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ORIGINAL PAPER

Characterization of forest fires in Catalonia (north-east Spain)

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Abstract The present study analyses the temporal variation in the distribution of the number of fires, area burned and fire sizes in Catalonia using fire data from 1942 to 2002. The study shows variations in the distribution of fire size over recent decades, with a significant increase in the number of very large fires. The study also analyses relationships between characteristics of the forest (altitude, slope, aspect, living fuels and species composition) and the probability of the fire occurrence. The analysis is based on the overlay of forest cover data and perimeters of forest fires during the period (1986–2002). Of the analysed variables, altitude affects most the probability of fire occurrence, with higher proportions of burned forest area at lower altitudes. Stand's vertical structure is also relevant, with lower proportions of burned area in stands with mature tree cover without understory. The study helps to analyse the strengths and weaknesses of forest and fire management policies, especially those related to forest and fuel management at the landscape level.

Keywords Fire management · Fire risk · Fire model · Fire characterization · Fire regime

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Introduction

Fire is an important element in the Mediterranean area, with a great influence on the ecological and economic aspects of forested areas. Fire determines the landscape structure and plant composition (Trabaud 1994), and causes the destruction of more trees than all the other natural hazards (diseases, insects, wind throws, frosts etc.) together (Alexandrian et al. 2000). Fire causes enormous economic and ecological damages, and loss of human life (Vélez 1990). In Catalonia, forest fires are perceived as the main environmental problem (Tábara 1996), attracting significant attention in the media and among politicians (Riera et al. 2004). One of the reasons for this increasing public awareness can be the increasing number of very large forest fires.

The need for information about the forest fires regimes has been previously mentioned as an element of fire management strategies (Rollins et al. 2002). Rollins et al. (2002) address the importance of understanding the factors that determine the landscape-scale spatial and temporal fire patterns in order to predict the effects of fire under changing climate, plan the restoration of fire as an ecosystem process, and mitigate possible hazardous conditions on a broad scale.

Many factors have been considered to explain the temporal variation in fire regime in recent decades in Spain: Climate change is one factor, with a clear relationship between increasing number of days with extreme fire hazard weather and the number and size of fires in the Mediterranean coast of Spain (Piñol et al. 1998). Changes in landscape configuration due to abandonment of traditional practices in rural areas increasing forest continuity and biomass accumulation (Badia et al. 2002), and other aspects related to the land uses (Velez 2002) have been considered to have a significant effect on the fire regime. Changes in ignition causes, with an increasing importance of human-related reasons (Vázquez and Moreno 1995), and even the success of the predominant fire suppression policy in Spain (Terradas and Piñol 1996; Piñol et al. 1998) have also been considered as influential factors in the increasing number of large fires.

Some recent studies have analyzed the spatial patterns of fire occurrence in Spain (Vazquéz and Moreno 2001; Díaz-Delgado et al. 2004). Vázquez and Moreno (2001) estimated the percentage of forest area burned depending on topographical variables, after mapping the historical fires of the period 1970–1990 in Central Spain. Díaz-Delgado et al. (2004) studied the spatial patterns of fire occurrence in Catalonia over the period 1975–1998, analysing the effect of vegetation, topography, climate and socio-economic variables on the proportion of forest area burned. The vegetation was classified using land uses and species composition, without considering the structure of the fuels.

The present study first analysed changes in the burned area, number of fires, and fire size distribution in the Catalonian region during 1942–2002. It then examined the influence of topography and forest cover on the probability of fire occurrence during the period 1986–2002, including the structure of living fuels. Finally, the implications of the results on forest management were discussed.

Materials and methods

Catalonia's area covers over 32,000 km^2, with altitudes varying form sea level to over 3,000 m, with approximately 60% covered by scrublands and forest. The forest area is dominated by *Pinus* spp. and *Quercus* spp. *P. sylvestris* dominated stands cover 20% of the forest area, *P. halepensis* 20%, *Quercus ilex* 16.6%, *P. nigra* 12.5%, *Q. suber* 4.8%, *P. uncinata* 4.8%, *Q. humilis* 4.0% and *P. pinea* 3.3%. Other species such as *Abies alba*, *Castanea sativa*, *P. pinaster* and *Q. cerroides* are also present, each one occupying 1–3% of the forest area (Gracia et al. 1997).

The analysis of the number of fires, size, and burned area in Catalonia was based on historical fire data from the Department de Medi Ambient i Habitatge and the Institut Cartográfic de Catalunya. The data consisted of information of 8,121 fire events with burned areas equal to or greater than 1 ha, which occurred in Catalonia during 1942–2002. The information used for this study consisted of the date of occurrence and the area affected by the fire. In order to observe temporal variations in the number and size of forest fires, information on three 20-year sub-periods (1942–1962, 1963–1982 and 1983–2002) were analysed, in addition to the whole period (1942–2002).

For the analysis of the fire probability in Catalonia the following steps were accomplished: the forest was first divided into classes of altitude, slope, aspect, fuel and species composition (Table 1). Then, the total area occupied by each combination of classes and the area of each combination within the perimeters of the forest fires occurred during 1986–2002 were calculated. This allowed the estimation of the proportion of each class of forest burned during the period, by dividing the burned area by the total forest area of the class. The data used consisted of the Spanish Forest Map on scale 1:50,000 (MFE50; BDN 2001), a digital terrain model of Catalonia with a resolution of 150 m, and the perimeters of forest fires, in Catalonia, larger than 20 ha, collected from 1986 to 2002. The fire perimeters were determined on a 1:50,000 scale by the Department de Medi Ambient i Habitatge and the Institut Cartográfic de Catalunya as follows: The information of the fire reports (date of the fire, coordinates of initiation point, estimated area burned, etc.) was compared with images of burned areas (LANDSAT, SPOT, CASI or ortophotos). For each fire, a file was created with geo-referenced data from the affected area, both before and after the fire. The data were processed to estimate the effect of fire on the vegetation cover, using the Normalized Difference Vegetation Index (NDVI) (Tucker 1985) and principal component analysis. Digital classification was used for delineating the fire perimeter. A post control phase allowed a more accurate differentiation of the burned and unburned areas. Unburned areas that were inside the perimeters were also delineated and they were not included in burned area.

The forest was classified according to five different criteria: altitude, aspect (direction of slope), slope, fuel, and tree species (Fig. 1). The values of the first three criteria were obtained from a digital terrain model (150 m grid size) using the Spatial Analysis module of ArcGIS 6.0 (layers a, b, c in Fig. 1). The values of the last two criteria (layer d in Fig. 1) were obtained as the combination of different fields present in the MFE50: structural type of the stand, and information on the forest cover if present (name, occupation and vegetation stage of development of the three main species in the stand). The structural type of the stand was used in order to eliminate areas of non-forest uses from the analysis, and to determine if other vegetation cover different than tree cover (pastures, bushes) was present in forest stands.

Table 1 Description of altitude, slope, aspect, fuel and species classes used in the study

Class	Altitude	Slope	Aspect	Fuel	Species
0				No information or vegetation cover < 20%	No trees with >20% coverage
1	0–400 m	<3%	315–45° (North)	Pasture or young regeneration (Pasture)	Pine (Pine)
2	401–1,600 m	3–11%	45–135° (East)	Bushes, small trees with height < 8–10 m (Young)	Oak (Oak)
3	1,601–2,300 m	12–19%	135–225° (South)	Trees with height > 8–10 m (Trees)	Pine–oak mixture (PineOak)
4	>2,300 m	20–35%	225–315° (West)	Trees with height > 8–10 m and bushes or young trees (TwoLayer)	Other species (OtherSp)
5		>35%			

The name of a categorical variable, as used in modelling, is given in parenthesis

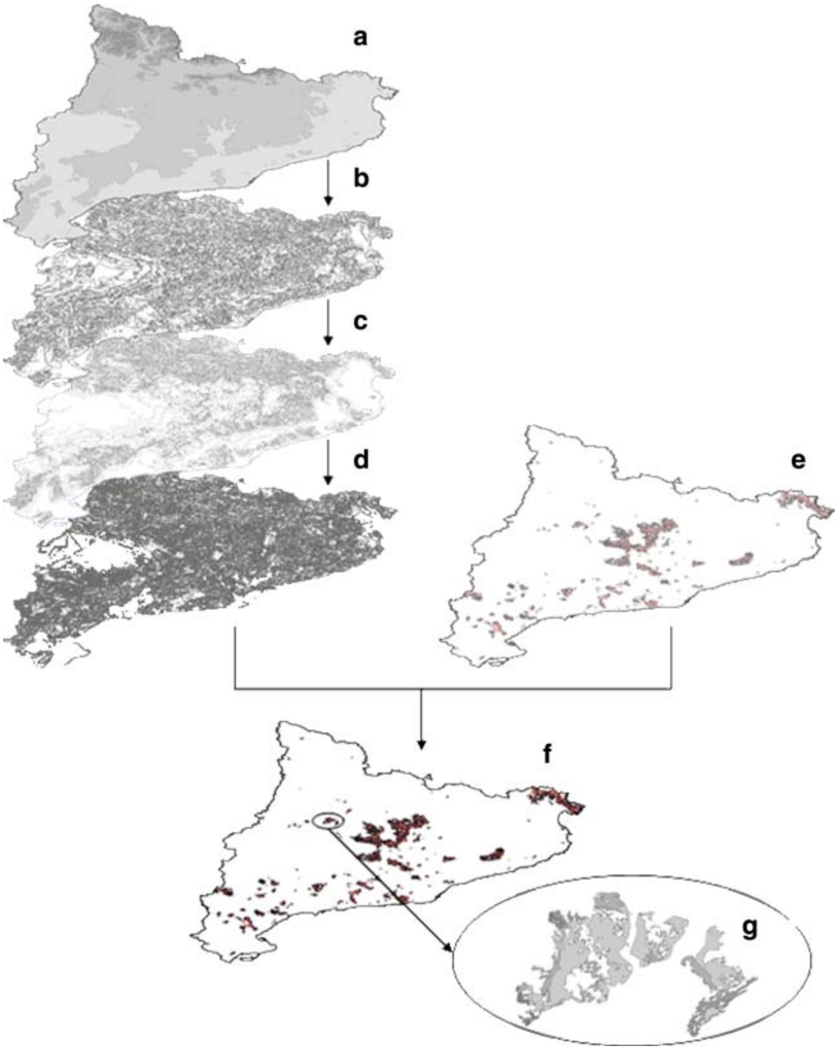

Fig. 1 Layers used to classify forest and calculate the proportion of burned area: altitude classes (**a**), slope classes (**b**), aspect classes (**c**), fuel and species classes (**d**), and perimeters of fire events (**e**). Layer **f** indicates forest classes enclosed within the fire perimeters, and **g** is an example of different forest classes within one fire event

The altitude classes (Table 1) followed the altitudinal series of vegetation applied in the IFN3. Aspect was divided into four classes depending on the main orientation of the slope (north, east, south, west). Slope classification was similar to the one applied in the IFN. Fuel class depended on the structural type of the stand and the stage of vegetation development. The stage of vegetation development followed the division indicated in the third national forest inventory IFN3 (ICONA 1993). Five species classes were used. A minimum vegetation cover of 20% was required for species and fuel classification; if the coverage was less that 20%, fuel and species class were zero.

Table 2 Number of fire events recorded during sub-periods 1942–1962, 1963–1982 and 1983–2002, and during the whole study period 1942–2002

Size (ha)	Period			
	1942–1962	1963–1982	1983–2002	1942–2002
<500	141	4,182	3,646	7,969
501–1,000	5	36	30	71
1,001–1,500	0	10	13	23
1,501–2,000	0	8	5	13
2,001–2,500	0	6	4	10
2,501–3,000	0	5	3	8
3,001–3,500	0	1	1	2
3,501–4,000	0	0	3	3
4,001–4,500	0	0	3	3
4,501–5,000	0	2	3	5
5,001–6,000	0	4	3	7
6,001–7,000	0	1	0	1
7,001–8,000	0	1	0	1
8,001–13,000	0	0	1	1
13,001–14,000	0	0	1	1
14,001–15,000	0	0	1	1
15,001–17,000	0	0	2	2
Total	146	4,256	3,719	8,121

For each of the three topographic criteria (altitude, aspect, and slope), the whole Catalonian territory was divided into classes, and a polygon coverage of classes was created using ArcGIS 6.0. For the two vegetation-related criteria (fuel and species) the classification was realized through simple selections and operations on the MFE50 attribute table creating one layer, which combined these two attribute fields (layer d in Fig. 1). A union operation of the different information layers permitted the creation of a new polygon coverage in which all the five chosen criteria were represented (Fig. 1). This coverage was used to estimate the area of each combination of classification criteria. There were 2,000 potential forest classes, but only 754 of these were present in Catalonia, of which 396 were affected by forest fires.

The calculations produced the proportions of burned areas for 754 forest categories differing in altitude, slope, aspect, fuel class, and species class. These data were used to fit a logistic model that described the dependence of the proportion of burned area on the classification criteria. Classes in which the fuel class was not zero were included in the analysis (691 classes). Class means of continuous variables (altitude, aspect, slope) were used as predictors whereas the categorical variables (fuel class, species class) were dealt with using dummy variables.

The predicted variable (y) was the logit transformation of the proportion of burned area:

$$y = \ln\left(\frac{p}{1-p}\right) \tag{1}$$

where

$$p = \begin{cases} 0.01 & \text{if} \quad P_{\text{burn}} \leq 0.01 \\ P_{\text{burn}} & \text{if} \quad 0.01 < P_{\text{burn}} < 0.99 \, . \\ 0.99 & \text{if} \quad P_{\text{burn}} \geq 0.99 \end{cases}$$

P_{burn} is the observed proportion of burned area. The logit transformation forces the prediction to be within zero and one. The model was estimated using the ordinary least squares (OLS) method in the SPSS program (SPSS 12.0). The model described the linear relationship between the logit transformation of the proportion of burned area and the predictors.

Results

Number and area of fires

During the whole study period (1942–2002), 8,121 forest fires were recorded in the study area (Table 2), burning 477,982 of forest land. Most of the area burned (67%) corresponded to 152 fires larger than 500 ha. During the first sub-period (1942–1963), only 146 fires were recorded, with a total burned area of 12,388 ha. Only 5 fires were larger than 500 ha, accounting for 27% of the total area burned. During the second sub-period (1963–1982), 4,256 fires were recorded, with a total burned area of 210,039 ha. Seventy-four of these fires were larger than 500 ha, accounting for 59% of the burned area. During the third sub-period (1983–2002), 3,719 fires were recorded, with a total burned area of 255,554 ha. Seventy-three fires were larger than 500 ha, but this time they accounted for 75% of the burned area.

During the first sub-period (1942–1962) the recorded fire events were rather few, and most events were in the last years of the sub-period (Fig. 2). The second sub-period (1963–1982) was characterized by a higher number of events, especially those burning less than 500 ha, but none over 10,000 ha (Table 2). The third sub-period (1983–2002) was characterized by the appearance of very large fires of over 10,000 ha (Table 2), which caused the concentration of most of the burned area in a few years (1986, 1994 and 1998), the remaining years having a relatively small burned area (Fig. 2). Only small differences were observed in fires (less than 500 ha) between the second and third period (Fig. 3). The number of fires smaller than 50 ha was clearly higher during the third sub-period (1963–1982).

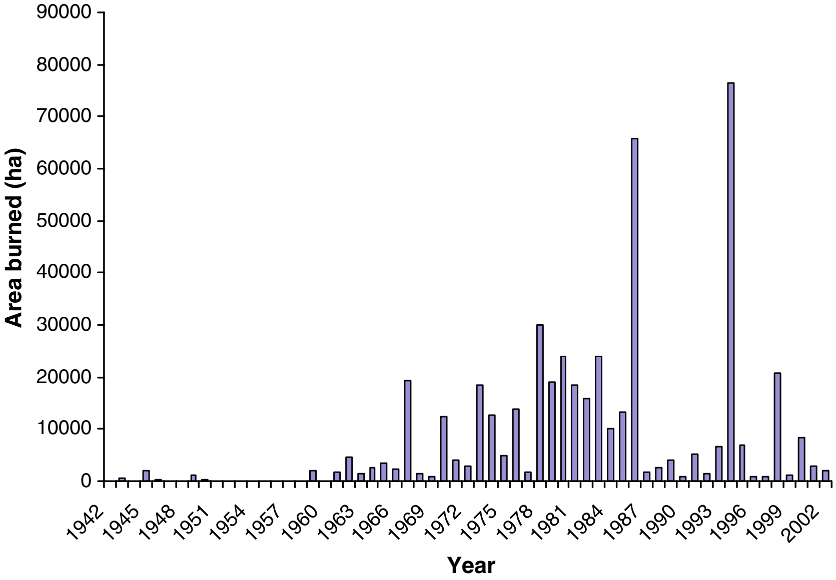

Fig. 2 Annual burned area recorded in Catalonia during the period 1942–2002

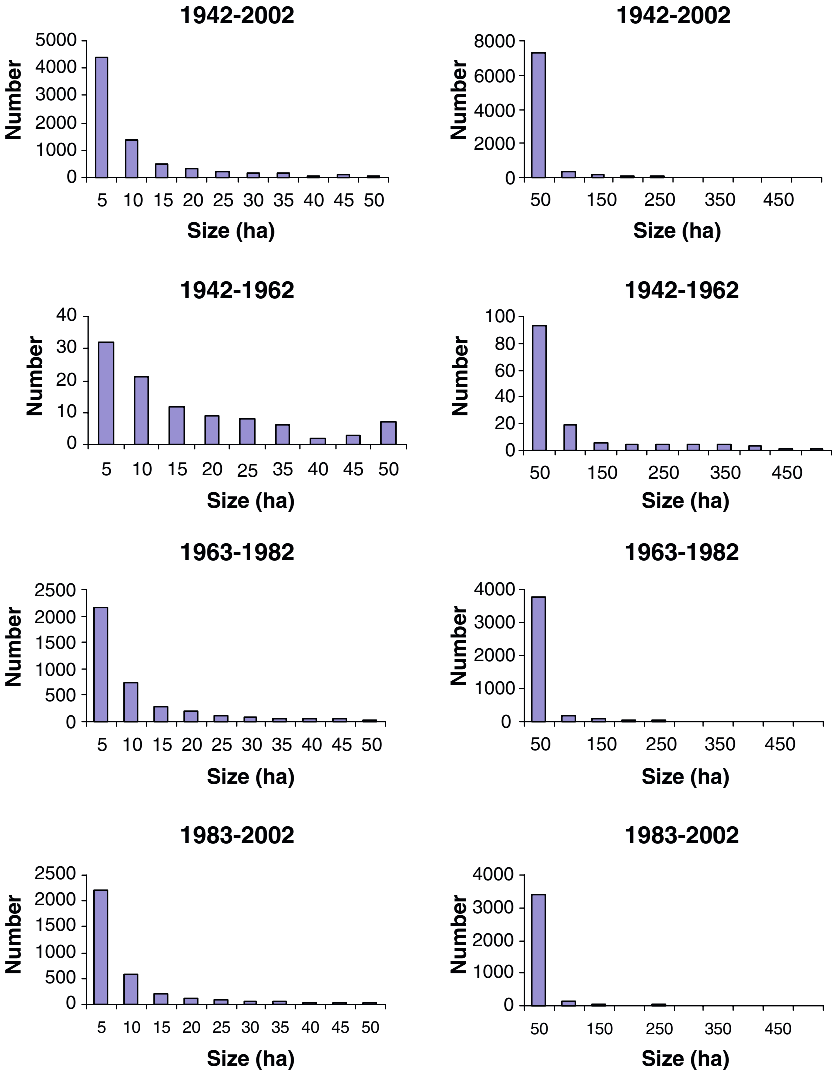

Fig. 3 Number and size distribution of small (<500 ha) fire events in Catalonia during the study period 1942–2002 and the sub-periods 1942–1962, 1963–1982 and 1983–2002. On the *left side*, the fires under 50 ha are shown, on the *right side* fires under 500 ha are shown

Proportion of burned forest

The best fit for the logit transformation of the proportion of burned area was obtained for the following model:

$$\begin{aligned} y = & -2.692 - 0.000830\mathrm{Alt} - 0.0606\mathrm{Slo} - 0.686\mathrm{North} \\ & - 0.721\mathrm{Young} - 2.692\mathrm{Trees} - 2.893\mathrm{TwoLayer} \\ & + 2.557\mathrm{Pine} + 3.793\mathrm{Oak} + 3.416\mathrm{PineOak} \\ & + 2.340\mathrm{OtherSp} \end{aligned}$$

where y is the logit of the proportion of burned area, Alt is altitude (m), Slo is slope (%) and the others are indicator variables that indicate the aspect, fuel or species class (see Table 1). All predictors were significant ($P < 0.05$). The RSME (root of mean square error) was 2.509 for the logit and 0.214 for the back-transformed proportion of burned area. The bias was 0 for the logit and –0.081 for the proportion of burned area. The R^2 (adjusted for the degrees of freedom) of the model was 0.38. The logit is converted into proportion of burned area as follows:

$$P_{\mathrm{burn}} = \frac{\exp(y)}{1 + \exp(y)}$$

According to the model, elevation and slope decrease the proportion of burned area (Fig. 4). The proportion is much lower on northern slopes than on other aspects. Areas with a tree cover (trees taller than 8–10 m) have a much smaller likelihood to be passed by fire than pastures and areas with bushes, young regeneration, or small trees. If an area occupied by trees has a lower story of bushes or small trees the probability to be burned is almost doubled (Fig. 4). Oak stands have the highest probability to be burned, followed by oak–pine mixtures, pine stands, and stands of other species. The high probability of oak may be due to interactions between classes (e.g. oaks are more often-bush like than pine, have more vertical structure in the stand, are located at lower elevations etc.). However, the interactions were not statistically significant model predictors.

Discussion

The analysis of historical fire data in Catalonia allowed us to determine changes in the distribution of fires, their number, size and affected area. When combined with other spatial variables such as topography and land cover, it was possible to establish certain patterns in the occurrence of fire at the landscape level, for example identify which kinds of forest are the most susceptible to fire. The results can help to identify weaknesses and strengths of alternative forest and fire management alternatives.

The temporal analysis of the fire data showed clear variations in the number of fires, their sizes and the total burned area over the period 1942–2002. The data from 1942–1962 had several gaps, which means that the results for 1942–1962 should be considered as underestimates and therefore unreliable. No drastic changes in the number of fires and total burned area were ob-

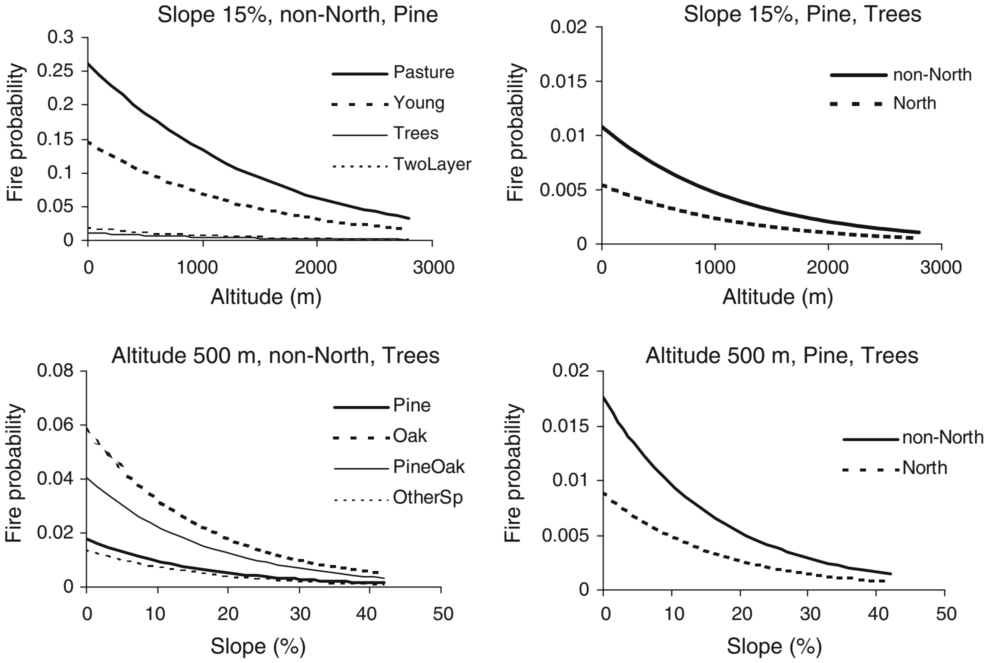

Fig. 4 Dependence of the probability to be burned by forest fire on altitude, slope, aspect, fuel class, and species class according to the model of this study. The class names and class descriptions are in Table 1

served between periods 1963–1982 and 1983–2002. However, during the last period (1983–2002), a high proportion of burned area was accounted for by a smaller number of large fires. It is not easy to determine how the changing factors (climate, ignition sources, land uses, suppression policies etc.) have affected the fire regime in Catalonia and at which level. Even if the changing conditions over the last decades on the three first factors (climate, ignition sources, land uses) have been reported to have a clear influence on the increment of the number of fires and fire size (climate according to Stocks 1993; Swetnam 1993; Piñol et al. 1998; ignition sources according to Vázquez and Moreno 1995; Terradas et al. 1998; land uses according to Debussche et al. 1999; Badia 2002; Lefort et al. 2003), it is difficult to define a certain starting point when the changes began to have a significant effect on the fire regime. However, the assumed variation in these factors has not had the expected effect on the change of some aspects of the fire regime, as the number of fires has decreased slightly and the total burned area has increased only slightly. In contrast, the number of catastrophic fires has increased significantly over the last decades, which can be related to the increment of continuous areas of forested land and the increase in the number of days with very severe fire-weather conditions, and also to increasing risk of ignition due to human causes.

On the other hand, an exact moment of change in fire suppression activities can be given. In 1986, a special fire prevention and suppression plan was adopted in the region (DARP 1999). The effect of fire suppression policies on the fire regime has resulted in strong debates within the scientific community, some studies suggesting that aggressive fire suppression contributes to the size reduction of fires and total amount of burned area (Stocks 1991; Ward and Tithecott 1993). However, others consider that a successful fire suppression policy can drive to a more homogeneous configuration of the landscape and a higher rate of fuel accumulation, which may increase the number of catastrophic fires (Minnich 1983, 2001). The third opinion is that fire suppression policies do not have any significant effect on the fire regime, especially on large fires (Moritz 1997, 2003; Keeley and Fotheringham 2001; Miyanishi and Johnson 2001; Bridge et al. 2005).

After observing the number and sizes of fires in our study area, we adventure to say that the trend in the Catalonian region is slightly increasing forest area affected by fires, with the number and area of small fires probably being controlled by the fire suppression efforts. However, it is difficult to see any significant effect of fire suppression on very large fires, which may be due changes in extreme weather conditions. The large fires represent an increasing percentage of the total area burned in the region. This trend is visible from the relatively small amount of area burned in most years of the period 1982–2002 when compared to the period 1962–1982 (Fig. 2).

The analysis of fire-landscape relationships used digitalized fire atlases, digital elevation models and forest cover maps. It provides useful information for evaluating factors that control fire regimes on regional scales (Rollings et al. 2002). Fire occurrence depends on multiple factors (vegetation cover, topography, climatic conditions etc.). The present study used only characteristics of the forest cover and topographical variables to explain variation in fire occurrence probability. The effect of altitude on the probability of fire is clear and strong, with lower and middle elevations being the most prone to fire. This result is in accordance with the suggestion that fire happens at elevations where fuel continuity and moisture are not limiting factors (Martin 1982). Altitude also correlates negatively with population density with a consequence that human-induced fires most probably decrease with increasing altitude. Aspect affects fuel moisture (Waring and Running 1998), and through fuel moisture it affects the fire occurrence probability. Most of the area burned in our study area corresponded to east and south aspects, which were also the most common forested areas. Slope is an important factor for determining fire behaviour and fire occurrence (Agee 1993) with higher frequencies normally found on steeper slopes, caused by the easiest transfer of heat uphill, possible ‘‘chimney’’ effects, and lower fuel moisture. In our case, however, most of the burned area was located on slopes between 3 and 19%, which also had the highest probability of fire. The reason why steeper slopes (more than 20%) had lower fire probabilities may be that most steep slopes are at high elevations in which moisture decreases the probability of fire. In regional analysis the previously mentioned effects of slope on fire occurrence may lose significance (Rollins et al. 2002).

Land cover (fuel and vegetation types) is expected to affect fire occurrence across the landscape, due to different probabilities of ignition (Burgan et al. 1998), vertical continuity of fuels (Pollet and Omi 2002), and the continuity across landscape of different types of forest (Weir et al. 2000). In our study, the highest fire probabilities corresponded to areas covered by bushes and young trees. This result, even if logical, has to be more deeply analysed, as some of the area corresponding to this fuel type may have changed during the study period, mainly due to fires occurring in more mature forest and a subsequent transition to earlier stages of development. On the other hand, mature forest with little or no under-story had low fire probabilities, which is logical and matches with previous studies (Pollet and Omi 2002; González et al. 2006). When a mature stand had an under-storey of bushes or small trees its likelihood to become burned increased clearly, which is in line with earlier studies (Rothermel 1983; Finney 1999). Of the tree species oak had the highest proportion of burned area, which is surprising because other authors (Velez 1990; Bond and Van Wilgen 1996) have pointed out the high flammability of coniferous species. The high probability of oak may be caused by interactions between species class and other variables like altitude and fuel class, but when those interactions were analysed they were not statistically significant model predictors. Another explanation may be the high resprouting capability of some Mediterranean quercus species such as *Q. ilex* and *Q.coccifera* (Retana et al. 1992; Pausas 1999), which can led to quercus dominated forest in places with high fire recurrence.

The observed increment of large fires can result in a significant increase in the total area burned. Fire suppression policies will find it hard to deal with extreme conditions favouring the occurrence of very large fire events. More emphasis has to be set in the management of fuels as a more feasible way to reduce hazardous conditions. In this context forest management can play a major role in fire prevention. Forest planning tools dealing with the problem in a landscape and even regional dimension, and permitting the manager to analyse the spatial arrangement of risky and non-risky forest types, can be an interesting approach (González et al. 2005). Further research is needed in the recognition of variables that make a forest type susceptible or resistant to fire, along with the spatial relationship between forest types that makes a landscape or region susceptible or resistant to fire.

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