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ANALYZING EXTREME DISTURBANCE EVENTS: FIRE IN LOS PADRES NATIONAL FOREST

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Abstract. Extreme disturbance events may strongly influence the structure and functioning of many ecosystems, particularly those in which large, infrequent events are the defining forces within the region. This paper introduces the *extremal fire regime* (i.e., the time series of the largest fire per year) and the assumptions implicit in its analysis. I describe the statistics of extremes and demonstrate their application to the fire regime of Los Padres National Forest, California, to compare two regions (i.e., Main and Monterey divisions), to test for a shift in fire regime due to fire suppression, and to examine climatic events as a forcing mechanism for large fires. Despite their similarity and proximity, the Main Division exhibited a much higher frequency of large fires (and shorter return time) compared to the Monterey Division. Comparison of time periods 1911–1950 and 1951–1991 indicated that fire suppression had no effect on the distribution of very large fires in the Main Division, although the frequency of fires smaller than ~4000 ha declined. Comparing distributions of an index for severity of Santa Ana conditions (i.e., characterized by hot, dry winds) and extreme fire events in the Main Division indicated a convergence of distributions with increasing event size. The distribution of fire events larger than ~4000 ha appears to be coupled with that of severe Santa Ana conditions, suggesting a strong climatic forcing for extreme fires and a threshold for the transition from small- to large-fire dynamics. Results indicate the usefulness of *extremal fire regime* analysis for comparisons over space and time and for examining a potential forcing mechanism. This approach can be applied to any disturbance regime in which large events play an important role, providing ecologists and land managers with a useful tool for understanding and predicting dynamics of extreme disturbance events.

Key words: climate; disturbance; extremal fire regime; fire size; landscape ecology; Los Padres National Forest; statistics of extremes.

INTRODUCTION

Ecological disturbances are relatively discrete events in time that disrupt ecosystem, community, or population structure and change resources, substrate availability, or the physical environment (White and Pickett 1985). Because large, infrequent disturbances may have a strong impact on ecological systems, leaving their mark over broad spatial and temporal scales, it is crucial for ecologists and land managers to understand and predict the dynamics of these extreme events. In this paper, I demonstrate a method for analyzing extreme events that will provide ecologists and land managers an important tool and a unique view of disturbance regimes.

Fire has long been recognized as a primary disturbance affecting the dynamics of many ecosystems, and quantitative measures of fire regimes and their statistical distributions (e.g., time-since-fire) have been investigated in forest ecosystem research (Heinselman 1973, Johnson and Van Wagner 1985, Johnson and Gutsell 1994). In many cases, fire regime analyses concentrate primarily on fire frequency at a site (Pyne 1984). The average return interval of fire may impact the evolution of life history strategies (e.g., Mutch 1970, Keeley and Zedler 1978), and vegetation type conversion can result from intervals that are substantially longer (e.g., Fisher et al. 1987) or shorter (e.g., Zedler et al. 1983). Much work has focused on the long-term stationarity of fire regimes (e.g., Clark 1989, Johnson and Larsen 1991, Swetnam 1993), often requiring fire-scar sampling over wide areas and hundreds of years.

Fire size has also received considerable attention at the landscape scale (e.g., Minnich 1983, Romme and Despain 1989). The concept of fire ''severity'' differs between ecosystems, due to differing plant and community responses, but larger fires are often considered more severe (e.g., greater erosion potential). If future nature reserves are protected islands in a sea of fragmented habitat, fire size is clearly a critical issue. How big should a nature reserve be in disturbance-mediated ecosystems to accommodate this crucial force? What is the probability of fires of a given size in a region, especially the unlikely extremes? Integrating and maintaining natural disturbance regimes are some of the most important and difficult issues in the design and management of nature reserves (Baker 1989, Turner et al. 1993).

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Traditional statistical approaches are not always adequate for analyzing extreme events, and this is true for many stochastic ecological phenomena (Gaines and Denny 1993). Instead of the mean as a measure of central tendency and variance as a measure of spread, one might rather focus on infrequent events in the tails of a statistical distribution. Fortunately, samples of extreme events taken over time (e.g., the largest event per year) make up a time series that can be analyzed through the statistics of extremes (Gumbel 1958). Previous work has examined statistical distributions in relation to fire size (e.g., Strauss et al. 1989, Yin 1993), although a specific distribution is usually assumed. A general approach is needed for analyzing extreme events in a fire regime, without requiring mapped or lengthy data sets, and that is the goal of the work described here. Although fire is the focus of this study, this approach applies to any disturbance regime (e.g., floods, windthrow, waves) in which extreme events play an important role.

In this paper, I apply the statistics of extremes to the fire regime of Los Padres National Forest (LPNF) on the central coast of California. The *extremal fire regime* (EFR) is defined as the time series of the largest fire (i.e., area burned) per year, and assumptions of the approach (e.g., independence of events and role of fuels) will be discussed. Applications consist of comparing fire regimes (i.e., cumulative distributions and return times for fires of various sizes), testing for a shift in fire regime due to fire suppression, and examining a potential forcing mechanism for extreme events. Through these applications, the statistics of extremes are shown to be a powerful tool in the analysis of large, infrequent events in an ecological disturbance regime. As this is a new approach for analyzing a fire regime, appropriateness of the method will also be discussed.

METHODS

Statistics of extremes

Fisher and Tippet (1928) first described the asymptotic theory of extreme value distributions, although the flood analysis of Gumbel (1958) is the most prominent early work on the statistics of extremes. Later authors derived generalized forms of extreme value distributions (e.g., Maritz and Munro 1967, Jacocks and Kneile 1975). The statistics of extremes have been applied to a wide variety of problems, and there are now current texts on applied (e.g., Kinnison 1985) and theoretical aspects (e.g., Leadbetter et al. 1983, Galambos 1987). Gaines and Denny (1993) described the statistics of extremes and its limitations for the study of ecological phenomena. A brief description of the statistics of extremes is given here, and the reader should consult the references for a more complete development. Notation will be similar to that used in Jacocks and Kneile (1975) and Gaines and Denny (1993).

This approach examines statistical properties of observations that are extreme in comparison to the rest of the same population. Considering event size as a random variable, X, let X_{max} represent the size of the largest event over a given time interval (e.g., the largest fire per year). The cumulative distribution, $F(x)$, to estimate the probability that the largest event in a single time interval will be smaller than some specific magnitude, x, is the following:

$$F(x) = P(X_{max} \leq x). \tag{1}$$

Since $F(x)$ describes the probability of a particular event happening during a single time interval (e.g., probability that the largest fire in a given year is a specific size or smaller), the return time, $T_r(x)$, is the expected number of time intervals before observing the largest event greater than some specific magnitude. Return times are calculated from

$$T_r(x) = \frac{1}{1 - F(x)}. \tag{2}$$

Alternative formulations are available (Gaines and Denny 1993) to examine events of the smallest magnitude over given time intervals.

A time series of extreme observations is the result of sampling primarily from the tail of the parent distribution describing the phenomenon. For a known parent distribution, it would be straightforward to characterize the distribution of its extremes. Three asymptotic families of distributions have been found (Fisher and Tippet 1928, Gumbel 1958) that characterize the extremal distributions of a variety of parent distributions. All three asymptotic families can be represented as a single generalized cumulative distribution, whose shape is determined by three parameters, α, β, and ε (Jacocks and Kneile 1975); here x still refers to event magnitude, i.e.,

$$F(x) = \exp\left(-\left[\frac{\alpha - \beta x}{\alpha - \beta\varepsilon}\right]^{1/\beta}\right) \tag{3}$$

with the constraints $F(x) = 0$ for $[x \leq \alpha\beta$ and $\beta < 0]$ and $F(x) = 1$ for $[x \leq \alpha\beta$ and $\beta > 0]$, because cumulative probability ranges between 0 and 1. Parameters, α, β, and ε are dimensionless, and they determine the category of distributions to which $F(x)$ belongs. As the "slope" parameter β approaches 0, this distribution approaches the Extreme Value distribution. For $\beta < 0$ it is of the Cauchy family, and for $\beta > 0$ it is of the Weibull family (Kinnison 1985). Other interpretations are possible for parameters, depending on the family. Modal event magnitude is ε; α measures how quickly $F(x)$ rises with the natural logarithm of time; and α/β estimates the limiting magnitude observable (Jacocks and Kneile 1975).

Because the parent distribution is often unknown, estimates of parameters α, β, and ε must be obtained

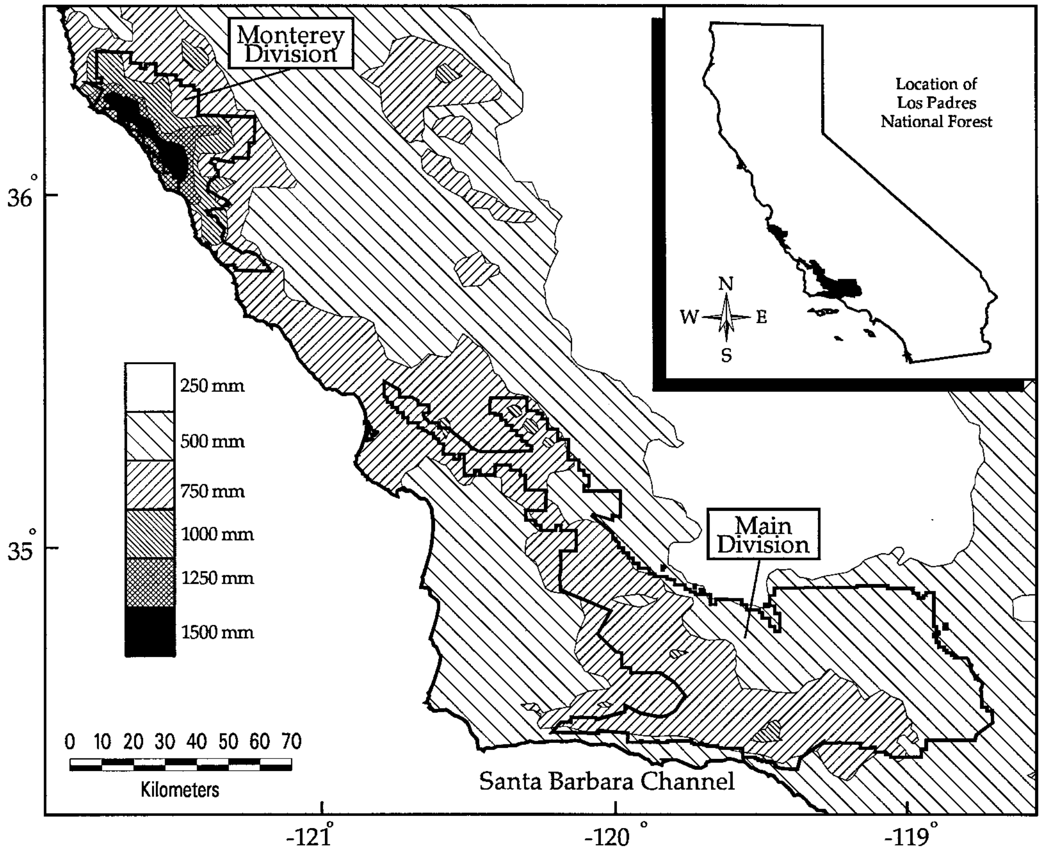

FIG. 1. Location map of Los Padres National Forest showing modeled annual average precipitation (Daly et al. 1994).

empirically. By creating a time series of the largest event per time interval (e.g., the annual maximum series making up the EFR) and ranking the sample values, x_i (where i is rank of the event in the time series and the smallest has rank = 1), an estimate of the cumulative distribution can be made from the following:

$$F(x_i) = \frac{i}{N + 1}. \quad (4)$$

Here N is the number of extreme events observed (e.g., number of years in fire record), which is also equivalent to the highest rank. While there are many available methods for nonlinear curve fitting, maximum likelihood techniques are commonly used for parameter estimation from this sample distribution function. Estimates of confidence intervals can then be made (see Appendix of Gaines and Denny [1993] for details) and used for predictions or comparisons between distributions.

Site description and data

Located along the central Coast Ranges and Transverse Ranges of California (Fig. 1), LPNF consists of ~710 000 ha and is divided into the Main and Monterey Divisions, covering ~585 000 and 125 000 ha, respectively. The area experiences a Mediterranean-type climate characterized by moderately wet winters and summer drought. Annual precipitation in the Main Division ranges from 250 to 1000 mm, and the Monterey Division is slightly wetter, ranging from 500 to 1500 mm per year (Davis and Michaelsen 1995). The vegetation is predominantly chaparral and coastal sage scrub, both of which are fire adapted. The Monterey Division is somewhat more rugged topographically, but both divisions share similar history and fire management.

There is some debate over whether large fires in southern California shrublands are a natural occurrence in these ecosystems. Minnich (1983, 1989) asserted that fire suppression has allowed extensive areas of highly combustible fuels to accumulate and that very large fires have resulted. In the LPNF area, analysis of sediment cores from the Santa Barbara Channel indicates that very large fires have been occurring for centuries (Byrne et al. 1977). Recent research on additional sediment cores from this region (Mensing 1993) also finds very large fires to have long been a natural part of chaparral ecology, suggesting that they are not due to fire suppression.

Without a much longer fire history, it is difficult to say how the modern fire regime differs from a presuppression regime. Johnson and Gutsell (1994) noted a possible change in fire frequency for LPNF in the early

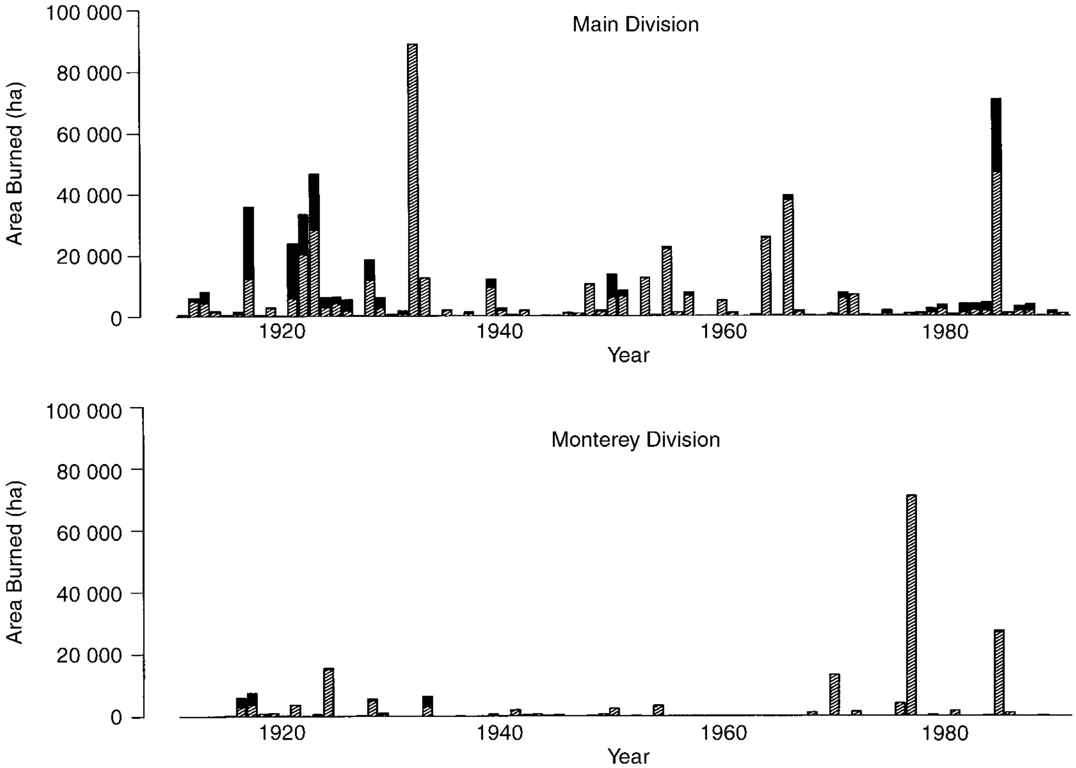

FIG. 2. Area burned annually in Los Padres National Forest, 1911–1991: Main (top) and Monterey (bottom) divisions. Bar heights represent total amount burned in all fires that year, and hashed portions represent contribution from single largest fire, i.e., that year's observation in the EFR (extremal fire regime).

1930s, but this is not necessarily related to fire size. Suppression has undoubtedly allowed older stands of vegetation to accumulate, but the role of fuels vs. weather is not clearly understood in controlling small- and large-fire dynamics in the LPNF region. Davis and Michaelsen 1995) found that fires >1000 ha dominate the current fire regime of LPNF and are strongly related to both low spring precipitation and Santa Ana events (i.e., when hot, dry winds blow predominantly from the northeast), conditions occurring since long before modern fire suppression. Large fires can also burn through or around patches of young chaparral (Dunn 1989), leading to further doubts about this being a fuel-limited system.

To analyze extreme events in the current fire regime, I created a time series of the largest annual fires for 1911–1991 from a database (nonspatial) maintained by LPNF. As stated earlier, I call this time series the *extremal fire regime* to differentiate it from other data and quantitative measures used to characterize fire regimes. Separate series were derived for the Main and Monterey divisions (Fig. 2) to compare EFRs of areas separated by a few hundred kilometers and with relatively similar climate, topography, vegetation, and fire management.

Although both Monterey Division and Main Division EFRs were stationary over time (see *Results*), I divided the Main Division EFR into 1911–1950 and 1951–1991 time periods to demonstrate this approach as a test for shifts in a fire regime. I divided the series at 1950 because that is when large air tankers were first used routinely in fire suppression (Davis and Michaelsen 1995), and a shift in EFR might be expected after this point. I then used additional fire data for two time periods (i.e., all fires for the Main Division, not only those in the EFR) to highlight the different effect of suppression on smaller vs. larger fires.

To examine extreme weather as a forcing mechanism for an EFR, I created a simple index based on the magnitude and duration of a Santa Ana event. I again focus on the Main Division EFR, due to data availability and the limited role of Santa Ana-type conditions in the Monterey Division. The daily maximum temperature recorded at the Santa Barbara airport is a good proxy for Santa Ana conditions and is strongly related to large fires in LPNF (Davis and Michaelsen 1995). A daily maximum of 32°C was chosen as the onset of a Santa Ana event (J. Michaelsen, *personal communication*). After onset, a running total of daily maximum temperatures was calculated until the daily maximum dropped below 32°C, giving a final index value for that event. For example, the sequence 29°, 33°, 34°, 32°, 28° of daily maximum temperatures (i.e., a 3-d event) has a final index value of 99°C.

I then created a new extremal series of the largest Santa Ana event for each year from 1941 to 1990 (Fig.

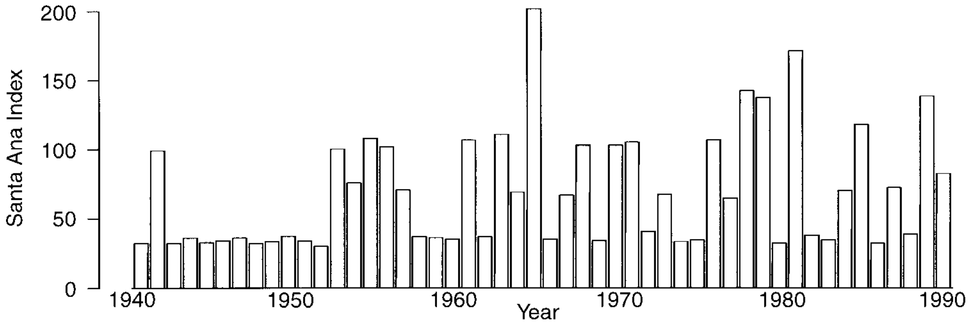

FIG. 3. Time series of annual maximum Santa Ana index developed from daily maximum temperatures at the Santa Barbara airport, 1941–1990.

3), the period for which these data are complete. Similar to Denny and Gaines (1990) who compared extremal distributions of observed wave forces and those from a theoretical model, I normalized the extremal Santa Ana series and the Main Division EFR (1911–1991) for comparison. Note that distributions being compared do not necessarily correspond to identical event dates (i.e., the largest Santa Ana event does not always produce the largest fire of that year and periods of record are different). It is the probability distribution of each extremal series and where they converge that are important. Although there is no clear translation between the ''force'' of a Santa Ana event and the size of a resulting fire, interesting insights are possible through this approach.

Appropriateness of method

I will comment here on assumptions implicit in EFR analysis and details of the statistics of extremes. One issue is how well an EFR characterizes the fire regime as a whole. Because the EFR series contains only the largest fire for each year, there will be many fires not included in this analysis. What percentage of total area burned is contained in the EFR? If the area burned by smaller fires comprises most of the area burned each year, analysis of the largest events may not be meaningful. How often are multiple large fires observed in the same year? This could happen occasionally, because there will be years of higher fire danger for various reasons (e.g., regional drought or vegetation dieback). If this happens frequently, EFR analysis may again be of limited use, despite its statistical validity.

An important assumption for the statistics of extremes is that data are independent and identically distributed (i.e., stationary over time), or nearly so. An approach to the stationarity issue is to remove trends in time series data (e.g., Gaines and Denny 1993) or to test for nonstationarity by comparing data from two time periods. If one is satisfied with the stationarity assumption, one can compare extremal distributions, even if they are of differing record length (e.g., comparing Santa Ana index for 1941–1990 with EFR for 1911–1991). Samples of $\geq$20 observations can provide accurate parameter estimations for extremal distributions, and accuracy is not necessarily improved with more observations. What is important is that the time series contain extremes that are truly large in relation to the total population (Jacocks and Kneile 1975), providing probability distributions that correctly characterize the likelihood of extreme events.

Independence of large fire events is a more difficult issue, because there is a period after a fire during which fire in that same location is unlikely. This dependence has both spatial and temporal dimensions to address. Spatially, one must examine the size of the largest fires in relation to the study area as a whole. If the largest fires routinely burn the majority of a study area, a larger study area will probably be required. Temporally, any dependence that exists will diminish with time as vegetation recovers and fuels accumulate. How long depends on the specific ecosystem and fire regime, but this does not invalidate use of the statistics of extremes. If dependency among samples decreases with time (i.e., if temporal autocorrelation approaches zero with increasing lags), the asymptotic distribution of extremes is the same as if samples were independent (Galambos 1987, Gaines and Denny 1993). For an EFR, significant negative autocorrelation in size for a decade or two (i.e., during postfire recovery) could violate the independence assumption, and a longer sampling interval or larger study area might then be required.

The above paragraph essentially addresses how small a study area can be, in relation to large fires and recovery time of vegetation, before assumptions are violated. One might also question what the upper limit is before a study area should be split and analyzed separately. For example, analyzing the EFR for all of California would not be meaningful. Because a fire regime is the result of complex interactions between climate, topography, and vegetation, one should probably split study areas containing large areas fundamentally different in these respects (e.g., mountainous coniferous forest and flat desert vegetation). Differences in climate at the synoptic or regional scale (i.e., hundreds to thousands of square kilometers) can provide guidelines for appropriate study areas. This is the size range of many national forests and parks, making

TABLE 1. Maximum likelihood estimates of model parameters for EFRs (extremal fire regimes) of the Main and Monterey divisions of LPNF. The period covered is 1911–1991; nine years without any fires were omitted from estimation for the Monterey Division.

Parameter	Main Division	Monterey Division
α	60.034	−0.219
β	−1.552	−2.573
ε	478.154	25.946
SE of α	40.078	0.841
SE of β	0.199	0.282
SE of ε	102.893	8.621
95% CI for α	−18.518 to 138.587	−1.867 to 1.429
95% CI for β	−1.942 to −1.162	−3.125 to −2.021
95% CI for ε	276.487 to 679.822	9.050 to 42.843

the EFR approach useful for those managing and analyzing disturbance regimes at this scale.

RESULTS

Appropriateness of method

In LPNF the largest fires account for most of area burned and are the defining events of the fire regime (Davis and Michaelsen 1995). It is uncommon to observe more than one very large fire in any given year (Fig. 2). The percentage of years in which the single largest fire accounted for more than one-half of the area burned that year was ~65 and 81% for the Main and Monterey divisions, respectively. Of the total area burned during 1911–1991, ~72 and 92% are contained in the EFR series of the Main and Monterey divisions, respectively. Because there are no accepted guidelines for a minimum percentage, the user must decide whether the EFR method is appropriate. As the EFR accounts for an increasing percentage of the total area burned, characterization of an EFR will tend to describe a fire regime in general. Because fire size was limited to area burned inside LPNF, results are valid only for this study area. If one included areas burned outside the LPNF boundary, some of the biggest EFR entries would probably be larger (i.e., increasing likelihood and decreasing return times of larger events). Fires outside the LPNF boundary are not recorded as reliably as those within, so these fires or fractions of fires were omitted. Manifestation of this ''edge effect'' in the analysis will vary by area and fire regime, highlighting the importance of how a study area is defined.

FIG. 4. Estimated cumulative probability distributions for EFRs (extremal fire regimes) of Main and Monterey divisions, 1911–1991. To account for nine years omitted from Monterey series, the cumulative probability of no fires for a given year, i.e., 9/81, is added to rescaled estimate of EFR, i.e., 72/81 × $F(x)$, for Monterey Division.

While the single largest fires in each division cover a great spatial extent (~56 and 15% of Monterey and Main divisions, respectively), none has approached burning the entire study area. If this had occurred, application of the statistics of extremes might not be valid. I calculated temporal autocorrelation in fire size out to a lag of 40 yr for each division, and no significant negative trends were observed. Thus, current EFRs at the scale of the entire study area are series of essentially independent events, and they appear not to be fuel-limited by postfire recovery of vegetation. No significant long-term trends were found in either EFR over time, indicating that they were also stationary during this period.

Comparison of two regimes

Estimated parameter values (Table 1) and extremal distributions (Fig. 4) for EFRs of the Main and Monterey divisions indicate a substantial difference between the areas. For any given fire size, the Monterey Division shows a much higher cumulative percentage (i.e., a greater portion of fires smaller than that fire size), meaning that larger fires are more common in the Main Division. Estimates for both cumulative distributions show the parameter $\beta < 0$, i.e., the Cauchy family of distributions, for which many of the moments are undefined. Therefore, calculating variances and confidence intervals about these EFR distributions is not possible. Nonetheless, comparing individual parameter estimates (Table 1), particularly the ''slope'' parameter β, indicates significant differences at the 95% confidence level between the two distributions.

From estimates of EFR distribution functions, one can calculate return times for fires of various sizes (Fig.

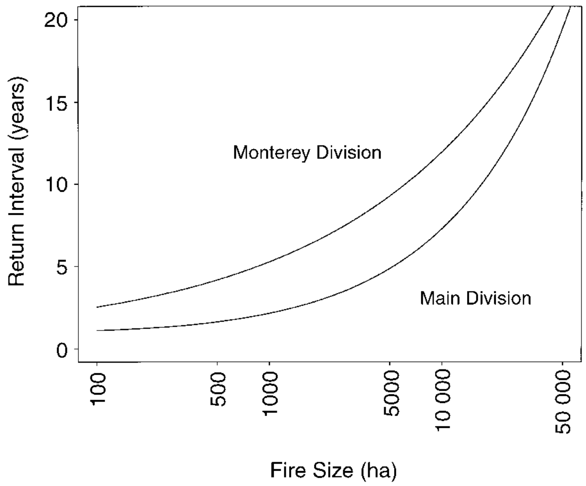

FIG. 5. Predicted return time in years of largest annual fire for Main and Monterey divisions. Monterey Division return times adjusted as noted in Fig. 4 legend.

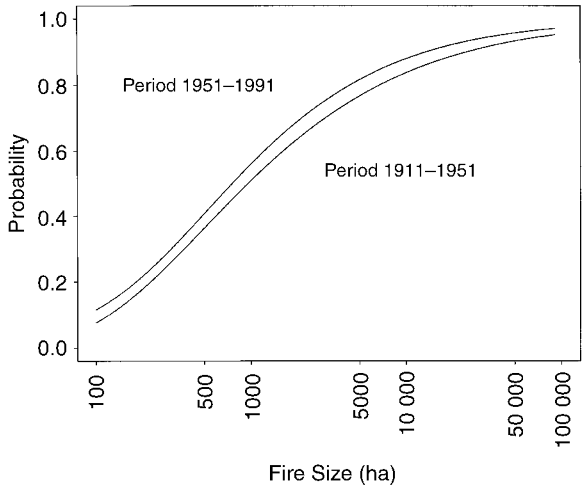

FIG. 6. Estimated cumulative probability distributions for EFRs of periods 1911–1950 and 1951–1991 for Main Division. The leftward shift is not significant; regardless, one might expect a shift to the right over time as a result of fire suppression.

5). Although one can predict events with long return times relative to the period of record (Jacocks and Kneile 1975), small differences in curve fitting can result in large fluctuations for longer return times. Only events with return times of ≤20 yr are shown here. For any given return time, the Main Division will experience fires that are much larger than those in the Monterey Division.

Shift in fire regime

To investigate the possible effect of fire suppression on an EFR, I estimated extremal distributions for two time periods in the Main Division (Table 2, Fig. 6). Estimated distributions are very similar in shape and position, and individual parameter estimates are not significantly different from each other. This verifies that the Main Division EFR is stationary over time and shows no shift in EFR due to modern methods of fire suppression adopted ~1950.

Forcing mechanism for extreme events

The Main Division EFR and the extremal Santa Ana index series were normalized by dividing by their respective median values, and extremal distributions were then estimated for comparison (Table 3, Fig. 7). Because there is no direct translation between the force of the largest Santa Ana event and the size of the largest fire per year, one would not expect distributions to match perfectly. In this case, the region of convergence is of interest. To the left of the intersection point at a normalized event size of ~1.5 (dimensionless), extremal distributions differ substantially in both shape and position. With increasingly larger events, extremal distributions cross and quickly converge, suggesting a coupling of processes in this size range.

DISCUSSION

Comparison of two regimes

The increased frequency of larger fires in the Main Division over that in the Monterey Division might be expected, based on differences in climate. In addition to receiving more precipitation, the Monterey Division is less likely to experience Santa Ana-type conditions typical of southern California. Although both regions are dominated by chaparral and coastal sage scrub, there is a larger percentage of mixed-evergreen forest in the Monterey Division (USDA 1988). Further research is necessary to examine differences in vegeta-

TABLE 2. Maximum likelihood estimates of model parameters for EFR for the Main Division of LPNF for comparison of time periods.

Parameter	Period 1911–1950	Period 1951–1991
α	0.434	70.762
β	−1.721	−1.495
ε	509.472	417.471
SE of α	62.924	55.946
SE of β	0.315	0.291
SE of ε	162.705	127.890
95% CI for α	−122.895 to 123.763	−38.889 to 180.414
95% CI for β	−2.338 to −1.104	−2.065 to −0.924
95% CI for ε	190.575 to 828.368	166.812 to 668.131

TABLE 3. Maximum likelihood estimates of model parameters for normalized EFR of the Main Division of LPNF (1911–1991) and normalized Santa Ana index (1941–1990). Both series were normalized by dividing by median value (i.e., 2594 ha for EFR and 52.5°C for Santa Ana index).

Parameter	Main Division EFR	Santa Ana index
α	0.023	−0.655
β	−1.552	−1.199
ε	0.184	0.736
SE of α	0.015	0.117
SE of β	0.199	0.188
SE of ε	0.040	0.036
95% CI for α	−0.007 to 0.053	−0.885 to −0.425
95% CI for β	−1.941 to −1.162	−1.568 to −0.830
95% CI for ε	0.107 to 0.262	0.665 to 0.806

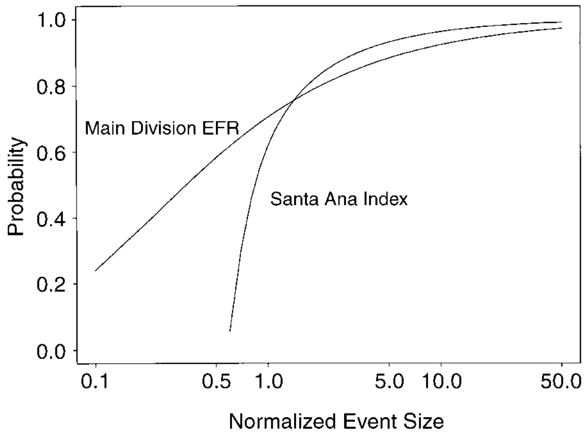

FIG. 7. Comparison of cumulative probability distributions for normalized EFR of Main Division (1911–1991) and normalized extremal distribution of Santa Ana index (1941–1990). The point of intersection is at an event size of ~1.5, equivalent to an ~4000-ha fire and 80°C Santa Ana index value.

tion between regions and to determine the relative importance of fuels. The fact that the Monterey Division is smaller in size is not related to differences in EFR distributions. This size difference might affect the largest possible fire observable (i.e., total area), but it would not alter the likelihood of fires smaller than this size.

It is striking to note the *magnitude* of differences between EFRs of the Main and Monterey divisions, given similarities in topography and fire management practices and that differences in climate and vegetation are manifested over only a few hundred kilometers. For example, 80% of fires in the Monterey Division will be smaller than ~900 ha, vs. ~5300 ha in the Main Division (Fig. 4). In return times, the 15-yr fire (i.e., the largest expected fire in a 15-yr period) is ~18 400 ha for the Monterey Division and ~32 800 ha for the Main Division (Fig. 5). Applied in this context, the statistics of extremes is a useful tool for quantitatively comparing disturbance regimes. Despite the similarity and proximity of regions, these results may indicate how sensitive EFRs are to small shifts in weather patterns or fuel types.

Shift in fire regime

From estimates of extremal distributions for 1911–1950 and 1951–1991, there has not been a significant shift in the Main Division EFR (Fig. 6). Therefore, modern methods of fire suppression since 1950 have not impacted the current EFR by increasing the likelihood of extreme fires. Because the EFR includes only the largest fire of each year, one might ask how this relates to the fire regime as a whole.

A rank-order plot of *all* fires in the Main Division provides another view of how fire suppression has impacted this disturbance regime. Fig. 8 shows the largest 40 fires for each time period, indicating a definite impact since 1950. Below a fire size of ~4000 ha, modern fire suppression has contained fires that do occur to a smaller size. Fires larger than ~4000 ha (i.e., those making up the majority of the EFR and total area burned over time) have not been impacted, as comparison of extremal distributions already indicated. EFR analysis provides one view of fire regime dynamics, but this can and should be augmented by examining all fires for a more complete understanding.

This interpretation differs from the view that large fires in shrublands of this area result directly from suppression of small fires (Minnich 1983, 1989). Much of LPNF is relatively inaccessible, making air tankers a notable improvement in suppression (i.e., getting to remote areas quickly). Impact on smaller fires is clear (Fig. 8), yet there was no change in EFR after 1950. Fire suppression in the early 1900s may have altered fuel patch distributions (i.e., altered spatial stationarity) to cause large fires in some California ecosystems (e.g., Minnich 1983, 1989), but it appears not to be the case in this study area. Local sediment core analyses indicate that very large fires have been occurring for centuries in this area (Byrne et al. 1977, Mensing 1993). In addition, the largest fire on record for the Main Division was in 1932, presumably before suppression had a great effect in such a rugged and remote area. Fires burned freely here prior to formation of LPNF (during 1898-1908) unless private property was threatened, and suppression efforts until 1932 were relatively ineffective (Brown 1945). Clearly, more research is required to establish how the current system compares to a presuppression fire regime. A climate-related gradient of fuel dependency may exist in Mediterranean-type shrublands of California, meaning that suppression should impact different areas in different ways.

Forcing mechanism for extreme events

Extremal distributions of Santa Ana events and the Main Division EFR intersect at a normalized magnitude of ~1.5, equal to a fire size of ~4000 ha (Fig. 7). Similar to findings of Johnson and Wowchuk (1993),

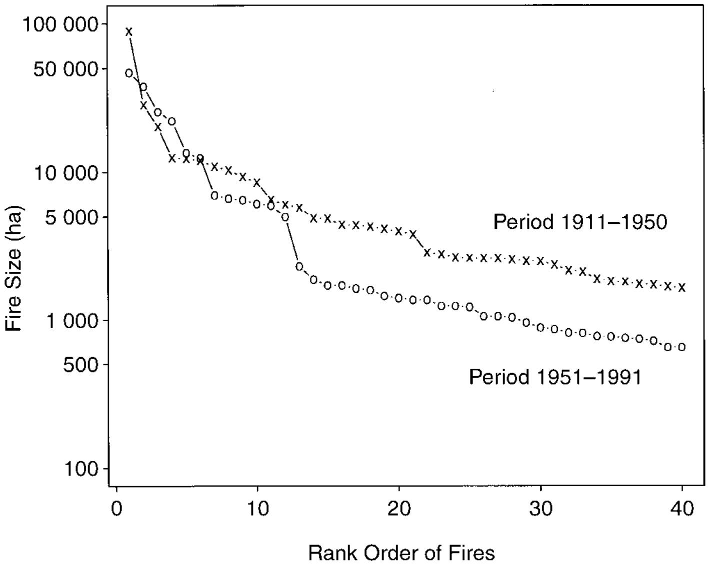

FIG. 8. Comparison of rank-order plots for periods 1911–1950 and 1951–1991 for Main Division. Distributions are mixed above a fire size of ~4000 ha; below this size, fire suppression has succeeded in keeping fires that do occur to a substantially smaller size.

this is a natural partitioning of fires driven primarily by a climatic forcing mechanism. Below a normalized event size of 1.5, extremal distributions in Fig. 7 differ substantially in shape and position, reflecting that Santa Ana events are not tightly coupled to fires in this size range. This is not surprising, considering the relative success of fire suppression during mild Santa Ana conditions. In addition, the index does not incorporate factors such as fuel conditions, which can play an important role during less severe weather.

Theoretically, the extremal distribution of a perfect index (i.e., accounting for all relevant factors) would mirror that of the EFR, reflecting the likelihood of all relevant forcing mechanisms. Here, extremal distributions do cross and quickly converge, suggesting that the distribution of Santa Ana events in the larger size range is more tightly coupled with the distribution of extreme fires. Although other factors still affect fire spread, extreme weather becomes an increasingly important forcing mechanism as event size increases, interacting with these other factors. As mentioned earlier, ~4000 ha was shown to be important in delimiting the effectiveness of suppression, and it is now clear why. Fires larger than this size usually occur under severe conditions, creating a fire dynamic that is generally immune to suppression. A normalized event size of 1.5 would represent a relatively severe 2-d Santa Ana event (i.e., ~40°C each day), during which fuel moistures decrease to critical levels and fires spread rapidly. As hot, dry winds persist, fires can escape initial attack and become very large, forcing fire suppression efforts to shift dramatically (i.e., focusing on the urban–wildland interface instead of encircling the fire perimeter). This appears to be a threshold at which the interaction of fire, fuels, weather, and fire suppression shifts from small- to large-fire dynamics in this system.

Despite its simplicity, applying the statistics of extremes to this forcing mechanism index has provided interesting insights into disturbance dynamics. Note that this comparison is not a rigorous test (i.e., other mechanisms could have similar distributions) and that all cumulative distributions must converge at 1.0. Comparing different periods of record (i.e., 1911–1991 for Main Division EFR and 1941–1990 for Santa Ana index) assumes that the likelihood of Santa Ana events was not significantly different earlier in this century, but this is reasonable. Regardless, results confirm that extreme weather is an important forcing mechanism in the current Main Division EFR, apparently driving the shift from small- to large-fire dynamics at a fire size of ~4000 ha. Again, it is difficult to say how this relates to a presuppression regime. This fire regime should become less fuel limited during extreme weather (e.g., Dunn 1989, Davis and Michaelsen 1995), as in other ecosystems (e.g., Bessie and Johnson 1995), and some degree of coupling between large fires and Santa Ana events has probably existed for centuries.

CONCLUSION

Quantitative approaches for characterizing disturbance regimes are necessary to understand ecological processes and manage disturbance-mediated ecosystems. The statistics of extremes is one such approach, focusing on the largest events over a period of record and providing a new view of disturbance regimes. In this paper I have introduced the concept of the *extremal fire regime* and applied it to LPNF in central coastal California. Results indicate the usefulness of EFR analysis for comparisons over space and time and for examining a potential forcing mechanism.

Mapped fire data will certainly augment future fire research in this area. One approach is to separate fires into small and large categories (e.g., using a 4000-ha threshold) to examine age-at-burn distributions of fuel types consumed. Results will address issues of fuel dependency and spatial stationarity and will further examine the shift from small- to large-fire dynamics. Future work is also necessary to determine impacts of fire suppression on natural fire frequency in this area (e.g., Johnson and Gutsell 1994) and the natural role of large fires. Effects of suppression probably vary with how much a fire regime is driven by fuels vs. weather, but this is a complex interaction with much yet to be learned.

Although findings of this study have practical implications for fire planning and management, there is more general significance. Because of the proximity and similarity of the two areas compared, one might expect environmental gradients over a few hundred kilometers to result in similar EFRs; however, this application shows substantial differences. This reflects the potential of EFR analysis for examining disturbance regime sensitivities to possible changes in climate (e.g., Knox 1993). Analyzing a forcing mechanism and identifying a shift from small- to large-disturbance dynamics are intrinsically interesting, but they also lead to more general questions. How are human actions impacting the behavior of forcing mechanisms, and can we predict how this may alter disturbance regime dynamics? Regardless of the disturbance or mechanisms in question, the statistics of extremes provide an important tool for analysis and management of ecosystems affected by large disturbances.

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