21. Sensitivity of Fire Regime in Chaparral Ecosystems to Climate Change

Frank W. Davis and Joel Michaelsen

The fire regime of an area is characterized by the type, intensity, size, return interval, and spatial pattern of fires that have occurred there over recent history. Fire regime is an emergent property of landscapes, expressing the interaction of climate, vegetation, topography, and land management. Thus the potential impact of climatic change on chaparral fire regime must be analyzed within a specific regional context. Ideally, the analysis should also account for the spatial arrangement of topography, vegetation types, ignition sources, and land cover types that serve as fire breaks, because fire regime and fire hazard may vary widely under the same climate, depending on how fire spread is regulated by these and other geographic factors.

In this chapter we analyze recent fire history and climate data from central coastal California in order to better understand the relationship between wildfire and climate in this region. We then employ a spatially explicit fire regime simulation model to study the sensitivity of one particular landscape in central coastal California to possible changes in seasonal temperature and precipitation associated with a doubling of atmospheric CO_2.

Several studies have analyzed potential impacts of global climate change on fire regime in Mediterranean ecosystems. Malanson and Westman (1991), and Westman and Malanson (1992), simulated growth of five dominant shrubs of the Venturan coastal sage scrub association under changing moisture gradients, fuel loads, and associated fire intensity (measured as total energy released). They also modeled interactions between climate change and air pollution effects. General circulation model (GCM) predictions of increased rainfall over southern California produced increased fuel loads and fire intensity. The higher fire intensity resulted in significant changes in community composition because it favored shrubs regenerating by seed over those regenerating primarily by resprouting. Taken together, ozone stress, increased rainfall, and increased fire intensity led to the elimination of all species under short fire return interval (10 years), and to significant changes in composition under 20- and 30-year fire return intervals.

Torn and Fried (1992) simulated the effect of global climate change on wildfire hazard in northern California by applying a mathematical model of fire intensity and spread to historical and predicted daily weather data. Model outputs were coupled to a fire-fighting module that predicted the kinds and cost of fire suppression activities that would be required to control the burns under different fuel conditions and population densities. Use of daily weather data rather than monthly or seasonal averages allowed them to capture the extreme meteorological conditions of high winds and low humidities under which most burning occurred in that area. Although results varied considerably among different GCM scenarios and fuel types, fire danger (potential rate of spread) was generally predicted to increase under a $2CO_2$ climate due to increased wind speeds and decreased relative humidities. The increase in spread rate, intensity, and area burned was large for grassland fuels, small for short and tall brush fuels, and negligible for redwood fuels.

We have studied the sensitivity of chaparral ecosystems in southern California to global climate change using REFIRES (Burrows, 1988; Davis and Burrows, 1993), a spatial simulation model that is designed to analyze the relationships between fire history and vegetation pattern in heterogeneous landscapes. Like the FINICS model used by Westman and Malanson (1992), REFIRES tracks fuel development and fire intensity over many fire cycles. Unlike FINICS, REFIRES lacks an autecological framework linking fire intensity to community composition. REFIRES is similar to the CCFMS model of Torn and Fried (1992) in that fire ignition and spread conditions are calculated from daily meteorological data using mathematical models of fire behavior. REFIRES has the added feature that fire behavior depends on the spatial distribution of fuels over the landscape, which are themselves a function of fire history. We believe that this is especially useful in understanding the consequences of climate change on fire-prone ecosystems over more than a single fire cycle.

Like the previous modeling efforts cited above, ours builds from the Rothermel fire model. This model has many limitations for predicting chaparral fire behavior. The assumption of a uniformly arranged fuel bed is rarely met in the field. The model predicts little to no spread in fuel beds consisting of only live vegetation, when in fact fire will burn through such fuels under high winds (P. Riggan, personal communication). Perhaps most importantly, the model was not formulated to predict fire spread for large fires burning under conditions of high winds and extreme atmospheric turbulence that characterize the modern chaparral fire regime.

Recognizing these limitations, not to mention the uncertainty associated with projecting future climate under increasing atmospheric CO_2 (see below), we have designed our modeling experiment to test how sensitive the fire regime in a heterogeneous California landscape could be to climatic change. Accordingly, we have parameterized REFIRES to span a reasonable range of future climate and fuel conditions. We will show that both actual and simulated fire histories are very sensitive to climatic variation, but that they are sensitive for somewhat different reasons. By combining empirical and theoretical analyses, we hope to demonstrate the potentially large consequences of global climate change on fire regime in chaparral ecosystems, but also to highlight some major sources of uncertainty currently limiting our predictive capabilities.

Existing Fire Regime

We analyzed fire history and climate data from the Los Padres National Forest (LPNF), California (Figure 21-1). The LPNF consists of 709,725 ha of the central Coast Ranges and the Transverse Ranges, stretching from Monterey (36.5°N, 122°W) to Castaic (34.5°N, 118.5°W). It is divided into two segments, the main division and the Monterey division. The terrain is rugged and largely inaccessible or accessible only via unpaved service roads. Elevations range from near sea level to over 1,750 m, with most LPNF lands situated between 200 and 1,200 m. Annual precipitation in the main division ranges from 250 mm to 1,000 mm or more at higher elevations, with 95% falling between November and March. The Monterey division is slightly wetter, receiving 500–1,500 cm of annual rainfall. Roughly 68% of the LPNF is shrublands, predominantly chaparral, but with coastal sage scrub on more xeric sites. Wildfires have been actively suppressed in LPNF since the early 1900s (Minnich, 1983), even in designated Wilderness Areas. However, suppression efforts became much more effective after 1950, when large air tankers were first employed routinely (Fritts Cahill, personal communication).

Fire history data were compiled by Fritts Cahill of the Los Padres National Forest from field notes, maps, and air photos. His fire history maps and database cover the period 1911–1992 and provide information on fire location and perimeter, ignition source, date of ignition, and area burned inside and outside the LPNF.

Based on LPNF fire history data, the modern fire regime of the LPNF can be summarized as follows:

Figure 21-1. Location map of the Los Padres National Forest.

Most Fires Are Started by Humans

Since 1950, 62 of 70 (89%) large (>400 ha) fires that occurred in LPNF were human ignited. Lightning is not as frequent here as in other chaparral regions in California (Keeley, 1982), but lightning ignition is still significant. Of the total burned area, 24.5% was burned in lightning fires, and the largest burn during the period was a 72,010 ha lightning event in 1977 in the Monterey division.

The comparison of ignitions from humans versus lightning is not straightforward, because the two differ systematically in their location and weather conditions. Human ignitions are concentrated along roads and campgrounds, and are often timed by arsonists to coincide with extreme weather conditions, whereas lightning ignitions cluster on peaks and along ridges and usually accompany milder weather in which wildfire is more easily contained. In any case, unless climate change includes a very large increase in lightning events in the region, the ignition regime is likely to remain dominated by humans.

Most Burning Occurs in Infrequent, Large Wildfires

Based on fossil charcoal records, the prehistoric fire regime of this region was characterized by relatively long fire return intervals of 60–100 years. Although fire size cannot be reconstructed with certainty from the

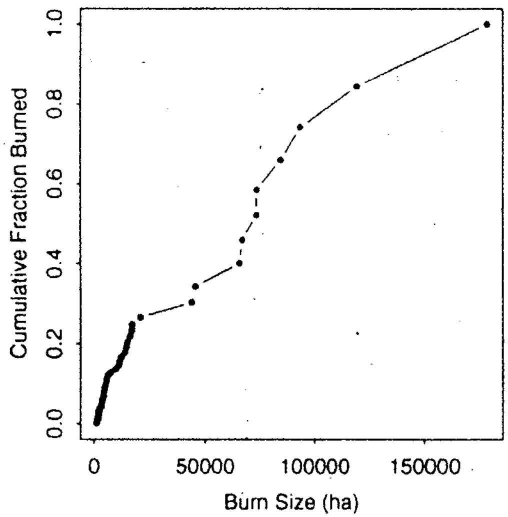

Figure 21-2. Cumulative fraction of total area burned in the Los Padres National Forest between 1950 and 1990 as a function of fire size, for burns greater than 400 hectares (unpublished data from F. Cahill, Los Padres National Forest).

charcoal records, very large fires were apparently not uncommon (Byrne et al., 1977).

Minnich (1983, 1989) asserts that in southern California fire suppression has reduced fire frequency, but that this has led to increased fire size. Certainly, low fire frequency allows older chaparral stands to develop extensive, high-mass fuels. An estimated 48% of chaparral in the Los Padres is greater than 50 years old, while only 24% is younger than 10 years. Between 1950 and 1991, fires in or adjacent to the LPNF consumed 465,898 ha. Of this area, 95% was in chaparral, and 96.7% of the total area burned in events exceeding 400 ha (1,000 acres). Perhaps more significantly, six burns accounted for nearly half of the total burned area during the period (Figure 21-2).

Nearly All Significant Fires Occur Between June and October During Extreme Summer Heat Waves and/or Under Strong Santa Ana Conditions

Large burns were nearly always initiated during extreme summer heat waves or during warm, very windy Santa Ana conditions that are most frequent between September and December. A similar relationship of weather to burning pattern occurs in other chaparral landscapes to the south (e.g., Radtke et al., 1977; Minnich, 1989). Under these extreme conditions, the probability of fuel ignition and the rate of fire spread both increase dramatically, defying efforts at fire suppression. The extreme

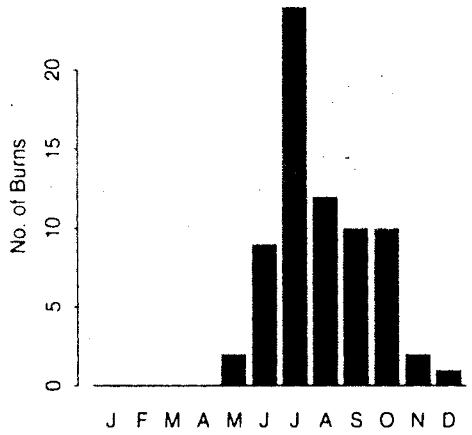

Figure 21-3. Monthly totals for area burned in the Los Padres National Forest, 1950–1991.

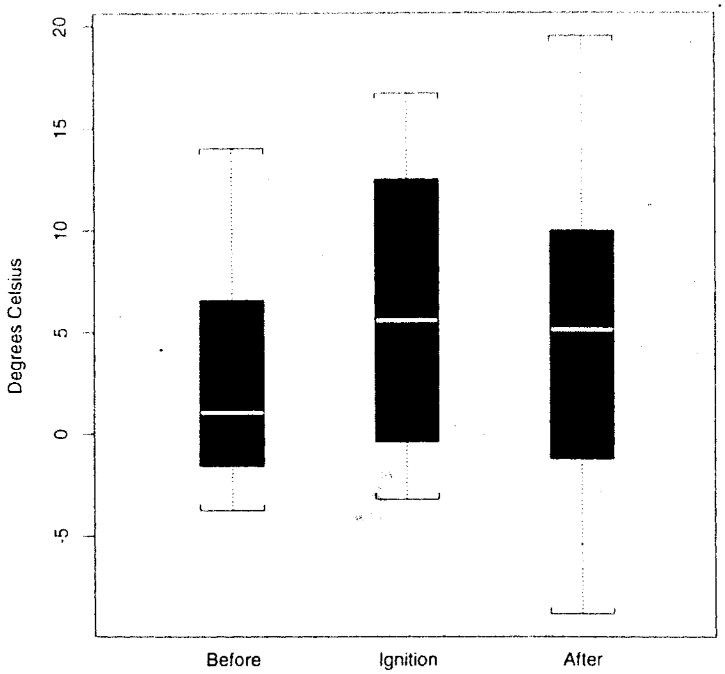

Figure 21-4. Boxplots summarizing the statistical distribution of daily maximum temperatures recorded at Santa Barbara, California on days when large (>400 ha) fires ignited in the Los Padres National Forest versus the previous or following days. Boxplots show the median, quartiles, and range of the data.

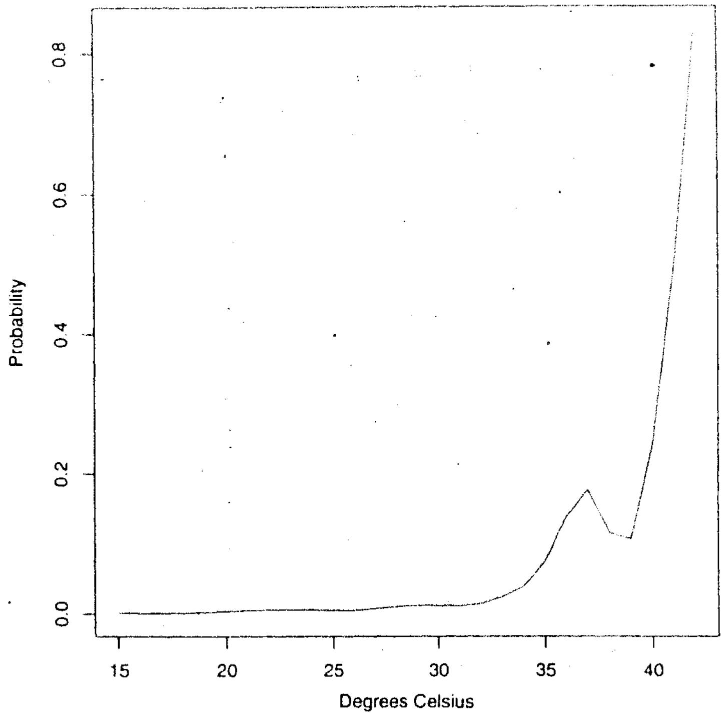

Figure 21-5. Probability of a large fire in the Los Padres National Forest as a function of daily maximum temperature at Santa Barbara, California.

conditions do not have to persist for the duration of a fire event, only long enough for the fire to grow too large for suppression forces to contain, at which point the fire may spread at lower rates under more moderate weather conditions (P. Riggan, personal communication).

Practically all large wildfires occurred between June and October (Figure 21-3). These events show a strong relationship to daily temperature data from the Santa Barbara airport, which, despite its coastal location, is strongly correlated with more interior localities during Santa Ana conditions when warm, dry air flows predominantly from the northeast. In the LPNF, 45 of 70 (64%) of large fires occurred during unusually warm periods (daily maximum temperatures at the airport greater than 30°C). Thirty-two of 70 (46%) occurred during Santa Anna conditions. Temperatures on the days when fires ignited were generally 3–5°C warmer than the monthly mean, and these conditions developed very suddenly (Figure 21-4). The frequency of such days is not correlated with average temperatures during the fire season. The probability of a large wildfire occurring somewhere in the main division of LPNF is close to zero on days in which maximum daily temperatures recorded at Santa Barbara are less than 25°C, and increases dramatically with increasing temperature for days exceeding 30°C (Figure 21-5).

Large Fires Are Much More Likely to Occur in Years with Very Low Spring Precipitation

Literature on chaparral combustibility has tended to focus on chamise (*Adenostoma fasciculatum*), which is readily ignited and can propagate fire under more moderate weather conditions than most chaparral species because of its relatively high proportion of fine twigs, high fuel surface-to-volume ratios, large dead fuel fraction, low live fuel moisture content, and large fraction of volatile chemicals in the foliage (e.g., Muller et al., 1968; Rothermel and Philpot, 1973; Hanes, 1971). However, many chaparral dominants of the central coast, including *Ceanothus megacarpus*, *C. spinosus*, *Quercus berberidifolia*, and *Arctostaphylos* spp., are coarser fuels with a low dead fuel fraction and lower potential velocities of combustion, and thus are much less likely to ignite and carry a fire than chamise under normal conditions (e.g., Riggan et al., 1988). Under dry, windy conditions, however, the same species yield very intense burns (Riggan et al., 1988). This relationship may explain in part the extreme sensitivity of wildfire hazard in the region to late winter and spring rainfall (Figure 21-6). Between 1915 and 1991, spring (March–May) rainfall at Santa Barbara averaged 114.8 mm, only 26% of the annual total. However, 82% of total burned area was contributed by years when spring rainfall was below 100 mm (52% of years), and 48% of the total burned following spring rain of less than 50 mm (21% of years). The correlation(r) between spring and total precipitation is only 0.62.

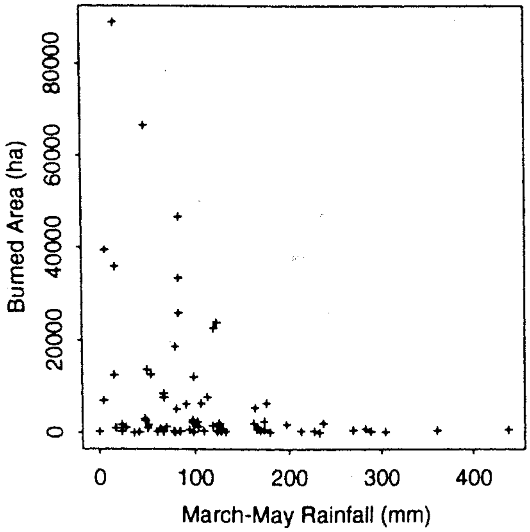

Figure 21-6. Total area burned in the southern division of the Los Padres National Forest as a function of total spring precipitation.

The Fire Interval Is Generally Much Longer Than the Time Required for Recovery of the Shrub Canopy

A rough estimate of fire recurrence interval may be obtained by dividing the total chaparral area of LPNF by the average hectares burned. Based on an estimated chaparral area of 482,607 ha and the assumption that 85% of the total area burned each year is chaparral, the fire recurrence interval for the period 1915–1991 is 58 years, and is 66 years for the period 1950–1991. For the Monterey Division, the return intervals are 55 and 42 years for the total record and modern period, respectively. While admittedly crude, the estimated recurrence interval is three to four times longer than the time required for reestablishment of a closed chaparral canopy. Whether fire can ignite and spread through the canopy is a complex function of dead fuel amount and size distribution, canopy structure and chemistry, and weather conditions. However, it appears that wildfire is generally not fuel limited at present, but is determined instead by the interaction between weather conditions and the effectiveness of suppression efforts.

Modeling the Sensitivity of Chaparral Fire Regime to Climatic Change

Modeling Fire Regime Using REFIRES

The REFIRES model was written by Burrows (1988), who provides a detailed description of the model as well as the source code. A summary of the model's formulation can also be found in Davis and Burrows (1993).

REFIRES operates on a spatial database of hexagonal cells, using maps of topography and potential vegetation together with daily weather and fuel moisture data from the fire season. The model simulates fuel development, fire start, and fire spread for multiple fire events over many fire seasons to develop a simulated fire history. Each fire event involves a possible ignition, an actual ignition, and fire spread. The number of possible ignitions per year is modeled as a Poisson process with the mean number per year set by the user. A possible ignition occurs when an ignition source is randomly placed in the region under weather conditions sampled from the daily weather records. An actual ignition can occur at that location depending probabilistically on weather and fuel conditions (Bradshaw et al., 1983). If actual ignition occurs, fire spread is simulated using the fire spread equations of Rothermel (1972) and Albini (1976) based on local conditions of topography, stand age, and meteorological conditions. One weather day is used per event, but temperature and humidity conditions alternate between daytime and nighttime values for that day to simulate fires that burn over one or more diurnal cycles.

The user defines a rate of spread below which fires are no longer assumed to spread. If the calculated rate of spread is less than this threshold, fires spread with probability equal to the calculated spread rate divided by the threshold spread rate. This threshold can be set low to simulate fire spread in unsuppressed conditions or set high to simulate fire spread under active suppression.

If fire spreads through the cell, the cell's age is set to zero and the fire then continues to spread to neighboring cells with probabilities and rates calculated on a cell-by-cell basis as determined by local fuel conditions, topography, and wind. Based on calculated fire spread rates and distances, the program keeps track of the time elapsed between ignition and when the burn reaches a cell. Daily maximum temperatures and minimum humidities are applied to cells that burn during daylight hours, and minimum temperatures and humidities are applied during nighttime hours. Wind speed and velocity are kept constant over each period.

Fires spread only by contagious diffusion, and not by spotting. Fires cease to spread when they reach the edge of the grid or encounter conditions for which the predicted spread rate falls below the threshold spread rate and spread is stopped probabilistically. Fuel recovery in burned cells is a function of the age and the potential vegetation of the cell and is independent of fire intensity.

After the model is run for a specified number of years, the model outputs fire regime statistics and fire history maps. Statistics include average ignitions per year, number of possible ignitions, number of actual ignitions, number of fires (by cell), fire size distribution, stand age frequency distribution, patch size distribution, and fire recurrence interval distribution.

In previous applications, the model was applied to test the relationships among fire size and recurrence interval, ignition frequency, and vegetation fragmentation for a small area of chamise and mixed chaparral near Lompoc, California. Climate is Mediterranean with a strong maritime influence and prevailing northwesterly winds. The topography is gently rolling uplands interrupted by wide stream valleys with short, steep slopes. Modeling was conducted here as part of longer-term studies on the fire history and ecology of the region (Davis et al., 1988). We operated REFIRES over a 1,865-ha region represented by 20,720 0.09-ha cells. Although relatively small compared to the extensive chaparral areas of the nearby LPNF, this test area is uniform in climate and physiography and is still large enough to study the interactions among ignition frequency, weather, and landscape heterogeneity.

For the present study, we used the same 1,865-ha study region, but modeled it as continuous chamise or mixed chaparral, unbroken by roads or development. Thus stand age and topography were the only sources of spatial variation. Topography was modeled using 30-m digital elevation data from the U.S. Geological Survey. Daily temperature and humidity data from nearby Santa Maria, California for the period 1975–1985 were obtained from the National Oceanic and Atmospheric Administration. A frequency distribution of hourly wind speed and direction was based on 12 years of data from Vandenberg Air Force Base, as summarized by Ogden (1975). Green fuel moisture readings for the period 1977–1990 were obtained from the Los Padres National Forest (Fritts Cahill, unpublished data).

Based on previous experience with the model, the frequency of possible ignitions was fixed at 1.0/yr. To simulate the effect of fire suppression, the threshold rate of spread was set at a relatively high level of 5 m/min. This threshold provides a reasonable approximation to the modern fire regime, based on model runs using a range of values from 1 to 10 m/min.

Modeling Future Climates

Available GCM climate scenarios for California under doubled atmospheric CO_2 provide a very weak basis for projecting future chaparral fire regimes, for several reasons. In general, there is a severe mismatch in spatial scales that makes any regional climate scenarios highly suspect. For example, the Goddard Institute for Space Science (GISS) GCM cell encompassing the study area is roughly equal proportions of ocean and land, and extends from northern Baja California to Sacramento, enclosing a wide range of climates. Very different energy budgets for ocean and land surfaces are a major driving force in current regional climates, particularly during the summer fire season. There is no straightforward way to infer this subgrid scale information from coarse resolution GCM outputs..

Looking more specifically at simulating changing fire regimes, it is apparent that GCMs are not particularly good at modeling the most important factors. Based on the relationships between climate and the existing fire regime discussed above; changes in spring precipitation and frequency of Santa Ana conditions during late summer and fall are the most important variables for predicting future fire regimes. The hydrologic cycles in GCMs are quite crude, and, as a result, they generally do a poor job of modeling soil moisture and precipitation (e.g., Dickinson, 1989; Milly, 1992). Perhaps most importantly, the wind conditions associated with Santa Anas are not likely to be modeled at all well. First, GCMs do not model surface wind patterns with enough accuracy and resolution to relate to local and regional fire hazard (Torn and Fried, 1992). (Consider that there is only a single roughness parameter for the entire GCM cell over California.) Second, the particular wind conditions that dominate the modern fire regime are short-term meteorological extremes that are not strongly related to monthly or seasonal climate variations over larger scales, i.e., the variables which GCMs do predict with some skill.

With these caveats in mind, it is possible to make some statements about the most likely changes in the aspects of climate important for the fire regime of central coastal California. It is unlikely that fire season temperatures will decrease. A temperature increase is reasonably likely, but the magnitude is quite uncertain, with a range of 1° to 4°C spanning the predictions for fire season months from the NASA Goddard Institute for Space Science (GISS), Princeton Geophysical Fluid Dynamics Laboratory (GFDL), and United Kingdom Meteorological Organization (UKMO) models. These increases were added to the daily maximum and minimum temperatures used as input to REFIRES. We adjusted the associated relative humidities to the new temperatures based on a linear regression of humidity versus temperature from local station data ($r^2 = 0.53$). As mentioned above, there is no relationship between average summer temperatures and the frequency of extreme Santa Ana conditions. Thus, we did not change the frequency of temperature outliers in our modeling.

As noted above, changes in precipitation are even more uncertain, but the various GCM results are in general agreement, showing that winter and spring precipitation will increase. For example, applying the GISS predictions to local station data yields a 36% increase in precipitation for the months of November through March, and a 59% increase in precipitation for the total in March and April. The GFDL model predicts a 21% increase in rainfall between November and March, and a 17% increase in the March/April total. The UKMO model predicts increases of 21% and 27%, respectively. These results are not sufficiently certain to rule out precipitation decreases, but we have chosen to assume that it will either remain constant or increase. Any decrease in precipitation will presumably exacerbate changes in fire regime that result from an increase in temperature. For the purposes of this sensitivity analysis, we considered an increase of 30% in spring precipitation, with an associated 5.25% increase in live fuel moisture during the fire season (based on regression of fuel moisture levels versus spring precipitation at Santa Barbara, Figure 21-7).

To study the sensitivity of fire regime to changes in vegetation structure and composition, two different fuel models were used to represent stand level fuel properties as a function of time since fire. The first model, which will be referred to as the Low Biomass model, is based on equations for chamise (*Adenostoma fasciculatum*) chaparral from Rothermel and Philpot (1973) (Figure 21-8a). The High Biomass model describes mixed chaparral, such as might occur on more mesic sites, with roughly twice the biomass of the chamise model (Figure 21-8b).

Both fuel models were run under present conditions and under higher fire season temperatures, with and without increased spring precipitation, to study the interactions among climate factors and site productivity in affecting fire regime. We should note that both fuel models predict a large increase in dead fuel fraction with increasing age. Recent studies

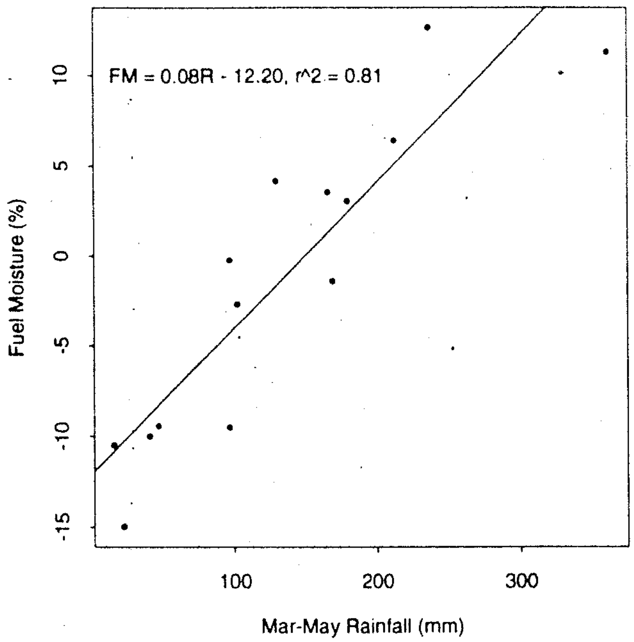

Figure 21-7. Fire season fuel moisture (chamise) for a station near Santa Barbara as a function of spring precipitation at the Santa Barbara airport, 1977–1990. Fuel moisture is expressed as the average departure from monthly means for June–October.

suggest that the actual amount of dead fuel is highly variable among chamise stands (Paysen and Cohen, 1990) and is also generally lower for other chaparral species (Riggan et al., 1988). Thus, the fuel models used here suggest a stronger relationship between age and combustibility than is actually observed under field conditions, and also depict fuels with higher combustibility than observed under many field conditions.

In summary, we have modeled fire regime under the following climate change scenarios:

1. Increased fire season temperatures and associated lower relative humidities, with no change in winds or live fuel moisture status (1° and 4°C increases);
2. 1° or 4°C increases in fire season temperatures, accompanied by a 5.25% increase in live fuel moisture during the fire season;
3. Changes in chaparral productivity under present climate conditions and under scenarios 1 and 2 above.

We have not included GCM predictions of changes in surface wind speed because of the modeling uncertainties mentioned above. Instead, modeling has been conducted using probability distributions for wind speed and

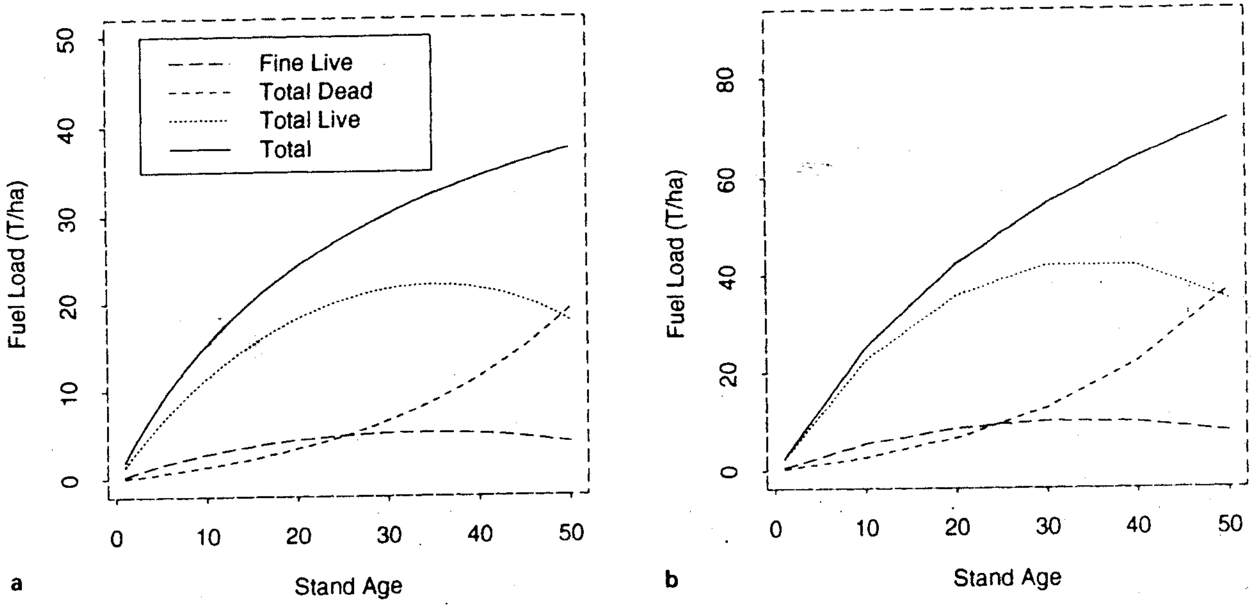

Figure 21-8. Fuel recovery models used in (a) the Low Biomass fire regime simulations, and (b) the High Biomass fire regime simulations.

direction derived from daily local station data. In summary, the model has been run under 10 different scenarios. Model runs of 1,000 years were run 15 times for each combination of climate conditions and fuel model.

Model Results

The modeled fire regime based on current climate data is similar to the actual regime in having many ignitions (229/1,000 years), but in being dominated by relatively infrequent, large burns. The average recurrence interval for the Low Biomass case was 66 years, and the largest 8% of the burns accounted for 50% of total burned acreage. For the High Biomass model, the recurrence interval was significantly shorter (48 years). Once again, the largest 8.3% of burns accounted for half of the total burned area.

The number of possible ignitions was relatively constant among model runs (due to constant frequency of possible ignition), but the ratio of actual ignitions to possible ignition, which depends largely on the amount and moisture content of fine dead fuels, was very sensitive to increased fire season temperatures (Figure 21-9). Compared to the value for current

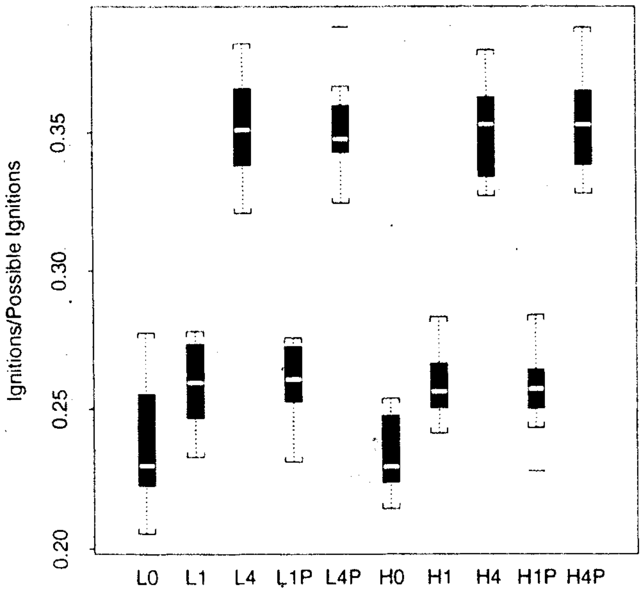

Figure 21-9. Boxplots of the ratio of actual to possible ignitions for 10 different fuel/climate scenarios based on Low (L) or High (H) biomass fuel models, current fire season temperatures (0), or increases of 1° or 4°C, and with current or 30% increase (P) in spring precipitation. For example, L1P is the low-biomass fuel model using climate data with a 1°C temperature increase and increased precipitation. Boxplots show the median, quartiles, and range of 15 1,000-year runs for each scenario.

Table 21-1. Statistical Summary of Relative Changes (%) in Simulated Fire Regime Under Various Future Climate Scenarios Relative to Current Climate Using the Low Biomass Model (L0)

	L0	L1	L4	L1P	L4P	H0	H1	H4	H1P	H4P
Actual/possible ignitions	0	9	49	10	49	−1	10	48	9	51
Fires/ignitions	0	−2	−5	−2	−4	−12	−12	−17	−14	−17
Fires/1,000 yrs	0	7	41	10	42	−11	−2	24	−6	27
Burned cells/ 1,000 yrs	0	9	31	0	19	36	42	58	29	51
Recurrence interval (yrs)	66	61	51	66	55	48	47	42	51	44

The mean fire recurrence interval (yrs) is also shown. Modeled conditions include Low (L) or High (H) biomass, current climate (0), 1° or 4°C increase in mean fire season temperatures with associated lower humidities (1 or 4), and a 30% increase in spring precipitation (P). Percentages are the means of 15 1,000-year model runs.

climate data using the Low Biomass model, this ratio increased by 9% and 49% for 1° and 4°C increases, respectively (Table 21-1). The ratio is not related to the fuel model, nor to increased live fuel moisture levels associated with increased spring precipitation.

For an ignition to evolve into a fire requires a combination of fuel, topography, and weather conditions sufficient to generate relatively high rates of spread. The number of fires per ignition actually decreases with increasing temperatures and increasing site productivity, less so with increasing precipitation (Figure 21-10, Table 21-1). This may seem contrary to the result that both the number of fires and the total area burned increase with increasing temperature (Figures 21-11 and 21-12). However, the decreasing fire recurrence interval under warmer or more productive conditions leads to a decrease in overall landscape combustibility. Thus, although ignitions increase, a smaller fraction of them actually occur on sites with sufficient fuels to promote a fire. This effect is most pronounced for the High Biomass model under a 4°C temperature increase, where the recurrence interval is only 42 years compared to 66 years for the Low Biomass model under present climate, and where fires/ignition decreases by 17% while the area burned increases by 42%.

Fire frequency is equally sensitive and total area burned is more sensitive to increased temperatures for Low Biomass versus High Biomass fuel models. For the less productive chaparral, fire frequency increases by 7% and 41% for 1°C and 4°C temperature increases, compared to 9% and 40% for the more productive case (Figure 21-11). However, total area burned using the Low Biomass model increases by 9% and 31% for 1° and 4°C increases, compared to only 4% and 16% for the High Biomass model (Figure 21-12). This is because increased temperatures have a larger proportional effect on spread rates through low fuel loads than

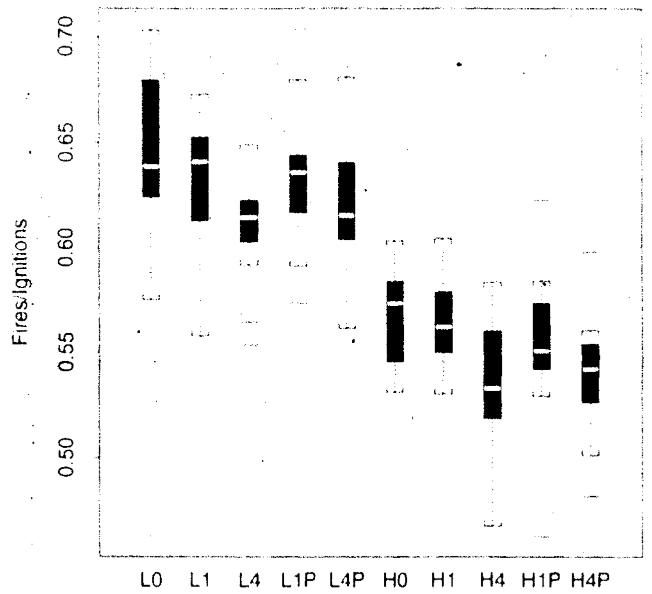

Figure 21-10. Boxplots of the ratio of fires to actual ignitions for the different fuel/climate scenarios. See Figure 21-9 for the abbreviation code and explanation of boxplots.

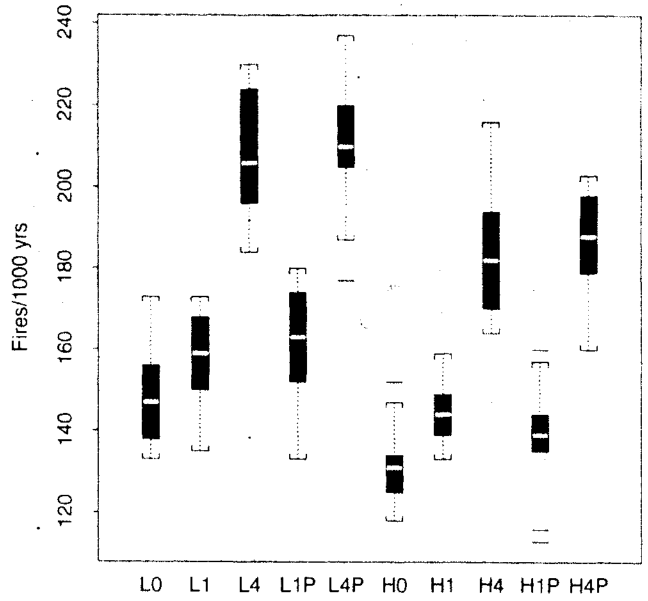

Figure 21-11. Boxplots of the number of fires per 1,000 years under the various fuel/climate scenarios, as explained in Figure 21-9.

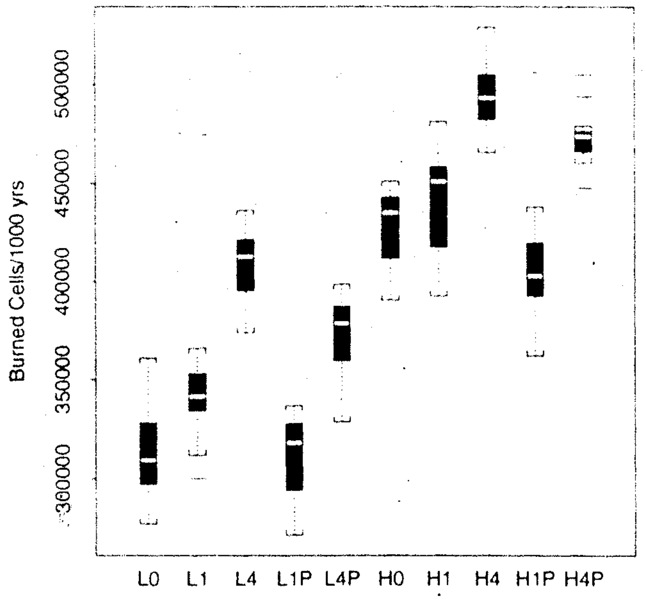

Figure 21-12. Boxplots of the total number of cells burned per 1,000 years, as explained in Figure 21-11.

through high fuel loads, where spread rates are more likely to exceed the suppression threshold even under current conditions.

Calculated rates of spread decrease with increased spring precipitation, which for the Low Biomass model effectively offsets a temperature increase of 1°C in terms of total area burned and fire recurrence interval (Table 21-1). The effect is even more pronounced for the High Biomass model, where the total area burned is predicted to decrease for a 1°C increase and wetter spring compared to the High Biomass model under the current climate. The effect of increased spring precipitation is similar in direction but relatively less important with a 4°C warming.

Conclusions

There are myriad direct physical and indirect biological relationships between regional climate and fire regime in chaparral. Obvious direct controls include lightning frequency and the effects of air temperature, relative humidity, and wind speed on dead fuel moisture, ignition, and fire spread. An example of indirect control is the relationship between seasonal soil water availability and plant growth and water status, which affect ignition probability, spread rate, and fire intensity. Chaparral species differ widely in their combustion characteristics, and thus climateinduced changes in stand composition can also affect fire regime variables such as fire recurrence interval, size, and severity. Predicting future fire regimes is especially complicated because increasing CO_2 may not only affect climatic variables, but may also alter plant physiology, water use efficiency, canopy structure, interspecific interactions, and community development after fire.

In this study we have only considered the direct consequences of climatic change on fire ignition and spread in chaparral, and have not treated the interactions among climate, fire frequency, and intensity, and potentially large changes in chaparral composition (e.g., Malanson and Westman, 1991). Incorporating a submodel into REFIRES to account for compositional dynamics would be relatively straightforward. Unfortunately there is not much information available to parameterize such a model.

The retrospective analysis of wildfire history in the Los Padres National Forest reveals a modern fire regime dominated by infrequent large, fires. These fires occur between June and October during short-lived meteorological events characterized by extreme high temperatures and winds. The timing and frequency of these events is not obviously related to seasonal or annual mean temperature conditions. Fire hazard also depends strongly on live fuel moisture levels, which are a function of late winter and spring precipitation. Fire hazard is greatly reduced in years when total spring rainfall at Santa Barbara exceeds 200 mm, and is extremely high in years where spring rain totals less than 50 mm. On average, fire spread does not appear to be limited by fuel availability, since most stands are mature, closed-canopy chaparral.

GCM predictions for future climate in southern California are very unreliable, particularly given the importance of extreme events in the fire climatology of chaparral. Another large source of uncertainty is the fire spread and fuel models used to simulate fire behavior. These models are particularly undependable under the high wind conditions typical of modern fire events. Nonetheless, the models give us an indication of how ignition, climate, vegetation, terrain, and fire management could interact to affect regional fire regime under a changed climate.

Using current weather data, fire regimes simulated by REFIRES resemble the actual regional regime in terms of fire recurrence interval and relative fire size distribution. The simulated regime is very sensitive to predicted increases in fire season temperatures, and is equally as sensitive to large changes in stand productivity. Total area burned is predicted to increase and fire recurrence interval to decrease significantly, even for a modest 1°C temperature increase. The effect of increased temperature is more pronounced for a less productive chaparral, where rates of spread are more frequently limited by both fuels and weather conditions. This effect of a 1°C increase in temperature is more than offset by an increase of 5.25% in summer fuel moisture levels. Increased fuel moisture does not affect the frequency of initial ignitions; rather, it operates to reduce spread rates by decreasing fire intensity and increasing the amount of heat required to bring neighboring fuels up to ignition temperature. Modeled fire regime is not as sensitive to spring precipitation as the observed fire regime, a result that is probably due to the use of a chamise fuel model rather than a fuel model closer to the mix of coarse, predominantly live fuels that actually characterize the region.

These results are based on present wind conditions, and could change dramatically depending on changes in that parameter. Most GCM models predict an increase in summer wind speeds under a $2CO_2$ atmosphere, which would certainly increase fire hazard as predicted by fire behavior models. However, wind is unquestionably the most difficult variable in any analysis of future fire regimes. Existing GCM models and fire behavior models are both very weak in their treatment of this variable. Some of the main difficulties in modeling wind effects on fire behavior include adequate characterization of spatial and temporal variability, especially in rugged terrain, accounting for local effects of the fire itself, and use of a single velocity to characterize a dynamic vertical profile.

The predicted increase in wildfire hazard under global warming is greater than that predicted by Torn and Fried (1992) for northern California, despite their specification of a future increase in wind velocities. This is partly due to regional differences in fire season climate, but is also due to differences in fuel models and model formulation. Because it includes the spatial and temporal dynamics of fuel loading on the landscape, REFIRES is probably more responsive to changes in ignition frequency and calculated rates of spread than the model used by Torn and Fried (1992), which treated chaparral as a single, uniform fuel.

We are currently exploring other interactions between climate and fire regime in this region using a much larger grid and more rugged topography. We also intend to analyze different wind scenarios, as well as sensitivity of the chaparral fire regime to variance in climate parameters. Results to date appear reasonable and certainly indicate the potential impact of global warming on fire in chaparral ecosystems. However, REFIRES itself requires many additional improvements, including a subroutine for fire spotting and a shorter time step for meteorological conditions (Davis and Burrows, 1993).

Given the importance of fire regime in chaparral ecosystems and in Mediterranean-climate ecosystems generally, and the apparent sensitivity of fire regime to climate and vegetation productivity and composition, we believe that research into the possible consequences of global changes in atmospheric CO_2 and climate on regional fire regimes must be given very high priority. This research should integrate both empirical, quantitative comparisons of fire regimes in areas under different climates and fire management systems, as well as simulation studies incorporating fire behavior models and ecological models of community development after fire. In particular, we need more information on fuel characteristics of different chaparral species and communities as a function of age and site conditions, and information on interactions among fire intensity, climate, and postfire vegetation development.

Acknowledgments. We would like to thank Mark Borchert and Fritts Cahill of the Los Padres National Forest for providing fire history, climate, and fuel moisture data for the forest. We also gratefully acknowledge David Burrows for assisting in parameterization and operation of REFIRES. Philip Riggan and a second reviewer provided very constructive reviews of the draft manuscript. Computing support for this research was provided by the Digital Equipment Corporation Sequoia 2000 project.

References

Albini FA. 1976. Estimating wildfire behavior and effects. USDA Forest Service General Technical Report INT-30. Inter-Mountain Forest and Range Experiment Station, Ogden, UT.

Bradshaw LS, Deeming JE, Burgan RE, Cohen JD. 1983. The 1978 National Fire Danger Rating System: Technical Documentation. USDA Forest Service General Technical Report INT-169, Inter-Mountain Forest and Range Experiment Station, Ogden, UT.

Burrows DA. 1988. The REFIRES (Regional FIre REgime Simulation) model: a C program for regional fire regime simulation. MA Thesis, University of California, Santa Barbara, CA.

Byrne R, Michaelsen J, Soutar A. 1977. Fossil charcoal as a measure of wildfire frequency in southern California: a preliminary analysis. Pages 361–367 in HA Mooney and CE Conrad, eds, Proceedings of the Symposium on the consequences of fire and fuel management in Mediterranean Ecosystems, Palo Alto, California. USDA Forest Service General Technical Report WO-3. Washington, DC.

Davis FW, Burrows DA. 1993. Modeling fire regime in Mediterranean landscapes. Pages 247–259 in S Levin, T Powell, and J Steele, eds, Patch Dynamics. Springer-Verlag Lecture Notes in Biomathematics, New York.

Davis FW, Hickson DE, Odion DC. 1988. Composition of maritime chaparral related to fire history and soil, Burton Mesa, Santa Barbara County, CA. Madrono 35:169–195.

Dickinson RE. 1989. Uncertainties in estimates of climatic change: a review. Climatic Change 15:5–13.

Hanes TL. 1971. Succession after fire in the chaparral of southern California. Ecol Monog 41:27–52.

Keeley J. 1982. Distribution of lightning and man-caused wildfires in California. In: CE Conrad and WC Oechel, eds, Dynamics and Management of Mediterranean-type Ecosystems. USDA Forest Service General Technical Report PSW-58, pp. 431–437.

Malanson GP, Westman WE. 1991. Modeling interactive effects of climate change, air pollution and fire on a California shrubland. Climatic Change 18:363–376.

Milly PCD. 1992. Potential evaporation and soil moisture in General Circulation Models. J Climate 5:209–226.

Minnich RA. 1983. Fire mosaics in southern California and northern Baja California. Science 219:1287–1294.

Minnich RA. 1989. Chaparral fire history in San Diego County and adjacent northern Baja California. In: SC Keeley, ed, The California Chaparral: Paradigms Re-examined. Natural History Museum of Los Angeles County Science Series 34:37–48.

Muller CH, Hanawalt RB, McPherson JK. 1968. Allelopathic control of herb growth in the fire cycle of California chaparral. Bull Torrey Bot Club 95:225–231.

Ogden GL. 1975. Differential response of two oak species to far inland advection of sea-salt spray aerosol. PhD Dissertation, University of California, Santa Barbara, CA.

Paysen TE, Cohen JD. 1990. Chamise chaparral dead fuel fraction is not reliably predicted by age. West J Appl Forestry 5:127–131.

Radtke KW-H, Arndt A, Wakimoto RH. 1977. Fire history of the santa monica Mountains. In: CE Conrad and WC Oechel, eds, Dynamics and Management of Mediterranean-type Ecosystems. USDA Forest Service General Technical Report PSW-58, pp. 438–443.

Riggan PJ, Goode S, Jacks P, Lockwood RN. 1988. Interaction of fire and community development in chaparral of southern California. Ecol Monog 58:155–176.

Rothermel RC. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service Research Paper INT-115. Inter-Mountain Forest and Range Experiment Station, Ogden, UT.

Rothermel RC, Philpot CW. 1973. Predicting changes in chaparral flammability. J Forestry 71:640–643.

Torn MS, Fried JS. 1992. Predicting the impacts of global warming on wildland fire. Climatic Change 21:257–274.

Westman WE, Malanson GP. 1992. Effects of climate change on Mediterranean-type ecosystems in California and Baja California. In: RL Peters and TE Lovejoy, eds, Global Warming and Biological Diversity. Yale University Press, New Haven, CT, pp. 258–256.