Effects of Fire Severity and Climate on Ring-Width Growth of Giant Sequoia After Fire

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Although fire has been recognized for several decades as a significant ecological force in giant sequoia (*Sequoiadendron giganteum*)-mixed conifer forests (Hartesveldt 1964, Biswell 1967, Hartesveldt and Harvey 1967, Kilgore and Biswell 1971, Kilgore 1973, Harvey and others 1980), little is known about the growth response of giant sequoia to different types of fire and post-fire climate conditions. As early as 1964, Hartesveldt observed that after two fires (1862 and 1889) in the Mariposa Grove in Yosemite National Park, "...more than one-half of the cored trees showed an increase in the middle of the 1860's, and several showed an increase immediately after the fire of 1889." He attributed this increased ring growth to temporary reduced competition from associated trees that were damaged or killed by the fires, resulting in improved soil moisture conditions for the more fire-resistant sequoias. Harvey and his colleagues (1980) also observed that radial growth increased in some giant sequoias following fire and other manipulation of understory vegetation. Growth releases frequently followed fire scars on the sequoia cross-sections analyzed for a reconstruction of giant sequoia fire regimes (Swetnam and others 1992). The most striking example was a tremendous growth increase in many sequoias following an A.D. 1297 fire in Mountain Home State Forest. This release was probably the result of a high intensity fire that killed many competing trees and increased nutrient, water and light availability for the survivors (Stephenson and others 1991, Swetnam and others 1992).

A goal of this study was to determine if fire severity could be quantified in terms of post-fire sequoia tree-ring widths. Quantification of fire severity by the magnitude and duration of post-fire sequoia growth increases may provide an objective basis for estimating past fire severities from observations of sequoia cross-sections collected for developing fire history chronologies. In addition to examining effects of fire severity on sequoia radial growth response, we examined some general relationships between climate, fire, and post-fire sequoia growth. We analyzed the effect of severe foliage damage on post-fire growth in the Partin Burn. For all burns and control sites, we also made categorical observations of sequoia seedling establishment around each adult sampled to investigate the effects of fire severity and post-fire climate conditions on seedling establishment and success.

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SITE DESCRIPTION

The study sites are located in the Giant Forest of Sequoia National Park, and Redwood Mountain Grove and Grant Grove of Kings Canyon National Park, California. Elevations of these groves range from 1,650 to 2,100 m. In addition to giant sequoia, dominant trees are primarily white fir (*Abies concolor*) red fir (*Abies magnifica*), sugar pine (*Pinus lambertiana*), ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*) and incense cedar (*Calocedrus decurrens*).

Mean annual precipitation is 108.2 cm at Giant Forest and 105.8 cm at Grant Grove. Most precipitation occurs in the form of snow during the four winter months from December through March. Summers are relatively dry, with about 30 cm of rainfall occurring in June through September.

The study included seven burn sites and four control sites. The burns were all prescribed burns conducted by the National Park Service. The dates of burns in Giant Forest were 1979 (Moro Burn), 1981 (Circle Burn), 1982 (Cattle Burn), 1984 (Class Burn), and 1985 (Broken Arrow Burn). The Partin Burn in the Redwood Mountain Grove occurred in 1977, and the Grant Burn in 1980. The control sites had not burned for at least 50 years and had characteristics as similar as possible to burn sites.

METHODS

Field Methods

A minimum of 50 large sequoias (>250 cm basal diameter) were randomly selected for sampling on each burn and control site (except where burns were small and contained less than 50 large sequoias). Two increment cores were taken in 1991 or 1992 from each tree. Cores were taken from opposite sides of the tree and as far away as possible from fire scars.

Observable fire-related impacts to surrounding trees were used to estimate fire severity. All non-sequoia trees within a radius equal to twice the area of the subject tree canopy were considered. We selected one of the following categories to describe these impacts:

0) No evident fire.
1) Light surface fire; no evidence of trees killed.
2) Light to moderate severity; some seedlings and/or saplings killed; charring on bark of living trees.
3) Moderate severity; most small trees and <50% of subcanopy trees killed; charring on bark of living trees.

4) High severity; >50% of the subcanopy trees killed or damaged; high charring and some crown damage on canopy trees, but <50% killed.
5) Very high severity; most subcanopy trees killed and >50% of canopy trees killed.
6) Fire too old and little evidence of fire impact remains.

In the same area around each subject tree, sequoia seedling establishment was categorized as:

0) No seedlings.
1) Scattered or few seedlings.
2) Pockets of seedlings.
3) Continuous, dense seedling growth.

We measured basal area scarred, estimated scar height and height of bark charring, and estimated percent new scarring. We also observed crown condition of each tree and measured the slope and aspect.

Lab Methods

Cores were surfaced and crossdated according to standard techniques (Douglass 1941, Stokes and Smiley 1968, Swetnam and others 1985). All the cores were measured for the period 1920-1990. The program COFECHA (Holmes 1983) was used to check the tree-ring dating and measurements for each site. The ring-width series were then standardized using a new program written by Richard Holmes called EXTRAP (Holmes 1993) which allows the user to choose a pre-disturbance period used for fitting an expected growth curve. We used the period 1920-1970 as the curve-fitting period for all sites. The EXTRAP program fit a negative exponential or a trend line to each series, whichever best fit the actual individual series' growth trend. It then extrapolated the curve into the post-disturbance (1971-90) period. Each measured series ring-width value was then divided by the expected growth value to produce a set of indices. We averaged these core indices into tree indices and the tree indices into a site chronology for each site. Standardization removed growth trend due to changing age and geometry of the trees and also scaled all the series to mean values of 1.00 so that trees with larger rings did not dominate over slow-growing trees with smaller rings in the analyses (Fritts 1976).

ANALYSES AND RESULTS

Burn and Control Site Comparisons

We conducted T-tests between each burn and its respective control site to determine if mean growth was significantly different for either the pre- or post-burn periods. For each burn, we used the total number of years in the post-burn period to determine the length of the tested pre- and post-burn periods. The number of years analyzed for each period ranges from five years in the 1985 Broken Arrow Burn to 13 years in the 1977 Partin Burn. Tree-ring time series are autocorrelated (Fritts 1976). Hence, individual years cannot be treated as completely independent observations, a key assumption of the T-Test. We found significant autocorrelation in a few of the time periods analyzed. To account for autocorrelation, we reduced the effective sample size (by reducing the degrees of freedom) when determining probability levels. Mean growth was not significantly different in the pre-burn periods between burn and control sites (Table 1). In the post-burn period, mean growth was significantly higher in burn sites than control sites for five out of seven burns. The two exceptions-- the Cattle and Grant burns-- were low to moderate severity fires that did not result in large post-fire increases.

Examination of the ring-width indices reveals the different growth responses between burns and between the burn and control sites (Figure 1). It is evident that a growth increase

Table 1—T-test results for differences in pre- and post-burn mean growth between burn and control sites. Asterisks indicate significantly different means within each comparison ($P<0.05$). Giant Forest is abbreviated by GF; Redwood Mountain is abbreviated by RW.

Site	Sample (# years)	Pre-burn mean growth	Post-burn mean growth
Moro Burn	11	1.05	1.51
GF Control	11	1.07	1.32
Circle Burn	9	1.04	1.67*
GF Control	9	1.05	1.37*
Cattle Burn	7	0.93	1.39
GF Control	7	1.02	1.39
Class Burn	6	1.30	2.06*
GF Control	6	1.12	1.41*
Broken Arrow	5	1.32	1.85*
GF Control	5	1.22	1.40*
Partin Burn	13	1.15	1.90*
RW Control	13	1.16	1.28*
Grant Burn	10	1.08	1.54
Grant Control	10	1.15	1.42

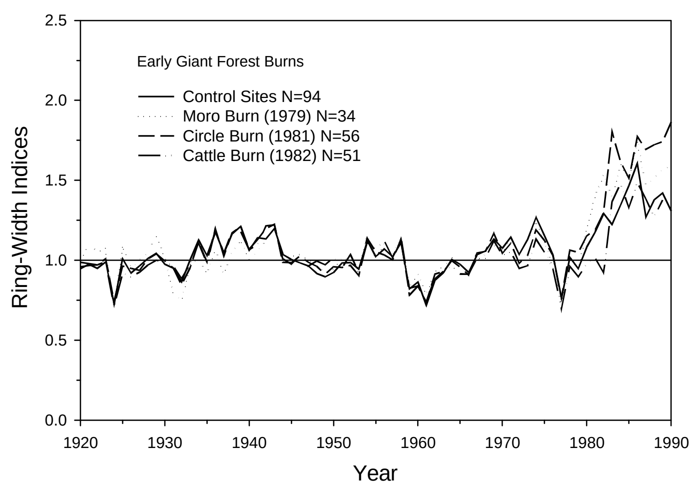

Figure 1—Standardized mean ring-width indices for the Moro, Circle, and Cattle burns and for the two Giant Forest control sites (which were averaged together to produce on set on control indices).

began at all sites in the late 1970's. Relatively wet climate conditions in the early 1980s (particularly the El Nino event of 1982/83) probably played an important role in the observed trend of increased growth at all sites through this period. Greater variability in growth patterns between sites in the 1980s was probably due to different timing of burns and subsequent growth increases in the sites. Note that the higher severity 1981 Circle Burn, which also preceded by one year the wet winter of 1982/83, had the largest and longest sustained growth increase, while the lower severity 1982 Cattle Burn had a growth increase similar to that of the unburned control sites.

Both mid 1980s Giant Forest burns (Class and Broken Arrow) had a dramatic growth increase in the post-burn periods relative to the control site indices (Figure 2). The control sites began to decline in growth by 1987, coinciding with drought conditions that persisted through the late 1980s. In these burn sites, it appears that fire moderated the effects of drought on sequoia growth.

Growth Responses to Different Fire Severities

We compared mean ring-width growth between trees sustaining different fire severities. Within each site, trees were grouped into low, moderate and high fire severity categories. "Low severity" included categories 1 and 2 (listed under the field methods section), "moderate severity" included category 3 and "high severity" included categories 4 and 5. For the Partin Burn, which had a large number of trees in both the 4 and 5 categories, these two groups were treated as "high" and "very high" severity.

For the Kings Canyon sites, burn indices were separated into the different fire severity levels estimated on the two burns. The Partin Burn included moderate, high, and very high severity levels, while the Grant Burn only had low and moderate fire severity. All three severity groups in the Partin Burn had significantly higher growth in the post-burn period than did the

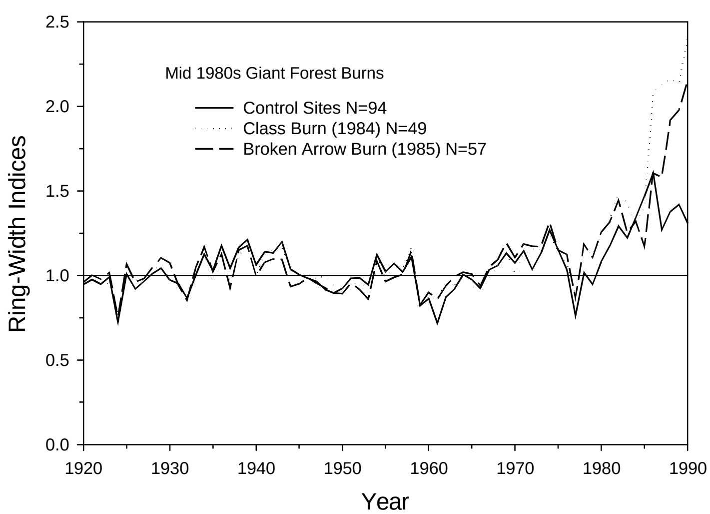

Figure 2—Standardized mean ring-width indices for the two mid-1980's Giant Forest burns (Class and Broken Arrow) and the Giant Forest control sites. Both burns had a dramatic growth increase in the post-burn periods relative to the control sites.

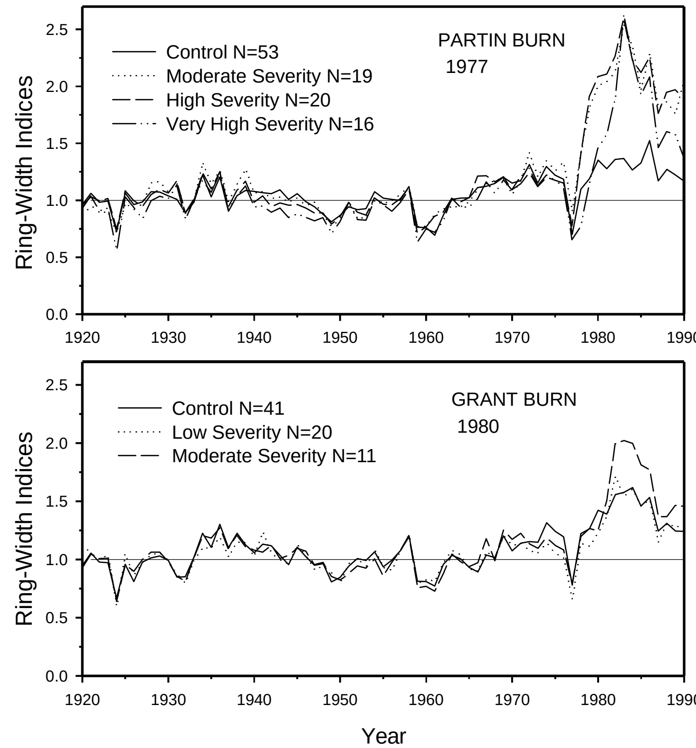

Figure 3—Standardized mean ring-width indices for burn and control sites in Kings Canyon National Parks. Burn indices were separated into groups of sequoias sustaining different fire severity levels. The Partin Burn included moderate, high, and very high severity fire, while the Grant Burn only had low and moderate severity fire.

Redwood Mountain control site. The moderate and high severity groups had a very similar growth pattern at this site, while the very high severity group showed a slightly delayed growth increase that declined more rapidly in the late 1980's. This difference was due to the extensive foliage damage sustained by three trees in the very high severity group. This foliage damage resulted in missing rings in these trees for several years after the fire, and also probably reduced their drought tolerance in the late 1980s. However, mean growth for this group was still significantly higher than that of the control site for the post-burn period (Tukey's Standardized Range Test, df=48, $P<0.05$).

The Grant Burn indices indicate that the low severity group had a growth pattern essentially identical to that of the control site. This suggests that low severity fire on this site did not reduce competition or increase soil nutrients enough to cause a growth increase above what would be expected from climate conditions alone. The moderate severity group showed a more pronounced growth increase which is significantly higher than that of both the low severity group and the control site (Tukey's Standardized Range Test, df= 27, $P<0.05$).

Individual Year Post-Burn Growth

Although mean growth for a post-burn period provides a useful measure for comparing burns to control sites and for comparing the effects of different fire severity levels on tree growth, it obscures the differences in growth responses for individual years between the fire severity categories. In order to examine how different fire severity levels affect growth in different years following a fire and to show the different patterns of growth responses for four fire severity levels, we first subtracted the mean growth of the control site from each burn series for each year analyzed (10 years pre-fire and 10 years post-fire). The result is a set of "difference series" from which effects of climate and site on growth should be removed, and what remains is primarily the growth response due to fire effects. A similar approach has been used in the study of the effects of air pollution and defoliation on tree-ring growth (Nash and others 1975, Swetnam and others 1985).

The low severity group is from the Grant Burn, the moderate group includes eight trees from the Grant Burn and eight from the Partin Burn. The high and very high severity groups are both from the Partin Burn. The sample size is 16 trees for each group. From figure 4, it is apparent that there is very little variation in the difference series in the pre-burn period for any group, due to the fact that the effects of climate on growth have been effectively removed. In the post-burn period, the series become quite different from each other. This is probably due to varying effects of different fire severities.

The trees sustaining low severity fire had almost no growth increase, while the trees sustaining high severity fire had the largest and most sustained growth increase. The trees in the moderate severity group showed a lower growth release peak and declined in growth more rapidly than those in the high severity group. For trees sustaining very high severity fire, including some trees with foliage damage, growth declined in the first years following the fire. This group, on the average, increased in growth during the second through fifth years following the fire and then declined more rapidly than the moderate and high severity groups.

Broken Arrow

In the mid-1980s, a small area in the Broken Arrow burn in Giant Forest generated public criticism of the prescribed fire program in Sequoia and Kings Canyon National Parks. Relatively high levels of bark char on one group of sequoias raised concern among some visitors about aesthetics and potential harm to giant sequoias resulting from burning. Our analysis of post-fire tree-ring widths indicates that four out of six trees in this group that sustained foliage damage did show ring growth suppressions after the fire. But by the third year after the fire, most of the trees had resumed near normal growth. During the third to fifth years following the fire, the mean growth of the 20 trees in Broken Arrow that sustained high severity fire was higher than that of trees in the low and moderate severity groups (Figure 5).

Trees sustaining low and moderate severity fire had very similar post-fire growth increases. The trees sustaining high severity fire had low growth in the two years following the burn, but then increased substantially in years three through five. This is a typical pattern observed in most burn sites with high severity fire.

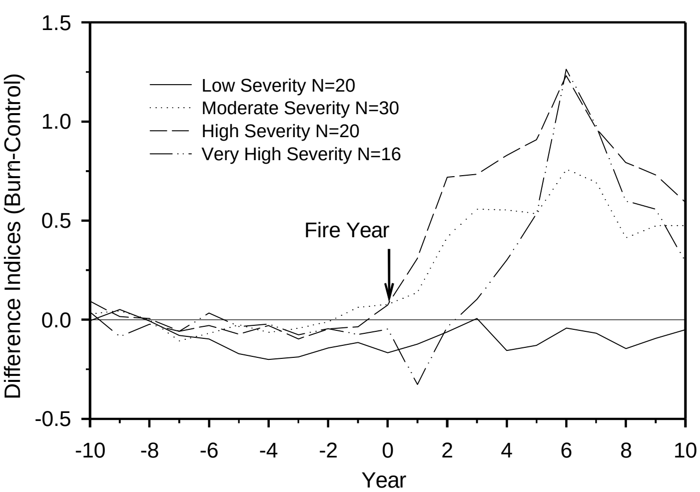

Figure 4—Difference indices (burn minus control indices) for sequoias sustaining four different levels of fire severity in Grant and Partin burns. Subtracting the control indices removes the effects of climate and site on growth; the remaining difference is primarily the growth response to fire.

Seedling Results

Both fire severity and post-fire climate conditions appear to be important to post-fire sequoia seedling establishment. Table 2 compares sequoia seedling establishment around all adult sequoias sampled in control sites and burn sites, separated into three different fire severity categories (low, moderate and high). In the control sites, only 3 percent of adult sequoias had surrounding seedling establishment, while in burns, sequoia seedling establishment was greater and generally proportional to fire severity. Seventeen percent of adult sequoias sustaining low severity fire, and 45 percent and 86 percent of adults sustaining moderate and high severity fire, respectively, had surrounding sequoia seedling establishment. The large difference in percent of adults with seedling establishment between these four groups indicates the importance of moderate to high severity fire to sequoia regeneration.

We also compared seedling establishment between two burns that preceded the wet climatic conditions of the early 80's (Circle and Partin) and two burns that were followed by drought conditions in the mid- to late-1980's (Class and Broken Arrow). All four burns included some moderate and high severity fire. Sixty-six and 76 percent of the adult sequoias sampled in the 1981 Circle Burn and the 1977 Partin Burn, respectively, had surrounding seedling establishment. Thirty-six percent of adult sequoias in the 1984 Class Burn and 42 percent in the 1985 Broken Arrow Burn had surrounding seedling establishment. The two burns followed by wet conditions had an overall higher percent of adults with seedling establishment as well as a larger number of seedlings (more adults with clumps of seedlings or continuous seedling cover--categories "2" and "3"). We conclude that sequoia seedling recruitment is most favored by a combination of moderate to high severity fire and wet post-fire climate conditions.

DISCUSSION

Prescribed fire generally appears to have positive effects on radial growth of adult giant sequoia trees. Most burns had significantly higher post-fire mean growth than control sites had for the same time period. Only two out of seven prescribed burns did not have significantly higher post-fire mean growth than control sites (Cattle and Grant burns). The relatively low

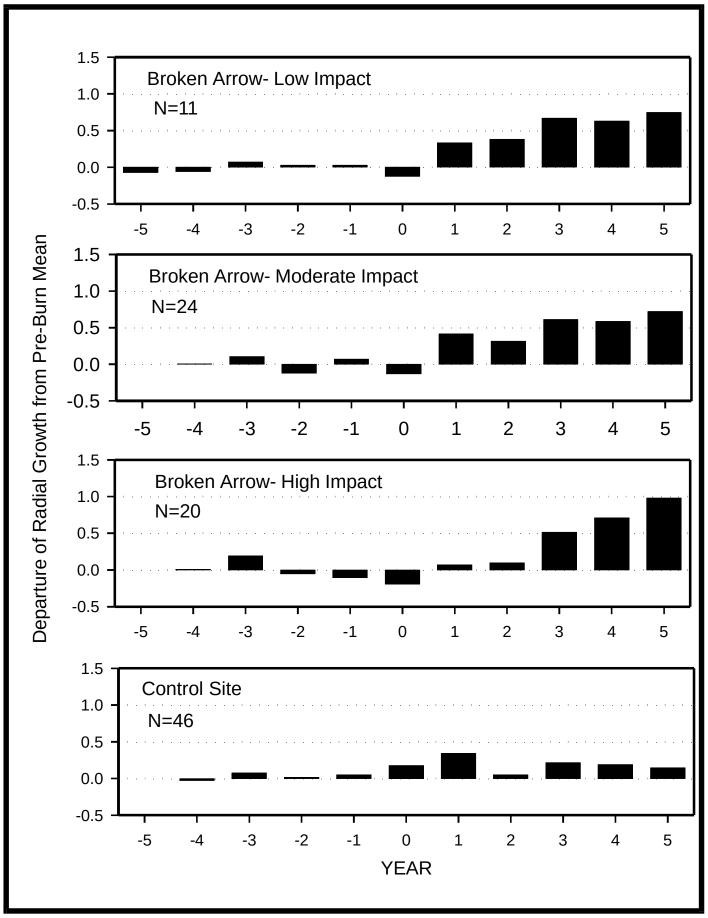

Figure 5—Growth for the five-year pre-burn and five-year post-burn periods relative to the pre-burn mean for each severity group in the Broken Arrow Burn and for the control site. In these graphs, year zero is the year of the burn, and growth for each year is graphed relative to its increase above or decrease below the five-year, pre-fire mean.

Table 2— Seedling abundance in control and burn sites. The relative frequency of adult sequoias with: (0) no surrounding seedling establishment, (1) a few scattered seedlings, (2) pockets of seedlings, and (3) continuous, dense seedling establishment.

Seedling Categories	Control	Low Severity	Moderate Severity	High Severity
	Percent			
0	96	83	55	14
1	4	13	22	23
2	0	4	22	54
3	0	0	2	10

fire severity of these two burns compared to the others may not have resulted in enough reduction in competition or nutrient increase to create substantially improved growing conditions in the post-burn period.

Some differences were evident in the growth response patterns between groups of sequoias sustaining low, moderate, high, or very high severity fire. We observed three general growth response patterns --minimal or no increase, associated with low severity fire; immediate, pronounced post-fire growth increase, associated with moderate and high severity fire; and a delayed growth increase associated with very high severity fire where foliage damage occurred. It is possible that these kinds of growth response patterns could be used to infer fire severities of older fires by examining post-fire ring-width patterns associated with known fire dates obtained from fire-scar analysis.

Positive post-fire effects seemed to moderate negative climatic effects on sequoia growth. This is most evident in the Class and Broken Arrow burns which occurred in the mid-1980s at the onset of drought conditions that persisted through the late 1980s. Both sites showed dramatic post-burn growth increases, while the control sites were declining in growth for most of this dry period. Climate did not appear to have a major effect on the magnitude of post-fire growth responses. Significant growth increases occurred in burns that preceded wet conditions as well as in burns that preceded dry years.

Post-fire climate conditions were more important to successful seedling establishment, with wet conditions being more favorable than dry conditions to seedling success. Harvey and others (1980) and Stephenson (1994) have also observed that seedling survival is greatest when the first one or two summers following a fire are wet. We found that seedling establishment was proportional to fire severity, with high and very high severity fire resulting in many more sequoia seedlings than low and moderate severity fire. In general, there is a positive relationship between disturbance size or intensity and the availability of resources for plant growth (Canham and Marks 1985). The gaps in the canopy created by more severe fire provide the increased light that the shade-intolerant sequoia seedlings require. Increases in available nutrients, in particular nitrogen, after fires in sequoia-mixed conifer forests (Kilgore 1973; St. John and Rundel 1976) also probably contribute to rapid early growth of sequoia seedlings, increasing their chances of surviving future fires and outcompeting other species. Climate and fire regime characteristics (fire size, frequency and severity) have interacting effects on sequoia seedling establishment and survival. These effects are reflected in the episodic nature of sequoia recruitment over time and space (Stephenson 1994).

MANAGEMENT IMPLICATIONS

Prescribed fire has positive effects on the radial growth of most adult giant sequoias, however, fire-damaged foliage is an important factor causing brief post-fire growth suppressions. Giant sequoias respond to fire in a variety of ways, including both growth increases and growth suppressions. The growth responses of giant sequoia to prescribed fires are not outside the range of growth responses observed in ring-growth patterns after presettlement fires (Swetnam and others 1992). This indicates that the prescribed burning in Sequoia and Kings Canyon National Parks has not resulted in "unnatural" growth responses in giant sequoias, even in the more severe burns criticized by some members of the public.

Although the Sequoia and Kings Canyon National Parks prescribed natural fire program does not have the explicit goal of promoting sequoia seedling establishment, the strong relationship between fire severity and numbers of seedlings establishing in the post-burn period suggests that burning plans should be flexible enough to allow (and even encourage) burns with a mosaic of fire severities. Adult sequoias appear to be well-adapted to sustain as well as benefit from a variety of fire severities, and sequoia regeneration is significant only in areas sustaining moderate, high, or very high severity fire.

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