Research Article

Multi-Millennial Fire History of the Giant Forest, Sequoia National Park, California, USA

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ABSTRACT

Giant sequoias (*Sequoiadendron giganteum* [Lindl.] J. Buchholz) preserve a detailed history of fire within their annual rings. We developed a 3000 year chronology of fire events in one of the largest extant groves of ancient giant sequoias, the Giant Forest, by sampling and tree-ring dating fire scars and other fire-related indicators from 52 trees distributed over an area of about 350 ha. When all fire events were included in composite chronologies, the mean fire intervals (years between fires of any size) declined as a function of increasing spatial extent from tree, to group, to multiple groups, to grove scales: 15.5 yr (0.1 ha), 7.4 yr (1 ha.), 3.0 yr (70 ha), and 2.2 yr (350 ha), respectively. We interpreted widespread fires (i.e., fire events recorded on ≥2 trees, or ≥25% of all trees recording fires within composites) to have occurred in areas of 70 ha to 350 ha at mean intervals ranging from about 6 yr to 35 yr. We compared the annual, multi-decadal and centennial variations in Giant Forest fire frequency with those documented in tree-ring and charcoal-based fire chronologies from four other giant sequoia groves in the Sierra Nevada, and with independent tree-ring-based reconstructions of summer drought and temperatures. The other giant sequoia fire histories (tree rings and charcoal-based) were significantly ($P < 0.001$) correlated with the Giant Forest fire frequency record and independent climate reconstructions, and confirm a maximum fire frequency during the warm and drought-prone period from 800 C.E. to 1300 C.E. (Common Era). This was the driest period of the past two millennia, and it may serve as an analog for warming and drying effects of anthropogenic greenhouse gases in the next few decades. Sequoias can sustain very high fire frequencies, and historically they have done so during warm, dry times. We suggest that preparation of sequoia groves for anticipated warming may call for increasing the rate of prescribed burning in most parts of the Giant Forest.

Keywords: dendrochronology, fire history, Giant Forest, giant sequoia, Sequoia National Park

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INTRODUCTION

Giant sequoia (*Sequoiadendron giganteum* [Lindl.] Buchholz) trees in California, USA, are among the most magnificent and awe inspiring living things on Earth. The largest trees exceed 10 m in diameter at the base and are 80 m or more in height. Beyond the astounding scale and aesthetic beauty of giant sequoias, another characteristic inspires our wonder: some sequoias are very ancient, exceeding 3200 years in age. Moreover, they contain a rich and detailed history of fire and climate within their annual tree rings.

From the late 1980s to the mid 1990s, we collected tree-ring samples from many sequoia trees for climate and fire history studies (Brown *et al*. 1992, Hughes and Brown 1992, Swetnam 1993, Hughes *et al.* 1996) (Figure 1). Our research built upon pioneering tree-ring work by Andrew Ellicott Douglass, considered to be the "father" of dendrochronology. At the encouragement of Ellsworth Huntington, who had done earlier tree-ring work in the sequoia groves (Huntington 1914), Douglass undertook a systematic sampling and intensive study of giant sequoia tree rings (Douglass 1919). An original impetus of this work was Douglass' desire to find a tree-ring record that extended far enough back in time to be useful for dating wooden beams from the ancient Pueblo ruins at Mesa Verde National Park and Chaco Canyon National Historical Park in the southwestern US. The giant sequoia chronology that he developed was long enough, with the oldest specimen dating back to 1306 B.C.E., but it was unhelpful in crossdating the archeological specimens because of climatic (and hence ring-width pattern) differences between the Sierra Nevada and southwest US. Nevertheless, Douglass' sequoia studies led to fundamental insights into the nature of tree-ring growth responses to the environment (McGraw 2003), and he used the sequoia record extensively in his climatic cycles studies (Douglass 1919). Importantly, Douglass developed an exactly dated and measured chronology of sequoia ring growth (Douglass 1945, 1949). Douglass' sequoia work was invaluable to our studies, providing information on where to find the oldest trees and a ring-width chronology for crossdating our numerous tree-ring and fire scar specimens.

Our giant sequoia fire history studies were initially prompted by a controversy in Sequoia, Kings Canyon, and Yosemite national parks regarding prescribed burning programs. The parks were pioneers in re-introducing surface fire into sequoia-mixed conifer stands in the late 1960s. A classic fire history study by Kilgore and Taylor (1979) and other studies in the groves (Hartesveldt 1964, Hartesveldt and Harvey 1967, Agee *et al*. 1977, Parsons 1978, Parsons and DeBennedetti 1979, Harvey *et al*. 1980) had supported the understanding that frequent surface fires played an important ecological role in sequoia-mixed conifer forest in the past, and that restoration of this keystone process was in keeping with National Park Service mandates (Leopold *et al*. 1963). Pre-

Figure 1. Surface fires (left) have been reintroduced to many parts of the Giant Forest, such as this 57 ha prescribed burn in July 2001. We tree-ring dated this large display section of a giant sequoia tree (right, GFV1), which is currently located near the General Sherman Tree. The GFV1 tree-ring record spanned the period 260 B.C.E. to 1950 C.E.

scribed fires in the groves during the early and mid 1980s, however, had occasionally resulted in significant scorching of sequoia boles, and mortality of many of the understory white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.) and red fir (*A. magnifica* A. Murray), but also some mortality of sequoias. Although reduction of understory tree density was an intended result of surface fire reintroduction, public concern led to a temporary suspension of the prescribed fire program, a review by a panel of scientists, and a call for more detailed fire history studies in the groves (N.L. Christensen, Duke University, unpublished report).

Our studies, funded by the National Park Service (and later the US Geological Survey Global Change Research Program and the California State Parks) were aimed specifically at sampling stumps of giant sequoias remaining from logging enterprises of the late nineteenth and early twentieth centuries. It is estimated that roughly one fourth of all giant sequoia trees were felled, including most of the big trees in the huge Converse Basin grove about 30 km north of the Giant Forest. Protecting some of the remaining sequoia groves, including the Giant Forest, was a primary stimulus for the establishment of Sequoia and Kings Canyon national parks (Dilsaver and Tweed 1990).

As Huntington and Douglass first recognized, the thousands of stumps in cut-over groves provided a remarkable opportunity for tree-ring sampling of ancient, dead sequoia trees. With the use of modern chainsaws and crossdating techniques, we had the opportunity to sample these stumps, as well as downed logs and standing snags, to an extent not possible during Huntington's and Douglass' time. Obviously, removing large partial cross sections from the boles of living giant sequoias would be unethical and not allowed. Dendrochronological crossdating, however, enabled us to accurately determine dates of annual rings and fire scars in long dead trees.

Our goal was to obtain fire histories extending back two millennia or longer, and to use these histories to evaluate temporal variability in fire occurrence and potential climatic controls. Ultimately, over the course of about seven years, we sampled more than 150 fire-scarred giant sequoia trees in seven groves (Giant Forest, Mountain Home, Big Stump, Atwell Mill, Mariposa, and North and South Calaveras). Fire history and fire climatology results from five of these groves (excluding the Calaveras groves) were partially described in several papers (Stephenson *et al*. 1991, Swetnam *et al*. 1991, Swetnam 1993, Swetnam and Baisan 2003). We also reconstructed fire histories along four elevational transects, including sites in forests dominated by ponderosa pine (*Pinus ponderosa* C. Lawson) and Jeffrey pine (*P. jeffreyi* Balf.) and mixed conifer forests above and below (in elevation) giant sequoia groves (Caprio and Swetnam 1995, Swetnam and Baisan 2003). These fire histories confirmed Kilgore and Taylor's (1979) findings that fire intervals were commonly sub-decadal to decadal within relatively small areas (<50 ha).

Other related work by our colleagues provided new insights on fire and tree demography (Stephenson *et al*. 1991) and the influence of contemporary prescribed and wildfires of different severities on giant sequoia ring-width responses (Mutch and Swetnam 1995). We also demonstrated a non-linear decrease in fire frequency with increasing elevation (Caprio and Swetnam 1995). More recent intensive and extensive studies of fire history at landscape scales in Sequoia and Kings Canyon national parks by Caprio and colleagues (Caprio and Lineback 2002, Caprio 2004) have expanded our understanding of elevational and aspect controls.

Our earlier work in the sequoia groves, and along the elevational transects, demonstrated that widespread fire years typically corresponded with drought years (Swetnam 1993, Swetnam and Baisan 2003, Caprio and Swetnam 2005). Lagging relationships (e.g., wet previous summers and subsequent dry summers) were identified in only the lowest elevation, pine-dominant sites. The long-term fire history from the giant sequoia groves also demonstrated a decadal to centennial association with summer temperatures: warmer periods were associated with increased fire frequencies in groves (i.e., 2 yr to 5 yr fire free intervals in areas of about 10 ha to 70 ha) and cooler temperatures were associated with reduced fire frequencies (i.e., 15 yr to 30 yr fire free intervals) (Swetnam 1993).

In this paper, we report our detailed fire history studies in one of the largest of the unlogged giant sequoia groves, the Giant Forest. Our earlier work and analyses primarily included only the fire scar sampling we had done in one sub-area within the Giant Forest, namely Circle Meadow (and some limited reporting of work in Log Meadow and Huckleberry Meadow areas in Caprio and Swetnam [1995]). In the later years of our sampling (early to mid 1990s), we expanded our collections in the Giant Forest to broaden the spatial coverage of the network of sampled trees in this grove and to lengthen the temporal record. Our earlier work had shown that this grove contains some of the oldest and best preserved fire scar material, with potential for extending fire history back more than 2000 years with good replication. In addition to our tree-ring studies, we also include here a comparison of fire frequency estimates derived from measurements of charcoal abundance in sedimentary core samples taken from wet meadows in the Giant Forest and other giant sequoia groves (Anderson and Smith 1997).

The Giant Forest has been a locus of numerous management fires since the late 1960s, with most occurring since the mid 1980s. As in most national parks and federally designated wilderness areas, fire management programs in the past few decades have primarily been concerned with reintroducing fire as a natural process. Therefore, in addition to reintroducing fire for the first time since fire exclusion began (circa 1860s in the Giant Forest), an implicit goal of these programs is to restore surface fire as a recurrent process. This goal raises fundamental questions that are increasingly pertinent because: (1) the initial reintroduction of fire (at least one event in the past few decades) has been accomplished over the majority of the Giant Forest, and (2) looming climate change as a consequence of anthropogenic greenhouse warming suggests that there is increased urgency to manage the groves to maximize their resiliency. We pose these three questions: At what frequency, seasonality, and extent did surface fires formerly burn within the Giant Forest? What role did climate variations play in determining these fire regime characteristics? Given the fire and climate history of the past 3000 years, what lessons and insights might we draw from this history as a guide to present and future fire management?

METHODS

Study Area

The Giant Forest in Sequoia National Park is perhaps the most famous of all sequoia groves. The Giant Forest contains the world's largest tree (General Sherman), and many other very large and spectacular sequoia trees and groups. Seasonally wet meadows are interspersed throughout the grove. The Circle Meadow area, where many of our sampled trees are located, is near the geographic center of the grove (Figure 2) and appears to contain many of the oldest living trees in the grove. The Giant Forest is on a rolling, bench-like topographic feature, varying in elevation from about 2000 m to 2100 m. All aspects are represented in the grove, but most solar exposure is to the west.

The overstory species composition in the Giant Forest is similar to other groves, although proportions and diameter distributions vary considerably from grove to grove (Rundel *et al*. 1977). White fir is usually the most common species by stem density, while giant sequoia dominates the canopy cover (Rundel *et al*. 1977). Other common associates include sugar pine (*Pinus lambertiana* Douglas) and Jeffrey pine. Red fir is an important associate in higher elevation, cooler parts of the grove. Ponderosa pine, incense cedar (*Calocedrus decurrens* [Torr.] Florin), and black oak (*Quercus kelloggii* Newberry) occur in lower elevation, drier portions of the groves with Pacific dogwood (*Cornus nuttallii* Audubon ex Torr. & A. Gray) common in more mesic settings.

The climate of sequoia-mixed conifer areas is Mediterranean, characterized by warm, dry summers and cool, wet winters (Stephenson 1998). Mean annual precipitation ranges from about 0.9 m to 1.4 m. The Giant Forest mean annual precipitation is 1.26 m (at 1950 m elevation). On average, about half this precipitation falls as rain and half as snow. Most precipitation occurs during the four winter months from December through March. Summer droughts are typical, often extending from May through September, although summer thunderstorms frequently occur over the mountains. Longer seasonal droughts of below average winter and spring precipitation have varied greatly in magnitude and frequency across all temporal scales, but relative to other periods during the past two millennia, the twentieth century sustained among the lowest frequency and severity of these droughts (Hughes and Brown 1991).

In the twentieth century, lightning was the dominant source of fire in the Sierra Nevada, accounting for at least 60% of all ignitions, and

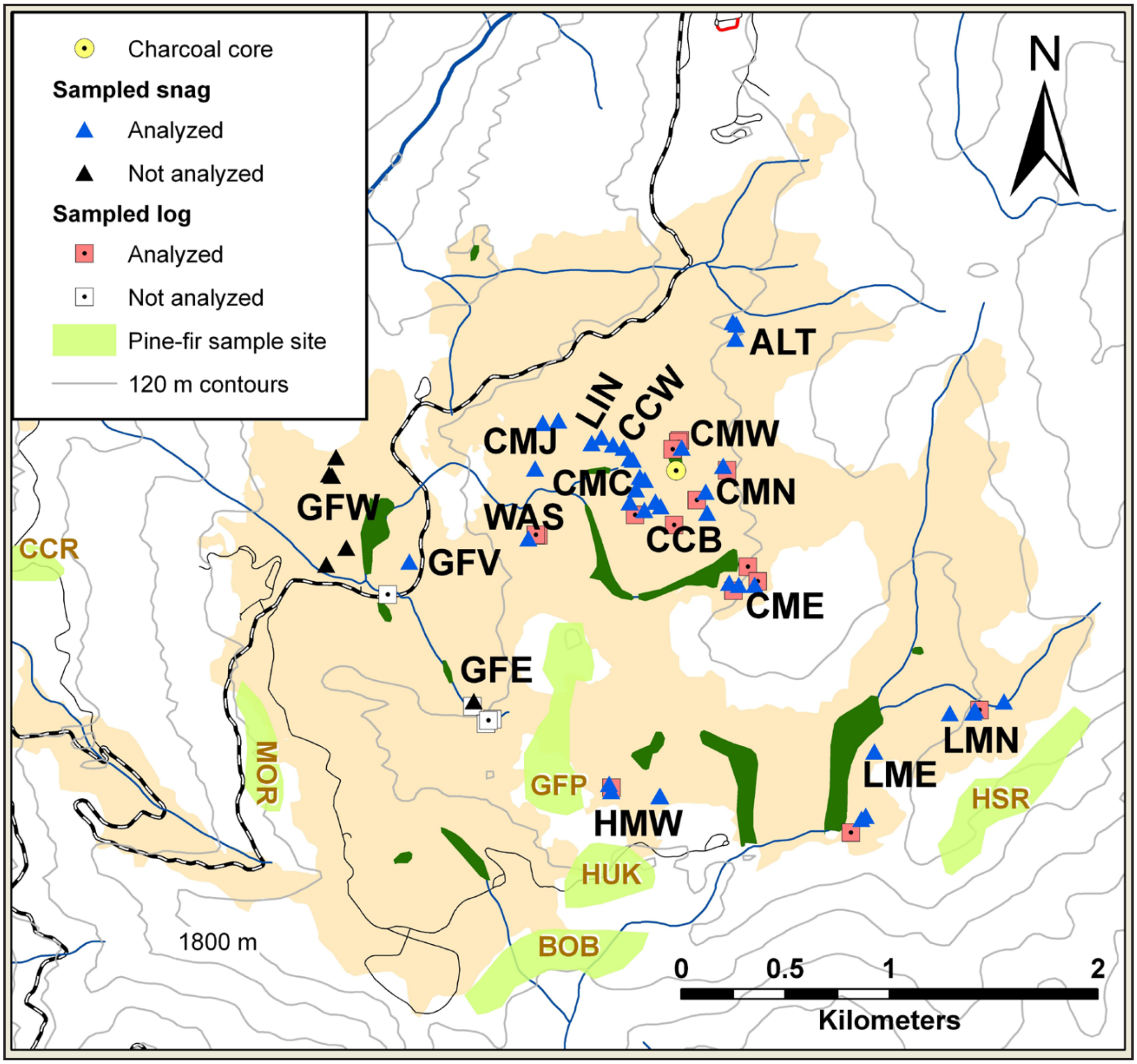

Figure 2. Map of the Giant Forest showing the locations of tree-ring collections and three letter group codes. The tan shaded area approximately encompasses the extent of living and dead giant sequoias. The light green shaded areas show the areas where fire-scarred pine and fir trees were sampled in mixed conifer forest that was lacking sequoias.

a much higher percentage in areas remote from humans. The lightning fire season in the Sierra Nevada peaks between the months of June and September (van Wagtendonk and Cayan 2008). In Sequoia and Kings Canyon national parks, July usually has the highest percentage of lightning-ignited fires (37%) with August the next highest (31%), followed by September (19%) (Vankat 1985). The percentage of total area burned by lightning fires parallels this pattern, except that July and August increasingly dominate the peak-burning season (47% and 43%, respectively).

Obtaining Fire Scar Samples

We began collecting partial cross sections from sequoia logs, snags, and stumps in the Giant Forest in 1988. This collection was part of a broader effort to develop fire scar-based fire histories in five giant sequoia groves in Sequoia, Kings Canyon, and Yosemite national parks, and Mountain Home Demonstration State Forest (we later added sixth and seventh grove collections from the North and South Calaveras groves). We sampled only dead trees because of the relative rarity and high value of ancient living sequoias, and our desire (and the park's) not to harm them. In some groves (e.g., Mountain Home, Atwell Mill, and Big Stump) we had access to numerous stumps remaining from the logging era (1890s to 1910s).

Although the Giant Forest was largely protected from cutting, we were able to sample a full cross section from the stump of a tree that had lived into the twentieth century: a tree we labeled GFV1. This tree was located in the Giant Forest Village area and was felled in 1950 by the National Park Service because it had a precarious lean toward several concession cabins in this area (Dilsaver and Tweed 1990: 246-248). A full cross section from near the base (about 5 m in diameter) was cut by the park in 1980 and erected as an outdoor display near the General Sherman tree (Figure 1). This cross section display has been viewed by millions of visitors over the years. During our collection efforts in the Giant Forest, we spent several days re-surfacing the entire cross section with belt sanders powered by a portable electric generator. We then carefully crossdated the rings and all of the visible fire scars. Subsequently, we also obtained partial cross sections from the original stump, as well as a collection of partial cross sections obtained some years before by the National Park Service. Using our observations from the full cross section and the partial sections that we brought to our laboratory in Tucson, Arizona, we developed the most comprehensive, complete fire scar dating and analysis of a single giant sequoia tree.

We used an inventory of giant sequoia trees to select other fire scarred sequoias for sampling extensively in the Giant Forest. This inventory is a surveyed and mapped database record of all living and dead sequoias in the parks, compiled by a private contractor in the 1960s (Hammon, Jensen, Wallen, and Associates, Oakland, California, unpublished report) (Figure 2). We used the maps and walking tours to identify groups of dead trees for potential sampling in different parts of the grove. During multiple trips throughout the grove, we visually inspected most (>90%) of the dead trees.

Criteria for sampling included: (1) the tree was dead (i.e., it was a stump, snag, or log); (2) the tree had multiple fire scar cavities, and multiple well-preserved scars were visible (as characteristic healing ridges); (3) the rings were visible within cavities or on broken or cut surfaces and the trees were determined to be relatively old, and numerous "buried" scars could be seen in the ring series extending toward the pith; (4) the tree was not immediately adjacent to a trail, or cut marks from our sampling would not be visible or would be easily hidden; (5) the tree or group of trees selected would provide relatively extensive spatial coverage of the grove; and (6) all selected trees were approved for sampling by a National Park Service representative.

We collected specimens from fire scarred trees in small clusters, or groups, so that composite fire scar records from this spatial scale could be assembled (Figure 2) (e.g., Kilgore and Taylor 1979, Baisan and Swetnam 1990). Individual trees typically do not include a complete record of fires that occurred at that point location (i.e., around the base of the tree), but a composite record from a set of trees (i.e., 2 to 10) would likely provide a more complete inventory of events in a relatively small area (i.e., less than 1 ha) (Kilgore and Taylor 1979, Dieterich 1980). A recent assessment of fire scar sampling methods and accuracy using independent twentieth century fire atlas records as a test has demonstrated that sampling groups (plots <1 ha) and compositing methods can provide accurate "point" fire frequency and relative areal extent estimates in frequent surface fire regimes (Farris 2009, Farris *et al*. 2010).

We used a very large chainsaw powerhead (about 50 cm^3 displacement) and bar lengths of up to 2 m to obtain multiple partial cross sections from each selected tree (Figure 3). Over the 5 field seasons in which we sampled dozens of sequoias, we became skilled in selecting dead trees with lengthy fire scar records and obtaining the highest quality specimens with the tools and time available. We found that the largest number of visible fire scars was often obtained by sampling as close to the ground level on the stems as possible.

This was an exceptionally arduous process. We typically spent one to two days obtaining 3 to 10 partial sections from multiple fire scar cavities on each tree. Considerable excavation and cleaning of dirt and rocks from fire scarred areas was often required before cutting. Pry bars and hammers were needed to extract the cut sections from the boles. Three or four people were needed for handling equipment and removing large partial cross sections that were up to 4 m^2 in surface area, 8 cm to 10 cm in thickness, and 75 kg in weight. When first cut and removed, most partial sections were heavy with moisture. We hauled specimens up to 2 km to roadways using wheeled litters and many assistants.

In addition to the partial cross sections, we also collected narrow radial sections from all sampled trees. These were sometimes obtained as "v-cuts" from stump tops (outside the Giant Forest) or flat surfaces created by the partial section removal, but more often were taken via "plunge cuts" into the bole (Figure 3). Using a smaller saw and bar length (<2 m), a skilled sawyer made two sets of parallel cuts in a stem aimed at the tree center. Then the larger saw and longer bar was inserted, and cuts were made to maximum depth with all cuts coming together at a point so that the long, narrow, pie-shaped radial section could be removed. These radial sections were useful in our crossdating of the partial cross sections because they were usually far removed from the distorted ring growth areas around fire scars.

Figure 3. Fallen giant sequoias, such as the one on the left near Log Meadow (group LMN), enabled us to obtain samples near the original ground level. Swetnam is shown standing in a fire scar cavity cutting a section from a buttress growing around the fire scars. In the middle photo, Swetnam and Baisan are inserting a 2 meter length chain saw bar into a snag (CMC3) to remove a radial section. This tree had innermost and outermost dates of 1240 B.C.E. (Before Common Era) and 1844 C.E., respectively. The photo on the right shows R. Scott Anderson and colleagues extracting a core sample from a wet meadow in a sequoia grove for pollen and charcoal studies.

The ring widths on many of these radial sections were subsequently measured and used by Malcolm Hughes and colleagues for dendroclimatic studies (Brown *et al*. 1992, Hughes and Brown 1992, Hughes *et al.* 1996).

In total, we sampled 68 individual giant sequoia trees in the Giant Forest for fire scar analysis (Figure 2). In this paper, we report and describe the results from 52 of these trees (Table 1). In a previous paper (Swetnam 1993), book chapter (Swetnam and Baisan 2003), and an unpublished report (T.W. Swetnam, University of Arizona, unpublished report), we described results from a subset of these specimens (i.e., 19 trees from Circle Meadow, four trees from Log Meadow, and three trees from Huckleberry Meadow). Only the Circle Meadow trees were used in the previous fire-climate analyses (Swetnam 1993). Lack of funding and availability of expert personnel time for dating work is a primary reason that the remaining trees have not yet been fully processed, and are not included here. All specimens (except for various display pieces returned to the parks) are held at the Laboratory of Tree-Ring Research in Tucson, Arizona, on long-term loan from the National Park Service, and are available for future studies. We estimate our giant sequoia collections from all sampled groves amounts to more than 100 m^3 in volume.

In addition to the collections from sequoia trees, we also obtained fire scar sections from 74 pine and fir trees within and near the Giant Forest (Figure 2). Results from most of these collections were described by Caprio and Swetnam (1995). We will compare summaries of the fire scar based fire return interval distributions estimated from these pine and fir trees with estimates from the giant sequoias.

Laboratory Dating of Fire Scar and Other Fire Indicators

The partial sections were sanded with belt sanders using successively finer grits (up to 400 grit). The specimens were then examined on large tables with variable power binocular microscopes (10× to 30×) mounted on long extendible arms. Lighted jeweler's magnifying glasses mounted on extendible arms were also useful for the dating work.

The tree rings were crossdated using a combination of skeleton plot procedures (Stokes and Smiley 1968) and ring-width pattern memorization. The latter approach, originally described by Douglass (1919), is based on the memorization of signature years (i.e., smallest ring years) that are consistent in the trees and region studied. We crossdated the first specimens collected with Douglass' original sequoia ring-width chronology, and later with new chronologies (Hughes and Brown 1992, Brown *et al*. 1992, Hughes *et al.* 1996).

Fire scars were dated by observing their position within the crossdated annual rings. Calendrical dates were noted for all fire scars appearing on each partial cross section. We found that several other tree-ring indicators provided additional important evidence of past fires because these features were consistently associated with actual fire scars. These indicators included growth releases and suppressions, traumatic resin ducts, expanded latewood, and ring wedging (Figure 4). On any given tree, a specific fire date was often recorded by multiple fire scars and other indicators in the same ring (or rings) on different partial sections from the bole. Some of the fire event indicators were not clearly assignable to a specific year, or there were other problems with the observations or dating (e.g., decayed wood in the scar area, identifying the year of a growth release, etc.). These were noted as questionable fire events in the database. For each tree, we then identified dates based on all indicator types (with or without questionable events), all indicators including only unquestioned fire event dates, and unquestioned fire scars only. We based our fire interval and time series analyses reported here on dates from (1) the unquestioned indicators of any type, and (2) separately on the unquestioned fire scars only. These are subsequently referred to as "all indicators" or "fire scars

Table 1. Characteristics of sampled sequoia trees in Giant Forest. The map section and tree numbers refer to the Sequoia Tree Inventory maps. We did not locate CME03 on the maps, but it was near CME02.

Group	Tree code	Map section	Tree no.	Inner date	Outer date	No. of fire scars	No. of all indicators	No. of partial sections
Circle Meadow Central	CMC01	NW5	A80	624	1716	33	45	7
	CMC02	NW5	A69	-728	1435	36	52	3
	CMC03	NW5	A100	-1239	1844	68	133	14
	CMC04	NW5	A85	-131	1923	32	55	5
	CMC07	NW5	G4	-411	470	10	31	1
	CMC08	NW5	A105	-791	1790	3	11	7
	CMC09	NW5	A47	-242	1140	13	35	2
Circle Meadow West	CMW01	SW32	O34	710	1654	29	32	5
	CMW02	SW32	O35	962	1926	18	28	3
	CMW03	SW32	O48	-11	1896	42	68	7
	CMW06	SW32	O53	769	1868	24	33	6
Circle Meadow North	CMN01	SW32	N114	-12	1200	28	45	2
	CMN02	SW32	N110	181	1571	6	29	3
	CMN03	NW5	B28	-217	1982	46	88	2
	CMN04	NW5	B35	625	1685	15	23	2
	CMN05	NW5	B94	33	1988	41	65	5
	CMN07	NW5	K38	-996	660	37	75	10
Circle Meadow East	CME01	NW5	L14	260	1714	41	56	5
	CME02	NW5	L13	-33	925	33	78	7
	CME03	NW5	–	446	1800	26	44	2
	CME04	NW5	K42	184	1764	6	59	3
	CME05	NW5	K50	81	1707	36	54	4
	CME06	NW5	K2	130	1858	34	63	6
Washington	WAS01	NE6	G17	-270	1740	73	97	11
	WAS02	NE6	G18	908	1725	18	43	3
	WAS03	NE6	F29	102	1806	33	67	5
Alta	ALT01	SW32	C74	-517	1378	45	107	7
	ALT02	SW32	C26	-346	1619	31	76	4
	ALT03	SW32	C24	-320	1036	31	57	9
Cattle Cabin	CCB	NW5	B101	-383	1402	43	58	8
	CCW01	SW32	P64	-1098	1300	30	75	4
	CCW02	SW32	P54	-1333	1061	28	55	5
	CCW03	SW32	P31	-921	1670	65	79	7
	CCW04	SE31	M22	-605	1986	47	66	8
	CCW05	SE31	M17	-582	1631	37	61	5
Lincoln	LIN01	SE31	M07	-998	1985	51	86	11
	LIN02	SE31	K38	-234	1702	20	25	3
Huckleberry Meadow	HMW01	SE6	M15	1	1989	66	90	8
	HMW02	SE6	M14	1001	1915	23	36	6
	HMW03	SE6	M09	-110	1421	35	64	5
	HMW04	SW6	O21	1556	1984	8	12	2
	HMW05	SW6	O20	735	1989	40	42	1
Giant Forest Village	GFV01	NW6	L1	-260	1950	84	125	5
Log Meadow North	LMN01	SE5	E12	445	1863	41	76	6
	LMN02	SW4	H27	-705	1856	31	119	6
	LMN03	SW4	H24	-563	1795	18	57	6
	LMN04	SW4	H06	159	1729	44	82	7
	LMN05	SW4	H14	1057	1973	9	27	3
Log Meadow East	LME01	NE8	O15	-415	1482	53	73	6
	LME02	SE5	O13	-543	1967	28	82	9
	LME03	SE5	B10	196	1808	27	48	6
	LME04	SE5	K11	447	1975	28	37	7

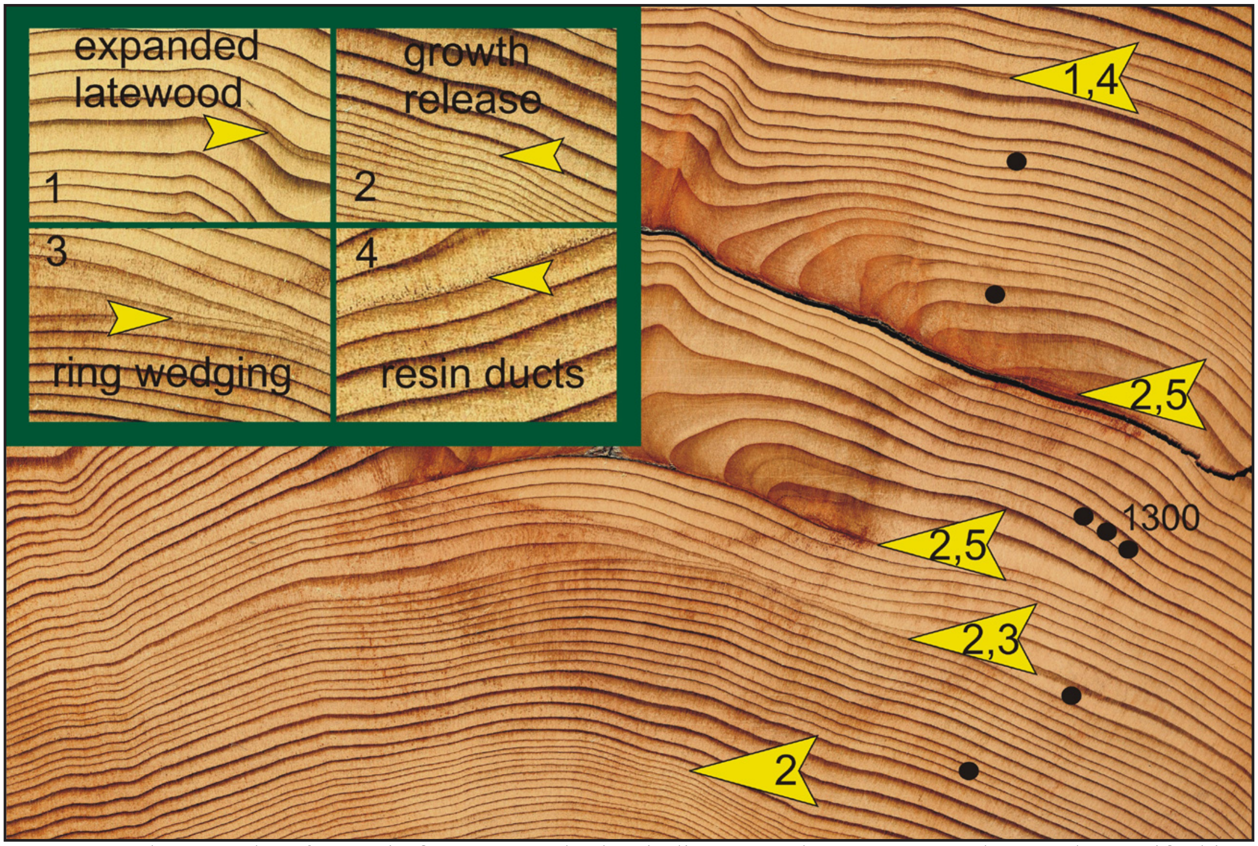

Figure 4. Photographs of sequoia fire scars and other indicators. The arrows, numbers and magnified images on the upper left refer to: 1) expanded latewood, 2) growth release, 3) ring wedging, 4) traumatic resin ducts, and 5) fire scars.

only." In addition to calendrical dates of fire scars, we also noted the relative position of the fire scars within the annual rings to estimate seasonal timing of past fires (Dieterich and Swetnam 1984, Baisan and Swetnam 1990).

In addition to the fire scar records, we also used a set of fire history reconstructions from sedimentary charcoal. These time series were from measurements of charcoal abundance in core samples taken from wet meadows on the west slope of the Sierra Nevada in or near the giant sequoia groves sampled for the tree-ring fire histories (Figure 3). These included Circle Meadow (two cores) in the Giant Forest, and the Mariposa and Mountain Home groves (Anderson and Smith 1997). Long sections of cores were impregnated with epoxy resin before production of semi-transparent thin-sections. Charcoal counts were then made along transects on the thin-sections, as outlined in Smith and Anderson (1995) and Anderson and Smith (1997). This method produced a continuous stratigraphic record with the advantage of allowing *in situ* study of the entire record. Charcoal particles for each 1 mm depth increment were identified and measured at 100× using a light microscope. All particles having one dimension >100 μm were measured with a reticle gridded in 100 μm increments. Cumulative particle area was determined for each transect.

Radiocarbon dating established the chronology of measured increments along the cores, and these dates were converted to calendar year BP (calendar years before present) using CALIB 4.3 (Stuiver *et al.* 1993). Dated charcoal counts for each transect of each sediment core were binned into 25 yr increments. Twenty-five years was chosen as a reasonable multi-decade resolution increment (bin) for the charcoal measurements. Finally, bins of equivalent dates of the five cores were summed together to produce a composite or regional time series for comparison with the tree-ring based fire histories from giant sequoia groves.

Fire Interval Analyses at Multiple Scales: Tree, Group, Multiple Groups, and Grove

We assessed fire interval distributions and temporal trends at four different spatial scales. The single tree record was from GFV1, while a group at the Circle Meadow East site (CME) represented the next scale up in extent (about 1 ha). The GFV1 record was appropriate to analyze at the tree level because it was the most comprehensive set of fire scar and other fire indicator observations from a single tree. We chose the CME group for detailed analyses because among the groups sampled it included a relatively large number of sampled trees (6), many partial sections (27), and a consistent sample depth (Table 1). Multiple groups were composited around Circle Meadow (about 70 ha), and finally all dated trees from the Giant Forest (encompassing about 350 ha) were composited for grove-wide estimates of fire frequency and temporal trends. We identified and used relatively well-represented time periods in terms of numbers of dated partial sections and trees for the fire interval distribution analyses. Only complete intervals (i.e., scar to scar dates, or intervals between other indicator dates) were included in the analyzed time periods. Statistical measures of central tendency and variance were computed for the single tree (GFV1), multiple-tree, group, and grove composites using spreadsheet routines.

Time series of fire frequency were computed and plotted using 50 yr or 25 yr moving periods. These periods were deemed reasonable lengths to assess multi-decade fire frequency (fire events per time period) variations. Fire frequencies were computed as the number of fire events occurring in each sequential 50 yr (or 25 yr) period, overlapping the previous 50 yr (25 yr) period by 49 yr (24 yr), and plotted on the central (twenty-sixth or thirteenth) year in the graphics.

For computational and plotting convenience, the time series graphs and interval and frequency estimates in this paper used the dendrochronology time scale, which includes a 0 year to begin the Common Era (C.E.) and assigns negative values to Before Common Era (B.C.E.) dates. When specific dates are mentioned in the text, they refer to the calendar year, which in the B.C.E. period is one year earlier than the dendrodate used in the data files and graphics (e.g., a dendrodate of the pith of tree GFV1 was –259 with a calendar date of 260 B.C.E.).

Fire and Climate Analyses

We compared extensive fire events recorded by at least 25% of all recording trees over the past 2000 years with an independent tree-ring reconstruction of summer (June, July, August) Palmer Drought Severity Indices (PDSI) for this region of California (Cook *et al*. 1999, 2004). We additionally used a tree-ring based reconstruction of summer (June, July, August) temperature relevant to the Giant Forest based on foxtail pine (*Pinus balfouriana* Balf.) and western juniper (*Juniperus occidentalis* Hook) ring-width chronologies from upper treeline sites (Graumlich 1993), and temperature related ring-width chronologies from upper treeline bristlecone pines (*Pinus longaeva* Bailey) in the Great Basin (Salzer *et al*. 2009). We evaluated decadal to multi-decadal scale temporal patterns of fire and climate associations using time series plot comparisons and correlation analyses (i.e., Pearson and Spearman Rank correlations). For all time series correlations, we used non-overlapping 25 yr or 50 yr fire frequency versus PDSI, tree-ring index, and temperature mean values. We used a lognormal transformation of the charcoal time series in plotting and correlation analyses.

RESULTS

Fire Interval Analyses at the Single Tree Scale

Analysis of the full cross section and multiple partial sections of GFV1 revealed that the innermost and outermost ring dates on this tree were 260 B.C.E. and 1977 C.E., respectively. The tree was felled in 1950 but portions of the stem (stump) showed continued erratic and slow growth after this time, probably owing to root grafting with its neighbors. A total of 125 fire events were observed; 84 fire events were recorded as fire scars, and 41 as growth releases, expanded latewood, or other indicators. The earliest fire date recorded by a growth release was in 181 B.C.E., and the earliest fire scar date was in 56 B.C.E. The latest fire date (recorded by a scar) was in 1915 C.E.

Another notable single tree record from the Giant Forest was provided by tree CMC3 (tree A100 in the sequoia tree inventory). This snag, located near Cattle Cabin (see photo of the radial sampling of this tree in Figure 3), had an innermost ring date (not pith) of 1240 B.C.E. and an outermost date of 1844 C.E. (bark date). At more than 3084 years, this tree is among the oldest known sequoias. A total of 122 fire events were recorded on this tree, and 87 of these dates were recorded as fire scars. The oldest fire scar date recovered in all of our sequoia collections (from all groves) was dated on this tree at 1125 B.C.E.

The shortest intervals between fires on GFV1 from 200 to 1700 C.E. were 2 yr to 4 yr (all fire indicators or fire scars alone, respectively), and the longest were 51 yr to 91 yr (all fire indicators or fire scars alone, respectively, Table 2, Figure 5). The 200 to 1700 C.E. period was used because this time included a relatively large and consistent number of trees and specimens in the overall Giant Forest collection (Figure 6). This common period provided a standard time for comparing fire frequencies at different spatial scales. Although GFV1 was the most intensively studied tree in our entire collection, it seems unlikely that we obtained a complete inventory of all fires that burned around its base over its lifetime. Some fires may have burned within the existing fire scar cavities and failed to create a scar for various reasons. Some fire scars may have been lost over time due to decay, burning off by subsequent fires; or, we may simply have not sampled the tree stem at the precise point where some events were recorded as scars. Growth releases (ring-width increases) were consistently related to fire events in giant sequoia groves, but very low intensity fires may not stimulate a release, and not all trees show releases even following moderate severity burns (Mutch and Swetnam 1995).

Mean fire-free intervals were about 16 yr based on all indicators, and 22 yr based only on fire scars over the analyzed 1500 yr period on GFV1. It should be remembered that these were measures of central tendency and descriptive of the interval distributions over long time periods. Because of the reasons described above (incomplete recording of fires), we interpret these to be conservative estimates of point fire intervals (i.e., shorter mean fire-free intervals may actually have occurred in this part of the Giant Forest near Round Meadow).

Considerable variability in fire frequency occurred during the GFV1 record (Figure 5A). Four periods were notable for highest frequencies based on both fire scars alone and all indicators : 4 fires to 6 fires per 50 yr during the early 600s, early 900s, late 1200s, and early 1600s C.E. Lowest fire frequency periods were somewhat different in the all-indicators record versus fire scars-alone record: in the fire scar-only record, 0 to 1 fires per 50 years prior to 100 B.C.E., and during the 100s, early 200s, late 500s and mid to late 1300s C.E.; in the all indicator record, 0 to 1 fire events in the late 200s B.C.E., late 100s C.E., early 400s, early 700s, early 800s, late 1400s, late 1600s, and after circa 1850 C.E. Overall, we interpret these temporal patterns to indicate that fire fre-

Table 2. Fire interval statistics for four different spatial scales in the Giant Forest, Sequoia National Park. All intervals were computed for the period 200 to 1700 C.E., except for the CME group scale, which was computed for the period 500 to 1700 C.E. Statistics were computed for fire intervals based on all fire indicators, all fire indicators recorded on two or more trees, fire scars only, and fire scars only and recorded on two or more trees. An additional composite category of all fire indicators as recorded on 25% or more of recording trees was also computed for the grove level of analysis.

Spatial scale	Approx.	No. of	Fire intervals (yr)					
Fire scar composite	area (ha)	trees	Mean	Median	Mode	Max.	Min.	Std. dev.
Single tree - GFV1	0.1	1						
All indicators			15.5	15	16	51	2	9.1
Scars only			21.9	17	16	91	4	16.3
Tree Group - CME	1.0	6						
All indicators			7.4	6	1	29	1	6.3
All, ≥2 trees			19.9	19	11	59	1	12.2
Scars only			13.7	11	9	52	1	10.5
Scars, ≥2 trees			27.0	25	25	67	6	14.3
Circle Meadow	70.0	37						
All indicators			3.0	2	1	19	1	2.5
All, ≥2 trees			5.6	4	1	29	1	4.9
Scars only			4.7	3	1	29	1	4.4
Scars, ≥2 trees			9.1	7	2	48	1	8.2
Giant Forest	350.0	52						
All indicators			2.2	1	1	13	1	1.7
All, ≥2 trees			3.9	3	1	17	1	3.4
Scars only			3.3	2	1	18	1	2.9
Scars, ≥2 trees			6.2	5	1	32	1	5.6
All, 25%			34.8	30	33	124	1	24.1

quencies (and mean intervals between fires) were as high as six events per 50 years (mean fire intervals of 8 yr to 9 yr) and as low as 0 or 1 event per 50 yr. The decline in fire occurrence after the 1860s was typical of other sequoia records from the Giant Forest and elsewhere (Caprio and Swetnam 1995, Skinner and Chang 1996, Caprio and Lineback 2002, Swetnam and Baisan 2003, Caprio 2004); the last two fire scar dates were 1863 and 1915 (C.E.). We have not located a documentary record of the 1915 event.

Fire Interval and Frequency Analyses at the Group, Stand, and Grove Spatial Scales

We analyzed fire frequency in the Circle Meadow area at two spatial scales: a single group (6 trees, CME) encompassing about 1 ha, and multiple groups surrounding the meadow (including 37 trees in groups CCW, CMW, CMN, CMC, CCB, CME, ALT, WAS, and LIN) encompassing about 70 ha (Figure 2, Table 1 and 2). The time periods we are most confident about in these data sets extend from circa 500 to 1700 C.E. in CME, and 200 to 1700 C.E. in the larger grouping. This interpretation of the most reliable periods for estimating fire frequencies was based on sample depth (i.e., number of trees with tree-rings present) (see Figure 6 and Table 1). The sample depth during these periods was at least 5 trees in the CME set and 20 trees in the larger Circle Meadow set. Prior to and after these times, sharply reduced sample numbers probably had an increasing effect on our ability to

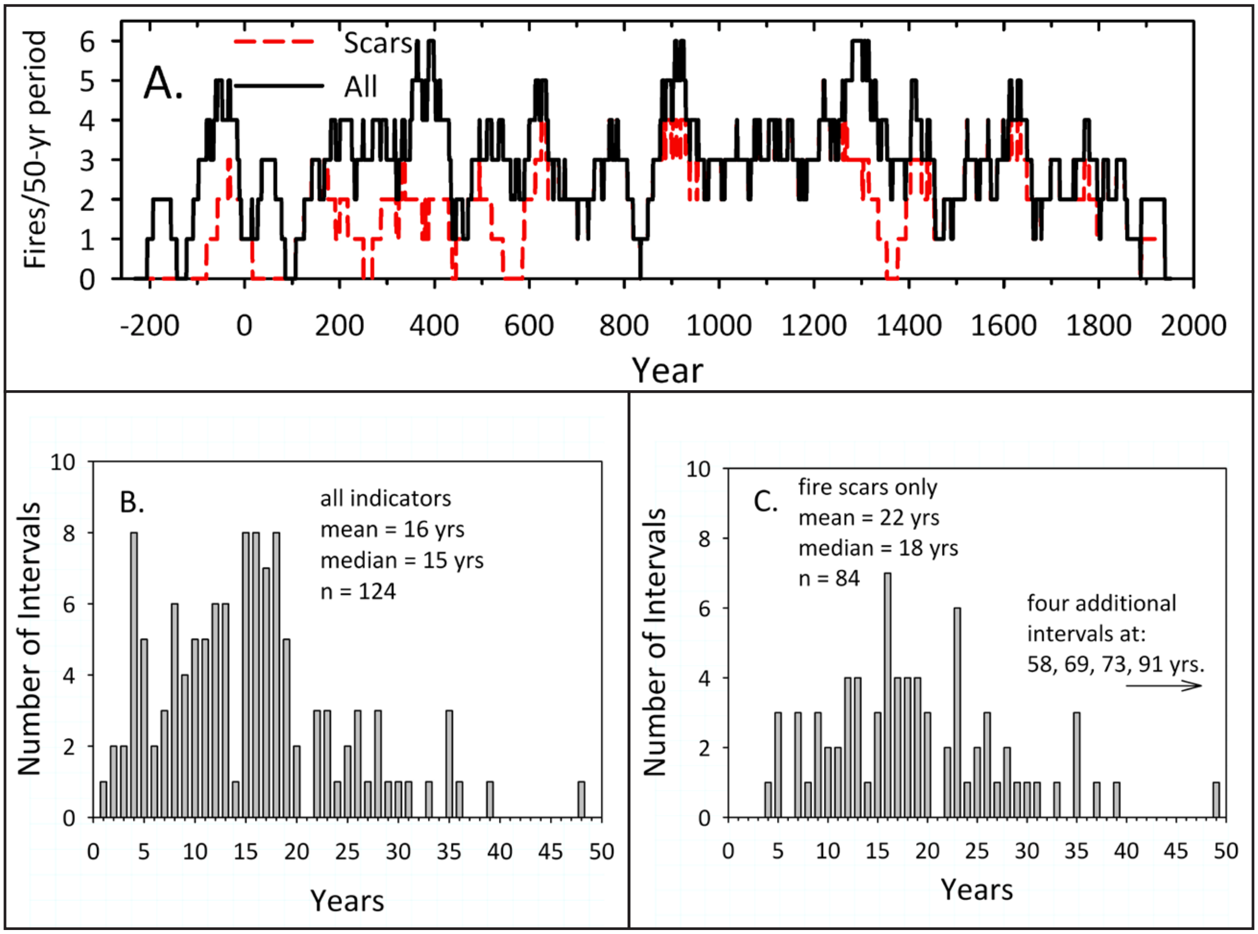

Figure 5. Temporal changes in fire frequency (A), and fire interval distributions for all fire dates (B) and fire scar dates alone (C), on a single giant sequoia tree, GFV1, for the period 181 B.C.E. to 1862 C.E.

detect all fire events and estimate fire frequency patterns.

The entire grove spatial and temporal analyses included fire dates from all 52 dated sequoia trees and groups available from the Giant Forest at this time, including all of the Circle Meadow, Log Meadow, and Huckleberry Meadow groups, as well as GFV1 (Figure 2). The area encompassed by these trees, as estimated by a convex hull (i.e., a polygon defined by a minimum area including all trees and all vertices of the polygon being convex, i.e., pointing outward) was about 350 ha in comparison to about 760 ha in total extent of the grove. The sampled trees were obviously not randomly or evenly distributed, but overall they provided a reasonable representation of substantial parts of the grove, in particular the central to southeastern areas of the grove. With eventual completion of dating and analyses of the Giant Forest Village specimens (GFV, GFE, GFW), the main areas that should be sampled in the future are the southwestern, northern, and northeastern quadrants (Figure 2).

The effects of spatial scale and tree-ring sample sizes in the assessments are evident in the fire interval statistics (Table 2) and the fire frequency versus sample depth time series (Figure 6). When all fire events (all indicators and fire scars) are included, the mean fire intervals decline as follows with increasing spatial extent from tree, to group, to multiple groups, to grove scales: 15.5 yr, 7.4 yr, 3.0 yr, and 2.2 yr, respectively (Table 2). Likewise, when only fire scars are included, mean fire intervals decline with increasing area, as follows: 21.9 yr, 13.7 yr, 5.6 yr, and 3.3 yr. Similar patterns are evident in scale effects when

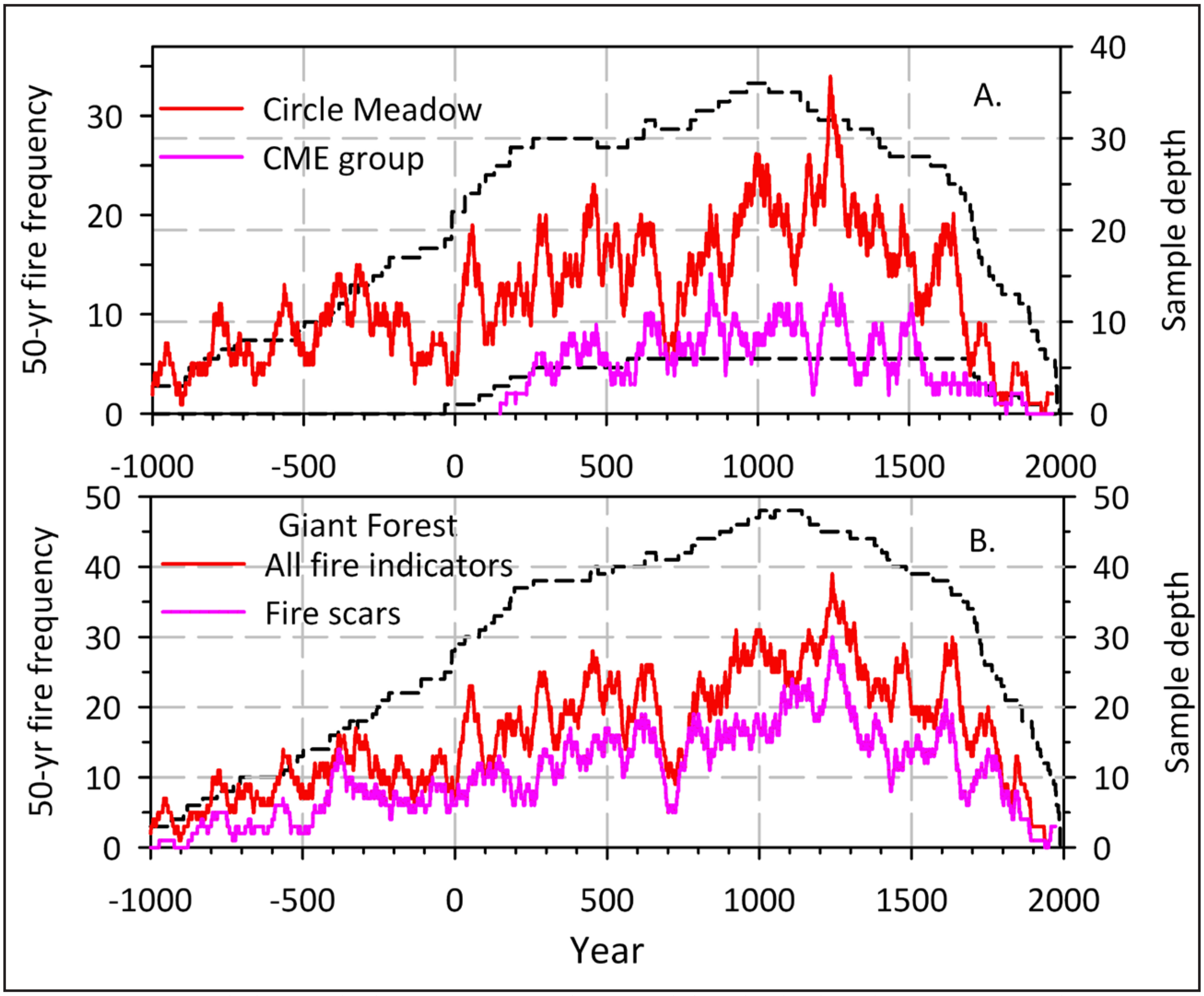

Figure 6. Temporal changes in fire frequency at three spatial scales in the Giant forest over the past 3000 years. In the upper graph (A), 50 yr moving fire frequencies (plotted on twenty-sixth year) are shown for a group of 6 trees (CME) sampled over an area of about 1 ha, and for several groups, and 32 trees combined over an area of about 70 ha near Circle Meadow. These time series are based on fire events from all fire indicators. The dashed lines show the sample depths in each time series. In the lower graph (B), fire frequencies are shown for all 52 dated trees from the Giant Forest. These time series are based on fire events from all fire indicators recorded by at least two trees and fire scars only as recorded by at least two trees.

applying filters to the fire event records, i.e., events recorded by a minimum of two trees in one set of estimates, or events recorded by 25% or more trees in another set (Table 2). Based on studies in other frequent surface fire regimes, we consider the ≥25% filter level to be an estimate of fires that typically spread across most or all of the sampled area (Swetnam and Baisan 2003, Van Horne and Fulé 2006, Farris *et al*. 2010). We applied this filter at the grove level only, with a result of mean and median fire intervals ranging between about 35 yr and 30 yr, respectively (Table 2).

The fire scarred pines and firs were from areas both within and on the edges of the grove, as defined by the extent of sequoia stems (Figure 2). These sites tended to be somewhat drier, steeper, with more southerly aspects and greater presence of Jeffrey pine than most of the Giant Forest sites. The area of the pine and fir sample sites ranged from about 11 ha to 40 ha. Mean fire intervals from

1700 to 1900 C.E. in these sites ranged from about 5 yr to 10 yr including events recorded by any tree within sites, and about 8 yr to 21 yr including only fire events recorded by ≥25 % of the sampled trees (Table 3). The two sites (GFP and HUK) that were within the grove had relatively longer mean intervals between widespread fires (i.e., ≥25 %) and were more similar to the sequoia fire interval estimates, i.e., 16 yr to 22 yr.

The moving period (50 yr period) fire frequency time series also showed effects of scale and compositing, but overall revealed similar temporal patterns at different scales (Figure 6). Maxima in fire frequency over the past 3000 years were evident during the period 1000 to 1300 C.E. The declining sample depth before 200 C.E. could be a reason that we do not detect higher frequencies in the earlier periods. Sample sizes for grove level analyses are less than 10 trees before about 600 B.C.E. The decline in fire frequency after 1300 until about 1700 C.E. (with a brief relative increase around 1600) is likely a genuine change that is not related to sample sizes. Sample depth is relatively high (generally >20 trees at Circle Meadow scale, and >30 trees at grove scale) during this period. Furthermore, similar patterns of decreased fire frequency after circa 1860 C.E. are well replicated in other sequoia, pine, and fir chronologies that span this latter period with high sample depth (e.g., Kilgore and Taylor 1979, Swetnam 1993, Caprio and Swetnam 1995, Caprio 2004).

Additional evidence that multi-decadal to centennial-scale trends of fire frequency in the Giant Forest tree-ring record are genuine and not driven primarily by sample size effects or other artifacts of our analyses comes from comparisons with tree-ring records from four other groves, and with sedimentary charcoal data (Figure 7). The five-sequoia grove tree-ring record shown in Figure 7 is the same one reported in 1993 (Swetnam 1993). This record includes 19 trees from Circle Meadow (a total of 90 trees were included in the five-sequoia grove record), so it is not entirely independent of the Giant Forest chronology. There is a re-

Table 3. Mean fire intervals in pine and fir sample sites (see Figure 2 for locations). These data were derived from composite fire scar records in these sites. The time period used in the analyses was 1700 to 1900 C.E. for all series. The "all" category refers to intervals between fires recorded on any tree within the site, and the "25 %" category refers to fires recorded on ≥25 % or more of trees within each site.

Site code			Fire intervals (yr)				
Fire scar Composite	Approx. area (ha)	No. of trees	Mean	Median	Min.	Max.	Std. dev.
BOB	40	9					
all			5.3	4	1	18	4.4
25 %			8.8	7.5	1	26	6.8
CCR	15	15					
all			6.0	5	1	20	4.3
25 %			9.1	7	4	20	5.0
GFP	27	9					
all			9.5	8.5	1	25	6.4
25 %			20.6	18	10	33	8.9
HSR	37	15					
all			7.8	6	1	26	5.9
25 %			14.3	15	5	26	6.9
HUK	15	6					
all			6.6	5	1	23	5.3
25 %			10.0	9	4	26	6.4
MOR	11	12					
all			6.6	5	2	22	4.9
25 %			12.8	12	5	22	5.8

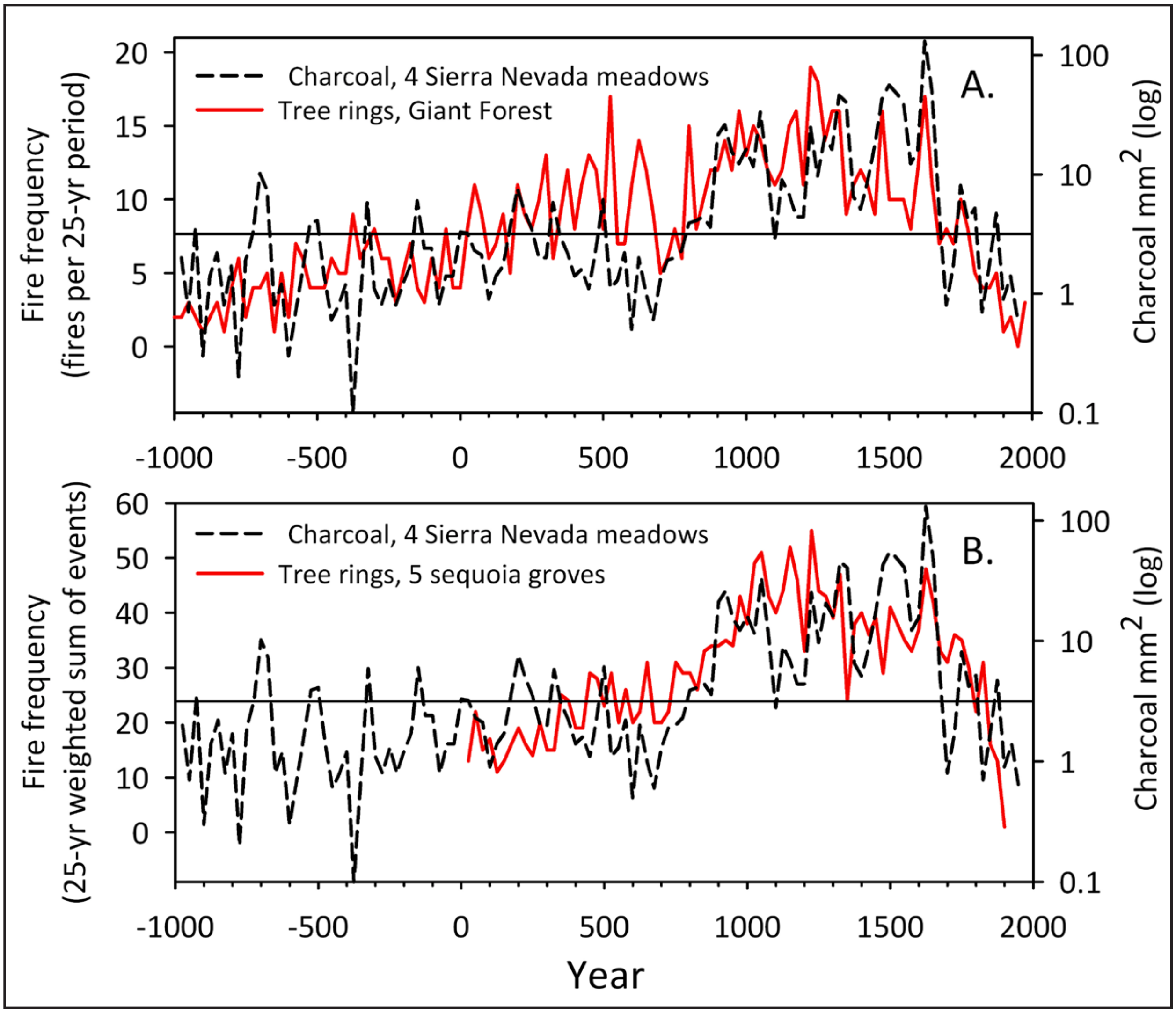

Figure 7. Comparison of Giant Forest fire history with other giant sequoia, tree-ring based and sedimentary charcoal based fire histories. The Giant Forest record (A) includes fire events recorded by two or more trees (all fire indicators) in 25 yr periods. The five-sequoia grove record (B) includes the events recorded in 20 yr periods in the Giant Forest (Circle Meadow area only), Mariposa, Big Stump, Atwell Mill, and Mountain Home groves (Swetnam 1993). These events are weighted by number of groves recording the same fire date (e.g., a 25 yr period with one four-grove fire event and one three-grove event would have a value of seven). The charcoal abundance series is calculated from five meadow or bog locations in the Sierra Nevada, including Circle Meadow (two cores) in the Giant Forest, and from the Mariposa and Mountain Home groves (R.S. Anderson, Northern Arizona University, unpublished data; Anderson and Smith 1997).

markable degree of correspondence between tree-ring and charcoal fire history time series, particularly in the fire frequency maxima during the Medieval Period (Figure 7). Both sets of series rise after about 800 C.E. and remain high until 1300 C.E., with subsequent decadal-scale spikes in fire frequency in the 1500s and 1600s C.E. Both series show common multi-decadal minima after 1800 C.E. and before circa 100 C.E.

Correlations and significance levels among the tree-ring and charcoal fire series are shown in Table 4. In general, these results show highly significant ($P < 0.001$) Pearson and Spearman Rank r values ranging from 0.53 to 0.65 over 2900 years.

Fire and Climate Analyses

Extensive fire events in the Giant Forest were clearly related to dry years (Figure 8A, Table 4). The most extensive fires (as defined by the ≥25% filter) corresponded very well with extreme drought years. Over the entire period, 41 of the 54 largest fire events (recorded by ≥25% of the trees) occurred during dry years, as indicated by negative PDSI values during those years (Figure 8), whereas 13 events occurred during relatively wet years. Notably, most of the relatively wet extensive fire years (8 of 13) occurred before circa 850 C.E. Although there were many extremely dry years without extensive fires, most of the largest fire years occurred during extreme drought years. The largest fire year, in 699 C.E., for example, was recorded on 28 of 36 (78%) trees in the tree-ring record during that year, and the PDSI value was –6.08. Other large fire years with extremely dry PDSI values were 809 C.E., 41%, –5.61; 868 C.E., 37%, –4.33; 913 C.E., 50%, –4.09; 1729 C.E., 53%, –4.82; 1777 C.E., 45%, –4.72; and 1795 C.E., 72%, –5.15. All but two of the 20 largest fire years sorted by percentage of trees recording occurred during negative PDSI years; the two exceptions were only moderately wetter than average: 728 C.E., 77%, 1.50, and 1485 C.E., 51%, 1.67.

Decadal to multi-decadal fire frequencies were moderately and significantly correlated to similar temporal resolution summer PDSI and foxtail pine-based temperature reconstructions (Figures 8B, 8C; Table 4). Dry and warm conditions were associated with higher fire activity. Fire frequencies were not significantly correlated with temperatures inferred from Great Basin bristlecone pine ring-width series (Table 4).

Seasonal Timing of Fires

We evaluated the intra-annual position of 594 fire scars (from 19 Circle Meadow trees only). We were unable to clearly identify ring positions of 42 (7%) of the fire scars because of wood decay, very narrow rings, or other problems. Among the remaining observations (552), we identified relative position of fire scars in five categories: first (EE), second (ME), or third (LE) portion of the earlywood, the latewood (L), or in the dormant position (D). The dormant position was identified when the scar appeared on the boundary between two rings and not clearly in either the latewood from the previous ring, or earlywood of the subsequent ring.

The observations of scar position in percentages of total fire scars were: EE = 1%, ME = 15%, LE = 20%, L = 46%, D = 17% (1% of scars were identified only to the general category of earlywood). This means that 63% of all fire events (recorded as fire scars in either the L or D position) probably occurred late in the tree-ring growing season, or soon after entering dormancy. It is possible that some of the dormant season scars reflect early season fires (spring or early summer) that occurred before ring growth began in the subsequent year. However, this is unlikely given that the typical fire season (in the modern era) is later in the summer (since 1930, only about 5% of fires were ignited by lightning before June, and these fires often have very low rates of spread in the generally moist litter and duff). We also checked carefully for any clues that a dormant season fire scar might date to the adjacent earlywood year (i.e., a spring or early summer fire) by noting scar positions in other places on the same tree or on other trees in the subsequent year. In general, we are fairly confident that most dormant season scars were formed in late summer or autumn, rather than spring or early summer.

Latewood and dormant season scars were typical in the other groves we have studied as well, but the percentages were higher (64% to 92%) than we observed in Circle Meadow set of trees. Our understanding of cambial phenology in giant sequoia is limited, but based

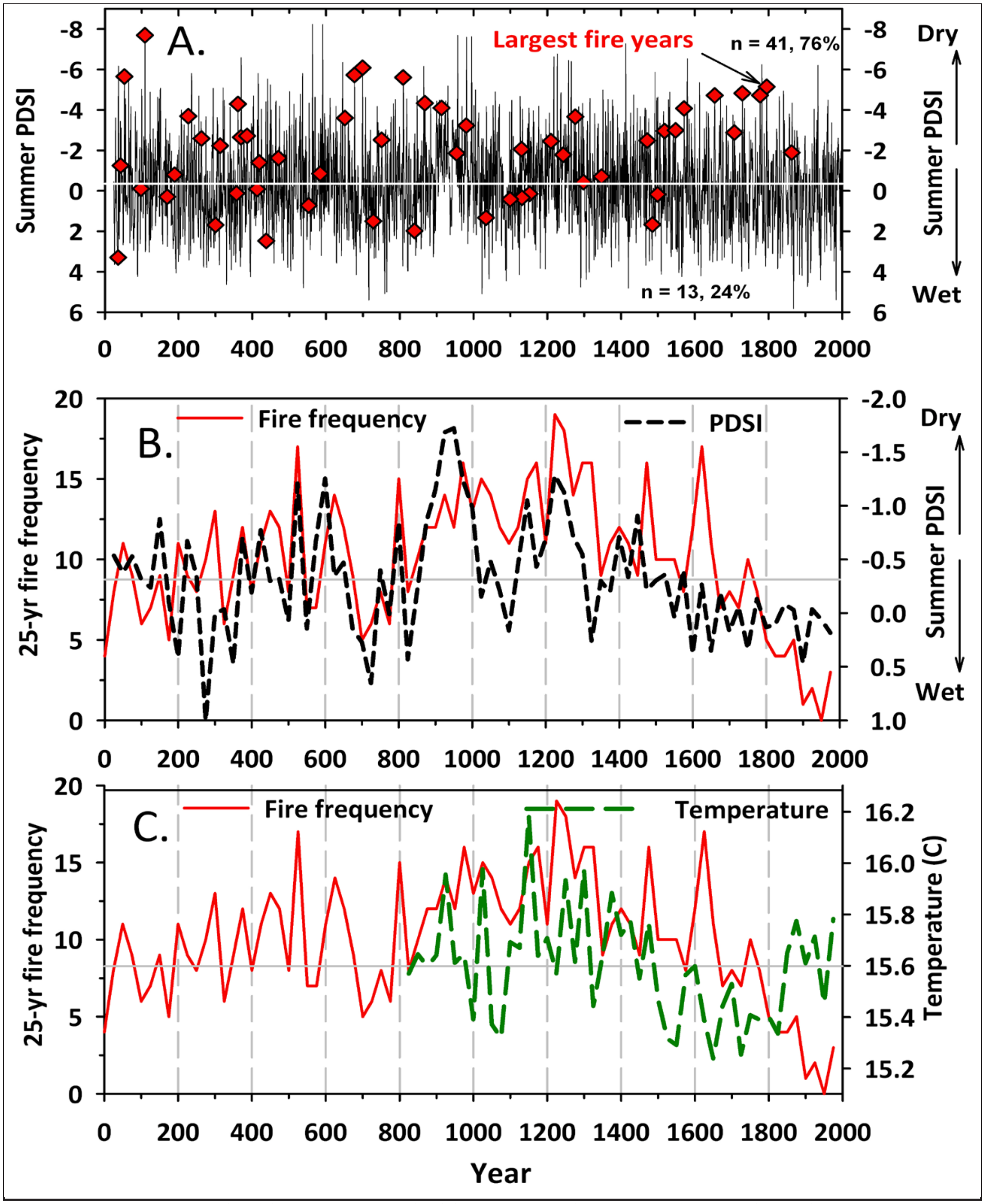

Figure 8. Giant Forest fire history compared with summer Palmer Drought Severity Index (PDSI, Cook *et al.* 2004) and temperature reconstructions (Graumlich 1993) from tree-ring chronologies. The upper graph (A) shows the 54 largest fire years (25 % or more trees scarred each year) superimposed on the annual PDSI time series. Seventy-six percent of these large fire years occurred during dry years. The middle graph (B) shows 25 yr non-overlapping fire frequencies and means of the PDSI series (dashed line). The bottom graph (C) shows 25 yr non-overlapping fire frequencies and means of summer temperature (dashed line). The 25-year binning of the PDSI series (B) shifts the mean of that series to negative (drier) relative to the mean of annual time series (zero, in A).

Table 4. Pearson and Spearman correlations between the giant sequoia fire frequency time series and the charcoal time series, Palmer Drought Severity Indices (from Cook *et al.* 1999, 2004), a regional bristlecone pine ring-width chronology from the Great Basin (Salzer *et al.* 2009), and a summer temperature reconstruction from foxtail pine and western juniper tree-ring width chronologies from the Sierra Nevada (Graumlich 1993).

Series comparison	Time period	Bin size (yr)	Pearson			Spearman	
			n	*R*	*P*	*R*	*P*
Giant Forest fire freq. vs. charcoal	975 B.C.E. to 1825 C.E.	25	113	0.55	<0.001	0.53	<0.001
five-sequoia grove fire freq. vs. charcoal	25 C.E. to 1825 C.E.	25	73	0.62	<0.001	0.65	<0.001
Giant Forest fire freq. vs. five-sequoia grove fire freq.	25 C.E. to 1825 C.E.	25	73	0.62	<0.001	0.59	<0.001
Giant Forest fire freq. vs. summer PDSI	50 C.E. to 1800 C.E.	50	36	-0.58	<0.001	-0.59	<0.001
	25 C.E. to 1825 C.E.	25	73	-0.47	<0.001	-0.48	<0.001
Giant Forest fire freq. vs. bristlecone pine ring widths (temperature)	50 C.E. to 1800 C.E.	50	36	0.14	0.42	0.14	0.42
	25 C.E. to 1825 C.E.	25	73	0.09	0.44	0.13	0.28
Giant Forest fire freq. vs. foxtail pine summer temp. reconstruction	825 C.E. to 1825 C.E.	25	41	0.46	0.002	0.45	0.003

on observations by park scientists (T.W. Swetnam, unpublished report), we offer the following provisional estimates of seasonal timing of fires based on fire scar position: Earlywood type fire scars were probably produced between the first week of June and last week of August or first week of September. Latewood type fire scars were probably formed by fires occurring from the first week of September to the third or fourth week of October. Dormant season scars were probably formed after mid October, but usually before December, depending on the year.

DISCUSSION

Fire scars and other fire indicators (e.g., growth releases) provide a nearly 3000 yr fire history for the Giant Forest. This is the longest tree-ring based fire history in the world. Substantial variations in fire intervals occurred at all temporal and spatial scales analyzed. Our multi-millennial fire history largely confirms the findings of Kilgore and Taylor (1979), who worked primarily in the Redwood Mountain Grove (about 20 km northwest of the Giant Forest). Their analyses relied on pine and fir stumps and spanned the past several hundred years. Their fire scar chronologies were developed using a ring counting and scar adjustment method described by Arno and Sneck (1977). This method may not produce accurate fire dates, resulting in potential biases in fire frequency estimates (Madany *et al*. 1982). Nevertheless, their estimates and ours are similar. In this regard, Kilgore and Taylor (1979) state:

> *From 1700 to 1875, fires of various sizes were found every 2-3 yr somewhere in a given drainage (not necessarily the same site) and every 5-9 yr in 3 ha to 16 ha sites. This compares with fires every 8-18 yr in 1 ha clusters and every 11-39 yr on individual trees. Scar records of pre-1700 fires suggest intervals fairly comparable to those from 1700 to 1875.*

Kilgore and Taylor (1979) were very aware of the effects of scaling and sample sizes on estimates of past fire frequency and intervals. To clarify their interpretations as affected by scale, they defined the two terms “fire frequency” and “fire incidence” as follows:

> *“Frequency” is used here to mean interval between fires on the same piece of ground and was calculated from records found on a single tree or a cluster of trees growing fairly close together. Fire incidence, however, was the interval between fires which burned some place in a particular sized unit of the forest, such as a drainage, but not necessarily involving the same point. Frequency, therefore, reflects fuel, climatic, and ignition factors inherent in the ecosystem or forest type, while fire incidence is also related in a major way to size of area being observed. For fire incidence, obviously, the larger the unit, the greater the number of fires and the shorter the interval between them.*

In this context, our “fire frequency” estimate (*sensu* Kilgore and Taylor [1979]) from a single tree (GFV1) ranged from about 16 yr to 22 yr (depending on fire indicators used) as compared to their 11 yr to 39 yr estimate, and our estimate from a cluster of trees of about 1 ha in extent (CME) ranged from about 6 yr to 14 yr compared to their 8 yr to 18 yr. In terms of “fire incidence,” our larger extent composites from the Circle Meadow area and all sites in the Giant Forest (about 70 ha to 350 ha) ranged from 2 yr to 4 yr as compared to their drainage-wide estimates of 2 yr to 3 yr.

Readers should bear in mind that mean fire interval (or fire frequency) estimates that we present here pertain to the standard definition (Romme 1980), i.e., intervals between fires of any size occurring within the specified sampling areas and time periods. These estimates should not be confused (or conflated) with “fire rotation,” “fire cycle,” or “population mean fire interval” (*sensu* Baker and Ehle [2001]). Although these fire metrics have different definitions, at some scales and in some landscapes, when only widespread fires are considered, their values can converge. Farris *et al*. (2010), for example, using a systematic and randomly distributed fire scar sample set, recently demonstrated that relative extent estimates of past fires based on percentages of trees recording an event were as strongly predictive (r^2 = 0.96) of absolute areas burned as recorded in independent documentary records. Furthermore, the ≥25 % filtered fire frequency closely approximated fire rotation estimates in the landscape that they studied (southwestern mixed-conifer and ponderosa pine forests; ≥25 % mean fire interval = 25.5 yr, fire rotation = 29.6 yr, 1937 to 2000 period, 2780 ha study area). In contrast, Collins and Stephens (2007) found that convex hulls drawn around fire scarred trees showing the same dates generally underestimated fire extent and area in their study in Yosemite National Park.

Our multi-scale analyses of sequoia fire interval distributions at tree, group, and grove levels provide a more detailed perspective of giant sequoia fire occurrence than previously described in published papers. However, these distributions provide only relativistic estimates of fire free intervals (or fire frequencies) within the scales, locations, and time periods described, and not absolute estimates of area burned. The sample densities (numbers of trees sampled per unit of area) are different at the various analyzed scales, so quantitative comparisons between scales could be compromised by a sampling density bias. Also, as we pointed out earlier, the spatial distribution of sampled sequoias was necessarily non-random, potentially introducing spatial biases. Despite these limitations, our fire interval estimates are consistent with findings in other studies. There is potential for overcoming these limitations, or at least evaluating their effects, in future studies of the Giant Forest collections by using various analytical tools such as kriging and event-area scaling analyses (Falk *et al*. 2007).

The temporal trends analyses of fire history changes in the Giant Forest generally paralleled our findings in four other giant sequoia groves in the Sierra Nevada (Figure 7). Maximum fire frequencies occurred during the Medieval Period from about 1000 to 1300 C.E. Fire frequencies were generally lower during the first millennium C.E., and after about 1850 C.E. The recent (since 1850 C.E.) decline in fire frequency was almost certainly due to a combination of human activities such as livestock grazing, cessation of burning by Native Americans, and fire suppression by government agencies (Vankat 1977, Kilgore and Taylor 1979, Swetnam 1993, Caprio and Swetnam 1995).

The expanded Giant Forest record lengthens our perspective into the first millennium of the Common Era (1 C.E. to 500 C.E.), and the last half of the Before Common Era millennium (500 B.C.E. to 1 B.C.E.). Although some of the centennial trends in these data are probably related to sample depth effects (i.e., fewer fires were detected when fewer trees were included in the composite data set), a substantial portion of these long-term trends were genuine and not an artifact of sampling or analyses. In a detailed study of sample size effects on fire frequency estimates (T.W. Swetnam, unpublished report), we used a boot strapping method applied to tree-ring data sets from five sequoia groves (sampled areas of about 13 ha to 70 ha.). We found that when fire events recorded by two or more trees were considered, after about 10 trees to 12 trees in the individual grove data sets, the fire frequency estimates were relatively unaffected by further increasing the sample size with areas and time periods held constant (see Swetnam and Baisan [2003] and Van Horne and Fulé [2006] for examples of applying the bootstrapping analyses for estimating sample size effects on fire frequency estimates).

Given these earlier findings and our current analysis, our highest confidence in the reconstructed decadal to centennial trends in fire frequency from sequoia samples is for the period from about 200 to 1700 C.E. The evidence supporting this interpretation includes: (1) there were relatively large sample sizes available during this period in the Giant Forest (>35 trees), (2) these fire frequency trend patterns were common to all of the groves (see Swetnam [1993]); and finally, (3) the independent charcoal time series from the same groves and nearby locations show similar multi-decadal to centennial patterns (Figure 7).

The close correspondence of the tree-ring and charcoal fire histories (Figure 7) is an important finding for several reasons. The idea of cross comparing and checking tree-ring and charcoal-based fire histories against each other has been a long sought-after goal, and clear correspondence of fire events in other "paleofire" records has rarely been achieved (e.g., Clark 1990, Whitlock and Millspaugh 1996, Allen *et al*. 2008). Typically, these comparisons involved a relatively small number of modern wildfires, tree-ring events or charcoal events, or for a single or a few sites, and only during recent decades or centuries. Here we show a good match of decadal and centennial patterns over nearly three millennia and at scales of a single grove to multiple groves across a region (the central, western slope of the Sierra Nevada) (Figure 7). This is particularly noteworthy given the different temporal resolutions of the tree-ring-fire scar and charcoal-^{14}C dating methods. The use of independently derived "multi-proxy" fire records in this manner lends confidence to our interpretations that both records are accurately reflecting decadal to centennial scale fire frequency patterns.

The importance of independent checks of temporal and spatial patterns of fire frequency variations in charcoal time series has greatly increased in recent years with the advent of regional to global scale compilations of charcoal data networks (Power *et al*. 2008). Temporal and spatial patterns in these long-term time series suggest centennial scale effects of humans and climate on regional to global biomass burning patterns (Marlon *et al*. 2008, 2009) with profound implications for our understanding of the "fire, climate, and human nexus" (Bowman *et al*. 2009). Continuous, multi-millennial, tree-ring based fire histories probably cannot be obtained from any other location in the world, so the sequoia record is uniquely valuable for this purpose of assessing confidence in using networks of charcoal data for interpreting long-term patterns, and vice versa.

Fire and Climate

Drought and fire are obviously linked, not just in mixed-conifer sequoia groves, but across the western US and elsewhere (e.g., Kitzberger *et al*. 2007, Heyerdahl *et al*. 2008, Littell *et al*. 2009). Our findings of a significant multi-decadal (as opposed to annual) association of fire and PDSI is somewhat new, although Cook *et al*. 2004 showed a similar graphical comparison using the original five-sequoia grove record from Swetnam (1993), as well as other western North American fire frequency reconstructions from charcoal time series. In our earlier work, we did not identify a decadal fire and drought association, but instead we found a rather strong inter-annual association (Swetnam 1993), a result that is replicated in Figure 8A using the expanded Giant Forest fire history.

The lack of a significant correlation between our giant sequoia fire time series and the Great Basin upper treeline bristlecone pine records is perhaps not too surprising. The bristlecone pine series was derived from stands in three mountains to the east of the Sierra Nevada: one was the White Mountains near the California and Nevada border, and the other two in Nevada (Salzer *et al.* 2009). It could be that local climate patterns in the sequoia groves, or sub-regional climate patterns on the west slope of the Sierra Nevada, are simply too different from climate patterns in the Great Basin. However, in our earlier comparison of the five-sequoia grove fire record with the upper treeline bristlecone pine record from Campito Mountain (in the White Mountains), we did find a weak but significant relationship for the 500 to 1850 C.E. period (Swetnam 1993). In any case, the more locally relevant (i.e., geographically closer) foxtail pine-western juniper based temperature reconstruction from westside Sierra Nevada locations shows moderate and significant correlations ($P <$ 0.01) with the original five-sequoia grove fire record and the new Giant Forest composite (Table 4). This supports our interpretation that decadal scale temperature fluctuations probably played some role in controlling fire frequency fluctuations over at least the past millennium.

The giant sequoia fire history indicates that fire frequency increased during the Medieval Period (about 800 C.E. to 1300 C.E.), and that major drought events, and to a lesser degree warming trends, probably contributed to this increase. A broad range of paleoclimatic, lake level, and fire history reconstructions confirm that the Medieval Period was exceptionally dry in the western US (Stine 1994, Brunelle and Anderson 2003, Cook *et al*. 2004, Hallett and Anderson 2010). This has generally been identified as the "Medieval Warm Period," but global extent comparisons of paleoclimatic data indicate that it was not a uniformly warm period around the planet (Hughes and Diaz 1994). Likewise, the so-called "Little Ice Age" was evident in documentary and paleoclimatic records for some regions, but not others, and has been identified as spanning a broad range of dates (typically post 1300 C.E., and extending as late as early 1800s C.E.; Mann [2002]). In general, however, the western United States, and specifically the Sierra Nevada, was clearly in a period of exceptional and extended drought about the late 800s C.E. to about 1300 C.E. (Cook *et al.* 2004).

Giant sequoia fire histories show the effects of this aridity with maximum fire frequencies recorded over the past two millennia.

The overall driest two periods in the western North American region in the Cook *et al*. (1999) network were centered on the mid 1100s C.E. and mid 1200s C.E., which correspond very well with decadal maxima in fire frequency in the giant sequoia groves. A generally wetter and cooler period in the early 1300s C.E. matches well with decreases in fire frequency that are particularly obvious in the Giant Forest fire scar chronology at time scales of years to decades (note that this rapid shift is not as visually obvious in the multi-decadal plots in Figure 8).

Although our data and analyses emphasize the role of climatic influences, we do not imply that climatic variations were the sole drivers of temporal fire regime variability at all scales. The climate-fire relationships we identify are highly significant from a statistical perspective, and while they are sometimes complex, the causal linkages between dry and warm conditions and enhanced fire activity at multiple scales are well established (e.g., Westerling *et al.* 2006, Heyerdahl *et al.* 2008, Littell *et al.* 2009). Nevertheless, at best, the regional climate indices we have available (including lagging relations and multivariate predictors) would probably explain between 30% and 50% of the total variance in the fire frequency time series (e.g., see Westerling and Swetnam [2003]). Therefore, it is quite likely that local scale drivers of fire frequency were also important, such as human-set fires and other ecological processes driving vegetation and fuel variations.

We have not addressed here the potential role of Native Americans in contributing to fire regime variations in the Giant Forest or other giant sequoia groves, but we acknowledge that it is quite possible that they had important effects, as others authors have concluded (e.g., Kilgore and Taylor 1979, Wickstrom 1987). This is a subject worthy of more study, and the data sets we have compiled could be very useful in this regard because they provide long records of climate, fire occurrence and seasonality from many locations with variable human occupation histories.

Management Implications

The ecological importance of fire to giant sequoias cannot be overstated. Other than the change of seasons, fire is the most recurrent and central process in determining the life history of this magnificent species (Harvey *et al.* 1980). Fire scars, other tree-ring indicators, and charcoal in wet meadow sediments from the Giant Forest and other sequoia groves show that the "normal" condition of these fire regimes is one of highly frequent surface fires. The most recent century and a half (since circa 1860 C.E.) of fire suppression by people is the most anomalous, low-fire frequency period in at least the past 3000 years.

Given future climate scenarios of increasingly warm and drought stressed conditions as a consequence of rising anthropogenic greenhouse gases (e.g., IPCC 2007, Barnett *et al*. 2008), it is appropriate to consider what fire regime conditions giant sequoias sustained during the previous most extreme warm and dry periods. During the warm and dry period, from circa 800 C.E. to 1300 C.E., surface fires burned in relatively small areas of the Giant Forest (e.g., the Circle Meadow area) at intervals of 2 yr to 4 yr. Widespread fires at this scale (i.e., about 70 ha) and time period typically burned at intervals of a decade or less. Widespread fires that encompassed most of the grove in a single year probably occurred three to five or more times per century.

The National Park Service has made progress in re-introducing fire in the Giant Forest and other groves. As of this writing, about two-thirds of the Giant Forest has had at least one prescribed, wildland fire burn since 1979. Some small areas of the grove have had as many as three burns during this period. Reduction of 150 years of accumulated fuels (living and dead) as a consequence of fire suppression is a difficult task, fraught with risk to both ecosystems and people. Hence, an incremental and adaptive management approach is wise. However, to the extent that initial fuel reductions may have been achieved at least in some areas, it may be that an accelerated rate of prescribed burning is justified on the basis of re-establishing conditions (fuels, nutrient cycling, etc.) that giant sequoia trees experienced and lived through during past extreme warm and dry periods.

Giant sequoias are a globally unique species of immeasurable inherent value, and they are a natural treasure of our nation and world. Sequoia mixed-conifer ecosystems should be managed wisely and carefully in coming decades to maximize the ability of ancient giant sequoias to withstand impending climate changes and their effects. The frequency, seasonality, and severity of fire that will enhance giant sequoia resilience to extreme climate change are not yet precisely defined. The past is an imperfect guide to the future or what may be ecologically sustainable or practical (Millar *et al*. 2007). Nevertheless, we submit that the fire history during the previous warmest and driest episode of the past 3000 years provides useful perspectives, if not specific guidance, regarding the range and variation of fire regimes under which ancient giant sequoias can survive.

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