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Fuel-Driven Fire Regimes of the California Chaparral

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Abstract. A comparison of burning patterns between southern California and Baja California is used to test explanations of fire behavior. Despite large differences in fire size, the average fire rotation period is roughly equivalent between southern California and Baja California: approximately 70 years. The differences in fire size, but similarity in fire intervals between these two regions is taken as evidence of time dependence in the fire regime.

Keywords: Fire history; fire policy; fire regimes; fuel load; suppression.

Introduction

In the autumn of 1993, southern California was again struck by large chaparral conflagrations as flame lines were fanned by strong Santa Ana winds into the wildland/urban interface at Laguna Beach, Malibu, Pasadena, and Cherry Valley. These fires easily overwhelmed suppression forces and destroyed about 1000 homes at an estimated cost of one billion dollars. This natural disaster has renewed the debate over the impacts of fire suppression in chaparral and whether suppression policies afford protection for those living within or near brushlands. Central to this debate is the assessment of the long-term spatial and temporal predictability of fire in this ecosystem.

Fire Regime Models

Keeley et al (1989) propose two general models to describe the chaparral fire regime (= fire frequency, intervals, size, intensity, and behavior): (1) the combustion of chaparral is driven by allogenic factors, such as ignitions, drought and weather; and (2) the combustion of chaparral is driven by the long-term fuel dynamics of the ecosystem. The significance of each model is important to fire management. If model (1) is most realistic, then fire history will be inevitably spatially and temporally random and management agencies will have difficulty in responding to episodes of high fire potential caused by fleeting allogenic factors. If model (2) better explains chaparral fire regimes, then management will be able to accommodate some degree of predictability in chaparral patch structure, including the future temporal and spatial distribution of fires.

Ignition/allogenic models

Ignition/allogenic models have in common the idea that allogenic factors enhance vegetation flammability over short time scales and permit extensive, temporally discrete outbreaks of burning unrelated to previous fire history and patch structure (Rowe 1979, Swetnam and Betancourt 1991, Christensen 1993). For example, it has been proposed that fire control has reduced the number of fires, lengthened fire intervals, and encouraged unnaturally high fuel build up and fire intensities (Hanes 1971, Dodge 1972, Bonnickson 1980, 1981). Estimates of past fire intervals, deduced from recent fire histories under suppression, and species life history attributes range from 10 to 40 years (Hanes 1971, Biswell 1974, Wright and Bailey 1982, Bonnickson 1980, 1981). A related view is that the infrequency and ineffectiveness of natural ignitions may limit fire return interval in arid shrubland ecosystems (Keeley and Zedler 1978, Keeley 1982, Christensen 1985). Presuppression fire intervals were similar to those at present (60 years), but individual fires were large due to the scarcity of natural ignitions which permit the development of extensive patches of old growth chaparral (Zedler 1977, Keeley and Zedler 1978, Keeley 1982, Christensen 1985, 1993). The fire regime is also believed to primarily reflect fire weather and droughts, which influence stand fire probability (Heinselman 1981a,b, Baker and Veblen 1990, Knight 1987, Swetnam and Betancourt 1991).

Fuel dynamics model

Fire occurrence in many woody ecosystems may be system-regulated in association with internal fuel build-up and successional processes (Loucks 1970, Heinselman 1981a,b, Forman and Godron 1986, Riggin et al. 1988). For the Californian chaparral, it has been hypothesized that chaparral fire regimes are driven by fuel dynamics (Minnich 1989). Because fires remove fuels responsible for the combustion, a time lag exists between fuel accumulation and burning, making fire biologically controlled, self-limiting, and thereby time-dependent. At the landscape scale, fire pattern is shaped by previous fire history because there exists spatially unequal probability of fire depending upon previous fire history and differential fuel build-up in the vegetation mosaic. A high rate of fire disturbances would produce small fires and enhance a fine-grained patch structure in the vegetation (Forman and Godron 1986). A self-regulating property in fire regime would give chaparral a high element of predictability: consistent rates of fuel accumulation and unfluctuating fire return intervals would result in steady turnover of vegetation over long time scales.

One way to evaluate the extent to which fire occurrence exhibits random fire sequences or is system-regulated is to examine a 100 year "natural experiment" in the Californian chaparral of the Peninsular Ranges which extend southward from southern California into northern Baja California, Mexico. In southern California, suppression has been official policy since the turn of the century. On the Mexican side, fire management has been established only very recently because the area was virtually undeveloped until World War II (Henderson 1964). Baja California was politically and economically isolated from the United States, and within México it was a distant outpost from México City. As a consequence, the area has supported low population densities (the population of the entire peninsula was <20,000 as late as 1920), and hosts a traditional rural economy of local cropping and transhumance cattle grazing that dates back to Dominican mission times in the late 18th century. Fires in the mountains spread unhampered to this day, and deliberate burning is still practiced by *vaqueros* and farmers. Fire control became official policy only by the 1960s, and has not been effectively practiced since then.

By comparing the fire history in southern California and northern Baja California, we can evaluate how chaparral fire regimes respond to differences in fire factors, such as ignition rates, succession processes, drought, and weather, as well as the relationship between the number of fires and fire size. For example, allogenic models would predict that increasing the number of fires would decrease fire intervals, while system regulation models would predict little change.

This paper summarizes a time-series, landscape-scale fire perimeter history for the period 1920-1971 over a narrow, relatively homogeneous zone of chaparral that includes San Diego County, henceforth termed "southern California", and northern Baja California, obtained from fire history records, aerial photographs, and landsat imagery (Minnich 1983, 1989).

Fire History of Southern California and Northern Baja California

During the study period 1920-1972 extensive burning took place throughout the Peninsular ranges of Baja California and southern California, consuming a total of 537,000 ha (Fig. 1). Burns in Baja were numerous (total, 2011 >15 ha) and relatively small (none >2,300 ha). In southern California there were only 373 burns but several were >20,000 ha. However, the average fire rotation periods, the time needed to burn an area equivalent to the vegetation area, are similar in both countries, 70 years in southern California and 72 years in Baja California (Table 1).

Few chaparral areas burned at short intervals. Contiguous fire sequences typically form extremely narrow overlap zones. The disproportionately small size of overlap zones to burn size suggests that fires die out soon after entering areas of previous burns. Most fires carried through old-growth chaparral (>50 years old).

System-regulation of the fire regime

The differences in fire size, but similarity in fire intervals in Baja California and southern California is evidence of time-dependence (system regulation) in the fire regime. Chaparral resists combustion until successional processes over time-scales of decades result in sufficient fuel build-up to carry fire easily. The short-term distribution of burns is influenced by previous burn history and patch structure. The inverse relationship between the number of fires and fire size indicates that numerous small fire events tend to fragment stands into a fine mixture of age classes, a process which appears to help preclude large fires. In southern California, the small number of fires leads to large burns and patch size elements.

The long fire rotation periods in chaparral are a consequence of fire behavior and successional processes. Chaparral fires are canopy burns related to the high continuity of fuels, and large stem-surface-to-volume ratios, promoting rapid oxidation (Countryman

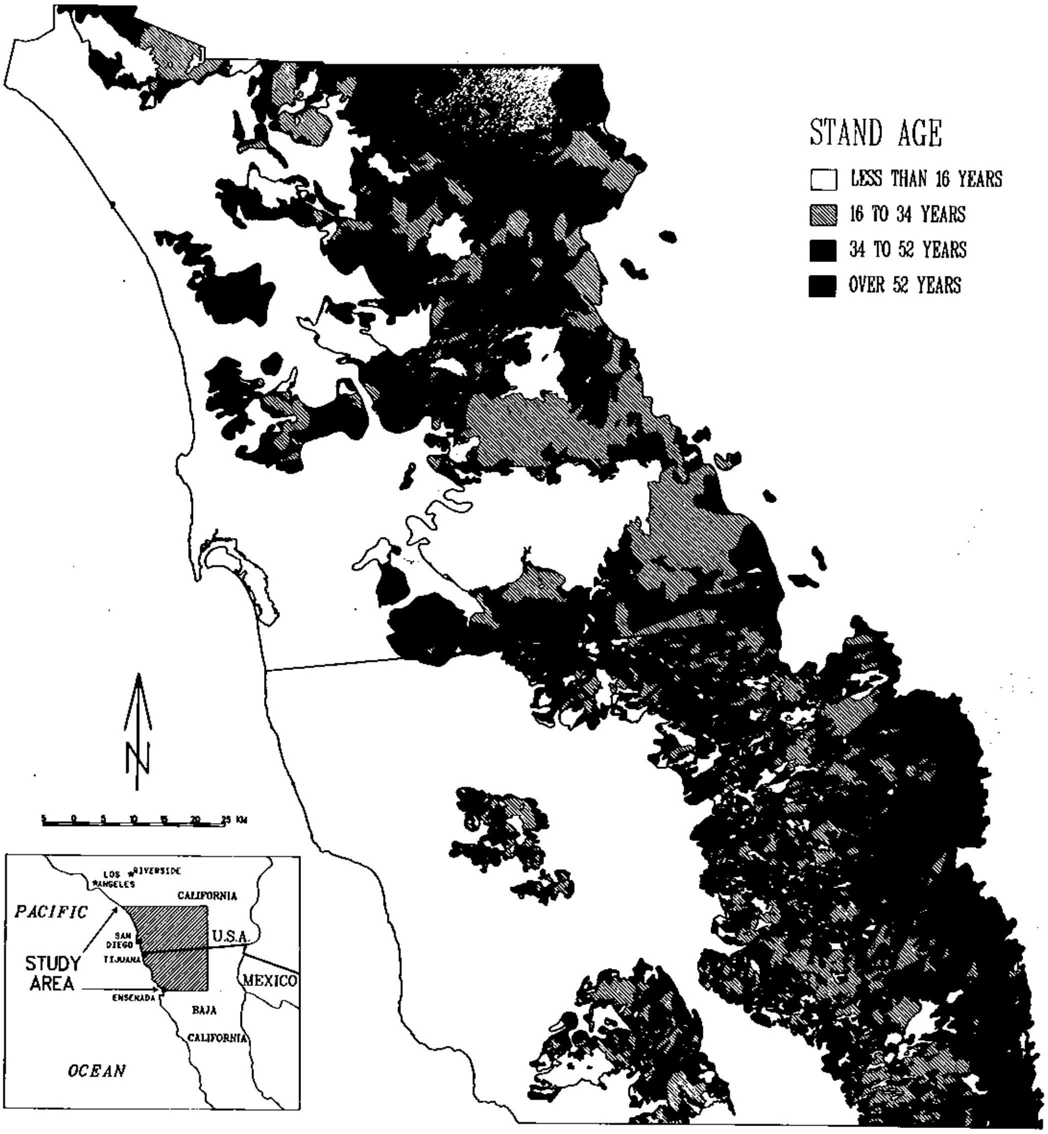

Figure 1. Composite stand age class of the chaparral in the Peninsular Ranges as of 1971. Unshaded areas along the coast and east of the mountains (right) are exotic grasslands, coastal sage scrub, or desertscrub ecosystems not subject to analysis in this study (from Minnich, 1989, with permission from the Museum of Natural History of Los Angeles).

and Philpot 1970, Philpot 977, Barro and Conard 1991). Hence, there is little carryover of fuels from a burn into the next successional sequence. The trend for increasing fire overlap with stand age (Minnich 1989) supports time-dependent models, but the mechanisms of succession-driven flammability are not adequately understood. After fire, burns are covered by only scarce scattered shrubs mixed with flashy fire annuals, but herb parts of many annuals shatter or decompose readily (due to low lignen content), and consequently are a poor source of fuels. Higher live shrub fuel moisture is produced by large root to canopy ratio and reduced transpiration stress in sprouting species. Sprouting shrubs and seedlings form a closed canopy after 5-20 years, and stand height reaches maturity after 30 years (Hanes 1981, 1988 Keeley and Keeley, 1989). Time-series aerial photographs show that canopy density continues to increase even after 40 years.

Chaparral flammability is believed to increase with age as the ratio of dead-to-live fuel increases (Rundel, 1983; Keeley and Keeley, 1989; Barro and Conard, 1991). Still, dead fuel build-up may not correlate with

Table 1. Summary of fire history, 1920-1971, for southern California and Baja California.

	Thousands of Hectares					
Vegetation Type	Total Area	No. of Fires	Burn Area	Two Burns	Three Burns	Fire Rotation Period (years)
San Diego County						
Chamise Chaparral	362.6	286	256.1	42.1	3.8	72.2
Mixed Chaparral	52.1	87	44.9	24.2	0.7	59.3
Total, Chaparral	414.7	373	301.0	66.3	4.5	70.2
Baja California						
Chamise Chaparral	238.2	1539	157.2	32	2.2	77.3
Mixed Chaparral	63.2	472	55.0	16.3	0.7	58.6
Total, Chaparral	301.4	2001	212.2	48.3	2.9	72.4

stand age, especially in broad-leaf chaparral types dominated by species in the genera *Arctostaphylos*, *Quercus*, and *Ceanothus* (Paysen and Cohen 1990). Alternatively, it has been proposed that as the community matures, the expanding foliage area of dominant shrubs advances, the seasonal soil drying hastens the onset of drought stress (Riggan et al. 1988). Thus, fire hazard is believed to increase primarily with total fuel build-up, inclusively, rather than live-to-dead composition.

Allogenic influences

With the exception of weather, there is little evidence that allogenic factors influence stand fire probability and produce outbreaks of fire unrelated to previous fire history and patch structure.

Drought. The correlation between broad-scale total burn area and precipitation departures was not significant (Baja California, $R^2 = 0.04$, $P = 0.59$; southern California, $R^2 = 0.14$, $P = 0.33$). Subnormal precipitation may lead to reduced living fuel moisture and elevated production of dead fuels from leaf shedding (Countryman and Philpot 1970). However, high winter precipitation tends to increase productivity, leaf area, and transpiration; greater soil moisture availability is compensated by greater soil depletion (Poole and Miller 1975; Ng and Miller 1980). Succession-dependence in the onset of drought seasonal stress may be produced by increasing foliage area (Riggan et al. 1988). Fire occurrence appears to be more related to the long-term build up of canopy and ligneous fuels over spans of decades than to short-term fluctuations in precipitation, shrub growth, and desiccation.

Ignition rates. Ignition rates have little influence on broad-scale burning rates in chaparral, as evidenced by the similarity of fire return intervals in Baja California and southern California, despite a six-fold difference in the number of fires. Furthermore, the lightning detection system reveals that cloud-to-ground lightning is a significant source of wildland fires in both regions (Minnich et al. 1993). Lightning detection rates for 1985-90 reveal that a 1000 ha patch of chaparral — the modal fire size in Baja California — would be struck every 2 years or about 35 times in a fire cycle of 70 years. At these rates a high proportion of lightning discharges would inevitably fail to establish fires for lack of fuel. Assuming the 3.5% fire initiation rate observed in comparable vegetation in the mountains of southern California (Minnich et al. 1993), lightning detection would produce as many fires as mapped for the Sierra Juárez (Fig. 1). Hence, the infrequency of fires in southern California is more likely to be brought about by initial attack suppression efforts than from a dearth of natural ignitions.

The low percentage of lightning strikes that presently initiate fires in southern California should not be interpreted as evidence for the ineffectiveness of natural discharges. Although thunderstorms are most frequent during the summer when the vegetation is desiccated, lightning ignitions seldom develop immediately into burns because of high humidity normally responsible for the associated convection. Lightning fires are quickly extinguished before developing into burns while anthropogenic ignitions occurring in hazardous weather have greater probability of escaping initial attack efforts.

The frequency of human versus lightning ignitions reveals little about fire regimes. The ignition of biomass is dependent on both fuel and environmental factors, and deliberate or accidental establishment of fires in natural, unmanipulated vegetation does not necessarily portend an anthropogenic impact in a fire-resilient ecosystem. Past burns affect future ignitions (Minnich 1987).

Fire weather. The most significant allogenic factor is fire weather, or the ambient conditions affecting the spread of flames. Fluctuations in relative humidity and wind speed can readily change the potential combustion of vegetation, regardless of vegetation structure and successional status. The energy level of a fire increases when dry air lowers dead and living fuel moisture by diffusion and transpiration. Wind speed drives fire intensity because advection is the primary mechanism of heat transfer (Countryman 1964, Countryman and Philpot 1970). Variation in mesoscale circulations or even wind shifts can produce local changes in fire intensity by orders of magnitude.

It is doubtful that differences in fire regime in Baja California and southern California are due to differences in climate. The fire season (June-October) is dominated by dry, subsiding air masses overlying the coastal marine layer, with similar mean annual temperatures, depth of marine layer, and mesoscale-scale wind circulations (Edinger 1959, Alvarez and Maisterrena 1977, Reyes-Coca 1990). The region is also too small for the development of distinctive surface winds, such as Santa Ana winds, relative to synoptic-scale circulations.

During daylight, prevailing winds in the northern Peninsular Ranges are mostly westerly in association with sea breezes, onshore pressure gradients, and slope winds produced by surface heating of complex terrain. Afternoon relative humidities vary from 20-40% and wind speeds from 5-10 m s^{-1} (Ryan 1983). After mid-September, onshore flow is increasingly interrupted by episodes of offshore Santa Ana winds of 10-20 m s^{-1} and relative humidities as low as <5-20%, in association with high surface barometric pressure over the Great Basin and northerly jet stream winds aloft (Schroeder et al. 1964, McCutchan and Schroeder 1973).

Evidences in fire weather, fire perimeter configuration, and fire season suggest that fires in southern California and Baja California are associated with different frequencies of weather types, with southern California fires occurring in more extreme weather. Fire perimeters in Baja California tend to have west-to-east long axes, while burns in southern California, especially large events, are mostly oriented north-to-south (Fig. 1). The dominance of west-to-east oriented burns in Baja California, parallel to prevailing winds, indicates that fire occurrence coincides during normal weather under locally generated slope winds that develop with weak ambient circulations of summer. Landsat data for 1972-1980 establish that most burning in Baja California occurs before September 15 when offshore winds are practically nonexistent (Minnich 1983). The north-to-south orientation of southern California fires correlates with offshore Santa Ana wind conditions, similar to those during the 1993 fire outbreak in southern California. Indeed more than half the area burned in southern California between 1920 and 1972 has coincided with offshore winds (Table 2). Landsat data reveals that nearly 80% of total burned area in 1972-1980 occurred after September 15, again mostly in Santa Ana winds (Minnich 1983).

Table 2. Percentage of areas burned by season and weather type in San Diego County.

	Percentage of Area Burned					
	Season			Weather Type[1]		
Period	Jan-May	Jun-Sep 15	Sep 15-Dec	Heat Wave	Santa Ana Wind	Marine Layer
1920-1937	2.9	20.5	76.6	4.6	86.5	8.9
1938-1955	0.4	62.5	37.1	65.0	30.0	5.0
1956-1971	1.2	15.7	83.1	14.5	71.6	13.9
MEAN	1.3	35.3	63.4	32.6	58.7	8.7

[1] Weather typology.
Marine Layer = onshore flow and slope winds with temperatures in inland valleys <100°F.
Heat Wave = onshore flow and slope winds with temperatures in inland valleys >100°F.
Santa Ana wind = offshore winds with relative humidity <20%.

Relationships between weather and fire size. The way in which weather influences fire size in southern California and Baja California is related to: (1) the minimum ambient weather thresholds necessary to sustain fire (threshold of combustion), versus the age, fuel build-up, and fire probability of stands; and (2) the effect of weather on broad-scale fire intensities. With respect to the latter factor, the energy release of fires is proportional to spread rates (Albini 1976 a,b), such that intense fires in extreme weather may consume more chaparral per time than fires in normal weather. However, since normal weather is temporally more frequent than extreme weather, there exists an area-weighted trade off, i.e, long-term slow combustion in modal weather versus rapid burning over short periods in extreme weather.

A critical question on the relationships between weather and broad-scale fire intensities and patch dynamics is the extent to which combustion thresholds are dependent on chaparral succession. If the chaparral fire regime is time-dependent and self-regulating, it would be expected that the thresholds of combustion would shift from extremely dry weather (such as Santa Ana winds) in young stands with limited biomass (Dunn 1988), to normal weather in mature stands. Alternatively, if chaparral is combusted only in extreme conditions regardless of stand age and fuel build-up, as presently in southern California, then one would expect only intense conflagrations with areal distributions unrelated to previous fire history.

Evidence from Baja California supports the view that without fire control, biomass burning would prevail in temperate weather: (1) fires there coincide with wind circulations associated with slope winds and penetration of the coastal marine layer; (2) fires seldom burn young stands (Minnich 1989); and (3) aerial photographs reveal burns with a braided configuration with countless islands of unburned cover. In the Sierra San Pedro Mártir, 150 km southeast of Ensenada, as much as 10 to 30% of chaparral within fire perimeters are unburned (Minnich and Dezzani 1991). Furthermore, Mexican forestry personnel have indicated that fires sometimes persist for weeks or months, alternately smoldering in large fuels in temperate weather, and expanding through brush during afternoons in dry weather. A fine-scale stand mosaic is created, even with fire intervals of 70 years, because slow fire movement under model weather conditions is often diminished or terminated at surrounding burns, even in stands as old as 20-40 years.

If extensive, long-duration creeping fires are possible without fire control, then the almost exclusive coincidence of large fires with extreme weather in southern California may be a result of suppression management. The ability for fire fighting agencies to stop fires is variously effective depending upon fire magnitudes. Intense fires are harder to fight than "cool" ones because higher fire line temperatures make burning fuels less approachable. High intensity conflagrations in extreme weather may thus arise from the selective elimination of countless small fires in normal weather. Such conflagrations typically denude extensive tracts of brush in a few days and consume >95% of stands inside perimeters. Landscape-scale patch size can be increased without changes in fire intervals because conflagrations in extreme weather consume both old-growth brush, as well as abnormally young stands (Dunn 1988).

Conclusions

The spatial and temporal aspects of the fire regime in the Californian chaparral show strong evidence of time-dependence and self-regulation. That prospective fires are influenced by the preexisting spatial structure of chaparral makes this ecosystem ideal for the establishment of a broad-scale planned burning management system because spatial variation in stand structure can limit fire movement, i.e, patch structure is an insurance policy to plan location and size of future burns. Moreover, the existence of a fine-grained mosaic under long fire intervals in Baja California is evidence that a planned burn mosaic can be managed under long fire intervals (at reduced cost), rather than at short intervals as deduced from ignition/allogenic fire regime models (e.g, Bonnickson 1980, 1981). Extensive-scale planned burning will help reduce uncontrolled fires in extreme weather, improving chances for fire management agencies to protect property and resources.

Literature Cited

Albini, F.A. 1976a. Estimating wildfire behavior and effects. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-30. 92 p.

Albini, F.A. 1976b. Computer based models of wildland fire behavior: a user's manual. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-30. 68 p.

Alvarez M. and J. Maisterrena. 1977. Climatological and meteorological characteristics of the Observatorio Astronomico Nacional at San Pedro Martir, B.C. Revista Mexicana de Astronomía y Astrofisica 2:43-52.

Baker, W.L. and T.T. Veblen. 1990. Spruce beetles and fires in the 19th century subalpine forest of western Colorado. Arctic and Alpine Research 22:65-80.

Barro, S.C. and S.G. Conard. 1991. Fire effects on California chaparral systems: an overview. Environment International 17:135-149.

Biswell, H.H., 1974. Effects of fire on chaparral, pp. 321-364. In T.T. Kozlowski and C.E. Ahlgren (eds), Fire and ecosystems. Academic Press, New York. 542 p.

Bonnicksen, T.M. 1980. Computer simulation of the cumulative effects of brushland fire management policies. Environmental Management 4:35-47.

Bonnicksen, T.M. 1981. Brushland fire-management policies: a cross-impact simulation of southern California. Environmental Management 5:521-529.

Byrne, R., H. Michaelson, and A. Soutar. 1977. Fossil charcoal as a measure of wildfire frequency in southern California. A preliminary analysis, pp 361-367. In H.A. Mooney and C.E. Conrad (eds), Proceedings of the symposium on environmental consequences of fire and fuel management in Mediterranean ecosystems. USDA Forest Service, General Technical Report WO-3.

Christensen, N.L. 1985. Shrubland fire regimes and their evolutionary consequences, pp. 85-100. In S.T.A. Pickett and P.S. White (eds), The ecology of natural disturbance. Academic Press, New York.

Christensen, N.L. 1993. Fire regimes and ecosystem dynamics, pp.233-244. In P.J. Crutzen and J.G. Goldammer (eds), Fire in the environment: the ecological, atmospheric, and climatic importance of vegetation fires. John Wiley & Sons, New York.

Countryman, C. M. 1964. Mass fires and fire behavior. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Research Paper PSW-19.

Countryman, C.M. and C.M. Philpot. 1970. Physical charactertistics of chamise as a wildland fuel. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Research Paper PSW-66.

Dodge, M. 1972. Forest fuel accumulation — a growing problem. Science 177:139-142.

Dunn, A. T. 1988. The effects of prescribed burning on fire hazard in the chaparral: Toward a new conceptual synthesis, pp. 23-29. In N.H. Berg (ed), Proceedings of the symposium on fire and watershed management. USDA Forest Service, Pacific Southwest Forest and Range and Experiment Station, General Technical Report PSW-109.

Edinger, J.G. 1959. Changes in the depth of the marine layer over the Los Angeles Basin. Journal of Meteorology 16:219-226.

Forman, R.T.T. and M. Godron. 1986. Landscape ecology. John Wiley & Sons, New York.

Hanes, T.L. 1971. Succession after fire in the chaparral of southern California. Ecological Monographs 41:27-52.

Hanes, T.L. 1981. California chaparral, pp. 139-174. In F. diCastri, D.W. Goodall, and R.W. Specht (eds), Mediterranean scrublands, Vol. 2. Ecosystems of the world. Elsevier Scientific, New York.

Hanes, T.L. 1988. Chaparral, pp. 417-469. In M.G. Barbour and J. Major (eds), Terrestrial vegetation of California (Second edition). California Native Plant Society, Sacramento.

Heinselman, M.L. 1981a. Fire and succession in the conifer forests of northern North America, pp. 374-405. In D.C. West, H.H. Shugart, and D.B. Botkin (eds), Forest succession: concepts and application. Springer-Verlag, New York.

Heinselman, M.L. 1981b. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems, pp. 7-57. In H.A. Mooney, T.M. Bonnicksen, N.L. Christiansen, J.E. Lotan, and W.A. Reiners (eds), Proceedings of the conference on fire regimes and ecosystem properties. USDA Forest Service, General Technical Report WO-26.

Henderson, D.A. 1964. Agriculture and stock raising in Baja California. Ph.D. dissertation, University of California, Los Angeles.

Keeley, J.E. 1982. The distribution of lightning and man-caused wildfires in California, pp. 431-437. In C.E. Conrad and W.E. Oechel (eds), Proceedings of the symposium on dynamics and management of Mediterranean-type ecosystems. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW-58.

Keeley, J.E. and S.C. Keeley. 1989. Chaparral, pp. 166-207. In M.G. Barbour and W.D. Billings (eds), North American terrestrial vegetation. Cambridge University Press, Cambridge, U.K.

Keeley, J.E. and Zedler, P.H. 1978. Reproduction of chaparral shrubs after fire: a comparison of sprouting and seeding shrubs. American Midland Naturalist 99:142-161.

Keeley, J.E., P.H. Zedler, C.A. Zammit, and T.J. Stohlgren. 1989. Fire and demography, pp. 151-153. In S.C. Keeley (ed), The California chaparral: paradigms reexamined. Natural History Museum of Los Angeles County, Los Angeles, Science Series no. 34.

Loucks, O.L. 1970. Evolution of diversity, efficiency, and community stability. American Zoologist 10:17-25.

McCutchan, M. H. and M. J. Schroeder. 1973. Classification of meteorological patterns in southern California by discriminant analysis. Journal of Applied Meteorology 12:571-577.

Minnich, R.A. 1983. Fire mosaics in southern California and northern Baja California. Science 219:1287-1294.

Minnich, R.A. 1987. Fire behavior in southern California chaparral before fire control: the Mount Wilson burns at the turn of the century. Annals of the Association of American Geographers 77:599-618.

Minnich, R.A. 1989. Chaparral fire history in San Diego County and adjacent northern Baja California: an evaluation of natural fire regimes and the effects of suppression management, pp. 37-47. In S.C. Keeley (ed), The California chaparral: paradigms reexamined. Natural History Museum of Los Angeles County, Los Angeles, Science Series No. 34.

Minnich, R.A. and Dezzani, R.J. 1991. Suppression, fire behavior and fire magnitudes in Californian chaparral at the urban/wildland interface, pp.67-83. In J.J. DeVries and S.G. Conard (eds), California watershed at the urban interface: proceedings of the third biennial watershed conference. University of California, Davis, Water Resources Center, Report No. 75.

Minnich, R.A., Franco-Vizcaíno, E., Sosa-Ramírez, J., and Chou, Y.H. 1993. Lightning detection rates and wildland fire in the mountains of northern Baja California, Mexico. Atmosfera 6:235-253.

Payson, T. E. and J.D. Cohen. 1990. Chamise chaparral dead fuel fraction is not reliably predicted by age. Western Journal of Forestry 5:127-131.

Philpot, C. W. 1977. Vegetative features and determinants of fire frequency and intensity, pp. 12-17. In H.A. Mooney and C.E. Conrad (eds), Symposium on the environmental consequences of fire and fuel management in Mediterranean ecosystems. USDA Forest Service, General Technical Report WO-3.

Reyes Coca, S., F. Miranda Reyes, and J. García López. 1990. Climtología de la región noroeste de México (Baja California, Baja California Sur, Sonora y Sinaloa). Parte I.- Precipitación: Series de tiempo del valor total mensual y estadísticas del año climatológógico. Grupo de Meteorología, Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE). Comisión Nacional del Agua (CNA). Reporte Técnico CIOFIT9001. Ensenada, Baja California, Mexico.

Rundel, P.W. 1983. Impact of fire on nutrient cycles in Mediterranean-type ecosystems with reference to chaparral, pp. 192-207. In F.J. Kruger, D.T. Mitchell, and J. Jarvis (eds), Mediterranean-type ecosystems: the role of nutrients. Springer-Verlag, New York.

Riggan, P.J., S. Goode, P.M. Jacks, and R.N. Lockwood, 1988. Interaction of fire and community development in chaparral of southern California. Ecological Monographs 58:155-176.

Rowe, H.S. 1979. Large fires in the large landscapes of the north, pp.8-32. In Proceedings: symposium on fire management in the northern environment. USDI, Bureau of Land Management, Alaska State Office.

Ryan, B.C. 1983. Fire potential in California: an atlas for fire managers. In Proceedings, eighth conference on probability and statistics in atmospheric sciences. American Meteorological Society, Boston, Massachusetts.

Schroeder, M.J., M. Glovinaky, and V. Hendricks. 1964. Synoptic weather types associated with critical fire weather. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station. Contract OCD-05-62-143. 492 p.

Swetnam, T.W. and J.L. Betancourt. 1991. Fire-southern oscillation relations in the southwestern United States. Science 249:1017-1020.

Wright, H.E. and A.W. Bailey. 1982. Fire ecology, United States and Canada. John Wiley & Sons, New York.

Zedler, P.H. 1977. Life history attributes of plants and the fire cycle: a case study in California chaparral dominated by *Cupressus forbesii*., pp. 451-458. In H.A. Mooney and C.E. Conrad (eds), Environmental consequences of fire and fuel management in Mediterranean ecosystems. USDA Forest Service, General Technical Report WO-3.