

SPATIOTEMPORAL ANALYSIS OF CONTROLS ON SHRUBLAND FIRE REGIMES: AGE DEPENDENCY AND FIRE HAZARD

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Abstract. Large fires in chaparral-dominated shrublands of southern and central California are widely attributed to decades of fire suppression. Prehistoric shrubland landscapes are hypothesized to have exhibited fine-grained age-patch mosaics in which fire spread was limited by the age and spatial pattern of fuels. In contrast, I hypothesize that fires during extreme weather conditions have been capable of burning through all age classes of the vegetation mosaic. Using the mapped fire history (1911–1995) of Los Padres National Forest, I analyzed burning patterns for hundreds of fires using a geographic information system (GIS). To estimate the degree of age dependency exhibited by the fire regime at different spatial scales, I employed methods of fire frequency analysis (i.e., fitting a generalized Weibull function to fire interval distributions). Statistics were also calculated using a temporal breakpoint of 1950 to assess possible effects of suppression. Results indicated that shrubland fires have frequently burned through young age classes of vegetation, exhibiting a minimal degree of age dependency. Findings were not scale dependent and were consistent for all but one region of the study area. The anomalous region exhibited a more rapid increase in the hazard of burning with fuel age, reflecting a moderately age-dependent fire regime; this difference probably resulted from the fact that the region is somewhat sheltered from extreme fire weather that commonly affects other shrublands. Exposure to extreme fire weather therefore appears to override the sensitivity of a fire regime to fuels characteristics at the landscape scale. Fire suppression has affected characteristics of smaller fires much more than those of larger fires. Since 1950, there has been a decrease in size and an increase in the number of smaller fires. Findings support the claim that fire suppression could offset ecological risks posed by increasingly frequent human-caused fires in specific areas, but with a net decrease in annual burning rate of ~14% across the landscape. Findings contradict the assertion that, in the absence of fire suppression, large fires would be constrained by more complex age-patch mosaics on the landscape.

Key words: chaparral shrublands; crown fire ecosystem; disturbance regime; fire frequency; landscape mosaic; Los Padres National Forest, California; suppression.

INTRODUCTION

There has been considerable debate about the effects of fire suppression on natural fire regimes in mediterranean-climate shrublands of California. These ecosystems are dominated by chaparral and coastal scrub vegetation, both highly adapted to fire. Based on comparisons of southern California and northern Baja California fire histories, Minnich (1983, 1989) and Minnich and Chou (1997) proposed that chaparral-dominated shrublands have fuel-dependent fire regimes strongly limited by the age and spatial pattern of fuels. If this hypothesis is correct, chaparral ecosystems should, in the absence of fire suppression, exhibit many small fires. The resulting fine-grained landscape mosaic and strong age dependence of fire behavior are then presumed to act as a feedback inhibiting subsequent large fires, because fires encounter neighboring patches of recently burned vegetation and stop spreading, even during extreme fire weather.

Fire suppression has altered fire regimes and vegetation characteristics in many ecosystems. Arguments against a fuel-driven paradigm for shrublands have emphasized: scarcity of lightning ignitions (Keeley 1982), natural contiguity in expanses of chaparral fuels (Christensen 1985, 1993), resilience of chaparral species to a variety of fire intervals (Keeley et al. 1989), transience of fine-grained age mosaics in simulation studies (Zedler and Seiger 2000), and a lack of temporal trends in fire history data (Conard and Weise 1998, Keeley et al. 1999). Charcoal content from marine sediment cores (Byrne et al. 1977, Mensing et al. 1999) also indicates that large fires have been common in some southern California shrublands for many centuries.

A growing body of work implicates climatic factors in large shrubland fires. Davis and Michaelsen (1995) found that large fires in Los Padres National Forest occurred during periods of low spring precipitation and Santa Ana winds. Moritz (1997) showed that probabilities for large fires in Los Padres National Forest during extreme fire weather had not changed due to suppression. Mensing et al. (1999) found that large shrubland fires followed multiyear periods of high pre-

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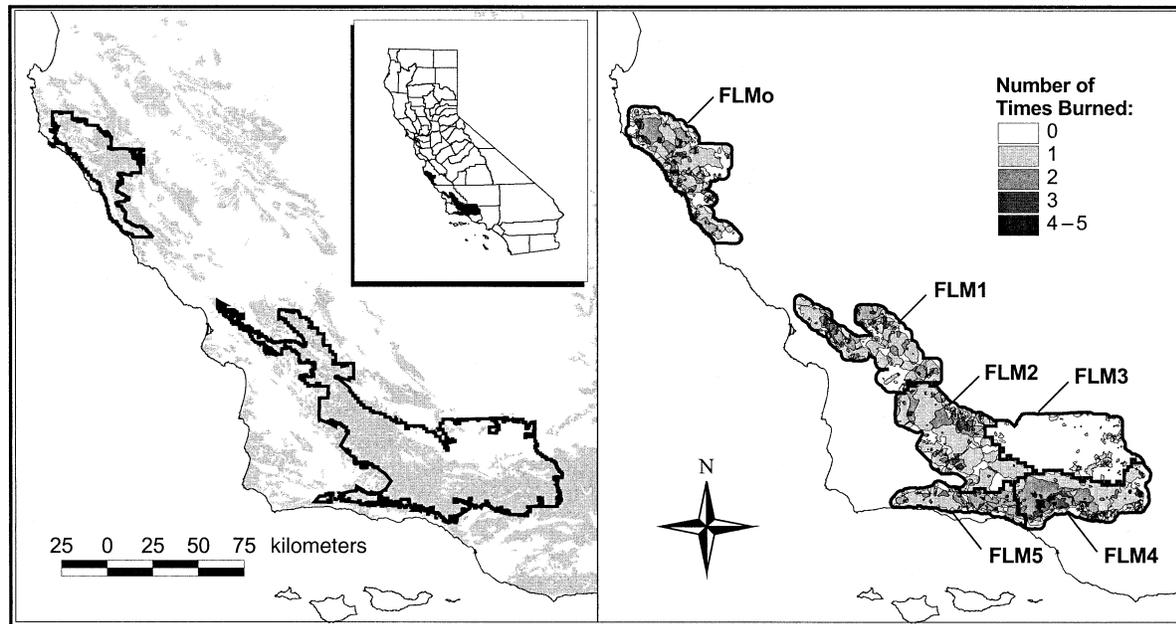


FIG. 1. Location map of Los Padres National Forest (LPNF). The Main Division and the smaller Monterey Division of LPNF are both dominated by mediterranean-type shrublands, which are shown as shaded areas in the left panel; vegetation types are based on the dominant classification of habitat type from the Gap Analysis database for California (*available online*).² The right panel indicates fire landscapes of LPNF (i.e., FLM1–FLM5 of the Main Division, and FLMo is the Monterey Division) and fire occurrence for the period 1911–1995; the study area includes a 3200-m buffer around LPNF boundaries.

precipitation. These studies suggest weather and climate as dominant controls on chaparral fire regimes, as opposed to age and spatial patterns of fuels.

Quantifying the relationship between fuel age and historical fire patterns clarifies the influence of the age-patch mosaic on fire behavior. In an age-dependent system, the probability of fire in young fuels would be low and increase over time. This deterministic relationship has been assumed for chaparral in fire behavior modeling (Rothenmel and Philpot 1973, Philpot 1977), but mounting evidence shows fuel loads to be highly variable and not necessarily controlled by age (Paysen and Cohen 1990, Riggan et al. 1994, Conard and Weise 1998, Regelbrugge and Conard, *in press*). Keeley et al. (1999) examined age classes burned in large fires in the Santa Monica Mountains, California and found no relationship to older fuels. These results were based on a subset of fires (i.e., size >5000 ha, since 1967, $n = 8$), so it is difficult to assess their generality.

In this study, I analyze the mapped fire history of Los Padres National Forest (Moritz 1999) to evaluate age dependency in chaparral-dominated fire regimes. My goal is to quantify variation in fire frequencies (Johnson and Gutsell 1994) and to determine if the hazard of burning increases with time since the last fire. If fire probabilities are determined by age, and if young patches in a vegetation mosaic can limit fire

spread under a variety of weather conditions, these constraints should emerge in fire history data. In contrast, historical fire patterns should show fires burning irrespective of fuel age if extreme fire weather is the dominant control. I will characterize fire interval distributions at several scales to test for scale-dependent controls, and I will also investigate how fire suppression efforts have influenced this fire regime.

METHODS

Study area and data

Chaparral-dominated shrublands are the most widespread vegetation of mediterranean-climate California. My study area consists of the Main and Monterey Divisions of Los Padres National Forest (hereafter, LPNF), located along the central Coast Ranges and the Transverse Ranges of Santa Barbara, San Luis Obispo, and Monterey Counties in California (Fig. 1). Elevation within LPNF ranges from sea level at the coast to ≥ 2600 m a few kilometers inland, with a median elevation of ~ 800 m above sea level (Moritz 1999). LPNF lands are within the Central Western and Southwestern biogeographic regions as described in Hickman (1993) for California, and they experience warm, dry summers and mild, wet winters typical of a mediterranean climate. There is a moderate precipitation gradient increasing to the north and decreasing inland from the coast. The Main Division receives from 250 to 1000 mm of annual precipitation; the Monterey Di-

² URL: <http://www.biogeog.ucsb.edu>

vision ranges from 500 to 1500 mm per year (Davis and Michaelsen 1995).

Shrublands dominate ~60% of LPNF, with ~55% being chaparral and the remaining 5% being coastal scrub (Moritz 1999). Although this study focuses on the shrubland-dominated portions of LPNF, patches of riparian woodlands, oak woodlands, mixed evergreen forests, coniferous forests, and grasslands are often interspersed with shrublands. Most dominant plant species are sclerophyllous and fire-adapted, such as chamise (*Adenostoma fasciculatum*), manzanitas (*Arctostaphylos* spp.), California lilacs (*Ceanothus* spp.), oaks (*Quercus* spp.), and sages (*Salvia* spp.). Species composition can vary with edaphic, topographic, and fire history-related factors. Postfire species composition, often similar to prefire composition, typically follows by resprouting from a fire-resistant burl, germinating from a long-lived seed bank underneath parent plants, or some combination of these methods. See Keeley (2000) for a more complete review.

The LPNF fire history (1911 to 1995) documents >4000 fires. Fires greater than ~125 ha that occurred near or within LPNF boundaries were mapped by U.S. Forest Service personnel and entered into a geographic information system (GIS) as polygon data. Omission of fires smaller than ~125 ha should not have an appreciable effect on analyses described here, as these fires account for only ~2% of the total area burned (Moritz 1999). Fire ignition locations for all fires, regardless of size, were also entered into a GIS as point data. Moritz (1999) regionalized the LPNF fire regime using both statistical clustering and regression tree analysis, generating six "fire landscapes" that are distinctive in spatiotemporal patterns of fire timing, sizes, causes, and intervals. Boundaries between these regions generally corresponded to physiographic features on the landscape, so fires tended not to spread from one region into another. Five of the fire landscapes are within the Main Division (i.e., FLM1–FLM5 in Fig. 1); the Monterey Division was considered a sixth unique region (i.e., FLMo in Fig. 1). FLM3, being primarily pinyon–juniper woodland, is the only fire landscape not dominated by chaparral and was not included in analyses.

Fire frequency analysis

I used fire interval distributions from LPNF to evaluate the age dependency of historical burning. For example, a distribution with reduced probability of fires in young fuels and increased probability in middle-aged fuels would be more age dependent than one not exhibiting this pattern. Fire interval distributions are often inferred from a time-since-fire map of stand ages on the landscape (e.g., Yarie 1981, Suffling et al. 1982, Johnson and Van Wagner 1985, Clark 1990, Johnson and Larsen 1991, Johnson and Gutsell 1994, Grissino-Mayer 1999). I generated fire interval distributions for LPNF through spatial overlay of individual fire events

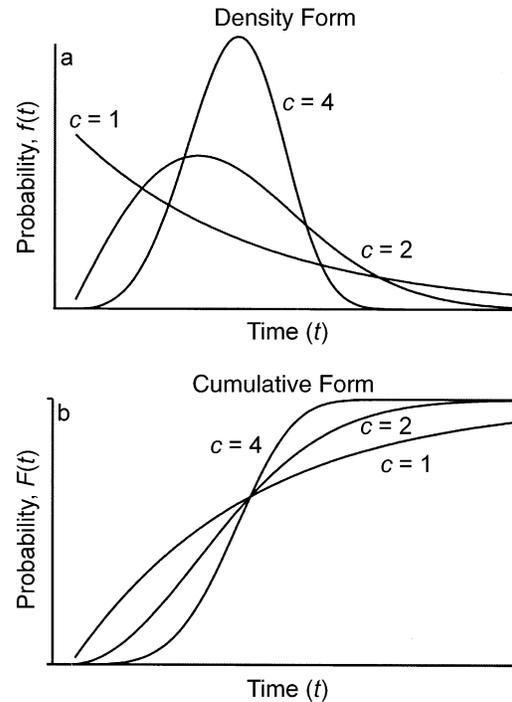


FIG. 2. The (a) probability density and (b) cumulative probability forms of fire interval distributions, showing probability of burning with time. Both forms represent the same age-at-burn data, demonstrating variation in shape due to different degrees of age dependency, holding scale parameter b constant (see *Methods* for parametric model descriptions). Higher degrees of age dependency correspond to greater degrees of kurtosis in density forms and more strongly sigmoidal cumulative forms, falling into a family of Weibull curves (i.e., $c > 1$). Fire regimes with a negative exponential shape (i.e., shape parameter $c = 1$) behave independently of fuel age.

in a mapped fire history (e.g., Baker 1989, Polakow and Dunne 1999). This approach was performed in a GIS, allowing direct generation of fire interval distributions and avoiding assumptions inherent in the time-since-fire map. Much of the LPNF study area has burned multiple times, as Fig. 1 indicates, making this fire history an excellent opportunity for the direct method of generating fire interval distributions.

After fire interval distributions were generated, models were fit to these data. Two parametric models have traditionally been used in quantifying the shape of fire interval distributions, the negative exponential and the Weibull (Johnson and Van Wagner 1985). Although these models are related statistically, they imply two different fire dynamics (Fig. 2). Fire interval distributions that are negative exponential in shape indicate a fire regime in which the age of fuels does not influence the probability of burning. A Weibull shape reflects lower probability of burning in younger fuels and the majority of burning in middle-aged fuels; less of the landscape survives beyond the middle-aged "peak"

of burning, so probabilities are again reduced for older age classes.

Fire interval distributions can be displayed in a probability density form, or as its integral, in a cumulative probability form. The cumulative form $F(t)$ is the probability that a fire will have occurred before or at time t , that is,

$$F(t) = \Pr(T \leq t) = 1 - A(t) \quad (1)$$

where $F(0) = 0$ and $F(\infty) = 1$. This range reflects that nothing can burn before time $t = 0$ and that all areas eventually reburn. $A(t)$ is the cumulative distribution often generated from a time-since-fire map (i.e., the landscape age-patch distribution at a specific point in time). The first derivative of the cumulative distribution $F(t)$ is the probability density form of the fire interval distribution $f(t)$, or the rate of change in cumulative area burned over time (Fig. 2). The probability density form reflects the frequency of burning in a specific time interval t to $t + \Delta t$, that is,

$$f(t) = \frac{dF(t)}{dt}. \quad (2)$$

In other words, this distribution gives the probability of burning in a given age class.

The two-parameter model that is typically fit to empirical fire interval data is a general expression with parameters that are ecologically meaningful. The cumulative form $F(t)$ and the probability density form $f(t)$ of the functions are as follows:

$$F(t) = 1 - \exp(-(t/b)^c) \quad (3)$$

$$f(t) = \frac{ct^{c-1}}{b^c} \exp(-(t/b)^c) \quad (4)$$

where time $t > 0$ and parameters $b > 0$ and $c \geq 0$. Parameter b , called the "scale parameter," has the dimensions of time and is the fire recurrence interval that will be exceeded 36.8% of the time (i.e., $F(t = b) = 63.2\%$). Parameter c , called the "shape parameter," is dimensionless and determines whether the distribution approximates a negative exponential or a Weibull. Technically, the model represents an infinite number of curves, and the negative exponential is actually a special case where $c = 1$ (Fig. 2). Values of $c < 1$ imply a decreasing likelihood of burning as fuels get older. All other values of $c > 1$ reflect an increasing likelihood of burning with age, with higher values of c indicating higher degrees of age dependency.

The "hazard of burning" (Johnson and Gutsell 1994) function $\lambda(t)$ gives the instantaneous potential that vegetation will burn during a specific time period. The hazard function $\lambda(t)$ therefore involves a conditional probability of burning in interval t , given survival (i.e., not burning) up to that point:

$$\lambda(t) = \frac{f(t)}{A(t)} = \frac{f(t)}{1 - F(t)} = \frac{ct^{c-1}}{b^c}. \quad (5)$$

The hazard function $\lambda(t)$ is sometimes called the "mo-

ment of mortality" or the "conditional failure rate" in survival analysis. This is an instantaneous rate (i.e., probability per unit time), as parameter b has the dimensions of time. Inspection of Eq. 5 reveals that with $c = 2$ the hazard of burning increases linearly with time, but at a rate determined by parameter b . Values of $c > 2$ reflect "exponential growth" of hazard over time, as t is raised to a power > 1 . Because the hazard function $\lambda(t)$ reflects both the probability of burning during age class t and the cumulative probability of living up to that point, $\lambda(t)$ is useful for measuring how time since the last fire at a location influences the next fire's likelihood. Graphing $\lambda(t)$ is therefore effective for comparing the degree of age dependency exhibited by different fire regimes.

All fire events cannot be used in generating fire interval distributions, because fires burning for the first time are of unknown age (e.g., Baker 1989). Roughly 78% (i.e., ~6755 km²) of the LPNF shrublands analyzed here have burned at least once over 1911–1995, but distributions are based on ~49% of the total area burned (i.e., the ~3285 km² burned more than once; Table 1). Distributions also omit any areas that will burn in future fires at ages > 85 yr, involving ~22% of the landscape that has yet to burn. Truncating old-age tails of distributions (i.e., at 85 yr) can have a predictable effect (Finney 1995) and should result in longer average fire intervals, as Reed et al. (1998) found. Future burning in very old stands could also spread observations across a wider range of ages, causing fire interval distributions $f(t)$ to be less strongly "bell-shaped" and more characteristic of the negative exponential (i.e., shape parameter $c = 1$). In contrast, the opposite bias may occur if many of the omitted areas that burned at an unknown age did so when they were relatively young. This could only have been possible if a large portion of the landscape had burned just before the period of record (i.e., late 1800s through 1910) and many of those areas reburned early in the fire history. My assumption in generating fire interval distributions from areas burned at least twice is that they are representative of the fire regime as a whole, at least for chaparral-dominated portions of LPNF. Accounting for different sources of censoring (e.g., Polakow and Dunne 1999) will be necessary to verify this assumption.

After quantifying areas that reburned at different ages, I converted areas to percentages and fit curves to the cumulative forms of fire interval probability distributions. Maximum likelihood estimators (MLE) of parameter values (e.g., Cohen 1965, Harter and Moore 1965) were derived through an iterative statistical procedure to minimize negative log-likelihood functions (Chambers and Hastie 1992). Past work has stressed whether a particular fire interval distribution is *either* a Weibull *or* a negative exponential (Yarie 1981, Johnson and Van Wagner 1985, Johnson and Larsen 1991, Finney 1995, Boychuk et al. 1997). However, factors

TABLE 1. Scales of aggregation for fire landscapes of Los Padres National Forest, California (LPNF).

Scale of aggregation	Unit of analysis	Unit area (km ²)	Area burned more than once (km ²)
Single unit	FLMo	1995	734
	FLM1	1830	573
	FLM2	2238	584
	FLM4	1692	1004
	FLM5	892	391
One neighbor	FLM1 and FLM2	4068	1157
	FLM2 and FLM4	3930	1588
	FLM2 and FLM5	3130	975
	FLM4 and FLM5	2584	1395
Two neighbors	FLM1, FLM2, and FLM4	5760	2161
	FLM1, FLM2, and FLM5	4960	1548
	FLM2, FLM4, and FLM5	4822	1978
Three neighbors	FLM1, FLM2, FLM4, and FLM5	6652	2552
All units	LPNF shrublands	8647	3285

Notes: Spatial units for fire frequency analysis are formed from contiguous areas at successively coarser scales. Fire interval distributions are generated from areas burned two or more times.

that influence fire dynamics vary continuously in space and time, and the age of fuels will play a stronger role in limiting or promoting fire spread in some ecosystems than others. I therefore base comparisons on parameter values instead of goodness-of-fit tests between distributions, focusing on the degree of age dependency and relative importance of controlling mechanisms. This agrees with our understanding of fire dynamics and is reflected in the infinite number of possible Weibull curves, the negative exponential being a single case (i.e., $c = 1$). Confidence intervals (CI) for parameters were estimated by bootstrap resampling of fire interval observations and fitting the model repeatedly (i.e., $n = 500$); 95% CI for each parameter were then derived from the tails of fitted parameter distributions.

Fire regimes are affected by several mechanisms that operate at different spatiotemporal scales. To investigate whether age dependency is sensitive to the spatial scale of analysis (e.g., Baker 1989), I hierarchically aggregated neighboring fire landscapes of LPNF at different levels of contiguity (Table 1). Because the Monterey Division (i.e., FLMo) is isolated geographically, it is evaluated only at the finest and coarsest scales of aggregation. I did not explicitly examine different temporal scales in the analysis of fire interval distributions, due to inherent limits in the length of the LPNF fire history (e.g., differential truncation of time series). However, I did evaluate 1950 as the transition to modern fire suppression (i.e., with implementation of aerial attack), to identify possible changes in fire sizes and area burned (e.g., Moritz 1997, Keeley et al. 1999). Climate is assumed to be stationary over the period of record.

RESULTS

Fire interval distributions

Fire interval distributions were highly variable, displaying little “preference” or “avoidance” of burning

in particular age classes. The probability density forms $f(t)$ of fire interval distributions (Fig. 3a) exhibit minimal evidence of kurtosis, and many units indicate substantial burning in fuel age classes of 10 yr old and younger. Several units also show substantial burning in quite old age classes. This is notable, as any burning away from the center of fire interval distributions will reduce kurtosis and push c values toward a negative exponential (i.e., $c = 1$). FLM5 exhibits the most “bell-shaped” curve of all units analyzed, indicating that most of the area burned there occurs in middle-aged vegetation. Larger units of analysis that include FLM5 (e.g., FLM2 and FLM5 or FLM4 and FLM5, not shown) also reflect this age dependence to some degree.

The coarsest level of spatial aggregation (far right of Fig. 3a) reveals a spike at 53 yr. This is caused primarily by areas in FLM4 that burned in 1932 and then again in 1985, evident at the finest level of spatial aggregation (FLM4, Fig. 3a). This peak persists for all scales of analysis that include FLM4 (intermediate scales not shown). Coincidentally, the peak at 53 yr is intensified by large areas in FLMo that burned in 1924 and then again in 1977, also an interval of 53 yr (FLMo, Fig. 3a).

The cumulative forms of fire interval distributions $F(t)$ show the same general lack of age dependence. All of the iterative MLE fits reached a solution (Table 2), and all closely match empirical patterns (Fig. 3b). Although not visibly striking, the width of fitted curves (Fig. 3b) reflects the range of possible values for $F(t)$, given the 95% CI for each parameter (Table 2). Curves fitted to the cumulative forms $F(t)$ tend to underestimate probabilities slightly for low and high values of t , while often overestimating probabilities for intermediate values. The cause of these errors is not obvious, but it may be related to the form of the model and the constraint that it pass through both 0 and 1.

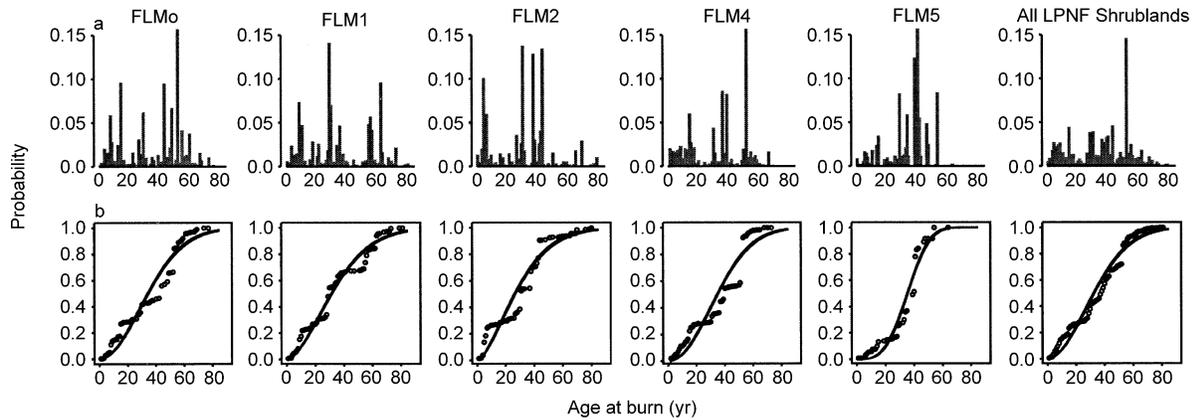


FIG. 3. The (a) probability density and (b) cumulative probability forms of fire interval distributions, based on empirical fire history data for LPNF. Distributions are shown only for the finest (i.e., FLMo–FLM5) and coarsest (i.e., entire study area) spatial scales of analysis. Intermediate units of analysis (not shown) were achieved by aggregating units at finer scales (Table 1). Width of fitted lines (b) reflect 95% CI ranges for fitted parameter values. FLM2 has the lowest degree of age dependency, and FLM5 the highest (i.e., $c = 1.56$ and $c = 3.33$, respectively).

Cumulative fire interval distributions are all sigmoidal to some degree (Fig. 3b), reflecting at least some age dependency (i.e., $c > 1$). The effect of age on fire dynamics is not strong, however, as most values of shape parameter c are between 1 and 2 (Table 2).

Only FLM5 indicates a notable degree of age dependence. Comparison of parameter estimates (Table 2) indicates that FLM5 has $c = 3.33$ (95% CI of 3.23–3.43), which is significantly higher than all other units and over twice that of neighboring unit FLM2. Cumulative fire interval distributions for any unit of analysis including FLM5 therefore show a more strongly sigmoidal shape. This evidence of age dependency is most obvious at the finest scale of analysis (FLM5, Fig. 3b), and it becomes less apparent at coarser scales (intermediate scales not shown); this trend is also evident in the c values for units of analysis containing FLM5 (Table 2). Differences in scale parameter b are less

striking, but FLM2 stands out as having a tendency toward shorter fire intervals (i.e., $b = 33.5$ yr, 95% CI of 33.0–34.0). Focusing on either parameter b or c , fitted values tend to show the highest variation at the finest scales (i.e., single units in Table 2) and converge at values of $b = 39.5$ yr (95% CI of 39.0–39.9) and $c = 1.91$ (95% CI of 1.87–1.95) for the largest unit of analysis. Considering all shrublands within LPNF, the fire regime is therefore apparently somewhat age dependent (i.e., $1 < c < 2$), but the uniqueness of FLM5 is not apparent at the coarsest scales.

Sensitivity to scale

There are no clear clusters in parameter space that would indicate scale dependency in the fire frequency distributions of LPNF. However, FLM5 is again unusual in that it does not hold to the general trend exhibited by other units of analysis. With the exception

TABLE 2. Parameter values for fire frequency analysis.

Unit of analysis	Scale parameter b (yr)	95% CI for b	Shape parameter c	95% CI for c
FLMo	41.4	40.9–41.9	1.94	1.90–1.99
FLM1	38.9	38.5–39.4	1.70	1.67–1.73
FLM2	33.5	33.0–34.0	1.56	1.53–1.60
FLM4	41.5	41.1–41.9	2.06	2.01–2.11
FLM5	39.5	39.3–39.8	3.33	3.23–3.43
FLM1 and FLM2	36.1	35.6–36.6	1.62	1.59–1.65
FLM2 and FLM4	38.6	38.1–39.1	1.82	1.77–1.86
FLM2 and FLM5	36.3	35.8–36.7	1.95	1.90–2.00
FLM4 and FLM5	41.1	40.7–41.5	2.28	2.22–2.34
FLM1, FLM2, and FLM4	38.7	38.2–39.1	1.78	1.75–1.82
FLM1, FLM2, and FLM5	37.2	36.8–37.6	1.83	1.79–1.87
FLM2, FLM4, and FLM5	38.9	38.5–39.3	1.98	1.94–2.03
FLM1, FLM2, FLM4, and FLM5	38.9	38.5–39.3	1.90	1.86–1.94
LPNF shrublands	39.5	39.0–39.9	1.91	1.87–1.95

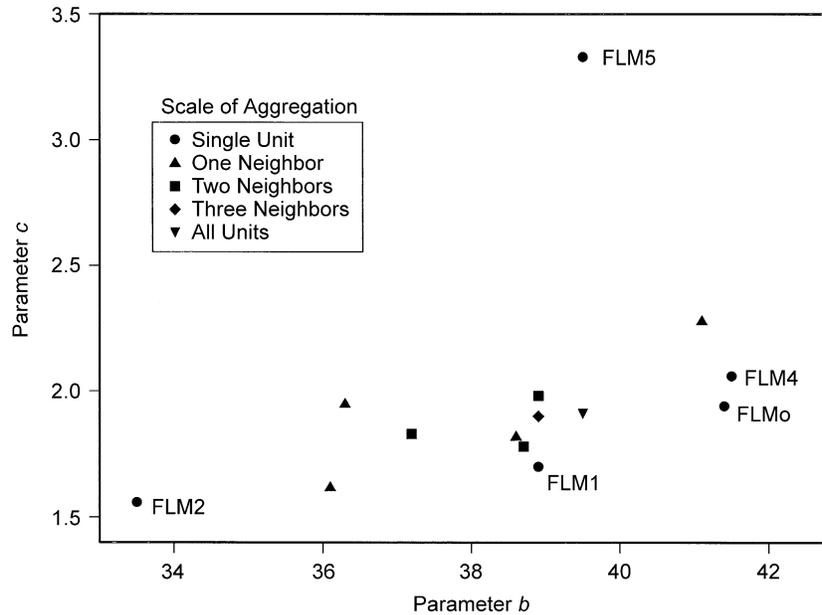


FIG. 4. Parameter values and scales of analysis. Parameter variability decreases and distributions become more similar at coarser scales of aggregation (Table 2), but this trend is not obvious when viewed in parameter space. Instead, there appears to be a trend of increasing age dependence (i.e., higher c values) with longer average burn intervals (i.e., higher b values). The location of FLM5 reflects its unusually high degree of age dependency. Only individual units at the finest scale of analysis are labeled.

of FLM5, there is a weak positive correlation between values of parameter b and parameter c (i.e., the upward trend in Fig. 4). This implies that longer fire return intervals are somehow associated with stronger age dependency. The trend may be a statistical artifact if the net effect of burning in young age classes is to reduce kurtosis in fire interval distributions $f(t)$ (i.e., lower c values), while also making mean fire intervals shorter (i.e., reflected in lower b values). However, substantial burning in older age classes will also reduce kurtosis in distributions, but push mean fire intervals higher, contrary to the trend observed here. The importance and cause of this trend is not clear.

Hazard of burning

Time since the last fire appears to have minimal effect on the likelihood of the next fire for most units of analysis. This is evident in the hazard of burning $\lambda(t)$, which represents the instantaneous probability of burning in year t , given that a fire has not occurred there yet (Fig. 5). As a comparison with LPNF shrublands, curves reflecting hypothetical parameter values of $c = 1$ and $c = 4$ are also displayed. With the exception of FLM5, $\lambda(t)$ remains low for all units well beyond the point at which the majority of burning has taken place (e.g., past $b = 39.5$ yr, when $\sim 63\%$ of burning has occurred). This is because the rate of increase in hazard

FIG. 5. Changing hazard with fuel age. Based on the function quantifying the hazard of burning with the time since the last fire (see *Methods* for $\lambda(t)$ definition), actual values of parameters b and c are used to generate curves for units of analysis within LPNF. FLM5 has the value $c = 3.33$ and is the only LPNF curve displaying even moderate increases in hazard over time. Hypothetical values of $c = 1$ and $c = 4$ are included for comparison (i.e., the dotted lines); a mean value of $b = 39.5$ yr was used for hypothetical curves.

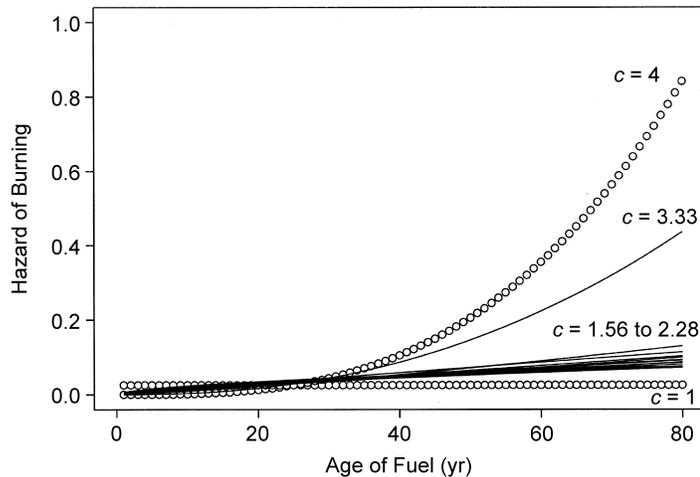


TABLE 3. Fire statistics for pre- and post-1950 in LPNF shrublands.

Statistic	1911–1995	1911–1949	1950–1995
Small fires (<4000 ha)			
Area burned (ha)	165 145	115 461	49 684
Mean size (ha)	52	96	25
Number of fires	3175	1208	1967
Annual number	37	31	43
Burn rate (ha/yr)	1943	2961	1080
Large fires (>4000 ha)			
Area burned (ha)	585 813	257 359	328 454
Median size (ha)	10 878	10 257	11 664
Mean size (ha)	16 738	15 139	18 247
Number of fires	35	17	18
Annual number	0.41	0.44	0.39
Burn rate (ha/yr)	6892	6599	7140
All fires			
Area burned (ha)	750 958	372 820	378 138
Mean size (ha)	234	304	191
Number of fires	3210	1225	1985
Annual number	38	31	43
Burn rate (ha/yr)	8835	9559	8220
Fire cycle (yr)	67	62	72

Notes: Figures reflect burning within administrative boundaries of LPNF, which comprise less area than fire landscapes (Moritz 1999). Fire cycle is the time required to burn the equivalent of the study area, based on annual burning rates. Median fire sizes are >0 ha only for the large fire category, as other categories contain hundreds of very small fires that never spread beyond the initial point of ignition. Due to completeness of LPNF records, mean and median fire sizes reported here are much smaller than those published for comparable shrubland-dominated regions (e.g., Keeley et al. 1999, Weise et al., *in press*), often by an order of magnitude.

is quite slow for $1 < c < 2$, the range in which most units of analysis fall. Even for FLM5, the hazard of burning is below that exhibited by a fire regime operating independently of fuel age (i.e., $c = 1$) until after 20 yr have passed since the last fire (Fig. 5).

Pre- and post-1950 statistics

Different subsets of historical data provide insight into the effects of recent fire suppression. Statistics for area burned, fire sizes, and numbers of fires within chaparral-dominated portions of LPNF are shown in Table 3. In addition to pre- and post-1950 statistics, I employed a fire size threshold of 4000 ha, dividing data into small and large fire groups. This size was previously found to be important in distinguishing between fires that had and had not been affected by recent fire suppression in LPNF (Moritz 1997).

Statistics for small fires (i.e., <4000 ha) have changed the most since 1950 (upper rows of Table 3). Fires smaller than this threshold have decreased substantially in size since 1950 (i.e., from a mean of 96 ha to 25 ha), but they occur more often (i.e., from 31 to 43/yr). These changes equate to an overall decrease in the annual burning rate of ~64% (i.e., from 2961 to 1080 ha/yr) for small fires since 1950. Large fires (i.e., >4000 ha) generally show the opposite trends since 1950 (middle rows of Table 3). Mean size of

larger fires has increased (i.e., from 15 139 ha to 18 247 ha), but the number of large fire events has decreased somewhat (from 0.44 to 0.39/yr). For large fires, the net effect is an increase in the annual burning rate since 1950 (i.e., from 6599 to 7140 ha/yr, or ~8%), partially offsetting decreases observed for smaller fires.

When fires of all sizes are considered (lower rows of Table 3), the more recent period entails smaller fires (i.e., from a mean size of 304 ha to 191 ha), more fires (i.e., from 31 fires to 43 fires/yr), and an overall 14% decrease in annual burning rates (i.e., from 9559 to 8220 ha/yr). Table 3 also includes the commonly used parameter of fire cycle, also called fire rotation interval, calculated as the time required to burn the equivalent of the study area. The 14% decrease in annual burning rate since 1950 equates to lengthening of fire cycle from ~62 to ~72 yr in the more recent period.

DISCUSSION

Age dependency and extreme fire weather

I found the vast majority of shrubland-dominated units of analysis to exhibit minimal increases in the hazard of burning over time. My goal has been to evaluate how the age-patch mosaic of vegetation affects the fire regime of California's chaparral-dominated shrublands, and there is little evidence to support the widespread assumption that complex age-patch mosaics could limit fire spread on the landscape. Patterns in most fire interval distributions of Los Padres National Forest have shown frequent burning in young patches, as one would expect in systems not limited by fuel age. Highly age-dependent systems (e.g., $c > 4$) would experience a much greater rate of hazard increase over time, and such fire regimes have been reported in the literature (e.g., Baker 1989, Clark 1990).

Results shown here do not appear to be strongly dependent on spatial scale (Johnson and Van Wagner 1985) or aggregation method (Openshaw 1983). Instead, I found longer fire return intervals to correspond with higher age dependency. Such a relationship could be a statistical artifact, but it may reflect variation in vegetation types, such as different shrubland species and their resistance to burning throughout their life cycles. It could also be due to vegetation patches, primarily grasslands, that occur at a scale finer than the one used in mapping the study area. Such inclusions could cause fire interval distributions of some shrublands to be mixed with those from vegetation that burns more readily and frequently. However, vegetation composition in Los Padres National Forest does not indicate that grasslands cause this trend. For example, FLM2 (i.e., lower b and c values) contains only 3.2% annual grasslands, yet FLMo and FLM4 (i.e., higher b and c values) contain 6.3% and 1.5% grasslands, respectively (Moritz 1999).

The increased age dependency observed in one region of analysis is probably related to a lack of local

exposure to extreme fire weather events. Differences in current vegetation or ignition characteristics (Moritz 1999) do not explain the high degree of age dependency reported for FLM5. Severe downslope winds occasionally cause extreme fire danger in FLM5 (Ryan 1996, Blier 1998), but these are localized phenomena and are often restricted to a few canyons. However, FLM5 is somewhat sheltered from extreme fire weather that routinely affects many shrubland ecosystems throughout central and southern California. This may be due to the unique east–west alignment of nearby mountain ranges that deflect northeasterly Santa Ana winds, the primary form of extreme fire weather in California's chaparral-dominated ecosystems. Santa Ana winds are synoptic-scale phenomena caused by pressure gradients between a region of high pressure in the Great Basin and low pressure in Arizona, northern Mexico, or coastal California (Schroeder et al. 1964, Fosberg et al. 1966, McCutchan and Schroeder 1973, Sommers 1978). Adiabatic heating occurs as these winds travel southward and westward, descending in elevation, and winds intensify as they are channeled through mountain passes and river valleys. Santa Ana events tend not to occur during the summer; they pose the greatest threat during the fall months when fuel moistures are lowest. This type of fire weather can cause very large fires (Countryman 1974, Minnich 1983, Davis and Michaelsen 1995, Moritz 1997, Keeley et al. 1999).

Exposure to extreme fire weather, either in frequency or intensity of events, may therefore override the sensitivity of a fire regime to fuels characteristics. This has already been shown through analysis of standard equations for predicting fire spread (Bessie and Johnson 1995) and simulation modeling in other ecosystems prone to stand-replacing fires (Turner and Romme 1994). Fire probabilities will clearly be affected by other climatic factors, such as biomass accumulation with abundant precipitation (Mensing et al. 1999) and vegetation dieback related to drought (Riggan et al. 1994), but extreme fire weather appears to drive the patterns observed here. During mild weather conditions, fuel load and fuel moisture can have a greater ability to alter fire spread probabilities in shrublands. However, sensitivity to fuel characteristics diminishes in the face of Santa Ana winds, which produce "the most severe fire danger known" (Schroeder et al. 1964: 5). This is because both live and dead fuel moistures drop to critical levels, and high winds drive fire through vegetation types and age classes that might not otherwise burn. Consequently, areas exposed to extreme fire weather events should be expected to exhibit less age-dependent burning than areas sheltered from such events.

Fire suppression and the landscape mosaic

As in many fire-prone ecosystems, a primary concern is how humans may have altered natural fire regimes.

Decreasing average sizes of smaller fires (i.e., <4000 ha) in Los Padres National Forest, in conjunction with increasing numbers of these fires, is consistent with the idea that fire suppression may be needed to offset increases in human-caused fires in shrubland ecosystems (Conard and Weise 1998, Keeley et al. 1999). However, the net effect of suppression in Los Padres National Forest is a decrease in annual burning rate of ~14% since 1950. If these trends are representative of shrublands in general, fire suppression over time could result in a longer fire cycle and a generally older age-class distribution on the landscape. A problem with this projection is that fire cycle and simple burning rates do not account for the tendency of some places to burn more often than others. For example, average fire intervals for Los Padres National Forest shrublands that have burned multiple times are actually in the 30–37 yr range (Moritz 1999), roughly half of estimates based on fire cycle calculations. Fire cycle is often used as a rough surrogate for actual fire intervals, but we do not know how to adjust fire cycle to account for spatial differences in burning patterns. Any conclusions about changes in fire cycle, regardless of the study, should therefore be viewed with caution.

The ability of some fires to burn through all age classes in many shrubland ecosystems indicates that fire suppression is not the direct cause of large fires. Where annual area burned due to small fires has dropped dramatically (e.g., ~64% in LPNF), it is conceivable that fire suppression has homogenized age-patch mosaics. Regardless, based on the general lack of age dependency reported here, young patches in many chaparral-dominated ecosystems are incapable of limiting fire spread during extreme fire weather. Before fire suppression, complex age-patch mosaics may have evolved over time, but even these landscapes would not be immune to large fires. Fine-grained mosaics were probably short-lived phenomena, given enough ignition sources (e.g., simulations of Zedler and Seiger 2000), if and where they did emerge. Under extreme weather conditions, fires would burn through all age classes, just as they do now. In contrast, we should expect recent fire suppression to have had the greatest effects on systems not frequently exposed to extreme fire weather.

Concluding that fire suppression does not cause large fires contradicts much of the current thinking behind ecosystem management in California's shrublands. Crown fire ecosystems (Johnson 1992, Turner and Romme 1994), or those naturally characterized by large fires that are stand-replacing and weather-driven, may be an appropriate model for chaparral-dominated ecosystems. Because fire spread in many shrublands can be more strongly driven by external climatic forces than constrained by internally regulated processes of vegetation development, fires can be large relative to landscape extent. Internal feedback mechanisms are not likely to produce shrubland landscapes that are in equi-

librium with regional disturbance regimes, as in the steady-state "shifting mosaic" of Bormann and Likens (1979). The issue of fire size is less of an ecological risk in shrubland ecosystems than clustered areas of high fire frequency and increases in human-caused ignitions. If fire intervals become too short, vegetation type conversion can occur (e.g., Zedler et al. 1983, Haidinger and Keeley 1993), leading to the invasion of nonnative species and further changes in fire regimes (D'Antonio and Vitousek 1992). Prescribed fires will not be useful in "restoring" an age-patch mosaic or eliminating large wildfires in many shrubland ecosystems, but they should still be helpful at strategic urban-wildland interfaces (Conard and Weise 1998, Keeley and Fotheringham 2001). However, even this approach will lose effectiveness as the number and length of these interfaces multiply. Analogous to restricting development in flood-prone environments, urban planning may eventually be forced to incorporate large fires as inevitable, naturally occurring events on many chaparral-dominated landscapes.

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