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Chapter 16

A Probabilistic View of Chaparral and Forest Fire Regimes in Southern California and Northern Baja California

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Abstract

Fire suppression in industrialized countries encourages massive smoke emissions from high-intensity fires as a result of two inextricably related processes under current suppression policies: the nonrandom occurrence of vegetation fires in extreme weather states and the anomalous accumulation of spatially homogenous fuels. We propose as an organizing idea that the natural long-term cumulative distribution of fires is focused by chance on modal weather states. Thus, while individual fires are each associated with unique combinations of weather and fuel conditions, vegetation mosaics are expressed in self-organized, stable distributions in the size, interval, and frequency of fires. Here we evaluate fire regimes by using spatially explicit data for chaparral and conifer forests and compare southern California (SCA) fire history under suppression with fire history produced by free-running fire (little or no suppression) in neighboring Baja California (BCA), Mexico. In SCA, suppression has reduced the number of fires, while increasing the size of old-growth patch elements and thus the spatial extent of subsequent fires. The selective dousing of fires starts nonrandomly limits extensive burning to rare periods of extreme weather. Free-running fires formerly spread in a broad spectrum of mostly normal weather over spans of months during summer and fall. This long forgotten property of fire regimes in California is still an ongoing property in BCA. Because plant response to perturbations depends on the cumulative effects of plant successions, those who study climatic relationships with fire regimes should consider the long-term dynamics of fuel accumulation as a source of outbreaks in vegetation mosaics. The development of fire

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*Corresponding author: E-mail: richard.minnich@ucr.edu management policies by the Mexican authorities should consider continued maintenance of the current fine-grained vegetation mosaic that is resistant to extensive fires.

16.1. Introduction

Wildland fire and smoke emissions occur in most of the world's vegetation (Golddammer, this volume; Moderate Resolution Imaging Spectroradiometer (MODIS) Rapid Response System: http://rapidfire.sci.gsfc.nasa.gov). While studies currently focus on possible increases in global ambient carbon from anthropogenic burning, fire suppression in industrialized countries also affects smoke emissions from vegetation fires. The systematic extinguishing of fire-starts exacerbates fire size and intensity. When fire cannot be contained, massive smoke emissions from high-intensity fires result from two inextricably related processes under current suppression policies: the nonrandom occurrence of vegetation fires in extreme weather states and the anomalous accumulation of spatially homogenous fuels.

In the southern end of the Mediterranean-climate (winter precipitation and summer drought) region of the North American Pacific coast, fire suppression in southern California (SCA), USA, has been associated with infrequent wind-driven fires (shallow mixing) that create coarse-grained burn mosaics. Dry, offshore Santa Ana winds advect smoke along surface air layers over urbanized coastal plains and valleys (Fig. 16.1). In neighboring Baja California (BCA), Mexico, which is rapidly urbanizing but still retains much of its original vegetation, free-running fire has been associated with frequent small blazes. These are pushed by prevailing onshore winds, resulting in fine-grained patch mosaics, with thin smoke layers that are often convected into the upper air layers (deep mixing). These smoke layers frequently disperse eastwards, away from population centers and toward the Sonoran Desert (Fig. 16.1; Minnich, 2006). In BCA, chaparral and mountain conifer forests burn two to three times per century (30- to 70-year intervals), but fires are nonrandomly constrained in self-organizing patch mosaics in which vegetation that has not burned over long periods is preferentially burned, in contrast to surrounding younger vegetation (Minnich, 1983; Minnich & Chou, 1997).

The self-organization of patch emplacement over long time scales can be understood from a probabilistic perspective, while recognizing the unpredictability of fires at short time scales. Large differences in fire outcomes can arise from the timing of fire-starts, becoming in effect a natural Monte Carlo experiment. While chaparral and forests gradually attain flammability at time scales of decades to centuries, fires are

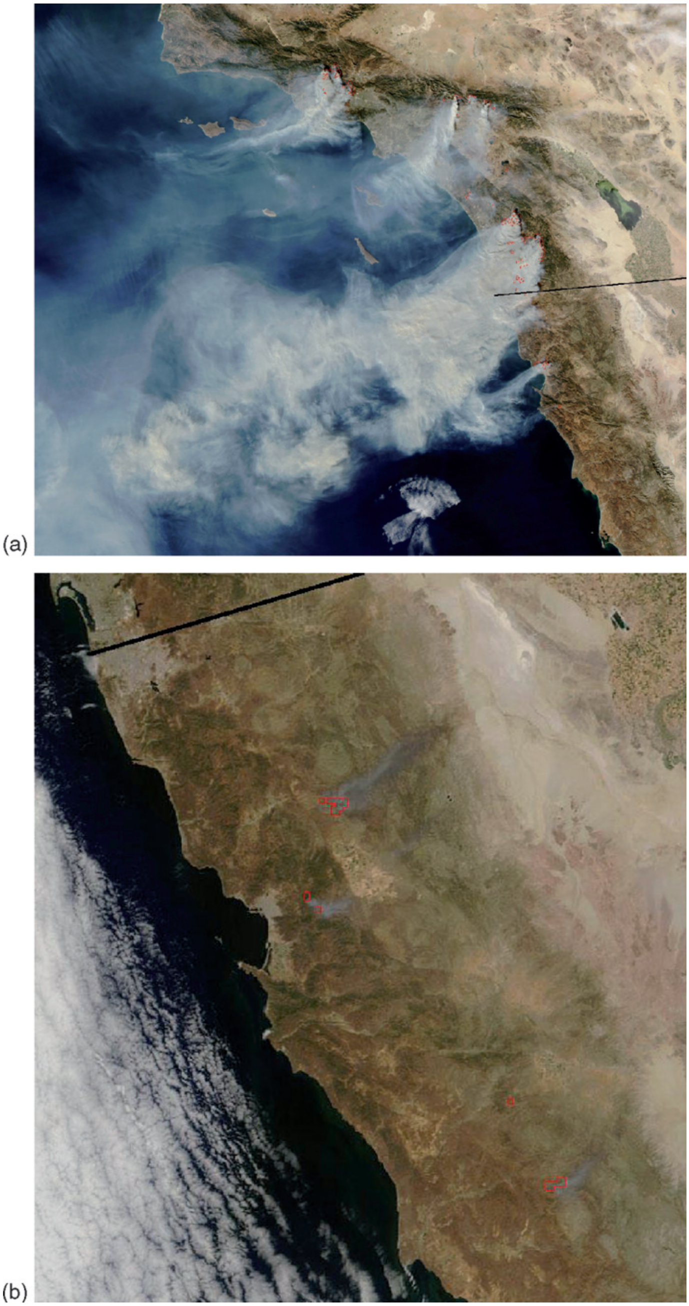

Figure 16.1. Smoke from chaparral fires in (a) southern California, October 26, 2003, and (b) Baja California, July 6, 2005. Areas in active burning are outlined in red. The U.S.–Mexico boundary is shown by black line. (Source: MODIS: rapidfire.sci.gsfc.nasa.gov)

triggered by "instantaneous" ignitions under a wide range of weather conditions, with divergent outcomes. This is the dilemma of fire ecologists seeking to discover the modal properties of fire regimes. It is also the dilemma of fire suppression policy. The nonrandom snuffing out of small fires, a selective process, causes unintended adjustments in the severity and size of subsequent fires, as well as to the structure of vegetation mosaics.

We propose as an organizing idea, that the natural long-term cumulative distribution of fires is focused by chance on modal weather states. Thus, while individual fires are each associated with unique combinations of weather and fuel conditions, vegetation mosaics are expressed in self-organized, stable distributions in the size, interval, and frequency of fires. The parameters that contribute to fire and patch dynamics include vegetation growth and fuel accumulation rates, stand-age thresholds for combustion, fuel properties and combustion of plant assemblages, ignition fluxes and fire establishment rates, fire weather, and self-organization of fire sequences.

In California, a research goal in fire ecology has been to develop databases on these properties of fire regimes prior to their alteration by land use and management. Currently, information on presuppression fire is fragmentary, site-specific, and retrospective because suppression has moved ecosystems away from presuppression states (see review in Minnich, 2007). Here we evaluate fire regimes by using spatially explicit data for chaparral and conifer forests and by comparing SCA fire history under suppression with fire history produced by free-running fires (little or no suppression) in BCA, Mexico. A divergence in fire regimes has persisted between these two otherwise similar regions since the early 20th century (Minnich & Chou, 1997). This "natural" experiment—caused by societal differences in land use and management—allows us to examine the response of fire and patch dynamics, as fire parameters have been changed by fire suppression policy.

16.2. Characteristic vegetation, patch mosaic dynamics, threshold of combustion, and fire weather window

Vegetation is similar from the east–west Transverse ranges north of Los Angeles and down the north–south Peninsular Range southward into BCA. Assemblages adapted to moist habitats gradually become less extensive and occur at higher elevations with decreasing latitude (Minnich, 2007; Minnich & Franco-Vizcaíno, 1998). Hillslopes from below 1500 to 2000 m are covered with extensive carpets of chaparral dominated by *Adenostoma fasciculatum* (chamise), *Adenostoma sparsifolium*, and members of *Ceanothus*, *Arctostaphylos*, and *Quercus*, with patches of serotinous conifer forests that include *Pinus coulteri*, *Pinus attenuata*, *Pinus muricata*, *Cupressus forbesii*, and *Cupressus arizonica*, as well as the nonserotinous pinyon *Pinus quadrifolia*. Basins and canyons contain woodlands of *Quercus agrifolia* and *Q. engelmannii*, with galleries of *Populus fremontii*, *Platanus racemosa*, *Alnus rhombifolia*, and *Acer macrophyllum* along streamcourses. Mixed evergreen forests of *Pseudotsuga macrocarpa* and *Q. chrysolepis* grow in canyons and north-facing slopes from near Santa Barbara to the mountains east of San Diego. *Q. chrysolepis* continues southward in canyons and rocky sites in BCA where it is joined by *Q. peninsularis*. Above 1500–2000 m chaparral gives place to mixed-conifer forest dominated by *Pinus jeffreyi*, *P. lambertiana*, *Abies concolor*, and *Calocedrus decurrens*. *P. ponderosa* is locally common in SCA, but does not occur in BCA, and conversely *Cupressus montana* is endemic to the Sierra San Pedro Mártir (SSPM) in BCA.

To explain differences in chaparral and forest fire regimes between SCA and BCA, a model that integrates fire weather and fuel-driven patch mosaics was proposed by Minnich (1983), Minnich and Chou (1997), and Minnich (2001). Self-organized mosaics composed of vegetation of different ages characterize the chaparral and mixed-conifer forest in BCA. In BCA chaparral, frequent stand-replacement fires produce fine-grained mosaics and discrete local-scale heterogeneity of fuels, with site-specific intervals of about two to three events per century. These mosaics are an outcome of time-dependent fuel accumulation within self-organized mosaics of patches that have burned at different times (Fig. 16.2). In SCA, suppression has reduced the number of fires, while increasing the size of old-growth patch elements and thus the spatial extent of subsequent fires. Fires nevertheless still spread in old stands, and site-specific fire intervals also average about two events per century (Wells et al., 2004). Self-organized mosaics develop from intense surface fires in mixed-conifer forest of BCA (Minnich et al., 2000). In SCA, suppression has excluded fire from most mixed-conifer forest since the late 19th century, resulting in massive increases in forest density and catastrophic stand-replacement fires (Goforth & Minnich, 2008; Minnich et al., 1995).

The threshold of flammability is coupled to fuel accumulation, increased leaf area, and greater transpiration in the later stages of plant successions. Fires consistently consume old stands, but are constrained in young stands because limited fuels narrow the “fire weather window” to the most extreme dry periods. The structure of shifting mosaics is locally modified in response to the unique weather states of individual fires (Minnich, 2006).

Nonrandom patch emplacement is explained from first principles of thermodynamics. Fires occur when the potential heat energy of

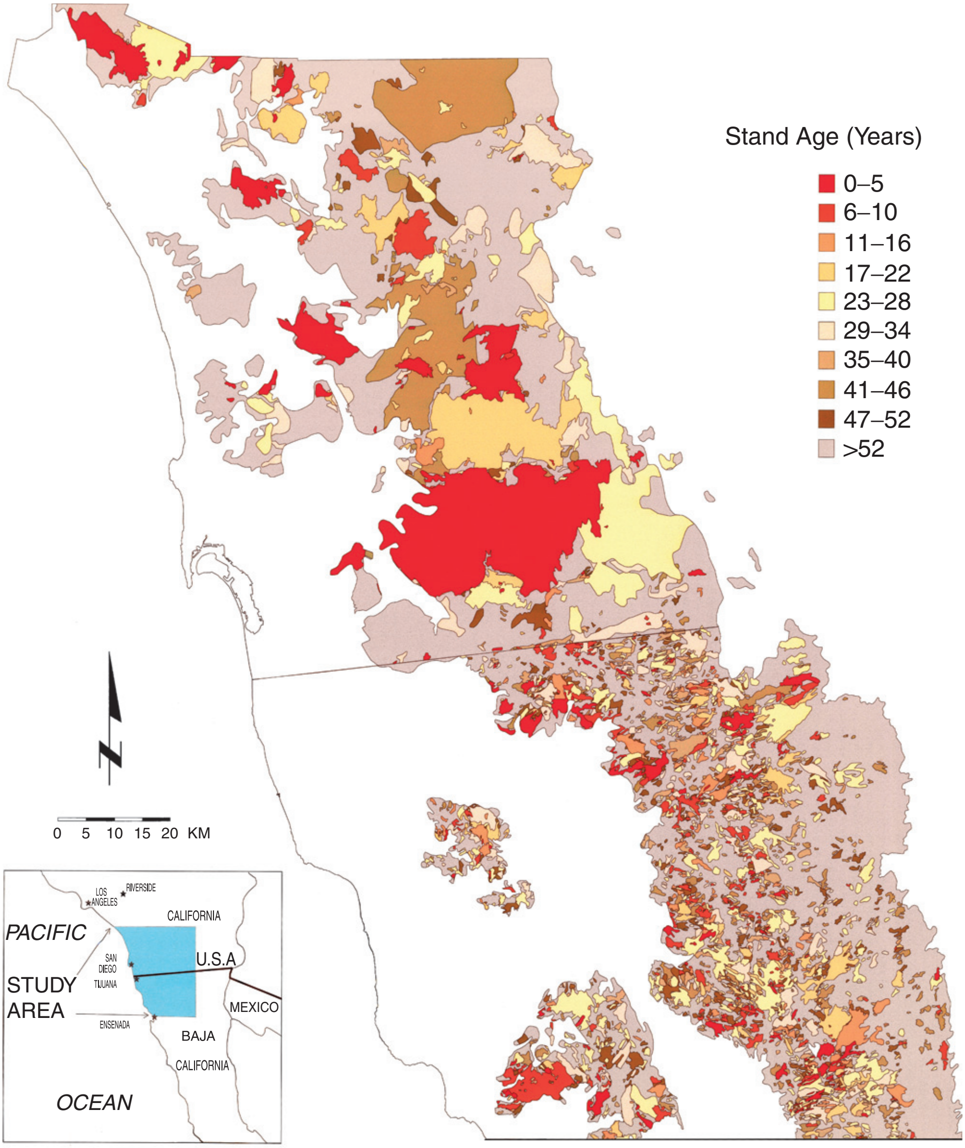

Figure 16.2. Chaparral patch mosaic in southern California and northern Baja California in 1971 (from Minnich & Chou, 1997). The current situation on the ground has been greatly altered by subsequent fires (see Fig. 16.1).

accumulated standing live and dead biomass exceeds the heat capacity of plant water content, i.e., the calorie-to-water ratio is >1 (Rothermel, 1972; Scott & Burgan, 2005). Riggan et al. (1988) proposed that, in chaparral, the expanding foliage area promotes seasonal drying, thus hastening the date of onset of seasonal drought stress with advancing stage of succession. This process increases the ratios of dead-to-live fuels in phase with fuel accumulation (Barro & Conard, 1991; Rundel, 1983; Sparks et al., 1993).

The fire weather window at a site is the full range of weather conditions capable of propagating fires, from a moist threshold to the driest weather of the climate (Fig. 16.3). Fire is unlikely in early successions because low biomass (available calories) coincides with low canopy leaf area and transpiration demand, thereby maximizing plant water. This results in a deficit in the ratio of carbohydrate calories to plant water calories as a heat sink (<1). The weather window enlarges gradually with time-since-fire due to cumulative fuel build-up, increasing dead fuel content, and increasing canopy transpiration that reduces live fuel moisture. The

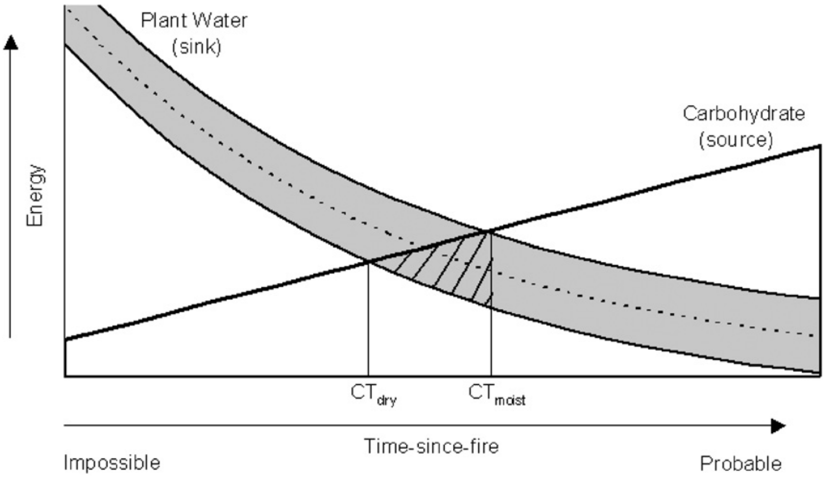

Figure 16.3. A conceptual model of carbohydrate (fuel) and plant-available water during postfire succession. The *y*-axis shows the biomass carbohydrate energy as a heat source and the energy of water as a heat sink. Carbohydrate increases linearly with cumulative growth of vegetation canopy. Average plant-available water (dashed line) decreases due to increasing leaf area and evapotranspiration demand but over a broad range (shaded belt) in response to short-term weather, seasonal drought, and interannual precipitation variability. Fires occur when carbohydrate as a heat source for combustion exceeds plant-available water as a heat sink. The fire weather window (hachured area) is limited to extreme weather states in early succession (CT dry) and expands into normal weather in later succession (CT wet). CT is the threshold of combustion.

different weather windows that result for each stand-age class contribute to the nonrandom turnover of patch mosaics. More extreme weather-risk states are required to burn vegetation in early successions than in later mature phases. Keeley et al. (1999) state that fires burn chaparral at any age, noting that fires overlap previous boundaries as young as a few years. However, local short-period overlap results from the momentum of fires crossing from old to young stands, and these incursions rarely extend far into young stands in transitions from older to younger stands (Minnich & Chou, 1997). In their work, edge effects are weighed instead of the whole landscape.

Rates of patch emplacement vary along climatic gradients. In BCA, chaparral on moist windward slopes of mountain ranges burns more frequently (high burn density per time with intervals of two to three events per century) than chaparral/pinyon woodlands on rain-shadowed leeward slopes (low burn density per time with <1 event per century) because productivity and fuel build-up rates are proportional to mean annual precipitation. Nearly contiguous burns from the coastal range to the crest of the interior range thin to scattered burns on the eastern escarpment (Fig. 16.2). Similarly, SCA chaparral has burned one to three times in the 20th century, while pinyon-juniper woodlands burned at rates of less than one per century in the same period (Minnich & Chou, 1997; Wangler & Minnich, 1996; Wells et al., 2004). The discontinuity in patch structure from BCA to SCA cannot be explained by climatic gradients because the fire regime discontinuity shifts from north-to-south, while gradients in temperature and precipitation run west-to-east in response to elevation gradients (Minnich & Chou, 1997). Alternatively, the transnational discontinuity is related to differences in fire establishment rates with management systems, which is seminal to differences in the size and number of fires, as well as fire weather.

The initial fire start is an intensely selective process. Suppression would have no effect (be random) on the weather of fires only if the firefighting system had a uniform capacity to influence the spread of flame lines, regardless of fire size or state of weather risk. This premise is unrealistic because the effectiveness of suppression energy produced to mitigate fire (clearing fuels, aerial placement of water drops or retardants) is dependent on the energy output of flame lines. Suppression influences fire primarily at the ignition phase (firefighting at the "initial attack" phase, i.e., surrounding fire-starts) when the fire is within the bounds of management. All fires begin at low rates of energy release, and then increase exponentially with increasing length of flame lines and rates of spread. Suppression forces extinguish practically all ignitions at <1 ha, but have little effect on escaped large fires because their energy release rates exceed the capacity for suppression by orders of magnitude. With free-running fire in BCA, random temporal fire occurrence in a modal weather state is a plausible assumption because lightning occurs in predictable atmospheric states. Deliberate burning does not produce nonrandom effects because human fire-starts take place at different times, with different effectiveness. Even circumstances of malicious burns timed to coincide with extreme weather would be mitigated by heterogeneous fuels of a fine-grained patch mosaic.

The probability that ignitions establish wildfires depends on the age and size of patch elements. Ignitions in recently burned patches not only have less chance of establishing fires than in old burns, but ignition success is also dependent on target size, as shown in the equation.

$$I_{\mathrm{p}} = (I_{\mathrm{ltg}} + I_{\mathrm{anth}})P\,F$$

where I_{p} is the patch ignition rate or number of ignitions in a patch per fire cycle (number of events $\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$), I_{ltg} the lightning detection rate (number of events $\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$), I_{anth} the anthropogenic ignition rate (number of human ignitions $\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$), P patch size (km^2), and F the vegetation fuel threshold, or the time required for vegetation to become flammable (yr) (Minnich, 2006). The equation holds that the proportion of ignitions that initiate fires is proportional to patch size but inversely related to flammability thresholds. Few ignitions establish fires of significant size in early successional states, even without fire control, for lack of fuel. If we consider only natural ignitions, at lightning detection rates of $1.0\,\mathrm{km}^{-2}\,\mathrm{year}^{-1}$ over a 50-year fire cycle (Minnich, 2006), a 1000 ha patch—the modal size in BCA—is struck about 500 times. At this rate, large patch targets in SCA (e.g., 10,000 ha) would experience 5000 strikes because of their size.

A universal property of fire regimes is that most ignitions fail to grow into "large fires" because of insufficient fuel. In BCA the number of large fires (>15 ha) is nearly an order of magnitude greater than in SCA, but the fine-grained mosaic in BCA represents relatively few fires as a proportion of the total ignition flux, about 1% of the natural ignition frequency. In the San Bernardino and San Jacinto Mountains of SCA the ratio of lightning fires to lightning detection rates varies annually from 1–11%, with ratios inversely related to lightning detection rates (Minnich, 2006). Increases in ignition rates due to anthropogenic ignition sources or temporal fluctuations in thunderstorm activity may shorten fire intervals by reducing the time lag between the threshold of combustion and ignition, but with diminishing returns created by the vegetation threshold which is related to the time-since-burn and moisture content. Increasingly fine-grained mosaic fragmentation approaches a theoretical limit in which infinitely numerous small fires account for an infinitely small burn area, i.e., target size and ignition success approach zero.

The view that ignitions are a "cause" of fires is a valid perspective only at instantaneous time scales but represents an error in first-cause logic that biases human perception to short-term fire processes, rather than the long-term accumulation of fuel through photosynthesis. A broad view requires consideration of the reverse: large fires, by removing fuel, influence the success of future ignitions. Studies that associate fire "cause" with individual fire areas, using records of fire management agencies (e.g., Stephens, 2005) are narrow and simplistic because this approach does not account for vegetation status (long-term cumulative fuel build-up) at the ignition site. Individual fire-starts provide little explanation of fire regimes because most fail to establish large landscape fires. An analogy would be to evaluate snow avalanching by counting snowflakes. While any one snow crystal may produce the weight that initiates downslope movement, the energy release of the avalanche would have been triggered by any given snowflake of the moment. Likewise, fire-establishing ignitions are one of many that could have triggered large fires. The successful ignition, whether initiated by man or lightning, is meaningless in the generic explanation of fire regimes.

An important question in patch dynamics is the threshold of fire size necessary to achieve nonrandom turnover of patches. Clearly, infinitely small ignitions operate independently of one another, but the chance that fire patches constrain their spatial extent increases with fire size. This limit represents an important threshold in fire size distributions. The threshold of patch interaction is a function of the rate of ignitions, with increasing fire establishment rates lowering the size threshold. Below this threshold fires have trivial influence on ecosystems, no matter how numerous (cf. Keeley et al., 1999).

16.3. Nonrandom weather of fires

The selective dousing of fire-starts affects the weather conditions that lead to large fires escaping the ignition phase of firefighting. Satellite imagery and serial aerial photographs document burning in BCA under prevailing sea breezes/onshore winds in summer, but during fall offshore Santa Ana winds in SCA (Minnich, 1983; Minnich & Chou, 1997). The difference in the weather conditions of fires across the international boundary reflects the nonrandom occurrence of large fires during extreme weather states, as a result of suppression (see Minnich, 2006, Fig. 2.1.2). Fire spread rates increase as the weather becomes drier, but over long time scales these rates respond to fire climate, which is described as the proportion of time in weather states along a normal statistical distribution. In this distribution, days associated with modest rates of burning in mature vegetation are most frequent. Days with high spread rates in extreme weather of the distribution are rare. Likewise days too moist for fire are also rare. In BCA modest spread rates are phased with a large portion of time in the summer fire season, i.e., "slow burning" that consumes large areas of the landscape. This limits extensive burning in rare periods of extreme weather. In SCA the nonrandom elimination of fire-starts reduces slow burning in normal weather states, and thereby selects for increasing area burned during states of severe weather risk, e.g., Santa Ana winds.

The differences in fire weather in SCA and BCA, specifically the frequency and intensity of Santa Ana winds, is not due to regional shifts in synoptic global circulation structure, which operate at scales of thousands of kilometers, compared to the 200-km length of this wildfire analysis. At synoptic scales, lands on one side of the international boundary will have virtually the same chance of being affected by any mode of atmospheric circulation as the other. Santa Ana winds have been documented in BCA from case studies (Castro et al., 2003; Figueroa-Gonzaléz et al., 2004; Westerling et al., 2004) and QuikSCAT measures of ocean wind vectors (Hu & Liu, 2003). Smoke and dust frequently extend far out to the Pacific on both sides of the border (Fig. 16.1, see book cover). Climatic evidence for the prominence of Santa Ana winds in BCA is the accumulation of dune material from lacustrine deposits drifted to the west side of Laguna Chapala of the Central Desert (lat. 29°N 115°W) by offshore winds after the desiccation of the lake at 7.45 ka (Davis, 2003).

Transborder differences in fire weather have persisted through the 20th century. MODIS satellite data and fire report data for 2003–2006 (Table 16.1) show that the total burn area in SCA was six times greater (764,000 ha) than in BCA (133,000 ha). The proportion of burned area with offshore winds was 77% (576,000 ha) in SCA compared to 39% (31,000 ha) in BCA, where most fires took place with prevailing westerly winds from June to August.

Long-duration fires increase the probability of fire spread in normal weather because the integrated departure from average weather (climate) decreases with increasing time scale. A forgotten element of presuppression regimes in the 19th century is that free-running fires spread in a broad spectrum of weather over spans of months until they were extinguished by the first rains of autumn (Minnich 1987, 1988). When flame line expansion was not occurring, local fires were stored by glowing

Table 16.1. Fire data for southern California (SCA) and northern Baja California (BCA), 2003–2006.

Year	Location/ area (mha)	Days with fires	Tot. fire-days[a]	Max. fire-day/fire	Max. fire duration	Burn area (kha)[b]	Burn area/ fire day	Burn area offshore winds (kha)	Offshore wind burn area/total burn area (%)
	SCA								
2003	2.0	23	77	11	13	320	4.2	310	97
2004		27	39	4	4	20	0.5	0	0
2005		32	38	3	3	7	0.2	6	86
2006		27	53	23	25	115	1.9	60	52
2007		73	132	49	61,55	317	2.4	210	66
Tot./Max.		182	334	49	61	764	2.3	586	77
% burned						38.0			
	BCA								
2003	1.2	47	84	11	10	15	0.2	5	30
2004		39	52	5	5	3	0.1	0.1	2
2005		63	110	15	59,34	30	0.3	9	29
2006		53	85	9	15	9	0.1	0.4	5
2007		49	74	8	53,43	23	0.5	17	78
Tot./Max.		251	405	15	59	80	0.3	31	39
Area wt.[c]		418	675	—	—	133.3	—	—	—
% burned						11.1			

Source: MODIS Rapid Response System, http://rapidfire.sci.gsfc.nasa.gov/.

[a] Two separate fires in one day = 2 fire-days.

[b] Southern California: Fire and Resource Assessment Program, http://frap.cdf.ca.gov/. Baja California: File data, CONAFOR, Comisión Nacional Forestal, Gerencia Nacional I, Peninsula de Baja California, Ensenada, Baja California.

[c] Days with fire and fire days normalized to differences in vegetation area in BCA and SCA.

combustion (cf. Lobert & Warnatz, 1993) in large fuels (tree snags, logs, root crowns) as virtual season-long ‘‘torches,’’ that established new flame lines when weather and fuel conditions permitted. Torch frequencies multiplied in frequency and became more widely distributed with each successive flame line expansion, dissipating only when the region was soaked by autumn rains.

Nineteenth century newspaper reports of smoke in SCA document that at least one fire persisted 1 month or longer most years, with several burning 3–4 months (Table 16.2). Detailed accounts in the western San Gabriel Mountains near Pasadena in the late 1890s reveal that three fires near Mt. Wilson consumed chaparral and local forests over periods of days or weeks, and remained latent by storing in coarse fuels for weeks,

Table 16.2. Long duration fires in southern California.

Year	Mountain range/region	Duration (Newspaper dates)
1869	E. San Gabriel/Cucamonga Peak[a]	July–October 2
1869	S. Bernardino/San Bernardino Peak[a]	July–October 2
1872	W. San Gabriel[a]	June–September
1872	San Bernardino/Santa Ana River[a]	July 4–September 14
1878	San Gabriel, Cucamonga Peak[b]	July 20–September 21
1878	San Gabriel/Big Tujunga Canyon[b]	July–fall rains
1881	San Bernardino	August–September
1882	San Bernardino/Lake Arrowhead[a]	September 7–16 (several weeks), Dec 20
1883	San Gabriel/Placerita-Soledad Canyon	September 25–November 29
1887	Northern Santa Ana	October 6–October 30
1888	San Gabriel, north of Pasadena	July 8–August 22
1888	San Bernardino/San Gorgonio	July 23 (two weeks)
1889	Santa Barbara/Rincon-Carpenteria	July 28–September 22
1889	Santa Monica	July 23–September 28
1891	Santa Barbara-Ventura/Montecito, Rincon	October 3–November 25
1891	Santa Monica	August 19–September 26
1894	Santa Inez/Santa Barbara	August 26–November 15
1895	Santa Monica	September 23–November 15
1896	San Gabriel/west of Mt. Wilson[a]	July 11–October 20
1896	E. San Gabriel/San Antonio Mtn.–Cucamonga Pk.	June 14–October 14
1898	San Gabriel/Mt. Wilson[a]	July 30–October 23
1898	San Bernardino/Running Springs	August 30–October 8
1899	San Gabriel/San Antonio	August 30–October 2, February 25, 1900
1899	San Diego/Cuyamaca	October 3 (several weeks)
1899	San Diego/Palomar	September, 27, 29 (two weeks)
1900	San Gabriel/Santa Anita Can.–W. Fork S. Gabriel[a]	July 23–September 2
1900	San Bernardino/Running Springs	August 17–October 10

Source: Los Angeles *Times* unless otherwise indicated.

[a] Minnich (1987, 1988). Newspapers were published weekly before 1878.

[b] Los Angeles *Evening-Express*, Los Angeles *Star*.

resulting in intermittent expansion throughout the dry season (Minnich, 1987).

In the 20th century, fires in SCA lasted only for days, rarely a week, before being encircled by firefighting forces, further aggravating area-weighted burning toward extreme weather states. Fires in BCA still burn as long as 1–3 months (Minnich et al., 2000). MODIS imagery documents a fire in 2005 south of Ensenada from August 26 to September 10 that burned only 1750 ha. Another fire in the foothills of the Sierra San Pedro Mártir (SSPM) in 2005 burned 5789 ha from July 6–15, and an additional 1150 ha from August 30 to September 2. In 2002, MODIS and 1-km visible GOES imagery recorded a 10,000 ha forest fire in the central SSPM from August 29 to September 15 (file data, Comisión Nacional Forestal, CONAFOR).

Fires in SCA continue to have short durations, larger sizes, and greater rates of vegetation consumption compared to BCA. Normalizing for vegetation area, the frequency of fires in BCA is about 2.3 times greater than in SCA, while the number of fire-days is about twice that of SCA. During the megafires of October 2003 and 2007, most burning in SCA occurred during a 1-week period (300,000 and 210,000 ha, respectively), while the total annual range in burn areas in BCA varied from 3000 to 30,000 ha yr^{-1}. During the MODIS reference period, the average area burned per fire-day was 2300 ha in SCA compared to 300 ha per fire-day in BCA (Table 16.1). The higher rate in SCA reflects the larger size of fires (more perimeter length in expansion), as well as higher linear-spread rates. This suggests that fires under suppression in SCA are characterized by higher fire intensities and greater smoke production, as compared to free-running fires in BCA, because more fuel area is being burned per time. In SCA the Zaca fire burned from July 4 to September 5, 2007, an unprecedented duration in the region since the initiation of fire suppression. However, this fire burned 100,000 ha at daily rates comparable to the mean for the MODIS reference period.

Lower fire intensities in BCA are also suggested by landscape-scale patterns in fuel consumption. Fires leave reticulate patchiness in which separated flame lines merge and depart with fluctuations in terrain, fuels, and weather. “Islands” of unburned vegetation may constitute a major portion of the landscape. For this reason even single burns may contribute to complex patchiness of mosaics (Minnich, 2006). In SCA wind-driven fires denude virtually all chaparral within the perimeter, further homogenizing patch mosaics.

An example of a slow-moving, long-duration fire in BCA is illustrated by a blaze in 2006 in the western SSPM. The fire established during thunderstorms at the base of the range and spread upslope in 70-year-old chaparral with anabatic winds (2440 ha; Fig. 16.4, Table 16.3). Flame lines expanded in the afternoons of June 3–4 and June 12–17. Mostly passive smoke developed from smoldering during humid weather on June 5–11 and June 21. Daily burn areas ranged from 50 to 1000 ha. The perimeter on its south flank was constrained for a continuous length of 7 km by a large burn that occurred in 1974, and its northeast flank was limited by burns that occurred in 1975 and 1987. The GOES weather satellite Fog Product (emissivity differences between 11 and 3.9 μm bands used to estimate fog depth) detected smoke layers as late as July 4.

16.4. Phase-transition fire regime

What happens when fire control is launched on a free-running fire regime? The result is a new pattern of increasing fire size and severity like that now being experienced with the establishment of suppression in Spain (Díaz-Delgado et al., 2005) and the Mediterranean Basin since the 1980s (Chuvieco, 1999). In SCA, newspaper accounts in the early 20th century detail the onset of suppression in the San Gabriel Mountains, including the construction of fuel breaks and the extirpation of small fires (Minnich, 1987). From 1905 to 1918 only 8000 ha burned in an area of 120,000 ha of chaparral, a rate consistent with a fire rotation period of 225 years, four times longer than actual mean fire intervals. Clearly, a net aging of chaparral took place across the range. The hiatus ended precipitously with a 50,000 ha fire outbreak in 1919 and a 20,000 ha fire in 1924, which together consumed nearly 60% of chaparral in that mountain range.

The limited acreage burned in the San Gabriel Mountains before 1919 is remarkable given the period's "low tech" suppression, but foresters had inherited a "well-managed" mosaic like that in present-day BCA. Forest reserve reports, U.S.–Mexican boundary surveys, and Forest Service surveys between 1895 and 1905 describe intricate chaparral patchiness and numerous small fires across the southern California chaparral landscape (Minnich, 1987, 1988). We propose that the onset of suppression temporarily lengthens regional fire intervals by about one-third of a fire cycle in chaparral. This is approximately the time required for fine-grained mosaics to age to the levels that would permit the differences in the size of fires that are now seen across the international boundary. During this "phase transition," the suppression of otherwise-rare viable ignitions postpones the establishment of mass fires in the oldest patches of an inherited fine-grained patch mosaic, as well as in younger stands that continue to resist ignitions. Eventually, the entire

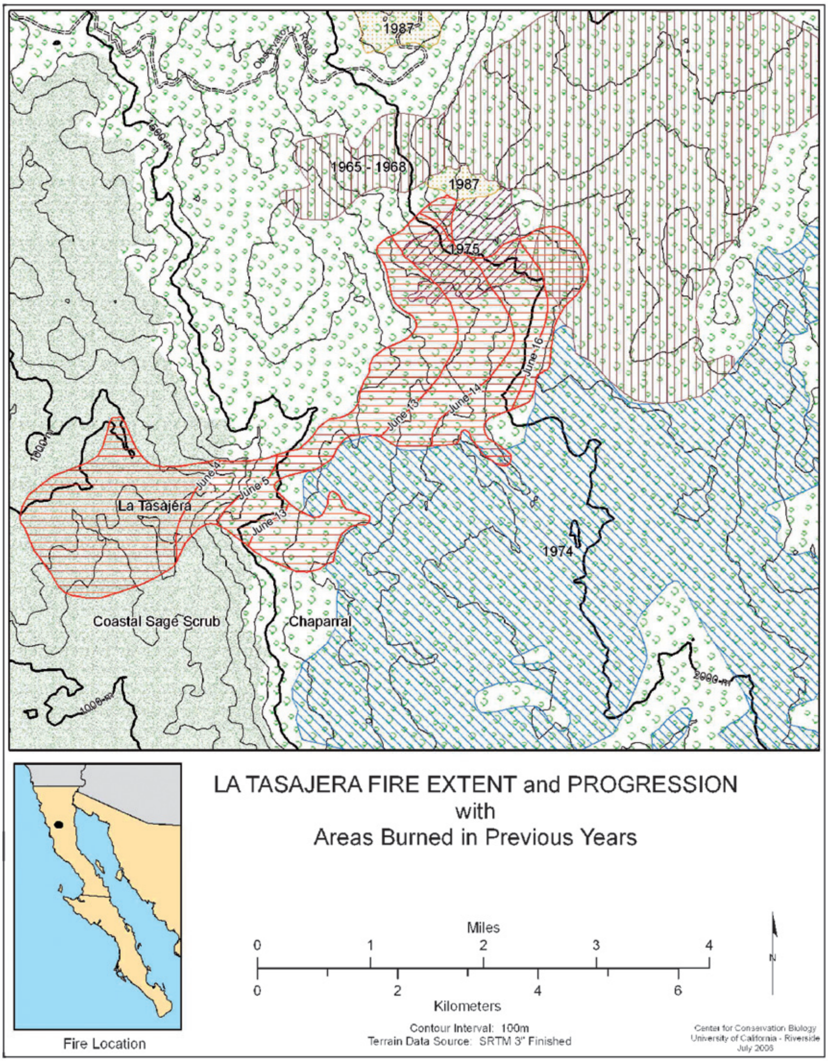

Figure 16.4. Fire perimeter and daily position of flame lines of a fire in 2006 fire in La Tasajera in the western Sierra San Pedro Mártir. Fire positions are mapped from daily true color (250 m resolution) and bands 7-2-1 imagery of the MODIS Rapid Response System (rapidfire.sci.gsfc.nasa.gov), from smoke in time-lapse animations of GOES 11-west weather satellite 1-km resolution visible channel, from "hot spot" animations in the GOES-west weather satellite 4-km resolution fog product archive in the National Weather Service, San Diego (animations by H.P. Wren, www.wrh.noaa.gov/sgx), and from ground photographs taken June 24–July 1, 2006. The fire perimeter is shown in relation to previous fire history mapped from aerial photographs in Minnich et al. (2000).

Table 16.3. Satellite and field data of the 2006 La Tasajera fire, Sierra San Pedro Mártir, northern Baja California, Mexico.

Date	Smoke (GOES 1-km visible)[a]	"Hot spot" (GOES 4-km fog product)[b]	Active flame lines (MODIS)[c]	Comments
June 2				Small thunderstorms
June 3	X	X	X	Small thunderstorms
June 4	X	X	X	
June 5		X		Thunderstorms
June 6		X		Thunderstorms
June 7		X		
June 8		X		
June 9		X		
June 10		X		
June 11		X		
June 12	X	X	X	
June 13	X	X	X	
June 14	X	X	X	
June 15	X	X	X	
June 16	X	X	X	
June 17	X	X	X	
June 18	X	X		
June 19		X	X	
June 20		X		
June 21	X	X		
June 22		X		
June 23				
June 24				
June 25				Thunderstorms
June 26				Thunderstorms
June 27				Smoke observed in field
June 28				Thunderstorms
June 29				Thunderstorms
June 30		X		Thunderstorms
July 1				Thunderstorms
July 2				Thunderstorms
July 3				Thunderstorms
July 4		X		Thunderstorms
July 5				Thunderstorms
July 6				

[a] http://archive.hpwren.ucsd.edu/SDW/VIS1/ANIMATIONS/.
[b] http://archive.hpwren.ucsd.edu/SDW/FOGREFL/ANIMATIONS/.
[c] MODIS Rapid Response System http://rapidfire.sci.gsfc.nasa.gov/.

mosaic ages so that both old and young patches reach flammable states, thus forming new, ever-larger aggregates of combustible patches, as well as ever-larger ignition targets. The large size of flammable patches eventually overwhelms initial attack capacity, leading to such anomalously large fires as those of 1919 and 1924. The evolution of coarse patch structure with suppression has since then predisposed the region to repeated cycles of excessively large burns. Such a transformation was recognized a century ago by William Mulholland, a perceptive engineer of the Los Angeles Water Department, who refused to allow his personnel to fight fire for the Forest Service in 1908 (Minnich, 1987).

Keeley et al. (1999, 2004, 2006) assert that fires were always large in SCA even into prehistory and at scales comparable to those recorded under suppression. This conclusion is based on the observation that fire sizes before 1950, when advanced suppression technology was introduced (airplanes, bulldozers, retardants), were as large as those thereafter. This model disregards the exclusive effectiveness of the initial attack phase of suppression, a process that triggered the onset of the phase transition in the early 1900s, when suppression resources were limited. Their model also disregards the fundamental observation that the energy release of large fires exceeds the energy produced by suppression technology, primitive or advanced, by orders of magnitude (Minnich, 2001). Hence, the 1950 time line is *ad hoc*. The model also suffers from the "shifting baseline syndrome" (Jackson et al., 2001). Only fire records under suppression are consulted. There was no concern to take official records until public policy and expenditures became committed to suppression about 1900 (Goforth & Minnich, 2007; Minnich, 1987). The stepwise shift in fire pattern along the international boundary was already conspicuous when the first aerial photographs were taken in 1938 (Fig. 16.5).

The October 2003 and 2007 firestorms in SCA have no historical precedent despite claims of "100-mile by 15-mile fire" (200,000 ha) near the town of Santa Ana in 1889 (Keeley, 2006; Keeley et al., 2004). Critical analysis of the 1889 fire using property tax records, voter registration rolls, claimed insurance, and place names (Goforth & Minnich, 2007) shows that the 1889 fire burned about 6500 ha of chaparral, or 40 times smaller than the 100-mile fire estimate. Goforth and Minnich (2007) also conclude that quantitative historical evidence is inadequate for reconstructing a statistical distribution of presuppression fire sizes.

From varved charcoal in the Santa Barbara Channel, Mensing et al. (1999) assert that the chaparral fires over the past 560 years were dominated by Santa Ana winds. The relationship between charcoal deposition, fire history, and discrete weather events is not constrained spatially or temporally. Ash deposits may arise from singular or multiple

Figure 16.5. Aerial photographs of the fire mosaic at Canada Verde on the international boundary east of Tecate, Baja California, in 1938. Black line delimits the international boundary. In BCA (below the boundary) is a fine-grained patch mosaic of recent burns (light areas of exposed granitic soil) and dark mature chaparral. Nearly all the area on the U.S. side is mature chaparral. The shift in patchiness along the international boundary at the time of these aerial photographs shows that differences in the chaparral fire regime between the U.S. and Mexico have prevailed since the early 20th century.

fire events. The transport of charcoal from watersheds, by wind or runoff long after fires, precludes specific correlation with discrete weather events operating at short time scales. For example, heavy ash deposition occurred in the Santa Barbara Channel with northerly Santa Ana winds on October 20, 2007 from the Zaca burn (Fig. 16.6), which occurred in July and August, with prevailing onshore winds, and at a season when Santa Ana winds are not part of the climate. The calibration data for varved charcoal are 20th century fire records that cannot account for the effects of fire suppression.

16.5. Fire and long-term climate change

Large fire outbreaks often coincide with short-term climatic perturbations such as extreme drought, moist periods with higher-than-normal fuel production, and sudden accumulations of dead fuel from dieback and pathogens. On the other hand, climatic relationships with fire regimes must also take stock of long-term dynamics of fuel accumulation in forest and brushland mosaics as a source of outbreaks, because plant response to perturbations depends on the cumulative effects of plant succession. We suggest that climatic variability as a forcing factor on burning in brushlands and forests is constrained by inertial forces of cumulative fuel build-up. This view can be addressed by a simple thought experiment. Does climate variability, especially precipitation, have the same effect on a 10-year old stand as on a nearby 100-year stand? If fires preferentially consume old-growth vegetation, then fuel build-up and transpiration demand linked to vegetation age may have more explanatory power in terms of fire outcomes than does climate variability. In addition, fluctuations in precipitation and plant-available water are also attenuated in areas where mean annual precipitation exceeds soil field capacities (Franco-Vizcaíno et al., 2002). Excess water tends to run off and does not affect the landscape evapotranspiration (ET).

In a hypothetical landscape with steady-state turnover of patches, regional calorie-to-water ratios and fire hazard would deviate mostly around a flat, long-term trend. This is due to negative feedbacks between fire hazard and vegetation (water) status. The response of the mosaic would depend on the time scale in relation to the mean fire interval of that vegetation type. In the short term, the lowering of fire thresholds during drought encourages the burning of ever-younger stands, increasing regional burn area. Moist years constrain fires to old stands, decreasing fire area. In the long term, large fire outbreaks from extreme drought lead

Figure 16.6. Ash plume pushed by Santa Ana winds over the Santa Barbara Channel from the Zaca burn on October 20, 2007. The fire burned in July and August with onshore winds. (Source: MODIS Rapid Response System, rapidfire.sci.gsfc.nasa.gov)

to reduction in age and fuel hazard of the landscape mosaic. Moist periods postpone burning, thus increasing regional fuel build-up.

Fire-scar dendrochronology (FSD) studies on changes in fire regime with climate variability rely on the assumption of covariance between the rates of tree scarring and landscape burning (Minnich, 2007). Spatial estimates of fire intervals using site-based FSD methods are equivocal and tend to underestimate, because mass burns that are responsible for most regional burning are accompanied by abundant microburns (ignition failures) symptomatic of long-tailed fire size frequency distributions (see also Baker & Ehle, 2001). It follows that transient fluctuations in the scarring record may also arise from site-specific microburns rather than rates of burning at the landscape scale.

For example, variable scarring rates due to the El Niño cycle (Swetnam & Betancourt, 1990) could also be reasonably explained by changing fuel moisture of the litter layer and microburn frequency, rather than changes in landscape-scale burning. The Pacific Decadal Oscillation (PDO; Chao et al. 2000; Minobe, 1997) is associated with the running precipitation means fluctuating 10% from the long-term mean in the western United States. However, such modest fluctuating means are attenuated by large-precipitation/field-capacity ratios. Landscape water demand may be more influenced by patterns of mosaic emplacement than by precipitation variability.

Westerling et al. (2006) posit that global warming has contributed to a substantial increase in large wildfires in the western U.S. beginning in the mid-1980s, with longer wildfire durations and wildfire seasons due to increasing spring/summer temperatures and earlier spring snow melt. The question remains as to what extent these trends affect plant-available water and fire hazard, especially if increases in plant transpiration and long-term changes in plant-available water are attenuated by precipitation/soil field-capacity ratios. The trend for longer duration fires must account for artificial effects of suppression that prevent secondary episodes of fire spread (Minnich 1987)—the selective effects for large fires coinciding with extreme weather states caused by the suppression of millions of fire-starts and aging mosaics of conifer forests from 1900 to 1985.

In the chaparral, long-term burning rates in SCA and BCA have not been in phase with climate perturbations. The total area burned at annual and subdecadal scales has been random, only with more amplified variability in SCA due to suppression (Minnich, 1983; Minnich & Chou, 1997). Short-term increases in flammability, due to unusually rapid build-up of dead fuel from pathogens or drought (e.g., Brooks & Ferrin, 1994; Davis et al., 2002; Riggan et al., 1994), have not been correlated with specific fire outbreaks. The question can be asked whether the recent

764,000 ha (38%) of chaparral burned in SCA since 2003 (MODIS) is a response to climatic forcing. However, MODIS also shows that burning rates in BCA remained within the range of burning rates during the previous 80 years (Table 16.1; cf. Minnich, 1983; Minnich & Chou, 1997). The frequent occurrence of landscape fires in BCA leads to modest interannual and interdecadal variability in burning. In SCA, transient fluctuations are dominated by rare enormous fire outbreaks (>50,000 ha, e.g., in 1970, 2003, 2007), even at decadal time scales (Minnich & Chou, 1997). The 2003 and 2007 fire sieges in SCA were an artifact of fire control policy, rather than an outcome of global climate change. A valid test of the global warming/fire hypothesis would be an examination of regions with free-running fire such as Mexico, northern Canada, or Russia (Webster, 2007), rather than ecosystems already contaminated by suppression.

16.6. Baja California is California's past

Fire regimes in forests and brushlands respond to vegetation dynamics over long time scales. To investigate modalities of fire regime properties, studies of landscapes need to adopt a probabilistic view of vegetation and fire using spatially explicit, historical approaches based on time-series data from aerial and space platforms, as well as ground-based sampling.

The U.S.–Mexican border region provides a fortuitous opportunity to study paired landscapes with differing land management and fire regimes for the development of policies that reintroduce fire in California ecosystems. The recent free-running fire history of BCA documents a mediated, self-organized fire regime that develops by chance. It also demonstrates that the potential for a "no management option" in California wildlands—no initial attack, no attempts to surround flame lines—would spontaneously produce more desirable fire outcomes than 20th century fire history under suppression in SCA with respect to fire size, intensity, ecological processes, and smoke dispersal. This fundamental finding gives support to new management options in which fire is allowed to burn at will in California wildlands, and firefighting is restricted to the wildland urban interface. Such policy change is rational only if it is assumed that continuation of suppression has trivial capacity to influence large fires. Baja California should continue to serve as a model of California's past, as well as a model for future fire management of the entire North American Mediterranean region.

The development of fire management policies by the Mexican authorities should consider continued maintenance of the current fine-grained vegetation mosaic that is resistant to extensive fire. Political will is required to resist public pressure to automatically "combat" all wildfires. Such momentary public pressure can only be dealt with by having clearly enunciated policy beforehand. The public's perception that fire results in the irretrievable loss of valuable forest resources should be addressed through education campaigns that point out the mountain forest's unaided survival through the millennia and their sudden vulnerability by the belated adoption of fire suppression policies that are already being abandoned in the developed world. The Comisión Nacional Forestal is currently developing wildfire management plans tailored to each state, and the draft plan for Baja California properly recognizes the region's unique characteristics that are very different from the rest of tropical Mexico.

Another concern relates to objections by astronomers to the degradation in atmospheric quality because of infrequent summer smoke over the National Astronomical Observatory (OAN) in the Sierra San Pedro Mártir. Minor reductions in observation time should be considered similar to disturbances due to weather and weighed against the inevitability of future firestorms like the 2003 and 2007 events just north of the border. The loss of Australia's Mount Stromlo Observatory during January 2003, in similar Mediterranean-type vegetation, should serve as a cautionary example. Detailed recommendations for the removal of fuels from areas adjacent to the OAN buildings have been provided by the authors and should be implemented. Fires—just like hurricanes, earthquakes, and other earth surface processes—should be seen as natural phenomena over which humans have little control in the long term.

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