intensities of fires that burned during climatic periods similar to the present, and that occurred within the last few millennia (Kilgore 1985; Parsons 1990a). (Whether or not Native Americans significantly influenced fire regimes, we know that fire regimes generally tracked climatic change; Swetnam 1993.) Good quantitative targets are available; tree-ring analyses have produced excellent multi-millennial records of climate, fire frequency, and fire season in several sequoia groves (Hughes and Brown 1992; Swetnam et al. 1992; Graumlich 1993; Swetnam 1993; Caprio and Swetnam 1995). Mutch (1994) has demonstrated that tree rings can also be used to infer past fire severity, but this approach has yet to be applied broadly (see also Caprio et al. 1994; Mutch and Swetnam 1995).

In contrast, no quantitative targets are presently available to allow managers to mimic lightning-only fire regimes. It would not be enough for managers simply to avoid interfering with lightning ignitions within groves; such a fire regime would not include fires that started outside of groves and would have burned into the groves if they had not been suppressed, and if land-use changes had not created barriers to fire spread. Targets for lightning-only fire regimes might be simulated using available fire spread models (e.g. Finney 1995). Patterns of lightning strikes and ignitions could be examined and the resulting fires would be allowed to burn across a simulated landscape free of "unnatural" barriers to fire spread. The simulated fire regime, including fires that the models suggest would have burned into groves from the outside, would then become the target for management-ignited prescribed fires.

Though fire is the most conservative tool for sustaining sequoia ecosystems, there are potential limitations to its use. Protection of people and property from escaped prescribed fires is of primary importance; fortunately, protection is usually a straightforward task. Perhaps the greatest hurdle is meeting air quality standards, both locally (which affects local residents and tourists) and regionally in the San Joaquin Valley. Air quality issues related to prescribed fire are discussed by Cahill et al. (1996).

Cutting and planting alone might be used to sustain groves, but this approach has its own problems. To prescribe cutting and planting as the primary grove maintenance tool presumes that we understand most aspects of sequoia ecosystem dynamics, and that we can mimic them without fire. This is probably true for regenerating the major tree species (which we understand relatively well), but not for most other organisms in sequoia ecosystems. If cutting and planting are used to sustain groves, the ecosystem consequences should be closely monitored and compared with those of burning. Of course, an intermediate path would be to use saws to girdle or fall trees which are then burned in situ, followed by planting and / or natural seeding. Again, the ecosystem consequences of this approach should be monitored.

Special attention might be given to restoring and maintaining the genetic integrity of sequoia groves (Fins 1979; Libby 1986; Fins and Libby 1994). For example, the Placer County Grove is a tiny grove consisting of six naturally-occurring sequoia trees. The grove lies far to the north of all other naturally-occurring sequoia groves and shows some unique genetic traits (Fins 1979; Libby 1986). Dozens of sequoia seedlings, probably from Mountain Home Grove, were planted among the Placer County Grove sequoias in about 1951. Some of these introduced sequoias are reaching sexual maturity, and thus threaten to introduce foreign genes into the local population. Maintaining the genetic integrity of this grove would be simple: the 45-year-old sequoia seedlings would be cut. This course of action was recommended at least seventeen years ago by Fins (1979), but still no action has been taken. If the genetic integrity of this unusual grove is to be maintained, the introduced trees should be removed immediately.

## Land Needs

### Grove Influence Zones

The MSA (U.S. Forest Service 1990) specified that sequoia grove boundaries would be defined by "... an interim 500 foot buffer extending from a hypothetical perimeter line around the outermost known giant sequoias in the Grove[s]." There was to be no logging or other mechanical entry in this zone, except that with the specific purpose of reducing fuel loads. An additional 500-foot zone, called the grove influence zone, was to extend beyond the 500-foot administrative boundary; certain restrictions were placed on logging within the grove influence zone. Many specific exceptions to these methods of defining groves and grove influence zones are listed in the MSA (U.S. Forest Service 1990). For example, several groves were to have 300-foot administrative boundaries surrounded by 300-foot grove influence zones. Additionally, topographic features such as ridges could take precedence in finalizing grove boundaries and influence zones, when such features logically and physically separated giant sequoias from the general forest. Rogers et al. (1995) describe the issues and mechanics that led to the final mapping of USFS groves and their influence zones.

The MSA's definition of grove influence zones has little ecological basis. USFS and other managers need an ecologically sound basis for defining grove influence zones, and must state clearly what land management practices are appropriate within these zones. The defining element of sequoia ecosystems is the giant sequoia itself; all known plant and animal species in sequoia groves (with the exception of a single species of beetle, Callidium sequoiarum, which is host-specific to sequoia) are also found within the much more extensive mixed-conifer forest surrounding groves (DeLeon 1952; Harvey et al. 1980). Thus, perhaps the most obvious measure of a sequoia ecosystem's sustainability is its ability to support sequoias themselves. To the best of our knowledge, high soil moisture availability in well-drained soils is the primary factor allowing sequoias to grow within present grove boundaries but not in adjacent mixed-conifer forest (Rundel 1969, 1972b). Thus, one of the primary needs for assuring sequoia ecosystem sustainability is undisturbed grove hydrology.

Until individual grove assessments suggest otherwise, the most conservative approach to restoring or maintaining grove hydrology (and therefore long-term sustainability) begins with defining a hydrologic influence zone—the local watershed above and adjacent to groves. Certain upslope areas falling within the same topographic watershed as a grove might be designated as outside of a grove's hydrologic influence zone, if it is convincingly demonstrated that there is no significant aboveground or belowground hydrologic connection with the grove. This might be true for the more distant portions of large watersheds. Such determinations will need to be made by qualified forest hydrologists working with sequoia ecologists.

An additional important component to the grove influence zone is defined by fire behavior. Fire influence zones should be added immediately adjacent to groves, and managed in such a way that fires entering the grove will behave as they would have in pre-Euroamerican times. Fire influence zones will usually be widest immediately below groves, but occasionally may extend beyond the hydrologic influence zones above groves, usually for groves that extend to ridgetops. The widths of fire influence zones will vary with local conditions, but typically might be the equivalent of two tree heights: 100 to 150 m (300 to 500 ft, which in this case is similar to the width of grove influence zone boundaries defined by the MSA). Individual fire influence zones should be determined by fuels and fire behavior specialists.

The boundary of the final grove influence zone would be defined by the wider of the hydrologic and fire influence zones at each point around the grove periphery. Conservatively, management practices within the grove influence zone would be limited to those identical to the management practices outlined for the groves themselves: protect and restore, then to the extent possible let natural processes (particularly fire) shape forest dynamics and hydrology.

### Additional Land Needs

The USFS and NPS collectively manage more than three-fourths of all grove area in the Sierra Nevada; public agencies as a whole manage about 90%. There is no compelling evidence that the long-term sustainability of giant sequoia ecosystems as a whole depends on adding more to the public land base. For example, it is highly likely that the majority of genetic diversity among sequoias is already found on public land, especially considering that genetic variation within groves tends to be greater than variation between groves (Fins 1979; Fins and Libby 1994; however, not all groves have been genetically explored). Additionally, a diversity of grove ownerships promotes a diversity of management approaches. Those private landowners who take an active interest in sequoia stewardship are potentially valuable partners with public agencies in determining the consequences of different management approaches to sequoia ecosystems.

However, logical reasons for public purchase of groves from willing private owners might include providing additional public recreational opportunities, conserving specific ecological or genetic features unique to particular groves, and increasing the public agencies' ability to manage grove areas already in their protection. For example, about 500 acres of private land within the Alder Creek Grove, if added to the USFS land base, would include the largest sequoia outside of the national parks (which also happens to be the sixth largest tree in the world; Flint 1987) and the only known wild example of the unusual "weeping" variety of giant sequoia (R. Rogers, personal communication). As a further example, USFS presently manages all of Freeman Creek Grove (a USFS Botanical Area) except for about 10 privately-owned acres in the heart of the grove. USFS purchase of this small parcel could greatly facilitate the future use of prescribed fire as a tool for managing the grove.

## Air Pollution

Some of the worst air pollution in the United States is found periodically along the western flank of the southern Sierra Nevada, the home of the vast majority of sequoia groves (Peterson and Arbaugh 1992; Cahill et al. 1996) (figure 55.11). Mature giant sequoias seem to be resistant to present levels of ozone, the most damaging component of Sierran air pollution. One hundred twenty-year-old sequoias exposed to ozone for two months, some at concentrations up to three times ambient, showed no visible foliar injury or detectable changes in photosynthetic rates (Miller et al. 1994). In contrast, newly-emerged sequoia seedlings were more vulnerable. Seedlings exposed to ozone over an entire summer showed very slight foliar injury at ambient ozone levels; however, those exposed to 1.5 times ambient levels showed extensive foliar injury and lowered photosynthetic efficiency (Miller et al. 1994; Miller 1996).

Some other tree species found in sequoia groves are more susceptible to ozone injury than giant sequoia—particularly ponderosa pine and Jeffrey pine. Ozone-sensitive individuals

**FIGURE 55.11**

As seen in this view from the edge of the Giant Forest sequoia grove, some of the worst air pollution in the United States is periodically found along the western flank of the southern Sierra Nevada, home of most of the world's naturally occurring sequoias. Sequoia seedlings, but not mature trees, show some damage at present levels of air pollution; ponderosa pine and Jeffrey pine are more strongly affected. Air pollution, unnatural effects of pathogens, and potential for climatic change all threaten giant sequoia ecosystems to varying degrees. (Photograph by Diane Ewell, courtesy of the National Park Service.)

of these pines show extensive foliar injury at present ozone levels in the southern Sierra Nevada (Peterson and Arbaugh 1992; Duriscoe and Stolte 1992; Patterson 1993; Miller 1996). Compared to ozone-resistant individuals, ozone-sensitive pines have lower photosynthetic rates, lose their needles earlier, and have diminished annual ring growth (Miller 1996). Smaller trees are the most severely affected. Pines in the Sierra Nevada east of Fresno, particularly in Grant Grove and Giant Forest of Sequoia and Kings Canyon National Parks, show some of the most severe ozone damage in the Sierra Nevada (Peterson and Arbaugh 1992; Stolte et al. 1992). Patterson (1993) found that nearly 90% of Jeffrey pines in or near the Giant Forest sequoia grove showed visible signs of ozone injury; however, he ranked only 10% of the pines as showing severe injury.

If ozone concentrations in the Sierra Nevada remain relatively constant into the future (as they have over the last decade, due to increasing pollution control efforts in the face of rapid population growth; Cahill et al. 1996), air pollution may have some limited effects on the genetic composition of sequoia seedling populations, while significantly contributing to increased death rates and decreased recruitment of ponderosa pine and Jeffrey pine within sequoia groves (Miller 1996). If pollution were to increase beyond present levels, adult pines stressed by air pollution (compounded by crowding caused by fire suppression) may become more susceptible to fatal insect attacks, as they have in the Los Angeles basin to the south (Miller 1973; Ferrell 1996; Miller 1996). Additionally, sequoia seedling establishment, survival, and recruitment might eventually be reduced (assuming that conditions for establishment are otherwise favorable). Options for counteracting the effects of air pollution include (1) reducing production of air pollution, (2) reducing competition among trees by thinning (whether by fire or saws), and (3) identifying, breeding, and planting pollution-resistant varieties of selected tree species. In the latter case, genetic diversity within groves may diminish.

## Pathogens

Annosus root rot (Heterobasidion annosum), a native fungus, may be killing more sequoias now than in pre-Euroamerican times. Fire suppression has allowed white fir to grow more densely in sequoia groves than it did in the past, meaning that there are more opportunities for root rot to spread from infection centers and to be transmitted to sequoias through root contact (Piirto 1977; Piirto et al. 1984). Sequoias weakened by root rot are more susceptible to falling than those free of infection. Restoration of groves to their more open pre-Euroamerican conditions probably will reduce the occurrence of annosus root rot; the direct effects of fire on the pathogen are less certain (Piirto et al. 1992). Serious consideration should be given to chemically treating freshly-cut fir stumps that might be created during grove restoration, which otherwise can provide a major entry path for various root rots (Ferrell 1996).

Throughout its range sugar pine, generally the second or third most abundant tree species in sequoia groves, is succumbing to white pine blister rust (Cronartium ribicola), an epidemic disease introduced from Asia. Attempts to eradicate white pine blister rust have been unsuccessful (Ferrell 1996); most likely, groves will continue to lose sugar pine. Consequently, populations of small mammals and birds that depend on sugar pine seeds might also eventually be reduced. Over the range of most sequoia groves, roughly ten percent of sugar pines are resistant to the epidemic strains of blister rust. However, a more virulent strain has been identified and its spread is a distinct possibility (Kinloch and Comstock 1980; Kinloch and Dupper 1987). Even if more virulent strains do not spread, sugar pines of all sizes will survive in groves, but in greatly reduced numbers. The effects of this change on other ecosystem components are unknown.

A long-term strategy for maintaining sugar pines in sequoia groves will probably include planting seedlings of resistant varieties taken from local stock. USFS already has tested thousands of candidate sugar pines for resistance, is protecting resistant seed trees, and is growing and planting resistant seedlings. NPS efforts lag.

## Climatic Change

There is no serious doubt that the average global temperature has been rising in this century (Houghton et al. 1990). Internationally, there is now a near-consensus among climatologists and atmospheric scientists that at least part of this warming is due to human activities (Kerr 1995). California, like the rest of the world, is vulnerable to climatic changes induced by the global increase in atmospheric greenhouse (heat-trapping) gases. Though available projections are crude, climatic models suggest that California and the Sierra Nevada may experience significant changes in temperature and the timing and amount of precipitation, leading to fundamental changes in climatic regime over the next several decades (Knox and Scheuring 1991; Westman and Malanson 1992). Snow melt, a major source of soil-water recharge in sequoia groves (Rundel 1972b; Stephenson 1988), is likely to come earlier in the spring than at present, potentially prolonging the summer drought characteristic of the Sierra's mediterranean-type climate. Depending on their magnitude, such climatic changes could have tremendous effects on giant sequoia ecosystems.

The paleoecological record is one of our best tools for understanding the possible magnitude of biotic changes resulting from climatic changes. Contrary to John Muir's glacial hypothesis (Muir 1876, quoted in Axelrod 1959), the fossil pollen record suggests that the present highly disjunct distribution of sequoias is due to the generally higher global summertime temperatures and prolonged summer drought in California of the early and middle Holocene (about 10,000 to 4,500 years ago) (Anderson 1994; Anderson and Smith 1994; this explanation was earlier proposed by Rundel 1972b and Axelrod 1986). During this period, sequoias were probably much rarer than today (at least in areas where they are presently found; Anderson 1994; Anderson and Smith 1994), existing only along creek and meadow edges where present groves exist. Pines were more abundant, firs less abundant. Only since cooling and shortening of summer droughts began about 4,500 years ago has sequoia been able to spread out and create today's groves, over a period of only two or three sequoia life spans (Anderson 1994; Anderson and Smith 1994).

This record of sequoia's response to past climatic changes offers an imperfect but instructive analog to the possible effects of future climatic changes. Projected increases in global temperature over the next several decades are of similar or greater magnitude than those that caused the dramatic increase in sequoia abundance during the last 4,500 years, but they are in the opposite direction (Houghton et al. 1990). It therefore seems reasonable to conclude that, if model projections are correct, increasing temperature over the next several decades, by inducing earlier snowmelt and prolonging summer droughts, may cause a return to conditions unfavorable to sequoias. An immediate effect probably would be a widespread and continuing failure in sequoia reproduction, even in the presence of prescribed fires; this would be a consequence of the high vulnerability of sequoia seedlings to prolonged drought (Harvey et al. 1980; Mutch 1994). Death rates might increase among adult sequoias and associated species as drought stress makes them more vulnerable to insects, pathogens, and air pollution. Of course, there may be other species in the giant sequoia community that would be equally or more severely affected by climatic change than sequoias.

Global warming might also increase the probability of destructive wildfires, particularly within groves that have not yet been restored. Models predict that global warming will be accompanied by increased lightning strike frequencies at the latitudes spanned by the Sierra Nevada (Price and Rind 1991). Compounding the possible increase in wildfire ignitions, extreme weather conditions are likely to make individual fires burn more total area, be more severe, and escape containment more frequently (Torn and Fried 1992). Ryan (1991) raises some of the questions faced by park and wilderness managers confronted with climatic change and the resulting changes in fire regimes and vegetation.

Managers have few, if any, viable options for counteracting the effects of climatic change. Mature sequoias cannot be transplanted upslope to cooler conditions, and even if seedlings are planted at higher elevations in an attempt to start new groves, soils there are less well developed and have generally lower water-holding capacities (Huntington et al. 1985). Selected areas within existing groves might be artificially irrigated to reduce drought stress, though increased competition with urban areas for water may limit the effectiveness of this admittedly desperate approach. More drastically, managers may choose to favor giant sequoias by severely thinning (whether with saws or with fire) non-sequoia trees within the groves, thereby reducing competition for water. Managers would also need to focus more closely on reducing surface and ladder fuels within groves to reduce the chances of severe wildfires.

# CONCLUSIONS AND STEPS FOR IMPLEMENTATION

## General Conclusions

I wish to highlight four broad conclusions. First, inaction threatens the sustainability of giant sequoia ecosystems; the ongoing changes in forest succession and buildup of hazardous fuels in most groves cannot be ignored. To do nothing is to assure greater changes away from some of the very conditions that inspired protection of the groves, until such time that severe wildfires preempt options for the future. Protection, restoration, and conservation of giant sequoia ecosystems demand active, science-based management, starting today and continuing indefinitely.

Second, our present knowledge of grove restoration and conservation is imperfect, meaning that grove managers must have the flexibility to change (and must change) their practices as knowledge increases. Rephrased, managers must practice adaptive management. Simply put, adaptive management is the common-sense approach to management, in which managers formalize the process of trying something, seeing what happens, learning from the experience, then trying something new. All too often, however, the cycle is broken at the "seeing what happens" stage; that is, adequate monitoring does not parallel management. If adaptive management (with its indispensable monitoring step) is successfully implemented, specific management prescriptions aimed at grove protection, restoration, and conservation will change as knowledge increases. Within the bounds outlined in this chapter, there is no single clearly correct approach to grove restoration and conservation; rather there is a suite of reasonable and practical approaches. Thus, the different sequoia management agencies are likely to apply a diversity of management approaches.

Corollaries of the preceding two paragraphs are that there will be uncertainties in sequoia management, and that management must move forward in spite of these uncertainties. Additionally, even if there were no uncertainties, attempts to restore groves to pre-Euroamerican conditions will be imperfect due to physical constraints.

Third, the new knowledge needed to guide sequoia management will grow most rapidly if the various land management agencies cooperate in management planning, management actions, and in comparing the consequences of their different management approaches. Coordinated research and monitoring is especially important during these times of shrinking budgets, and would offer indispensable support to the ambitious restoration efforts outlined on previous pages. A step in the right direction has been made with the recent formation of the Giant Sequoia Ecology Cooperative, which includes representatives from the U.S. Forest Service (USFS), National Park Service (NPS), the National Biological Service, California Department of Forestry and Fire Protection, and the University of California. However, it is highly unlikely that the Cooperative will be effective unless new funds become available for coordinated research and monitoring.

Finally, for USFS to meet its new mandate, permanent new base funding must be earmarked for sequoia management, research, and monitoring. It will be expensive to meet the demands of the Mediated Settlement Agreement (MSA) (U.S. Forest Service 1990) and Stewart's (1992) policy directive; this reality cannot be avoided. Private funds in support of management, research, and monitoring can and should be sought, but are not likely to be adequate or provide needed program continuity. Even if public acceptance were to allow the sale of trees removed during grove restoration, such funds might only partly offset costs. And once groves are restored, their maintenance will require committed, active management indefinitely into the future, albeit at a lower level.

Nearly all research and monitoring in support of sequoia management has been funded by NPS or the National Biological Service. These agencies have never had a base-funded sequoia program; funding has been temporary and sporadic, often in response to crises (e.g. see Parsons 1990b). The latest flurry of research and monitoring began in 1987 and is likely to end when funded projects in the National Biological Service's Sierra Nevada Global Change Research Program expire in September of 1996.

## Implementation

The following summary steps can help guide sequoia managers in their efforts to protect, restore, and conserve sequoia ecosystems:

1. Prioritize groves for fire protection and restoration. Sequoia National Forest personnel already are analyzing the data needed to prioritize groves for protection and restoration according to their vulnerability to wildfires. The assessments should consider fuel conditions within groves, fuel conditions adjacent to groves, and historic patterns of ignitions. This information can be translated into probability of groves experiencing damaging wildfire by using available fire behavior and spread models (e.g. Finney 1995). Protection is to a large degree automatically conferred by grove restoration; thus both goals might be met in one step. In fact, it can be reasonably argued that actions toward both goals (protection and restoration) must proceed simultaneously, since fire protection alters forest structure.

2. Define broad goals for restoration and conservation. The interagency Giant Sequoia Ecology Cooperative and interested publics, as required by the National Environmental Policy Act and the MSA (U.S. Forest Service 1990), should be consulted before finalizing broad goals for restoration and conservation. I suggest that a reasonable restoration goal (subject to modification as knowledge increases or policy changes) is to come as close as is practical to restoring grove structure and function to the usual range of conditions that existed during the 1,000 years preceding Euroamerican settlement. The goal as it is stated is meant to allow managers to step back from the unrealistic limitations that would be imposed by trying to replicate conditions calibrated to a specific year or other narrow time period. The term "usual range of conditions" is meant to exclude socially unacceptable extremes that may have occurred during the last 1,000 years, though these extremes may have been important in shaping modern groves. If prescribed fire is chosen as the main tool for maintaining restored groves, a choice consistent with policy must be made between two possible fire regimes: mimic fire regimes from pre-Euroamerican periods with climates similar to today's (which includes both lightning and Native American ignitions), or mimic a lightning-only fire regime.

3. Define targets for individual groves. Ideally, defining targets for restoration of individual groves will be guided by an inventory of past and present ecological conditions in each grove (see the section "Grove Restoration"). However, given the immediate need for grove protection through fuel reduction, two actions should proceed simultaneously: determining targets for restoration for individual groves, and restoration itself, with the former staying at least one step (one grove) ahead of the latter. Inevitably, lack of information, time, or funds will mean that there are uncertainties in defining targets for restoration; however, present conditions in many (if not most) groves are such that it may be worse not to act at all than to go forward armed with limited knowledge. (It is important to emphasize that we do already know much about sequoia grove dynamics—particularly about the conditions needed for sequoia regeneration.) Restoration targets should err on the side of the conservative; once trees are removed, they cannot be put back. Individual grove targets should be developed and reviewed with the aid of knowledgeable sequoia experts, including members of the interagency Giant Sequoia Ecology Cooperative. As before, public participation should be nurtured, as required by the National Environmental Policy Act and the MSA.

4. Choose restoration tool(s) and approach. Once targets are defined, grove restoration can be accomplished using fire, saws, or some combination of the two. Each tool has advantages and disadvantages, as listed in table 55.1. If saws are used, consideration should be given to immediately treating freshly-cut stumps with borax or some other agent to reduce the possibility of annosus root rot establishment. Felled trees would either be burned on-site (with or without being chipped before burning) or removed. If they are

removed, the MSA (U.S. Forest Service 1990) specifies that it should be done with minimal site disturbance, such as by using helicopters or other low-impact means (cut-to-length systems might be a less expensive option on shallower slopes [O'Connor 1991; Hartsough and McNeel 1994]). Regardless of the tool used, restoration will likely proceed in ways unlike standard silvicultural treatments. Restoration targets will be based on ecological principles aimed at re-creating variable pre-Euroamerican conditions, not on commodity values, maximization of site production, or ease of silvicultural treatment. Commodity production, however, could be an incidental byproduct of restoration (see below). Restored groves will include suppressed trees, insects and pathogens, snags, logs, brush patches, small forest gaps of different sizes, and different levels of forest thinning which grade into one another—sometimes gradually, sometimes more abruptly.

If saws are used as the main tool for grove restoration, restoration costs might be partly offset by the incidental sale of the trees removed. Adoption of this choice would likely involve intense public participation, as required by the National Environmental Policy Act and the MSA. With inadequate public participation, some members of the public might suspect that managers are trying to make restoration pay for itself by adding high-valued trees to those being removed; public involvement would likely reduce the potential for misperceptions. Additionally, detailed grove restoration plans should be reviewed by the interagency Giant Sequoia Ecology Cooperative, which includes members from USFS, NPS, the National Biological Service, the California Department of Forestry and Fire Protection, and the University of California. This would be in addition to the public involvement required by the National Environmental Policy Act and the MSA. At their discretion, members of the Cooperative might ask for additional reviews by other sequoia managers and researchers.

5. Implement adaptive management. Adaptive management cannot go forward unless an active research and monitoring program is developed to determine the ecosystem consequences of the different agencies' approaches to sequoia grove management. Ideally, monitoring programs will involve close cooperation among sequoia researchers and managers, coordinated by the interagency Giant Sequoia Ecology Cooperative. The information gained by these efforts would be used to continually assess and refine management approaches.

For the agencies managing giant sequoias, meeting obligations to protect, restore, and conserve sequoia ecosystems will be difficult, time-consuming, and expensive. Grove management cannot go forward piecemeal, drawing only from resources ultimately dedicated to other tasks. Efforts seem sure to fail unless there is strong institutional support at all levels, including programmatic designation and significant permanent base funding. Responsible stewardship therefore demands a deep and continuing commitment from the management agencies.

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## NOTES

1. Willard (1994a) corrects some errors in Rundel's (1972a) grove list, and recognizes 65 groves (lumping several of Rundel's groves).
2. Percentages are derived from the latest estimates of grove areas, as compiled by R. Rogers (USFS), P. Lineback (NPS), J. Manley (NPS), and D. Willard (1994b). The new estimates of grove areas dramatically reverse Hartesveldt's estimates of 21% managed by USFS and 68% managed by NPS (Hartesveldt et al. 1975). Still earlier estimates by the California Department of Natural Resources (1952) had roughly equal areas managed by USFS and NPS (38% and 41%, respectively). It appears that earlier estimates were biased by both underestimated USFS grove acreages and overestimated NPS acreages; however, estimates of total grove area in the Sierra Nevada are virtually unchanged. Though more accurate than earlier estimates, the estimates presented in this chapter may change as information improves.
3. Although the USFS uses preserve, I prefer the term conserve. Conserve implies maintaining dynamic grove ecosystems within a range of desired conditions, whereas to some people preserve implies maintaining groves in an unchanging state—an impossible task.

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Back to CD-ROM Table of Contents