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Author(s): Max A. Moritz, Jon E. Keeley, Edward A. Johnson and Andrew A. Schaffner
Source: *Frontiers in Ecology and the Environment*, Vol. 2, No. 2 (Mar., 2004), pp. 67-72
Published by: Wiley on behalf of the Ecological Society of America
Stable URL: https://www.jstor.org/stable/3868212
Accessed: 23-01-2020 18:06 UTC

Testing a basic assumption of shrubland fire management: how important is fuel age?

Max A Moritz[1], Jon E Keeley[2], Edward A Johnson[3], and Andrew A Schaffner[4]

This year's catastrophic wildfires in southern California highlight the need for effective planning and management for fire-prone landscapes. Fire frequency analysis of several hundred wildfires over a broad expanse of California shrublands reveals that there is generally not, as is commonly assumed, a strong relationship between fuel age and fire probabilities. Instead, the hazard of burning in most locations increases only moderately with time since the last fire, and a marked age effect of fuels is observed only in limited areas. Results indicate a serious need for a re-evaluation of current fire management and policy, which is based largely on eliminating older stands of shrubland vegetation. In many shrubland ecosystems exposed to extreme fire weather, large and intense wildfires may need to be factored in as inevitable events.

Front Ecol Environ 2004; 2(2): 67–72

Despite a long-standing recognition of fire's crucial role in many terrestrial ecosystems, uncertainties and disagreements over fire management strategies persist. For regions with a Mediterranean climate, modern fire suppression is commonly thought to increase the likelihood of large and intense wildfires. However, debates over fire suppression effects and needed landscape treatments, especially for shrublands in Australia (Bradstock and Gill 2001; Whelan 2002) and California (Minnich and Chou 1997; Keeley *et al.* 1999; Keeley and Fotheringham 2001; Minnich 2001; Moritz 2003), often involve a fundamental assumption about aging fuels and increasing fire probabilities.

The costs of fire suppression in southern California have continued to rise over the past several decades, and there have been increasing losses of property and human life due to wildfires (CDF 1995). The multiple fires of late October 2003, with over 300 000 ha burned in a single week, brought the "fire problem" of densely populated southern California to national attention. The flames were driven by the hot, dry winds typical of the region (Figure 1), overwhelming fire suppression forces and burning through entire neighborhoods at points along the urban–wildland interface. As in many fire-prone ecosystems, the success of past suppression measures is generally believed to have allowed larger and older stands of even-aged vegetation to develop on these shrubland-dominated landscapes, a situation that purportedly generates larger and more intense wildfires (Minnich 1983). However, the importance of young vegetation patches in the landscape age-patch mosaic is based on the premise that fire probabilities are strongly controlled by the age and spatial patterns of fuels.

A fire regime is a statistical characterization of recurring fire in an ecosystem, and parameters that are often measured include fire interval, size, intensity, and season. Quantifying average parameter values and their natural ranges of variation is important in understanding natural fire regimes and how recent human activities may have altered them. In forests that prehistorically experienced relatively frequent, low-intensity understory fires, such as the ponderosa pine (*Pinus ponderosa*) forests of the southwest US, modern fire suppression is believed to have increased the likelihood of large, high-intensity fires that are stand-replacing (Covington and Moore 1994). In contrast, in ecosystems naturally characterized by infrequent, stand-replacing fires, fire suppression has probably had less impact on natural fire regimes. This is because large fire events in crown fire ecosystems are more driven by extreme weather conditions than they are limited by fuel characteristics (Turner *et al.* 2003).

The natural fire regime of California's shrublands is typically one of high-intensity, stand-replacing fires. Despite being a crown fire ecosystem with relatively little surface fuel, the natural fire regime of most shrublands is widely seen as controlled by age-related characteristics of vegetation. The validity of this age-dependent view, and thus the likely effects of modern fire suppression, have been debated in the literature over the past decade, and were reviewed in a recent forum (Keeley and Fotheringham 2001; Minnich 2001). The fires of 2003 in southern California demonstrated once again that living within or near fire-prone shrubland landscapes poses serious risks, and that debates over this issue have immediate relevance. It is therefore necessary to examine critically the

[1]*Department of Physics, University of California, Santa Barbara, CA (current address: Ecosystem Sciences Division, Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA)*; [2]*US Geological Survey, Western Ecological Research Center, Sequoia Field Station, Three Rivers, CA and Department of Organismic Biology, Ecology, and Evolution, University of California, Los Angeles, CA*; [3]*Department of Biological Sciences, University of Calgary, Calgary, Alberta, Canada*; [4]*Statistics Department, Cal Poly State University, San Luis Obispo, CA.*

Courtesy of NASA/GSFC

Figure 1. *Fires in southern California on October 26, 2003. The smoke plumes indicate the direction and strength of the severe Santa Ana winds. The red dots represent actively burning fires, most of which were in shrublands. The study area (see Figure 2) includes the region shown here and extends north approximately 100 km.*

assumption of age dependency in controlling shrubland fire regimes, since it is the basis of many fire management activities in these ecosystems. Here we synthesize and reanalyze previously published data from both sides of the debate to quantify the relationship between stand age and the hazard of burning (Johnson and Gutsell 1994) in shrublands. If shrubland fire regimes are strongly affected by age patterns of fuels, this control should be evident in historical fire data.

■ Methods

Study area

The fire data utilized here encompass the full range of shrubland-dominated landscapes in coastal central and southern California, consisting of mapped fire histories from ten different units of analysis (Figure 2). These shrubland landscapes extend southwards from Monterey County, past the US–Mexico border, representing approximately 500 km of latitude, and gradients in precipitation, growing season, ecological communities, and land use. Each fire history represents tens of thousands of hectares burned, hundreds of fires, and periods of record ranging from about 50 to 85 years. The study area is restricted to coastal scrub- and chaparral-dominated shrublands, based on mapped vegetation types. Vegetation data (Figure 2) are from the California Gap Analysis Project (Davis *et al.* 1998), with the exception of shrublands south of the US–Mexico border (Minnich and Chou 1997).

To test the assumption of age dependency, we examined previously published fire data for subregions of Los Padres National Forest (LP) (Moritz 2003), the Santa Monica Mountains National Recreation Area (SM) (Polakow *et al.* 1997), southern California (SCA), and northern Baja California (BCA) on either side of the US–Mexico border (Minnich and Chou 1997). All subregions are spatially distinct units of analysis, with the exception of SM, which is analyzed by shrubland vegetation type.

Quantifying hazard

If factors related to fuel age acted as a strong control on fire probabilities, this would be evident in the amounts and frequencies of burning through different age classes of vegetation. One method for evaluating age effects in fire interval data is through fire frequency analysis, commonly based on fire history maps that record time since fire (ie stand ages) or sequential patterns of burning on a landscape (Johnson and Gutsell 1994). Hazard functions, which reflect how the probability of fire changes with the age of fuels, can then be derived by fitting a flexible, generalized Weibull model to fire interval probability distributions. This function is also known as the "instantaneous

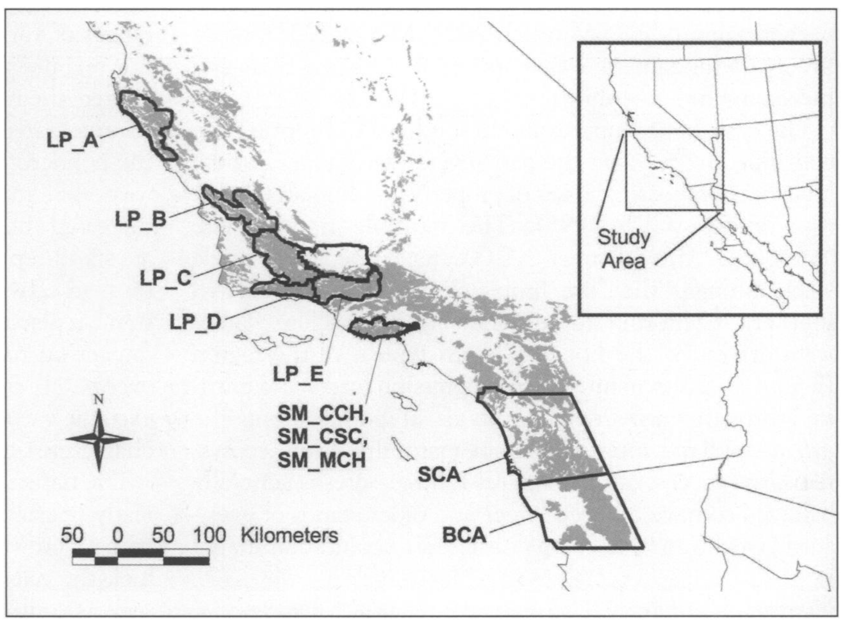

Figure 2. *Location of study area and extent of shrublands. Sites consist of subregions of Los Padres National Forest (LP), the Santa Monica Mountains National Recreation Area (SM), southern California above the US–Mexico border (SCA), and northern Baja California below the US–Mexico border (BCA). A non-shrubland portion of LP (north of unit LP_E) is not included in analyses described here. SM data are divided into three separate types by dominant shrubland classification (SM_CCH, SM_CSC, and SM_MCH represent data for chamise chaparral, coastal scrub, and mixed chaparral areas, respectively), while other study areas are spatial subregions.*

death rate" or the "moment of mortality" in survival analysis. The hazard of burning $\lambda(t)$ typically involves two estimated parameters and takes the form:

$$\lambda(t) = \frac{ct^{c-1}}{b^c}$$

where t is time since the last fire in years. The two estimated parameters in the Weibull model include the scale parameter b, related to the expected interval between fires, and the shape parameter c, which captures how the hazard of burning changes with time since the last fire. If hazard does not change with time since fire, this is reflected by shape parameter $c = 1$. Higher values reflect increasing fire hazard with the age of fuels. Values of $1 < c < 2$ reflect a hazard that grows at a diminishing rate (t is raised to a power less than 1), while $c = 2$ indicates a linear increase in hazard of burning with time. As shape parameters become increasingly larger than 2, they reflect increasingly steep growth in hazard rates for older age classes of fuels (exponential growth). Thus, hazard functions provide a simple test for the assumption that fires are constrained by the age patterns of fuels.

The fire frequency analyses presented here are all area-based and employ the same general approach to hazard analysis, although they reflect minor differences in data sources and statistical methods. Fire interval distributions for LP regions were generated from overlapping fire events for 1911–1995 (Moritz 2003). Fire interval data were not available for SM, but Weibull parameter values were obtained from estimates based on overlapping fire events for the years 1925–1998 (Polakow *et al.* 1997). Fire interval distributions for SCA and BCA were based on time-since-fire maps as of 1971, and limited to nine age classes extending back to about 1920 (Minnich and Chou 1997). Weibull parameters for all regions were obtained through maximum likelihood estimation and were based on historical fire patterns. Statistical model fitting accounted for censored distributions (ie truncated in time) only in the case of SM (Polakow *et al.* 1997).

■ Results

Based on visual inspection of fire interval data (Figure 3), most of our study areas did not appear to exhibit a strong age effect of fuels. If there was a marked age effect then one would expect sigmoidal curves; in other words, these distributions should show relatively flat slopes in the initial decades after a fire, and much steeper slopes in medium-aged fuels, as more burning takes place. The only distribution exhibiting a somewhat sigmoidal (S-shaped) form, form was that of region LP_D (Figure 3). Other distributions exhibited relatively steep slopes in the first few decades, reflecting substantial burning through all of these age classes of fuels (about 25% before age 20). Fire interval distributions also indicated that the majority of burning occurred by a relatively young age (about 50% by age 40), far earlier than the average intervals estimated at roughly

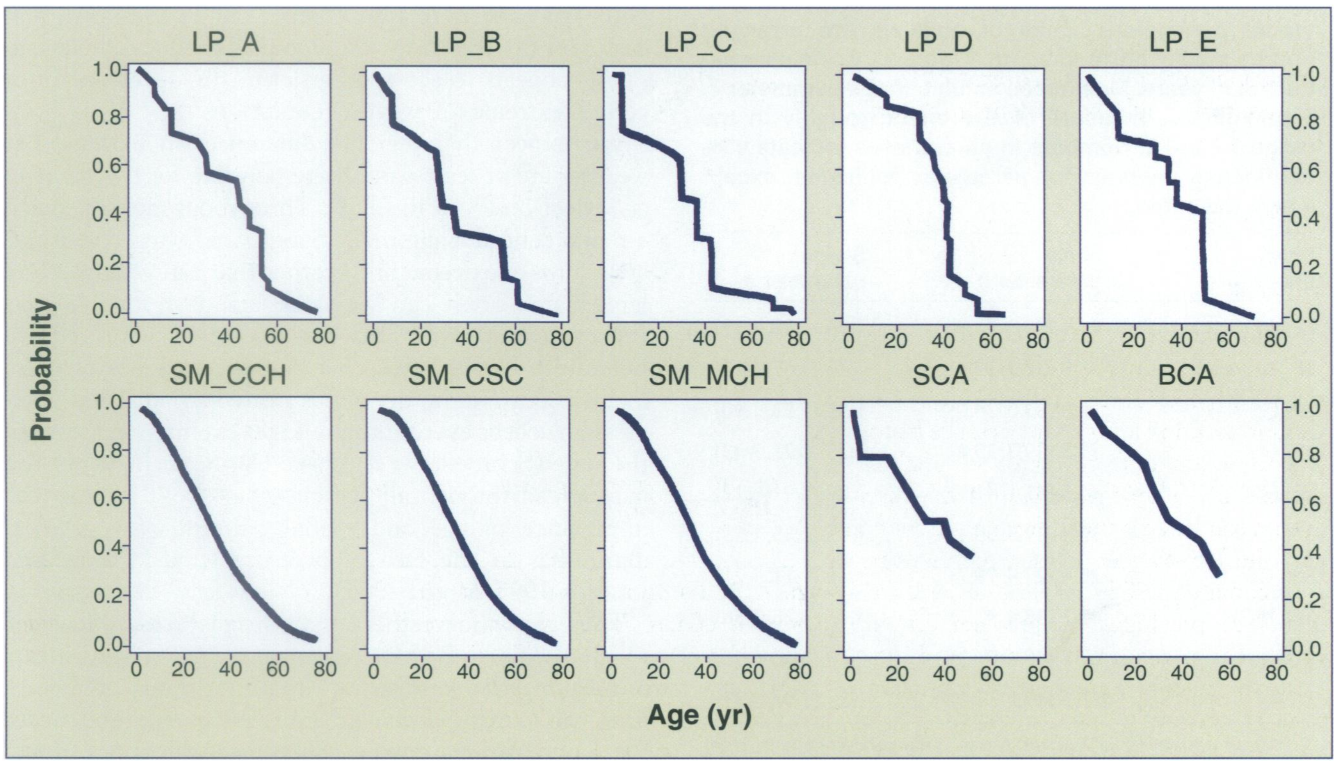

Figure 3. *Cumulative forms of fire frequency distributions from historical data. Subregion LP_D is the only area exhibiting a relative lack of burning in young age classes and a notable increase (a sharp steepening in slope) after about the first two decades.*

70 years for some shrublands (Minnich and Chou 1997).

Estimated hazard functions (Figure 4) confirmed the visual interpretation of fire frequency distributions, and provided a yardstick for a more quantitative comparison (see Table 1 for fitted parameter values). Shape parameters from all but one of the ten sites reflected a minimal effect of stand age; they were either not significantly different from 1 (ie completely independent of age) or fell roughly into the range $1 < c < 2$. For example, the mean hazard of burning for most shrubland regions (all curves in Figure 3 excluding LP_D) is ~2.4% in year 20, while by age 60 it has only grown to ~4.9%. Thus, instead of increasing sharply with age, the majority of shrublands exhibited a hazard of burning near a constant rate (about 2.7% per year) or not far above it. Historical fire patterns and quantitative measures of hazard therefore refute the common assumption that fire probabilities in shrublands are strongly driven by vegetation age, and that large fires are necessarily caused by a buildup of older fuels.

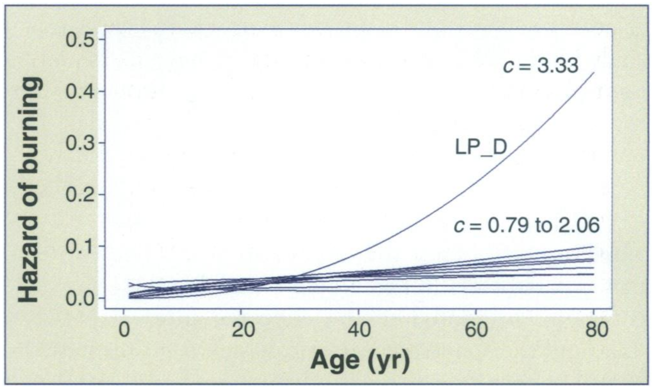

Figure 4. *Change in hazard of burning over time. All study areas but one show minimal increases in hazard over time. Region LP_D, located near Santa Barbara, is the only one exhibiting a marked increase as fuels get older; a relatively high value of shape parameter* c *= 3.33 reflects this trend.*

■ Fire weather conditions

Across our ten sites, one stands out as distinct from the others. At the western end of the Santa Ynez Mountains, subregion LP_D is bordered by the Santa Ynez River to the north and by the coastal plains near the city of Santa Barbara to the south (Figure 2). Unlike most sites in the study, this area showed a more marked increase in fire hazard in older age classes of fuels. By age 60, the hazard of burning here was 300–500% higher than the other shrubland landscapes analyzed (Figure 3). We do not know why this site exhibits a stronger age effect, but a number of factors need further investigation: (1) early successional species composition and growth rates here may result in less hazardous conditions during years immediately following a fire; (2) this area abuts the highly urbanized Santa Barbara region, so a better developed fire-fighting infrastructure may have resulted in fewer fires and/or earlier fire detection over the period of record; (3) topographically, this area is bounded by potential barriers to fires coming out of the north and east; and (4) the east–west alignment of local mountain ranges appears to act as a barrier to the development of certain extreme fire weather conditions.

Table 1. Maximum likelihood estimates for Weibull model parameters. Units of analysis are arranged approximately north to south (Figure 2). Scale parameter *b* is in years. Most areas exhibit shape parameter *c*, a quantitative measure of age effect, roughly in the range $1 < c < 2$. Numbers in parentheses indicate 95% confidence intervals for parameter estimates, except where indicated.

Study area	Scale parameter *b*	Shape parameter *c*
LP_A	41.4 (40.9, 41.9)	1.94 (1.90, 1.99)
LP_B	38.9 (38.5, 39.4)	1.70 (1.67, 1.73)
LP_C	33.5 (33.0, 34.0)	1.56 (1.53, 1.60)
LP_D	39.5 (39.3, 39.8)	3.33 (3.23, 3.43)
LP_E[1]	41.5 (41.1, 41.9)	2.06 (2.01, 2.11)
SM_CCH[2]	35.3 (32.8, 38.1)	1.45 (1.35, 1.55)
SM_CSC[2]	29.4 (27.4, 29.7)	1.16 (1.11, 1.21)
SM_MCH[2]	40.3 (38.4, 42.6)	1.42 (1.28, 1.56)
SCA1	62.9 (49.6, 76.2)	0.79 (0.60, 0.98)
BCA	53.1 (49.2, 57.0)	1.23 (1.07, 1.39)

[1]Confidence intervals for LP_E and SCA show shape parameters to be nearly indistinguishable from $1 < c < 2$. In the case of SCA, $c \approx 1.2$ if the youngest age class is omitted from parameter estimation; this is an indication of minimal age effect very close to that of neighboring BCA, as would be expected. [2]Intervals reflect 90% confidence values.

We suspect that regional differences in extreme fire weather are at least partially responsible for the stronger age effect observed in LP_D. Throughout most of southern and central California, "Santa Ana" wind conditions are a form of extreme fire weather that can generate very large blazes. These can last for several days, involve gusts exceeding 100 kph, and are associated with relative humidities below 10%. One or more episodes of these foehn winds (warm, dry winds heated by adiabatic compression) occur every autumn across extensive portions of the state (Schroeder *et al.* 1964). During such events, fire may spread through all age classes of fuels, because the importance of age and spatial patterns of vegetation diminishes in the face of hot, dry winds (Bessie and Johnson 1995; Moritz 2003).

These synoptic weather conditions play a less important role in the Santa Barbara region, so the age-related effects of fuels may be stronger as a result. Although temperatures can increase during a Santa Ana event, residents of the Santa Barbara coastal region do not report extreme winds, even when severe conditions are occurring in adjacent regions such as Ventura County. This phenomenon has not been formally studied, but may perhaps be related to a series of local mountain chains that potentially block the formation of Santa Ana winds in coastal Santa Barbara. Examination of weather station data during the Santa Ana-driven fires of 2003 revealed that winds in the Santa Barbara region were indeed much less severe than in other areas (MA Moritz unpublished). Severe fires during the unusual downslope canyon wind condition known as "sundowner winds" have been reported for the Santa Barbara region (Ryan 1996), but these do not pose the same fire danger as Santa Ana winds, because they are typically of shorter duration and localized to a few watersheds.

■ Fire management and planning

Just as in other crown-fire ecosystems, most of the area burned in California's shrublands is historically due to a small number of fires that burn under extreme weather conditions (Minnich 1983; Moritz 1997; Keeley *et al.* 1999). One might therefore expect most burning to be more dependent on extreme fire weather than on the age and spatial patterns of fuels (Turner *et al.* 2003). Nonetheless, much of the fire management and fire policy seem to be based on a deterministic relationship between the age of vegetation and inherent flammability characteristics. This view follows from trends of biomass accumulation with age in shrubland vegetation.

Although the ratio of dead to live fuels purportedly increases with stand age, recent studies cast doubt on this generalization (Payson and Cohen 1990; Regelbrugge 2000). Regardless of how fuel accumulation and flammability may vary with age, it is not generally acknowledged that there are natural tradeoffs in the importance of shrubland fuel characteristics as weather conditions become more severe. Contrary to popular belief, on most shrubland landscapes these tradeoffs result in extreme fire weather overwhelming the influence of the age and spatial patterns of fuels. This general finding is strikingly consistent over broad spatio-temporal scales and among different fire frequency data types and approaches (see Methods). Our findings are also consistent with another recent study of fire patterns in shrublands of the Los Angeles region (Peng and Schoenberg in press).

It is noteworthy that scenarios of climate change and wildfire in California focus on changes in fuel characteristics, as opposed to potential changes in fire weather patterns (Torn *et al.* 1998; Field *et al.* 1999). Our results indicate that, because characteristics of fuel accumulation do not always control burning probabilities, it should not automatically be assumed that future climates which increase fuel loads will alter fire regimes. Future patterns in the intensity and frequency of extreme fire weather may be a much more important factor in such scenarios.

The lack of a strong age effect of fuels should have major implications for planning and management in many shrubland ecosystems. Our results contradict the widely held belief that large wildfires in California shrublands are the direct result of unnatural fuel accumulation due to fire suppression. Before modern suppression methods were introduced, extreme weather conditions could have infrequently generated large conflagrations that spread through all age classes of vegetation, just as they do now (Moritz 2003). These findings are important for fire management, because local US Forest Service departments consider pre-fire fuel manipulations a primary means of dealing with the fire hazard inherent in these shrublands (Conard and Weise 1998). Rotational prescription burning to maintain a landscape mosaic of different age classes is thought to inhibit large fire development; however, the present study suggests that this strategy will be ineffective. Prescription burning in these crown-fire ecosystems also has limitations not experienced in forest ecosystems. It can be ecologically harmful to native species to employ prescription burning in relatively young shrublands before a sufficient seed bank has accumulated to ensure successful regeneration (Odion and Tyler 2002). In addition, prescription fires in older shrublands are limited to weather conditions that minimize the chances that the flames will escape containment (in winter and spring), but these conditions may also inhibit post-fire recovery of vegetation (Keeley 2002).

Although prescription burning and other fuel manipulations should still be useful at strategic locations along the urban–wildland interface, we may need to accept large fires as natural and inevitable events on many shrubland landscapes. Because several of our conclusions parallel those about fire management in Australian shrublands (Bradstock and Gill 2001; Whelan 2002), this study has relevance for many fire-prone regions that are routinely exposed to extreme fire weather. Minimizing losses of life and property will ultimately require a science-based approach that integrates fireproofing of structures, intelligent landscaping, better evacuation preparation, and land use planning that constrains rapidly expanding urban–wildland interfaces.

■ Acknowledgments

We thank S Cole, D Odion, and D Sapsis for review and comments on a draft of this paper. MA Moritz was partially supported by a grant from the James S McDonnell Foundation during preparation of the manuscript.

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