USING BIGCONE DOUGLAS-FIR FIRE SCARS AND TREE RINGS TO RECONSTRUCT INTERIOR CHAPARRAL FIRE HISTORY

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ABSTRACT

Bigcone Douglas-fir (*Pseudotsuga macrocarpa* [Vasey] Mayr) is a long-lived, fire-adapted conifer that is endemic to the Transverse Ranges of southern California. At the lower and middle reaches of its elevational distribution, isolated stands of bigcone Douglas-fir are surrounded by extensive stands of chaparral. Our dendrochronology investigations have revealed that these ancient trees commonly record multiple past fires as fire scars in their lower boles. We hypothesized that the fire-scar record found within and among bigcone Douglas-fir stands reflects the temporal and spatial patterns of fire in the surrounding chaparral. We compared the fire scar results with independent, twentieth century fire atlas data to assess our interpretations. Using fire scars and ring-growth changes, we reconstructed fire history in Los Padres National Forest and investigated changes in fire regime characteristics over the past several centuries.

Our analyses confirm that the tree-ring record can be used to accurately reconstruct past fire occurrence and extent patterns both within bigcone Douglas-fir stands and surrounding chaparral stands. Many extensive fires were apparent in both the pre- and post-twentieth century period indicating that such events were a natural component of the system. However, many smaller fires were also evident in the tree-ring record, and more of these types of events occurred during the nineteenth century (and earlier) than during the twentieth century. We also identified a shift after the late nineteenth century to potentially more severe fires within and among stands, and by inference the surrounding chaparral. These findings suggest that land management policies, rates of human-set fires, or climatic variations may have played a role in shaping the contemporary fire regime, and that this recent period is different in some respects from the pre-twentieth century regime. Replication of this work in other mountain ranges, in addition to comparisons with climate and human histories, will provide valuable insights into our understanding of the relative roles of humans versus climate in changing bigcone Douglas-fir and chaparral fire regimes.

INTRODUCTION

In July 2007, just one year after the 2006 Day Fire (64 000 ha), another chaparral-driven blaze, the Zaca Fire, burned nearly 100 000 ha in Los Padres National Forest and surrounding areas. Total fire suppression costs were approximately 185 million US$. Since the turn of the nineteenth century, mega fires have been a common and increasingly costly occurrence in southern California. Since the 2003 firestorms, property damage from southern California wildfires is estimated to be over 3 billion US$ with fire suppression costs at more than 1 billion US$ (http://www.fire.ca.gov/).

Within the scientific community there is an animated discussion regarding the size and frequency of pre-historic chaparral fires and the role twentieth century land management practices have played in shaping modern fire regimes characteristics (e.g., see Minnich 2001 and Keeley 2001). Some believe that these contemporary mega-fires are at least partly a consequence of nearly 80 years of fire suppression, and resulting spatial changes in fuels (Minnich 2001). Others believe that they are mainly a natural product of the interaction between drought, extreme winds, and vegetation characteristics (Keeley and Zedler 2009). However, the observational basis of these perspectives are derived primarily from twentieth century fire atlas records, late twentieth century remote sensing data, and from a relatively limited number of nineteenth century accounts in newspapers and other historical documents (Minnich 2001, Keeley and Zedler 2009). Given the large impacts of recent mega fires in southern California, and the profound policy

and management implications of scientific interpretations of the underlying causes of these events, it is crucial that we extend our historical perspectives of fire regime changes and dynamics in this region by providing a rich, temporal data set against which these competing perspectives can be tested.

Chaparral vegetation is composed of relatively fast growing, dense, flammable shrubs and is the dominant vegetation type in southern California. This fuel type accounts for 95 % of the area burned in southern California from 1950 to 1991 (Davis and Michaelsen 1995). Chaparral fires are typically intense, fast moving, and can occur at relatively short intervals (i.e., <20 years, but typically 30 years to 60 years; Barro and Conard 1991). Previous work (Rothermel and Philpot 1973, Minnich and Chou 1997, Minnich 2001) has advocated age-dependency as a primary fire control in southern California chaparral systems. Within these landscapes, the probability of fire in relatively young patches of chaparral is low and increases over time. The spatial patterns of burns are constrained by previous fire history, which in turn creates a time-dependent, self-organized mosaic of fuel ages. However, external drivers, such as weather, ignition rates, and topography, can influence fire occurrence and thus can alter this deterministic relationship independent of fuel production. Unique synoptic climate patterns, coupled with extreme wind events, create one of the most fire-prone landscapes in North America (Barro and Conard 1991). Ample precipitation typically falls from late December through March; however, seasonal drought characterizes the remainder of the year. In autumn, after nearly

six months of little to no precipitation, multi-day Santa Ana wind events are a common occurrence, with the number of events peaking in December (Raphael 2003). These hot, dry föhn winds have the potential to turn small fires into landscape-scale conflagrations.

In addition to natural factors that promote fire hazard, increased human-caused ignitions, which are highly correlated to population growth, have complicated the situation (Keeley and Fotheringham 2001). Historically, ignitions are thought to have been the limiting factor in the southern California fire environment. The confluence of events—seasonal or annual drought, high winds, sufficient fuels, and ignitions—required to create a widespread fire (i. e., >5000 ha) was relatively uncommon. However, with a population of more than 23 million people, ignitions are no longer a limiting factor. Coupled with persistent or recurring droughts in recent years, multiple large fires have become a common occurrence within the region (Keeley and Fotheringham 2001).

Presently, a shared stance among some managers and the public is that large chaparral fires are a product of past land use practices rather than a characteristic of the chaparral community. This idea draws from the paradigm established largely in conifer forests of the western US (especially semi-arid ponderosa pine [*Pinus ponderosa* C. Lawson] forests), where recent widespread, severe fires are at least partly a result of past land uses (e.g., logging, livestock grazing, and fire suppression). These practices have led to heavy, continuous fuels promoting uncharacteristically severe and extensive fires (Pyne *et al.* 1996, Allen *et al.* 2002). Based on this fuels paradigm, state and federal agencies spend millions of dollars each year in southern California on widening and maintaining fuel breaks and prescribed burning to prevent large fires from occurring (Minnich 2001). Additionally, hundreds of millions of dollars are spent aggressively suppressing fires that threaten to become large.

Yet, these efforts have failed to prevent the large mega fires of recent years (Keeley and Zedler 2009).

Background

A broad consensus now exists among ecologists that stand-replacing fires, with 20-year to 60-year fire return intervals, are generally natural in southern California chaparral communities (Mensing *et al.* 1997, Moritz *et al.* 2004). However, there is substantial uncertainty about the historic range of variability of fire frequency and size in this type, especially over time scales of centuries. Moreover, the relative role of human-induced changes and climatic variability is unclear (Keeley and Fotheringham 2001, Minnich 2001, Keeley 2004).

Minnich (2001) has argued, using aerial images of modern fire perimeters, that fire suppression in southern California has resulted in extensive even-aged patches of chaparral and has eliminated natural, fine-grained chaparral mosaics like those he has documented in northern Baja California, Mexico. Others (Mensing *et al.* 1999, Keeley and Fotheringham 2001, Moritz *et al.* 2004, Westerling *et al.* 2004) have countered this argument with data indicating that chaparral fire regimes in southern California, with the exception of increased fire frequency, have not changed over time and that fire suppression, stand age, and fuel loads play a minimal role in shaping the current state of fire occurrence and size. Recent work has demonstrated that chaparral fires can and have spread though all age classes of vegetation when exposed to extreme weather conditions. However, in the absence of these conditions, age-related effects of fuels can exhibit stronger controls over fire spread (Moritz *et al.* 2004).

The frequency of fire events in southern California has increased in the modern era, perhaps due in part to an increase in human-caused ignitions that occur throughout the year

in conjunction with the introduction of non-native grasses (Keeley 2004). Presently, non-native grass species replace chaparral communities when fires occur at intervals of less than 10 years, because most chaparral species cannot produce a viable seed bank or resprout effectively before that time (Keeley 2006, Syphard *et al*. 2006). While these two factors are playing an increasingly important role in the fire ecology of southern California, twentieth century observational data suggest that weather and climate variables, in particular Santa Ana winds and drought, are still the most important driver of fire occurrence and size in southern California (Keeley 2004, Moritz *et al*. 2004, Keeley and Zedler 2009).

This finding is supported by analysis of wind-deposited charcoal in varved sediments. Charcoal records from Santa Barbara Channel sediments indicate that large fires (>20 000 ha) have consistently occurred at intervals of 20 years to 30 years (Mensing *et al* 1999). The Santa Barbara charcoal record illustrates that this frequency has not changed substantially over the past 560 years, which includes periods of Native American, Spanish, and Euro-American tenure (Mensing *et al*. 1999). This record provides long-term perspective for the Santa Barbara region, but it lacks specific fire history information at stand or landscape scales. Moreover, the spatial and temporal resolution of the charcoal time series is too coarse to resolve fire sizes or seasonal to inter-annual patterns of fire occurrence. Despite recent advances in chaparral ecology and southern California fire history reconstruction (e.g., Everett 2008), little is known about the long-term ecological variability of these ecosystems.

Dendrochronology and fire-scar dating has been used extensively in other regions of the western United States to evaluate long-term changes in fire frequency and extent in relation to land use history and climate (e.g., Swetnam 1993, Veblen *et al*. 1999, Grissino-Mayer and Swetnam 2000). Recent studies have demonstrated the utility of spatially distributed fire-scar data (collected via random, systematic, or targeted sampling) to reconstruct spatial extent of past fires within sampled areas (e.g., Heyerdahl *et al*. 2001, van Horne and Fulé 2006, Hessl *et al*. 2007). Furthermore, well-distributed spatial networks of fire-scar samples have been shown to accurately reconstruct the spatial extent and fire frequency patterns in independently mapped records of fires from the twentieth century (Collins and Stephens 2007, Shapiro-Miller *et al*. 2007, Farris *et al*. 2010).

Unfortunately, chaparral vegetation is usually not directly suitable for dendrochronology because fire scars are generally not formed on shrub stems, the growth rings in many shrub species are difficult to discern or crossdate and, more importantly, stands are typically consumed by each subsequent fire, erasing the record of past events. However, embedded within chaparral landscapes are stands of bigcone Douglas-fir (*Pseudotsuga macrocarpa* [Vasey] Mayr), whose fire history, we hypothesize, reflects that of the surrounding interior chaparral landscape.

Bigcone Douglas-Fir

The distribution of bigcone Douglas-fir is limited to the Transverse and Peninsular ranges of southern California. It is a native evergreen conifer that can grow to heights of 15 m to 30 m and diameters of 55 cm to 155 cm. Although the species can be found at elevations ranging from 600 m to 2720 m, a majority of the populations can be found within 1000 m to 1800 m elevation above sea level (McDonald and Littrell 1976). Here, disjunct stands, often associated with an understory of canyon live oak (*Quercus chrysolepis* Liebm.), are surrounded by extensive chaparral communities (Figure 1). Typical stands are restricted to slopes greater than 35 % and can range in size from 5 ha to 50 ha or more (Minnich 1977).
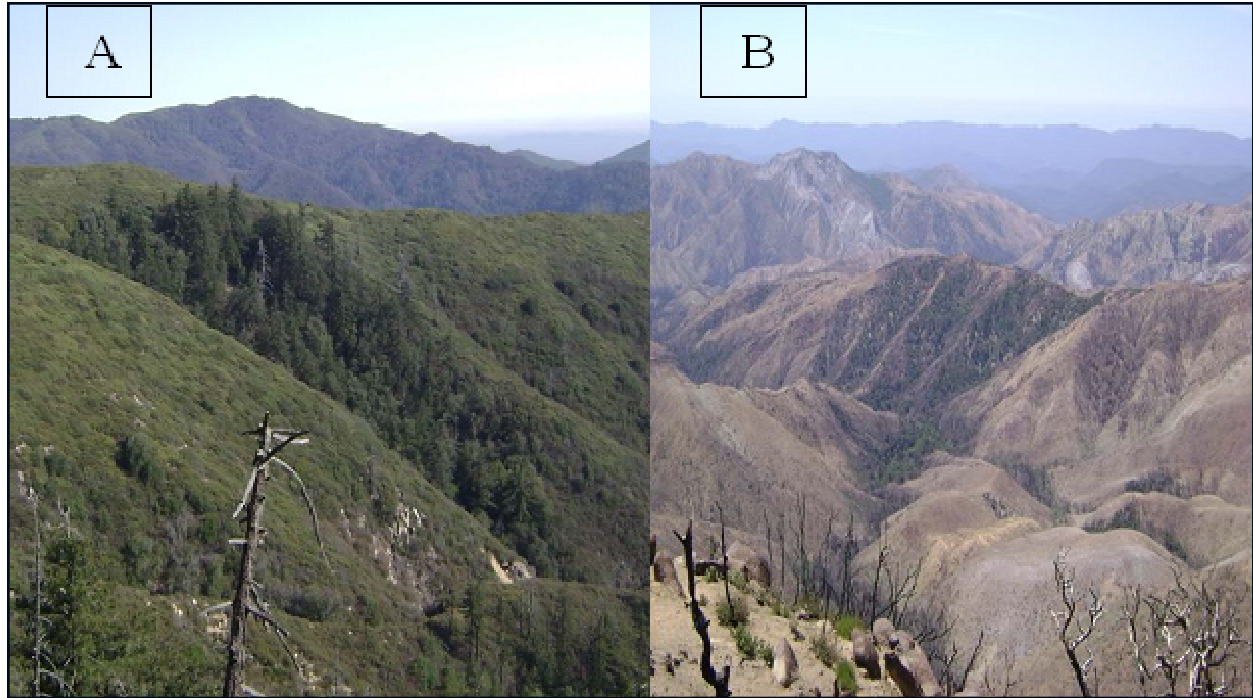
Figure 1. (A) Isolated bigcone Douglas-fir stand surrounded by chaparral in Cleveland National Forest. (B) A large stand of bigcone Douglas-fir that survived the 2007 Zaca Fire in Los Padres National Forest.

The largest stands are found on more mesic, north-facing slopes; however, stands can be found on all aspects, particularly at higher elevations. Bigcone Douglas-fir is one of the most fire resistant and adapted conifers in the world, with an ability to survive fires of high intensity and severity because of its thick bark (usually 15 cm to 20 cm), and its ability to prolifically resprout new branches and needles from the bole and existing branches following a fire (Figure 2). If terminal and axillary buds are killed in a fire, epicormic buds in the axils of branches will typically sprout new shoots within one to three years after the fire event (Vander Wall *et al*. 2006).

These adaptations suggest that the species has evolved to survive multiple fire events that sweep through these stands from the surrounding chaparral. Individual trees frequently incur basal fire scars during fire events. We have found that these fire scar events corresponded temporally (i.e., synchronously) between trees within patches as well as between patches separated by continuous chaparral in many cases.

Therefore, we hypothesize that those synchronous fire-scar events in multiple bigcone Douglas-fir stands are evidence supporting the inference that the intervening chaparral landscape (but not necessarily all of it) also burned. If this hypothesis is correct, then the relative extent of fire-scar synchrony within a study area provides an estimate of the relative extent of past chaparral fire events. Obviously, such spatial and temporal inferences based on fire-scar synchrony require testing with independent fire extent records.

The objective of this research was to determine the frequency of historical chaparral fires and estimate their relative extent over the past several centuries by sampling and dendrochronologically dating fire scarred trees found within extensive chaparral landscapes. We tested our hypothesis and assumptions using a fire atlas of modern era fire events as a corroborative tool to assess how well, and in what manner, the fire-scarred stands recorded known twentieth century fire events.

Figure 2. (A) Bigcone Douglas-fir with lower branches scorched by the 2007 Zaca Fire, Los Padres National Forest, and (B) bigcone Douglas-fir branches resprouting new clusters of leaves and branchlets following the 2007 Zaca Fire, Los Padres National Forest.

METHODS

Site Description

The main division of Los Padres National Forest is a rugged 585 000 ha landscape (Figure 3). Elevations range from sea level to 2692 m. Vegetation below 1800 m is dominated by chaparral and coastal sage scrub. The climate of the forest is classically Mediterranean with cool, wet winters, and warm, dry summers. Median annual precipitation for Santa Barbara is 38.9 cm, with the majority falling between January and March (Davis and Michaelsen 1995). At higher elevations, on west-facing slopes, precipitation can be twice the amount of that at sea level. A majority of the fires that start in the middle to upper elevations of the Transverse Ranges are ignited by lightning, which occurs at significantly higher rates with increasing elevation and distance from the coast (Keeley 2006, van Wagtendonk and Cayan 2008). The frequency of lightning strikes peaks in Septem-
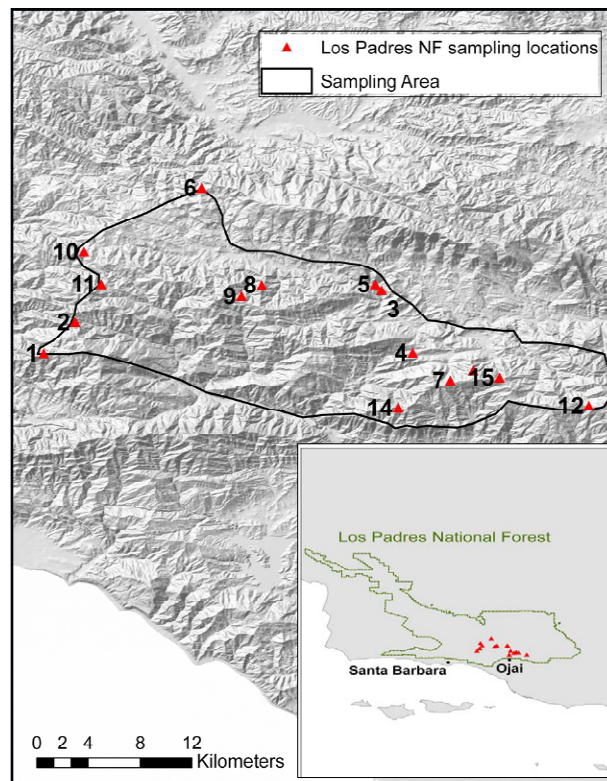

Figure 3. Sampling locations and area within the main division of Los Padres National Forest in southern California.

ber. Strike densities for this region (excluding the highest elevations) are among the lowest in the United States (Keeley 2002).

During the fall and winter months, strong offshore Santa Ana winds, driven by synoptic-scale atmospheric patterns, can persist for several days across southern California. Recurrent föhn winds result when a steep pressure gradient exists between Great Basin high pressure cells and Pacific Coast low pressure cells. Events typically last two to three days and can occur several times per month, with peak occurrence in December (Raphael 2003). Wind speeds of 40 km hr^{-1} to 60 km hr^{-1}, relative humidity of less than 10 %, and temperatures greater than 35 °C are not uncommon (Schroeder *et al.* 1964, Keeley 2004, Westerling *et al.* 2004). These extreme weather conditions occur during the tail end of an annual drought when fuel moisture conditions are at their lowest.

Sample Collection and Preparation

Due to wilderness designations, limited road access, and the generally remote nature of the stands within an impenetrable sea of chaparral, our sampled sites were restricted to accessible stands, which were often within 3 km of an access road. Within stands, our objective was to obtain a sufficient number of fire-scarred specimens to acquire the longest and most complete possible fire record at sampled points and within stands (Dietrich and Swetnam 1984, Swetnam and Baisan 2003). Individual trees were chosen using a sampling criterion similar to that of stand selection (accessible and well distributed). Average site elevation was 1441 m with a range of 1104 m to 1618 m (Table 1).

Open cat faces on bigcone Douglas-fir trees are an uncommon occurrence and, when

Table 1. Elevation, number of samples, fire events (total and by indicator type), average mean fire intervals and average point mean fire interval for 15 sites in Los Padres National Forest for the period 1600 to 2005.

| Site number | Elevation (m) | Sample size (trees) | Fire events (*n*) | Events documented by | | Mean fire interval (yr) | Median fire interval (yr) | Fire return interval (yr) | | Avg. point mean fire interval (yr) |
				Scar	GC			Max.	Min.	
1	1535	7	19	9	10	20.65	20.0	41	5	29.57
2	1547	5	18	14	4	15.29	9.0	78	4	34.86
3	1104	4	8	6	2	34.43	31.0	64	13	23.28
4	1118	6	20	16	4	19.89	14.0	41	4	31.06
5	1129	4	20	15	5	20.84	17.0	54	4	30.66
6	1540	4	13	11	2	28.00	21.5	68	6	27.97
7	1450	5	15	14	1	24.71	24.5	53	6	45.34
8	1605	4	16	11	5	25.47	21.0	55	5	22.62
9	1516	3	9	8	1	30.00	21.0	60	3	31.90
10	1547	4	9	7	2	39.00	22.0	48	4	29.79
11	1605	5	13	11	2	24.50	42.0	64	10	26.01
12	1618	12	27	15	12	13.58	10.5	61	4	29.65
13	1453	10	28	19	9	13.00	11.5	36	3	25.08
14	1257	4	9	7	2	34.75	25.5	100	2	23.86
15	1525	8	14	8	6	25.38	18.0	58	4	36.33
Avg.	1441	5.7	15.9	11.4	4.5	24.57	20.6	58.7	5.1	29.87

present, are relatively poor recorders due to decay and burning out by subsequent fires. Trial and error sampling of full bark trees revealed that buried scars were very common on most trees within stands. At each of the stands we visited, an abundant tree-ring based fire history was evidently available for sampling (i.e., presence of bark charring and basal wounds) and no stands were passed over due to a lack of material. We subsequently targeted our sampling toward obviously older trees (as indicated by bole size, branch characteristics, etc.,) and those with characteristic furrows in the boles, which indicated healed over scars. Using a chainsaw, a skilled sawyer made plunge cuts to extract partial sections on upslope sides of living and standing dead trees as well as on downed snags. Typically, the partial wedge sections extracted were about 25 cm to 35 cm wide, 3 cm to 5 cm thick, and 50 cm to 70 cm long, extending to the tree center when feasible. Approximately 88 % of all full bark trees sampled had buried scars evident in the partial section. The average number of scars per sample was 3.2, while the maximum number of scars on one sample was 11.

We also observed and documented abrupt growth changes evident in the ring-width patterns of our specimens that were associated with fire scars or occurred following known fire dates. While changes in growth can be caused by various means (e.g., stand opening and reduced competition from wind-throw and other mortality agents), we believe these changes frequently result from a shift in resource availability due to fire mediated mortality (Mutch and Swetnam 1995). Unlike fire scars, fire related growth changes usually do not begin the same year as the fire event because cambial growth often ceases prior to most fire events in southern California. Because it can take several years for trees to recover from fire damage and take advantage of the decreased competition for resources, growth changes typically begin in the years following the fire. For growth changes that

were corroborated by a fire scar within the same stand, the average lag between the fire scar and associated growth change was 2.2 years. The average number of growth changes per sample was 7.2, while the maximum number on one sample was 18. Growth change magnitude and duration were visually estimated and began when ring widths became substantially larger or smaller than the preceding 5 to 10 rings and were at least three years in duration. The event was considered completed when ring widths returned to pre-fire sizes. We recorded release events when ring widths increased by more than 150 %. Suppression events were identified when ring widths decreased by more than 50 % (Figure 4).
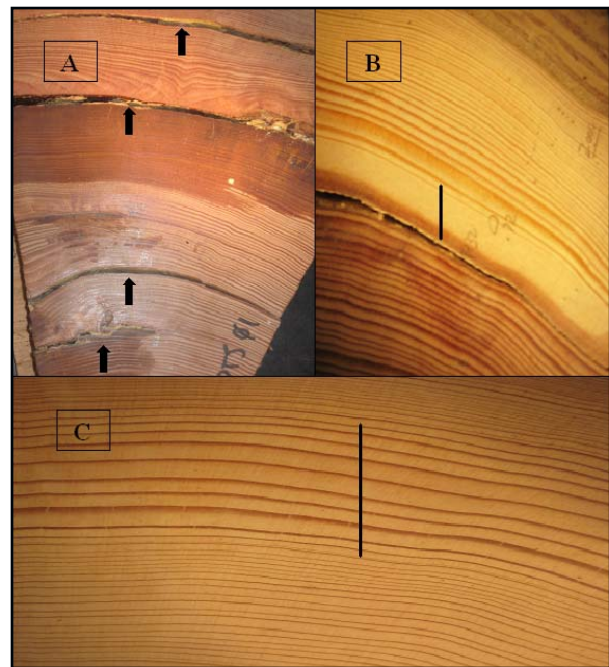

Figure 4. Three partial bigcone Douglas-fir sections taken from Los Padres National Forest. The sample in the upper left hand corner (A) shows multiple fire scars clearly recorded in the tree-ring record. The sample in the upper right hand corner (B) shows an extreme example of nearly 40 years of growth suppression, indicated by the black bar. The suppression began after the 1932 Matilija Fire. The sample at the bottom (C) shows no scarring but does have a strong growth release (marked by the black bar) that begins in 1784, two years after the reconstructed 1782 fire, and ends roughly 10 years later. This 10 yr period of growth is noticeably larger than the previous and following years of growth.

Using a belt sander, we sanded all sections to a high-grade polish using progressively finer paper. Each section was cross-dated using standard dendrochronological techniques to determine the exact calendar year (Dietrich and Swetnam 1984, Baisan and Swetnam 1990) and the approximate beginning and end of growth change periods (Mutch and Swetnam 1995).

Fire History Reconstruction and Analysis

The fire-scar dates from all sampled trees within each stand were composited into stand level chronologies using FHX2 and FHAES, which are integrated software packages for graphing and statistical analysis of fire histories (Grissino-Mayer 2001, http://frames.nbii. gov/fhaes). When at least one tree within a given stand recorded a fire scar, that event was considered a fire year in the stand level fire-scar chronology. If two or more trees within the same stand exhibited marked changes in growth (either positive or negative) in the same year, then that year was considered a fire year in the stand level growth change chronology. The fire-scar and growth change chronologies were then amassed into stand level fire chronologies. All fire-scar dates were included in the stand chronologies. However, when a growth change incident occurred within two years of a dated fire scar, the growth-based occurrence was assigned to the fire year of the dated fire scar, and not considered a separate fire event. For each stand chronology, we calculated the composite stand mean fire interval (MFI), along with the median and range based on fire scars and growth changes.

The stand level chronologies were further compiled into a landscape fire chronology, which allowed us to assess the frequency, relative extent, and synchroneity of fire events across our sampling area. Two reconstruction techniques were employed. One was based on fire-scar data alone (SCAR). The other was based on fire events (EVENT) derived using a combination of fire scars and growth changes. The SCAR-based reconstruction represents a more conservative approach and required at least two scars from different stands for the fire to be included in the landscape fire chronology. The EVENT-based reconstruction required at least one scar and one growth change from separate stands as the minimum requisite for inclusion into the landscape fire chronology.

The relative extent of fires was determined using filtering methods based on minimum percentages of stands recording a fire. The commonly used 10 % and 25 % filters in fire history studies were used to generate averaged landscape MFIs. For comparison purposes, we calculated and compared landscape MFIs derived from the SCAR- and EVENT-based fire history reconstructions. The 10 % composite filter, in which at least 10 % of stands were recording a fire somewhere within the sampled landscape, was generally used to indicate less extensive, more localized fire events. The 25 % composite filter was typically used to infer more extensive, landscape level fire events (Swetnam and Baisan 2003).

It should be noted that MFI is not equivalent to natural fire rotation, which is the average time required to burn over an area equal to the size of the study area. Nor is it equivalent to the so-called population MFI, which is the average time between fires occurring at any random point in the sampled area. The MFI is defined here simply as the average interval between any detected fire occurring anywhere within a sampled area (Romme *et al.* 1980). In the case of filtered fire events, we infer that these MFIs are intervals between fire events of increasingly larger areas burned within the study area in a relative sense only. In other words, 25 % filtered fire events are interpreted to have burned relatively larger areas than 10 % fire events.

We examined temporal changes in 10 % and 25 % landscape composite MFIs, for both

reconstruction techniques, using 1864 as a benchmark for shifts in fire regime characteristics due to modern anthropogenic influences, in particular Spanish settlement and congregation of Native Americans into coastal missions. This year also marks the beginning of a prolonged fire-free period that appears to be a significant departure from the previous centuries of fire history.

We also examined the number and types of indicators used to reconstruct each fire year. This allowed us to assess the relative influence of indicator type (fire scar or growth change) on fire frequency and relative extent estimates, and to test for differences in scarring rates over time. Results from a Kolmogorov-Smirnov test for goodness-of-fit indicated that the distribution of fire intervals were non-normal. Therefore, potential differences between MFI estimates and differences over time were tested using the non-parametric Mann-Whitney U test. The null hypothesis was that MFIs did not differ significantly among the comparisons. We rejected the null hypothesis when probability levels for the individual tests were less than 0.05.

Fire Atlas Corroboration

For each stand, we compared fire events including fire scars and growth changes recorded in the stand level tree-ring record with documented modern fires using the California Fire History Database (http://frap.cdf.ca.gov/). This atlas contains fire names, dates, and perimeter boundaries for all known fires larger than 40 ha that have occurred within Forest Service boundaries since 1910. It should be noted that fire atlases of this sort have an unknown level of accuracy and completeness, especially for early time periods. Moreover, unburned areas within polygons are generally not included. Hence, we consider comparisons of tree-ring evidence with fire atlas data a form of corroboration, rather than an absolute test of

accuracy (Farris *et al.* 2010). Indeed, it is possible that in some cases the tree-ring evidence (particularly fire scars) is a more accurate, high-resolution representation of fire events (at least at point locations) than mapped fire perimeters in the documentary record.

A common objective of fire history research is to obtain a complete inventory of fire years within a given area, particularly major fire years with widespread burning (Swetnam and Baisan 2003, Van Horne and Fulé 2006). Examination of the California Fire History Database (CFHD) indicates that eight modern era chaparral-driven fires (1917, 1928, 1932, 1948, 1972, 1985, and 2002) have occurred in at least one sampling location and that these fires burned a total of 167 013 hectares. The 1932 Matilija Fire (89 100 ha) and 1985 Wheeler #2 Fire (30 191 ha) dominate the sampled landscape during the twentieth century, accounting for more than 70 % of the cumulative 167 013 ha burned.

Assessments were made on a point-by-point basis. At each point, a tree-ring based fire record was created by describing when and how each fire event was recorded (i.e., via fire scar or growth change). We then compared this record with the CFHD. Based on error typology work described in Falk (2004) and also used by Farris *et al.* (2010), we assessed total accuracy and potential errors of fire event detection using fire scars, growth changes, and a combination of both indicators. Type I errors occur when a tree-ring based fire year is detected in a stand despite that location being outside the document-based fire perimeter in that year, while Type II errors occur when tree-ring samples from a stand within a document-based fire perimeter fail to show a fire in that year.

RESULTS

We cross-dated 85 trees from 15 sites across Los Padres National Forest. The 15

sites cover over 40 000 ha (Figure 3). Within each stand, we sampled an average of 6 trees, with a minimum of 3 and maximum of 12 trees per stand. The year 1600 marked the earliest date that 80 % of the stands and more than 30 % of the individual trees were recording fire scars (Figure 5). Therefore, the well-replicated period from 1600 to 2005 was used for the quantitative analyses.

During the period from 1600 to 2005, 238 fire indicators (either fire scars or growth changes) were cross-dated, and 72 % of the events (*n* = 171) were identified using fire scars. All 171 fire-scar records were accompanied by a corresponding growth change event within the same stand; however, because these supplementary growth change events were associated with fire scars from the same stand, they were not included in the analysis. The re-

maining fire events (*n* = 67), those with no direct fire-scar evidence within the same stand, were resolved using only growth change data (Table 1).

At the landscape level, 31 fire years (those occurring in at least two stands in the same year) over the period from 1600 to 2005 were reconstructed using fire scars and growth changes (Figure 6). Twenty-eight (approximately 90 %) of these fires were reconstructed using at least two fire scars, while the remaining three events were reconstructed using at least one fire scar and one growth change indicator (Figure 5).

Fire Atlas Corroboration

The number of actively recording stands within each of the eight mapped modern fire
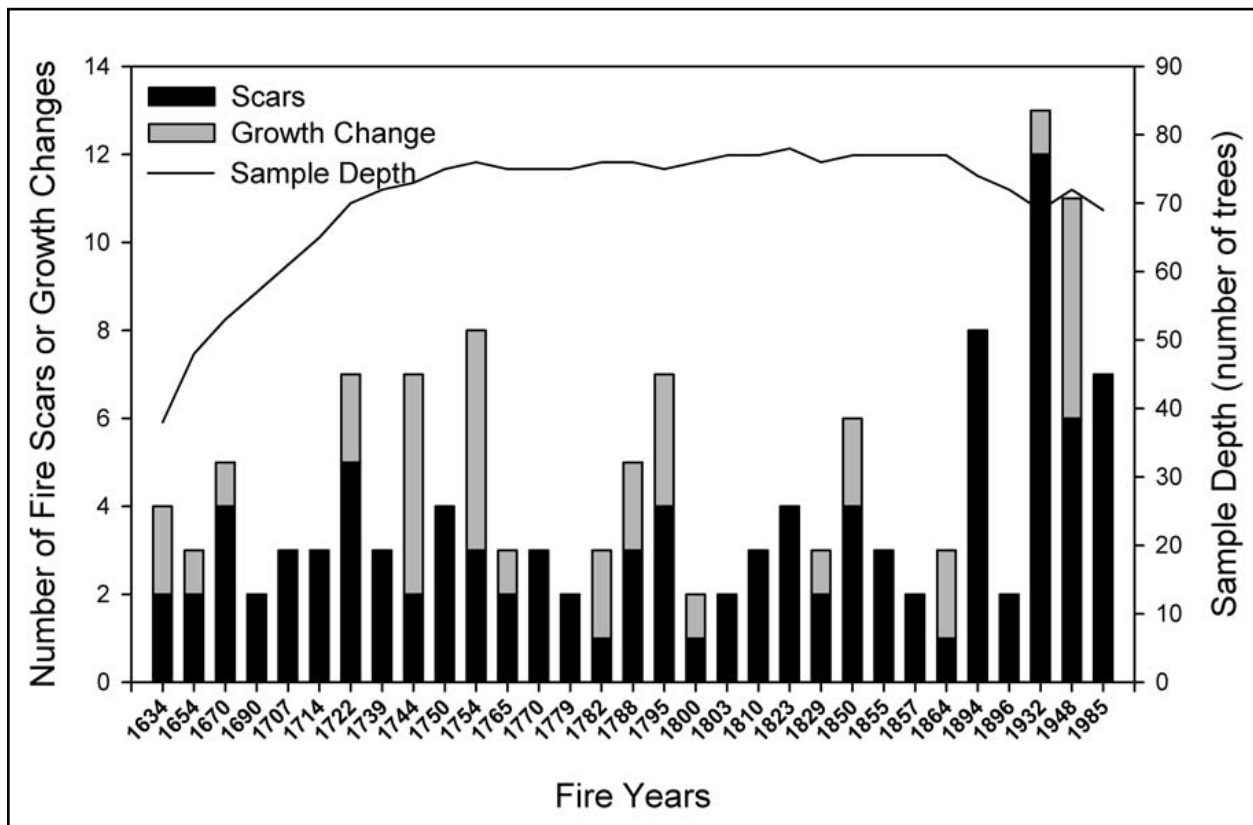

Figure 5. All Los Padres National Forest reconstructed fires, by number of stands and indicator type (fire scar or growth change), for the period 1600 to 2005, as well as individual tree sampling depth for the same period. By the year 1600, 32 % of all trees are considered recording.
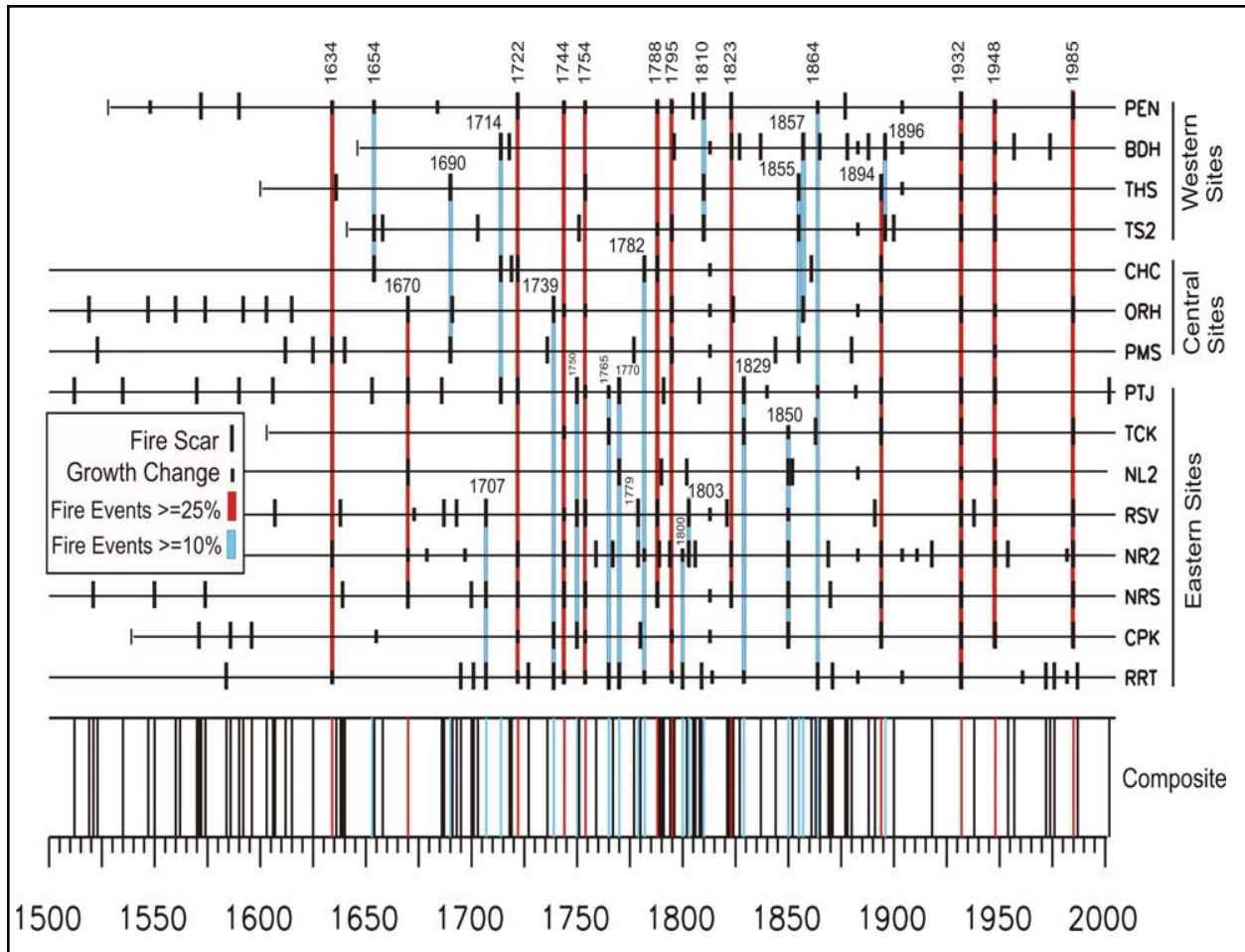
Figure 6. Fire history chart depicting all reconstructed fires in the period 1600 to 2005 for Los Padres National Forest. Red lines indicate widespread fires (25 % composite filter; four or more bigcone Douglas-fir stands) and blue lines indicate smaller, localized fires (10 % composite; two or three bigcone Douglas-fir). Composite depicts all fire events recorded by at least one fire scar. Dates recorded only by growth changes are not included. Growth change data prior to 1600 is not depicted in this representation.

perimeters ranged from 1 to 12, for a cumulative total of 120 possible outcomes. Using only growth change information as evidence of fire produced the lowest number of correct outcomes (96 out of 120), resulting in an 80 % overall rate of agreement. Using both fire scars and growth changes as indicators of fire evidence, the tree-ring record was in agreement with the CFHD 86 % of the time (102 out of 120 possible outcomes). Using only fire scars as evidence, this overall number increases to 91 % (109 out of 120 possible outcomes) (Table 2).

There were 11 instances (9 % Type I error rate), using fire scars and growth changes,

where evidence of fire was detected within the stand despite being located outside the mapped fire perimeter. Using only fire scars, the Type I error rate is only 2 %. Except in one case, these false detections were, on average, 10 km from the mapped perimeters with a range of 5 km to 15 km. Conversely, Type II error rates using fire scars and growth change data (5 %) are lower than that observed when using only fire scar evidence (7.5 %) (Table 2).

Fire History Results

Mean fire intervals. Average point MFIs, using both fire-scar and growth change indica-

Table 2. Error matrix showing number of bigcone Douglas-fir sites within and outside mapped perimeters that recorded a fire year, using fire scars, growth changes and a combination of both indicators as evidence in Los Padres National Forest. Overall accuracy was determined by dividing the number of correct outcomes by the total number of possible outcomes. Type I errors occur when evidence of fire is present outside a mapped perimeter, while Type II errors occur when evidence of fire is absent within a mapped perimeter.

Method	Presence/Absence	No. of sites inside mapped perimeter	No. of sites outside mapped perimeter	Overall accuracy (%)	Type I error (%)	Type II error (%)
Fire scars only	Fire scar present	25	2	90.8	1.6	7.5
	Fire scar absent	9	84			
Growth changes only	Change present	21	11	80.0	9.2	10.8
	Change absent	13	75			
Scars & growth changes	Fire event present	28	11	85.8	9.2	5.0
	Fire event absent	6	75			

tors, for all 85 trees was 29.87 years, with a range of 22.6 years to 45.3 years. The MFIs for individual stands, also using both indicator types, ranged from 13 years to 39 years, with an average of 24.6 years (Table 1). The 10 % and 25 % composite filter MFIs, averaged across the 15 sites, were generated to assess fire regime characteristics at a landscape level. Two reconstruction approaches (SCAR- and EVENT-based) were used. No significant differences *(P* = 0.49) were observed between the SCAR MFI (13.0 years) and EVENT MFI (11.7 years) using the 10 % composite filter (Table 3). Under the 25 % composite filter, the SCAR MFI (52.5 years) was substantially longer than the EVENT MFI (27.0 years). The difference was not statistically significant (*P* = 0.06), but nearly achieved our *a priori* significance level of *P* < 0.05 (Table 3) (Figure 6).

MFIs over time. Despite what appears to be substantial differences in the 10 % and 25 % MFIs (i.e., the mean values), none of the pre- and post-1864 interval distributions were significantly different at the *P* < 0.05 level. The 10 % composite filter MFIs, for both the SCAR- and EVENT-based techniques, more than doubled in (mean) length after 1864. Again, comparative tests of the interval distributions did not show significant differences at our *a priori* level, but nearly so (*P* = 0.08 and 0.07, respectively). Likewise, the pre-1864 MFI was more than double that of the post-1864 MFI under the SCAR-based reconstructed 25 % composite filter, and was nearly but not quite significant (*P* = 0.06). No such distinction between pre- and post-MFIs was observed using the EVENT reconstruction technique (*P* = 0.16) (Table 4).

Table 3. Los Padres National Forest averaged mean fire intervals, by composite filter, for the two reconstruction techniques for the period 1600 to 2007. No statistical significance (*P* < 0.05) was found in the comparison of reconstruction type (SCAR and EVENT) for either composite filter.

Filter type	SCAR-based MFI (min. 2 scars)		EVENT-based MFI (min. 1 scar + 1 GC event)		*P*-value
	Years	*n*	Years	*n*	
10 % composite	13.00	27	11.70	30	0.49
25 % composite	52.50	6	27.00	13	0.06

Table 4. Los Padres National Forest averaged mean fire intervals, by composite filter type, before and after 1864. No statistical significance ($P < 0.05$) was found in the comparison of pre- and post-1864 mean fire intervals for either composite filter type within both reconstruction techniques.

	SCAR-based MFI					EVENT-based MFI				
	1600 to 1864		1865 to 2005		*P*-value	1600 to 1864		1865 to 2005		*P*-value
Filter type	Years	*n*	Years	*n*		Years	*n*	Years	*n*	
10% composite	10.14	23	25.60	5	0.08	9.20	25	24.20	5	0.07
25% composite	90.00	2	33.75	4	0.06	24.00	9	33.75	5	0.16

Scarring rates and growth change events over time. The average number of stands that recorded fire events in the form of fire scars up to 1864 was 2.4. Beginning with the 1894 fire, this number rises significantly to 7.0 ($P = 0.006$). Conversely, the number of stands that record fire events in the form of growth changes remains unchanged over this same period ($P = 0.71$) (Figure 5).

DISCUSSION

Our results provide the first multi-century, high-resolution fire history of chaparral fire regimes in southern California. Our findings also illuminate, for the first time, long-term fire regime patterns in bigcone Douglas-fir stands, a species whose conservation is considered a high priority by the Forest Service.

The results of the fire atlas corroboration indicate that the bigcone Douglas-fir fire-scar record generally reflects the history of widespread fires in surrounding chaparral. Overall agreement between the tree-ring record and the CFHD ranged from 80% using only growth change data, to 91% when using fire scar evidence alone. While all three techniques provide a robust validation of the modern fire record, each has its own strengths and weaknesses. Using just fire-scar data provides the highest level of corroboration and lowest Type I error rate, which suggests that fire-scar evidence, when available, can provide highly accurate spatial and temporal estimates of widespread fire events. However, not all samples

record or preserve fire evidence in the form of scars, and this contributes to the slightly higher Type II error rate. Despite a slightly lower percentage of overall agreement (86%), using growth changes in conjunction with fire scars lowers the Type II error rate. This suggests that growth change data enhance the ability to detect fire evidence when conditions prevent scar formation or preservation. However, a substantially higher Type I error rate is associated with this methodology. Using only growth change information provides the lowest percentage of overall agreement, with a roughly equal chance of obtaining a Type I (9.2%) or Type II (10.8%) error.

The indication of fire evidence outside of the mapped perimeter may imply that some growth events are not evidence of fire and instead reflect other environmental changes. However, it is also possible that the use of both indicators may provide a more accurate estimate of twentieth century fire perimeters and history of smaller, undocumented fires (Figure 7). In one instance, the false detection was less than 100 m from the mapped fire perimeter. In this case, it seems likely that the mapped fire perimeter is inaccurate. In the other cases, the false detections were at least 3 km from the mapped perimeter. However, the CFHD is considered to be complete only for fires greater than 40.5 ha (J. Miller, Forest Service, personal communication). The absence of these smaller events in the dataset may inflate the perceived error rate of our corroboration. Given the high fidelity of the tree-ring record and
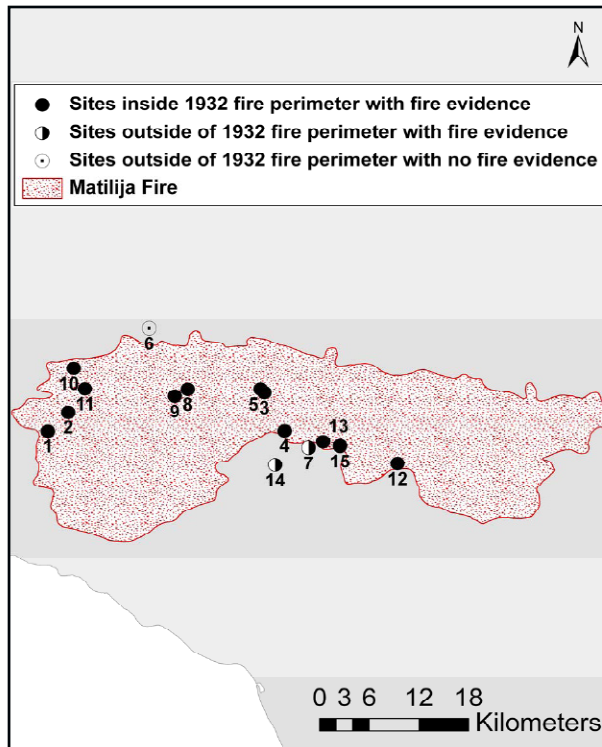
Figure 7. 1932 Matilija Fire perimeter with big-cone Douglas-fir stand locations in Los Padres National Forest. Full black points indicate sites within the fire perimeter that recorded the fire. Half black points indicate sites outside the fire perimeter that do not record the 1932 fire. Open points indicate sites outside the fire perimeter and have some indication of fire activity in 1932.

the lack of a complete record of all fires, it is a reasonable assumption that the false detections are actually separate fire events, which occurred during the same year and went undetected or unrecorded.

No statistical differences in interval distributions were observed between either of the reconstruction techniques (SCAR- or EVENT-based) using the 10 % filtered composites. In fact, the SCAR MFI (13.0 yr) and the EVENT MFI (11.7 yr) are within two years of each other and both methods suggest that small, localized events occurred at decadal intervals. In other words, about once per decade, somewhere within the sampled landscape, a fire would spread through areas encompassing 2 or 3 of the sampled stands. However, it appears that this component of the fire regime has been

essentially eliminated from the present day chaparral fire regime. Under both reconstruction techniques, the modern era 10 % composite MFIs (~25 years) is now roughly equal to the modern era 25 % composite MFI (~30 years). This suggests that widespread, landscape-scale fires now dominate the twentieth century fire regime, but that previously there was a mixture of relatively small and large fires. This may be related to the large majority of modern era fires that are extinguished well before they reach 4000 ha, which has been identified as an approximate tipping point at which fires tend to become less controllable and often larger in size (Moritz 1997).

Without a fully systematic sampling approach (e.g., gridded or random), estimates of historical fire sizes in terms of absolute number of hectares must be considered relatively coarse. However, convex hulls drawn around opportunistically sampled fire-scar locations have been shown to be reasonable estimators of twentieth century fire extent (Falk 2004, Collins and Stephens 2007, Shapiro-Miller *et al.* 2007). The simplicity of this methodology can lead to either overestimation or underestimation of fire sizes. Convex hulls can produce a conservative estimate of fire size when study sites do not span the entire larger landscape where fires could have, and undoubtedly did, spread. Conversely, the methodology can lead to an overestimate of fire size as there were probably many patches of unburned landscape within the actual fire perimeter.

Using this methodology, we estimate that the average fire size for 10 % composite fires was roughly 3600 ha, with a range of 2143 ha to 41 712 ha. This estimate does not include fires that burned in only one stand (not included in the landscape scale MFI reconstruction) or those that burned two stands (convex hulls require a minimum of three points), which presumably represent smaller fire events than those used to generate our 10 % composite fire size estimate. Regardless, it is interesting to

note that our estimate of 3600 ha for these smaller events is similar to the 4000 ha threshold identified in Moritz's (1997) study of Los Padres National Forest chaparral fire regimes. Moritz demonstrates that fires that burn less than 4000 ha are more likely to occur in moderate weather conditions when Santa Ana winds do not occur.

A non-significant difference (at $P < 0.05$ level) in the 25 % composite fire interval distributions was estimated between the two reconstruction techniques, but the SCAR-based MFI (52.5 yr) was nearly twice as long the EVENT-based MFI (27.0 yr). We posit that differences in these interval distributions are actually real, and are ecologically important. The statistical significance of the non-parametric means test (Mann-Whitney) result missed achieving our *a priori* set level by 1 chance in 100, (i.e., a *P* level of 0.06 rather than a *P* level of 0.05). It is entirely possible that a larger sample size might enable the use of a more powerful parametric test, or a more robust significance estimate that would detect a difference at the $P < 0.05$ level. In any case, a probability of obtaining these two interval distributions from the same (or indistinguishable) fire interval populations by chance in only 6 tries out of 100 is small.

Our 25 % composite EVENT MFI of 27.0 years is consistent with existing historical fire information available for the region and with MFIs at varying spatial scales within this study. Mensing *et al*. (1999) found that Santa Ana-driven, landscape-scale fires have occurred, on average, at 24-year intervals over the past 560 years. Using both fire scars and growth changes, the average MFI for individual bigcone stands is 24.6 years, while the average point MFI is 29.9 years (Table 1). We believe that the pattern observed here is one that reflects a fire regime that is not strongly scale-dependent. When this pattern occurs, it is generally indicative of very widespread fires acting as the dominant fire regime characteristic

(Falk 2004). Furthermore, our results provide a more spatially specific validation of the Mensing *et al*. (1999) estimate despite having minimal overlap in sampling areas.

The 25 % composite MFI identifies events that occurred in four or more isolated stands. When convex hulls are drawn around the indicating stands, we estimate that the average fire size of these more extensive fires to be roughly 17 000 ha, with a range of 9802 ha to 74 778 ha. Again, given the nature of this approach, it is likely that many of these fires were much larger and contained large patches of unburned landscape within them, but our estimate is in accordance with the Mensing *et al*. (1997) classification of large fires events as those greater than 20 000 ha.

It should also be noted that almost all of the 25 % fire events were recorded in sites spanning three sub-areas across the study area (eastern, western, and central sites), whereas most of the 10 % fire events were recorded in sites restricted to only one or two sub-areas (Figure 6). Exceptions were 1670 (25 % fire event recorded in two sub areas), and 1864 (10 % event recorded in three sub-areas). Given the large sample size during the 1860s, it seems likely that the 1864 fire event was actually two separate, non-contiguous burns. This convergence of evidence implies that the 25 % composite MFI is likely reflective of extensive, wind-driven fire events.

Minnich and Chou (1997) suggest that the systematic suppression of ignitions promoted the landscape-scale fire events that plague twentieth century southern California. They contend that fire suppression has increased fuel continuity by deferring the combustion of chaparral vegetation patches relative to local thresholds of fuel accumulation. This, in turn, has selected for escaped fires in mature patches to coincide with extreme wind events, which create conditions that are unmanageable from a fire suppression standpoint. The current fire regime of rapid fire spread and extensive patch re-burn is,

therefore, interpreted to be a product of these management actions (Minnich and Chou 1997).

The tree-ring record does, in fact, show an abundance of pre-historic localized fire events, which may have produced a relatively fine-grain mosaic of chaparral age classes. Both widespread and localized fires populate the fire history of Los Padres National Forest until 1864. The tree-ring record then begins to show a perceptible decrease in localized events into the twentieth century. Following a 30 yr absence of much fire evidence of any kind, 1894 marks the first of four widespread fire events that dominate the late nineteenth and twentieth century fire history record. Also evident during this transitional period is an increase in scarring rates amongst trees during the widespread events. Beginning with the 1894 fire and continuing into the modern period, the number of fire scars detected per fire increased, on average, from 2.5 (1600 to 1893) to 7.0 (1894 to 2005). The sample depth of individual trees remained relatively constant over this time, which indicates that the observed increase is not an artifact of numbers of fire scarred trees included in the sample set (Figure 5).

We hypothesize that the increased scarring rate may reflect increasing severity of fires in the late nineteenth and twentieth centuries relative to earlier periods of our record. Changes in fire severity within stands may have been related to fire suppression activities resulting in changes in fuel continuities or types in the understory of these bigcone stands. However, many experts believe that effective fire suppression in southern California did not start until the early 1950s, which is decades after the increase in scarring prevalence that we observed (Davis and Michaelsen 1995, Moritz 1997, Keeley 1999). For example, Forest Service records indicate that within the 1932 Matilija Fire perimeter, only two lighting-started fires were suppressed in the previous 22 years (Keeley and Zedler 2009). Moreover, we lack any evidence at this time of changes in fuels within bigcone Douglas-fir stands.

Alternatively, changes in fire occurrence or severity could be related to climate variations or seasonal timing of fires. Recent work by Keeley and Zedler (2009) suggests that increased drought occurrence, coupled with increasing ignitions by humans, may explain the abundance of modern landscape-scale fires. Evidence linking drought and increased wildfire activity (i.e., numbers of large fires or total areas burned) are increasingly apparent across the western US (Westerling *et al.* 2006) and may be playing some role in the southern California landscape (Keeley and Zedler 2009). It is more difficult, however, to assess changes in severity because most fire atlas data do not include severity classifications, and only recently are these types of data becoming available from remote sensing. Finally, many of the modern era ignitions, like the Matilija Fire, are human-caused. It is possible that pre-historic ignitions were more likely to be lightning caused; however, the fire-scar evidence suggests that there were more fires in the past than in the twentieth century in our study area. This suggests that, even prior to Spanish and Anglo settlement, there had been anthropogenic fire use in our study area to some degree. It is possible that something in the nature of human use, such as increased road access, arson, or a seasonal shift in ignitions, has led to starts that were more likely to turn into large, severe fires. These types of changes may well have created different burning conditions, especially in the presence of extreme wind events.

The role of human-caused ignition in the pre-historic era cannot be ignored. Native Americans often used fire to manipulate vegetation, and their subsequent removal from the landscape following Spanish settlement deserves attention as a possible contributing factor to fire regime alterations. The historical influence of Native Americans on chaparral fire regimes has not been completely resolved; however, there is little doubt that fire was used to some extent to purposely alter vegetation patterns (Keeley 2002). Ethnographies of

southern Californian natives suggest that fire was prominently used for a number of purposes (Anderson 2006). Christenson (1990) found widespread archeological evidence in all 32 US Geological Survey quadrangles of what is now San Diego County.

The establishment of the San Buenaventura (1782) and Santa Barbara (1786) missions represents the first major European effort to settle the central coast region of California. By the turn of the century, much of the native population had been brought onto the mission territories. The frequency of fire that we observed in the 1700s is higher than that observed in the years following Spanish settlement of the region. Additionally, some stands, located near prominent water sources in Los Padres National Forest, have substantially higher fire frequencies than others. Site 2 (near modern day Pendola Campground) and Site 13 (Nordoff Ridge above Ojai) are two stands with shorter intervals than most (MFIs of 15 years and 13 years, respectively).

The establishment of Spanish pastoralism at the turn of the eighteenth century and subsequent congregation of Native Americans into areas near Spanish missions may have concentrated fire use in the lower foothills of the coastal ranges and thereby eliminated or reduced the human component of the fire regime in the chaparral dominated interior of the coastal ranges by the mid-1800s (Keeley 2002). The nearly complete absence of localized fires after the 1860s is apparent in our reconstruction, and this may have contributed to a shift towards more severe and widespread fires around the turn of the century.

Putting our findings together with existing knowledge, we hypothesize that numerous small fires, which typically ignited during the summer months and occurred under moderate weather conditions, were relatively common in the historical southern California chaparral landscape. Occasionally, these small fires would smolder and hold over into the autumn months when strong Santa Ana winds have the potential to turn localized events into landscape scale conflagrations. Lack of noticeable change in frequency of widespread events over the past 400 years, as evidenced in this study and Mensing *et al.* (1999), coupled with the fact that more than 90 % of the fire scars in the tree-ring record were positioned in the latewood or dormant portion of each ring (K. Lombardo, University of Arizona, unpublished data), implies that landscape-scale fires have shaped the chaparral landscape for many centuries. As in recent decades, past widespread fires were likely driven by extreme winds and drought conditions.

From our fire history, we interpret that many localized fires, fueled by occasional lightning strikes and possibly ignitions by Native Americans, were frequent but not extensive. Because many fires were relatively small in size (occurring in fewer than three stands), we speculate that these fires could have played a considerable role in shaping the ecology and structure of bigcone Douglas-fir and chaparral stands without significantly changing the frequency or extent of widespread fires.

It is apparent from ecological and historical evidence that chaparral communities may not persist when mean fire intervals are less than 10 yr to 15 yr (Keeley 2006, Syphard et *al.* 2006). If the 10 % composite MFI were to be interpreted as a return interval for a specific point in space, then it would seem that intervals of less than 15 years, like that seen in both the EVENT- and SCAR-based reconstructions, would run counter to chaparral life histories and survival strategies. However, the composite MFIs are not equivalent to average point fire intervals, population means fire intervals, or natural fire rotation. They are an estimation of average intervals between fires of any size, or of an estimated size class, occurring anywhere within a study area (Romme *et al.* 1980).

In this case, our 10 % composite MFI estimates that somewhere within the sampled

landscape a fire of approximately 4000 ha occurred every 10 yr to 15 yr, though not necessarily in the same location. Furthermore, the average point MFI is 29.9 years, while the average MFI for individual bigcone Douglas-fir stands is roughly 24.6 years (Table 1). The multi-decadal nature of the intervals reflected in the point and individual stand record would seem to provide another line of evidence that supports the conventional body of literature regarding chaparral life history and reproduction strategies.

Prior to 1894, fire scar evidence became less abundant and growth changes played a more prominent role in the tree-ring record (Figure 5). This, coupled with the observed similarity between the SCAR- and EVENT-based 10 % composite MFIs and the nearly 20 yr difference in 25 % composite intervals, implies that including the growth change information is essential for obtaining a full picture of temporal changes. We posit that more variable fuel loads (and possibly types of fuels) created by numerous small fires resulted in reduced synchrony and scarring rates within and among widespread stands. The scar record was abundant enough to reconstruct a robust fire history as only 3 of the 31 reconstructed fire events were based on one scar and one growth change indicator. However, growth change data prior to 1894 becomes increasingly important as a method of estimating the relative extent of past fire events, particularly large fires, as variability in fuel loads was likely greatest over large areas.

Given the novelty of our approach, we acknowledge that uncertainties remain regarding the connections between fire severity, growth changes, and scarring patterns. More observations and sampling work focusing on these links is needed to assess the strength of our interpretations of scarring rates and growth change data. In particular, it would be valuable to evaluate observed fire severity levels within and between stands during recent fires and compare them with scarring rates and subsequent ring growth changes in surviving trees. Likewise, more extensive and spatially distributed tree-ring collections could lead to more robust tests (or even calibration) of the tree-ring record with recent mapped fire occurrence and severity data. It would also be valuable to assess historical aerial and ground-based photographs to evaluate the possible changes in extent and connectivity between bigcone Douglas-fir stands over the past 50 yr to 100 yr, because if spatial changes have occurred, this might be a factor explaining some of the changes in the tree-ring and fire history record.

In summary, this comprehensive case study provides a historical examination of fire history in a chaparral dominated landscape and gives land managers a frame of reference that could support decision-making and assist in the development of current and future chaparral fuel management strategies. Additional studies in other areas and at other elevations are needed before these findings can be applied more generally across the southern California landscape. Understanding how this fire history relates to one developed from low elevation stands that border residential development is of particular interest. Southern California has one of the highest numbers of housing units located within the wildland-urban interface and, despite recent economic difficulties, housing growth in these areas is expected to continue in the future (Radeloff *et al*. 2005, Safford 2007). In light of our findings, we suggest that effort and costs may be better spent on wildland-urban interface management and updating zoning regulations to reflect the current scientific consensus. In the context of low fuel moisture levels and strong Santa Ana wind events, irregular spatial arrangement of fuels has been shown to be ineffective in controlling fire spread in chaparral landscapes (Moritz 1997, Keeley 2001, Keeley and Zedler 2009). The historical and modern records both imply that large, landscape-scale fires are inevitable in chaparral landscapes.

ACKNOWLEDGEMENTS

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