RESTORING NATURAL FIRE TO THE SEQUOIA-MIXED CONIFER FOREST: SHOULD INTENSE FIRE PLAY A ROLE?

Nathan L. Stephenson
David J. Parsons
Thomas W. Swetnam

ABSTRACT

The giant sequoia-mixed conifer forests of the southern Sierra Nevada are commonly described as being subject to frequent, low intensity fires. Management programs designed to maintain these forests are based on this assumption. Questions have recently been raised regarding the possible role of local high intensity fires in this community type. Millennial-length fire chronologies developed from fire scar analysis, records of charcoal deposition from sediment cores, analysis of forest age structure, and observations of modern fire behavior are now being used to reassess conventional wisdom regarding natural fire regimes, including the importance of fire intensity in perpetuating giant sequoia groves. Policy and management implications regarding the restoration of natural ecosystem processes are considered.

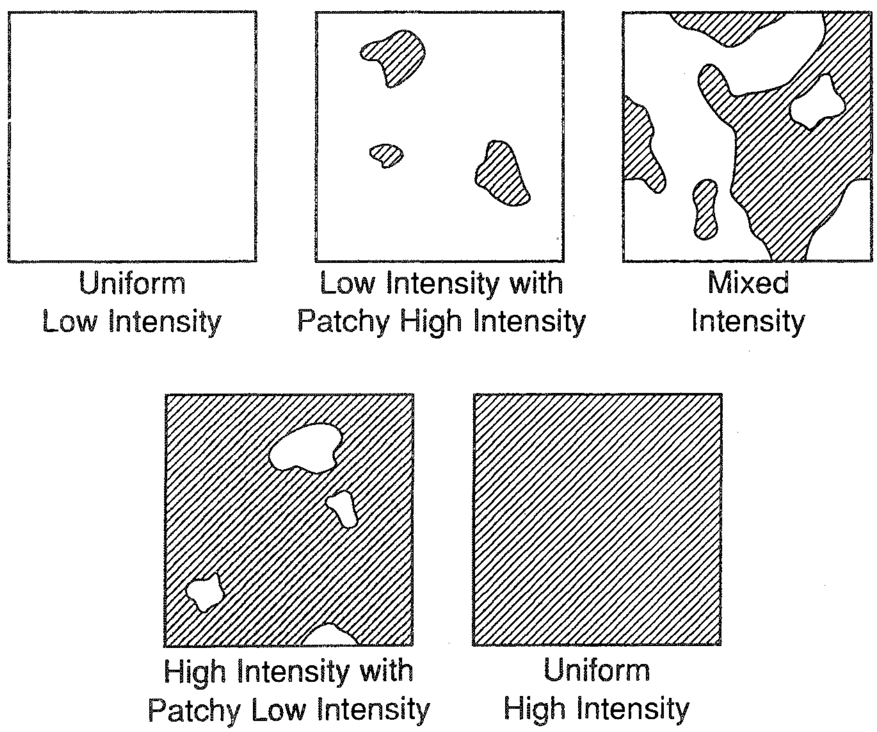
INTRODUCTION

In its charge to preserve examples of natural ecosystems, the National Park Service faces a complex goal. External influences, including air pollution, expanding human populations, and the spread of alien species, together with pressure from visitor use and management actions, are changing our parks into increasingly vulnerable ecological islands. The restoration or maintenance of a semblance of naturally functioning ecosystems has become ever more difficult (Graber 1983, Chase 1987). In the case of many western parks, the reintroduction of natural fire regimes represents the principal effort to restore natural processes to forests and woodlands (Parsons et al. 1986).

In the giant sequoia (*Sequoiadendron giganteum* [Lindl.] Buchh.) dominated forests of Sequoia, Kings Canyon, and Yosemite national parks in the central and southern Sierra Nevada of California, nearly a century of fire suppression has altered forest structure (Parsons and DeBenedetti 1979, Bonnicksen and Stone 1982), fuel and nutrient dynamics (Agee 1968, Parsons 1978), and successional patterns (Hartesveldt and Harvey 1967, Bonnicksen and Stone 1982). Concern over these changes, and recognition of the need to restore fire as an ecological process, was first effectively voiced over a quarter century ago (Leopold et al. 1963). Recent efforts to reverse the effects of fire suppression and eventually to restore fire to a more natural role have received considerable attention (Bonnicksen and Stone 1985, Parsons et al. 1986, Swetnam 1988).

To be effective, a program designed to restore fire as a natural process requires, among other things, an understanding of natural fire regimes (including fire intensity) and their effects on forest structure (Christensen et al. 1987, Parsons in press). To properly characterize a fire regime, it is necessary to document the frequency with which different types of fires recur over time. Previous authors have defined "fire types" strictly in terms of intensity (Heinselman 1985, Kilgore 1987); however, such definitions fail to take into account the patchy nature of fires. To account for such patchiness, we define here five fire types representing points along a continuum of increasing dominance by intense fire (Figure 1): 1) uniform low intensity, in which all or most canopy trees survive; 2) low intensity with patchy high intensity (also called "patchy high intensity" for convenience), in which groups of canopy trees are killed locally within a matrix of surviving trees; 3) mixed intensity,

Figure 1. Fire types used to characterize fire regimes. White represents areas of low intensity fire (all or most canopy trees survive), whereas crosshatching represents areas of high intensity fire (all or most canopy trees are killed). A more complex model would also include patches of intermediate mortality and unburned areas within burned areas.



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

In discussions of fire types, spatial scale must be defined. For example, at a large scale (10,000-100,000 ha) the extensive fires that swept the greater Yellowstone area in the summer of 1988 were probably best characterized as mixed intensity. At a small scale (10-100 ha), however, the fires were best characterized as either uniform low intensity or uniform high intensity. For the remainder of this paper (unless otherwise explicitly stated) spatial scale is assumed to be roughly comparable to the size of individual sequoia groves which range from 1 to 1000 ha but mostly are 10 to 100 ha.

The frequency of different fire types through time characterizes the fire regime. For example, though the most recent presettlement fires in the sequoia-mixed conifer forest of the Sierra Nevada probably were low intensity with patchy high intensity (see "Evidence of Patchy High Intensity Fires" below) occurring at intervals of 3 to 35 years (Kilgore and Taylor 1979), at a longer return interval individual fires may have been mixed intensity or even high intensity with patchy low intensity (see "Tree Rings, Fire Scars, and Growth Releases" below). On a time scale of centuries, the fire regime itself may change in response to climate change, making it difficult to pinpoint one particular fire regime as "natural" for a region (Swetnam, unpublished data). Natural must be defined relative to a particular climate regime or period of time.

In this paper, we briefly review evidence that natural fire regimes of the sequoia-mixed conifer forest included fires of low intensity with patchy high intensity, and perhaps also mixed intensity or predominantly high intensity. We then outline ongoing research (and preliminary findings) designed to better understand fire regimes and their role in shaping forest structure. Finally, we discuss the management implications of high intensity fires in sequoia-mixed conifer forests.

EVIDENCE OF PATCHY HIGH INTENSITY FIRES

Historical Accounts of Fires

Examination of historical accounts of pre- and early post-settlement fires in the sequoia-mixed conifer forest reveals considerable evidence that fires were mostly low intensity with patchy high intensity. John Muir's (1901) detailed observations of an 1875 fire in the sequoia forest between the middle and east forks of the Kaweah River provide a vivid account of patchy fire behavior and effects. A fire that raced up steep chaparral-covered slopes, upon entering a sequoia grove "...became calm...creeping and spreading beneath the trees where the ground was level or sloped gently." In some areas, however, he could see "...big bonfires blazing in perfect storms of energy where heavy branches mixed with small ones lay smashed together in hundred cord piles. . . huge fire-mantled trunks on the hill-slopes glowing like bars of hot iron,. . . [and] young trees. . .vanishing in one flame two or three hundred feet high." It is clear that fuel accumulation and consequent fire behavior, including areas of locally intense fire, were patchy. Since Muir's observations occurred at a time when visitors to the area were still infrequent, Bonnicksen (1975) concluded that the observed fuel accumulations "were probably not unlike those which existed in the primeval sequoia groves under a periodic fire regime." Bonnicksen further concluded that "most fires in these forests. . .were of variable intensity. . .with occasional bursts of energy that destroyed 200 year old giant sequoia and other similar size trees." If anything, the observed 1875 fire behavior may have been less intense than typical presettlement fires in that a decade of heavy use by cattle and sheep (Vankat and Major 1978) had likely thinned the understory and compacted ground fuels (Dudley 1896).

Other early observers, noting the numerous burned out cavities in large old sequoias, speculated that locally intense fires created the extensive basal fire scars and those extending high on the trunk (Sudworth 1900, Fry and White 1930). Reynolds (1959) quotes Kotok (1933) regarding fire history in adjacent pine forests as being "a succession of fires, some light in intensity doing minor damage and others less frequent but more devastating."

Other early observers recognized the importance of variable intensity fire in developing spatial patterning of vegetation within primeval sequoia forests. Muir (1901) referred to fire as ". . .the master. . .controller of the distribution of trees." Fry and White (1930) recounted a 1905 lightning fire in the Garfield Grove of Sequoia National Park that burned about one hectare in dense forest of old and young sequoia, fir, and pine. Every tree was destroyed except eight of the largest sequoias. Show and Kotok (1924) described the primeval pine and mixed conifer forest of the Sierra Nevada as "uneven-aged, or at least even-aged by small groups. . .patchy and broken." They further commented that "local crown fires may extend over a few hundred acres, but the stands in general are so uneven-aged and broken and have such a varied cover type that a continuous crown fire is practically impossible." Although many such accounts appear in the context of descriptions of open, park-like forests maintained by frequent, low intensity fires, ample evidence can be found that historic fires included patches burned by high intensity fire. This patchiness both resulted from and helped to maintain a mosaic of vegetation and fuels.

Observations of Modern Fires

Though average fuel loads today may be greater than in presettlement times due to decades of fire suppression, observations of modern fire behavior can complement historical accounts, thereby adding to our understanding of the nature of variable fire intensity. Prescribed burns that were intended to be low intensity fires to remove surface fuels and to thin understory trees have, on occasion, burned with local high intensity. For example in 1977, after two years of extreme drought in the southern Sierra Nevada, a prescribed fire in the Redwood Mountain Grove of Kings Canyon National Park burned hot enough in a 4-ha patch of particularly heavy fuel accumulation to kill all trees except large giant sequoias. Even sequoias over 2 m in diameter suffered foliage kill up to 40 m or more. The monarch sequoias in this hot spot today show vigorous post-fire ring growth (L. Mutch, pers. comm.) while an even-aged cohort of young sequoias carpets the understory (Figure 2). Smaller local hot spots (a few tenths of a hectare or less) have been observed on other prescribed burns.

Another example, perhaps of an extreme of fire behavior in sequoia groves, was the 1987 Pierce wildfire which burned with mixed to predominantly high intensity through a 20-ha section of Redwood Mountain Grove that had not burned for at least a century. Mortality was high in all canopy trees except the largest sequoias. Foliage scorch occurred well into the canopy of even the largest sequoias, and 24 of 148 sequoias over 2 m in diameter were scorched to the crown. One year after the fire, 14 of these sequoias appeared to be dead. Interestingly, the wildfire fell to lower intensity when it swept into an adjacent area that had been prescribed burned 10 years earlier. In 1886, a locally intense fire in the Burnt Grove portion of Redwood Mountain Grove apparently killed most trees, including several large giant sequoias, over several hectares. If these examples reflect natural fire behavior in areas of heavy fuel accumulation during presettlement times, then large giant sequoias sometimes may have been the sole survivors of locally intense fires, and perhaps occasionally even they were killed.

Figure 2. A portion of a 4-ha sequoia-mixed conifer stand that burned intensely in 1977 (photo taken in 1987). Notice the large giant sequoia that survived the fire, and the dense carpet of vigorous young sequoias that became established following the fire. In some areas, the young sequoias are now as tall as a person.

Sequoia Seedling Establishment and Forest Structure

Knowledge of the factors controlling sequoia seedling establishment coupled with knowledge of modern forest structure can supply further evidence of patchiness in natural fire regimes. In the sequoia-mixed conifer forest, virtually all giant sequoia seedling establishment is limited to burned areas. Seedlings grow best where fires burned hottest; more seeds fall from the serotinous cones, the resulting seedlings grow faster, and a greater proportion of them survive (Harvey et al. 1980). Perhaps the most important reason for increased seedling growth and survival after hot burns is increased sunlight availability due to canopy thinning (Harvey et al. 1980, see also Stark 1968). Patchiness in fire intensity, therefore, leads to patchiness in sequoia regeneration. Indeed, the largest cohort of healthy young sequoias presently to be found in Sequoia and Kings Canyon national parks covers 4 ha that burned intensely, killing all trees except large sequoias, in a prescribed burn in 1977 (see "Observations of Modern Fires" above).

Clumps of mature, apparently even-aged sequoias are common in sequoia groves. Huntington (1914), having counted the annual rings of 470 sequoia stumps, noted that "it is the habit of the sequoia to grow in groups, oftentimes half a dozen trees of the same age forming a circle. Frequently a tract of many acres is covered with trees of practically the same age." In Sequoia National Park, some clumps of large sequoias (such as the Parker Group, Senate Group, House Group, and Founders Group) are well known tourist attractions, usually covering 0.1 to 0.2 ha and consisting of some 5 to 20 huge sequoias of similar size and presumably similar age. Some unnamed and lesser known clumps consist of over 50 trees covering more than 0.5 ha. Bonnicksen and Stone (1981) demonstrated that, in addition to giant sequoia, the other common tree species of the sequoia-mixed conifer zone can be found in groups of trees of similar size and presumably of similar age. These tree aggregations, as defined by Bonnicksen and Stone's particular methods, usually covered from 0.01 to 0.16 ha. Taken together with our knowledge of sequoia seedling establishment, these observations of forest structure suggest that at least some natural fires burned hot enough to create local canopy gaps that subsequently set the stage for the abundant and successful recruitment of groups of new sequoias.

Unanswered Questions

Historical accounts of fires, observations of modern fires, observations of sequoia seedling establishment, and analysis of modern forest structure all provide evidence consistent with the view that 1) the natural fire regimes of the sequoia-mixed conifer forest included fires of low intensity with patchy high intensity and 2) high intensity fire was an important determiner of forest structure. However, several questions remain unanswered. What proportion of the groups of apparently even-aged sequoias really are even-aged? Are these groups exclusively the products of local high intensity fires, or are they also the products of low intensity fires? Does the giant sequoia depend on locally intense fire to maintain abundance in the community? Were natural fire regimes also characterized by occasional mixed intensity or predominantly high intensity fires? These questions are presently being addressed by the fire research programs at Sequoia, Kings Canyon, and Yosemite national parks.

ONGOING RESEARCH

An integrated, multidisciplinary research program is evaluating a number of issues that have been raised regarding the role of fire and the effects of variable fire frequency and intensity in the sequoia-mixed conifer forest of the Sierran parks (Christensen et al. 1987, Parsons in press). Several of these studies will provide insight into natural fire regimes and their effects on forest structure.

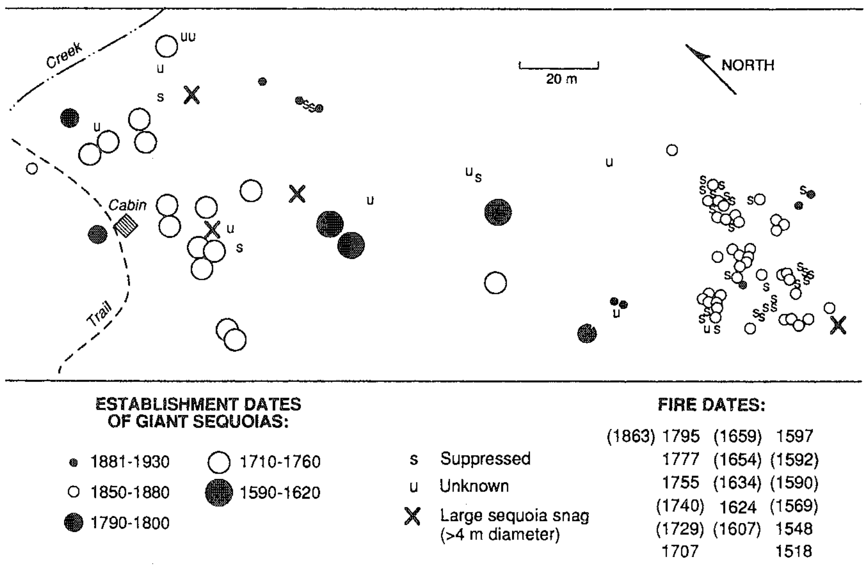
Forest Age Structure

To further elucidate natural fire regimes and their effects on the sequoia-mixed conifer forest, forest age structure is being compared with known fire histories in several sequoia groves. In areas for which millennial fire chronologies are being developed from tree-ring crossdating of fire scars (see Swetnam and Baisan 1988), all living sequoias in stands ranging from about 3 to 16 ha are being mapped and cored for age determination. Other more abundant tree species are being mapped and cored in subplots within the main stands.

Preliminary results are available from a 2-ha portion of the Cattle Cabin stand in Giant Forest, Sequoia National Park, where all 109 living sequoias less than 140 cm dbh have been cored to determine establishment dates. No establishment dates have yet been determined for the 22 living sequoias greater than 140 cm dbh, nor were establishment dates determined for 10 sequoias in which rot was encountered while coring, or for some other reason the annual rings could not be counted. In addition, 30 sequoias with average ring widths of 0.6 mm or less were considered to be suppressed and were not used in analyses of age structure; examination of full cross sections of dead sequoias with such narrow rings showed that many rings were locally absent, meaning that age estimates based on core counts could underestimate actual age.

Most of the sequoias in the stand belonged to one of two obvious groups of approximately even-aged trees, one of which became established in the early 1700s, the other of which became established in the late 1800s (Figure 3). Of the unsuppressed sequoias in the youngest clump, the majority (28 of 39 trees) had estimated establishment dates between 1862 and 1868. There is probably some error in these dates, mostly due to error in estimating the number of

Figure 3. Estimated establishment dates of giant sequoias less than 140 cm dbh in the Cattle Cabin stand, Sequoia National Park. Most sequoias belong to two clumps—one that became established in the late 1800s, probably in response to the fire of 1863, and one that became established in the early 1700s, probably in response to the fires of 1707, 1729, 1740, and 1755. Fire dates without parentheses indicate that distinct fire scars for that date were found on two or more trees on opposite sides of the stand. Fire dates with parentheses indicate that distinct fire scars for that date were found on one or more trees only on one side of the stand, hence it is less certain that the fire actually burned through the stand.



rings missed when a particular core did not strike the tree's pith, or error in estimating the number of years it took a particular tree to grow to the height cored. When only those trees with the most accurate age estimates (the pith was hit within 20 cm of ground level) were considered, 13 of 15 trees were estimated to have become established from 1864 to 1867.

During the 1800s, the only fire to burn in the immediate vicinity occurred in 1863. The estimated dates of establishment for the sequoias in the youngest group strongly suggests—within the range of error inherent in estimating ages by ring counts—that the sequoias germinated soon after this fire.

All 14 trees in the older group became established between 1710 and 1760. In contrast to the 1800s, the early 1700s was a time of frequent fires; fires burned in the vicinity in 1707, 1729, 1740, and 1755. It appears that sequoia establishment in the older group is attributable to several (if not each) of these fires.

Eight small sequoias became established in the stand between about 1882 and 1924—a period for which there is no evidence of fires. However, from the 1870s to the 1920s, the Cattle Cabin area was used regularly for livestock grazing (Wm. Tweed, pers. comm.). It is possible that disturbances caused by the animals and their caretakers exposed mineral soil on which these young sequoias could become established in the absence of fire.

Can the two main patches of sequoia recruitment be attributed to locally intense fires? We will take two approaches to answer this question. First, we will determine the ages of all other living trees (besides sequoias) in subplots centered in the sequoia clumps. If all other trees show establishment dates equal to or more recent than the establishment of the sequoias, it will be taken as evidence that the fire was locally intense enough to create a canopy gap. Second, we will attempt to determine the year of death of large sequoia snags found near the clumps. It is relatively common in sequoia groves to find one or two large, charred sequoia snags near or surrounded by what appears to be even-aged sequoia reproduction; this is also the case for the Cattle Cabin stand (Figure 3). Did the large trees that became these snags die in a locally intense fire that led to the sequoia recruitment we observe today? We will investigate this possibility by using tree-ring crossdating to determine the years of death of the snags, then compare this with the years of establishment of the younger sequoias. If these dates match, and also correspond to the year of a fire in the local fire scar record, it will strongly suggest that a locally intense fire was responsible.

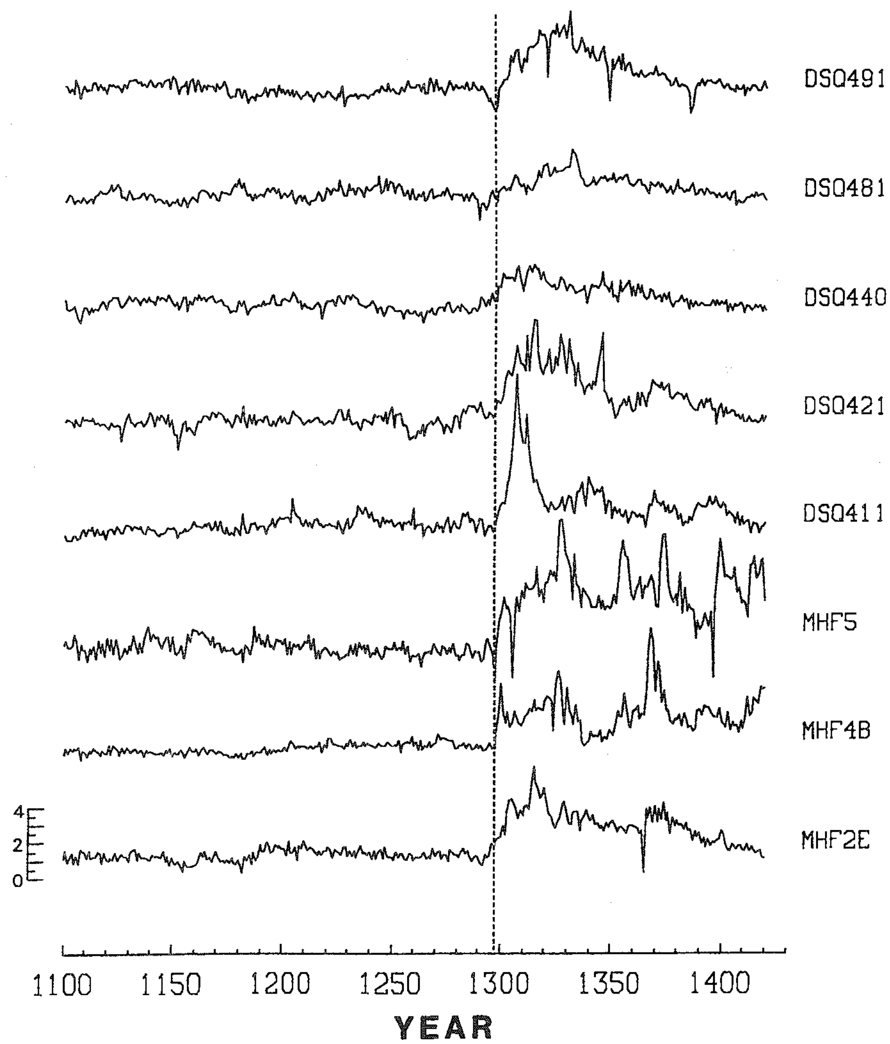
Tree Rings, Fire Scars, and Growth Releases

Tree ring analysis and fire scar dating of partial cross sections from sequoia stumps and logs suggest that mixed intensity or possibly even predominantly high intensity fires may also have occurred in sequoia-mixed conifer forests. Of five fire-scarred trees analyzed in the Mountain Home Grove (30 km south of Sequoia National Park), four contained a fire scar in the year AD 1297 (Swetnam and Baisan 1988). Two lines of evidence lead us to believe this 1297 fire was more intense than other fires in sequoia groves 1) the fire was followed by a dramatic growth release in the surviving sequoias over a broad area, and 2) the fire was followed by pronounced new sequoia recruitment.

Of the five fire-scarred trees, all showed a dramatic growth increase after the 1297 fire (Figure 4). The post-1297 growth release is so obvious and distinctive that we were able to visually identify it on the tops of numerous other stumps in the grove, in areas over 3 km apart. Additionally, among 16 sequoia stumps that A. E. Douglass (1971) measured and dated in the Mountain Home Grove, eight of the nine trees that established before 1200 exhibited a growth release following 1297.

Before 1297, the growth of some sequoias was very low with little year-to-year variation (see Figure 4, MHF 4B), suggesting a relatively closed-canopy forest in which growth may have been limited by competition for nutrients, light, or water. However, it seems unlikely that the growth release following 1297 could be attributed to a fire-induced increase in soil nutrients alone; soil nutrients increase after all fires, but not all fires result in very large and

Figure 4. Ring-width series of the 1100 AD to 1420 AD portions of eight Mountain Home sequoias. The scale on the lower left is millimeters. The vertical dotted line shows the timing of the 1297 fire. Most of these trees and others from Mountain Home show a strong growth release immediately following the 1297 fire. Another release is evident in some trees following a fire in 1365. The MHF specimens were fire-scarred stumps sampled in the summer of 1987 and the DSQ specimens were sampled by A. E. Douglass in 1925.



sustained growth releases. Instead, we hypothesize that the 1297 fire was hot enough to kill competing trees over a relatively large area, resulting in a substantial increase in light and water availability which in turn resulted in a widespread growth release in the surviving sequoias. We hope to confirm this hypothesis by looking for equivalent growth releases in sequoias that have survived recent high intensity fires or logging.

Of the seven remaining trees that Douglass sampled, six apparently germinated within about a 20-year period following 1297; pith dates of these trees ranged from 1300 to 1327. Given that the pith dates came from cut surfaces one to two meters above ground level, and given that it probably took the trees several years to reach that height, it is likely that germination followed the 1297 fire very closely. We take this as further evidence that the 1297 fire significantly thinned the forest canopy.

Although it seems very likely that the 1297 fire in the Mountain Home Grove was responsible for the immediate and abrupt growth release, details of the mechanism involved are as yet uncertain. The frequency of this type of fire in sequoia groves is also unknown. Additional fire scar samples, more extensive observations of the spatial distribution of the growth release following 1297, and more detailed study of the age structure of living and dead sequoias on the site should provide a clearer picture of these events and their significance. Fire-scar chronologies exceeding 2,000 years in length are currently being developed for the Mountain Home Grove and several other giant sequoia groves. These chronologies should reveal whether fires of the magnitude of the 1297 fire occurred in other groves, or whether such a fire was unique to the Mountain Home Grove.

Paleoecology

Ongoing studies of the biogeography and disturbance history of giant sequoia forests, including analysis of pollen and plant macrofossils in meadow sediments, are designed to trace the relative importance of giant sequoia and associated species throughout the Holocene (about 11,000 years before present to present). This research, under the leadership of R. Scott Anderson of Northern Arizona University, is also investigating the relative abundance of charcoal in different layers of meadow sediments. Preliminary findings indicate that fire has been a factor in sequoia forests for at least the past 10,000 years. Measures of charcoal abundance in several groves indicate a highly variable deposition rate, including generally higher abundances from about 10,000 to 3,000 years ago. Assuming that charcoal abundance is related in some way to fire importance, it appears that the occurrence of fire has been variable throughout the Holocene (R. S. Anderson, pers. comm.). This temporal variability in charcoal abundance supports previous findings for conifer forests in the southern Sierra Nevada (Davis et al. 1985). Continuing studies are planned to improve the temporal precision of the charcoal record through thin layer sampling of sediment cores from sites near areas where fire chronologies are developed from fire scars.

MANAGEMENT IMPLICATIONS

Fire management programs in the national parks of the Sierra Nevada are designed to mitigate the effects of nearly a century of fire suppression by reducing accumulated fuels followed by restoration of fire as a natural process (Bancroft et al. 1985). The restoration of completely natural fire regimes is a long-term goal that may never be fully accomplished. Yet, both in planning program objectives and in developing prescriptions for individual burns, managers are faced with a need to understand the natural fire regime, including fire size, frequencies, and the relative proportions of different fire types through time.

Although the total area of sequoia-mixed conifer forest that has been prescribed burned to date is relatively small, concern has been expressed over both biological and visual effects of the program. Uncertainty over the magnitude of change in forest structure and fuel accumulation that has occurred as a result of fire suppression has raised questions regarding the effects of prescribed burning under "unnatural" conditions (Bonnickson and Stone 1985). For example, do unnaturally heavy fuel accumulations result in unnaturally hot prescribed burns, which in turn result in unnaturally high root and tree death? The effects of prescribed, as opposed to historic natural fires, on pathogens and nutrients are also largely unknown. Concerns over visual impacts of prescribed burning have focused on bark char, foliage scorch, and fire scar enlargement. These concerns raise questions regarding the relative importance of visitor expectations of a visually pleasing scene as opposed to policy directives to maintain natural landscapes and processes (Cotton and McBride 1987).

To date, both the biological and aesthetic concerns that have been raised have focused on a few localized areas that burned at relatively high intensity. In 1986, such concerns led the National Park Service to appoint an independent panel of outside experts to review the prescribed fire program in sequoia-mixed conifer forests. The panel's charge included evaluating the status and scientific basis for the burn program, including the impacts of prescribed as opposed to natural fire on sequoias. While generally supporting the program objectives, the panel focused attention on the need to better understand natural fire regimes, including effects of fires of variable frequency and intensity on the forest (Christensen et al. 1987). In response to panel recommendations, a comprehensive research program was undertaken to address many of these questions (Parsons 1990). The results are expected to provide an improved basis for making management decisions.

The available data suggest that high intensity fire, whether patchy or more widespread, played a role in presettlement sequoia-mixed conifer forests. Ongoing research should help determine the prevalence of high intensity fires and their importance in shaping the forest. Depending on the ultimate research findings, managers will need to confront a new series of questions. For example, if the generation of magnificent groups of monarch giant sequoias requires fires hot enough to open the canopy, park managers will have to consider explicitly incorporating local high intensity fire into the management program; it is already incorporated to the minor extent that sometimes small high intensity fires occur in otherwise low intensity prescribed burns. But how much high intensity fire can we live with? Even if the conditions existed for a mixed intensity or predominantly high intensity fire to burn naturally (such as the fire inferred to have burned naturally in the Mountain Home grove in 1297), and assuming it were in our power to prevent such a fire, should we prevent it? In this case, pressures to save the big trees as individual objects would likely overcome those voices calling for the preservation of natural processes. Such a potential scenario mandates the development of explicit decision-making criteria for managers. It is critical that such scenarios be anticipated and criteria developed before managers are caught off guard.

SUMMARY AND CONCLUSIONS

Current fire management programs in the sequoia-mixed conifer forest are primarily aimed at restoring more natural fuel conditions, thus setting the stage for permitting natural ignitions to burn or for using prescribed burns to simulate natural fires (Christensen et al. 1987). In order to wisely manage natural ignitions and simulated natural fires, managers must understand natural fire regimes, including the role of intense fire. Ongoing studies of forest structure, fire history, and vegetation history will improve our understanding of fire regimes and how they shape forests.

Presettlement fire regimes of the sequoia-mixed conifer forest often have been characterized as sequences of frequent low intensity fires (Hartesveldt 1964, van Wagtendonk 1985, Kilgore 1987). The evidence presently available suggests that patchy intense fires (and perhaps predominantly intense fires) existed in presettlement times, and that these fires may have been important determiners of forest structure and composition. Thus, in more detailed descriptions of fire regimes, natural fires may be best characterized as having been patches of high intensity fire within a matrix of low intensity fire, with the frequency and relative area covered by intense fires varying over time. Rather than treating forests and the fires that burn them as homogeneous units, this view emphasizes patch dynamics (see Bonnicksen and Stone 1982, Pickett and White 1985).

Future fire management planning will need to explicitly address intense fire. If occasional intense fires are found to be critical to the maintenance of a healthy sequoia forest, managers will be forced to consider trade-offs between preserving natural ecosystems and providing for visitor safety and visitor expectations of unblemished scenes.

ACKNOWLEDGEMENTS

Thanks go to Diane Ewell, Todd Bohle, Lisa Park, and Carl Roland for collecting, counting, and interpreting increment cores from giant sequoias; to Chris Baisan, Tony Caprio, and Peter Brown for collecting and interpreting fire scar material and commenting on early drafts of the manuscript; and to Patti Haggerty for supplying unpublished data on the effects of the Pierce wildfire. B. Kilgore, T. Nichols, J. Van Wagtendonk, S. Veirs, and an anonymous reviewer provided valuable comments on an earlier draft of the manuscript.

LITERATURE CITED

Agee, J. K. 1968. Fuel conditions in a giant sequoia grove and surrounding plant communities. Master's thesis. University of California, Berkeley.

Bancroft, L., T. Nichols, D. Parsons, D. Graber, B. Evison, and J. van Wagtendonk. 1985. Evolution of the natural fire management program at Sequoia and Kings Canyon National Parks. Pages 174-180 *in* Proceedings of the Symposium and Workshop on Wilderness Fire. USDA General Technical Report INT-182.

Bonnicksen, M. 1975. Spatial patterns and succession within a mixed conifer-giant sequoia forest ecosystem. Master's thesis. University of California, Berkeley.

Bonnicksen, T. M. and E. C. Stone. 1981. The giant sequoia-mixed conifer forest community characterized through pattern analysis as a mosaic of aggregations. Forest Ecology and Management 3:307-328.

Bonnicksen, T. M. and E. C. Stone. 1982. Reconstruction of a presettlement giant sequoia-mixed conifer forest community using the aggregation approach. Ecology 63:1134-1148.

Bonnicksen, T. M. and E. C. Stone. 1985. Restoring naturalness to national parks. Environmental Management 9:479-486.

Chase, A. 1987. How to save our national parks. The Atlantic Monthly July(1987):35-44.

Christensen, N., L. Cotton, T. Harvey, R. Martin, J. McBride, P. Rundel, and R. Wakimoto. 1987. Review of fire management program for sequoia-mixed conifer forests of Yosemite, Sequoia and Kings Canyon national parks. Unpublished report to National Park Service, San Francisco.

Cotton, L. and J. R. McBride. 1987. Visual impacts of prescribed burning on mixed conifer and giant sequoia forest. Pages 32-37 *in* Proceedings of the Symposium on Wildland Fire 2000. USDA Forest Service General Technical Report PSW-101.

Davis, O. K., R. S. Anderson, P. L. Fall, M. K. O'Rourke, and R. S. Thompson. 1985. Palynological evidence for early holocene aridity in the southern Sierra Nevada, California. Quaternary Research 24:322-332.

Douglass, A. E. 1971. Climatic cycles and tree growth. Reprint of 1919, 1928, and 1936 editions of Vols. I, II, and III, respectively, Carnegie Institute of Washington Publication No. 298. Cramer and Swan, New York.

Dudley, W. R. 1896. Forest reservations: with a report on the Sierra Forest Reservation, California. Sierra Club Bulletin 1:254-267.

Fry, W. and R. White. 1930. Big trees. Stanford University Press, Stanford, California.

Graber, D. M. 1983. Rationalizing management of natural areas in national parks. The George Wright Forum 3(4):48-56.

Hartesveldt, R. J. 1964. Fire ecology of the giant sequoias. Natural History 73:12-19.

Hartesveldt, R. J. and H. T. Harvey. 1967. The fire ecology of sequoia regeneration. Pages 65-77 *in* Proceedings Seventh Annual Tall Timbers Fire Ecology Conference. Tall Timbers Research Station, Tallahassee, Florida.

Harvey, H. T., H. S. Shellhammer and R. E. Stecker. 1980. Giant sequoia ecology: Fire and reproduction. Scientific Monograph Series No. 12, National Park Service, Washington, D.C.

Heinselman, M. L. 1985. Fire regimes and management options in ecosystems with large high intensity fires. Pages 101-109 *in* J. E. Lotan, B. M. Kilgore, W. C. Fischer, and R. W. Mutch, tech. coords. Proceedings-Symposium and Workshop on Wilderness Fire. USDA Forest Service General Technical Report INT-182.

Huntington, E. 1914. The climatic factor as illustrated in arid America. The Carnegie Institute of Washington, Publication No. 192, Washington, D.C.

Kilgore, B. M. 1987. The role of fire in wilderness: A state-of-knowledge review. Pages 70-103 *in* R. C. Lucas, compiler. Proceedings—National Wilderness Research Conference: Issues, State-of-Knowledge, Future Directions. USDA Forest Service General Technical Report INT-220.

Kilgore, B. M. and D. Taylor. 1979. Fire history of a sequoia-mixed conifer forest. Ecology 60:129-142.

Kotok, E. I. 1933. Fire as a major ecological factor in the pine region of California. Proceedings of the Fifth Pacific Service Congress, Canada 5:4017-4022.

Leopold, A. S., S. A. Cain, C. M. Cottam, I. N. Gabrielson, and T. L. Kimball. 1963. Wildlife management in the national parks. American Forests 69:32-35, 61-63.

Muir, J. 1901. Our national parks. Houghton, Mifflin and Co., Boston.

Parsons, D. J. 1978. Fire and fuel accumulation in a giant sequoia forest. Journal of Forestry 76:104-105.

Parsons, D. J. 1990. The giant sequoia fire controversy: the role of science in natural ecosystem management. Pages 257-268 *in* Proceedings Third Biennial Conference on Research in California's National Parks. USDI National Park Service Transactions and Proceedings Series No. 8. Washington D. C.

Parsons, D. J. In press. Restoring fire to the Sierra Nevada mixed conifer forest: Reconciling science, policy and practicality. *In* Proceedings, First Annual Meeting of the Society for Ecological Restoration and Management.

Parsons, D. J. and S. H. DeBenedetti. 1979. Impact of fire suppression on a mixed-conifer forest. Forest Ecology and Management 2:21-33.

Parsons, D. J., D. M. Graber, J. K. Agee, and J. W. van Wagtendonk. 1986. Natural fire management in national parks. Environmental Management 10:21-24.

Pickett, S. T. A. and P. S. White. 1985. The ecology of natural disturbance and patch dynamics. Academic Press, New York.

Reynolds, R. D. 1959. Effect of natural fires and aboriginal burning upon the forest of the central Sierra Nevada. Master's thesis. University of California, Berkeley.

Show, S. B. and E. I. Kotok. 1924. The role of fire in California pine forests. U.S. Department Agriculture Bulletin 1294.

Stark, N. 1968. The environmental tolerance of the seedling stage of Sequoiadendron giganteum. American Midland Naturalist 80:84-95.

Sudworth, G. B. 1900. Notes on big tree groves. USDA Forest Service, California Forest and Range Experiment Station, Berkeley, California. U.S. Senate Document No. 393.

Swetnam, T. W. 1988. Forest fire primeval. The World and I. Sept.(1988):236-241.

Swetnam, T. W., and C. H. Baisan. 1988. Giant sequoia fire history: A feasibility study. Final contract report to Sequoia and Kings Canyon national parks, Cooperative Agreement No. CA-8000-1-0002.

Vankat, J. L. and J. Major. 1978. Vegetation changes in Sequoia National Park, California. Journal of Biogeography 5:377-402.

van Wagtendonk, J. W. 1985. Fire suppression effects on fuels and succession in short-fire-interval wilderness ecosystems. Pages 119-126 *in* Proceedings of the Symposium and Workshop on Wilderness Fire. USDA Forest Service General Technical Report INT-182.