Dissertationes Forestales 23

Integrating fire risk into forest planning

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Academic Dissertation

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ABSTRACT

The present thesis deals with the inclusion of fire risk considerations into forest planning in Catalonia (North-East Spain). The first part of the thesis focused on the modeling the susceptibility of different kinds of forest to fire (Studies I, II, III and IV), and the second part on the inclusion of the acquired knowledge about fire risk into forest planning systems (Studies V and VI).

The models were developed for forest planning purposes, all the predictors being easily obtainable through forest inventories or forest simulators, some of them being also dependent on forest management. Studies I and II developed models for predicting the probability of fire occurrence, using data on fire perimeters, the Spanish forest map (MFE50), and the second Spanish Forest Inventory. In Study III, models to predict the fire damage at stand level and the post-fire tree survival probability were developed using data from fire perimeters and from the second and third Spanish Forest Inventory. The models developed in Study IV were based on the opinions of experts with respect to the vulnerability of different forest stands to fire. Studies I and II showed that elevation plays a mayor role in determining the probability of fire occurrence, forest stands located in lower elevations being more frequently affected by fires. The results obtained also indicate that mature stands, with low vertical irregularity, and no presence of ground vegetation have the lowest risk of fire. Large trees in dominant positions are the least susceptible to fire mortality.

The model developed in Study II for predicting the probability of fire occurrence was included in two different planning applications. The first application (Study V), solved a stand level problem on the optimal management when the objective function was maximized subject to fire risk. The second application (Study VI) consisted of a landscape level problem where different landscape metrics were analysed as means to modify the spatial configuration of a forest landscape through forest planning, taking into account the stands’ fire resistance. The summary of the thesis also presents a regional scenario analysis in which the developed models to predict the probability of fire occurrence, degree of damage, and probability of tree survival were used in simulations, which predict the standing and harvested volume of timber. The studies indicate that the optimal rotations of stands shorten when the risk of fire increases. The timber yields at a regional level can be significantly overestimated (10-20%) if the risk of fire is not considered.

Keywords: risk management, optimal stand management, spatial optimisation, landscape structure, fire occurrence model, fire damage model, expert modelling

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Joensuu, May 2006

José Ramón González Olabarria

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following papers referred into the text by the Roman numerals I-IV:

I González, J.R., and Pukkala, T. 2006. Characterization of wildfire events in Catalonia (north-east Spain). Submitted manuscript.

II González, J.R., Palahí, M., Trasobares, A. & Timo Pukkala, T. 2005. A fire probability model for forest stands in Catalonia (north-east Spain). Annals of Forest Science 63:169-176.

III González, J.R., Trasobares, A., Palahí, M., & Timo Pukkala, T. 2006. Predicting tree survival in burned forests in Catalonia. Submitted manuscript.

IV González, J.R., Kolehmainen, O., and Pukkala, T. 2006. Using expert Knowledge to model forest stands vulnerability. Submitted manuscript.

V Gonzalez, J.R., Pukkala, T. & Palahi, M. 2005. Optimising the management of Pinus sylvestris L. stand under the risk of fire in Catalonia (north-east Spain). Annals of Forest Science 62: 493-501.

VI González, J.R.. Palahí, M. & Pukkala, T. 2005. Integrating fire risk considerations in forest management planning in Spain – a landscape level perspective. Landscape Ecology 20 (8): 957-970.

J.R. González was responsible for the data analysis, compiling the results and writing all the articles. T. Pukkala supervised the writing process and the analyses of all the papers and prepared the simulation-optimisation programs used in Studies V and VI. M. Palahí and A. Trasobares participated in the analysis and writing process of the studies where they appear as co-authors. O. Kolehmainen provided the regression analysis software used in Study III, gave instructions for its use, and participated in finalising the report.

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1 INTRODUCTION

1.1 Catalonian forest and fires

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 (Figure 2 and 3). Approximately 61% of the region is covered by shrublands and forest, the share of forest being 37.9 % of the total area (Gracia et al. 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 et al. 1992).

Timber production is not an important component of the total production of the primary sector in Catalonia. However, the total share of the products related to the forest sector and its transformation chain represents over the 4% of the total Gross Production of Catalonia, primarily due the importance of non-timber products such as cork, mushrooms, pine seeds, truffles, hunting, fishing etc. (Plana and Domingez 2000). Additionally, if we consider other values of the forest or positive externalities, that normally fail to be included into the market such as; namely protection against erosion, watershed management, recreational values etc. (Merlo and Rojas 2000), it is easy to understand the important role that forests play in Catalonia.

Fire can be considered a natural element of the Mediterranean forest, determining its species composition and landscape structure (Trabaud 1994). The threat that fire entails to the private and public goods provided by the forest and even to the security of people has been reported extensively. In the Mediterranean area, forest fire is the most important cause of tree mortality, far ahead of any other biotic or abiotic hazard (Alexandrian et al. 2000), being also the cause of human casualties (Velez 1990).

Catalonia has not escaped the presence of forest fires and their effect on the environmental, economical and social values. Even during the middle ages, forest fires and their impact on the local economy captured the attention of some Catalan municipal authorities (Lloret and Marí 2001). However, during the last decades the problem has take a new dimension due to changes in the fire regime (Figure 4 and 5), attracting significant attention in the media and among politicians (Riera and Mogas 2004) and leading to increased public concern (Tábara 1996). Many factors have been considered to explain the variation in the fire regime in recent decades in Spain: Climate change (Piñol et al. 1998), changes in landscape configuration, (Badia et al. 2002), other aspects related to the land uses (Velez 2002), changes in the ignition causes (Vázquez and Moreno 1995), and even the success of the predominant fire suppression policy in Spain (Terradas and Piñol 1996, Piñol et al. 1998).

Figure 1. Location of Catalonia.

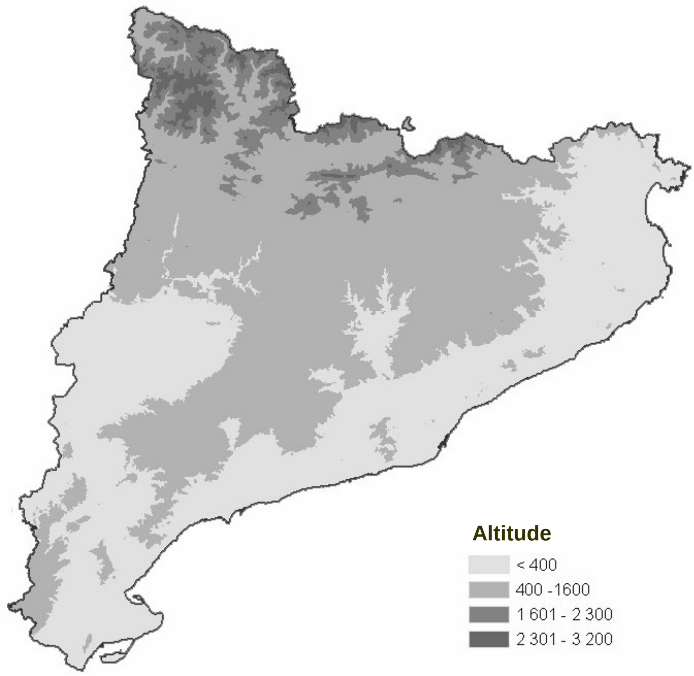

Figure 2. Altitude ranges according to the altitudinal series of the Spanish Forest Inventory: *Colino* < 400 m, *Montano* 400-1600 m, *Subalpino* 1601-2300 m and *Alpino* >2300 m.

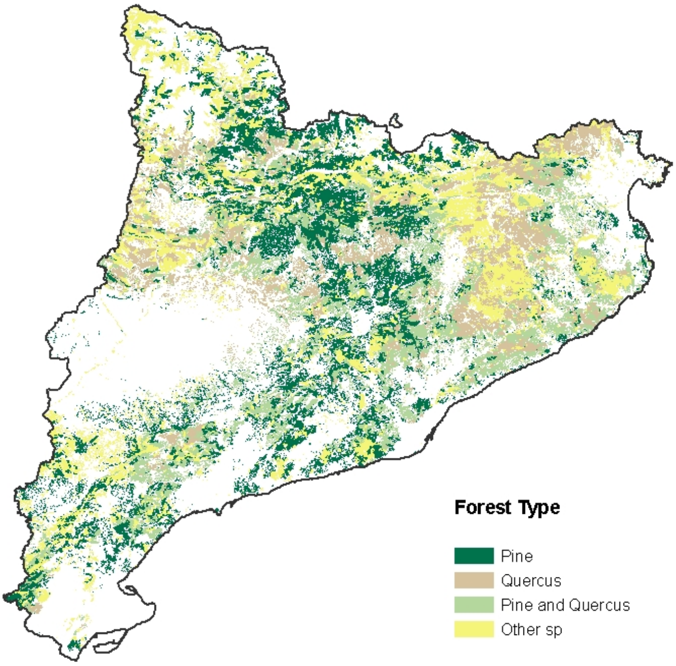

Figure 3. Distribution of forest types in Catalonia.

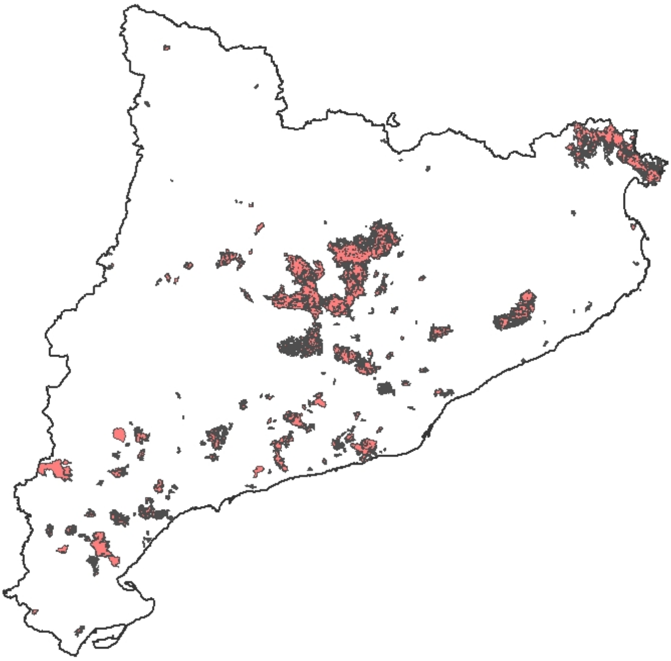

Figure 4. Distribution of forest fires (over 20 ha) in Catalonia during 1986-2000.

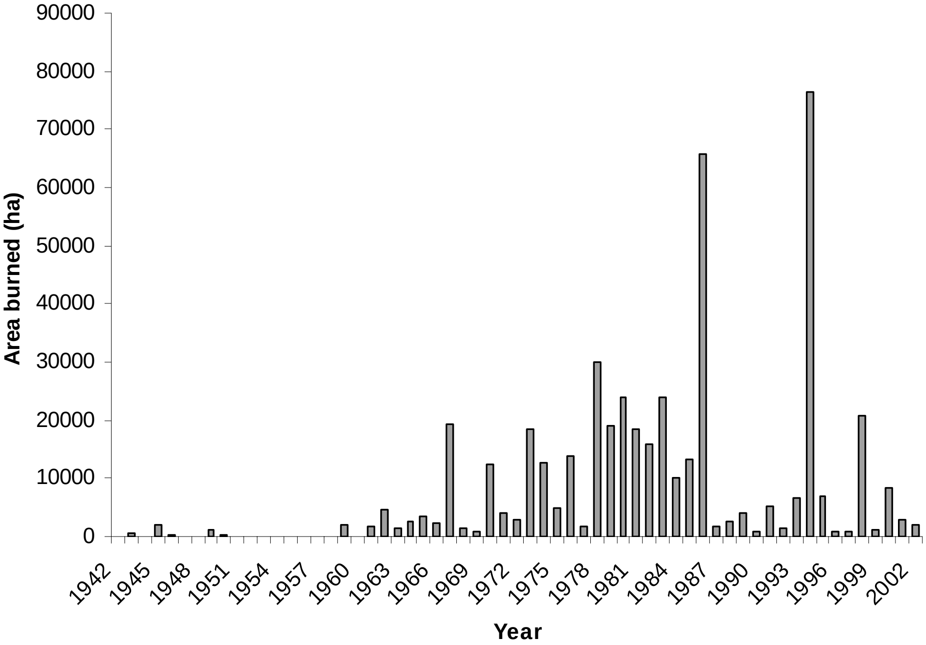

Figure 5. Temporal distribution of the area burned in Catalonia.

1.2 The Need for including fire risk considerations in forest planning

The impact that forest fires have on the forest sector in Catalonia and the high cost of the current fire suppression policies, call for new approaches to deal with such a relevant problem as forest fires. In this context, the integration of fire risk considerations in the decision-making process of forestry is a crucial step that has to be taken. Therefore, more emphasis needs to be placed on methods for risk assessment, fire danger rating, modelling fire behaviour, and on fire-related silvicultural treatments and forest planning approaches.

The inclusion of the risk of fire into forest management and planning offers two clear opportunities. On one hand, modelling fires enables the manager to analyze the risk and uncertainty as a result of forest fires, helping to assess the expected losses that fires may cause on the forest outputs, thereby providing a more realistic estimation of future incomes and reducing the uncertainty involved in the decision-making process. On the other hand, forest management and planning offers an appropriate framework for identify efficient, and active measures for long term fire prevention.

Classical methods for forest management planning in Spain have been focused on timber production objectives, especially with the aim of obtaining a regulated forest that provides a sustainable forest yield in perpetuity. These so called regulation methods struggle when they have to deal with the multiple uses of the forest (recreation, nature conservation, carbon sink, biomass production, watershed protection etc.). Moreover, classical regulation methods are based on the assumptions that the prevailing conditions at the beginning of the planning period will continue to exist in the future (Palahí 2002). These assumptions can hardly be applied to forest ecosystems and markets. Due to the long-term planning horizons and the natural and economic hazards affecting forest ecosystems, risk and uncertainty are terms implicit to forest management (Gadow 2000).

The use of modern forest planning systems permits the inclusion of multiple objectives and the opinion of the forest stakeholders in the management decision process. Contemporary planning methods are able to integrate stand-level and forest level management objectives, and provide optimal solutions to the planning problems in a systematic and cost-effective way, using quantitative optimization techniques.

Modern forest planning adheres to the following steps (Pukkala 2006): Firstly, the goals and constrains are defined, and the management alternatives (treatment schedules) are produced for the stands over the planning period. All the combinations of the management alternatives define the decision space. The effects of implementing these alternatives are predicted using a stand simulator and models. Secondly, a planning model is prepared, using the outputs estimated for the different management alternatives and information about the preferences of the stakeholders. Thirdly the planning model is solved using numerical optimization techniques. The solution obtained then becomes a candidate plan for evaluation by the decision makers, and posterior implementation if accepted (Figure 6).

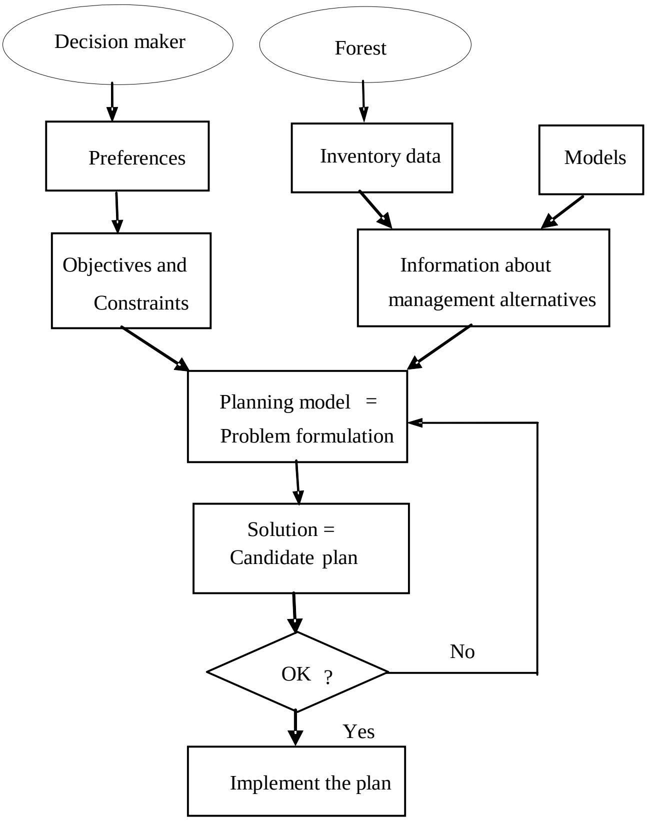

Figure 6. Elements of numerical forest planning.

If fire risk is to be included in forest management planning, models for assessing the probability of fire occurrence, potential fire damage and fire vulnerability are required. As stands are regarded as the basic and indivisible forest management unit and treatment schedules will be chosen for each stand, it is logical that developing stand-level models should be the first step for the inclusion of fire risk 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.

Since fire spreads in a specifically spatial manner, the use of spatial objectives and constraints in landscape-level forest planning is the next logical step to address the problem of fire risk in forest management and planning. Several authors have suggested fragmenting high risk forest landscapes through fuel breaks or changing the spatial arrangement of low/high risk stands and their connectivity in order to create spatial patterns in the forest that reduce the overall risk of fire (Hirsch et al. 2001, Finney and Cohen 2003, Loehle 2004). One approach to achieve objectives related to the landscape spatial configuration of the forest is the use of landscape metrics. Landscape metrics are variables that measure the sizes, shapes and connectivity of forest patches of a certain kind (McGarical and Marks 1995). In the case of fire, the connectivity, shape and amount of fire resistant/prone stands may be the objective, which is pursed using different landscape metrics. The previously mentioned stand-level models can be used to indicate which stands are more vulnerable or resistant to fire.

As fire is a threat to the forest sector economy at a regional or even national level, it is logical that the last step to be taken is the inclusion of fire risk in broad scale scenario analysis (Gadow 2000). This approach will allow the estimation of the expected losses due to fire, on a regional scale, permitting the decision-makers to develop policies based on real data and scientifically sound expectations.

1.3 Aims of the study

The aim of the present thesis is to develop tools to address the problem of forest fires in Catalonia to effectively support the decision-making in forest management planning. In order to achieve this general objective the work is divided into two parts. The first part deals with the problem of acquiring knowledge about the susceptibility of different kinds of forest to fire. The second part consists of the integration of knowledge into modern planning systems, and demonstrations on the use of these planning systems in forest management planning.

The specific objectives of this dissertation were to:

i. analyse the temporal and spatial patterns of forest fires in Catalonia during the period (1942-2002), in order to discern possible variations in the fire regime over the last decades;

ii. examine the influence of controllable forest characteristics on the probability of fire occurrence;

iii. develop models to assess the impact of fire on forest stands;

iv. analyse the effect of fire risk on the optimal stand management;

v. include the risk of fire in a forest-level planning problem where the reduction of the risk of fire is a management objective; and

vi. include empirical models for the risk of fire in long term scenario analysis.

In the first stage of the study, the fire regime in Catalonia was analysed. Then, models to assess the probability of fire occurrence and to predict the damage caused by fire in different forest stands were developed. The models were used in stand and forest level planning problems to assess the effects of fire considerations on the outcome of the analysis. An additional example of the use of the stand level models in regional scenario analysis is presented as the last part of the study.

During the reading of this thesis different concepts related to “fire risk” will appear. Some of these concepts will be clarified in this section. United Nations (1992), defined the concept risk as the expected loss due a certain hazard for a given area and period of time. The two main components of the risk by fire in forest planning are: the probability of fire occurrence on a certain area and time period, and the potential damage caused by fire in that area once the fire occurs, normally expressed in monetary terms.

The first two studies of the thesis, even if the term risk of fire is used, are only focused on the process of modeling the fire frequency and probability of fire occurrence. This means, that only information about if a fire event occurs or not, in an area or location during a time period, can be extracted from them. The third study even if focused in the post-fire tree survival, use terms as stand-level fire damage that is referred to the relative amount of trees killed by fire, rather than monetary loss. In the fourth study the concept vulnerability of a stand to fire is included, being considered as the probability of a stand to be totally or almost totally destroyed by fire once fire is present in the stand. In the fifth study, the term risk of fire is more consistently used, as in the stand level application the expected monetary losses due fire are estimated. In the sixth study, the probability of fire occurrence is again used as a fire risk estimation, but only to convert it into a problem specific fire resistance index. Those terms mentioned in the present paragraph and their implications, are more extensively explained in each of the studies were they are applied.

2 FIRE RISK IN FOREST PLANNING

The need for assessing the impact that fires have on the forest ecosystems, and including fire related constraints into forest management has been addressed before. The first studies that tried to explain the behaviour of wildland fires in a systematic way, and the first approaches to include fire risk into forest management planning appeared in North America in the beginning of the 1980’s. In the present chapter, a general review of studies that are considered relevant to understanding the advances related to the inclusion of forest fires into forest management planning is presented. The studies will be divided in three main groups; the first one dealing with the modelling of forest fires and fire risk, the second group mentioning some approaches to the inclusion of fire risk into stand-level management planning, and the last group focusing on the in inclusion of fire risk into forest-level management planning.

2.1 Fire models

An important group of models with a clear relevance for forest management is the one dealing with fire regime, fire frequency and their relation with forest age. These models represent the first step to understand the susceptibility of a forest to fire depending on forest characteristics, especially stand age. Johnson and Gutsell (1994) reviewed concepts such as time-since-fire, fire interval and fire hazard, and also proposed techniques for making empirical studies about fire frequency. Some earlier studies used some of the techniques later presented by Johnson and Gutsell (1994) to analyse fire regimes in North America (Madany et al. 1982, Johnson and Van Wagner 1985, Bergeron 1991). The analysis of fire regimes has continued until our days, including the distribution of fire sizes as a result (Moritz 1997, Brown et al. 1999, Cumming 2001, Moritz 2003). In some cases explanatory variables that may affect the fire regime have been analysed, and relevant results found. For example, McKenzie et al. (2000) predicted fire return intervals using explanatory variables such as elevation, precipitation, temperature and vegetation conditions. Cumming (2001) used the forest composition as a variable to explain the fire size distribution, and Rollings et al. (2002) evaluated relationships between fire regime, landscape characteristics, and climate. As it can be observed, the analysis of fire regimes has been a prolific field of study during the last decades, and the inclusion of additional explanatory variables still offers opportunities for further studies. Morgan et al. (2001) presented a state of the art review about mapping fire regimes on different spatial scales, dividing previous studies depending on the used data and methodological approach, giving some recommendations for future study and mentioning gaps in knowledge to be filled.

2.2 Stand level applications

Several studies have focused on the economics of timber management and the optimal management of forest stands under the risk of forest fire. During the 1980’s the subject of study in North America was the optimal rotation age of the stand with the objective of maximize the timber revenue (Martell 1980, Routledge 1980, Reed 1984, Reed and Errico 1985, Cautfield 1988). However, relevant differences can be observed between the studies. Martell (1980) used discrete time frameworks and age-dependent fire probabilities to solve the rotation decision making problem. Routledge (1980) also used a discrete time frame, but the effect of fire risk was analysed considering different age-independent hazard probabilities. Reed (1984), on the other hand, had a continuous framework, and fires were considered to occur independently of age and time. Reed and Errico (1985) used the results from the previous study (Reed, 1984) to develop “fire adjusted, rotation-volume curves” providing a graphical technique to solve the problem, considering both age-dependent and age-independent fire occurrence. In the case of Caulfield (1988), stochastic dominance analysis was applied to modify Martell’s (1980) rotation model and incorporate decision-makers risk aversion into the optimal rotation decision problem. In recent years other studies have also covered the issue of estimating optimal forest rotations under fire risk. For example, Englin et al. (2000) included timber and amenity values of the forest to examine optimal rotations in multiple-use forest, and Kuboyama and Oka (2000) used national level statistical data to create an age-dependent probability model to include different hazards in the optimisation problem.

Many other studies have dealt with the inclusion of non-fire related risks in the optimal management of forest stands. Some of the studies presented the possibility of optimise not only rotation length, but also other management variables such as time and intensity of the thinnings (Pukkala and Miina 1997, Thorsen and Helles 1998, Möykkynen et al. 2000, etc.). A common feature in most of these studies is the use of non-linear optimization algorithms.

2.3 Forest and landscape level applications

The studies that deal with the inclusion of fire risk in forest level management planning can be divided into two main groups: one group, “economic approach planning” focusing on the potential losses in timber supply caused by forest fires, and the other group, “ecological approach planning” considering fire as a natural element of the forest ecosystem and using forest management to emulate natural fire regimes.

The economic approach group includes some of the first studies in which the risk of fire has been included into forest-level management planning. Van Wagner (1983) used hypothetical forests and random fires to address the importance that forest fires have on the timber supply and calculated the annual allowable cutting limit to maintain a fully regulated forest depending on the proportion of area burned. Cohan et al. (1986) integrated decision trees to analyse different sources of uncertainty, including fire, in a decision making process for fuel and timber management. In Reed and Errico (1986), the optimal harvest schedule under fire risk conditions was examined using the Monte Carlo method. Teeter and Dyer (1986) proposed multiattribute utility theory to evaluate fire management strategies when the economic efficiency and the risk associated with each alternative are considered. Gassmann (1989) developed a computational algorithm to maximize the expected volume of timber harvested over a finite time horizon, considering the proportion of timber destroyed by fire as random. Boychuk and Martell (1996) included stochastic fire in a multistage stochastic programming problem in order to optimise the forest management when maintaining long term timber supply was the objective. Martell (1994) applied a similar version of the model developed by Reed and Errico (1986) to identify and evaluate harvest schedules in a hypothetical forest management unit. Thompson et al. (2000) included in their planning system a model to rank forest stands with respect to their fire risk, a forest simulation model to estimate the development of the forest, a forest valuation model to evaluate the economic value of the forest with and without fire, a forest management module considering management constrains, and heuristic optimisation to solve the planning problem when maximal forest value and minimal fire hazard were the objectives. Kalabokidis et al. (2002) presented a theoretical methodology to estimate forest fire risk, including forest management as a factor determining the forest’s resistance to fire. Some studies have also tried to incorporate spatial and economic considerations into planning problems. For example Johnson et al. (1998) used spatial simulation of the forest under fire risk and heuristic optimisation techniques to achieve different ecological goals together with timber harvest objectives. Hof and Omi (2003) used a grid based approach and linear programming to apply long-term fuel management as a way to optimise fire spread delays. Loehle (2004) used a percolation model to analyse the possibility of reducing fire risk through landscape compartmentation resulting in increased forest yields.

Studies that use the ecological approach rely on the idea that forest management emulating past fire regimes helps to reduce undesirable effects coming from commercial timber harvesting, allowing to keep or even increase the levels of forest diversity and helping to create more natural landscape patterns. As a common way of implementing the management problem, studies representing the ecological approach try to create cutting areas that reassemble the spatial and temporal distribution of the burned areas described by the fire regime present in the study area (Hunter 1993, Attiwill 1994, McCarthy and Burgman 1995, Bergeron et al. 1999, Cissel et al. 1999, Bergeron et al. 2001, Harvey et al. 2002). A slightly different approach is the use of fire regime models in forest scenario simulators to analyse forest dynamics under different management regimes and disturbance regimes, for instance LANDIS (He and Mladenoff 1999) and DRYADES (Mailly et al. 2000).

3. MATERIAL AND METHODS

3.1 Fire data

Data on the historical occurrence of fire was obtained from the Department de Medi Ambient i Habitatge and the Institut Cartográfic de Catalunya in two different forms. One of the forms consisted of the date of occurrence and the area affected by the 8121 fire events (larger than 1 ha) recorded in Catalonia during the period 1942-2002. These data were used to observe the temporal variation in the number and size of forest fires (Study I). The other kind of fire data consisted of the perimeters of the fires larger than 20 ha, determined by the Department de Medi Ambient i Habitatge and the Institut Cartográfic de Catalunya on a 1:50 000 scale. The fire perimeters were used in Studies I, II and III, to determine the amount of forest area burned in different forest types (Study I) and to determine the plots of the Spanish National Forest Inventory (ICONA 1993) affected by fire (Study II, III). The time period of the fire perimeters used in the three studies varied depending on the study’s objective and the other data used, being from 1986 to 2002 in Study I, from 1991 to 2002 in Study II, and from 1989 to 2001 in Study III.

3.2 Forest maps and fire frequency

For the analysis of the fire probability in Catalonia (Study I) the forest data were obtained from the Spanish Forest Map on scale 1:50 000 (MFE50; BDN 2001) for the provinces of Barcelona, Gerona, Lérida and Tarragona. The forests present in the MFE50 were divided into classes of altitude, slope, aspect, fuel and species composition, in order to estimate the total area occupied by each class. The values of the first three criteria were obtained from a digital terrain model (150 meters grid size), and the values of the last two criteria were obtained as the combination of different fields present in the MFE50 (Table 1).

Table 1. Description of altitude, slope, aspect, fuel and species classes used in Study I. The name of a categorical variable, as used in the model, is given in parenthesis.

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^o (North)	Pasture or young regeneration (Pasture)	Pine (Pine)
2	401–1600 m	3–11 %	45–135^o (East)	Bushes, small trees with height <8–10m (Young)	Oak (Oak)
3	1601–2300 m	12–19 %	135-225^o (South)	Trees with height >8–10m (Trees)	Pine–oak mixture (PineOak)
4	> 2300 m	20–35 %	225-315^o (West)	Trees with height >8–10m and bushes or young trees (TwoLayer)	Other species (OtherSp)
5		> 35 %			

The amount of area burned from each class during the period 1986-2002 was estimated by overlaying the classified forest map and the perimeters of the fires occurring during this period. The proportion of burned area in each class was used to develop a linear regression model in which a logit transformation (Equation 1) of the proportion of area burned (P_{burned}) was predicted using the classification variables as predictors.

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

where $p = \begin{cases} 0.01 & \text{if} \quad P_{burned} \le 0.01 \\ P_{burned} & \text{if} \quad 0.01 < P_{burned} < 0.99 \\ 0.99 & \text{if} \quad P_{burned} \ge 0.99 \end{cases}$

3.3 Spanish National Forest Inventory

Data from the Spanish National Forest Inventory (IFN; ICONA 1993, DGCN 2003) were used to develop stand level fire occurrence and damage models (Study II and III). These data consisted of a systematic sample of permanent plots, distributed on a square grid of 1 km, with a re-measurement interval of approximately 10 years. All the plots in the Catalonian region were considered during the modelling process. The 2nd and 3rd IFN in Catalonia took place in the periods 1989 to 1990 (2nd) and 2000 to 2001 (3rd), and covered a surface area of 32 114 km^2. The IFN inventory plots in Catalonia represented 52 different forest types. The elevation of the plots ranged from sea level up to over 2300 m.

For Study II, data from only one measurement (2nd IFN) were used. The inventory plots that were measured over the whole of Catalonia (10 855) were combined with the perimeters of fires occurring in Catalonia during the period 1991-2002 to determine which plots were affected by fire during that period and which ones were not. The IFN plots located within fire perimeters were classified as plots that were burned during the 12-year period. The data showed that 770 out of the 10 855 IFN plots were burned. The data were analysed using binary logistic regression in order to assess the effect that different stand variables had on the fire occurrence probability.

When the damage caused by fire was analysed at the stand level (Study III), a different approach was applied. In this case, data from both IFN measurements were used, but only from the plots that were located within the perimeters of the forest fires that took place between the two inventories (722 plots). The process of deciding which plots were burned and which ones were not was similar to the process used in Study II, except that perimeters of fires from 1989 to 2001 were used instead. The Spanish National Forest Inventory permitted determining which trees present in the 2nd measurement survived until the 3rd measurement. The variable that was used to describe the damage at the stand level was the proportion of trees that died as result of fire (Table 2). A linear stand-level model was later developed, using the ordinary least square method, for predicting the stand-level fire damage. Several stand-level variables related to the stand structure, species composition, and location of the stand were tested as predictors. The logit transformation of the proportion of dead trees (similar to Equation 1) was used as the predicted variable.

A tree-level binary categorical variable was created, equalling 1 if a tree survived the fire and 0 if the tree died. This resulted in 3369 survivors and 6229 dead trees (Table 2). This new variable was used to develop two models for predicting the probability of a single tree surviving a fire event. The modelling process in this case used the binary logistic regression method. One of the models used tree and stand characteristics as predictors, while the other was based on tree size and the stand-level degree of fire damage.

Table 2. Number of observations (N), observed survival probability (Survival), mean proportion of dead trees (Damage) in the burned plots dominated by the eight most common tree species and in the whole material of Study III.

Dominant species	Tree level data		Stand level data		
	N	Survival	N	Damage	Standard deviation
Pinus sylvestris	574	0.74	23	0.32	0.34
Pinus pinea	280	0.92	16	0.18	0.35
Pinus halepensis	2201	0.50	286	0.45	0.46
Pinus nigra	4741	0.67	276	0.42	0.41
Pinus pinaster	106	0.55	5	0.40	0.55
Quercus faginea	240	0.48	7	0.11	0.29
Quercus ilex	552	0.62	41	0.19	0.38
Quercus suber	628	0.94	35	0.11	0.21
Total	9598	0.65	722	0.38	0.43

3.4 Expert opinions

In Study IV, the source of data used to model the stand vulnerability to fire, was the opinion of experts in fire ecology and fire prevention. The opinions of 16 experts were collected through an internet questionnaire. This questionnaire was based on the comparison of pairs of forest stand images with respect to the vulnerability of the represented stands to fire.

A total number of 90 images representing 90 stands were used in the study (Table 3). The stands were divided into two similar groups inside the same questionnaire, each group being analysed separately. One of the groups used 49 images, including 39 virtual reality images and 10 photos, and the other group used 41 images, including 33 virtual reality images and 7 photos. Once the results of the questionnaires were received, the data were analysed using regression methods for pairwise comparison (Alho et al. 2000). The relationships between stand characteristics and the priority given by the experts to the stands were modeled.

Characteristic	Mean	Minimum	Maximum
Number of trees per ha [1)]	714	0	3037
Understory (plants/ha) [2)]	840	0	4000
Basal Area (m2/ha)	29.8	0	128.2
Dg (cm) [3)]	27.4	0	47.8
CV [4)]	1.03	0	2.71

Table 3. Means and ranges of different characteristics in the stands of Study IV.

[1)] number of trees per ha includes all the trees with diameters over 5 cm

[2)] understory comprise bushes and trees with diameters under 5 cm

[3)] Dg is the mean diameter of the trees weighted by the tree basal area

[4)] CV is the coefficient of variation in diameter including the understory (a diameter of 2.5 cm was assumed for each plant in the understory)

3.5 Stand level optimisation

In Study V, an existing stand-level simulation-optimisation system (Palahí and Pukkala 2003) was modified to find the optimal stand management schedule under risk of fire. The stand data used in the study came from plots measured during the Second Spanish National Inventory of 1991 in the province of Gerona (northeast Spain), and represented poor, medium and good site fertility for even-aged P. sylvestris stands (Table 4).

Plot	Hdom	T	SI	N
1	5.8	24	17	2228
2	10.7	25	24	1934
3	12	19	30	2069

Table 4. Characteristics of the stands used in Study V. Hdom: dominant height; T: stand age (years); SI: site index (Hdom at 100 yr); N: number of trees per hectare.

The simulation system used the same growth, regeneration and mortality models, and the same economic parameters as in the study of Palahí and Pukkala (2003). The main difference from this previous study was the inclusion of the risk of fire in the simulation. The risk of fire was considered either exogenous or endogenous to the stand characteristics. When the risk was considered exogenous, the fire occurrence probability was considered constant through time and independent of the stand characteristics. When the risk was considered endogenous, the fire occurrence probability depended on stand characteristics according to the model developed in Study II. In both cases, the input to the optimisation system consisted of the average objective function value of 500 stochastic simulations (Figure 7). The optimisation algorithm of Hooke and Jeeves (1961) was used to find the optimal management schedule for the three different P. sylvestris stands, when maximal soil expectation value was the objective.

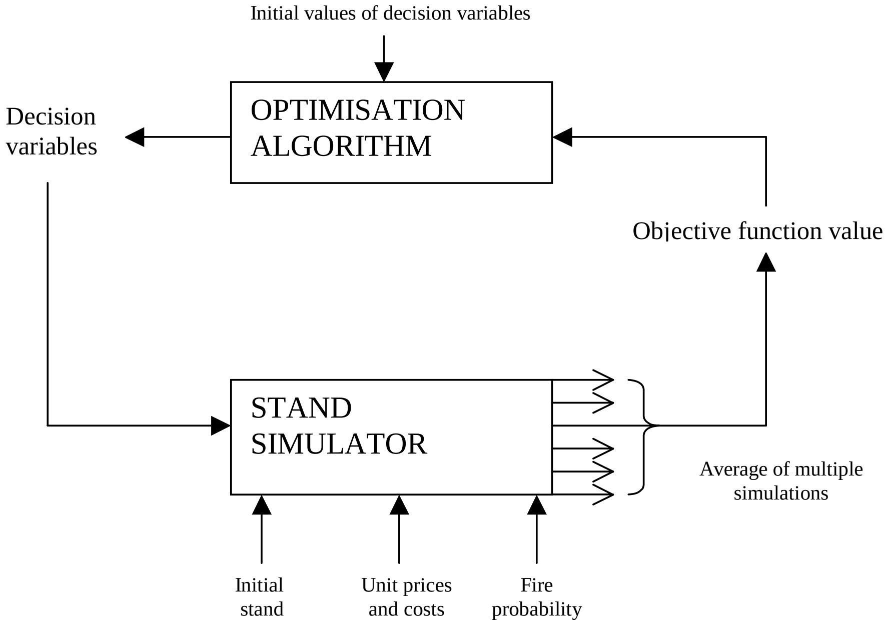

Figure 7. Structure of the stochastic simulation-optimisation system.

3.6 Forest level optimisation

In Study VI a forest planning system called MONTE (Palahí 2002; Pukkala 2003) was used to compare the effect of different landscape metrics, computed from the fire resistance indices of stands, on the optimal management when the reduction of the risk of fire is a management objective. The study was conducted on two different artificial forest landscapes. Both of the artificial forests consisted of 900 square-shaped stands, 16 ha each, distributed as a grid of 30 columns and 30 rows. The stands represented real data from the second Spanish National Forest Inventory (ICONA, 1993). One of the forest landscapes (Random forest) consisted of 900 different stands randomly distributed through the grid, and the other (Uniform forest) consisted of a single stand data assigned to all the grid cells. The risk of fire in a forest stand was predicted using the fire risk model developed in Study II and then converted into a fire resistance index (RES). The value of RES was equal to 1 if the predicted risk of fire was equal to 0, and RES was equal to 0 if the risk of fire was equal to the maximum estimated risk among the plots of the IFN for Catalonia (0.25 probability of fire during 12 years). The values of the stands RES indices and the spatial configuration of the landscape were used to calculate six different landscape metrics: mean fire resistance (MR), share good-good boundary (G-G), share of good-bad boundary (G-B), mean difference (MD), mean of neighborhood minima (MMin), and mean of neighborhood maxima (MMax). These landscape metrics were analysed as means to affect the risk of fire at the landscape level in numerical optimisation.

Alternative treatment schedules were simulated for the stands for a 30-year planning period. Different even- and uneven-aged management schedules were simulated by modifying the rotation period and the basal area that activated the thinnings in the case of even-aged management, and the basal area that activated the cuttings in the case of uneven-aged management. Tree different planning problems were formulated for both forests. In the first case, only the value of one of the landscape metrics was considered as an objective variable. In the second case, an additional cutting target was included as objective variable to the previous planning problem. The third planning problem had also two objective variables, one being the value of a landscape metric and the other a certain target value of the mean resistance at the end of the planning period. The optimisation problems were solved using the Hero (Pukkala and Kangas 1993) and tabu search (Glover and Laguna 1993) heuristics with one- or two stand neighborhood (Heinonen and Pukkala 2004), depending on which method worked best in a particular problem.

The landscapes produced by maximizing different landscape metrics were evaluated afterwards using a simple fire spread simulator. In the simulation, lightning strikes hit random stands, which caught fire with the probability equal to the fire risk index of the stand. These stands were marked as burning stands, and had the possibility of spreading fire to their neighbor stands with the probability inversely proportional to the neighbor’s resistance index. After this, a burning stand was marked as burned stand and was no longer capable of spreading fire. The process stopped when there was no burning stands left in the forest. The mean area burned of 1000 different simulations was used to evaluate the whole landscape’s resistance to fire.

4. RESULTS

4.1 Models for fire risk assessment

4.1.1 Fire frequency (Study I)

The analysis of the number and size of the fires occurring in Catalonia showed an increment in the number of large fires during the last two decades, but the total burned area did not change significantly from the previous 20 year period.

The analysis of the proportion of area burned during the period 1986-2002 resulted in the development of a model with the following form:

$$y = -2.692 -0.000830Alt -0.0606Slo -0.686North -0.721Young -2.692Trees - 2.893TwoLayer +2.557Pine +3.793Oak + 3.416PineOak + 2.340OtherSp \tag{2}$$

where y is the logit transformation of the proportion of burned area during a 17-year period (Equation 1), *Alt* is altitude (m), *Slo* is slope (%) and the other explanatory variables correspond to the classes given in 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.

According to the model, increased elevation and slope reduces the proportion of burned area. The proportion of area burned is much lower on northern slopes that on other aspects. Areas with tree cover (trees taller than 8–10 m) have a much smaller likelihood to be burned 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 of being burned is almost double. 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 being burned 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.)

4.1.2 Fire occurrence model (Study II)

In Study II the model for the probability fire occurrence was:

$$P_{fire} = \left(1 + e^{-(-1.925 - 2.256\ln\left[\max(\{Ele - 6\},1) + 0.01\right] - 0.015Dg + 0.012G - 1.763P_{hard} + 2.081\left(\frac{s_d}{Dg + 0.01}\right)} \right)^{-1} \tag{3}$$

where P_{fire} is the 12-year probability of fire occurring in a given stand, *Ele* is elevation (in hundreds of meters), *Dg* is the basal-area-weighted mean diameter (cm) of trees, *G* is the total basal area (m^2ha^{-1}), P_{hard} is the proportion of hardwood species of the number of trees ha^{-1}, and s_d is the standard deviation of trees' breast height diameters (cm).

All variables included in the logistic model were logical and significant according to the Wald test ($p<0.05$).

According to the model, the higher the elevation, proportion of hardwoods, and mean diameter, the lower is the probability of fire. Stands with high values of basal area and wide diameter distributions have a higher probability of fire occurrence.

4.1.3 Fire hazard model (Study III)

In Study III, two different kinds of models were developed, a stand level damage model which predicts a transformed proportion of trees killed by fire, and tree level models to predict the probability of a single tree to survive. The stand level damage model had the following form:

$$y = -6.131 - 0.329G + 0.60\,Slope + 2.266\,Pine + 4.319\left(\frac{G}{D_q + 0.01}\right) + 6.718\left(\frac{s_d}{D_q + 0.01}\right) + e \tag{4}$$

where $y = \ln(P_{dead} / (1 - P_{dead}))$, P_{dead} is the proportion of dead trees (of the number of trees), G is the stand basal area (m^2ha^{-1}), *Slope* is the percentage of altitude change per distance (%), *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 parameter estimates of the stand damage model were significant at the 0.05 level. The coefficient of determination (R^2) was 0.173, the bias was 0, and the relative standard error was 116% of the mean of predicted values if calculated in the original units (P_{dead}).

According to the model, the relative damage decreases when stand basal area increases. Higher values of $G/(D_q+0.01)$ and $s_d/(D_q+0.01)$ increase the damage. The other two factors that contribute to a high fire damage are steep slopes and pine dominance.

The two tree survival models differed in terms of predictors; one model used tree and stand characteristics as predictors (Equation 4), while the other was based on tree size and the stand-level degree of fire damage (Equation 5). The models are as follows:

$$P_{sur}^{1} = \left(1 + e^{-\left(-2.035 + 0.036d - 0.026BAL + 0.084Dg + 0.062G - 1.722\left(\frac{s_d}{Dg + 0.01}\right) + 1.299PPinea + 1.431QSuber\right)}\right)^{-1} \tag{5}$$

$$P_{sur}^{2} = \left(1 + e^{-(2.224 + 0.110\,d - 7.117\,P_{dead})}\right)^{-1} \tag{6}$$

where P_{sur} is the probability of survival, d is the diameter of the tree at the breast height (cm), *BAL* is the basal area of the trees larger than the subject tree (m^2ha^{-1}), *Dg* is the basal-area-weighted mean diameter (cm) of trees, *G* is the total basal area of the stand (m^2ha^{-1}), s_d is the standard deviation of breast height diameter (cm), and *PPinea* and *QSuber* are dummy variables indicating whether the tree is *Pinus pinea* or *Quercus suber* (if the tree is *P. pinea*, *PPinea* equals 1 and if it is *Q. suber*, *QSuber* equals 1, and 0 otherwise), and P_{dead} is the proportion of dead trees.

All variables included in the models were significant according to the Wald test ($p<0.05$), and no significant multicollinearity was observed between the variables in the models. The Nagelkerke R^2 was 0.165 for Equation 5 and 0.788 for Equation 6.

According to the first model (Equation 5) trees with larger diameters and in dominant positions (low *BAL* value) have a higher probability of surviving a fire. Furthermore, trees in forest stands with higher values of *G* and *Dg*, but with low variability of stand diameters (s_d/(Dg+ 0.01)) have also higher survival probabilities. The first survival model also shows that *P. pinea* and *Q. suber* trees have a better post-fire survival capability. According to the second survival model (Equation 6), large trees in stands with low expected damage are the most likely to survive.

4.1.4 Expert model for vulnerability (Study IV)

The analysis of the experts' opinions in Study IV resulted in the development of two very similar models for the two groups of images:

Group 1: $$\ln(v_1) = -0.0002540\ Und - 0.51966\ CV \tag{7}$$

Group 2: $$\ln(v_2) = -0.0001667\ Und - 0.46898\ CV \tag{8}$$

where v_1 and v_2 are the predicted priorities of the stands in terms of low vulnerability to fire, calculated from the comparisons in group 1 and 2 respectively, *Und* is the number of bushes and trees with diameters under 5 cm, and *CV* is the coefficient of diameter variation. In both models the variables were significant, and the R^2 was 0.19 for Equation 7 and 0.10 for Equation 8.

The results of this study showed that the amount of understory and the structural irregularity of the stands had a clear influence on the experts' opinions, even-aged stands with no understory being preferred in terms of fire resistance to uneven-aged stands, or stands with an abundant understory.

4.2 Application of the models

4.2.1 Optimal stand level management under risk of fire (Study V)

The optimal management schedule in even-aged forest stands showed a clear tendency of shorter rotation length when the risk of fire increased (Table 8). When the risk of fire was considered as exogenous to the forest management, shortening rotation was the only clear effect of fire risk on the optimal management. If the risk was considered to be endogenous to the stand management, a clear effect of risk on the thinnings regime was observed, with earlier and more intensive thinnings with increasing fire risk.

Table 8. Optimal rotation length of a forest stand depending on the nature and amount of fire risk.

Exogenous risk of fire		**Endogenous risk of fire**	
Fire probability (1)	Optimal rotation, years	Multiplier (2)	Optimal rotation, years
0	84	0	90
0.5	79	0.5	71
1	78	1	66
2	75	2	56
5	59		

(1) 12-year probability of fire occurrence for exogenous fire risk.

(2) Multiplier of the stand level fire occurrence model of Study II for endogenous fire risk.

4.2.2 Forest level application (Study VI)

The use of different landscape metrics as planning objectives in Study VI, resulted in clearly different spatial configurations of the forest at the end of the planning period, regarding the fire resistance of the stands (Figure 8). A comparison between the two forests revealed that the influence of the landscape metrics on the final landscape configuration depended significantly on the initial landscape. The results also revealed that maximizing different landscape metrics implies different costs and benefits as they require allocating diverse management practices in different areas of the landscape. The analyses of this study also showed that a forest landscape can be configured to very different directions with the help of landscape metrics, even when the harvest level or the overall resistance was fixed.

The use of landscape metrics such as G-G (resistant-resistant boundary maximised) or MMin (mean of neighbourhood minima maximised) as objective variables had similar effects on the landscape, both producing smooth landscapes with the fire-resistant stands aggregated and connected to each other. A completely different effect was observed when MMax (mean of neighbourhood maxima maximized) was used as an objective variable, resulting in highly fragmented landscapes in which there are narrow corridors of both fire-risky stands and fire-resistant stands.

When the obtained landscapes were tested using the fire spread simulator developed in Study VI, it was observed that those landscapes were the least damaged in which the mean resistance of stands was good. With the same mean resistance, discontinuities between risky and resistant stands further decreased the simulated fire damage. Such discontinuities can be obtained for instance by maximizing the MD (mean difference), G-B (resistant-nonresistant boundary), or MMax metrics.

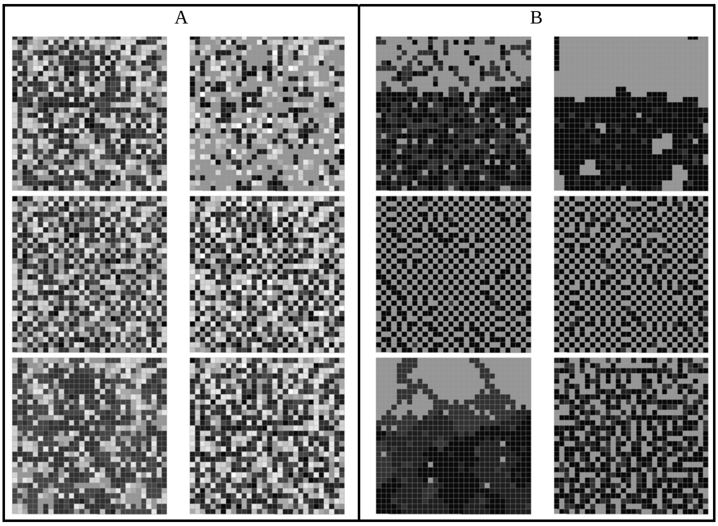

Figure 8. Value of fire resistance index at the end of the planning period in Random forest (A) and Uniform forest (B) when one of the landscape metrics was maximized with an additional mean resistance target at the end of the plan. Dark tones imply low resistance. The maximized landscape metric is: top left, MR; top right, G-G; middle left, G-B; middle right, MD; bottom left, MMin; bottom right, MMax.

4.2.3 Regional scenarios

Another way to use the models presented in Studies II and III is their inclusion in regional scenario analyses. For the present study case, a forest scenario simulator (ESCEN) was used to generate 60-year scenarios for the standing and harvested volume of different stands in Catalonia, with or without the effect of fire. The simulator used tree-level growth models, (Trasobares and Pukkala 2004a, Trasobares et al. 2004) to estimate the development of the stands over time. Fire risk was considered in the simulator by generating the fire occurrence stochastically for the stands using the model presented in Study II (Equation 3), after which the degree of damage was predicted with the stand level damage model presented in study III (Equation 4). A stochastic component corresponding to the residual variation of the stand-level damage model was added to the prediction. As the simulator used individual trees, the survivors were selected using Equation 6. The management options used during the simulations were similar to those ones indicated by Trasobares and Pukkala (2004b).

The data used to test the simulation system consisted of plots from the Spanish National Forest Inventory chosen randomly from two provinces of Catalonia. A total of 2484 plots where chosen from Lérida and 900 plots from Tarragona. Each plot was considered to represent a forest area of 100 ha with similar characteristics as the plot. The simulator was run for three different scenarios. In the No fire scenario the risk of fire was not considered. The Fire scenario generated stochastic fires and mortality as explained above with no direct effect on the ingrowth, apart from the decreased competition. The Fire+Ingrowth scenario decreased the amount of ingrowth proportionally to the simulated degree of fire damage. The effect of fire on ingrowth lasted for 20 years.

The results of the scenarios consist of the standing volume and the harvested volume for the forest area represented in Lérida (Figure 9) and Tarragona (Figure 10) during the 60-year study period. The standing volume was predicted for the present moment and for the future with a 20-year periodicity. The harvested volume of timber was estimated for each 20-year interval, starting from 2007. The results show that a clear overestimation of the standing and harvested volume will be obtained if fire risk is not taken into account. The effect of fire is greater in Tarragona which is a more fire-prone area than Lérida. This difference probably comes from the fact that many inventory plots of Lérida were located in high elevation with lower probabilities of fire occurrence.

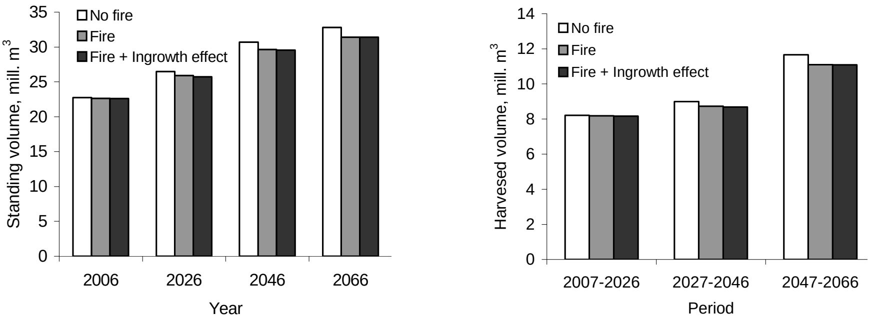

Figure 9. Standing and harvested timber volume for 248 400 ha of forest in Lérida, using three different fire risk scenarios

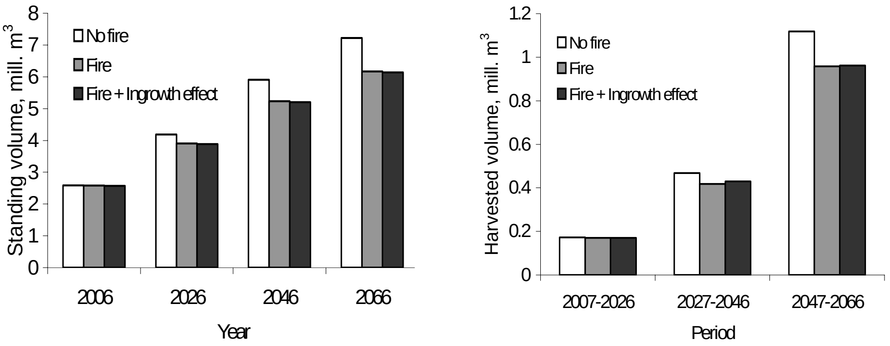

Figure 10. Standing and harvested timber volume for 90 000 ha of forest in Tarragona, using three different fire risk scenarios.

5 DISCUSSION

5.1 Modelling fire risk

The models developed in Studies I, II, III were based on overlaying fire perimeters with data from the Spanish forest map (MFE50) and from the Spanish national forest inventory (IFN II and IFN III). These data provided an outstanding database in terms of size, representation of forest conditions and fire regimes in Catalonia. The data enabled the capturing, in a systematic way, the effect that different stand characteristics have on the probability of fire occurrence (Studies I and II), and the effect that forest fire has on the tree mortality in different kinds of forest stands (study III).

The fire perimeters used in Studies I, II and III, corresponded to the fires larger than 20 ha for the whole Catalonian region. The absence of smaller fires did not cause a major problem, as they only represented approximately 5% of the total burned area. The temporal and spatial frames of the studies were considered large enough to represent the current fire regime in Catalonia. However, longer observation periods will certainly enable one to develop a deeper knowledge of an event as erratic as fire.

The use of the Spanish forest map (MFE50) allowed the analysis of certain patterns that control the probability of fire occurrence at the landscape and regional levels (Study I). The use of the whole forested area of Catalonia presented a clear advantage over inventory plots when the objective was to represent the total area covered by different kinds of forest and the proportion of its area affected by fires. However, this dataset had weaknesses in terms of data accuracy, because the information obtained from the forest map was only a rough description of the stand characteristics. The low accuracy as a result of the methodology used in Study I may have been partially resolved if additional classes were included for each of the classification criteria.

The Spanish National Forest Inventory, used in Studies II and III (ICONA 1993, DGCN 2003), provided a highly accurate database, which was representative of most of the forest conditions in the study region. The spatial distribution of the sample plots and the temporal interval between measurements were found to be adequate for capturing the characteristics of the fire regime in the region and the relationships between fire events and stand characteristics. The possibility of identifying if a single tree present in the second IFN was dead or alive during the third IFN allowed the estimation of the degree damage and tree survival probability after a fire occurs in a stand. However, the Spanish forest inventory was not designed to develop the kind of models presented in Studies II and III. Some limitations arise from the use of these data for developing fire occurrence and damage models. The size of the plots is relatively small and all the stand variability may not be fully represented. The data for small trees (< 7.5 cm of diameter) is restricted only to their number, which does not permit a detailed analysis of their effect on the risk of fire. The information about bush presence is also relatively scant, not permitting the analyst to have a clear picture on the role of bushes in the accumulation of ground fuels in the plots. Other limitations related to Studies II and III, and with great relevance in forest planning, were the inability to recognize from the data the amount of those dead trees that could be salvaged, and the lack of information about the fuel management operations that had been conducted in the plot. The relatively low explanatory power of the models presented in studies II and III can be explained by the stochastic nature of fire occurrence and post-fire tree mortality. Because the models were developed for forest planning, tissue damage or fire severity could not be used as predictors (study III). The inclusion of these variables would surely have increased the degree of explained variance of our models, but unfortunately their future values are not known in forest planning.

The use of experts' opinions was considered a suitable way to acquire new information in scarce data environments. For this reason, expert knowledge was used to model the relationship between variables such as ground vegetation and stand vulnerability to fire in Study IV. The results obtained in this study were promising, and a clear relationship was found between the understory abundance, vertical continuity of living fuels and the priorities given by the experts with respect to the vulnerability to fire. The study was a preliminary trial of using a new methodology. It indicated that the methodology employed is flexible, easy, cheap and meaningful for compiling expert knowledge and treating it in a systematic and numerical way. However, the design of the questionnaire had deficiencies that limited the ability of the method to capture the relationships between fire vulnerability and some important variables related to the stand structure. Excessive interactions between the variables analysed, altogether with the rather low consistency between and within judges, may be the causes for the low predictive capability of our models.

The models presented in this dissertation help the forest manager to include the risk of fire into forest management planning, as they relate the structure of a forest stand with the main components of the fire risk (fire occurrence probability and fire damage). The use of the models developed in Studies II and III for forest planning purposes is especially straightforward for two main reasons. Firstly, the models are rather simple and use variables that are easily obtainable through forest inventories or predictable with models. Secondly, several of the predictors are controllable through forest management, meaning that the models not only allow the estimation of the fire risk depending on the stand characteristics, but they also indicate how the risk of fire can be modified through forest management.

The results obtained in Studies II and III were logical and agreed with previous studies about the effect of the used variables on the probability of fire occurrence and on the damage caused by fires. For example, altitude has been mentioned before as a factor that may affect fire occurrence probability (Martin 1982), due its effect on fuel moisture and fuel continuity. Elevation did not play a mayor role in the case of fire damage, as most of the fires occurred in low elevation areas where fuel moisture is not a limiting factor.

Species composition has also been mentioned as a factor affecting both fire occurrence and fire damage, pines being especially susceptible to fire (Velez 1990, Bond and van Wilgen 1996) due to their high inflammability. Slope was found to increase the damage caused by fire, which agrees with the idea that steeper slopes increase the intensity of fire due to the easier transfer of heat uphill, possible "chimney" effects, and lower fuel moistures (Agee 1993). On the other hand, slope was not found as a significant predictor for fire occurrence probability, which may be explained by the fact that big fires accounting for most of the area burned enclose a wide range of aspects and slopes. The effect of other predictors that were used to describe the stand structure were in accordance with previous studies indicating that mature even-aged stands have a lower expected fire risk than multi-layered and young even-aged ones (Pollet and Omi 2002, Agee and Skinner 2005, Peterson et al. 2005).

The models developed to predict the post-fire tree survival probability (Study III), differ from most of the existing models in the use of stand related variables as predictors, instead of the widely used tree tissue damage or fire behaviour variables (Fowler and Sieg 2004). The use of stand variables comes form the idea that the stand structure, as mentioned before, has a clear effect on the fire damage, and when the model is used for forest management planning purposes stand variables are more useful than variables obtained from a study of a single or a limited number of fire events. However, a variable like the diameter of the trees was used in our models, which is also common in most of the previous studies dealing with post-fire mortality, the general consensus being that larger trees have more chances to survive a fire (Ryan and Reinhard 1988; Linder et al. 1998; Beverly and Martell 2003; Hély et al. 2003; McHugh and Kolb 2003). This agrees with the results of Study III.

Ground vegetation was not found significant in Studies II and III for explaining the fire occurrence probability and the degree of fire damage. This may be partly because ground vegetation could have changed significantly during the study period, i.e. between forest inventory and forest fire (Outcalt and Wade 2004), implying that the initial amount of bushes and small trees may not have described well enough the situation of these variables in the year of fire event.

5.2 Application possibilities

The models presented in Studies II and III give us information about the endogenous stand factors that affect fire risk, and how the risk can be modified by varying those factors through forest management. These models can be used in multiple applications related to the integration of fire risk into forest management planning. For example, they can be used in stand-level optimisation studies, like Study V, which permits one to maximize the objective function taking into account the endogenous risk, i.e. the risk which depends on forest management. In Study V, only fire occurrence probability was applied, but the damage model could be added to the simulator. Even if some important aspects such as the nature of the surrounding stands were not included in the models developed in this study, the results obtained provide valuable information about the management practices that may reduce potential losses in the stand due to fire.

Another possible use of the developed models is their inclusion in landscape-level planning studies, such as the one presented in Study VI. As fire spread is a spatial event, the relevance of studies that include the spatial arrangement of forest stands depending on their fire resistance is clear in order to reduce fire risk (Loehle 2004). Study VI presents a methodology to modify the spatial configuration of a forest landscape through forest planning, taking into account the stands' fire risk. The optimal landscape configuration for reducing the overall risk of fire at landscape level was not directly optimised, but the results of using different landscape metrics was tested afterwards using a fire spread simulator. Improving the analysis of the forest landscape configuration with respect to the fire behaviour, including additional variables in the fire spread simulator such as topography, will be a logical step in order to select the landscape metrics that are to be included in forest planning problems when reduced risk of fire is one of the objectives.

Another direct use of the presented models is scenario analysis at a regional level (Section 4.2.3). In countries where the importance of forest fires is as obvious as in Spain, estimation of the future forest resources and outputs is badly biased if the effect of fire is omitted. The inclusion of fire risk in scenario analyses reduce the uncertainty by anticipating the forest stocks and the outcomes of management alternatives in a systematic way (Gadow 2000), and identifying management options that reduce the expected losses due to fire. Tools such as the one used in Section 4.2.3, can be of great help to policy-makers dealing with the regulation of forest subject to an important risk component. However, the analysis also has limitations, for instance the omission of the effect of small trees on the expected fire damage, or the effect of fire on the species succession.

5.3 Future research needs

The inclusion of fire risk considerations in the numerical analysis of forest management planning is a relatively new field of research. Due to its novelty there are still important knowledge gaps that must be filled before everyday use of forest planning tools in long term fire prevention policies becomes a reality. In this context, an obvious research need is the development of similar models as the one presented in Studies II and III for other regions, allowing the acquisition of a stronger understanding of the relationships between risk of fire and stand characteristics. It would be relevant also to develop models that relate stand structure and the abundance of understory, as well as models that use understory abundance to predict fire risk. Another important research need is the analysis of the effect that socio-economic variables have on the risk of fire, in order to integrate them in the management planning process. Analysis of potential uses for burned timber and considering it in the economic optimisations could also offer a new perspective in this field of research. If spatial considerations are to be included in landscape level planning as a mean to reduce the overall risk of fire, improve the analysis of the effect that different landscape configurations have on the risk of fire has to be a priority. This analysis will permit one to select those landscape metrics that lead to less vulnerable forest structures for their use in forest level optimisations. The inspection of forest configurations could be done by using existing or new fire spread models. In any case the chosen fire spread models must be based on variables available for forest planning.

Forests in the Mediterranean region are recognised as providers of multiple products and services rather than timber alone. For this reason the need for analysing the effect that fire has on those products and services, and their incorporation into the forest planning process appears evident to provide information about the losses or even benefits that fires may cause in our forest.

In the Mediterranean region, the heaviest investments regarding fire management are done on fire-fighting equipment rather than prevention (Velez 2002). 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. Forest planning can be applied as the first step of an integrated fire prevention process. This step must be followed by other practices such as short term fuel management strategies in sensitive areas, and optimal allocation of the infrastructures supporting fire extinction efforts. The reduction of risk does not necessarily mean intensified suppression policies. Instead, the risk of fire should be considered in ordinary silvicultural management and forest planning as a way to find efficient means to minimize fire damage cheaply, which can also include ways to facilitate punctual fire extinction interventions.

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