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Large, high-intensity fire events in southern California shrublands: debunking the fine-grain age patch model

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Abstract. We evaluate the fine-grain age patch model of fire regimes in southern California shrublands. Proponents contend that the historical condition was characterized by frequent small to moderate size, slow-moving smoldering fires, and that this regime has been disrupted by fire suppression activities that have caused unnatural fuel accumulation and anomalously large and catastrophic wildfires. A review of more than 100 19th-century newspaper reports reveals that large, high-intensity wildfires predate modern fire suppression policy, and extensive newspaper coverage plus first-hand accounts support the conclusion that the 1889 Santiago Canyon Fire was the largest fire in California history.

Proponents of the fine-grain age patch model contend that even the very earliest 20th-century fires were the result of fire suppression disrupting natural fuel structure. We tested that hypothesis and found that within the fire perimeters of two of the largest early fire events in 1919 and 1932, prior fire suppression activities were insufficient to have altered the natural fuel structure. Over the last 130 years there has been no significant change in the incidence of large fires greater than 10 000 ha, consistent with the conclusion that fire suppression activities are not the cause of these fire events. Eight megafires ($\geq$50 000 ha) are recorded for the region, and half have occurred in the last five years. These burned through a mosaic of age classes which raises doubts that accumulation of old age classes explains these events. Extreme drought is a plausible explanation for this recent rash of such events, and it is hypothesized that these are due to droughts that led to increased dead fine fuels that promoted the incidence of firebrands and spot fires.

A major shortcoming of the fine-grain age patch model is that it requires age-dependent flammability of shrubland fuels, but seral stage chaparral is dominated by short-lived species that create a dense surface layer of fine fuels. Results from the Behave Plus fire model with a custom fuel module for young chaparral shows that there is sufficient dead fuel to spread fire even under relatively little winds. Empirical studies of fuel ages burned in recent fires illustrate that young fuels often comprise a major portion of burned vegetation, and there is no difference between evergreen chaparral and semi-deciduous sage scrub.

It has also been argued that the present-day fire size distribution in northern Baja California is a model of the historical patterns that were present on southern California landscapes. Applying this model with historical fire frequencies shows the Baja model is inadequate to maintain these fire-prone ecosystems and further demonstrates that fire managers in southern California are not likely to learn much from studying modern Baja California fire regimes. Further supporting this conclusion are theoretical cellular automata models of fire spread, which show that, even in systems with age dependent flammability, landscapes evolve toward a complex age mosaic with a plausible age structure only when there is a severe stopping rule that constrains fire size, and only if ignitions are saturating.

Key words: 19th century; Baja California; chaparral; fine-grain age patch mosaic; fire history; high-intensity fires; megafires; sage scrub; Santa Ana winds.

> *During the past three or four days destructive fires have been raging in San Bernardino, Orange and San Diego ... It is a year of disasters, wide-spread destruction of life and property—and, well, a year of horrors.*
>
> —*The Daily Courier*, San Bernardino, 27 September 1889

Introduction

Shrubland-dominated landscapes in California have fuel characteristics conducive to high-intensity wildfires that commonly reach sizes of 10 000 ha or more (Keeley et al. 1999). Some researchers have postulated that such fire events are anomalous and were unknown prior to putative perturbations of the natural fuel structure by 20th-century fire suppression (Bonnicksen 1981, Minnich 1983, 1995, 2001). These authors have argued that

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historical fire regimes were profoundly different than contemporary fire regimes. In their model, frequent lightning or Indian burning created a fine-grain age patch mosaic of small low intensity smoldering fires, and the resulting patchwork of young and old fuels prevented large fires due to the inability of young seral stands to carry fire. Proponents of this model predict that if the purported 19th-century fire regime were restored to contemporary landscapes, then large high-intensity crown fires could be prevented. Although many have discounted this model (Keeley et al. 1989, 1999, Zedler 1995, Moritz 1997, 2003, Conard and Weise 1998, Zedler and Seiger 2000, Keeley and Fotheringham 2003, Moritz et al. 2004), it is being advocated in newspaper op-ed pieces (Minnich 2003, Chastain 2007), in national newspaper stories (LaFee 2004, Vick and Geis 2007) and Web sites of timber advocacy groups (e.g., California Forest Foundation 2007), as well as in a recent *Ecological Applications* paper (Goforth and Minnich 2007). We believe the time is right for a more thorough analysis of this fine-grain age patch mosaic model as it has the potential for affecting public opinion, and ultimately resource allocation for fire management activities, as well as stalling needed land zoning reforms (Gang 2007, McDaniel 2007, Phelps 2007).

Large high-intensity fires

Large infrequent disturbances have always been major drivers of ecosystem structure and function (Turner and Dale 1998), but increasingly in a world filled with people, they pose significant challenges. This is certainly the case for wildfire, which has repeatedly overwhelmed the capacity of fire managers to regulate it, especially in the fire-prone Mediterranean climate region of the Pacific Coast. One of the most basic questions is what can be done, through modified management practices and land development policies, to make fires less damaging to humans and their property.

In the western United States, large wildfires in recent decades have been ascribed to past management practices that have altered fuels in many forested ecosystems (Allen et al. 2002). It is widely believed that very large high-intensity fires in these ecosystems are anomalous events that were unknown historically. This model is most applicable to southwestern U.S. ponderosa pine and southeastern U.S. longleaf pine forests. These landscapes historically experienced a very high frequency of lightning ignited fires, which in the absence of human interference, maintained open tree canopies and limited surface fuels, and this promoted a regime of low intensity surface fires (Glitzenstein et al. 1995, Allen et al. 2002).

Large high-intensity crown fires are considered to be a natural feature in many ecosystems (Turner and Romme 1994, Johnson et al. 2001, Meyn et al. 2007; Keane et al., *in press*), including California shrublands, which are often driven by severe winds known as Santa Anas (Fig. 1). However, some argue that in the absence of human interference, fires in California chaparral shrublands were small and of low to moderate intensity (Bonnicksen 1981, Minnich 1983, 1995). They claim that frequent natural lightning ignited fires burned small patches (100–1000 ha) at a sufficient frequency and arrangement to produce landscape mosaics of fuels, and once a patch burned it would act as a barrier to fire spread for several decades due to insufficient fuels. They contend that the appropriate fire management for this landscape is one that couples a wildland fire use policy for summer wildfires with extensive landscape scale fuel modification through rotational prescribed burning that produces a fuel mosaic putatively capable of preventing large wildfires (Minnich and Dezzani 1991, Minnich and Chou 1997, Minnich and Franco-Vizcaino 1999, Minnich 2001).

Hypothesis and predictions

Here we test the null hypothesis that prior to aggressive fire suppression, fire regimes in the shrubland dominated landscape of southern California were characterized solely by low to moderate intensity fires that generated a fine-grain age patch mosaic of fuels, which prevented large fires. The alternative hypothesis is that large contemporary shrubland fires are within the historical range of variability for this landscape.

This fine-grain age patch model has profound implications for fire management because it contends that large catastrophic wildfires on these landscapes are the fault of fire suppression policy that has perturbed the 'natural' fire regime, and the appropriate remedy is to abandon total fire suppression. The alternative hypothesis argues that large catastrophic fires are the result of internal and external natural forces and vulnerability of human communities is tied more to inadequate land planning and infrastructure protection.

Predictions deduced from the fine-grain age patch null hypothesis, and tested here, are:

1) There is no credible evidence that 19th-century fires were large (10^3–10^5 ha) or high intensity (flame lengths > 5 m).

2) Early 20th-century fires are linked to immediate disruptions in natural fire regimes due to fire suppression of natural lightning-ignited fires, and large fires have increased throughout the 20th century.

3) Fire spread in California shrublands is age dependent such that fires will not spread in early seral stages because of their low dead-to-live fuel ratio, imposing a threshold age of about two to three decades before these stands become flammable.

4) The fine-grain patchwork of fire sizes in Baja California represents the historical condition in southern California and when this model is coupled with the historical fire frequency from lightning ignitions it will predict a stable equilibrium in fire regime within the expected historical fire return interval of 50–100 years.

5) Theoretical models constrained by patch age should develop fine-grain structure spontaneously,

FIG. 1. Santa Ana wind-driven fires and smoke in 2003 from Ventura County, California, USA, to San Antonio de Las Minas near Ensenada, Mexico (SALM arrow). Note the apparent lack of Santa Ana winds on the fire farther south near Santo Tomás (ST arrow at bottom of panel) due to effects of the Gulf of California and San Pedro Mártir (see Keeley and Fotheringham 2001*a*, *b*). Image captured by the Moderate Resolution Imaging Spectro-radiometer (MODIS) on the Terra satellite on 26 October 2003. ⟨http://earthobservatory.nasa.gov/NaturalHazards/shownh.php3?img_ id=11799⟩

which once present will persist on the landscape due to resilience to changes in ignition and fire behavior.

METHODS

Historical accounts of 19th-century fires in southern California were obtained from newspapers on microfilm at the California State Library (Sacramento, California, USA), unpublished reports in the U.S. National Archives (San Bruno, California; Laguna Niguel, California; and Washington Archives II, College Park, Maryland) and U.S. Forest Service (USFS) Angeles National Forest (Supervisor's Office, Arcadia, California), and library materials. Copies of the 1878 Tujunga Cañon Fire perimeter map were copied from maps on file at the USFS Angeles Forest Supervisor's Office, Arcadia, California and from the U.S. National Archives, Washington Archives II, College Park, Maryland.

Numerical fire history data were obtained from multiple sources. The California Department of Forestry and Fire Protection, Fire and Resource Assessment Program (FRAP) Statewide Fire History electronic database is generally complete for fires greater than 40 ha but most fires less than 25 ha are not included.

Individual fire reports for selected years were obtained from one of the national archives offices listed above or directly from a regional USFS office. Long-term trends in fire size were done with least-squares regression analysis using Systat 11.0 (Systat, Richmond, California, USA).

Palmer drought severity indices (PDSI) were obtained from two sources: one for 20th-century data by month (*available online*)[6] and one for summer PDSI for the 19th century (*available online*).[7]

Modeling of expected fire behavior using either field measures of fuels or standard fuel models was done with Behave Plus 4.0. This is a PC-based software application for Microsoft Windows used to predict wildland fire behavior (software *available online*).[8] Rothermel equations that are used in the Behave Model have short comings when applied to chaparral (Zhou et al. 2005), but we believe it is appropriate to our application in young seral chaparral. Here dead fuels dominated and the bulk were within 75 cm of the soil surface.

Theoretical expectations of the fine-grain age patch model were explored with a cellular automata model, which creates a square map divided into cells that have two properties, location in the *x–y* grid and age, the number of time steps (years) since that cell was "burned." These kinds of models have been proposed by a number of others, usually with the intent of building a model that would replicate fire behavior in real landscapes (Clarke et al. 1994, Encinas et al. 2007, Yassemi et al. 2008). The minimum age at which burning is possible (minage) is either a constant throughout a given run or allowed to vary from one year to the next. In both cases, it is assumed to be constant over the landscape. The model moves by 1-yr time steps, incrementing the age of all cells each year prior to the "burn season." Within a given year, the burning process is initiated by one or more random ignitions. If the age of the element receiving the ignition is greater than minage, that cell burns in its entirety and its age is set to zero, if it is less than minage, the cell does not burn. The fire spreads contagiously and probabilistically The propagation of the fire to the eight cells that touch on a burning cell (the "Moore neighborhood" [Gaylord and Nishidate 1996]) is limited stochastically by a "probability of propagation" that can vary from zero (the fire cannot spread from the cell ignited) to one (the fire will spread to all of the adjacent cells ≥minage unless they are already burning). The probability of propagation is constant for each simulation run. Wind and slope effects and spotting, the spread of fire by the dispersion of burning brands beyond the flame front, are not included in the model.

In the first series of simulations, all cells were of age 1 at the beginning to observe the development of the age mosaic from a uniform condition. In the second set of simulations, the starting landscape began with an age mosaic in which ages between 0 and *minage* years were assigned randomly and independently to each cell. The model was run to determine the length of time until coalescence was substantially achieved as indicated by 90% or more of the cells burning in a single year. Since the first simulations showed that coalescence would not occur for low values of probability of propagation only values of 0.4 and above were used. The simulation was run multiple times at each combination of propagation probability and number of strikes per cell to average out random variability. Runs were made with up to 40 000 cells, but as the outcomes for smaller areas were substantially the same, results are presented for a 900- and 2500-cell landscape. The model was programmed in MATLAB 7.5 (The MathWorks, Natick, Massachusetts, USA) and run on a Macintosh G5 computer (Apple Computer, Cupertino, California, USA).

Results and Discussion

Large historical fires in the 19th century

Here we investigate the question, are contemporary fires in southern California greatly outside the historical range of variability in terms of size and intensity because of 20th century fire suppression? We test the following prediction deduced from the fine-grain patch model: There is no credible evidence that 19th-century fires were large (10^3–10^5 ha) or high intensity (flame lengths $\gg$ 5 m).

On these landscapes, the fine-grain age patch model predicts that fire suppression is the primary factor disrupting natural fire regimes. Pre-suppression era logging, which is known to have increased fuels in some western forests is not a factor on these shrubland landscapes. Pre-suppression era grazing, which reduced the incidence of grass-driven fires and caused an increase in saplings and other ladder fuels in some southwestern pine forests (Savage and Swetnam 1990), does not apply to these shrubland landscapes as the primary impact of grazing has been to type convert shrublands to grasslands with lower fire hazard (Keeley and Fotheringham 2003).

In the 19th century, before development of roads in most mountainous areas of southern California, and lack of an organized fire fighting force, fire suppression was very limited. Rural residents did fight fires, but it was largely defensive and focused on stopping fires from destroying structures and crops on outlying ranches and farms (Kinney 1900) and "no effort was made to stop [fires] after they reached the mountains" (Mendenhall 1930). In short, fire suppression did not affect wildland fire regimes in any significant way in this region. The overview of 19th-century fires presented here depends heavily on historical accounts of large fires that are captured in the 108 newspaper reports transcribed in Appendix A.

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[6] ⟨http://www1.ncdc.noaa.gov/pub/data/cirs/drd964x.pdsi.txt⟩

[7] ⟨http://www.ncdc.noaa.gov/paleo/usclient2.html⟩

[8] ⟨http://www.firemodels.org/content/view/12/26/⟩

1878 Tujunga Cañon Fire

The earliest fire recorded in the CalFire FRAP historical fire database is a 24 100-ha 1878 fire in the vicinity of Tujunga Canyon in the western end of the San Gabriel Mountains of Los Angeles County. Many years later, Mendenhall (1930) described this fire and noted it was in the first half of September. The Los Angeles Daily Herald (Appendix A: transcript 6) reported for a dateline "SAN FERNANDO, Sept. 11 [1878]" that "A fire originated in the brush near the little Tujunga Cañon on the 9th instant, at about ten o'clock A. M., and was soon beyond control." The article notes that within the first four hours the fire consumed over 7000 ha and was still burning. Based on this initial rate of spread, and the fact that it was reported to be burning in the backcountry the following day (Appendix A: transcript 10) makes it likely that this was the 24 100-ha fire reported in the FRAP database. Based on the fire map, and accounts of the fire from residents (Mendenhall 1930), it is also possible that this fire joined another fire that ignited the same day to the east of Tujunga Canyon on the San Pascual Ranch, near the present-day town of Montrose (Appendix A: transcript 8). Fire complexes are not uncommon today, and thus this might appropriately be called the 1878 Tujunga Cañon fire complex.

This fire spread at such a rate that it could hardly have been of low or even moderate intensity. It certainly was not "a slow smoldering fire" of the kind postulated to be characteristic of the fine-grain age patch mosaic model. More likely it resembled another fire at the same time in that vicinity: "As soon as the brush was ignited the blaze traveled like wildfire, consuming everything in its way. In a short time it whiened [sic] out and swept along in a swathe of flame two miles broad…nobody can face the heat, it is so intense, and this morning a party who tried to control the cause of the fire found it impossible to live within sixty yards of it" (Appendix A: transcript 7). Other fires that same year also suggest high intensity, such as "The scene of the conflagration seemed not over a mile distant, while it was, in fact, nearer twenty miles. As a spectacle it was a superb success …" (Appendix A: transcript 8). Like these 1878 shrubland fires, many others during the 19th century were clearly high-intensity fires (Appendix A).

This 24 100-ha 1878 Tujunga Cañon Fire is not compatible with the picture of a historical fine-grain age patch model of small, low-intensity fires, therefore, it is not surprising that proponents of that model have questioned this event (Goforth and Minnich 2007). They presented "independent physical evidence" that purportedly showed the size of this fire was greatly exaggerated. Their evidence consisted of fire scar dendrochronology studies by Kerr (1996), which were putatively within the fire perimeter, yet showed no evidence of the 1878 fire. They failed to recognize, however, that although in close proximity, the fire perimeter and fire scar sample areas did not overlap (Fig. 2). Other evidence they presented against the existence of this fire is the suggestion that the fire perimeter map was fabricated and more urban legend than real. In support of this, they demonstrated that the 1878 fire perimeter map lacked detailed convolutions characteristic of modern fire perimeters However, in 1878, reconnaissance was done on foot and horseback, using Land Survey maps that were less detailed than later USGS topographic maps, and thus there would have been limited capacity to produce a detailed fire perimeter map. We doubt this lack of precision would be taken by many people as evidence that the fire event never occurred.

1889 Santiago Canyon Fire

A contender for the largest wildfire in California history occurred in late September 1889; long before fire suppression policy in the region. It ignited in Santiago Canyon, in the northern part of the Santa Ana Mountains in Orange County, and is here referred to as the 1889 Santiago Canyon Fire (Fig. 3). Conditions leading up to this event include a somewhat more severe than usual annual drought, with less than 1 cm of precipitation being recorded south of there in San Diego for the previous five and one-half months (USDA Weather Bureau 1934). Ten days before the big fire event, there was "a Norther" (Appendix A: transcript 65) or foehn-type Santa Ana wind (Appendix B), further drying shrubland fuels. Following this, temperatures remained high and contributed to several significant fires in San Diego and San Bernardino counties (Appendix A: transcripts 19, 20, and 21).

Following closely on this period of severe fire weather, the Santiago Canyon Fire began the morning of 24 September 1889, coincident with a new Santa Ana or "Norther" wind event, which blew with considerable intensity throughout the region, including San Bernardino, Riverside, San Diego, and Orange counties. This particular Santa Ana wind event lasted three full days after the fire began with temperatures increasing to a peak of 32°C on 26 September and was described as being of unusual severity; "blowing a hurricane" and "the blinding dust and heat next to intolerable" (Appendix A: transcripts 24–29, 31, 32, 34, 37, 40–42, and 65).

Interpreting the historical reports on the behavior of this 1889 fire requires some understanding of Santa Ana winds. In the Santa Ana Mountains, these dry foehn winds commonly exceed 100 km/h and the primary orientation of these offshore winds changes from a northeast wind in the northern part of the range to an east wind farther south (Appendix B: Fig. B2). In addition, on the leeward (coastal) side of mountains, the differential heating and cooling of valleys vs. slopes, and land vs. ocean, produce thermal forces that can disrupt the foehn flow (Edinger et al. 1964:12, Rosenthal 1972:5.19–5.23). As a result, during midday, there is often a reverse flow (Appendix B: Fig. B3) that can

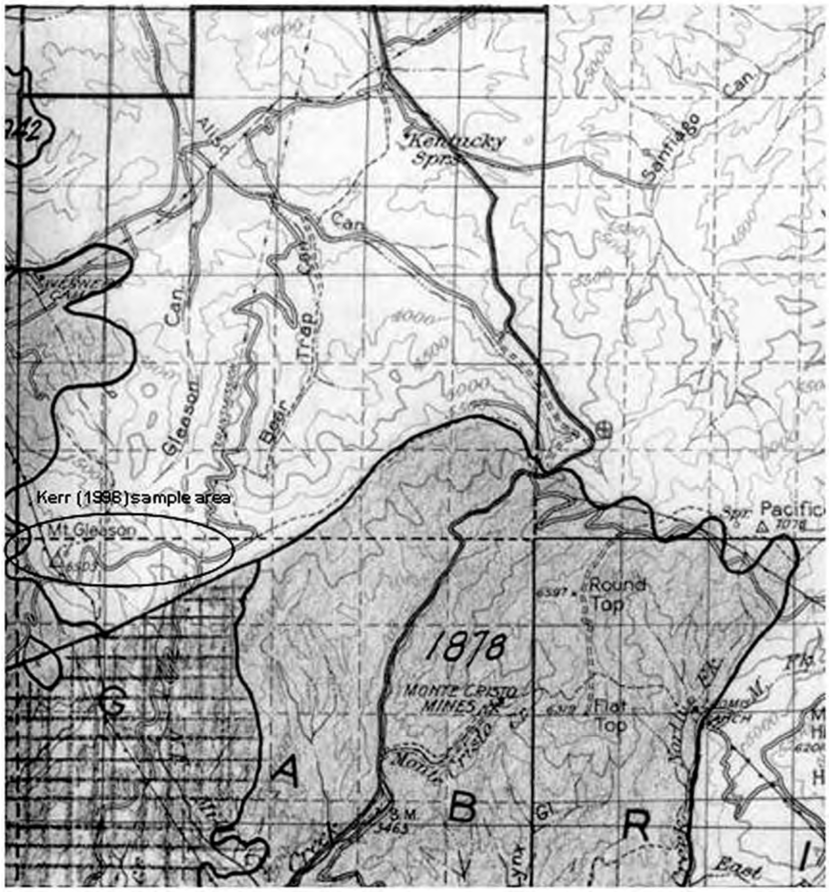

FIG. 2. Close up of the northern fire perimeter of the 1878 Tujunga Cañon Fire (shaded area) and location of fire-scar dendrochronology study area sampled by Kerr (1996) that is outside the fire perimeter. The fact that Kerr (1996) did not detect the 1878 fire would be expected and should not have been used by Goforth and Minnich (2007) as evidence that the fire perimeter map was in error.

spread fire in erratic and unpredictable directions. These alternating winds have profound impact on large-fire behavior. As described by Orange County Fire Authority Battalion Chief Mike Rohde (*personal communication*), "It's not uncommon for onshore winds to either develop at low elevations or at least to 'stall' a Santa Ana during peak daytime convective heating. The Santa Anas will often regain strength at night as the foehn wind doesn't have to 'fight for dominance' with the solar-driven diurnal wind. Santa Anas often peak shortly before or just after dawn because of this condition. With this kind of behavior, the fire receives the best of all possible burning conditions by either (1) developing high-intensity fire runs in canyons with accompanying strong thermal smoke columns (caused by slope and fuel driven fire), and then the deposition of fire brands and long range spotting as the Santa Ana winds aloft shear off the smoke column, causing heavy spotting downwind [see similar behavior described by Albini 1983], or (2) by stretching out the fire's perimeter when up-canyon runs are followed by the resurfacing of Santa Ana winds."

The 1889 Santiago Canyon Fire was accidentally ignited in the northwestern foothills of the Santa Ana Mountains (Fig. 3), east of El Modena in Santiago Canyon (apparently on Noland's ranch; Appendix A: transcript 40, but cf. transcript 47) "and as the wind was blowing a perfect gale from off the desert the mountains were soon red with the angry flames" (Appendix A: transcript 22). Reports show the fire burned very rapidly ("in less than five minutes from the time the fire broke loose, the whole side of the mountain was ablaze") (Appendix A: transcript 40), and within the first six hours extended 25 km northeast to southwest (Appendix A: transcript 26). Although the prevailing northeasterly offshore flow of air dominated the fire behavior, there were erratic winds in the foothills and mountains that also carried the fire north and eastward (Appendix A: transcript 22; see also Appendix B for further insights into erratic wind behavior during Santa Ana wind events). By the first evening of the fire, it was reported that "about 25 miles [40 km] of the mountains east of Santa Ana are on fire, and doing great damage east and south of El Toro" (Appendix A: transcript 28). It would

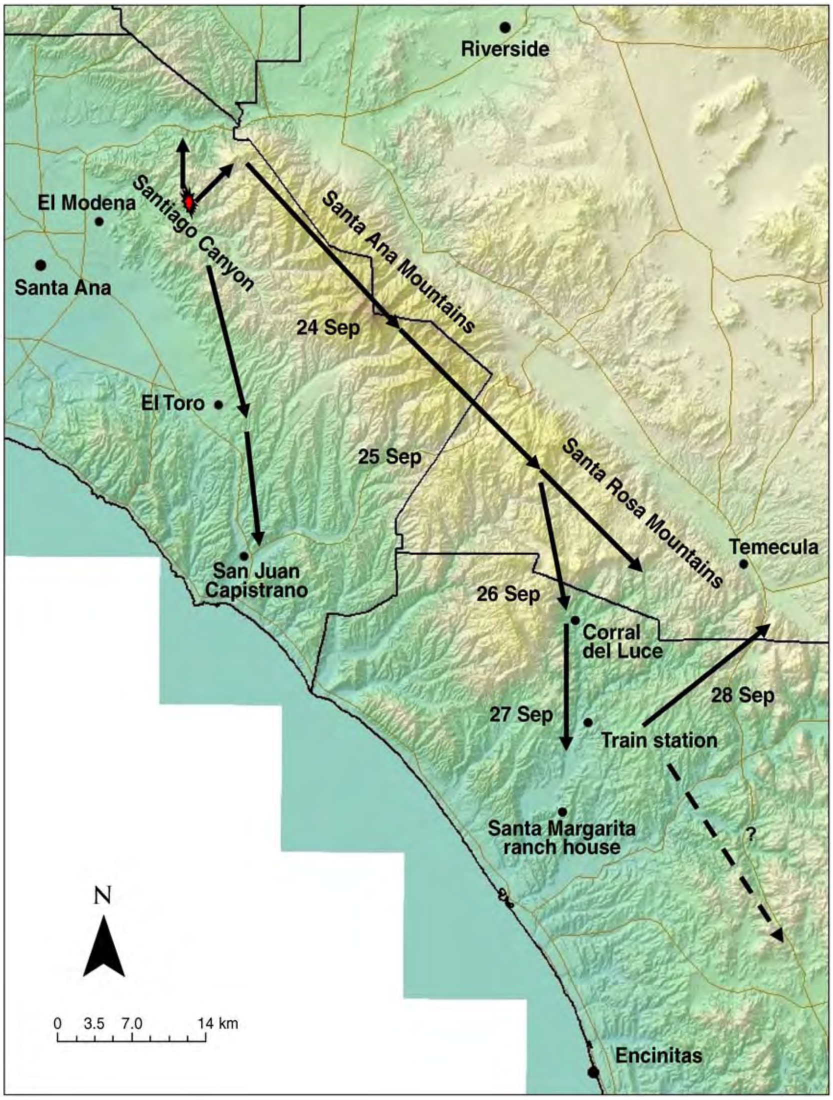

FIG. 3. The daily fire activity for the 1889 Santiago Canyon Fire based on newspaper accounts (see Appendix A for details). Fire runs are indicated with arrows, and associated dates are based on newspaper accounts cited here. These reports show that the fire ignited in Santiago Canyon (indicated by flames) and during the first day (Tuesday, 24 September 1889) burned south of El Toro in the coastal foothills, and in the mountains a distance of ~40 km (similar runs have been observed in recent Santa Ana wind-driven fires; see Appendix C). On Wednesday, the fire continued burning southward both in the mountains and along the coastal plain, at one point threatening the city of San Juan Capistrano. By the third day, the fire had burned about 50 km north–south in the mountains and to the present-day community of De Luz. Strong east winds then drove the fire toward the Santa Margarita ranch house. When the offshore flow abated, the onshore flow carried the fire eastward toward Temecula. At this point, the fire was likely driven by the steep topography, daytime down-canyon flowing winds that push fires eastward, as is the case with modern fires in this region (Schroeder 1959). Newspapers reported burning east of Encinitas (Appendix A: transcript 62), but it is unclear if this was part of the Santiago Canyon Fire. Other locations mentioned in the text include the Santa Ana River, which runs east to west along the northern end of the Santa Ana Mountains, and the city of Anaheim, northwest of El Modena.

appear that the winds were spreading the fire with embers far beyond the fire front based on the description that the first "night large fires were seen in many places on the hills, and the glow arising from the canyons showed that great fires were raging in them. The flames in many places spread with alarming rapidity" (Appendix A: transcript 26).

"The views from the housetops was a grand one. Never before have the people here witnessed such a natural pyrotechnic display. Looking eastward the entire heavens is one bright-red glare. Citizens in the entire valley are thoroughly aroused, and all are doing all they can to protect their property" (Appendix A: transcript 22). The immensity of this fire is illustrated by the report that not only citizens facing the fire on the western side of the range were impressed by the nighttime pyrotechnics, but the fire was also visible 50 km away on the eastern side of the range (with peaks 1200–1600 m):

TABLE 1. Details of megafires of ~50,000 ha or larger in southern California, USA.

Year	Fire name	County†	Month ignited	Duration of Santa Ana winds (d)	Area burned (ha)	Number of structures lost	No. deaths
1889	Santiago Cyn	Orange	Sep	3	125 000 (200 000?)	0	0
1932	Matilija	Santa Barbara	Sep	>5	89 100	0	0
1970	Laguna	San Diego	Sep	2.5	70 500	382	8
1985	Wheeler #2	Ventura	Jul	0§	49 700	26	0
2003	Cedar	San Diego	Oct	2	109 500	2400	15
2006	Day	Ventura	Sep	1	65 500	11	0
2007	Zaca	Santa Barbara	Jul	0§	97 300	1	0
2007	Witch	San Diego	Oct	3	80 200	1736	2

Notes: Fire size is from California Department of Forestry and Fire Protection, Fire and Resource Assessment Program (FRAP) database, except 1889 Santiago Canyon Fire, which is based on the analysis in the present paper and 2007 Witch Fire from CalFire website. Associated duration of drought prior to fire was measured by the Palmer drought severity index (PDSI scale is –6 to 6, with negative values being drier than average). All fires were human ignited (either direct incendiary fires or indirectly due to power lines). Fires where Santa Ana winds were a factor some time during the fire are indicated; however, all fires were associated with weather that included high than normal temperatures, very low humidity, and erratic winds.

† County where the bulk of the fire burned.

‡ Monthly records unavailable; based on paleo reconstructions for summer drought; PDSI for 1887 = –0.65, 1888 = 0.39, 1889 = –0.47.

§ Although outside the Santa Ana wind season, severe fire weather including extreme temperatures, low humidity, and erratic winds were factors.

¶ For the six months prior, all months were below –5.00 PDSI.

"Forest fires in the mountains east of Santa Ana raged all day and last night the light reflected upon the sky from the fire in that direction was plainly seen in this [Riverside] city" (Appendix A: transcript 25).

In addition to burning in the mountains (Appendix A: transcripts 22, 24, 34, and 39) the fire burned westward into the coastal plain as passengers on the San Diego train [along a coastal route through San Juan Capistrano] reported "the fire was raging on both sides of the track, and they thought they would be smothered before they got through the burning district" (Appendix A: transcript 27).

The following day (25 September) it was reported that "this morning a stiff breeze is blowing and the smoke is increasing, showing that the fires are spreading" (Appendix A: transcript 26). At this time, winds were still going strong (Appendix A: transcript 40) and were driving the fire in a southwestward direction as it was reported that "The devastating fire still continues in portions of the canyons ... At San Juan Capistrano last night great danger was experienced in keeping fire from the heart of the city" (Appendix A: transcript 55, see also transcript 48).

The fire was still burning on the third day as reported from Santa Ana, "The fires in the mountains east of the city are not yet extinguished as was evidenced by the scene this morning at 3 o'clock. The whole eastern horizon was brightly illuminated and presented a majestic and sublime sight" (Appendix A: transcript 39). This was verified by the report, "fire which has been burning for the past two days still continues in the cañons" (Appendix A: transcript 51). Although the fire burned the coastal plain as far south as San Juan Capistrano, it is not clear from newspaper accounts whether or not this fire front continued burning southward. However, the fire was very active in the mountains of eastern Orange and western Riverside counties. For two days, it burned along an estimated 50 km of the Santa Ana and Santa Rosa Mountains, now the Santa Rosa Plateau (Appendix A: transcript 62). Around 26 September, the fire burned into San Diego County and at that point was described as having swept "an immense territory" (Appendix A: transcript 60). When it reached "Coral del Luce," a stable owned by an Englishman named Luce (Rivers 1999) at the site of the present-day community of De Luz (Fig. 3), the southward momentum switched and it was driven hard by a strong "east wind [(consistent with documented wind patterns, see lower portion of Appendix B: Fig. B2), which] then brought on fire in the direction of the [Santa Margarita] ranch" (Appendix A: transcript 60). Before reaching the ranch house near the coast, the offshore winds abated and the fire was picked up by onshore breezes (see Appendices B and C) that pushed the fire eastward, and days later "the fire [was] still raging in the mountains" (Appendix A: transcript 60). During this time it burned as far east as Temecula in Riverside County and may have been responsible for the burning as far south as Encinitas in San Diego County (Appendix A: transcript 62).

Based on the area circumscribed by the reports of 1889 (Fig. 3), we believe that a conservative estimate for this fire would be ~125 000 ha, and if the reported burning as far south as Encinitas were part of this same fire, it would have been more like ~200 000 ha. The aftermath of this and other fires in the region that same week is portrayed in a newspaper report the following week: "The fires in the valleys and foothills lately have almost hidden the lofty peak of San Bernardino [Mt. San Gorgonio] from sight. He appears dimly, if at all,

Table 1. Extended.

Antecedent drought	
Number of months with negative PDSI	Mean PDSI for months antecedent to fire
‡	−0.25
23	−2.22
14	−1.81
7	−1.23
54 out of prior 61	−2.36
12	−2.11
20	−2.99
17	−3.62¶

and as if floating in cloudland" (Appendix A: transcript 63). "It is a year of disasters, wide-spread destruction of life and property—and, well, a year of horrors" (Appendix A: transcript 53).

Of course, the exact dimensions of the 1889 Santiago Canyon Fire are not ever likely to be known for sure, however, the magnitude of our estimate is vetted by a first hand account that places it on the same scale as the largest 20th-century fires in California. USFS Assistant Regional Forester for California, L. A. Barrett (1935) reported in a compilation of newspaper accounts of California fires, "I was living in Orange County at the time and well remember the great fire reported herein from September 24 to 26 [1889]. Nothing like it occurred in California since the National Forests have been administered. In fact in my 33 years in the Service I have never seen a forest or brush fire to equal it. This one covered an enormous scope of country and burned very rapidly." Mr. Barrett's USFS career in California included the 1932 Matilija Fire that was over 89 000 ha, which provides a lower baseline for the 1889 Santiago Canyon Fire.

The 1889 Santiago Canyon Fire stands as a clear example of a massive high-intensity crown fire in the absence of a prior history of fire suppression. Its size was of the same magnitude as the largest fires recorded in southern California since annual record keeping began in the early 1900s (Table 1). Even if this fire was only half as large as our most conservative estimate (125 000 ha), it would still rank as one of the largest fires in California's history. This fire event was remarkably similar to modern fire events such as occurred in 2003 and 2007 in that significant fires were occurring in several counties at the same time. In 1889, in addition to the Santiago Canyon Fire, there were big fires in San Bernardino (Appendix A: transcripts 21, 25, and 43) and southern San Diego counties (Appendix A: transcripts 29, 30, 33, 36, 44, 50, 57, and 59), all driven by the same Santa Ana wind event. What is strikingly different from 21st-century fire events is that despite the magnitude of the 1889 fires, few structures and lives were lost. Thus, on this southern California landscape the primary change that has made fires destructive is not a change in the size and intensity of wildfires, but a change in the size and distribution of the human population (Keeley et al. 1999).

An alternative interpretation of the 1889 Santiago Canyon Fire

Goforth and Minnich (2007), as advocates of the fine-grain age patch hypothesis, do not believe that the historical accounts of the 1889 Santiago fire are accurate. In search of "objective" evidence of fire size, they investigated insurance claims made after the fire and mentions of damage to specific properties in the newspapers. They did not consider that there could be a substantial spatial bias in these accounts if the fire burned beyond the more densely settled lower foothills and coastal plain and into the mountain slopes where inhabitants were sparse, and insurance probably not the norm. That the fire did extend into these areas is attested by numerous accounts in the newspapers that report the fires burning in the "mountains" (Appendix A: transcripts 22, 24, 25, 28, 34, 39, 52, 55, and 60). Today there are 3 million people living in Orange County, primarily in the coastal plain, and the rugged chaparral covered Santa Ana mountain range is mostly national forest land and largely unoccupied; thus, it seems certain that in 1889, with a population of only 13 000 in the entire county, that other than a few miners and grizzly bear hunters (Sleeper 1976), these mountains were unsettled. One would not expect insurance claims from the vast majority of area burned by the 1889 Santiago Canyon Fire.

Goforth and Minnich (2007) estimate by their methods (elaborated in Appendix D) that the full extent of the fire was only about 15 km (see their Fig. 2a). This is grossly inconsistent with newspaper accounts that reported the fire having spread 25 km during the first six hours and 40 km by that evening. After two more days of intense Santa Ana winds, it would have spread considerably farther, and numerous newspaper accounts discussed here corroborate that conclusion.

One reason Goforth and Minnich (2007) failed to appreciate the extent of the Santiago Canyon Fire is their assumption that the fire reported on the Santa Margarita Ranch in northern San Diego County (Appendix A: transcript 60) was a smaller (Appendix D), separate, and isolated event. This, in part, is due to an error in interpreting historical names. Three days after the Santiago Canyon Fire began, *The Daily San Diegan* on 29 September 1889, in an article titled "An Immense Territory Swept by the Flames," stated that "…The fire originated at the Coral del Luce and extended to the Santa Rosa Mountains, and the east wind then brought on fire in the direction of the ranch, and it is estimated that fully 65,000 acres were burned before the fire was extinguished… ." Goforth and Minnich (2007) make the unsubstantiated claim that the newspaper was in error and that the site they were really referring to was "Corral de la Luz," a train station in the coastal plain near the Santa Margarita Ranch house. Such an assertion might be credible if in fact there was no such place as "Coral del Luce" but there was a stable run by an Englishman named Luce (Corral del Luce) located between the eastern end of the Santa Margarita Ranch and Rancho Santa Rosa (Elliott 1883, Rivers 1999) in the mountains near the present-day community of De Luz (Fig. 3 and Appendix D). According to the newspaper account, the fire that threatened the ranch was an extension of burning in the "Santa Rosa Mountains" (present-day Santa Rosa Plateau), and Luce's corral was only about 5 km southwest of these mountains. Other newspaper accounts report that burning in these mountains extended for 50 km (Appendix A: transcript 62), which would have overlapped considerably with the Santiago Canyon Fire (Appendix A: transcript 28). In light of this, and the fact that there were three days of intense Santa Ana winds blowing fire in a southwesterly direction, and the newspaper story about the Santa Maragarita Ranch fire referred to an "immense territory" having been burned, there is good reason to interpret this as part of the Santiago Canyon Fire (Fig. 3).

Goforth and Minnich (2007) claim that newspaper reports of the 1889 fire are exaggerations, if not outright fabrications, and represent a classical case of "yellow journalism" designed solely to create readership. Yellow journalism is a pejorative term that was coined about a decade after the 1889 fire and connoted unethical or unprofessional journalism, particularly the use of highly sensational headlines. Goforth and Minnich (2007) quote 1889 headlines such as "Fearful Flames," "Small Towns in Peril," or "Great Fires Raging Around Santa Ana" as examples. Such headlines, however, are quite comparable to contemporary headlines; e.g., "Wildfires Rage" (San Diego Union-Tribune, 22 October 2007), "300,000 Flee Fires, Blazes March Toward Coast" (San Diego Union-Tribune, 23 October 2007), or "Amid Fear and Uncertainty, a 'Staggering' Evacuation" (USA Today, 24 October 2007). In fact, the 1889 headlines are not only similar but the articles (Appendix A) read very much like contemporary articles describing catastrophic fire events. One major difference is that contemporary headlines inevitably occur on the front page because they are a major concern to population centers that have expanded into the wildlands. Nearly all of the 19th-century reports occurred on subsequent pages, perhaps because mountain fires were of less immediate concern.

In what seems to be a desperate attempt to diminish the magnitude of the 1889 Santiago Canyon Fire, Goforth and Minnich (2007) fall back on "an old proverb [that] states that smoke travels farther than flames." They use this to dispute a first hand account of the fire appearing to extend from "the mouth of the Santiago Canyon southward toward San Juan Capistrano" (Appendix A: transcript 48). Their contention is that because the sky was smoky, the observer on the hotel roof in Anaheim would not have been able to see flames as far away as San Juan Capistrano, and therefore was reporting on smoke that had drifted that far south. However, they ignore the fact that during Santa Ana wind conditions smoke from wildfires is normally blown offshore and does not "drift" southward (Fig. 1). In addition, reliance on proverbs ignores a more trusted approach to vetting newspaper stories, namely corroboration from another source; in this case there is a separate newspaper report to the effect that "At San Juan Capistrano last night great danger was experienced in keeping a fire from the heart of the city" (Appendix A: transcript 55).

Finally, Goforth and Minnich (2007) dispense with the report of Regional Forester L. A. Barrett on the fire size by noting that it lacks credibility since he was only 15 years old at the time of the fire. Even if Barrett's statement were the only data on fire size, we don't see that his age is an important determinant of its validity. Regardless, it matches well with independent contemporary accounts from newspapers, and since it was given by a professional forester who had a long history of responsible leadership positions in the USFS, it would seem unlikely that it was a baseless exaggeration. See Appendix D for further discussion of their criticisms.

Summary of 19th-century shrubland fires

Large high-intensity chaparral fires were regular occurrences throughout southern California in the 19th century, with such events occurring somewhere in the region in over 50% of the years during the last quarter of the century (Appendix A). These were fast moving and of considerable fire intensity, and based on the huge plume evident in 19th-century photographs (e.g., Fig. 4), it would appear they were substantial enough to create their own weather. Marine charcoal deposition records suggest such massive high-intensity wildfires have long been a part of this landscape (Byrne et al. 1977, Mensing et al. 1999).

Small fires would have occurred then, as now, but there is no evidence that their spatial distribution produced a landscape immune to large high-intensity fires. The primary evidence for a strictly fine-grain fire regime in southern California are the contemporary patterns of burning in Baja California, where it has been repeatedly assumed that the only difference between Baja and southern California is a difference in fire suppression policy (Minnich 1983, 1995, Minnich and Chou 1997). This conclusion has been challenged as there are numerous physical, biological, and sociological differences between these regions that have not been given sufficient consideration (Strauss et al. 1989, Keeley 1995, 2006, Moritz 1997, 2003, Zedler and Oberbauer 1998, Keeley and Fotheringham 2001*a*, *b*, Halsey 2004). Most relevant is the much greater rural population immediately south of the border with huge impacts on fire ignitions and vegetation fragmentation (Dodge 1975). Farther south, the fire regime changes due to the apparent lack of Santa Ana winds south of

Ensenada (contrast lack of smoke plume for the fire at Santa Tomas vs. the Santa Ana driven fire near San Antonio de las Minas north of Ensenada in the remote image in Fig. 1).

Prior to the modern era of intensive rural land use in Baja California, there is evidence that Baja California burned in large high-intensity wildfires similar to those in southern California. This is supported by the log book of English explorer George Vancouver (Vancouver 1798) who described a large Santa Ana wind-driven fire in 1793 in the vicinity of Bahia Todos Santos near present-day Ensenada in northern Baja California "[10 December 1793] . . . During the forenoon immense columns of smoke were seen to arise from the shore in different parts, but principally from the south-east or upper part of the bay, which towards noon obscured its shores in that direction. These clouds of smoke, containing ashes and dust, soon enveloped the whole coast to that degree, that the only visible part was the fourth point of the above-mentioned bay, . . ." [and on 11 December 1793] "The easterly wind still prevailing, brought with it from the shore vast volumes of this noxious matter. Two opinions had arisen as to the cause of the very disagreeable clouds of smoke, ashes, and dust, in which we had been involved the preceding day. Volcanic eruptions was naturally the first conjecture; but after some time, the opinion changed to the fire being superficial in different parts of the country; and which by the prevalence and strength of the north-east and easterly wind, spread to a very great extent. The latter opinion this morning evidently appeared to be correct. Large columns of smoke were still seen rising from the vallies behind the hills, and extending northward along the coast . . . To the south of us the shores exhibited manifest proofs of its fatal effects, for burnt tufts of grass, weeds, and shrubs, being the only vegetable productions, were distinguished over the whole face of the country, as far as with the assistance of our glasses we were enable to discern; and in many places, at a great distance, the rising columns of smoke showed that the fire was not yet extinguished." Clearly, this was a very large fire by an objective observer who had little incentive to sensationalize his account. Such fire events may not have been unusual on the Baja landscape even into the 20th century because the 16–18 year span in aerial photographs used by Minnich (1995) to document the apparent lack of such fires in Baja could have easily missed large fire events (Keeley and Fotheringham 2001*a*, *b*). Also, satellite images from the 2003 firestorm indicate a large wildfire north of Ensenada, Mexico (SALM in Fig. 1), and a report from the 2007 firestorm documents a fire over 15 000 ha south of the border (Hernandez 2008).

The 19th-century vegetation patterns

The fine-grain age patch model predicts that the landscape prior to 20th-century fire suppression comprised a complex mosaic of young and old patches of shrublands sufficient to provide barriers to fire spread. Definitive tests of this prediction are difficult because, despite a plethora of early California histories, the vast majority of historians have been concerned with the personalities that colonized this landscape and very few with the landscapes themselves. The primary evidence comes from 19th-century forest reserve surveys conducted by USGS biologist J. B. Leiberg.

FIG. 4. Fire plume from a 19th-century fire in the San Gabriel Mountains, Los Angeles County (from Kinney [1900:45] with the legend "Forest Fire in Sierra Madre Mountains, July 22, 1900. Taken Twenty-five miles from fire") (see Appendix A: transcripts 94–108). Photographs of other high-intensity southern California shrubland fires are on pages 43 and 49 in Kinney (1900).

Based on Leiberg's reports (1899*a*, *b*, *c*, 1900*a*, *b*, *c*) it has been estimated that 90% of the 214 000 ha of shrublands on the San Jacinto Forest Reserve in Riverside County were older than 30 years of age at the end of the 19th century and other reserves in southern California were in a similar state (Keeley and Fotheringham 2001*a*). Since there is general agreement that 30-year-old shrublands are highly flammable, it is hard to conceive of an age distribution pattern in which fuel age would have been a factor in preventing large wildfires.

To support their contention that the pre-suppression landscape had an age mosaic capable of stopping large fires, Minnich and his coauthors often cite Leiberg's (1899*a*, *b*, *c*, 1900*a*, *b*, *c*) forest reserve reports, pulling out quotes they claim support the notion of a fine-grain age patch mosaic due to small fires. For example, the

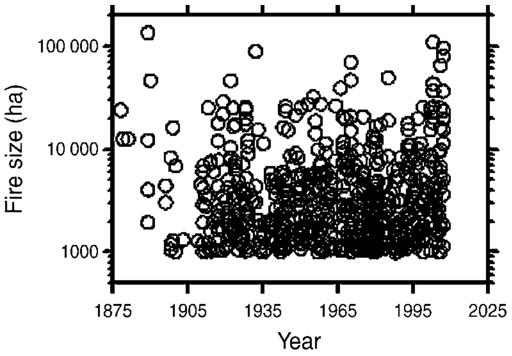

FIG. 5. Fire size during the latter part of the 19th and throughout the 20th century (based on the California Department of Forestry and Fire Protection, Fire and Resource Assessment Program [FRAP] database, plus U.S. Forest Service (USFS) data on 2007 large fires, and additional 19th-century fires not in the FRAP database but with clear estimates of size in newspaper reports in Appendix A). Regression analysis for year vs. fire size: $r^2 = 0.000$, $P = 0.67$, $n = 671$ fires for all fires 1000 ha or larger; $r^2 = 0.001$, $P = 0.73$, $n = 87$ fires for fires 10 000 ha or larger. This region does not fit the generalizations made by Westerling et al. (2007) of a temporal increase in the number of large fires for the western United States, although their conclusions were based on a much broader region and over a much shorter period of study.

Leiberg quote that "[Chaparral] ... is a growth which varies from extremely dense to thin or open, but rarely forms very large, uninterrupted patches. The dense portions are commonly separated by narrow lanes ['recent burns' inserted here by Goforth and Minnich (2007)], which are either wholly free from brush, or bear a scattered growth so thin as to offer no serious obstacles to travel." Goforth and Minnich's interpretation inserted in this sentence seems incorrect to us since fires do not burn in "narrow lanes" and the level of detail presented in Leiberg's documents suggests to us that he would have indicated these "narrow lanes" were past fires if in fact that were the case. More likely Leiberg was describing interruptions in the chaparral due to surface or subsurface rock outcrops, ridgelines or wildlife trails from deer or grizzly bears that made their homes in chaparral. More to the point though, Leiberg himself contradicts Goforth and Minnich's interpretation that these narrow lanes in the chaparral fit the fine-grain age patch mosaic model in his own conclusion that "The natural lanes existing throughout the chaparral are too narrow to serve as efficient fire breaks" (Leiberg 1900*c*:477). Other quotations from the literature (e.g., Kinney 1887, Mendenhall 1930) used by Minnich and co-authors follow a similar selective use of information and often do not provide a complete picture.

We find no support for the idea that the pre-fire-suppression landscape was a mosaic of young and old chaparral capable of preventing the spread of large fires.

20th-century fires

Proponents of the fine-grain age patch mosaic model contend that fire suppression impacts were almost immediate and this accounts for well documented large fires throughout the 20th century (Minnich 1989, Goforth and Minnich 2007).

Organized fire suppression in southern California began in the early 1900s. In the first few decades, fire fighting was an extension of 19th-century practices in that it was largely defensive and focused on stopping fires from moving into rural areas. Minimal effort was made to suppress natural ignitions in remote regions. Where resorts had been constructed, such as in the canyons on the southeast side of the San Gabriel Mountains bordering the growing Los Angeles Basin, organized fire suppression began in the late 19th century, although it was not generally very effective (e.g., Appendix A: transcripts 95–108). Throughout the southern California region, a policy for suppression of all fires on USFS lands evolved slowly in the early part of the 20th century and was limited due to the inaccessibility of rugged and roadless areas, coupled with limited fire-fighting resources and transportation (Mendenhall 1930, Brown 1945, Show 1945). Sterling (1904) described the fire-fighting situation in the San Gabriel mountains of Los Angeles County, "the country itself, which is so rough as to be almost inaccessible in parts, and so wild and isolated that the maintenance of a thorough patrol is difficult," and this applied to other ranges in the region. On the lower-elevation lands protected by the state, fire suppression was limited and disorganized until the 1920s or later (Clar 1959). At both the state and federal level, fire suppression became much more aggressive following WWII with improved vehicles and road access and the increasing use of airplanes and helicopters (Pyne 1982, Cermak 2005, Godfrey 2005). However, despite all this, statistics show a shortening of the fire rotation interval in the second half of the 20th century due to limitations in fire fighting capacity to keep up with increased human ignitions (Keeley et al. 1999).

Since USFS record keeping began around 1910, there have been large fire events once or twice a decade somewhere in the region (Fig. 5). We interpret these as a natural continuation of the historical pattern of fire on these landscapes that likely has been present throughout the Holocene. However, proponents of the fine-grain age patch model have argued that even the very earliest 20th-century fires were the result of fire suppression activities disrupting natural fuel mosaics. For example, Goforth and Minnich (2007; also Minnich 1987) claim that one of the first big 20th-century fires, the 1919 Ravenna Fire (Fig. 6), which burned 30 350 ha of rugged chaparral landscape on the Tujunga District of the Angeles Forest (Mendenhall 1930), was an unnatural event resulting from fire suppression. Since Goforth and Minnich (2007) provided no evidence to support their claim that fire suppression was immediately effective in disrupting natural fuel patterns, it is at best a hypothesis. Here we test their hypothesis and predict that if true, then one would expect that prior to 1919 a large enough

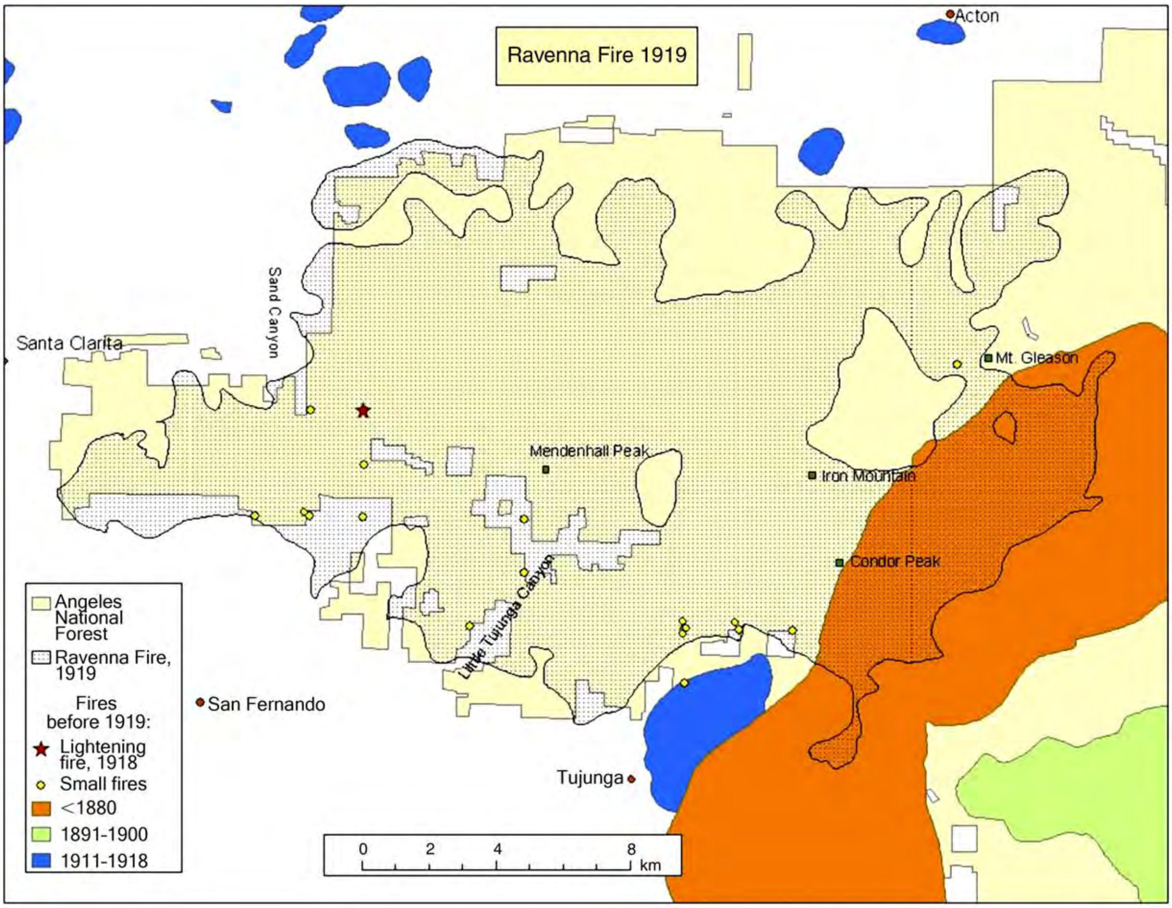

FIG. 6. The 1919 Ravenna Fire (name according to the CalFire FRAP database; named the Tujunga Fire in Show [1945] and the N. Fork Pacoima Canyon Fire by the Los Angeles County Fire Department). Since record keeping began in 1911, the only record of lightning fires suppressed within the 1919 fire perimeter is one 2-ha fire with point of origin indicated by a star. Points of origin for anthropogenic fires are indicated with solid circles, most of which were less than 0.1 ha; the largest was 150 ha (individual fire records from USFS Angeles National Forest). The only prior fire substantive enough to be included in the FRAP database was the 1878 Tujunga Cañon Fire, orange area on lower right.

number of lightning-ignited fires would have been suppressed within the perimeter of this fire to eliminate the "natural" fuel mosaic. One could postulate various models for the number of suppressed fires required to disrupt the putative fuel mosaic, but in all cases it surely would be a number far greater than the single lightning-ignited fire the records show was suppressed during the period of record keeping from 1911 to 1919 (Fig. 6). Clearly, disruption of the natural lightning-fire regime cannot explain the large high-intensity Ravenna Fire of 1919. Nor can elimination of Native American burning within the fire perimeter area as there were no permanent Indian settlements in this rugged landscape (McCawley 1996). Between 1911 and 1919, a small number of human-ignited fires were suppressed along the southern boundary of the subsequent Ravenna Fire perimeter (Fig. 6), but more than three-fourths of the interior and northern portion of that fire had no fire suppression activity prior to 1919. At the same time as this fire, there was another fire of similar magnitude burning on the same forest. Fire fighters at this time were under no illusion that these were the fault of past fire-suppression activities altering fuel patterns. Rather, as Cermak (2005:98) points out, in 1919 "Weary firefighters realized that despite all of the lessons learned over the previous nine fire seasons, they could not stop a wind-driven fire in southern California chaparral. . . . These fires established in the minds of the firefighters from District 5 and Washington the view that southern California national forests had a special fire problem that required special fire control measures.

Other large fire events that occurred early in the 20th century are also not explained by fire-suppression impacts. As early as 1913, the Barona Fire burned 26 500 ha of dense shrublands on the Cleveland National Forest. No lightning fires were reported suppressed during the first few years of fire reporting within the perimeter of that fire so there is no rationale for attributing this fire to suppression activities. On the Los Padres National Forest (then known as the Santa

FIG. 7. Seral-stage chaparral in spring 2007, five years after the Bouquet Canyon Fire, dominated by resprouting *Adenostoma fasciculatum* and ephemeral subshrubs from dormant seedbanks (primarily *Lotus scoparius*) in northern Los Angeles County (Photo credit: J. Keeley). During the 2007 Buckweed Fire, 2700 ha of this Bouquet Canyon Fire were re-burned.

Barbara National Forest) there were several large fires in the early 1920s, but the 1932 Matilija Fire, at nearly 90 000 ha (Table 1), stands out as one of the largest in California's history (Appendix E). The enormity of this fire can in no way be attributed to antecedent fire suppression actions disrupting natural fire regimes. In the prior 22 years of forest service protection, only two lightning-ignited fires were suppressed within the 89 100 ha area of the 1932 Matilija Fire, and loss of Native American burning was not likely a factor due to the extreme ruggedness of the area (Appendix E).

To summarize, on these shrubland dominated landscapes large fires over 10 000 ha are not unique to the 20th century and, as shown in Fig. 5, there is no evidence they are increasing. Such fires have occurred at least once a decade somewhere in the region since the late 19th century, and probably throughout most of the Holocene. As with other crown fire ecosystems (Johnson et al. 2001), it is apparent that large high-intensity wildfires are a predictable feature of chaparral dominated landscapes and are not the fault of past fire suppression policy.

The role of fuel age in shrubland fires

Another prediction of the fine-grain age patch mosaic model is that chaparral shrublands do not accumulate a sufficient quantity of the more easily ignited dead fuels to propagate fire until it reaches at least 20–30 years of age (Minnich 1987, 1995, Minnich and Chou 1997, Goforth and Minnich 2007). These authors have never directly tested this proposition, rather they have relied on indirect evidence in the form of burning patterns north and south of the U.S./Mexican border, and assumptions about the role of fire suppression. One empirical study that could be cited in support of their model is Green's (1981) investigation of "controlled burns." He found that under normal fire prescriptions of little to no wind and moderately high humidity, some shrub fuel types were difficult to burn if less than 20 years of age. Green's findings were supported by Philpot (1977) who applied the Rothermel Fire Model to chaparral fuels and showed an apparent age effect when wind was not a factor. However, Philpot also found that under high winds the fine-grain model was not supported because fires readily carried in 10-year-old chaparral stands.

The notion that young chaparral acts as a barrier to fire spread, particularly under windy conditions, has been disputed from empirical studies of fire behavior (Dunn 1989, Keeley 2002*a*, Moritz 2003, Keeley et al. 2004). The primary reason early seral stages of chaparral readily carry fire is because they are dominated by an ephemeral flora that dries each summer, producing a highly combustible fine fuel load. During these years stands commonly have a substantial cover of subshrubs and slightly woody suffrutescents such as *Lotus scoparius*, *Helianthemum scoparium*, and *Calystegia macrostegia*, forming dense contiguous surface fuels (Fig. 7). A study of three-year-old chaparral stands in San Diego County showed that the fuel loads were substantial in these early seral stages; >15 Mg/ha, mostly divided between dead fine fuels (≤1 cm diameter) and coarser fuels (>1 cm) in unburned skeletons, plus a smaller quantity of live foliage, mostly resprouts (R. H. Halsey and J. E. Keeley, *unpublished data*). We have modeled the fire behavior for these early seral stage fuel loads and found that for fuel moisture conditions typical of late summer and fall, young chaparral is capable of rapid fire spread, even under low to moderate wind conditions (Fig. 8).

This model prediction is borne out by empirical analysis of fuel ages consumed in southern California wildfires. The 2003 Cedar and Otay fires burned through a mosaic of young and old age classes (Keeley et al. 2004). In addition, in the 2007 fires that consumed 279 700 ha, more than 30 000 ha was from reburning of four-year-old fuels from the 2003 fires (H. Safford, *unpublished data*). Although sometimes young age classes may present a barrier to fire spread, this is seldom the case under weather conditions typical of late summer and fall (Keeley 2002*a*).

One of the complications of the fine-grain age patch model is that, according to its advocates, it only applies to evergreen chaparral and not to sage scrub (Minnich 1995, Goforth and Minnich 2007). This conclusion derives from a study in Baja California that suggested differences in burn-patch size between sage scrub and chaparral (Minnich 1983). This was attributed to differences in fuel structure between these two vegetation types, and is the basis for their belief in fundamental differences between chaparral and sage scrub in susceptibility to reburning at young ages. However, they did not consider alternative explanations for their Baja patterns, such as distributional differences in sage scrub and chaparral relative to human ignitions (Wells et al. 2004). Minnich (1995) claims that the seral stage fuel structure in chaparral prevents it from burning when young, but not so in young sage scrub (apparently he believes the fine-grain age patch model only applies to chaparral). We tested the claim about age-related differences in burning of chaparral and sage scrub by examining the distribution of age classes burned in the 10 largest fires in the Santa Monica Mountains of Los Angeles and Ventura counties (Fig. 9). The analysis conducted by NPS resource specialist R. Taylor (*unpublished data*) demonstrated clearly that young chaparral readily burns (e.g., Fig. 9a, d, e, f, h) and that there is no consistent difference between chaparral and sage scrub. Thus, not only does the fuel structure in young shrublands not act as a barrier to fire spread, but there is no difference between chaparral and sage scrub.

This accords with the behavior of most southern California wildfires, which burn through many vegetation types and have fire perimeters that seldom correlate with vegetation boundaries. In the 2007 fires in southern California, the extensive reburning of 2003 fire scars comprised sage scrub and chaparral, more or less equally (J. Franklin, *unpublished data*). This should not be at all surprising since there is a remarkable similarity in species composition and cover by the major growth forms between early seral stages of the two vegetation types (Keeley et al. 2005, 2006).

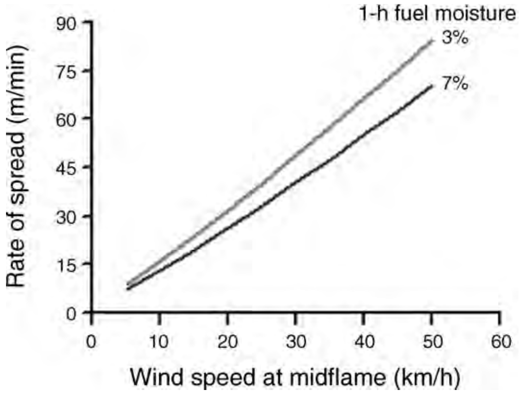

FIG. 8. BehavePlus 4 model results using a custom fuel model for early seral stage chaparral fuels similar to those depicted in Fig. 7, although from a site in San Diego County; dead fuels were 6, 4, and 3.58 Mg/ha for 1-, 10-, and 100-h fuels, respectively; and live fuels were 0.38 and 2 Mg/ha and 30% and 50% moisture for herbaceous and woody fuels, respectively; (R. H. Halsey and J. E. Keeley, *unpublished data*). Rothermel equations that are used in the Behave model have shortcomings when applied to mature chaparral where live fuels dominate; however, in these young seral stands, dead fuels dominated and the bulk of the dead fuels were within 75 cm of the soil surface. (See footnote 8 for BehavePlus 4 software.)

A corollary of the fine-grain age patch model is that large high-intensity wildfires are only possible when fire suppression creates a putatively unnatural coarse-grained pattern of older dead fuels. However, empirical studies show the probability of burning does not increase in older chaparral stands (Schoenberg et al. 2003, Moritz et al. 2004). Also, proponents of the fine-grain model have always assumed that fire suppression policy equates with fire exclusion, but this has not been the case in southern California (Moritz 1997, 2003, Conard and Weise 1998, Keeley et al. 1999, Weise et al. 2002). Indeed, contemporary fire regimes have had a much higher fire frequency than historical fire regimes (H. D. Safford and D. Schmidt, *unpublished data*).

Causes of megafires

The observation that a majority of megafires on our landscape have occurred in recent decades (Table 1) is commonly cited as evidence that fire suppression has disrupted natural fuel patterns. The above discussion of fuels fails to support this conclusion, however, it does leave open the question of why the apparent rash of megafires? An obvious explanation lies in the effect of climate since modeling studies show that weather and climate are commonly more critical in driving fire behavior than fuels in many ecosystems (Cary et al. 2006).

We hypothesize that anomalously long and severe drought is a critical factor in the generation of 20th-century megafires and this is supported by a consistent

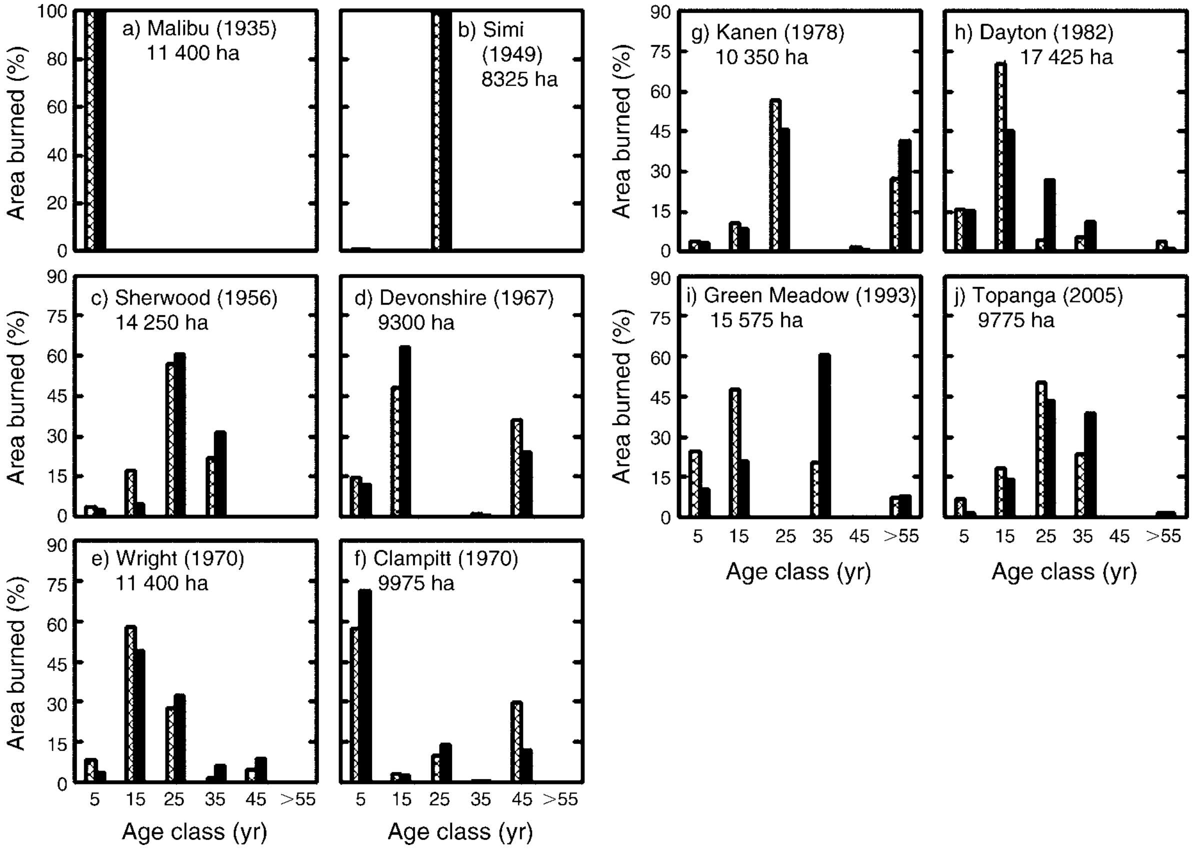

FIG. 9. Age classes of chaparral and sage scrub burned by the 10 largest fires in the Santa Monica Mountains (R. Taylor, *unpublished data*). Fire name, year, and area burned are shown also. Cross-hatched bars are sage scrub, and black bars are chaparral.

pattern of anomalously long droughts prior to our largest fires (Table 1). The causal relationship between drought and megafires may vary with the timing of the fire. For example, the 2007 Zaca Fire, which burned in midsummer, was likely facilitated by the extraordinarily low live fuel moisture for that time of year (Fig. 10). However, this explanation would not apply to autumn fires such as the 2007 Witch Fire (Table 1), since even during the extreme drought year of 2007, the live fuel moisture in October did not differ from the long term

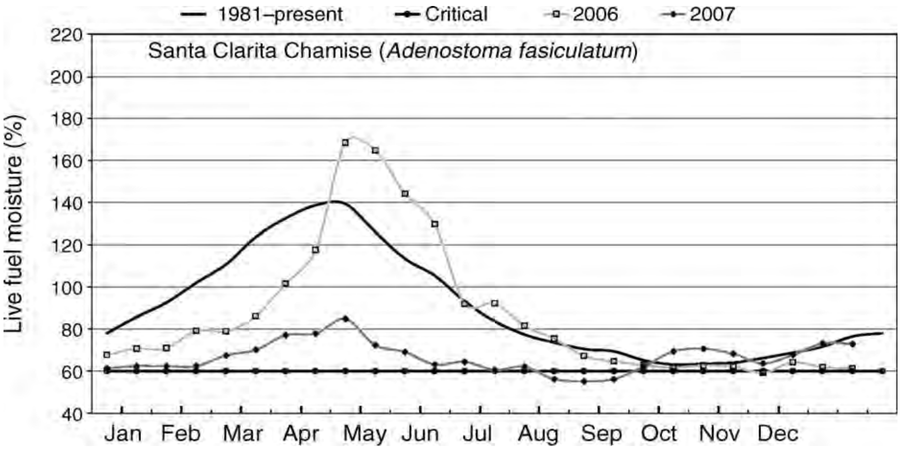

FIG. 10. Live-fuel moisture in the widespread chaparral shrub *Adenostoma fasciculatum* from Santa Clarita in northern Los Angeles County for 2006 and 2007, and the 27-year average. The critical level is 60%, which is the lower threshold for live foliage to survive. ⟨http://www.fire.lacounty.gov/Forestry/FireWeatherDangerLiveFuelMoisture.asp⟩

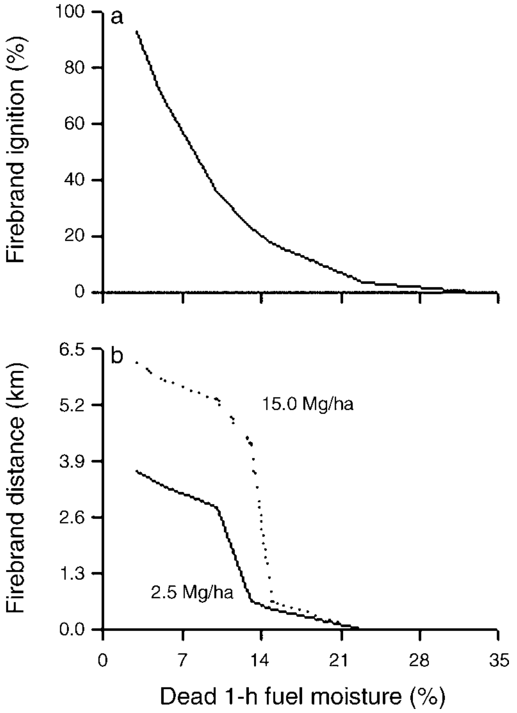

FIG. 11. BehavePlus 4 model results on (a) probability of firebrands igniting and (b) spotting distance from wind-driven surface fire for two amounts of dead fuel; using high-load dry-climate shrub S5 fuel model and wind speed of 80 km/h. (See footnote 8 for BehavePlus 4 software.)

average (Fig. 10). This is because in most years the mediterranean climate results in an annual late spring and summer drought, so that live fuels are normally at their lowest physiological threshold in the autumn; the main exceptions being years with unusually wet springs (Dennison et al. 2008).

We hypothesize that the primary reason anomalously long and extreme droughts lead to megafires is the increased generation of dead fuels in the year or years prior to the fire. Under extended droughts, the live-fuel moisture drops below physiological thresholds, resulting in mortality of twigs and branchlets, or entire shrubs, and greatly increases the dead fine fuel load (e.g., Buck 1951). This was widely observed prior to the 2003 and 2007 fires (Lloret et al. 2004, California Wildfire Coordinating Group 2007, Kelly 2007; J. E. Keeley, *personal observations*).

One of the important differences between live and dead fuels is in their role in spreading fires from embers or firebrands that ignite spot fires. Although live fuels can become embers, the probability of firebrands igniting in live fuels (nearly always with fuel moisture levels above 40%) is low. Under autumn Santa Ana wind conditions, dead fuels have less than 5% moisture content and when embers land in them they have a very high probability of igniting (Fig. 11a). Although the fire front spreads rapidly under high winds, it is always substantially slower than the wind speed (Beer 1991), and thus firebrands lofted above the fire have the potential for greatly increasing the rate of fire spread. As the quantity of dead fuels increase, the probability of long distance transport increases (Fig. 11b), and even more so in rugged terrain with high ridges and canyons characteristic of much of southern California. This hypothesis is supported by field observations; e.g., the fire management officer on the 2003 Cedar Fire has stated that the much greater success of long distance embers igniting spot fires was in his opinion a primary reason this fire ranks as one of the largest in state history (Richard Hawkins, *personal communication*). One of the important features of this model is that dead fuels persist long after drought and may have a continuing legacy for many years, even if the drought dissipates.

Whether or not these extraordinary droughts and the fires accompanying them are due to anthropogenically induced climate change, as may be the case in high elevation western forests (Westerling et al. 2006), is not known. Using the annual average Palmer drought severity index for southern California we find there is a significantly negative decline between 1895 and 2007 ($P = 0.004$, $r^2 = 0.07$, $n = 113$ years) and when averaged per decade it is apparent that the last several decades, on average, have been drier than earlier periods in the 20th century (Fig. 12). We contend that there is a causal relationship between this drought and the large number of megafires in recent years (Table 1), but it is too early to tell if this drought is part of an anthropogenically driven climate change induced trajectory of continued drought, or part of a natural cycle. The sequence of decades with negative PDSI observed in the last 40 years is not novel if a longer time scale is considered; e.g., a similar period of drought occurred in the 19th century (e.g., 1840–1880 in

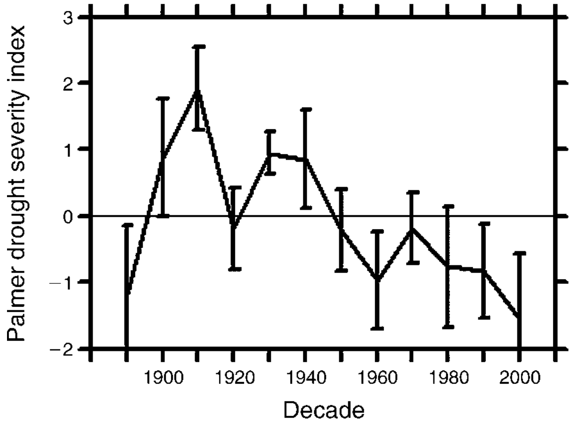

FIG. 12. Decadal average for the Palmer drought severity index (PDSI) for the southern California region (the first decade comprised only the years 1895–1899, and the last decade, 2000–2007). Negative values indicate drier than normal conditions. Error bars (SE) illustrate that all decades have had some wet years, but on average the region has experienced drought over the past half century. Analysis of variance of decadal mean PDSI was significant ($P < 0.001$).

TABLE 2. Frequency of fire events by size class observed in Baja California and considered to be representative of the natural fire pattern in southern California (Strauss et al. 1989, based on Minnich 1983) and calculated fire rotation intervals based on documented lightning fire densities.

Median size class (ha)	No. fires	Percentage of fires	Calculated area burned (ha)† Santa Ana Mountains‡	Calculated area burned (ha)† Santa Monica Mountains§
40–100	167	43.2	12 096	5140
100–200	84	21.8	13 080	5559
200–400	61	15.8	18 960	8058
400–800	29	7.5	18 000	7650
800–1600	19	4.9	23 520	9996
1600–3200	17	4.4	42 240	17 952
3200–6400	4	1.0	1920	816
6400–12 800	4	1.0	3840	1632
12 800–25 600	1	0.3	19 891	8453
25 600–51 200	0	0.0	0	0
>51 200	0	0.0	0	0
Total area burned (ha) in 1 million ha of landscape after 100 years			153 547	65 257
Rotation interval (yr)			651	1532

Notes: For the Santa Ana Mountains we used an average of four lightning-ignited fires per million hectares per year reported for Orange County (Keeley 1982) and for the Santa Monica Mountains an estimate of 2.2 lightning fires per 1 million hectares per year (Keeley 2006).

† Calculated area (ha) burned in 100 years, based on the number of lightning fires per 1 million hectares per 100 years.

Cook et al. [2004]), and in other periods before that (Stahle et al. 2007). Of course even if this recent drought is cyclical, anthropogenic global warming may diminish the magnitude of the upturn in this drought cycle.

In addition to climate-driven temporal variation in megafires (Table 1), there is also a marked pattern of spatial variation as well. These huge fires do not have an equal likelihood throughout the region because topography and vegetation distribution play important roles in determining the ultimate size of fires. It is more than mere coincidence that megafires (Table 1) have occurred either in San Diego County (in the southern part of the region) or in Santa Barbara/Ventura counties (in the northern part of the region). The general topography of both sub-regions supports large contiguous east-west swaths of shrubland fuels where both offshore and onshore wind flows can drive fire over very long distances. Indeed, the sites of the Matilija and Zaca fires (Table 1) are described as having "the greatest unbroken expanses of chaparral in California" (Cermak 2005:121). Counties such as Los Angeles, San Bernardino, and Riverside, dominated by the east–west transverse ranges, largely lack such topographic patterns. For example, the Santa Monica Mountains have been repeatedly burned by large Santa Ana wind driven fires, but the largest on record was a mere 17 400 ha (National Park Service, Santa Monica Mountains National Recreational Area, *unpublished data*). Megafires (e.g., Table 1) would not be predicted for this landscape because Santa Ana wind driven fires follow a north-south trajectory (Weide 1968) and ultimate fire size is constrained by urban development on the northern boundary of these mountains and by the Pacific Ocean on the southern boundary. Similar arguments have been offered for the apparent lack of recent megafires in northern Baja California (Keeley and Fotheringham 2001*a, b*), although prior to intensive land use and habitat fragmentation, such events did occur (Vancouver's Diary from 1793 cited above).

Testing the fine-grain age patch model on southern California landscapes

It has been argued that contemporary fine-grain burning patterns in Baja California represent the historical patterns in southern California (Minnich 1983, 1995). If this is so, then the distribution of fire sizes in pre-suppression California should have resembled that of Baja California (Table 2). If we take this as the fixed probability distribution for fire sizes, then knowing the number of natural fire starts per year allows the calculation of the average area burned per unit time, and from this the rotation interval (area burned divided by total area per year). We use lightning ignition data from two coastal mountain ranges, the Santa Ana Mountains in Orange, Riverside, and San Diego counties, and the Santa Monica Mountains in Los Angeles and Ventura counties (Table 2). We estimate that with the Baja model, the fire rotation intervals would be over 650 years for the Santa Ana Mountains and over 1500 years for the Santa Monica Mountains. Clearly, to produce fire rotations sufficient to maintain these fire-adapted ecosystems (one or two fires per century) the average area burned per year must be much greater than can be accounted for by this Baja model. Either there would need to be many more ignitions than the empirical data indicate, or, as we believe, the historical fire regime did not follow the Baja model but rather consisted of small fires punctuated at periodic intervals by large fire events. Since the lighting season in coastal California is just weeks prior to the Santa Ana wind season it seems likely that prior to human interference, lightning-ignited fires persisted on the landscape until they were picked up and driven by Santa Ana wind events, and this is when the bulk of the landscape burned (Keeley and Fotheringham 2003).

Cellular model predictions from the fine-grain age patch mosaic model

Can the fine-grain model work in theory? To explore this, begin with the simplest model that contains the essential parts of the hypothesis: age, ignition events, and fire size. This can be adequately represented by the "cellular automata" class of models. In an age when there is strong and often ill-placed bias toward complex multi-parameter models (May 2004, Pilkey and Pilkey-Jarvis 2007) it is necessary to justify this choice. Modeling fire behavior upward from first principles has proven difficult (e.g., Finney 2004, Zhou et al. 2005). Therefore it makes sense to take the simplest system and see if it reproduces in a qualitative way the postulated behavior of the fine-grained hypothesis. If it does not, then either the hypothesis is wrong, or there are one or more other factors that need to be considered.

But even a cellular model is more complex than is required to show that the fine-grain hypothesis cannot stand without the inclusion of a fire-stopping rule that is independent of age. Simple logic tells us that if we have a completely deterministic system and we start with a fine-grain age mosaic (not saying how it emerged) with no ages greater than the youngest age at which a cell will burn, and have at least one ignition event per year per age patch, the age mosaic will persist forever and can be as fine-grained as the distribution of lightning ignitions. As each age patch achieves the minimum age at which it will burn, it will be ignited, and since it will be surrounded by younger patches the fires will extinguish along the age boundaries. But if the age mosaic did not already exist, it would be impossible for it to emerge without an age-independent stopping rule. If the landscape had a uniform age no fire would spread when the landscape was less than the minimum age (hereafter, minage), and the entire landscape would burn if it were greater than or equal to minage. The proponents of the fine-grained hypothesis must explain how the fine-grained mosaic necessary to it arises.

If we approach reality more closely by including stochasticity, the flaw in the fine-grain assumption can be made clear by a simple diagram plotting the ages on the two sides of an age boundary (Fig. 13). Both sides will age at the same rate, so that the change in the system over time is represented by lines moving parallel to the line of no difference; farther from this line if the current difference in age is larger, and closer if the age difference is smaller. If it is zero, the system moves along the line of no difference (Fig. 13). The deterministic situation just described exists when a cell burns as soon as it reaches minage (Fig. 13a). After burning, the age of that cell drops to one of the axes (age of the cell just burned = 0). After this, the two cells age but the older cell will reach

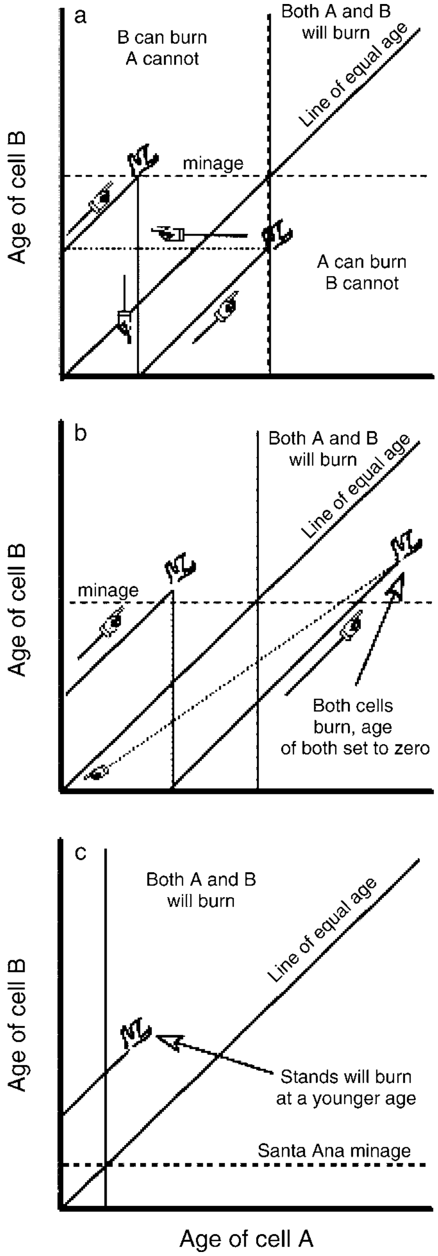

FIG. 13. Perpetuation or loss of an age boundary. (a) The deterministic behavior alleged in the "fuel paradigm." An age boundary persists because the older vegetation will first reach "minage" (youngest age at which vegetation will burn), receive an ignition, and burn. If fire is certain, the boundary will persist forever. (b) If random variation in timing of ignition allows vegetation on both sides of the boundary to reach an age at which they will burn, the age boundary will disappear at the next fire. Over the whole landscape, this process will tend toward coalescence of the age mosaic. (c) If minage varies, so that at some times more of the landscape is liable to burn, the age boundary is much more likely to be eliminated. From this, one would predict that variable "minage" would cause coalescence to occur more rapidly, with or without random ignition. The figure is modified from Zedler and Seiger (2000).

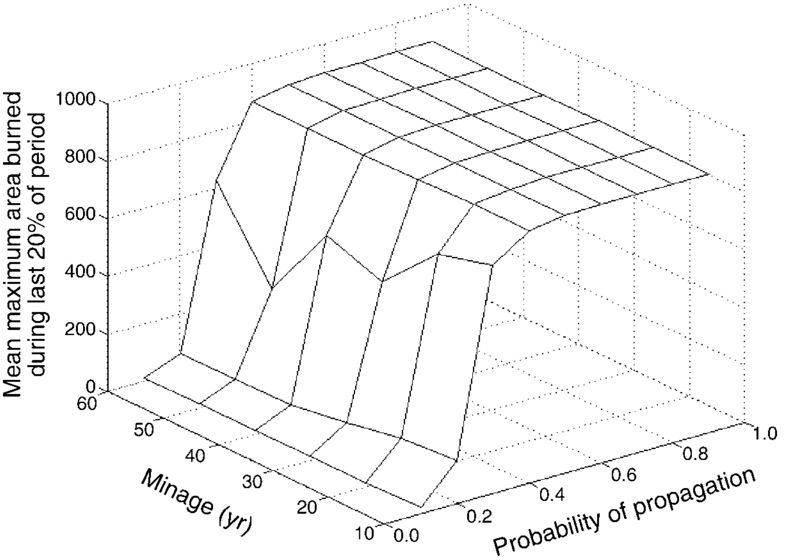

FIG. 14. Effect of minage (youngest age at which vegetation will burn) and probability of propagation (probability that fire will transfer to an adjacent unburned cell) on the maximum area burned during the last 20% of the simulation period (to minimize the effect of transient conditions). The simulation is run for 500 years for a 900-cell landscape. Beyond a probability of propagation of 0.5, the system is locked into very large fires, regardless of minage or, as shown in the text, the number of ignitions.

minage first, will burn, and return to zero on the other axis, and so on forever (Fig. 13a). But there are two ways this beautiful system can be disrupted stochastically. If ignition is not certain on a cell achieving a burnable state, then a cell can age past minage and the system can move into the upper right quadrant when both cells are older than minage. A fire at that time will set both cells to zero, the age boundary will disappear, and the system will be trapped forever along the line of no difference and the cells will coalesce (Fig. 13b). Alternatively, if minage is not fixed, so that in some years much younger cells can burn, it is possible for the condition in one year to be, e.g., "one could burn, one cannot" and in the next to be "both will burn" (Fig. 13c). As discussed above, this is what follows when an ignition event occurs during Santa Ana winds. And since these two departures from determinism are not mutually exclusive, both can operate to break down a preexisting age mosaic.

Adding both spatial pattern and stochasticity to the mix by use of a cellular model underscores the conclusions from these simple demonstrations. Since the proponents give no general guidance as to which factors other than age will cause a fire to go out, we incorporated this into our model by varying the probability that fire would spread from one cell to the next ("probability of propagation"), with these probabilities applying across the entire landscape. With a probability of 1, all adjacent cells greater than or equal to *minage* will burn, with a probability of 0, only the ignited cell would burn and fire size would be limited to one cell regardless of the age of the surrounding cells.

Our first series of runs varies the probability of propagation, the minimum age (*minage*) and the number of ignition events on a landscape of uniform age to explore the conditions under which a complex age mosaic will develop. To avoid the early transient conditions, the metric for our response variable is the largest fire in the last 20 simulated years. We choose a 30 × 30 landscape consisting of 900 grid cells.

Our results show that the postulated age mosaic will not develop except at low values of probability of spread. At probability values of 0.4 and above, the largest fires in the last 20 years of the simulation burn the entire landscape (Fig. 14). Varying minage has almost no effect, except at transitional probabilities of spread (Fig. 14). At a probability value of 0.3, greater values of minage result in smaller maximum fire size, though this may be a transient phenomenon.

The only possibility for the growth of a fine-grain mosaic is with a very low probability of spread. If ignitions are few (one per year, or in the simulation 0.0004 ignitions$\cdot$cell$^{-1}\cdot$yr^{-1}) and probability of propagation only 0.2, the system starts with a relatively large fire when the landscape first reaches minage, and then evolves toward a mixture of very small and medium size fires which appears to be the persistent state (Fig. 15a). The reason for this behavior can be gauged by noting that the average age of the landscape increases sharply and then tends to level off well above minage (Fig. 15). This is because the number of ignitions is not sufficient to burn all of the landscape that is burnable at this probability of propagation. These characteristics do not match those predicted by the fine-grain age patch model.

Increasing the ignitions by two orders of magnitude, but still with 0.2 probability of propagation also produces a complex age landscape and a pattern of burning that does resemble the ideal state postulated by

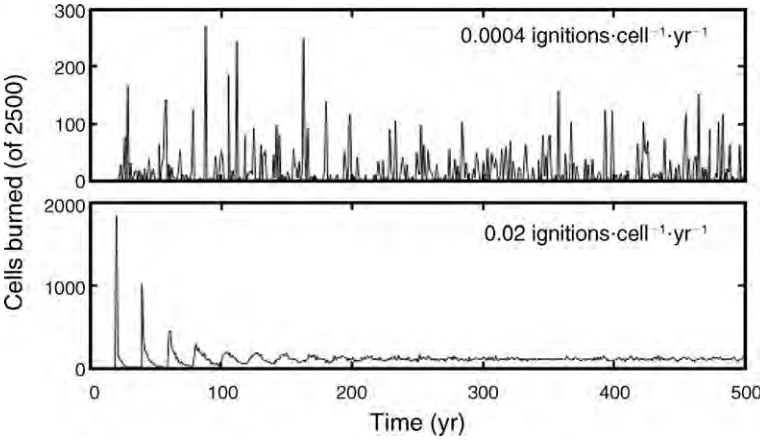

FIG. 15. Simulated results for a 2500-cell universe with a minage of 20 years, a probability of propagation from one cell to the next of 0.2, and 1 or 500 ignitions per year. At one ignition per year, this low probability of propagation produces a quasi-stable situation with a variable but generally small area burned per year. At 500 ignitions per year, the system oscillates with a period that corresponds to minage, toward a stable situation of consistently small area burned per year.

the fine-grain mosaic. As with the single ignition case, there is a large fire when the landscape first reaches minage, but then the system evolves toward small fires each year, corresponding closely to the situation postulated by the fuel-age paradigm proponents (Fig. 15), except that the average age of the vegetation oscillates toward a value well below minage (Fig. 16). Because of the high number of ignitions (500, or one for each five cells per year), any given age patch has a high probability of being ignited even if it is not burned in its entirety, making the evolution toward a complex age mosaic possible. While this outcome demonstrates the mathematical possibility of a fine-grain mosaic, it creates an unusually young landscape, and requires a severe stopping rule in the form of a low probability of propagation, and an unrealistically dense and uniform temporal and spatial coverage by ignition sources. With more realistic probabilities of propagation, the system rapidly moves to an all-or-nothing burn pattern, and with number of ignitions relatively unimportant (Fig. 14). We conclude that it is not possible to produce a landscape with a plausible fine-grain age distribution without unrealistic assumptions.

We also explored the problem from the other side, that is, beginning with a complex age mosaic and measuring the time it takes for this to revert to a large fire system, one in which 90% or more of the landscape burns in a single year. To show the strong effect of variable minage on the coalescence process (cf. Fig. 13), we ran two sets of simulations both of which started with 900 cell landscapes in which there were patches with random ages between zero and minage. In the first, minage was held constant across simulated time at 25 years. In the second, minage values varied from year to year. The minage in a particular year was selected from a normally distributed random population with a mean of 25 and a standard deviation of 5. In both, there was only a single ignition per year. The results show both that a constant minage takes more time to coalesce, and that the probability of propagation has a greater effect (Fig. 17). The results for both situations demonstrate that a random mosaic will coalesce with time, and that this coalescence process is greatly accelerated if minage varies stochastically, as the simple model of Fig. 13 would predict.

These simple models show that any convincing hypothesis for the evolution of the age patch structure of a chaparral landscape must have a much more complicated stopping rule that involves more than age. For a spatial pattern to have a stable age structure, a new age boundary must be created for each one that is destroyed. If the fine-grain mosaic hypothesis is to be

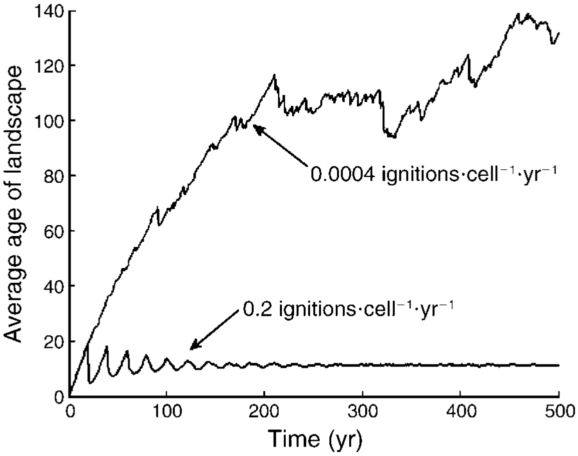

FIG. 16. Data from the simulations run for Fig. 15 expressed as the average age of the landscape. With only one ignition per year, the average age increases consistently and then tends to level off. This is because the low probability of spread insures that only a small part of the landscape will burn, despite the fact that many cells are well beyond the minage. In contrast, with saturating ignitions (lower line), the average age of the landscape stabilizes at about half of minage because any area that achieves minage will burn.

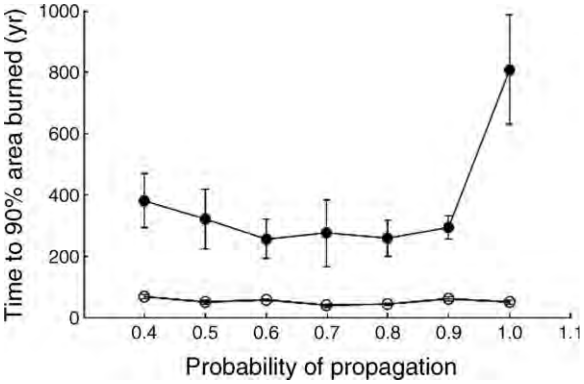

FIG. 17. Comparison of "time to coalescence" starting from a random distribution of ages in simulated landscapes subjected to constant (solid circles) and variable (open circles) minimum ages at which the cells will burn for different probabilities of spread from one "burning" cell to the next. Error bars are ±SD for samples of 25 runs. Note that the error bars for the variable case are contained within the symbols. For this run, the "landscape" consists of 900 grid cells, and minimum age is taken as 25 years. Above a probability of propagation of 0.4, all possibilities evolve toward eventual coalescence, but this occurs less than 25% of the time when the minimum age is allowed to vary normally about the mean with standard deviation of 5 years.

saved, how this process works must be clarified and real-world examples presented.

In summary, the only plausible conditions where the fine-grain age patch model would evolve toward a complex age mosaic would be if the environment were saturated with ignitions and if fires are patchy, which appears to be the case on certain forest types such as southwestern ponderosa pine and southeastern longleaf pine. These are ecosystems with historical patterns of frequent low severity understory surface-fire regimes made possible by an annually renewing herbaceous layer clearly separated from the tree canopy layer. Transferring that model to California shrublands cannot be justified.

CONCLUSIONS

In southern California, modern fire regimes have much in common with historical regimes. This landscape has been subject to large high-intensity wildfires long before Euro-Americans settled the region and such fire events cannot be blamed on land management practices. As is the case today, historical fire regimes were characterized by many small fires but the bulk of the landscape burned in infrequent massive wildfires, often driven by severe weather that involved high temperatures, low humidity and high winds. The primary difference today is that, due to human ignitions, there are many more fires and the rate of burning far exceeds historical levels (as illustrated by fire frequency departure analysis [H. D. Safford and D. Schmidt, *unpublished data*]). Thus, the idea that fire suppression has altered fuel structure in ways that make this landscape more vulnerable to large fires is demonstrably false for southern California.

Historically, climatic variation probably caused considerable fluctuation in the timing and size of fires. Human ignitions have been part of the picture for thousands of years, and in coastal valleys Native American populations increased fires sufficiently to type convert shrubland landscapes (Timbrook et al. 1982, Keeley 2002*b*). However, the most important change in the region has been the 20th century increase in human populations and concomitant increase in fires, coupled with demographic patterns that have resulted in increased human mobility and dispersion into previously isolated chaparral landscapes. Although fire suppression policy has been in effect for over a century, aggressive fire control has been in effect for about half that time. Its increasing technological capacity and impressive organizational advances however, have not been able to counteract the temporal and spatial expansion of anthropogenic ignitions. In particular, contemporary populations have increased the likelihood of ignitions during Santa Ana wind events, and, by the increasing spread of population centers to interior regions, have increased the potential fire size under offshore wind patterns.

The present analysis points toward several management recommendations. Attempts to create a mythical fine-grain age mosaic are doomed to fail. Burning large areas on a 15–20 year rotation in small patches would require massive investments and a significant risk of damaging fire escapes that can cause expensive losses of property. In addition, even if such a mosaic were created, under a wide range of conditions, such sites would not prevent the spread of wildfires. Recent history suggests that the accumulated work of decades could be swept away in a single large fire under severe weather.

Fuel treatments may be a barrier to fire spread under benign weather, and under more severe weather, provide access and anchor points for fire fighting activities. They also contribute to reduced flame lengths and provide defensible space around urban developments. Thus, attention needs to be given to their most strategically useful placement on the landscape, so that they are cost effective. In addition to their monetary cost, fuel treatments have potential negative impacts on resources (Keeley 2005, Ingalsbee 2006), and thus they need to be done judiciously. Application of fuel treatments beyond the wildland-urban interface zone may have tactical value, but much research is still needed on the most cost-effective placement of these treatments.

This analysis suggests that the greatest improvements in reducing community vulnerability to wildfires is not like going to come from improved fuel treatments or fire suppression capabilities, but rather from changes in human infrastructure. The most significant advances are likely to come from improved fire prevention and careful analysis of land planning and zoning issues.

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APPENDIX A

Transcripts of newspaper articles or book sections describing large, high-intensity fires from the 19th century in California counties from Santa Barbara south. (*Ecological Archives* A019-004-A1).

APPENDIX B

Southern California Santa Ana foehn wind characteristics and their relationship to fires in the region (*Ecological Archives* A019-004-A2).

APPENDIX C

Lessons from the 2007 Santiago Fire applied to the reconstruction of the 1889 Santiago Canyon Fire (*Ecological Archives* A019-004-A3).

APPENDIX D

Further notes on Gorforth and Minnich's (2007) alternative interpretation of the 1889 Santiago Canyon Fire published in Ecological Applications 17:779–790 (*Ecological Archives* A019-004-A4).

APPENDIX E

The 1932 Matilija Fire perimeter and prior 20th-century fire history (*Ecological Archives* A019-004-A5).