Historic Fire Regime in Southern California Shrublands

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Abstract: *Historical variability in fire regime is a conservative indicator of ecosystem sustainability, and thus understanding the natural role of fire in chaparral ecosystems is necessary for proper fire management. It has been suggested that the "natural" fire regime was one of frequent small fires that fragmented the landscape into a fine-grained mixture of age classes that precluded large, catastrophic fires. Some researchers claim that this regime was lost because of highly effective fire suppression and conclude that if fire managers could "restore" a regime of frequent fires with widespread prescription burning, they could eliminate the hazard of catastrophic fires. The primary evidence in support of this model is a study that compared contemporary burning patterns in southern California, U.S.A., a region subject to fire suppression, with patterns in northern Baja California, Mexico, where there is less effective fire suppression. We found that differences in fire regime between these two regions are inconclusive and could not be ascribed conclusively to differences in fire suppression. Historical records suggest that the natural fire regime in southern California shrublands was rather coarse-grained and not substantively different from the contemporary regime. There is no evidence that fire-management policies have created the contemporary fire regime dominated by massive Santa Ana wind-driven fires. Increased expenditures on fire suppression and increased loss of property and lives are the result of human demographic patterns that place increasing demand on fire-suppression forces.*

Régimen Histórico de Incendios en Zonas Arbustivas del Sur de California

Resumen: *La variabilidad histórica del régimen de incendios es un indicador conservador de la sostenibilidad del ecosistema y por lo tanto se necesita conocer el papel natural del fuego en ecosistemas de chaparral para un manejo adecuado. Se ha sugerido que el régimen 'natural' de incendios estuvo compuesto por pequeños incendios que fragmentaron el paisaje en una mezcla de grano fino de clases de edades que previno incendios grandes catastróficos. Algunos investigadores aseguran que este régimen se perdió debido a la alta efectividad en la suspensión de incendios y concluyen que si los manejadores de incendios pudieran 'restaurar' un régimen de incendios frecuentes mediante la prescripción de quemas dispersas se podrían eliminar los peligros de los incendios catastróficos. La evidencia primaria en apoyo a este modelo es un estudio que comparó los patrones contemporáneos de incendios en el sur de California, USA (sujeto a supresión de incendios) con patrones del norte de Baja California, México (con menor supresión efectiva de incendios). Encontramos que las diferencias en el régimen de incendios entre estas dos regiones son inciertas y que estas diferencias no se pueden atribuir conclusivamente a las diferencias en supresión de incendios. Los registros históricos sugieren que el régimen natural de incendios en las zonas arbustivas del sur de California fue mas bien de un grano grueso y no fue sustancialmente diferente al régimen contemporáneo. No existe evidencia de que las políticas de manejo de incendios han creado el régimen contemporáneo de incendios dominado por fuegos masivos conducidos por vientos de Santa Ana. El incremento en gastos para la supresión de incendios y el incremento en la pérdida de propiedades y vidas son el resultado de patrones demográficos que colocan una demanda creciente en la supresión de incendios.*

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Introduction

The types of inferences drawn from observations differ among disciplines and often contribute to scientific disputes, such as the controversy over the natural fire regime in southern California and Baja California shrublands (Minnich 1983; Keeley et al. 1989; Moritz 1997; Conard & Weise 1998; Zedler & Oberbauer 1998; Minnich & Franco-Vizcaino 1999). We examined the evidence from past fire regimes, the inferences drawn from those observations, and the implications for contemporary fire management of southern California shrubland ecosystems.

Understanding the natural role of fire in any ecosystem has value beyond merely satisfying curiosity. Modern land managers are increasingly concerned with sustainable, ecosystem-level management, and the historical variability in fire regime is considered a conservative indicator of sustainability (Millar 1997). We know from empirical studies that diversity in chaparral is threatened by fire frequencies that are too high (Keeley 1995), and theoretical studies suggest that very low frequencies may also be a threat (Zedler 1995). Thus, an understanding of natural fire regimes may provide useful guidelines for future management.

Reconstructing the Natural Fire Regime in California Shrublands

Some ecosystems, such as the ponderosa pine–dominated forests in the western United States, have a well-documented fire history (Skinner 1997). Fire scarred trees indicate that low-intensity surface fires were common prior to European colonization, and fires have largely been suppressed during the twentieth century. In contrast, California shrublands burn in stand-replacing crown fires that kill all aboveground biomass; thus, we lack a precise historical record of fires. Consequently, conclusions about the historical role of fire in chaparral will always be more controversial than those for many other forested ecosystems.

One attempt to fill this void of historical information was a Landsat remote imagery study (Minnich 1983) comparing a 9-year record (1972–1980) of burning in chaparral and coastal sage shrublands between southern California and Baja California and demonstrating differences in burning patterns north and south of the U.S.–Mexico border (Fig. 1a). It was posited by Minnich (1983, 1989, 1995, 1998) that because fire suppression was not practiced in Mexico, the burning patterns observed south of the border reflected the "natural" condition for southern California. This regime was hypothesized to be one of frequent, small fires that fragmented the landscape into a fine-grained mixture of age classes that precluded large, catastrophic fires. Minnich claimed that the primary reason this natural regime had been lost in southern California was the practice of highly effective fire suppression. Further, he proposed that if fire managers could "restore" a natural fire regime of frequent, small fires through prescription burning, they could eliminate the hazard of catastrophic fires in southern California. This philosophy is currently reflected in fire-management plans for all southern California national forests (Conard & Weise 1998). Because of the social, economic, and political implications of these ideas, they deserve critical examination.

Evaluating the Baja California Model

Minnich's (1983) study, represented in Fig. 1a, has an inherent bias that has not been widely appreciated. Although the figure legend in the original paper purported to show only the difference in burning patterns as observed from Landsat remote imagery over a 9-year period (1972–1980) in both Baja and southern California, the figure was biased by the inclusion of two massive fires (1932 and 1970) in southern California that were outside the comparison period. These two fires were the largest in California's history and were mapped from U.S. Forest Service records not available for Baja California. With these two fires removed (Fig. 1b), the differences are far less striking and the conclusion that large fires are restricted to north of the border is called into question. Strauss et al. (1989) examined only the legitimate Landsat imagery comparison (Fig. 1b) and found no evidence of differences between the regions north and south of the border (cf. Chou et al. 1993).

Later studies (Freedman 1984; Minnich 1989, 1995, 1998; Minnich & Dezzani 1991) used historical aerial photographs of Baja California to compensate for the detailed records available north of the border. These studies concluded that, in contrast to the situation in southern California, large fires were absent from Baja California as far back as 1920.

Techniques used to achieve a long-term absence of large fires in Baja California make it difficult to embrace this finding. Studies by Minnich were based on three aerial photographic records, 1938, 1956, and 1972, representing a 16- to 18-year gap between photographs. Minnich contended he was able to detect all fire boundaries that had occurred during the gap between photographs; fire perimeters were even drawn back to 1920, despite a lack of photographs before 1938. The support for this procedure was the author's testimony that he could detect known fire perimeters many years after a fire. A more rigorous and acceptable scientific procedure is the use of a "blind control," in which an observer is asked to detect patterns without prior knowledge of fire perimeters. Although we do not doubt that localized fires known to the observer may remain detectable from aerial photographs for a decade or more, large fires not known to the observer, particularly ones with borders that extend beyond the scale of the photograph, may not be recogniz-

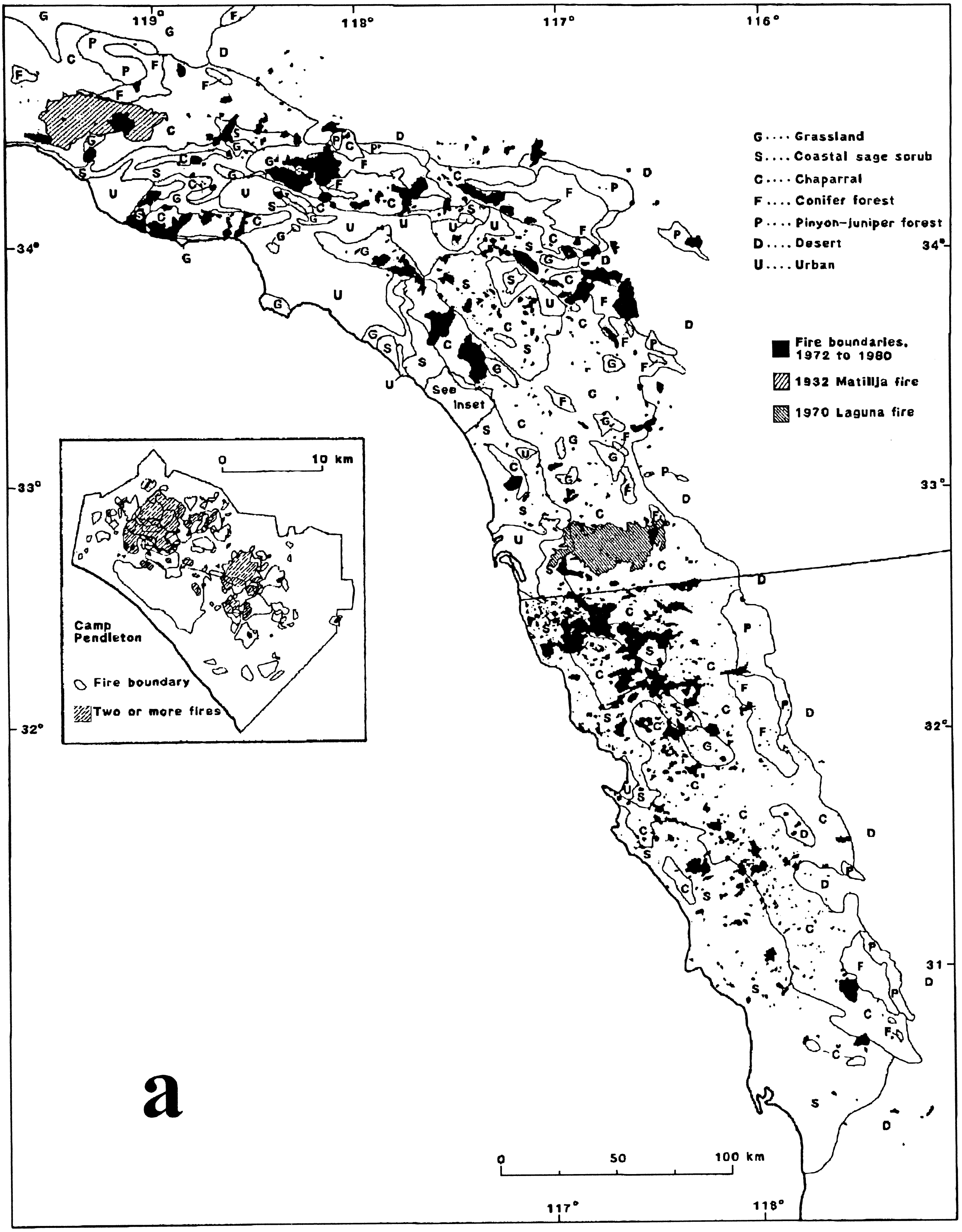

*Figure 1. Figure 1 from Minnich (1983) showing (a) "Wild-land fires in southern California and northern Baja California, 1972 to 1980. . .[D]ata were mapped from Landsat imagery." Although not stated in the original figure legend, (a) includes the two largest fires in California history, which occurred outside the Landsat imagery period. (b) Wildland fires in southern California, and northern Baja California, with large fires that fell outside the Landsat imagery study removed. We acknowledge permission of the American Association for the Advancement of Science to reprint Fig. 1 from Minnich (1983, Science **219:**1288).*

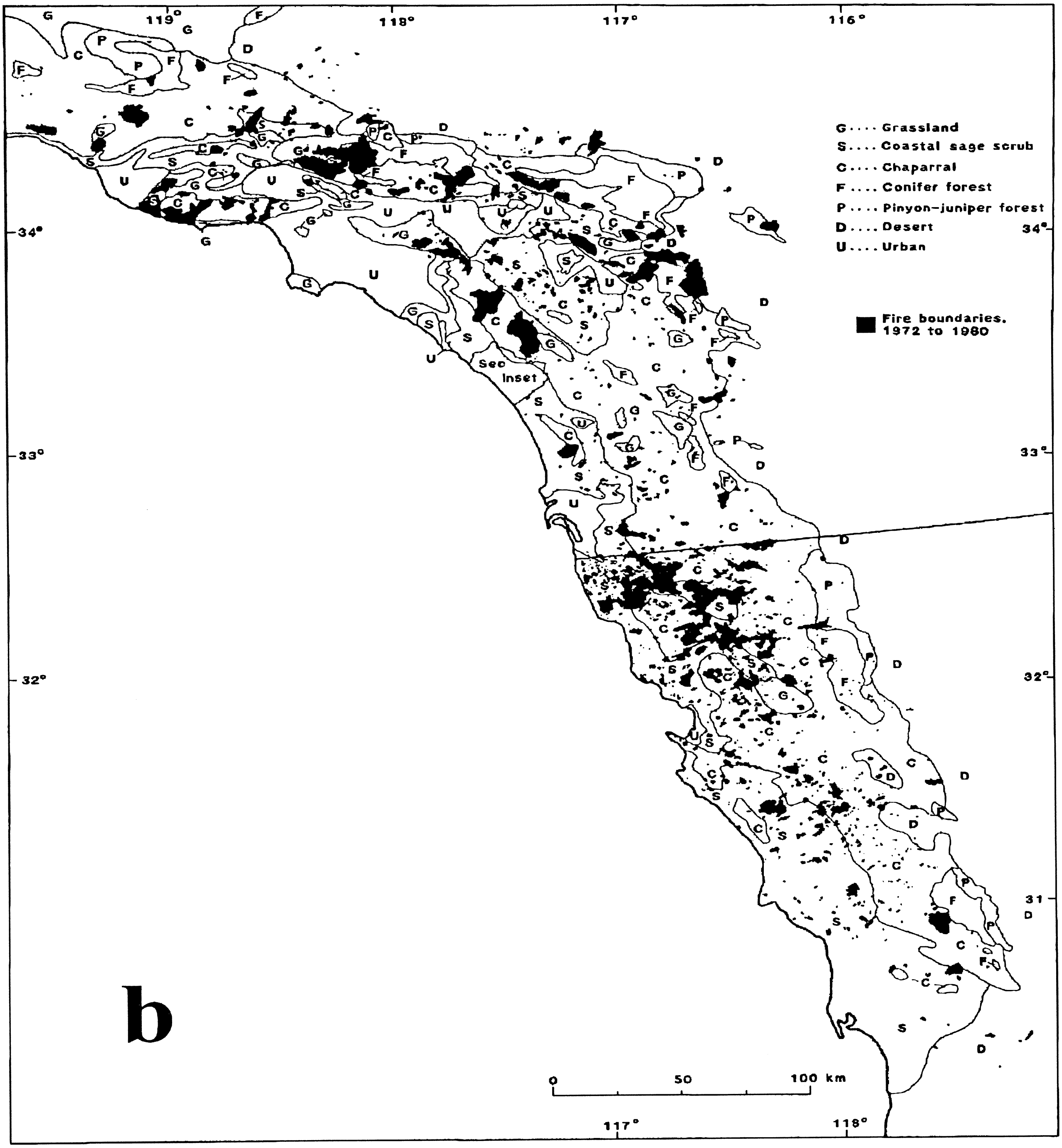

Figure 1. continued

able 16–18 years after a fire. At the very least, many researchers would require proof of such detective ability before drawing inferences about fire history. Such evidence is particularly important because several authors have reported large fires in northern Baja California (e.g., Henderson 1964; Haiman 1973; Amaya 1991).

In general, historical data for Baja California do not approach the quality of the written records available north of the border, so, beyond recent Landsat records, we know relatively little about the fire history of that region (Fig. 1b). Further, it is debatable whether or not the Landsat images demonstrate significant differences between southern California and northern Baja California (e.g., Strauss et al. 1989; c.f. Chou et al. 1993). But assuming, for the sake of argument, that one accepts the inference that differences exist, there is still much room for doubt as to the explanation for them. Minnich (1983, 1989, 1995, 1998) assumes that fire suppression policy is the only relevant difference between southern California and Baja California, but this contention has never been demonstrated rigorously. More important, this conclusion is unwarranted in the absence of consideration of potential differences in landscape, climate, and land use between southern California and Baja California.

Factors that need serious consideration before one can accept the contemporary Baja California burning regime as representative of the "natural" southern California fire regime include the following: (1) There is an extraordinary difference in fire frequency between regions north and south of the border. (2) Fire climates are not entirely comparable north and south of the border. (3) Climates and soils differ between the two regions in ways that could affect patterns of fuel production. (4) Landscape characteristics in Baja California may be less conducive to large fires such as those that occasionally occur north of the border. (5) There are many differences in land use between these regions, some of which could contribute to differences in patterns of burning.

Difference in Fire Frequency

Fire prevention is much less effective in Baja California and thus, due to human ignitions, fire frequency is up to five times greater there than in southern California (Minnich 1989, 1995; Minnich & Dezzani 1991; Henderson 1964; Haiman 1973; Keeley 1982; Freedman 1984). North of the border, the only place one sees a similar number of human-caused fires is on Camp Pendleton Marine Base, and these data were excluded from the earlier analysis of southern California because of "anomalously high ignition rates" (Minnich 1983). Higher ignition rates in Baja California are reflected in the marked differences observed in the amount of burning immediately north and south of the border (Fig. 1b).

Minnich et al. (1993) argue that in Baja California the larger number of human-caused ignitions is irrelevant in determining the mosaic pattern of burning because, even without this human subsidy, ignitions from lightning would be saturating. They reported approximately one lightning strike per 1000 ha per year in shrubland ecosystems of northern Baja California. No data were presented on the percentage of these strikes that ignite fires, and there was no direct evidence of saturation per se. Relative to other regions such as the southwestern United States (Reap 1986), northern Baja California experiences a low density of lightning strikes.

Saturation implies that additional ignitions will not affect fire frequency and burning patterns. Inconsistent with the notion of saturation is Haiman's (1973:174) report that in surveys of residents in the Sierra Juárez of northern Baja California, the major complaint was "directed towards the traditional ranchero activity of burning the montane ranges during the summer months." If lightning-ignited fires were "saturating," then the ranchero activities would not add to the fire regime and pose a risk to the local residents. It is implied by Minnich et al. (1993) that lightning saturates the environment north of the border as well, which would be evident if fire suppression did not extinguish these natural fires. But countless examples of humans subsidizing natural ignitions are noted to have occurred long before active fire suppression in southern California, beginning with the nineteenth-century settlement period (Barrett 1935; Brown & Show 1944; Lee & Bonnicksen 1978). Also, the assumption that lightning ignitions are saturating in the southern California environment is called into question by the fact that area burned is correlated with number of fires ($r^2 = 0.71$), which is correlated with population density (Keeley et al. 1999). Humans affect fire frequency, and this effect appears to be much greater south of the border. Even if lightning-ignited fires were saturating in Baja California, humans ignite fires far outside the natural fire season (Henderson 1964; Haiman 1973; Freedman 1984), and this alone could greatly alter natural burning patterns.

Comparability of Fire Climates

Massive fires in southern California are commonly driven by foëhn-type Santa Ana winds, but these winds diminish south of the border (Henderson 1964; Mitchell 1969; Markham 1972; Pyke 1972; Haiman 1973; Freedman 1984). Although these winds are controlled by regional synoptic patterns that include a Great Basin high-pressure cell and Pacific Coast trough of low pressure (Schroeder et al. 1964), their ultimate manifestation is a result of local topography (Fosberg et al. 1966; Schroeder & Buck 1970). For example, the steep eastern escarpment and lack of low passes precludes such foëhn winds on the western slopes of the southern Sierra Nevada. In Los Angeles County, these winds are funneled through passes in the east-west trending Transverse Ranges and thus are predominantly northern or northeastern winds (Edinger et al. 1964; Weide 1968). In San Diego County they are strictly eastern winds (Campbell 1906; Sommers 1978) because of the north-south orientation of the peninsular ranges. These ranges extend southward into Baja California, where the sharp eastern escarpment of the Sierra Juárez and the San Pedro Mártir, coupled with the Gulf of California to the east, limit the formation of foëhn winds (Henderson 1964).

Most fires in northern Baja California are driven by onshore northwestern breezes (Minnich 1983, 1989, 1998), and these have a different capacity for fire spread than fires driven by Santa Ana winds. Minnich contends that the absence of Santa Ana wind-driven fires south of the border is due to the lack of contiguous older stands of vegetation with fuel sufficient to carry fire. This conclusion is disputed by the fact that these winds diminish the further south of the border one goes, and the fact that in southern California Santa Ana winds will drive fire through nearly any age class of fuel (Keeley et al. 1999).

Factors Affecting Fuel Production

Annual precipitation is substantially different between the regions we compared. The "fire suppression zone" of southern California considered by Minnich (1983) extends northward to Santa Barbara and may have up to double the precipitation observed at comparable elevations in the "nonsuppression zone" of northern Baja California (Markham 1972; Pyke 1972; Haiman 1973) (Fig. 2). Haiman (1973) showed that winter cyclonic systems were more predictable in southern California than in Baja California, and that, for similar elevations and distance from the coast, only one out of six storms produced comparable precipitation at sites in northern Baja California. Also, half of the storms deposited more than 75% greater precipitation in San Diego County (Table 1). In addition, there is an earlier cut-off of late winter and early spring precipitation the further south of the border one goes (Pyke 1972). Although summer monsoon rains are more predictable south of the border, this input is of marginal importance because it comprises a small fraction of the annual precipitation. In addition, higher summer evaporative demand is thought to make much of it unavailable to shrubs (Minnich & Franco-Vizcaino 1999), as has been demonstrated for Arizona chaparral subject to similar summer monsoon rains (Vankat 1989).

Differences in precipitation between southern California and Baja California could have profound effects on primary productivity and rates of fuel production. Less fertile soils in Baja California chaparral (Franco-Vizcaíno & Sosa-Ramirez 1997) would further exacerbate differences in primary production. Although precise comparisons of primary production are not available, Freedman (1984) estimates that similar-aged chaparral stands have 40% less cover in Baja California than "comparable" sites north of the border. The positive correlation between precipitation and fire occurrence within the chaparral type north of the border in San Diego County is direct evidence that precipitation affects fire regime (Krausmann 1981). Slower fuel accumulation in Baja California could have profound effects on rates of fire spread and patterns of burning.

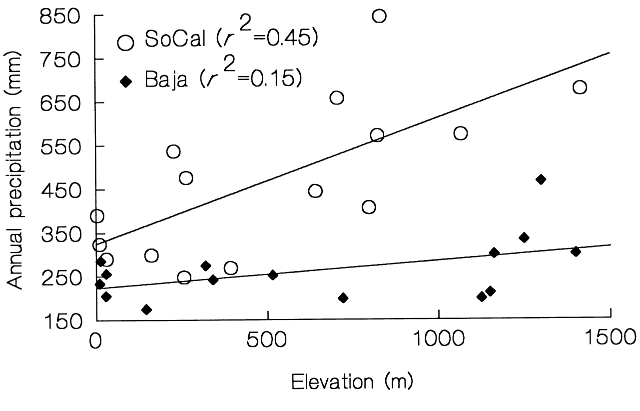

Figure 2. Precipitation for selected sites at different elevations in southern California (SoCal) and northern Baja California (Baja). Relationship between precipitation and elevation is significant ($p < 0.01$) *for southern California but not significant* ($p > 0.05$) *for Baja California (data from Henderson 1964; Haiman 1973; and National Oceanic and Atmospheric Administration, climatological data, annual summary).*

Landscape Features

Differences in landscape have not been considered. Immediately south of the interior border crossing at Tecate, the topography changes and much of the chaparral-dominated landscape is a plateau, which lacks the topographic heterogeneity present north of the border (Haiman 1973). This is important in terms of both direct and indirect effects on fire regime. Rugged topography directly affects rate of fire spread through heating of adjacent fuels as well as creation of wind turbulence. Indirectly, rugged terrain in semiarid regions may lead to greater primary production and thus greater fuel production. For example, a plateau receives three times greater solar insolation than north-facing slopes, and this difference is not offset by south-facing slopes, which at these latitudes differ from flat surfaces by only 12% (Frank & Lee 1966). Higher solar insolation in this region likely translates into greater evaporative loss and less production on the Sierra Juárez plateau than in the adjacent San Diego County. Also, vegetation on slopes commonly receive underground water subsidies from upslope drainage (Rowe et al. 1954). These differences could have profound effects on primary production, fuel accumulation, and ultimately on fire regimes.

Also, in Baja California chaparral comprises about one-third less area than it does north of the border (Minnich 1989), and it typically is bordered by less flammable pinyon communities on the east (Minnich & Franco-Vizcaíno 1998). In all of northern Baja California there are few if any areas of contiguous chaparral the size of the massive Santa Ana–driven Matilija or Laguna fires recorded in southern California (Fig. 1a).

Patterns of Land Use

Differences in land use may affect burning patterns. Working ranches north of the border are significantly larger than the legally mandated patchwork of small farms and ejidos south of the border (Henderson 1964), and on ejidos fire is used regularly to remove brush and expand grazing lands (Henderson 1964; Freedman 1984). In contrast, despite the thousands of permits issued by the State of California for brush burning since 1945, few ranch-

Table 1. Comparison of precipitation in six storms during the winter of 1970-1971 among southern California and comparable sites in northern Baja California (from Haiman 1973).

Location	*Distance to coast (km)*	*Elevation (m)*	*Precipitation (mm)*
California (lat. 32°35′-32°55′)			
San Diego	0	0	102
Barrett Dam	50	585	168
Cuyamaca	60	1305	201*
Baja California (lat. 31°50′-32°10′)			
Ensenada	0	0	86
Ojos Negros	30	700	77
San Juan Dios	62	1250	84

*n = 5.

ers in southern California have applied for such permits (California Division of Forestry 1978). In addition, in many parts of Baja California such as the Sierra Juárez, cattle graze over much of the chaparral lands (Henderson 1964), reducing fine fuels and physically trampling the shrubs (Freedman 1984), both of which affect fire spread.

Model of the Natural Fire Regime in Southern California Shrublands

Parameters of a fire regime include the mean and variance in fire frequency, fire intensity and severity, and fire season. In California chaparral and coastal sage scrub, the contemporary fire regime is reasonably well documented (Rogers 1942, Keeley 1982, 1992, 1998; Minnich 1983, 1989, 1998; Dunn 1989; Moritz 1997; Conard & Weise 1998; Keeley et al. 1999). Fire-rotation intervals, which are regional averages, are 30–40 years, and the range is illustrated by site-specific fire-return intervals, which vary from <5 to >100 years. They are always crown fires, and although the number of fires peaks in the summer, the bulk of the area is burned in autumn (Fig. 3). Fire intensity and severity are variable, depending upon fuels, weather, and topography. The majority of contemporary fires are small (10–10^3 ha), and only a tiny percentage become large (10^5–10^6 ha). These large fires are usually coincident with weather conditions generated by foëhn winds known as Santa Anas in southern California, Mono winds in central California, northeastern winds in northern California (Schroeder et al. 1964), or more localized "sundowner" winds in coastal Santa Barbara County (Ryan 1996).

It is questionable whether or not these parameters are representative of natural (pre-human influence) conditions because of the opposing anthropogenic impacts of fire suppression and increased fire ignitions. It is our intent to start with this contemporary regime and evaluate the extent to which the natural fire regime may have deviated from this pattern.

Based on the highly significant relationship between wildfire ignitions and increasing population density during the twentieth century (Fig. 4), it is apparent that the contemporary fire frequency is markedly higher than what would be experienced in the absence of human subsidy. This human influence is spatially variable, being most prominent in wildland areas adjacent to coastal population centers and decreasing in influence in the in-

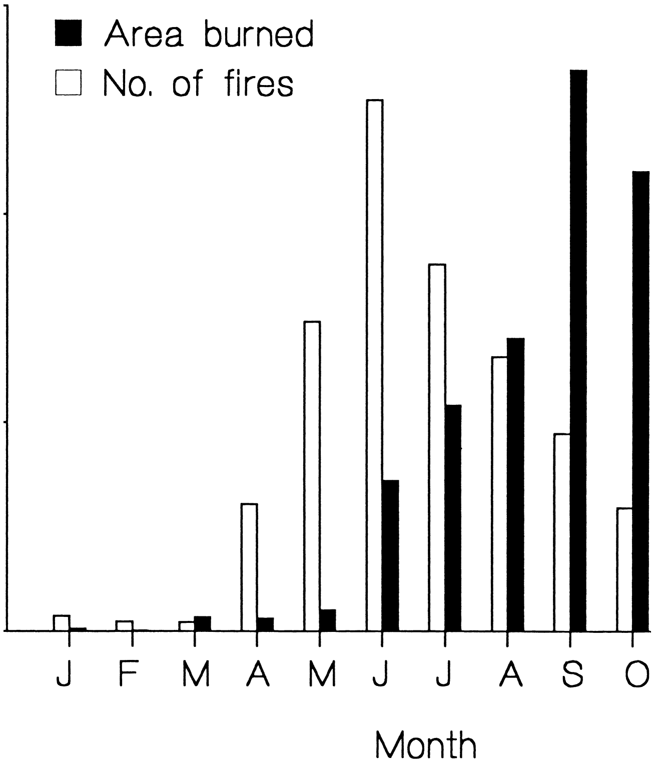

Figure 3. Monthly distribution of fire frequency and area burned (1910 –1999) for Los Angeles County (data from the California Fire History Database, California Division of Forestry and Fire Protection, Fire and Resource Assessment Program, Sacramento).

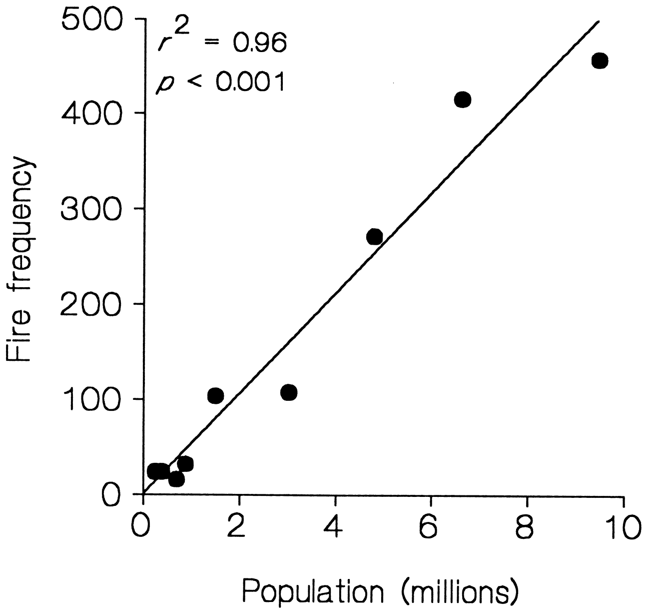

Figure 4. Fire frequency each decade since 1910 versus population density at the beginning of each decade for Riverside and Los Angeles counties in southern California (data from Forstall 1998; Keeley et al. 1999).

terior and at higher elevations (Keeley 1982; Keeley et al. 1999; Moritz 1999). This relationship between population density and number of fires has been noted since the early decades of the twentieth century (Brown 1945; Clar 1959).

Human fire subsidy began with the Native American occupation of California (Knowles 1953; Timbrook et al. 1982; Wickstrom 1987). Patterns of spatial variation were similar to those of contemporary anthropogenic effects, but, relative to contemporary California, were likely limited due to low population density and reduced mobility. Native Americans increased fire-return intervals in areas near coastal communities and surrounding slopes, but may have had limited effect on the broader landscape (Cooper 1922; Bolton 1927).

Under natural conditions, lightning is the only predictable source of ignition, but its importance varies spatially throughout the state in a pattern nearly opposite that of human-ignited fires (Keeley 1982). Thunderstorms are rare near the coast and most frequent at higher elevations in the interior. In the coast ranges east of Monterey, a 50-year record for the chaparral-dominated Pinnacles National Monument indicates only a single lighting-ignited fire (Greenlee & Moldenke 1982). In the coastal Santa Monica Mountains of southern California, no lightning-ignited fires have been recorded in the 60-year fire record (National Park Service fire records on file at the Santa Monica Mountains National Recreation Area Headquarters); lightning-ignited fires have been observed in this range (M. Morais, personal communication), but clearly they are not common.

In southern and central coastal California, lightning-ignited fires increase with distance from the coast and with elevation (Table 2). For example, the San Bernardino National Forest, the most interior forest with the highest elevation, has the highest density of lightning-ignited fires, most of which originate in coniferous forests. Even here, the density is not extraordinarily high, with an average of one lightning-ignited fire per year per 10,000 ha, which is more than an order of magnitude greater than the density in coastal foothills (Table 2).

Model of the Natural Fire Regime

Lightning-ignited fires are spawned by thunderstorms concentrated in interior mountains in July and August. Historical accounts of fire in the San Gabriel and San Bernardino mountains of southern California during the latter quarter of the nineteenth century (Minnich 1978, 1987) give some insight into fire behavior that was unabated by active fire suppression. Although these fires were not necessarily all natural lightning-ignited fires (e.g., Leiberg [1899*c*] was certain that miners were responsible for much of this burning), they nonetheless provide some insight into fire behavior in the absence of fire suppression.

Several conclusions can be drawn from this record: (1) Presuppression chaparral fires were always stand-replacing fires that burned with "irregular" behavior, sometimes creeping through brush and other times raging, so fire intensity and severity were variable. (2) Fires would commonly burn for months before being extinguished by rain or natural barriers, but despite this long period of activity they often covered a relatively modest area (e.g., the 1898 Mt. Lowe Fire burned for 3 months and consumed only 2300 ha). (3) Fires occasionally would "hold over" in logs, even during rainstorms, to be reignited at a later time.

The lightning-ignited fires that burned slowly for months or "held over" in logs would certainly have been a ready source of ignition when the predictable Santa Ana winds began in September. Although this juxtaposition may not have occurred frequently, when it did occur it likely would have resulted in a massive landscape-scale burn. Indeed, these Santa Ana winds of 100 km per hour, coupled with extremely low relative humidity, can generate fires that may cover 30,000 ha in a day (Phillips 1971), and often such fires will burn for days at a time (Chandler 1963; Schroeder et al. 1964; Countryman 1974). Thus, we hypothesize that the majority of fires were small in the pre-suppression landscape, but the bulk of the landscape burned in a few large fires that occurred at unpredictable intervals in association with autumn foëhn winds.

Site-specific fire-return intervals were almost certainly highly variable, with some montane lightning hotspots experiencing fires every few decades and coastal sites

Table 2. Total number of fires and hectares burned and percentage due to lightning during the 1970s for lower-elevation foothills (California Division of Forestry [CDF] jurisdiction) and higher-elevation interior mountains (U.S. Forest Service [USFS] national forests) in southern and central-coastal California (from Keeley 1982).

CDF ranger unit / USFS national forest	*Total no. of fires* (per 10^6 hectares per decade)	*Total area burned (ha)* (per 10^6 hectares per decade)	*No. due to lightning (%)*	*Area due to lightning (%)*
Foothills (CDF)				
Monterey/San Benito	3,140	53,570	2	<1
San Luis Obispo	3,310	44,130	2	<1
San Bernardino	9,680	12,240	4	11
Riverside	17,620	332,950	1	5
Orange	42,900	120,830	<1	<1
San Diego	9,450	20,930	3	6
Mountains (USFS)				
Los Padres	2,340	49,720	9	56*
Angeles	4,980	214,460	15	4
San Bernardino	4,400	41,030	24	6
Cleveland	4,870	121,370	11	<1

**Much of this is due to a single lightning-ignited fire (Marble Cone fire) in 1977.*

remaining fire-free for a century or more. Regional rotation intervals were likely longer than at present, perhaps 70 years or more for interior regions (Minnich 1989, 1998; Conard & Weise 1998) and presumably much longer near the coast. In short, the fire regime was one of localized fires, punctuated by periodic massive fires, a pattern predicted by modeling studies of the central coastal chaparral (Greenlee & Langenheim 1990).

Pros and Cons of the Fire Model

It could be argued that, despite the potential temporal juxtaposition of lightning-ignited fires prior to the severe autumn fire-weather conditions, frequent lightning fires that burned under moderate weather conditions would create a fine-grained mosaic of young age classes, capable of acting as a barrier to the spread of large Santa Ana–driven fires (Minnich 1989, 1995, 1998). Often cited in support of such a model are the nineteenth century forest-reserve surveys made by U.S. Geological Survey scientist John Leiberg in the San Gabriel, San Bernardino, and San Jacinto mountain ranges. These documents are extremely important because they represent some of the few descriptions of chaparral shrublands prior to fire control. One quote by Leiberg (1899*a*) is often cited in support of the age-mosaic model: "Recent fires—that is to say, within the last eight or ten years—have burned over about 14,000 or 15,000 acres [approximately 5920 ha] scattered throughout the reserve in small tracts."

At a landscape scale, however, Leiberg's comments do not describe a fine-grained age mosaic capable of preventing Santa Ana–driven fires. Indeed, Leiberg was reporting on the total burning observed across the 214,575 ha of brush on the San Jacinto Reserve (Leiberg 1899*a*, 1900*c*). Thus, according to his estimate, only about 2.8% had burned during the last decade of the nineteenth century (similar proportions appear to apply to the San Gabriel and San Bernardino reserves [Leiberg 1899*b*, 1900*a*, 1900*b*; Kinney 1887]). At this rate of burning it is estimated that, at any point in time, over 90% of the chaparral in the San Jacinto Reserve would have been three or more decades old, which surely describes a landscape capable of fueling a large, catastrophic Santa Ana–driven fire. Any lack of large fires at the turn of the century was not due to limited fuels but more likely to limited ignitions coincident with severe fire weather. Today, higher population density in the San Jacinto Range produces a greater number of ignitions, resulting in a rate of burning more than three times that observed by Leiberg (U.S. Forest Service, unpublished data).

It is hypothesized that, given sufficient time—half a century or more—most chaparral regions would have experienced the proper juxtaposition of lightning-ignited fires followed by severe fire-weather conditions to result in massive landscape-scale fires. On the time scale of centuries, fire-rotation intervals likely varied due to stochastic factors, although on longer time scales changes in climate might have altered return intervals as well (e.g., Swetnam 1993).

Illustrative of the natural pattern is the 72,400-ha Marble Cone fire ignited by lightning on the Los Padres National Forest in 1977 (Davis 1977). Some suggest that this fire resulted from unnatural fuel accumulation due to half a century of fire suppression. There was nothing unnatural about the Marble Cone Fire, however, because a similar-sized fire (60,700 ha) occurred in the same area in 1906, prior to active fire suppression (Greenlee & Moldenke 1982), and other large fires were recorded even earlier (Talley & Griffin 1980). Although the Marble Cone fire was not driven by foëhn-type winds, it did occur under severe fire-weather conditions. Another lightning-ignited fire on the Los Padres Forest in 1999 (the Kirk Complex Fire) illustrates that, under severe weather conditions, fires are not blocked by young stands of chaparral, because the Kirk Fire reburned much of the Marble Cone burn (M. Borchert, personal communication).

Other massive chaparral fires are also known from historical records prior to effective fire suppression. For example, one of the largest fires in Los Angeles County (24,000 ha) occurred in 1878 (Keeley et al. 1999). The largest fire in Orange County's history burned over a quarter million hectares in 1889 (Lee & Bonnicksen 1978); Kinney (1900), Barrett (1935), Brown and Show (1944), and Brown (1945) provide further examples of large chaparral fires prior to fire suppression. As is the case today, some of these historical fires were of sufficient intensity to severely denude slopes, resulting in catastrophic flooding, and this occurred often enough to be the primary impetus for the creation of California's first federal forest reserve—the San Gabriel Timberland Reserve—in 1892 (Lee & Bonnicksen 1978).

Paleoecological records reveal that these large fires driven by Santa Ana winds were a prominent feature of the landscape long before European settlement (Mensing et al. 1999). In the Santa Ynez Range of Santa Barbara County, massive Santa Ana–driven fires have occurred several times per century over the past 560 years, a frequency that did not change during the settlement period or following fire suppression.

The contemporary fire regime in southern California shrublands mirrors the natural fire regime far more closely than is generally credited (c.f., Bonnicksen & Lee 1979; Minnich 1983, 1995, 1998; Davis 1995; Pyne 1995). As is the case today, the natural fire regime was likely characterized by many small fires and a few large fires that consumed the bulk of the landscape. Fire intensity and severity were variable, as is the case today. The majority of fires occurred in summer, but in all likelihood the bulk of the landscape burned during autumn, when fuels were at their driest and weather conditions the most severe. This pattern has not changed today (Fig. 3). The primary change in the fire regime has been the marked increase in fire frequency in areas of high population density such as southern and central coastal California (Moritz 1997, 1999; Conard & Weise 1998; Keeley et al. 1999). One consequence of this shorter fire-return interval has been widespread conversion of shrublands to non-native annual grassland (Keeley 1990; Minnich & Dezzani 1998). Today, fire suppression is required just to maintain some semblance of the natural fire regime (Conard & Weise 1998).

Implications for Fire Management

Fire-management plans in southern California national forests have placed inordinate stock in the notion that fire suppression has been sufficiently effective to allow unnatural fuel accumulation, which has led to an unnatural fire regime that includes large, catastrophic wildfires. Fire suppression, however, has not effectively reduced the area burned (Conard & Weise 1998; Keeley et al. 1999; Moritz 1999). Also, large Santa Ana–driven fires are not dependent on an unnatural accumulation of fuel; rather, they appear to be a natural feature of this landscape (Mensing et al. 1999). The important implication of these findings is that we have not, through fire management policies, created the contemporary fire regime.

Nevertheless, nearly every decade in the twentieth century has been characterized by increased expenditure for fire suppression and greater losses of property and lives (California Department of Forestry and Fire Protection 1999). We propose that both increased fire-suppression costs and increased property loss are best explained by changes in human demography.

For much of this century, wildland fire frequency has been driven by population density (Fig. 4): more people on the landscape equals more fires. Because both state and federal fire-suppression funds are available on an as-needed basis (Mutch 1997), every decade requires more fire suppression just to maintain some semblance of status quo. In short, increased expenditure on fire suppression is a direct result of increased fire ignitions, coupled with increasingly sophisticated and expensive fire-fighting technology.

The determining factor in whether or not a fire becomes large is the coincidence of an ignition with severe fire weather. Indeed, nationwide, weather during fire is considered the most important determinant of the costs of suppression (Schuster et al. 1997). Fires ignited under severe weather conditions defy suppression, however, and thus fire managers have made limited progress in reducing the number of catastrophic fires. To their credit, though, the number of such fires has not greatly increased either. Indeed, fire suppression has become increasingly effective when measured as the area burned per number of fire starts (Keeley et al. 1999).

Why then does the loss of property and lives increase every decade? The primary culprit is the fact that growth in southern California cities has not come from changes in density but rather from expansion of boundaries, a pattern evident in cities in other parts of the United States and the world (Knight & Gappert 1989). Consequently, there has been an extraordinary expansion of the urban-wildland interface and a changing pattern of mixed urban and wildland patches (Davis 1989). During the twentieth century, changes in the fire regime have been dwarfed by changes in land-development patterns, which have made more people vulnerable to the natural forces long present on the landscape (Zivnuska & Arnold 1950; Davis 1965; Bradshaw 1987). Illustrative of this is the fact that in the 60-year period prior to 1980, 3802 structures were destroyed by wildfires in California; in the subsequent 14 years the number more than doubled (Coleman 1996). Further adding to the financial losses is the steady increase in property values attendant with economic inflation.

Management plans that call for widespread prescription burning to "recreate" a landscape mosaic of different age classes of vegetation will not stop large, catastrophic fires (Moritz 1997, 1999; Conard & Weise 1998; Keeley et al. 1999). We do not suggest that prescription burning is no longer an effective management tool. Under moderate weather conditions, young vegetation age classes may play a critical role in enhancing effective fire suppression, and fire suppression under moderate weather conditions will not lead to catastrophic fires if weather conditions change abruptly. In light of the many limitations to prescription burning in California shrublands (Conard & Weise 1998), increasing demands will be placed on the most cost-effective use of such fire-management practices and will require further study as to the most strategic placement of prescribed burns. Across the California shrubland landscape, however, fire suppression is still one of the most important tools in the fire manager's arsenal.

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