Modelling the risk of forest fires in Catalonia (North-East Spain) for forest management planning purposes

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Abstract

The inclusion fire risk assessment into forest management enables the manager to analyse the risk and uncertainty due to forest fires, and assess the expected losses that fires may cause on the forest outputs. On the other hand, forest management and planning offers an appropriate framework for identifying efficient measures for long term fire prevention. If fire risk is to be included in forest management planning, models for assessing the probability of fire occurrence, and expected fire damage are required. As stands are regarded as the basic and indivisible forest management units, it is logical to develop stand-level models as the first step of including fire risk considerations in forest planning. These models must be based on stand variables the future value of which is known with reasonable accuracy. If a model is to be used for forest planning purposes, it also has to consider variables that are under the control of the manager. In that way the manager will have the possibility of minimising the expected losses due fire as a management objective in numerical planning calculations. Such models have been developed for Catalonia (North-East Spain) using data from the Spanish national forest inventory and perimeters of fires that occurred in Catalonia. Those models showed that both the occurrence of fires and the potential damage caused by fires are related to stand characteristics such as species composition, tree size, stand structure, and to topogeographical variables such as elevation and slope.

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Introduction

Fire is the most important cause of tree mortality in the Mediterranean basin (Alexandrian and others 2000), and a threat to private and public goods provided by Mediterranean forest. In Catalonia, forest fires are perceived by the public as the main environmental problem (Tábara 1996). During the last decades the problem of forest fires in Catalonia has taken a new dimension due to changes in the fire regime, larger and more destructive fires are more common (González and Pukkala 2007). One reason for the change in the fire regime is the lack of proper forest management due to abandonment of rural areas and the low profitability of traditional forest practices. This leads to the accumulation of forest fuels.

In this context, the inclusion of fire risk analysis in forest planning is clearly justified. Such analyses help to reduce the uncertainty by anticipating the outcomes of management alternatives in a systematic way, and identifying management options that reduce the expected losses due to fire (Gadow 2000). The inclusion of fire risk in forest management planning requires a set of models for assessing, in a quantitative way, the risk of fire attached to different forest types and management options. This information can be generated using statistical methods and historical data on forest fires and forest characteristics. Once such models are developed, they can be included in forest simulators. In this way, the risk of forest fires can be considered explicitly in forest planning problems.

If the risk of fire is to be included in forest planning, models for assessing the probability of fire occurrence and the potential damage caused by fire are required. These models should be able to predict the long-term consequences of management alternatives. Therefore, they must be based on predictors, which can be easily calculated with a reasonable accuracy, and which are under the control of the forest manager. The variables driving the behaviour of wildland fires are normally grouped into climatic, topographic and fuel related variables. Among these, only fuel can be controlled (Weatherspoon and Skinner 1995). Variables related to the aboveground vegetation such as stand density, species composition, vertical structure of the canopy, tree size and hierarchical position of the trees are all known, controllable and related to fuels. They are therefore useful predictors in models that are used in forest planning systems. As stands are regarded as the basic forest management unit it is reasonable to developed models for the stand level. Based on this rationale, the following models were developed:

1. A model that predicts the probability of fire occurring in a forest stand.
2. A model that predicts the damage caused by fire in a forest stand, once fire occurs.
3. A model to predict the survival probability of each individual tree in a burned stand.

Modelling the risk of fire in Catalonia

Catalonia is located in the north-east of the Iberian Peninsula, occupying an area of over 32 000 km^2 (Figure 1). The majority of the territory is dominated by a typical Mediterranean climate with a pronounced seasonality, characterized by cold and moist winters and dry and hot summers (Terradas and Piñol 1996). The altitude in the region ranges from sea level to over 3000 meters, playing an important role in local weather conditions and distribution of forest types. Approximately 61% of the region is covered by shrublands and forest, the share of forest being 37.9 % of the total area

(Gracia and others 2004). The Catalonian forests are dominated by pines including: *Pinus halepensis*, *P. sylvestris*, *P.nigra*, *P. uncinata* and *P. pinea*, and oaks such as *Quercus ilex, Q. suber and Q. humilis*, followed by other species such as *Fagus sylvatica*, *Castanea sativa*, *Abies alba*, *P. pinaster* and *Q. cerrioides*. A total of 131 tree species have been found in the Catalonian region (Gracia and others 1992).

The data used for modelling the occurrence and effect of forest fires consisted of the National Forest Inventory (NFI) data and fire occurrence data (Figure 1). The 2nd Spanish National Forest Inventory for Catalonia with fire perimeters was used for the occurrence model while data from the 2nd and 3rd NFI were used for the damage and survival models. The Spanish National Forest Inventory consists on a systematic sample of permanent plots, distributed on a square grid of 1 km, with a re-measurement interval of 10-years (ICONA 1993; DGCN 2005). The fire data consisted of the perimeters of fires larger than 20 ha, determined on a 1:50 000 scale by the *Department de Medi Ambient I Habitatge* and the *Intitut Cartográfic de Catalunya.* The fire perimeters were used to determine which plots were affected by fire during the time period considered in the model.

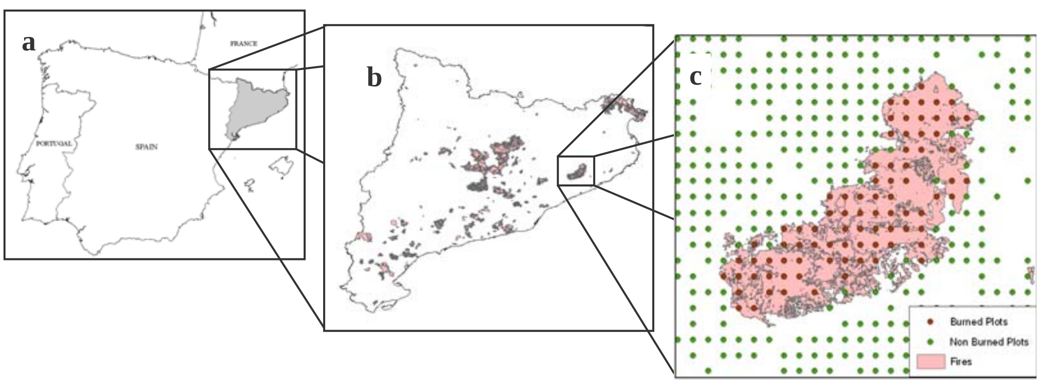

Figure 1— Location of Catalonia (**a**) Distribution of forest fires occurred in Catalonia during the period 1989-2002 (**b**), a part of the national forest inventory plots used in the study (**c**).

Modelling the probability of fire occurrence

The perimeters of the fires occurring in Catalonia 12 years after the 2nd measurement of the NFI plots were used to determine which NFI plots were affected by fire during that period and which plots were not. From a total of 10 855 plots used in the study, 770 were affected by one of the 231 fires (>20 ha) occurring in Catalonia during the period 1991-2002. With this information, binary logistic regression was applied to determine which stand characteristics had a significant effect on the probability of fire occurrence (González and others 2006), and the following model was developed:

$$P_{fire} = \left(1 + e^{\left(-1.925 - 2.256 \times ELE - 0.015 \times Dg + 0.012 \times G - 1.763 \times P_{hard} + 2.081 \times \left(\frac{SD}{Dg + 0.01} \right)\right)} \right)^{-1} \qquad (1)$$

where P_{fire} is the 12-year probability of fire occurring in a given stand, *ELE* is a transformation of the elevation, *Dg* is basal area weighted mean diameter of trees (cm), *G* is the stand basal area (m^2/ha), P_{hard} is the proportion of hardwood species present in the stand, and *SD* is the standard deviation of the diameters trees (cm). The last predictor *(SD/(Dg +0.01))* expresses the relative variability of tree diameters. The variable is close to 1 in rather uneven ages stands, and approaches to 0 in homogeneous stands. Variable *ELE* is equal to ln(max{1, *Elevation*-6)), where *Elevation* is in hundreds of meters above sea level. This transformation of elevation was used to express a trend in the modelling data which indicates that most fires occur at elevations lower than 700 metres.

The variables used as predictors in the model can be divided into variables dependent on forest management (*G, Dg*, P_{hard}, and the relation between *SD* and *Dg*) and variables related climatic conditions (*ELE*). The probability of fire occurrence is high for forests located between 0 and 700 metres a.s.l. Dense stands with an abundant conifer mixture and with high variation in diameter tend to increase the probability of fire occurrence (Figure 2). On the contrary, the presence of hardwoods and the absence of small trees reduce the probability of fire.

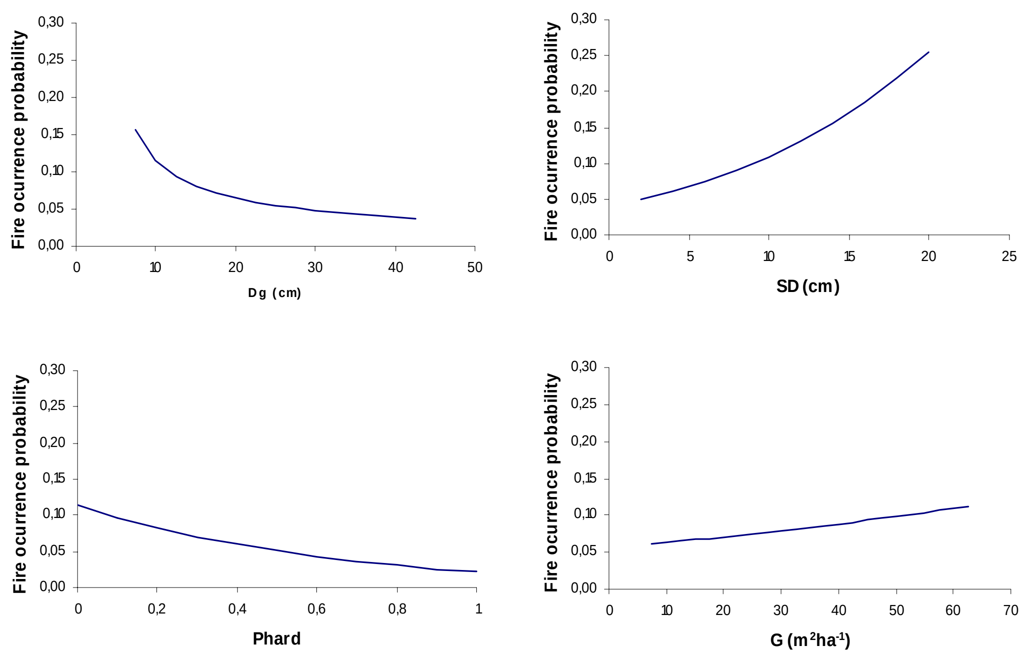

Figure 2— Effect of basal-area-weighted mean diameter (*Dg*), standard deviation of dbh (*SD*), proportion of hardwood of the number of trees (P_{hard}), and total basal area (*G*) on the probability of fire occurrence.

Modelling stand damage and tree survival in fires

The effect of a forest fire on a forest stand, was estimated from the changes observed in the plots of the NFI plots affected by fire during the period between the 2nd and 3rd measurement (aprox 10-years). The use of permanent plots by the Spanish National Forest Inventory allowed us to identify which trees present in the 2nd NFI died before the 3rd NFI. A total of 722 plots were affected by fire during the study period period. During the 2nd NFI there were 9598 trees on these plots, of which 6229 survived until the 3rd NFI while 3369 died, accounting for a 0.65 survival rate, versus the 0.96 observed in the non-burned plots (Table 1). This permitted us to model the damage caused by fire, and the probability of tree survival probability in forest fires as a functions of different stand and tree-level characteristics (González and others 2007a).

	Tree level data			Stand level data		
	N	Survival	Baseline	***N***	Damage	Standard deviation
Pinus sylvestris	574	0.74	0.959	23	0.32	0.34
Pinus pinea	280	0.92	0.979	16	0.18	0.35
Pinus halepensis	2201	0.50	0.966	286	0.45	0.46
Pinus nigra	4741	0.67	0.979	276	0.42	0.41
Pinus pinaster	106	0.55	0.988	5	0.40	0.55
Quercus faginea	240	0.48	0.978	7	0.11	0.29
Quercus ilex	552	0.62	0.979	41	0.19	0.38
Quercus suber	628	0.94	0.974	35	0.11	0.21
Other sp.	276	0.67	0.970	33	0.07	0.25
Total	9598	0.65	0.964	722	0.38	0.43

Table I— *Number of observations (N), observed survival probability (Survival), and mean proportion of dead trees (Damage) in the stands for the eight most common tree species and the whole study material (Total). "Baseline" is the mean survival probability in non-burned inventory plots.*

The stand-level damage model had the following form:

$$y = b_0 + b_1 G + b_2 Slope + b_3 Pine + b_4 \left(\frac{G}{D_q + 0.01} \right) + b_5 \left(\frac{s_d}{D_q + 0.01} \right) + e \qquad (2)$$

where $y = \ln(P_{dead} / (1 - P_{dead}))$, P_{dead} is the proportion of dead trees in the stand (in terms of number of trees), G is the stand basal area ($m^2 ha^{-1}$), *Slope* is the percentage of altitude change per distance change (%), *Pine* is a dummy variable which equals 1 if the stand is dominated by pines (> 50 % of basal area is pine) and 0 otherwise, s_d is the standard deviation of the breast height diameters of trees (cm), D_q is the quadratic mean diameter (cm) of trees, and e is the standard deviation of the residual (standard error). The predictor $G/(D_q+0.01)$ is non-linearly related to the number of trees per hectare. The last predictor $s_d\,/(D_q+0.01)$ expresses the relative variability of tree diameters. The variable is close to 1 in rather uneven stands and approaches to 0 in homogeneous stands.

Additionally, a model was developed using binary logistic regression to predict the probability of a single tree to survive a fire event, depending on the size of the tree and the level of damage caused by fire at stand-level.

$$P_{sur} = \left(1 + e^{-(b_0 + b_1 d + b_2 P_{dead})}\right)^{-1} \tag{3}$$

where P_{sur} is the probability of survival, d is the diameter of the tree at the breast height (cm), and P_{dead} is the proportion of dead trees.

From the models it can be concluded that once a fire takes place, stands on steep slopes, with an abundance of small trees and high variation in tree size are the most vulnerable to fire in terms of damage (proportion of dead trees). The smallest trees in these stands are the most susceptible to die (Figure 3). These results are in accordance with previous studies in terms of indicating the most vulnerable forest structures (Pollet and Omi 2002, Agee and Skinner 2005) and trees (Ryan and Reinhardt 1988; Peterson and Arbaugh 1989; Beverly and Martell 2003; Hély and others 2003; Rigolot 2004). The models suggest that conversion of uneven stands into even-aged forest structures and adequate thinnings are feasible silvicultural means to reduce the risk of fires (both fire occurrence and fire damage). No significant differences were observed between different species with respect to their survival probability, except in the case of *Pinus pinea* and *Quercus suber* that showed a special resistance to fire-induced mortality (more details in González and others 2007a)

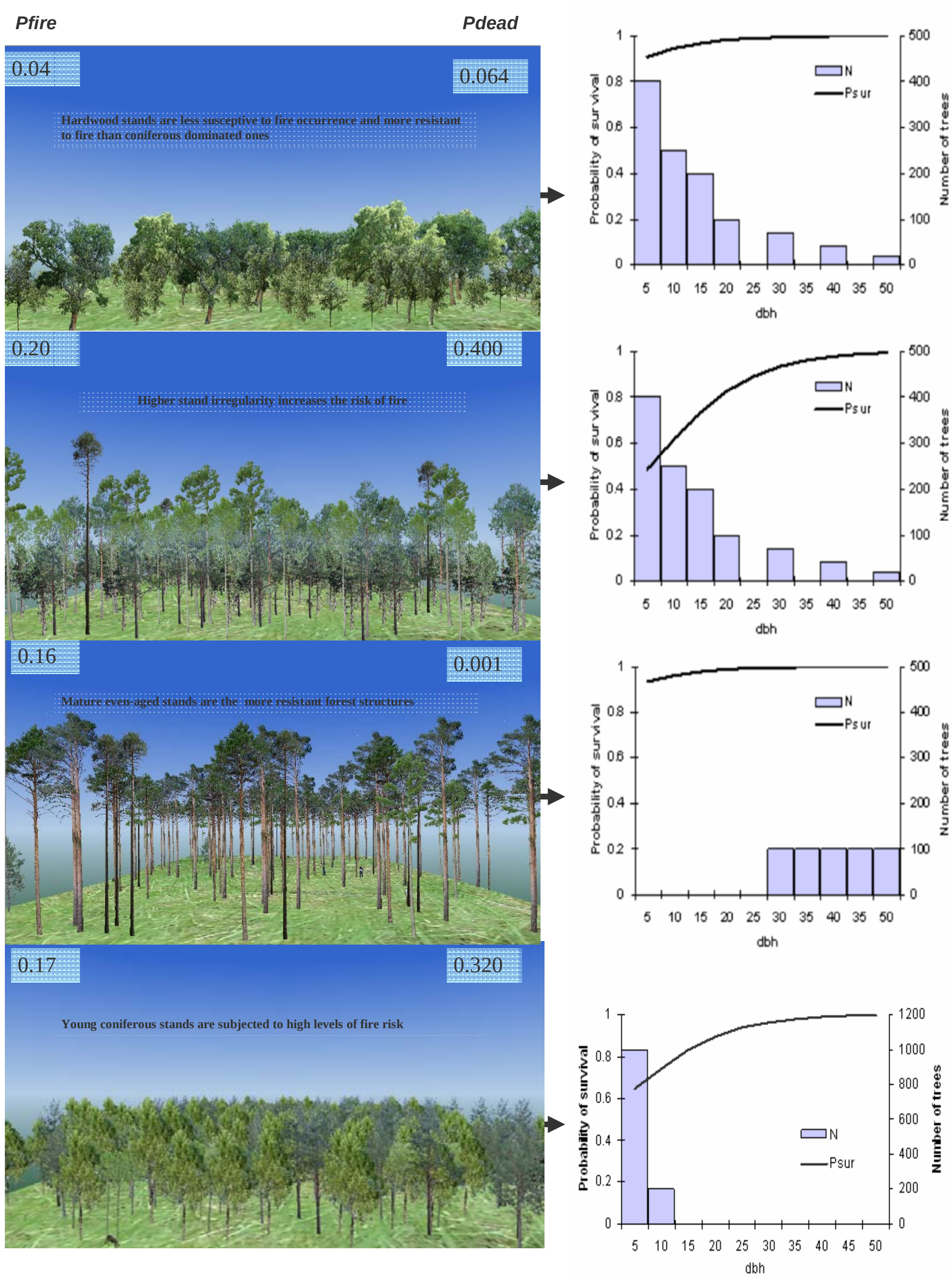

Figure 3— Fire risk depending on the stand structure and composition (altitude 700 meters and slope 12%). The images on the left represent different forest stands and their predicted probability of fire occurrence (*Pfire*) and damage in proportion of dead trees (*Pdead*). On the right, the diameter distributions (N, number of trees per diameter class) and the survival probability if trees in different diameter classes (*Psur*) are shown.

Conclusions and application of the models

In the Mediterranean region, the heaviest investments regarding fire management have been on fire-fighting equipment rather than prevention. However, during the last decades fire prevention has gained reputation as an efficient and cost-effective way to deal with forest fires. In this context, forest management planning can make a major contribution to reduce the long-term fire vulnerability of our woodlands, providing new tools for active and sustained fire prevention policies, which can be integrated into the forest management process, providing new opportunities for rural areas.

The presented fire occurrence, damage and survival models were developed based on variables measured on regular inventories. Some of the variables used in these models depend on forest management, meaning that the risk of fire can be modified through forest management. These characteristics make the models especially appropriate for forest management planning purposes, and allow their use in multiple studies and applications related with the inclusion of fire risk into management planning. These models, based on empirical data, are in line with the concepts and knowledge widely accepted by the experts on forest fires about forest characteristics that have an impact on this type of risk.

The models presented can be used to simulate the development of forest stands under the risk of forest fires, by generating stochastically fire occurrences and damages caused by them. Stochastic simulations have been found to be useful to solve stand level optimization problems were minimizing the risk of forest fires was an objective (González and others 2005b, González and others 2007c). These stand level optimizations can be used to define management guidelines for forest stands under the risk of fire. Another application for such stochastic simulations is their use in regional scenario analyses (González 2006). Scenario analyses can use a network of inventory plots, like the Spanish national forest inventory one, and a set of predefined management instructions, to predict the development of the forest resources in a certain region. Finally, the models can be used to calculate fire resistance indexes for alternative management schedules of stands. These indexes can be used to calculate various landscape metrics for fire resistance, which can be used as objective variables on numerical optimization. Landscape metrics help in reaching such landscape compositions and configurations that are resistant to forest fires (González and others 2005a).

Variables not included in the models, like the abundance of ground vegetation and dead fuels, play a mayor role in defining the behaviour and the severity of forest fires (Rothermel 1983; Finney 1999). These variables affect the vulnerability of a forest stand to fire, and can be controlled through forest management. However, the inclusion of such variables requires information which is difficult to obtain or predict over long periods of time and across heterogeneous landscapes (He and Mladenoff 1999). Attempts were made to include ground vegetation as a predictor in the models but the results were encouraging. Other approaches, such as modelling the knowledge of experts in fire ecology and fire fighting, proved to be an interesting an viable way to analyze the effect that ground vegetation have on the vulnerability of a forest stand to fire (González and others 2007b).

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