Detection of nonlinearities in the dependence of burn area on fuel age and climatic variables

Suggested running head: Nonlinear dependence on fuel age and climate

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Abstract

Evidence from Los Angeles County in California, USA suggests that the relationships between wildfire burn area and fuel age, temperature, precipitation, and fuel moisture are not linear. Instead, the relationships appear to have thresholds. The data seem to support the notion that fire risk is nearly constant provided various conditions are met: that fuel age and temperature exceed a given threshold, and that fuel moisture and precipitation are sufficiently low. There appears to be little distinction in terms of wildfire risk between conditions that are sufficient for wildfires and those that are extreme.

Keywords: Fire weather; time-since-fire; temperature; precipitation; fuel moisture; Los Angeles; California; chaparral; fire statistics; thresholds

Introduction

Ecological variables such as temperature, fuel moisture, and precipitation have been posited to have a monotonic impact on fire occurrence: the hotter and drier the weather and soil, the more area one expects to burn (Simard et al. 1987, Pyne 1997). Similarly, fuel age (also called time-since-fire) has been claimed to have a similar monotonic effect, with fire risk at a location increasing as the time since the location has last burned increases. Such relationships are based largely on the results of laboratory experiments and occasionally on detailed analyses of particular fires or fire seasons, and in some commonly used models for fire danger, linear relationships are assumed as first-order approximations of wildfire burn rate (see e.g. Pyne et al. 1996, Viegas et al. 1999, and references therein). In analyses of empirical data on wildfires over many years, linear regressions on ecological factors or fuel age have been found to predict a high proportion of the variation in burn area (Flannigan and Harrington 1988, Turner and Romme 1994, Larsen 1996).

The goal of the present analysis is to verify the extent to which empirical data from Los Angeles County agree with these linear relationships. Further, our intent is to identify departures from linearity, so that existing models for fire hazard estimation may be improved. Assumptions are kept to a bare minimum and no explicit parametric models are employed. Instead, we use nonparametric estimation techniques and smoothing methods which are broadly applicable and are useful for exploring and highlighting aspects of the relationships between burn area and other variables.

Evidence against the principle that the relationships between burn area and ecological variables are linear has already been reported in various areas. For instance, Li et al. (1997) and McCarthy et al. (2000) investigate the effect of fuel age and explore various alternatives to the linear model. Viegas and Viegas (1994) find significant curvature in the relationship between precipitation and annual burned area in Portugal, and offer the explanation that heavy precipitation may decrease wildfire risk in the short run while increasing wildfire risk in the long run by causing an increase in vegetation growth. A similar observation for Southern California was reported by Minnich (1983). This explanation would account for the observed nonlinear relationship between precipitation and burn area, when viewed on an annual scale. The focus of the present paper is on departures from linearity for wildfire and ecological variables observed instead on a monthly scale. Such an analysis may yield information more relevant to the question of how to improve models of fire weather and overall fire risk. Note that the concern in the present analysis is the overall burn area for Los Angeles County over a given time period, rather than prediction of the propagation of existing fires.

Data

Our available data on the history of wildfire occurrences in Los Angeles come from the Los Angeles County Department of Public Works (LACDPW) and the Los Angeles County Fire Department (LACFD). The LACDPW dataset contains information on 2,104 fires each burning an area greater than 1 acre (.405 ha) dating from 1878 to 1996; the data prior to 1940 is thought to be of questionable completeness and accuracy. Each fire record consists of a polygon representing the area burned by the fire, originally sketched by teams of field engineers and subsequently scanned and converted into a polygon computationally. The resulting polygons are very precise: LACDPW officials estimate that location errors in the polygons are on the order of 10-20 meters at most. Data from LACFD consists of 705 fires between 1966 and 1996, and this catalog is thought to be a complete list for fires burning at least 100 acres (40.5 ha). The two datasets agree closely for major fires in the period 1966–1996.

The frequency-area distribution of wildfires burning more than a minimum cutoff area is typically approximated by a Pareto (power-law) or tapered Pareto curve (e.g. Turcotte et al. 1999; Paik Schoenberg et al. 2002). This power-law relation appears to be a reasonable approximation for the LACDPW catalog, as seen in Fig. 1 (although there does seem to be some curvature). In light of the model put forth by Turcotte et al. (1999), the nonlinearity in Fig. 1 for areas smaller than 15 ha may suggest incompleteness in the LACDPW catalog for wildfires burning less than this area.

Of concern in the present analysis is the monthly burn area rather than the number of fires; though the two variables are correlated ($r = 0.46$), the former depends less critically on the minimum area threshold of the dataset. The proportion of area that burns has been used as an estimate of the probability of burning a point (PBP) (see e.g. Gill et al. 2000 and McCarthy et al. 2000) and hence may be more relevant in terms of assessment of overall fire risk for Los Angeles County.

Our data on some important covariates come from a variety of sources. Live fuel moisture estimates provided by LACFD are derived by field engineers from the Vegetation Management Program of the Division of Forestry. The live fuel moisture dataset, consisting of biweekly estimates for the period 1981 to 1999, was obtained by gathering fuel samples consisting of approximately 190 g of shrub each at various locations, which were then weighed, dried, and weighed again. Live fuel moisture is recorded as $100 \times (m_g - m_d)/m_d$, where m_g is the gross mass of the fuel and m_d is the mass of the fuel after it has been dried: for Los Angeles chaparral, a live fuel moisture index of 200 indicates high moisture content, whereas a value of 60 indicates extreme dryness. Precipitation data have been made available by the Institute of the Environment (IoE) at the University of California, Los Angeles, including hourly precipitation records at 13 stations in Los Angeles County. These records are complete for all stations between 1984 and 1993, with several stations containing records before 1984 and several containing records past 1993. In considering average monthly precipitation in the analysis to follow, we averaged the precipitation across all 13 stations. Detailed Los Angeles County temperature data is publicly available from the National Oceanic and Atmospheric Administration (NOAA); this includes average, high, and low temperatures sampled at a variety of sites in Los Angeles County. We focus on the monthly average temperatures, which are available dating from 1878 to 1998.

Figure 2 shows annual variation and trends in wildfire burn area (based on annual totals from the LACDPW data) and average temperature. While temperature appears to increase steadily over the years, the burn area data is dominated by high year-to-year variability. Note that the increasing trend observed in the burn area data is likely an artifact due to incompleteness in the dataset prior to 1940.

Figure 3 shows seasonal variations in burn area, live fuel moisture, temperature and precipitation, from 1984 to 1994, and Figure 4 shows monthly averages of these four variables over the same time period. In both figures, the three climatic variables are monthly aggregates averaged across observation stations. The seasonal patterns in these variables are readily evident. Note that much of the burning occurs in September and October, when hot, dry Santa Ana winds typically are present in Southern California (Minnich 1983). Not surprisingly, in the winter months there is a marked decrease in wildfire burned area and temperature, and an increase in fuel moisture and precipitation.

Methodology

We investigate the relationship between monthly wildfire burn area and fuel age as follows. For each time interval u, we take the total amount of u-year-old fuel in Los Angeles County which burned, and divide this by the amount of u-year-old fuel which was available. Note that computation of this ratio involves calculating and summing the reburn areas over all years in the LACDPW dataset, which involves computing thousands of polygon intersections and hence is a considerable computational burden. The relationship between fuel age and the proportion of fuel of that age which burned may subsequently be examined in a scatterplot. To highlight the overall trends, the scatterplot is smoothed using a local linear smoother (see Fan and Gijbels 1996, Fox 2000). Note that this method of obtaining fuel age data by using spatial-temporal maps of fire history is very similar to the methodology of Gill et al. (2000) and McCarthy et al. (2000) except that we compute overlaps between the actual wildfire polygons drawn by Fire Department officials whereas Gill et al. (2000) and McCarthy et al. (2000) use LANDSAT imagery and hence pixels (1 ha each) as the units of analysis, which simplifies things computationally but may result in some loss of precision. Note also that our method differs critically from the time-since-fire curve methodology of e.g. Johnson and Gutsell (1994) (see also Johnson and Van Wagner 1985; Johnson and Larsen 1991). The method outlined by Johnson and Gutsell (1994) uses total annual burn area only and is hence very important for the case where the precise spatial mosaics of past fires are not observed. However, when such information is available, both our method and that of Gill et al. (2000) and McCarthy et al. (2000) use spatial-temporal data on overlaps between fires to provide much more accurate information on fuel age.

The relationships between monthly wildfire burn area and fuel moisture, temperature, and precipitation are assessed using non-parametrically smoothed scatterplots of area burned versus the ecological variables. The resulting curves provide easily interpretable summaries of the relationship between wildfire activity and the climatic variables. For each pair of variables, we limit our analysis to the observations occurring in the years of overlap for both datasets in question, using the LACFD wildfire catalog for the wildfire data.

Construction of confidence bounds for the relationships is useful in order to help distinguish between fluctuations in the smoothed scatterplots which may be spurious from those which appear to be significant. Rather than assume a parametric model, the bootstrap may be employed to provide estimated confidence bounds: one simply resamples pairs (x, y) from the empirical distribution, where x is the value of a covariate (e.g. average temperature) for a given time period, and y is the total (or percentage) area burned by fires in that time period. Bootstrap confidence bounds have the attractive feature that their validity does not depend on a simplistic parametric model for fire occurrence (see e.g. Efron and Tibshirani 1993).

Since ecological variables such as temperature and precipitation are obviously strongly dependent, it is useful to assess the relationships between wildfire activity and these variables both individually and collectively. Hence we inspect the relationship between pairs of ecological variables, again using non-parametrically smoothed two-dimensional scatterplots.

Results

Figs. 5a-d show the relationships between the area burned by wildfires and fuel age, fuel moisture, temperature, and precipitation, respectively. The solid lines represent the aggregated data, smoothed by local linear regression. It should be noted that there was considerable scatter about each of these curves before smoothing. The dashed lines represent bootstrap 95% confidence bounds.

The curves in Figs. 5a-d suggest nonlinear, threshold relationships with all four variables. For instance, burn area appears to increase steadily with fuel age up to ages of about 30 years, and the confidence bounds indicate that this increase is statistically significant, in the sense that the mean burn percentage of 10-year-old fuel lies well outside the 95%-confidence bounds for 30-year-old fuel, for instance. (Note that little attention should be paid to the apparent non-zero intercept for fuel of zero age, which is purely a result of the fact that values are smoothed over multiple years.) However, the burn rate does not appear to increase with fuel age among areas that have not burned in 30 years or more. Similarly, burn area seems to decrease steadily and significantly as live fuel moisture increases, for average monthly fuel moisture indices greater than 90, but the burn rate does not vary substantially over the range of 55 to 90 in live fuel moisture. These results suggest that, rather than linearly increasing with fuel age and linearly decreasing with fuel moisture, the burn rate may be nearly constant provided that the fuel age is at least 30 years and the monthly average fuel moisture index is less than a threshold of about 90. Similarly, average burn area appears to increase with monthly average temperature up to a threshold of 21^oC, and level off for temperatures above this threshold. While there is an apparent decrease in average area burned in months with over 2cm of precipitation, there is no apparent trend as monthly precipitation decreases below 2cm.

Fuel moisture, temperature, and precipitation are obviously strongly interrelated. Figs. 6a-c show the smoothed averages of the wildfire burn area across pairs of climatic variables. One sees for instance from Fig. 6a how the relationship between burn area and fuel moisture varies with temperature; it appears that in months where the average temperature is low, burn area varies relatively little with fuel moisture, whereas when the average temperature is high (e.g. 25^oC or higher), burn area seems to depend much more heavily on fuel moisture, even for average monthly live fuel moisture indices less than 90. The interplay between fuel moisture and precipitation is similar: variations in fuel moisture appear to have a more pronounced effect on burn area when precipitation is low, and vice versa. Similarly, when temperatures are low, variations in precipitation appear to have little effect on burn area, but when temperatures are high there appears to be a substantial linear effect for precipitation. However, the dependence of burn area on temperature appears to be relatively constant throughout; there appears to be relatively little difference in average burn area between temperatures of 21^oC and temperatures of 27^oC, regardless of fuel moisture and precipitation.

Discussion

The relationships between wildfire burn area and fuel age, fuel moisture, precipitation, and temperature all appear to be nonlinear. Our results suggest the presence of threshold-type relationships: wildfire burn area appears to increase steadily as fuel ages and temperatures increase and as fuel moisture and precipitation decrease, but once certain levels of each of these variables are achieved, the increase in wildfire risk appears to cease. In addition, the different climatic variables interrelate in important ways: for instance variations in fuel moisture seem to have a greater effect on the burn rate when precipitation is low than when precipitation is high.

The observed thresholds for fuel age, monthly average live fuel moisture index, precipitation, and temperature are approximately 30 years, 90%, 2cm, and 21^oC, respectively. The threshold of 30 years for fuel age is not surprising, given that the Los Angeles County vegetation is dominated by chaparral which is known to have a lifespan of comparable length (Hanes 1971). What is surprising, however, is that similar threshold-type relationships are observed for the climatic variables as well, and furthermore that all four of the thresholds are present at the high end of the wildfire activity spectrum. A possible interpretation is that large wildfires occur primarily when conditions for their ignition are ripe, but that there is little distinction in terms of wildfire risk between conditions that are sufficient for wildfires and those that are extreme. Ours is somewhat similar to the conclusion arrived at by Keeley et al. (1999), who found that large catastrophic wildfires in Southern California "are not dependent on ancient stands of brush". Such interpretations may have obvious implications for governmental issuance of fire danger and fire hazard warnings, as well as other assessments of wildfire risk.

One limitation on the interpretability of our results is that the ecological variables analyzed here are observed only over limited time scales and with somewhat limited precision: for each of the variables, samples are obtained only over a relatively course grid of locations within Los Angeles County. Further study is needed in order to determine the nature in which results such as those presented here depend on the temporal and spatial scales of the analysis. In particular, it may be that the relationship between meteorological variables and burn area is not pronounced on a monthly scale because chapparal takes an extraordinarily long time to dry out compared with other vegetation types (Minnich 1983). This could explain why the hottest, driest months in Los Angeles County do not experience significantly greater burn areas. In addition, it is important to note that although several covariates are examined here, there are numerous others which may interact in important ways with these variables. Hence our observed relationships may depend critically on other variables such as land use and fire prevention policies, wind speed and direction, etc. Wind is known to have a particularly pronounced impact on fire incidence and spread (e.g. Viegas 1998), but wind data is not amenable to the type of analysis performed here: directionality is a crucial component to wind data, which may be summarized by sheer stress tensors τ_0 (see e.g. Viegas 1994) rather than by real numbers as in the case of temperature, precipitation, and live fuel moisture. Hence the analysis of the effect of wind on burn area requires a fundamentally different type of analysis than that employed here. Another important direction for future research is to investigate the interactions between variables such as wind, land use, fire prevention policies, etc., and those used in the present analysis and the effect of these interactions on burned area. As noted in Gill and McCarthy (1998), "one would have to be wary of changes over time in factors affecting areas burned other than the weather."

Although Los Angeles County wildfires are a significant matter, another important item for future research is to investigate how effectively our methods and results extend to wildfires in other areas. In particular, the observed relationship between burn area and fuel moisture for Los Angeles chapparral is likely to differ markedly from that for vegetation types in other regions, where live fuel moistures may differ markedly from those in the present analysis.

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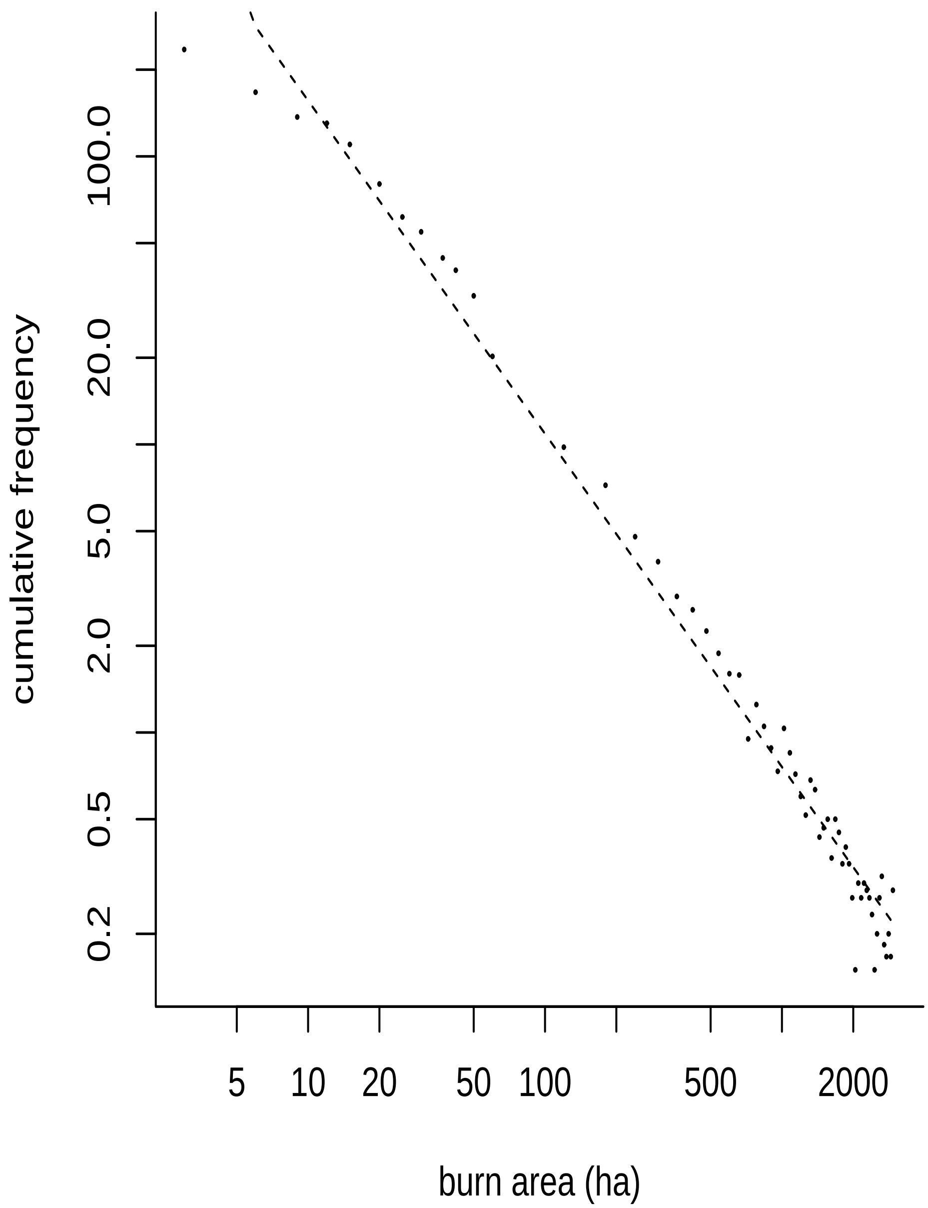
Figure 3: Seasonal variations in Los Angeles County from 1984 to 1994 in a) burn area; b) fuel moisture; c) temperature; and d) precipitation.

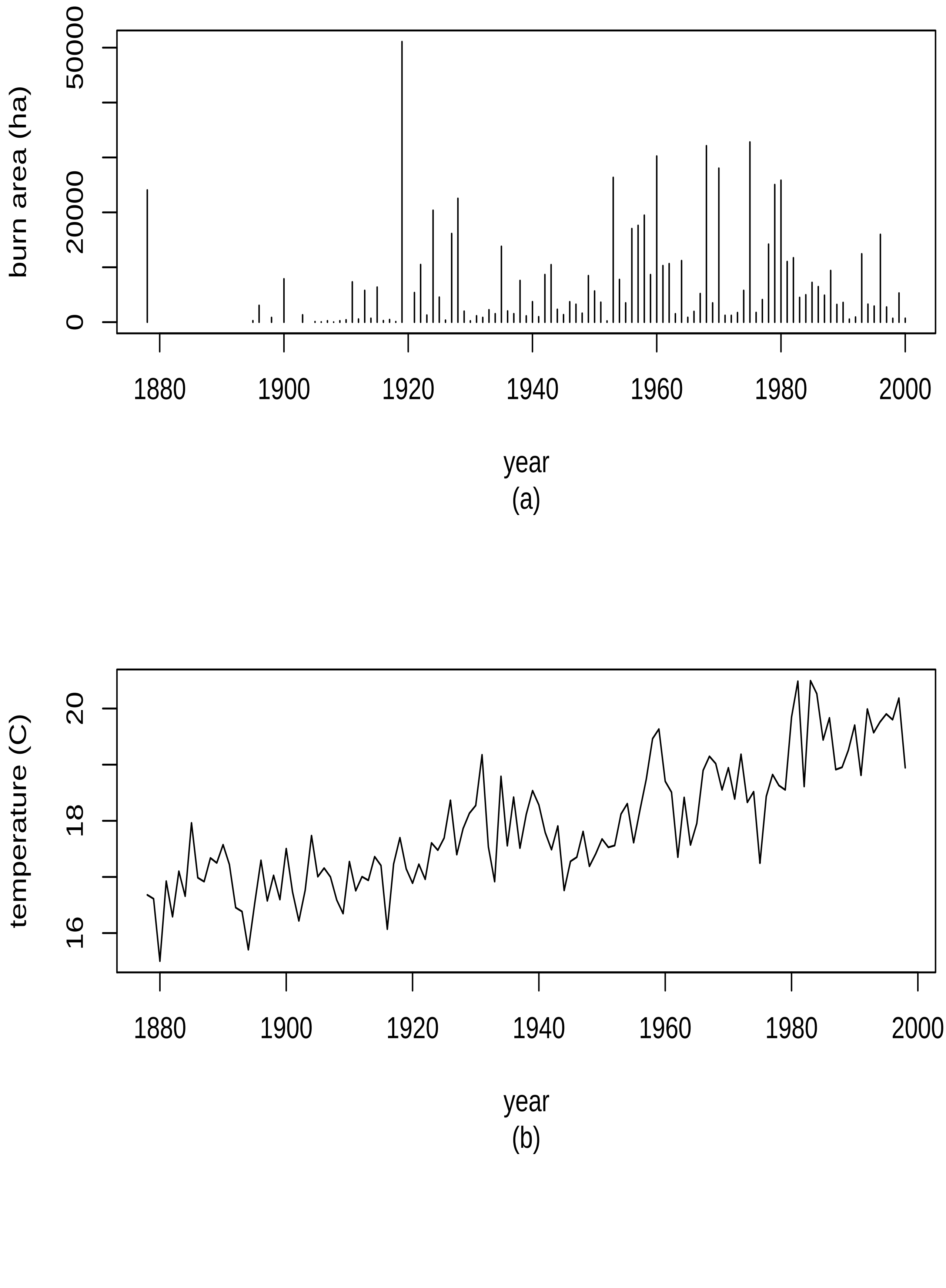
Figure 4: Monthly averages for Los Angeles County, 1984-1994, of burn area, fuel moisture, temperature and precipitation.

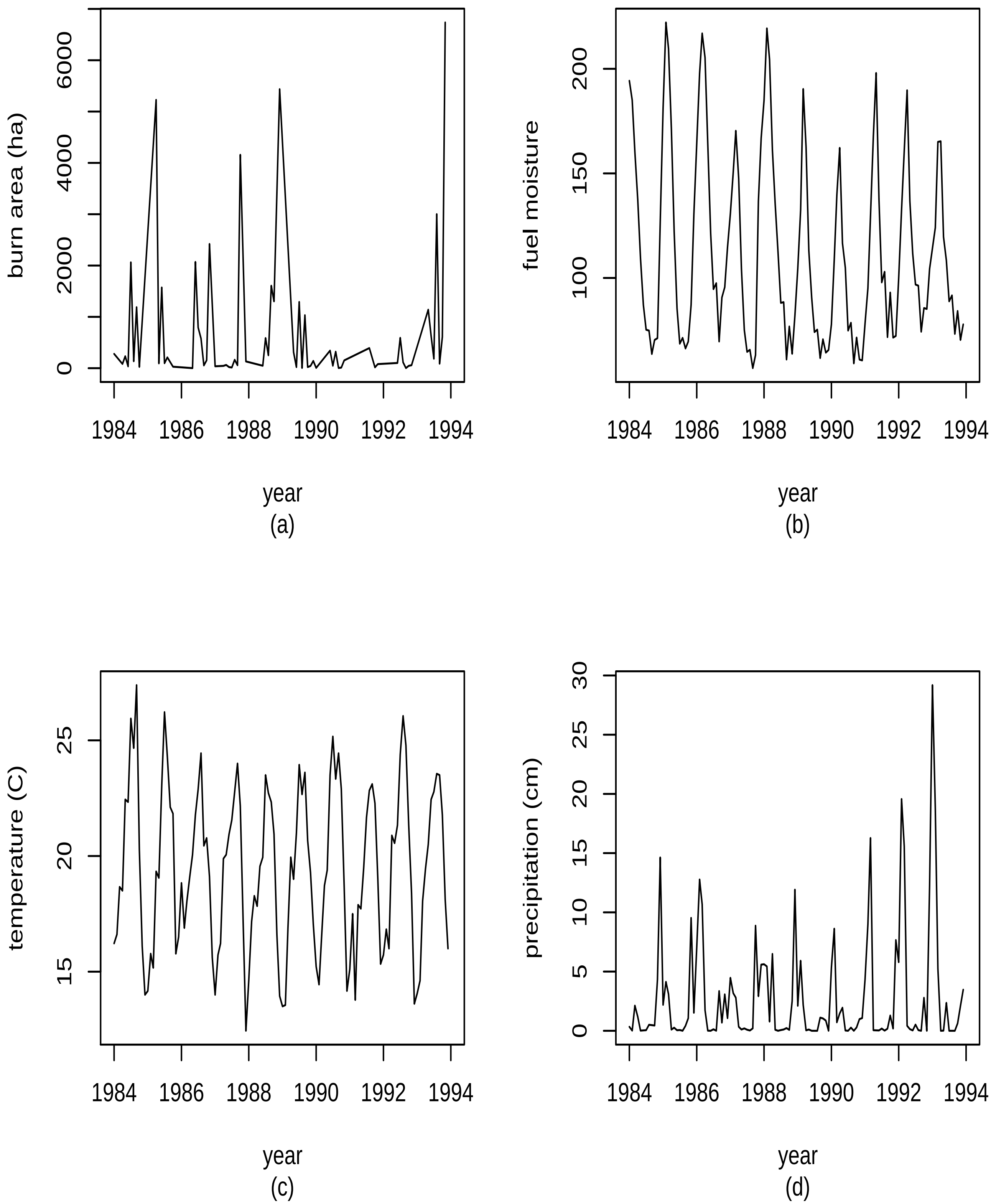
Figure 5: Smoothed scatterplots of burn area versus fuel age, fuel moisture, temperature and precipitation. For fuel age, burn area is recorded as the proportion of available fuel of that age. Fuel moisture, temperature, and precipitation are monthly averages, and for these variables the average amount of burned area per month is presented.

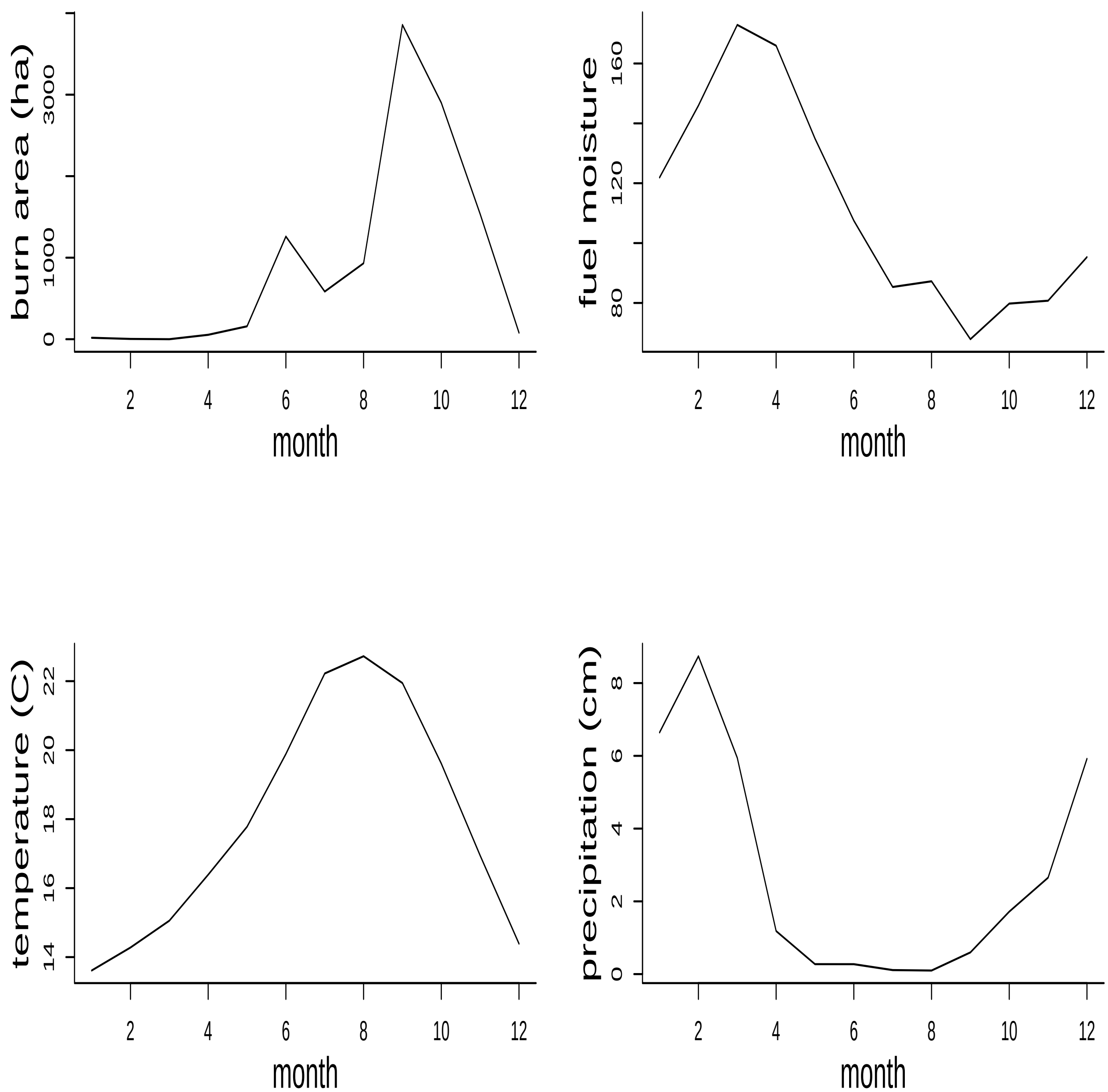
Figure 6: Smoothed plots of monthly burn area versus a) fuel moisture and temperature; b) fuel moisture and precipitation; c) temperature and precipitation.

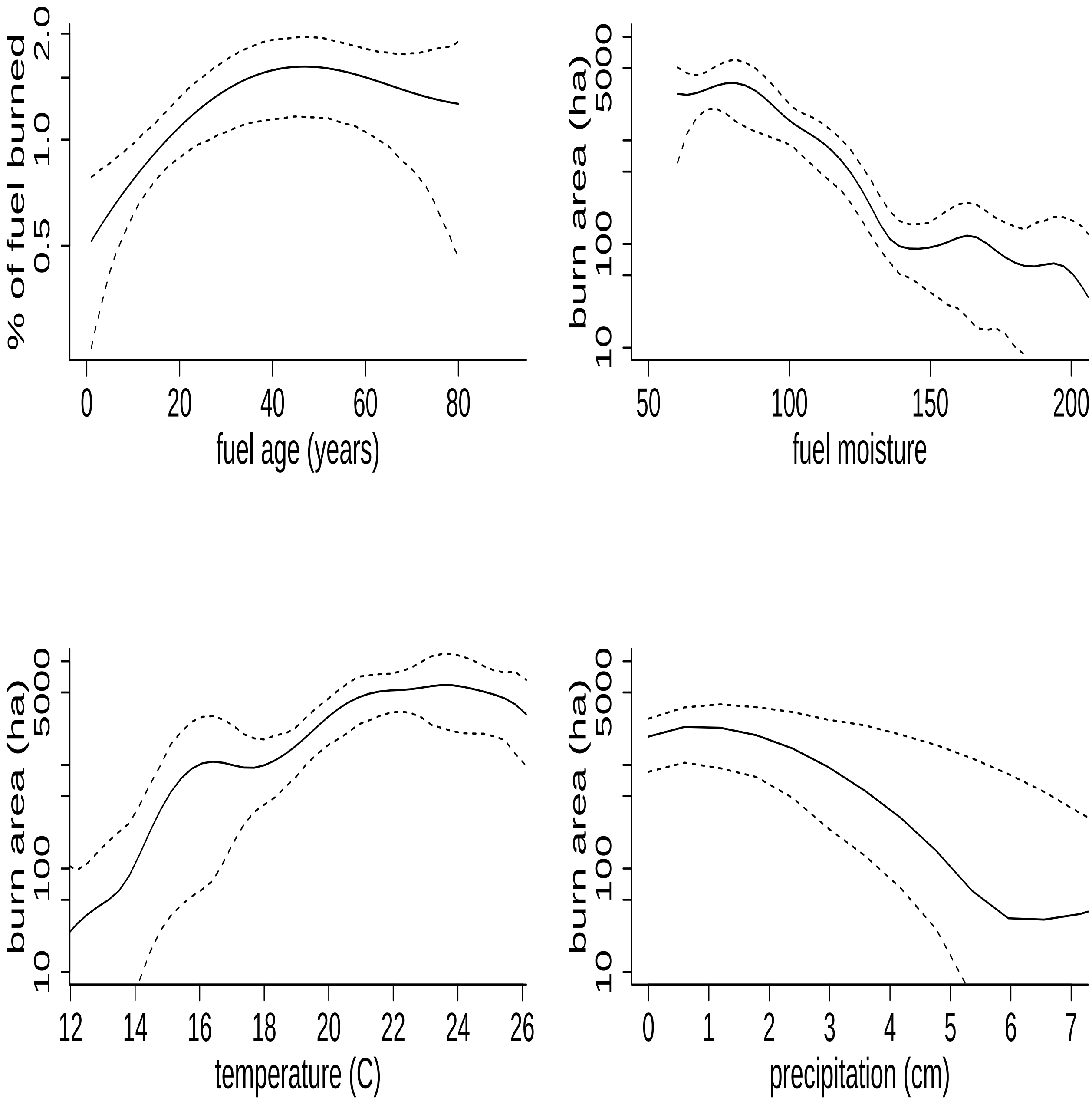


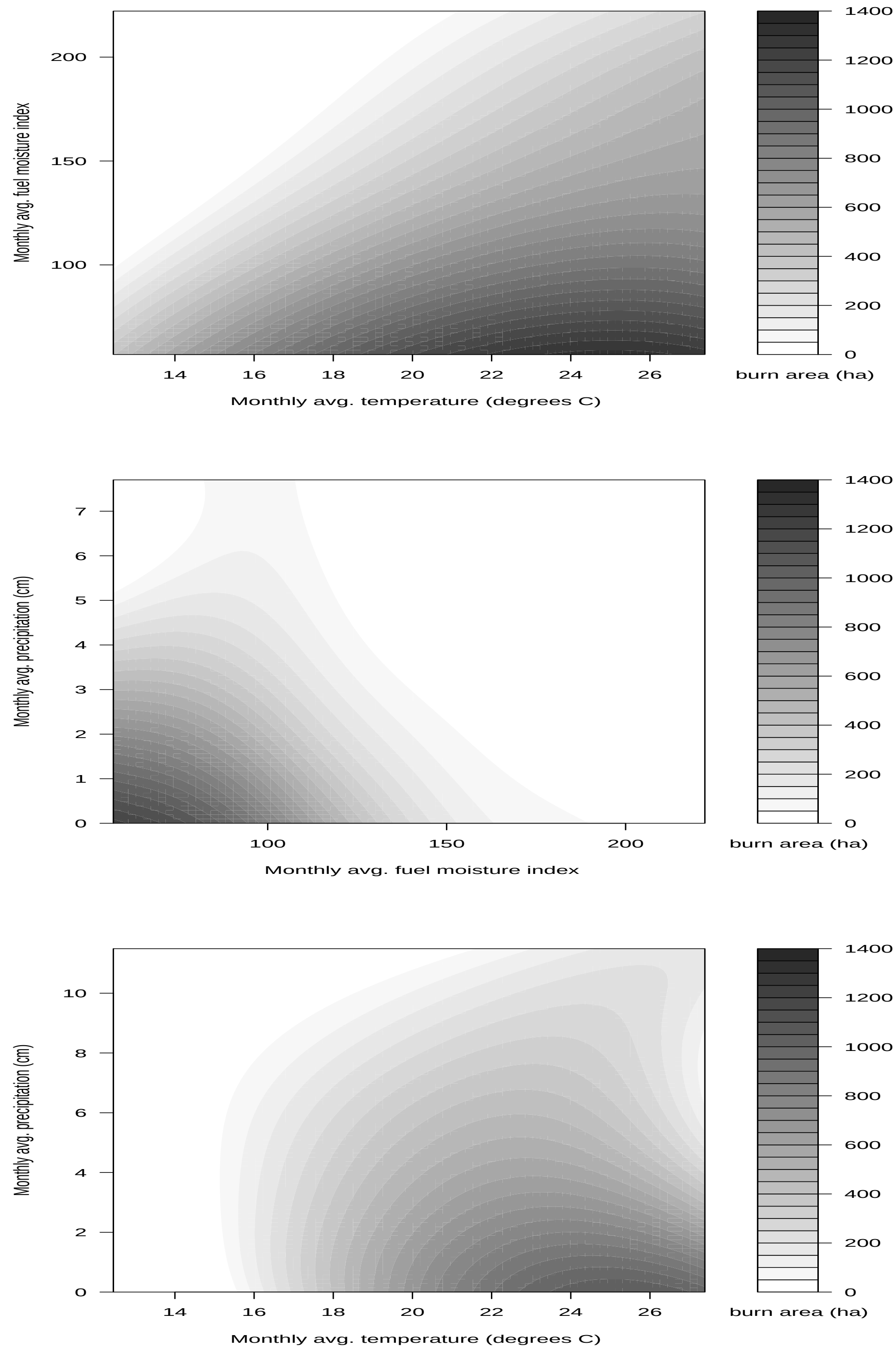
cumulative frequency
100.0
20.0
5.0
2.0
0.5
0.2
5
10
20
50
100
500
2000
burn area (ha)


burn area (ha)
0
20000
50000
1880
1900
1920
1940
1960
1980
2000
year
(a)
temperature (C)
16
18
20
1880
1900
1920
1940
1960
1980
2000
year
(b)


burn area (ha)
0
2000
4000
6000
1984
1986
1988
1990
1992
1994
year
(a)
fuel moisture
100
150
200
1984
1986
1988
1990
1992
1994
year
(b)
temperature (C)
15
20
25
1984
1986
1988
1990
1992
1994
year
(c)
precipitation (cm)
0
5
10
15
20
25
30
1984
1986
1988
1990
1992
1994
year
(d)


burn area (ha)
0
1000
3000
month
2
4
6
8
10
12
fuel moisture
80
120
160
month
temperature (C)
14
16
18
20
22
month
precipitation (cm)
0
2
4
6
8
month


% of fuel burned
0.5
1.0
2.0
0
20
40
60
80
fuel age (years)
burn area (ha)
10
100
5000
50
100
150
200
fuel moisture
burn area (ha)
10
100
5000
12
14
16
18
20
22
24
26
temperature (C)
burn area (ha)
10
100
5000
0
1
2
3
4
5
6
7
precipitation (cm)


Monthly avg. fuel moisture index
200
150
100
14
16
18
20
22
24
26
Monthly avg. temperature (degrees C)
1400
1200
1000
800
600
400
200
0
burn area (ha)
Monthly avg. precipitation (cm)
7
6
5
4
3
2
1
0
100
150
200
Monthly avg. fuel moisture index
1400
1200
1000
800
600
400
200
0
burn area (ha)
Monthly avg. precipitation (cm)
10
8
6
4
2
0
14
16
18
20
22
24
26
Monthly avg. temperature (degrees C)
1400
1200
1000
800
600
400
200
0
burn area (ha)