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# Integrating fire risk considerations in landscape-level forest planning

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ABSTRACT

The low timber returns of Mediterranean forests, together with their high fire risk, has led to negligent forest management. Absence of management has in turn been blamed for increasing the risk of fire, thus forming a vicious circle of low profitability, little management and high risk of fire. Developing forest planning tools that maximize both economic objectives and fire resistance could help to revive the forest sector in the region and generate long-term fire prevention strategies. In the present study, we simultaneously maximized timber income and the overall fire resistance of the landscape to generate management plans for a typical forest landscape in the Pre-Pyrenees of Catalonia (North-East Spain). The risk of fire was integrated into the economic objective by incorporating potential fire losses in the expected net income. Landscape metrics describing fire resistance were also included in problem formulations. The results show that this approach greatly improves management efficiency in terms of economic profitability and fire resistance.

## 1. Introduction

Forestry in Catalonia, as in most of the northern Mediterranean basin, is adversely affected by two major constraints: low profitability and recurrent wildland fires. Three factors mostly explain the low profitability: (i) slow growth rate due to limited water availability, (ii) mountainous terrain that hampers forestry operations and makes them costly and (ii) the constant threat of fire.

Forest fires, although they can be considered as intrinsic to the Mediterranean forest ecosystem (Trabaud, 1994), are directly linked to forest management, or rather to the absence of such management at present. An increase in the forest land area in the region due to extensive planting of new forest during the second half of the twentieth century, together with a decreasing rural population and the consequent lack of forest management (Badia et al., 2002) has produced a high vulnerability to forest fires through increased forest continuity and biomass accumulation. The vicious circle of negligent management due to high risk and uncertainty and increasing risk of fire because of scant management can be broken by selecting and implementing cheap, efficient fuel management strategies. Forest management planning helps managers find strategies that reduce fire risk in an economically viable way.

Different management prescriptions at stand level have different effects on fire behavior when fire strikes a stand (Weaver, 1943; Agee and Skinner, 2005; Peterson et al., 2005). This variability can be translated into variations in the expected level of fire damage (Pollet and Omi, 2002; González et al., 2007). For example, even-aged management, with low thinning, can break the fuel ladder that induces severe canopy fires. However, low thinning is seldom profitable in slow growing uneven-sized forest, as it incurs early costs that are seldom covered by the discounted income from the final cuttings. By contrast, selection cuttings provide a constant flow of logs, making uneven-aged management more profitable than even-aged management (Solano et al., 2007; Hyytiäinen and Haight, 2009). However, uneven-aged management does not significantly improve the resistance of a stand to fire, as it maintains a wide diameter distribution favoring a vertical continuity of living fuels.

Since fire is a spatially explicit phenomenon, the assumption that it will affect forest stands independently of other factors is unrealistic. Fire intensity and severity in a given forest stand do not depend only on the characteristics of that stand, but also on the intensity of the fire at the time of its arrival, so that the characteristics of adjacent stands have an impact on fire effects in the given stand (Wilson and Baker, 1998; Agee et al., 2000; Yoder, 2004; Konoshima et al., 2008). Modifying the spatial distribution of fuel types across the landscape is thus one way to alter the behavior of fire and its potential area of spread. Following this principle, several authors have considered fragmenting landscapes using less vulnerable stand structures to create fuel breaks and thereby reduce the risk of fire spread (Hargrove et al., 2000; Finney, 2001; Hirsch et al., 2001; Loehle, 2004; Calkin et al., 2005; González et al., 2005a; Finney et al., 2007).

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If fire risk is included in landscape level forest planning, with the intention of improving the profitability of forestry and minimizing the effect of fire, several different aspects need to be considered. In the case of mountain forests the spatial allocation of treatments largely determines the costs, due to the strong influence of slope and distance to road on harvesting costs. Additionally, the potential fire damage depends on the stand structure and composition that result from the selected treatments. The degree of damage caused by fire, which is of an endogenous nature, will affect the expected income obtained from a stand. If management is selected so as to minimize fire-related losses, treatment costs may be higher but a more fire-resistant stand with lower expected economic losses is attained. Another aspect to consider is that the complex terrain profile of mountain landscapes and the patchwork of different land uses and forest types will also influence the fire behavior within those landscapes. The location of resistant and sensitive stands also has an impact on the overall fire resistance of the landscape. Forest stands and forest landscapes are dynamic due to stand development and management, resulting in temporal variation in fire resistance and fire occurrence. Estimating the current and future probability of fire occurrence is a prerequisite for predicting the potential fire losses in alternative forest plans. Hence fire occurrence affects the ranking of forest plans, and the forest plan, when implemented, has an impact on the probability of fire occurring in the landscape.

Several studies have approached the problem of incorporating wildfires into forest planning (Bettinger, 2010) by developing planning models that include the potential impact of fire on timber supply. These studies can be divided into two groups according to how wildfire risk has been incorporated into the planning problem. The first group incorporates fire risk in a spatially inexplicit manner, either assuming a deterministic amount of losses (Reed and Errico, 1986; Martell, 1994) or using stochastic simulations of fire occurrence (Boychuk and Martel, 1996; Gassmann, 1989; Armstrong, 2004; Haynes and Quigley, 2001; González et al., 2005a). The second, more recent group incorporates fire spread models to assess the impacts of fires explicitly during the planning period (Shifley et al., 2000; Peter and Nelson, 2005; Provencher et al., 2007; Campbell and Dewhurst, 2007). The complexity of the current fire spread models makes it difficult to compare many different candidate plans in terms of fire damage. For this reason, studies that incorporate fire risk into the selection of an optimal plan in a spatially explicit way are rare, and they deal with very simple forest landscapes (Konoshima et al., 2008) or are based on the simulation of a limited number of fires to adjust the fire risk during the planning period (Bettinger, 2009; Kim et al., 2009).

The complexity of solving planning problems that include multiple objectives and constraints, some of which are spatial, calls for the use of flexible optimization methods such as heuristics (Reeves, 1993; Pukkala, 2002). Minimizing the spread and severity of forest fires in a landscape can be considered as a typical planning problem that requires the use of heuristics, since it usually considers several aspects related to forest management in addition to the effect of fire itself. Furthermore, models used to represent fire spread across irregular landscapes are non-linear in nature, and therefore are difficult to acknowledge in a linear or mixed-integer format. For these reasons, heuristic optimization has become popular in landscape level forest planning when minimizing the threat of wildfires (Thompson et al., 2000; Calkin et al., 2005; González et al., 2005a; Hummel and Calkin, 2005).

The present study analyzes the effects of fire risk on optimal management using different types of objective variables. Our intention was to find problem formulations that led to efficient plans in terms of reduced fire risk and economic profitability. The analysis helps us gain a better understanding of the effect of fire risk considerations on the profitability of forestry and the optimal timber management in Catalonian forests in the Pre-Pyrenees. The management objectives were timber income and the overall fire resistance of the landscape. The risk of fire was integrated into the economic objective by predicting the potential fire losses and calculating the fire-adjusted expected net income. The net income also depended on harvesting costs, which in turn depended, among other things, on slope and distance to road. To use fire resistance as an objective variable, fire resistance indices were calculated for each management schedule of each stand. In all, five different planning problems were formulated and solved using simulated annealing optimization. To estimate the probability of fire occurrence across the landscape and during the planning period, a fire spread simulator was developed using a cellular automaton model. The fire spread model was used to adjust the probabilities of fire occurrence during the optimization process. The study plans were developed using the Monte forest planning system (Pukkala, 2003), modified for this purpose.

## 2. Materials and methods

### 2.1. Study forest

An artificial landscape was a created with the intention of emulating the conditions of an existing forest-dominated landscape in the Pre-Pyrenees of Catalonia. The artificial landscape covered 11 214 ha, divided up into 3738 hexagons each of area 3 ha. Of these, 3365 hexagons corresponded to forested land, and the remaining 373 hexagons corresponded to non-forest land uses. The hexagons were grouped into 125 forest blocks (compartments) which corresponded to moderately uniform areas in terms of forest cover and land use (Fig. 1). Thus the block defined an area of homogeneous forest characteristics.

The Spanish forest map on scale 1:50 000, MFE50 (Base de Datos de la Naturaleza, 2001), was used to define the blocks and their primary use (forest, non-forest). For the forest blocks and the corresponding hexagons, forest information was obtained from the plots of the third Spanish National Forest Inventory, IFN3 (Dirección General para la Biodiversidad, 2003). If more than one inventory plot fell within the same forest block, the plot closest to the block centroid was selected to represent the forest conditions. For forest blocks with no inventory plot within their area, an inventory plot in the vicinity of the forest was used; this plot had to be dominated

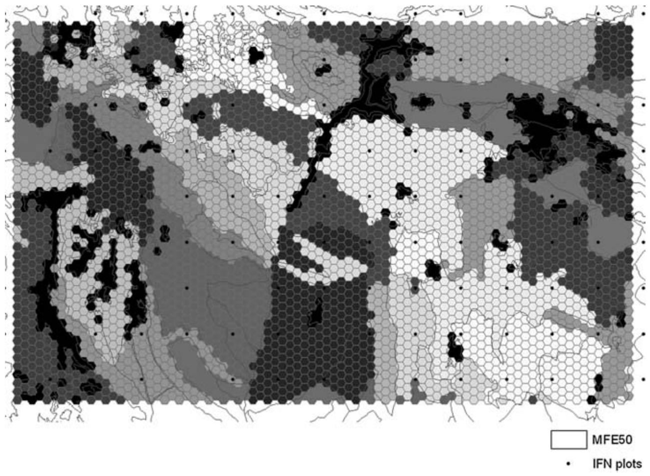

**Fig. 1.** Distribution of the hexagons and blocks of the study forest. Black hexagons represent non-forest land. The boundaries of the blocks were defined using the Spanish forest map, MFE50, whereas the growing stock data were inferred from the National Forest Inventory, IFN.

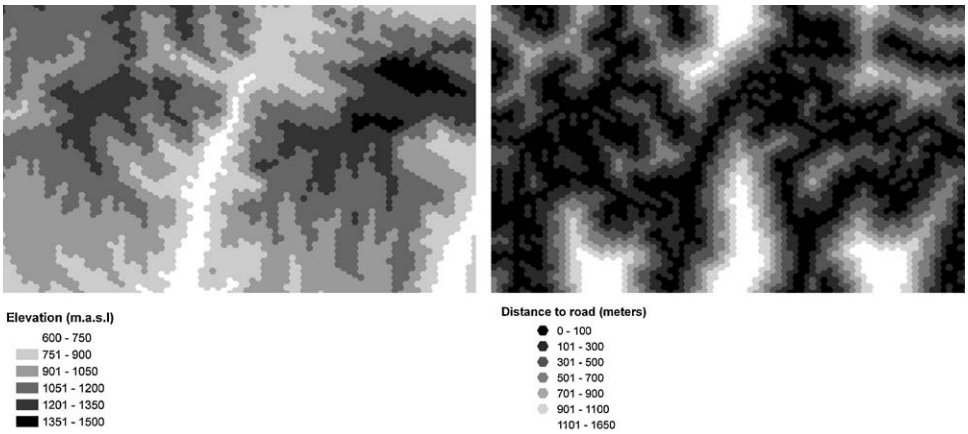

**Fig. 2.** Elevation and distance to roads across the landscape.

by the same tree species and have the same stage of development as indicated in the MFE50.

For each of the hexagons, the following information was recorded: (i) land use (forest, non-forest) obtained from MFE50; (ii) site quality, species composition and diameter distribution obtained from IFN3, (iii) average slope and elevation obtained from a digital terrain model, and (iv) distance to the closest road estimated using the road network from the cartographic map of Catalonia on scale 1:50000. A file was also created indicating the adjacency relations between hexagons. Adjacencies were required in fire spread simulations and to calculate the spatial objective variables used in the optimizations.

The landscape was characterized by its mountainous nature, elevation ranging from 614 m to 1494 m (Fig. 2). The average slope was 43%, ranging from 2% to over 100% (100% = 45°). The average distance of the hexagons to the closest road was 380 m, in the range 0–1650 m (Fig. 2).

The landscape analyzed was composed mainly of pine-dominated stands. *Pinus sylvestris* was the most common species, both in terms of area dominated and timber stock (Table 1). *P. sylvestris* appeared in pure stands or mixed with other pines such as *P. uncinata* at higher elevations or *P. nigra* at lower ones. Admixtures of *P. sylvestris* with *Quercus petraea* and *Q. faginea* were also common. *P. nigra* and *Q. ilex* were common in the lower parts of the %landscape, where *Crataegus* sp. also occurred as an accompanying species. The westernmost part of the landscape included a forest block dominated by *Q. petraea*.

### 2.2. Simulated treatments

Even-aged and uneven-aged management schedules were simulated for the forest hexagons over the 30-year planning period, which was divided up into three 10-year subperiods. Simulation of stand development used individual tree models (Trasobares et al., 2004a,b). When simulating even-aged management schedules the stand was low-thinned when it had reached a thinning limit (basal area that triggers thinning), and it was regenerated by the shelter tree method when it had reached the rotation age. The baseline rotation length and thinning limit of a stand depending on the dominant tree species and site quality based on previous studies dealing with optimal stand management (Palahí and Pukkala, 2003; González et al., 2005b; González-Olabarria et al., 2008) In all, 27 alternative even-aged management schedules were simulated for each stand by applying three different multipliers for rotation length, thinning limit and thinning intensity. In addition, nine uneven-aged management schedules were simulated by combining three different cutting limits (basal area that triggers selection felling) with three different cutting intensities. As in the case of even-aged management, the uneven-aged management schedules were based on previous studies, as in Trasobares and Pukkala (2004).

**Table 1**
Initial distribution and timber stock of the tree species present in the case study forest.

| Tree spp. | Area dominated (ha) | Timber volume ($m^3$/ha) |
|---|---|---|
| *P. sylvestris* | 5769 | 41.5 |
| *P. uncinata* | 0 | 6.8 |
| *P. nigra* | 3426 | 4.4 |
| *Q. petraea* | 264 | 0.8 |
| *Q. faginea* | 0 | 0.0 |
| *Q. ilex* | 636 | 1.2 |
| *Crataegus* sp. | 0 | 0.2 |
| Total | 10095 | 36.9 |

### 2.3. Timber prices and cost functions

The net income from a cutting was calculated by subtracting the harvesting costs from the roadside value of the harvested timber. The volumes of harvested timber assortments were calculated with taper models using the top diameters and minimum piece lengths given in Table 2. The roadside prices of timber assortments were based on statistical data from Catalonia. One characteristic of the timber market in the region is that good quality medium-sized timber (poles) may have better price than larger assortments (sawlogs). Because quality is difficult to predict, the price for poles was set equal to the price of sawlogs (Table 2). Another characteristic of the region is the high price of oak timber, which

**Table 2**
Definitions and roadside prices of different species and timber assortments.

| | Log-size | Pole-size | Particle-board-size |
|---|---|---|---|
| Minimum top diameter | 20 cm | 10 cm | 8 cm |
| Minimum piece length | 3 m | 6 m | 1.5 m |
| Tree species | Roadside price (€/$m^3$) | | |
| | Log-size | Pole-size | Particle-board-size |
| *P. sylvestris* | 45 | 42 | 21 |
| *P. unchinata* | 42 | 42 | 21 |
| *P. nigra* | 42 | 42 | 21 |
| *Q. petraea* | 40 | 40 | 23 |
| *Q. faginea* | 40 | 40 | 23 |
| *Q. ilex* | 40 | 40 | 23 |
| *Crataegus* sp. | 35 | 35 | 20 |

does not depend on the size of the assortment. Oak wood is used mainly as fuelwood.

The harvesting costs were divided into felling and transportation costs. Both types of costs were estimated using functions that included the size of the harvested trees and the accessibility of the stand, using the following equations adapted from Solano et al. (2007):

$$\text{Felling cost}\,(€/\text{m}^3) = \exp(3.406 - 0.568\ln(d) + 0.01\text{slope})$$

$$\text{Transporting cost}\,(€/\text{m}^3) = \exp\,(4.396 - 0.11d^{0.5} + 0.012\text{slope} + 0.001\text{dist})$$

where $d$ is the diameter of the tree (cm), slope is the percentage altitude change per unit distance (%), and dist is the distance to the nearest road (m).

### 2.4. Calculation of fire loss

Fire risk was integrated into the planning problem by predicting its effect on the timber income. For this purpose, the probability of fire occurring in the stand during a period of time was calculated for each hexagon along with the effect that the fire would have on the stand in terms of potential damage. Fire probabilities were used in optimization in an iterative way (Fig. 3). The method consisted in simulating fire spread in the landscape, calculating fire probabilities, and then using these probabilities in optimization.

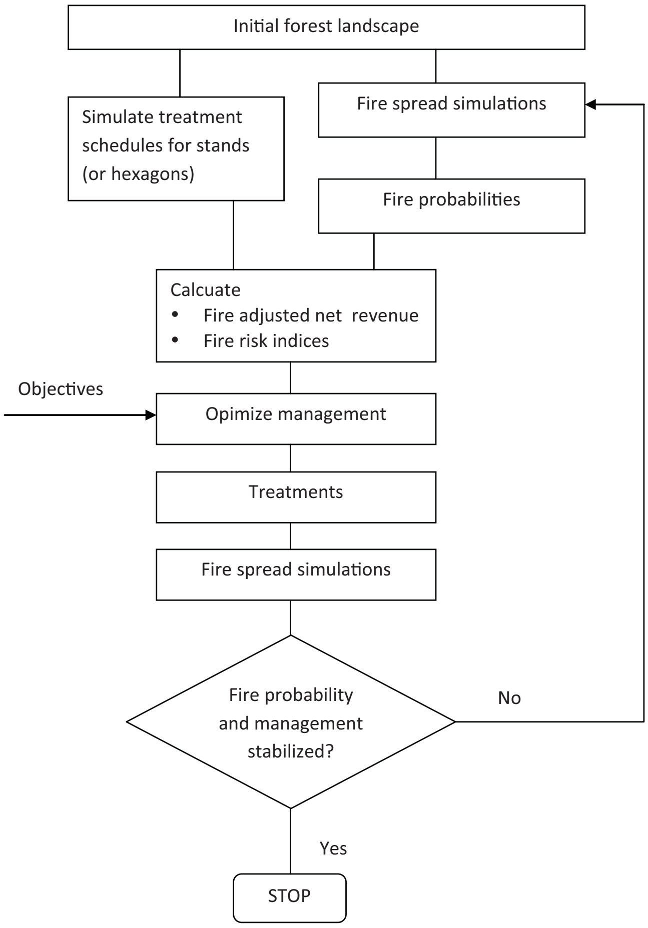

**Fig. 3.** Flow chart of the proposed approach for integrating fire risk assessment in numerical forest planning.

#### 2.4.1. Potential fire damage

Fire damage was considered to be endogenous and therefore dependent on stand characteristics and forest management. It was assumed that if a fire entered the stand (hexagon), the amount and distribution of fuels, along with the topographic and climatic conditions, would influence the intensity of fire in the stand (Agee and Skinner, 2005; Peterson et al., 2005) and therefore the level of damage it caused. For the purpose of estimating fire-related damage in forest stands, a model was developed using data from burned stands of the second and third Spanish National Forest Inventory for Catalonia:

$$y = -6.270 + 0.061\text{slope} + 2.333\text{pine} + 4.790\left(\frac{s_{\text{d}}}{D_{\text{q}} + 0.01}\right) + e \quad (1)$$

where $y = \ln(P_{\text{dead}}/(P_{\text{dead}} - 1))$. $P_{\text{dead}}$ is the proportion of dead trees (of the number of trees), slope is the percentage of altitude change per distance (%), pine is a dummy variable equal to 1 if the stand is dominated by pines (>50% of basal area is pine) and 0 otherwise, $s_{\text{d}}$ is the standard deviation of the breast height diameters of trees (cm), $D_{\text{q}}$ is the quadratic mean diameter (cm) of trees, and $e$ is residual. The model was fitted using the same data as in González et al. (2007). This model was used to predict the proportion of trees killed by fire.

#### 2.4.2. Probability of fire occurrence

Fire behavior inside a forest stand depends not only on the characteristics of the stand, but also on adjacent stands (Agee et al., 2000; Agee and Skinner, 2005; Calkin et al., 2005; Konoshima et al., 2008) and their relative positions. Since the post-fire tree mortality in a specific forest location strongly depends on the intensity of the fire, measured or predicted post-fire mortality can be used as a surrogate for fire intensity, and also as a measure of potential fire spread to adjacent stands. Additionally, it has been reported that the rate and direction of fire spread depend on topography (direction and steepness of the slope).

Based on this principle, a fire spread simulator was developed, using cellular automaton modeling. For each fire spread simulation, the simulator allocated a fire ignition point randomly across the landscape. Once the fire had started, the selected hexagon was marked as burning, spreading fire to its adjacent hexagon $j$ with a probability that depended on the slope and the characteristics of the neighboring hexagon. The probability that the fire would spread from a burning hexagon $i$ to an adjacent hexagon $j$ was defined as $P_{\text{spread}\,ij} = w_{ij}(P_{\text{dead}\,j})$, with $w > 1$ for upslope neighbors and $w_{ij} < 1$ for downslope neighbors (see Fig. 4). In a subsequent step, the previously burning hexagon was considered as burned, and no longer spreading fire, and those hexagons to which fire had spread in the previous step were now burning and therefore able to spread fire to any of their non-burned or non-burning adjacent hexagons. A fire simulation ended when there were no more burning hexagons.

Using the fire spread simulator, the initial 5-year probability of fire occurrence was estimated for each hexagon in our landscape. This estimate was obtained by running 5000 fire spread simulations, and then counting how many times a fire affected each of the hexagons. The mean probability that a hexagon was burned in the 5000 simulations was considered a good proxy of the real probability of fire occurrence in Catalonia in the light of historical fire records in the region from 1992 to 2008. In these records the mean number of fires equal to or larger than 3 ha was approximately one fire every 5 years in an area equal to our landscape, which gives similar average fire probabilities as that obtained from our fire spread model.

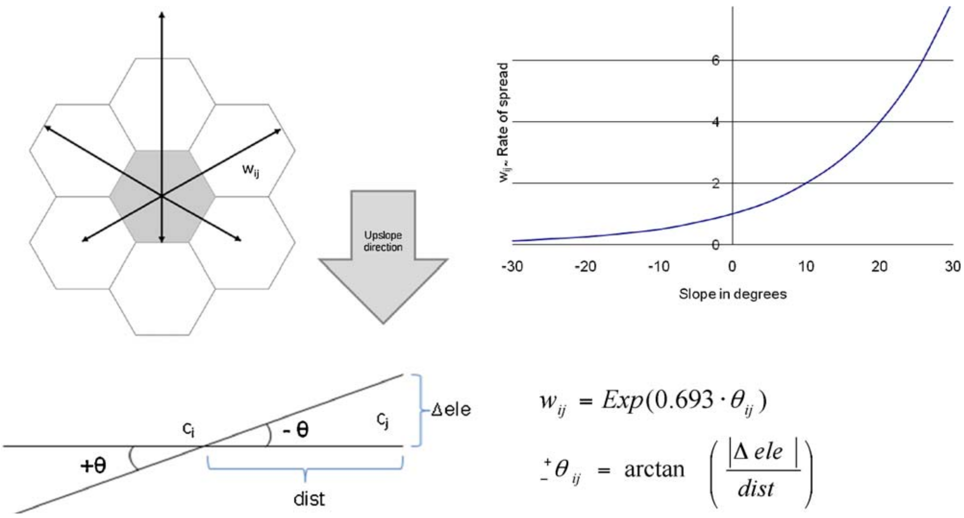

**Fig. 4.** Estimating the effect of slope on the probability of fire spread beween adjacent hexagons ($w_{ij}$). $\theta_{ij}$ is the slope between the centers of hexagons $i$ and $j$ ($c_i$ and $c_j$ in the fig.) defined by the distance (*dist*) and elevation difference ($\Delta ele$) between $c_i$ and $c_j$. The rate of spread doubles for every 10° slope increase (McArthur, 1967; Van Wagner, 1988).

### 2.4.3. Adjusting the fire occurrence probability during optimization

The fire spread simulator makes it possible to evaluate the overall resistance of the resulting landscapes to fire spread. It can also be used to update fire probabilities in the course of an optimization process. To produce a management-adjusted fire occurrence probability for each hexagon we used a stepwise procedure (Fig. 3). First, the fire occurrence probability was estimated for the initial landscape, and was assumed to remain constant over the whole 30-year planning period. Second, for a defined planning problem, an optimal forest plan was selected using these fire probabilities. Third, a new set of fire occurrence probabilities was calculated for the hexagons and 10-year time periods based on the temporal evolution of the forest according to the previously selected plan. This process of selecting the optimal forest plan and then adjusting the fire probabilities of the hexagons and 10-year time periods was repeated until the fire probabilities and the selected treatments were stable (usually four times).

### 2.4.4. Estimating the effect of timber losses on the expected income

By considering the probability of fire occurrence together with the fire damage, it was possible to approximate the expected income from a hexagon at risk of fire, depending on the selected management schedule. The income from the forest without fire ($R_T$) was first calculated. The following formula was then used to estimate the expected income from a cutting conducted after $T$ years:

$$\mathrm{EI}_T = \underbrace{\prod_{t=0}^{T}(1-p_t)}_{P(\text{not burned})}\cdot \underbrace{R_T}_{\text{net revenue}} + \underbrace{\left[1-\prod_{t=0}^{T}(1-p_t)\right]}_{P(\text{burned})}\cdot \underbrace{\frac{1}{T}\sum_{t=0}^{T}(1-P_{\text{dead}\,t})}_{\text{average salvage rate}}\cdot \underbrace{R_T}_{\text{net revenue}} \tag{2}$$

where $\mathrm{EI}_T$ is the expected income; $p_t$ is the probability of fire occurrence in year $t$; $T$ is the number of years from now to the cutting; $R_T$ is the timber income obtained in the cutting; and $P_{\text{dead}\,t}$ is the damage caused by fire in year $t$, calculated using Eq. (1). Calculation was simplified so that $p_t$ values were calculated for the initial state of the hexagon and updated at 10-year intervals.

## 2.5. Fire related indices

Although the inclusion of fire losses in the expected income has an impact on fire risk, a set of fire-related indices was developed with the intention of further improving the fire resistance of the landscape. These indices were named: fire resistance index, fire safety index, and fuel break index. The fire resistance index $F^{\text{res}}$ was defined as the expected proportion of surviving trees if a fire occurs, $F^{\text{res}} = (1 - P_{\text{dead}})$. The fire safety index $F^{\text{saf}}$ was defined as the expected proportion of surviving trees during a time period, for a given fire occurrence probability, being $F^{\text{saf}} = (1 - P_{\text{fire}}P_{\text{dead}})$, where $P_{\text{fire}}$ is the probability of fire ocurrence during a 10-year subperiod. The fuel-break index $F^{\text{br}}$ was created with the intention of identifing high-risk hexagons and allocating fuel treatments to high-risk locations. The fuel-break index was defined as $F^{\text{br}} = ((1 - P_{\text{dead}})P_{\text{fire}})$. It was considered to be “high” when the value was equal or higher than 0.02. Agregating hexagons with high fuelbreak index should create fuel breaks in fire-prone places and stop fire spread.

## 2.6. Planning problems and optimization

Five different planning problems were formulated to analyze the effect of different objectives on the nature and allocation of treatments. To aid comparison of the results, a fixed cutting target of $4 \times 10^5$ m$^3$ during the planning period was set for all the plans except one. The exception was the no-management plan, which assumed that the forest was left to develop without any treatments. Plan 1 maximized the net income, the difference from the remaining plans being that no expected losses due to fire were considered. Plan 2 maximized the expected net income (Eq. (2)) considering potential fire losses. Plan 3 maximized the mean fire safety index of the forest without considering costs (net income was not included in the objective function). Plan 4 maximized the expected net income simultaneously with the mean fire safety index and fire resistance index. The last plan (Plan 5), maximized the expected net income, mean fire safety index, and the share of common boundaries between adjacent hexagons with fuel break index $\geq$0.02. The intention was to create fuel breaks in places where fire probability was high. In the optimization for Plan 5, fire probability was calculated without the effect of fuel breaks, *i.e.* the fuel break index was added to the problem formulation at the final iteration.

Utility functions were used to combine multiple objectives (Pukkala, 2002). Utility functions transform the absolute values of objective variables into subutility values. The functions were as follows:

| | |
|---|---|
| Plan 1 | $U = 1/2u_{\mathrm{h}}(H) + 1/2u_{\mathrm{ni0}}(N)$ |
| Plan 2 | $U = 1/2u_{\mathrm{h}}(H) + 1/2u_{\mathrm{ni}}(N^{\mathrm{adj}})$ |
| Plan 3 | $U = 1/3u_{\mathrm{h}}(H) + 1/3u_{\mathrm{wr}}(F^{\mathrm{saf}}) + 1/3u_{\mathrm{wr}}(F^{\mathrm{res}})$ |
| Plan 4 | $U = 1/3u_{\mathrm{h}}(H) + 1/3u_{\mathrm{ni}}(N^{\mathrm{adj}}) + 1/3u_{\mathrm{wr}}(F^{\mathrm{saf}})$ |
| Plan 5 | $U = 1/6u_{\mathrm{h}}(H) + 1/6u_{\mathrm{ni}}(N^{\mathrm{adj}}) + 1/6u_{\mathrm{wr}}(F^{\mathrm{saf}}) + 3/6u_{\mathrm{fb}}(\mathrm{FB{-}FB})$ |

where $U$ is the total utility, $u_{\mathrm{h}}, u_{\mathrm{ni0}}, u_{\mathrm{ni}}, u_{\mathrm{wr}}, u_{\mathrm{fb}}$, are the subutility functions for the different planning objectives, $H$ is 30-year cutting volume, $N$ is net income calculated without fire losses, $N^{\mathrm{adj}}$ is the expected net income adjusted for fire losses, $F^{\mathrm{saf}}$ and $F^{\mathrm{res}}$ are the mean fire safety and mean fire resistance indices and FB-FB is the share of boundaries between adjacent fuel-break hexagons (fire-resistant hexagons in fire-prone locations). For most objectives ($N$, $N^{\mathrm{adj}}$, $F^{\mathrm{saf}}$, $F^{\mathrm{res}}$ and FB–FB) the subutility functions were linear with a subutility equal to 0 for the lowest possible value, and 1 for the maximum reachable. In the case of the harvest ($H$), a value of 1 was given to the subutility function if the target value ($4 \times 10^5$ m$^3$) was achieved and 0 to the minimum and maximum possible values, forcing the system to reach the target harvest almost exactly.

The optimization problems were solved using a simulated annealing (SA) algorithm (Reeves, 1993) with a two-stand neighborhood (Heinonen and Pukkala, 2004). This method was selected for its capacity to find good solutions and avoid local optima (Bettinger et al., 2002; Heinonen and Pukkala, 2004). A simulated annealing algorithm involves a sequence of iterations, or random moves from a current solution to a neighborhood solution. To avoid premature convergence, which may lead to local optima, SA also accepts non-improving moves with a small probability, decreasing towards the end of the optimization (Dowsland, 1993). The selection of non-improving moves is determined by a cooling schedule.

In this study, the best of 500 initial random solutions was selected as the initial solution. From the initial solution, two random hexagons were selected to implement candidate moves, *i.e.* the management schedule of both hexagons were changed simultaneously. If the two simultaneous changes improved the solution they were accepted. Non-improving moves were accepted with a probability of $p = \exp((U_{\mathrm{new}} - U_{\mathrm{old}})C_i^{-1})$, where $U$ is the total utility, and $C$ is the "temperature" defining the probability of accepting a non-improving move. During the optimization process, $C$ decreased following a cooling schedule, reducing the probability of accepting non-improving solutions, until it reached a stop temperature close to 0. An initial temperature of 0.003 and a cooling multiplier of 0.99 were used. The number of iterations (attempted moves) at the initial temperature was 3365, equal to the number of forest hexagons, and the iteration multiplier was 1.1, so the number of iterations increased by 10% each time there was a change in $C$. The stop temperature was set at 0.0000013, which can be considered adequate for non-spatial problems but highly time-demanding for spatial problems (Heinonen and Pukkala, 2004).

The calculations were done in a computer with an Intel Core Duo 2 CPU, 2.87 GB of RAM, and a process speed of 2.19 GHz. On average, running the fire spread simulations required to obtain the probability of fire occurrence for a single landscape configuration took about 20 min, and to obtain an optimal forest management for a defined fire occurrence probability took about 45 min, if there were no spatial objectives, and 2 h if there were spatial objectives.

## 3. Results

### 3.1. Allocation of forest treatments

Plan 1, which maximized the non-adjusted net income, used much selection felling, due to its greater net return compared with low thinning. Low thinnings followed by final shelter wood cuttings was proposed only in non-steep hexagons close to roads (Fig. 5). Not considering the potential fire losses in optimization yielded a fire risk plan with a high overestimation of the economic return (Table 3). The plan produced a very fire-prone landscape, second in expected burned area after the no-management scenario (Table 4).

All the plans where the fire-adjusted net income was an objective (Plans 2, 4 and 5) resulted in similar plans in terms of $N^{\mathrm{adj}}$. $N^{\mathrm{adj}}$ was almost the same in Plan 2, where the adjusted net income was the sole objective, and Plan 5, in which fire safety and resistance were additional objectives. Plans 2 and 5 propose both low thinnings and selection cuttings to balance the need to obtain positive net incomes (selection felling) and reduce fire risk (low thinning). In both plans most cuttings were placed close to the road network to reduce harvesting costs (Fig. 5). However, although both plans achieved similar values of adjusted net income, Plan 5 managed at-risk hexagons in a way that significantly reduced the fire spread potential within the landscape at the end of the planning period (Table 4). The estimated burned area in 2040–2050 was 793 ha for Plan 2 and 665 ha for Plan 5.

When fire resistance and fire safety were maximized, without economic objectives (Plan 3) the results differed drastically from the other plans in terms of the location and type of cuttings (Fig. 5). Plan 3 proposed much low thinning, due to its improving effect on fire resistance. The treated hexagons were not always near the road network (Fig. 5), implying high logging costs and low net income (Table 3). This plan was the best in terms of fire risk but by far the most costly.

In Plan 4, the adjusted income was maximized together with the mean fire safety index and mean fire resistance index. The plan resulted in a moderately resistant landscape and an economically viable solution. This plan can be considered as an intermediate one with fire losses slightly higher than in Plan 3 (Table 4) and expected incomes slightly lower than in Plans 2 and 5. Plan 4 relied mainly on low thinnings to reduce the risk of fire. Although selection cuttings were proposed, they were significantly fewer than in Plans 2 and 5. The spatial allocation of treatments followed similar patterns as in Plans 2 and 5, short distance to road being a prerequisite for a cutting proposal (Fig. 5).

### 3.2. Fire occurrence probabilities and fire spread patterns

For all the plans, and also for the no-management option, the mean probability of fire occurrence tended to decrease with time as the forest developed. However, the post-plan probability of fire occurrence sometimes increased (no management, Plan 1 and Plan 2).

In general, we observed that those plans where a fire-related landscape metric was included as an objective variable in the planning problem showed a continuous temporal decrease in the potential fire spread. The potential fire spread after the planning period was lower for those plans that had already achieved low fire occurrence probabilities during the planning period. For those plans where the fire occurrence probability showed a rise at the end of the planning period, this was caused by the incorporation of new young trees in some of the non-treated hexagons and also in some hexagons treated with selection cuttings, with a resulting decrease in mean tree diameter (see Eq. (1)).

A clear relationship between amount of low thinnings and expected burned area was found; the plans that applied much low

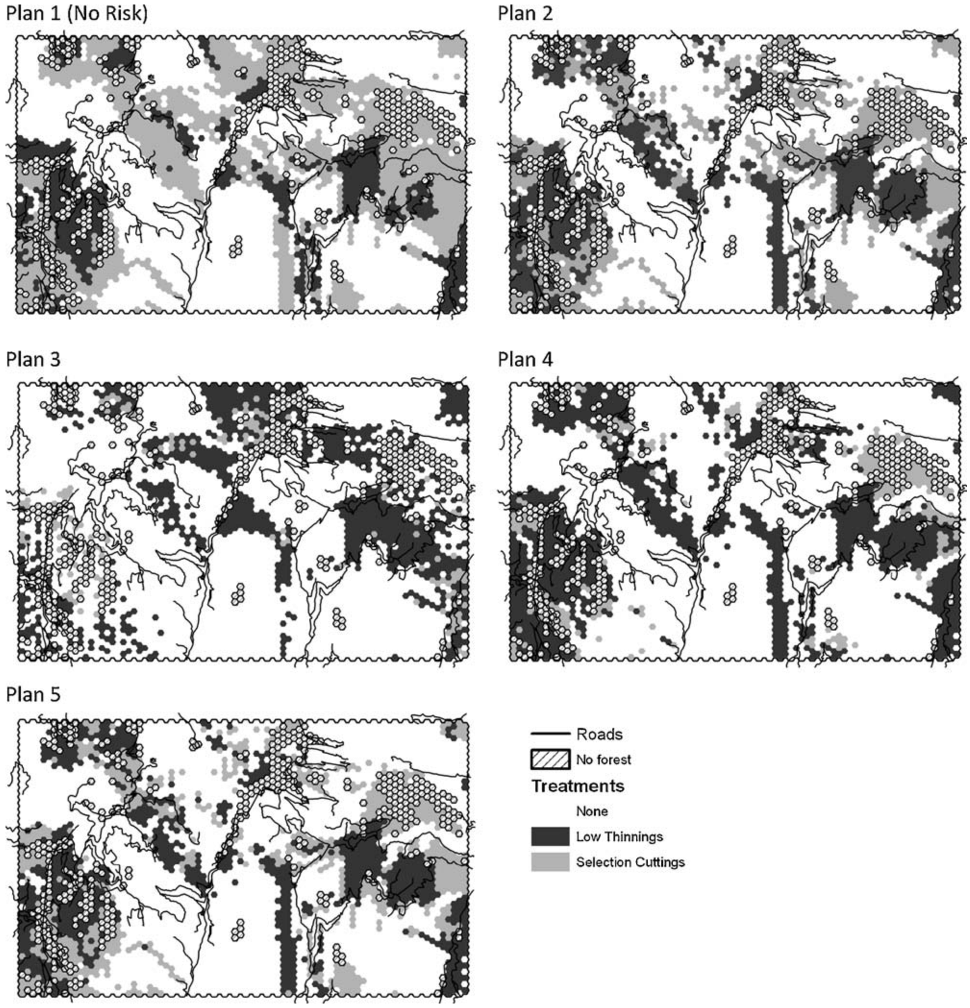

**Fig. 5.** Location of forest treatments in alternative management plans.

**Table 3**
Areas of treatments and expected net income in different forest plans.

| | Forest plan and objective variables | | | | |
|---|---|---|---|---|---|
| Treatment | 1 $N$ | 2 $N^{adj}$ | 3 $F^{saf} + F^{res}$ | 4 $N^{adj} + F^{saf} + F^{res}$ | 5 $N^{adj} + F^{saf} + F^{br}$ |
| Low thinning (ha) | 2982 | 3462 | 7605 | 5142 | 3552 |
| Seed tree cut (ha) | 1497 | 2067 | 1251 | 2118 | 1989 |
| Selection felling (ha) | 7212 | 3753 | 1893 | 1269 | 3681 |
| Remove overstory (ha) | 1305 | 1260 | 522 | 1311 | 1221 |
| $N$ (mill. €) | 7.23 | 6.80 | 2.81 | 6.12 | 6.71 |
| $N^{adj}$ (mill. €) | 1.01 | 2.87 | -2.58 | 2.47 | 2.84 |

$N$ = net income calculated without fire losses; $N^{adj}$ = expected net income adjusted for fire losses; $F^{saf}$ = mean fire safety index; $F^{res}$ = mean fire resistance index; FB–FB = share of boundaries between adjacent fuel-break hexagons (fire-resistant hexagons in fire-prone locations).

**Table 4**
Fire occurrence probabilities (5-year probabilities) and expected burned area during the planning period and during the following 10 years. The values were obtained by running the fire spread simulator 5000 times.

| | Average fire occurrence probability | | | | Burned area | |
|---|---|---|---|---|---|---|
| | Period 1 2010–2020 | Period 2 2020–2030 | Period 3 2030–2040 | Post-plan 2040–2050 | Plan period 2010–2040 | Post-plan 2040–2050 |
| No management | 0.054 | 0.042 | 0.038 | 0.056 | 2996 | 1237 |
| Plan 1 | 0.054 | 0.041 | 0.035 | 0.039 | 2901 | 884 |
| Plan 2 | 0.054 | 0.036 | 0.031 | 0.035 | 2685 | 793 |
| Plan 3 | 0.054 | 0.032 | 0.024 | 0.019 | 2445 | 421 |
| Plan 4 | 0.054 | 0.033 | 0.026 | 0.023 | 2508 | 506 |
| Plan 5 | 0.054 | 0.037 | 0.030 | 0.029 | 2690 | 665 |

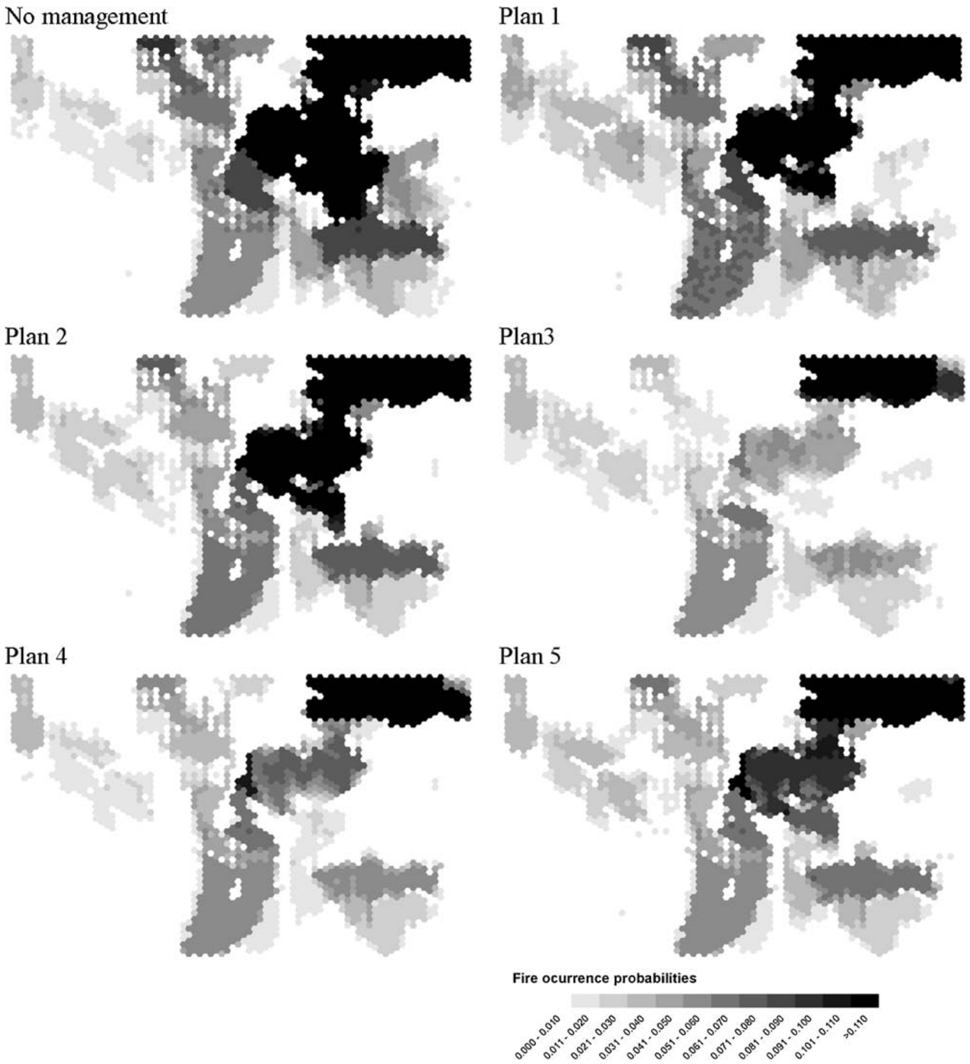

**Fig. 6.** Fire spread probabilities across the landscape for the different plans at the end of the planning period.

thinning were the most fire-resistant at the end of the planning period. Also, the allocation of treatments across the landscape had an impact on fire resistance. For example, Plan 5, with similar low thinning and selection cuttings areas as in Plan 2, led to a significant reduction in the expected burned area, due to the allocation of low thinnings in high-risk locations, which generated effective fuel breaks.

Maps of the fire probability at the end of the planning period show that the no-management option resulted in the most vulnerable landscape, with a higher number of hexagons liable to be repeatedly affected by fire (dark areas in Fig. 6). Those plans that produced a landscape with a lower fire spread potential (Plans 3, 4, and 5) were also able to reduce the overall probability of fire occurrence within the landscape, this reduction being most evident in the central area of the landscape (Fig. 6).

One characteristic of all the plans is the appearance of areas where the probability of fire occurrence is always high (Fig. 6, top right corner of the landscape). An analysis of the forest data showed that most of these forest patches were occupied by forest stands on poor sites in the early stages of development. These young stands did not reach the minimal tree size or stand basal area for cutting, and so did not qualify for treatment alternatives that would improve fire resistance. Since these young stands had a low fire resistance already at the beginning of the planning period they had a strong impact on the overall fire spread potential and fire occurrence probability in the landscape.

## 4. Discussion

One of the main problems when assessing the risk of fire in forest planning is identifying the proportion of the risk arising from exogenous factors and the remaining proportion that is under the control of the forest manager and so is endogenous. Forest plans cover relatively long time periods (years to decades), adding uncertainty to the prediction of some of the variables that affect the behavior of fire. For example, predicting the time that fire will strike a forest and the exact weather conditions before and during a fire is impossible. Understanding the processes that underlie the accumulation of fuels over long periods in heterogeneous landscapes is already a difficult task (He and Mladenoff, 1999). However, it is widely recognized that variables directly related to forest management at the stand level (stand structure and composition) and the landscape level (spatial configuration) play a major role in determining the potential spread and severity of fire, and the subsequent damage caused.

Following recent suggestions (Bettinger, 2009, 2010) a new approach is proposed for integrating fire risk assessment in numerical forest planning. This approach is based on an iterative process of (i) simulating fires, (ii) calculating fire probabilities, and (iii) optimizing forest management until stabilization is achieved in fire spread simulations and forest treatments. This method lets us select a forest plan based on previously acquired knowledge on the effect of the selected plan on the evolution of fire risk. At the same time, this approach gave an opportunity to identify critical locations where specific stand treatments should be allocated (Finney and Cohen, 2003), and to acquire information on how to modify the spatial continuity of hazardous fuels across the landscape in an economically effective way (Loehle, 2004).

The fire spread simulator, developed to generate the fire probabilities, considered the endogenous nature of fire severity and stand resilience (González et al., 2007) and the relative elevation of neighboring stands (McArthur, 1967; Van Wagner, 1988), but omitted the effects of weather and surface fuels. Including weather and surface fuels in a fire spread model would allow more accurate predictions of the burned area (Finney, 2001). However, the absence of reliable information about the future evolution of these factors prevents their use in long-term forest planning (Martell, 2001).

The results of the study showed that including fire risk in forest planning has an impact on the selection of the management schedules for the stands. For example, mainly uneven-aged management was proposed when the net income was maximized regardless of the risk of fire. These schedules were partially replaced by even-aged management when fire risk and potential fire losses were considered. These results agree with recent work by Hyytiäinen and Haight (2009) and Solano et al. (2007) who state that uneven-aged management is often more profitable than even-aged management if fire risk is not considered, but as fire risk increases, even-aged management becomes more profitable, especially if the discounting rate is low.

Additionally, it was observed that logging costs, which depend on the distance to road and slope, had a clear effect on the spatial distribution of the management actions. For example, in forest plans where net income was maximized without explicit spatial objectives the results showed a tendency to aggregate cuttings close to the road network, so as to minimize harvesting costs. Thus road accessibility and slope greatly affected the aggregation of the forest operations, as stated by Gustafson (1996). Allocating treated hexagons near the road network not only improved economic profitability, but also created continuous fuel breaks along roadsides, especially when even-aged management was used. This effect could be especially useful given that fires in Catalonia are usually ignited by human activity and so tend to occur most often near roads (Badia-Perpinyà and Pallares-Barbera, 2006; González-Olabarria et al., 2010). The presence of resistant forest stands in places where fires are likely to start should reduce the probability that ignition will go on to initiate a full wildfire, by providing conditions that favor successful extinction.

Our results show that the plans that adjusted economic expectations on the basis of fire risk (Plans 2, 4 and 5) were the most efficient (Fig. 7). Thus problem formulations 2, 4 and 5 allowed efficient forestry in terms of economic profitability and fire risk reduction. All the other plans were clearly inefficient. For example, Plan 1, where no potential fire losses were considered when the net income was maximized, had significantly lower adjusted incomes than Plans 2, 4 and 5. Additionally, Plan 1 resulted in a landscape that was more vulnerable to fire spread than the other plans. At the opposite extreme, Plan 3, where fire resistance was the only management objective, although resulting in the most fire-resistant landscape, was economically very inefficient (Fig. 7). The forest plans that considered both risk-adjusted economic objectives and fire resistance indices resulted in the most efficient management (Plans 4 and 5).

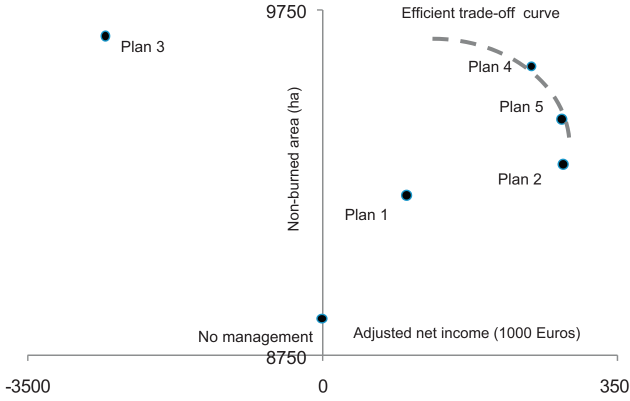

**Fig. 7.** Relationship between fire resistance, expressed in terms of the average non-burned area per fire at the end of the planning period, and adjusted net income in the studied forest plans.

Our study suggests that appropriate forest management planning makes it possible to obtain reasonable income from commercial timber management while at the same time using management as a long-term fire prevention strategy. However, the study shows that the resulting outcomes of the plans depend closely on the initial conditions of the forest. The spatial distribution of the forest blocks and their stand structure dictated the feasible treatments. The topography and distribution of the road network have a strong impact on the optimal allocation of treatments. For this reason, although different outputs are obtained by selecting different forest plans, certain patterns are common to all plans. For example, some blocks were never selected for management, owing to low stand density, young tree age, steep slope or distant location. One possible management option for these stands, not considered in the present study, is the application of treatments that avoid transportation costs, such as low thinnings followed by on-site slashing or prescribed burning of cut trees. The presence of these blocks, together with the characteristic topography of the forest and the spatial distribution of non-forest areas, causes a repetition of similar fire spread patterns in all the plans (Fig. 6). Increasing the length of the planning horizon would most probably show more differences between the management strategies followed in Plans 1–5.

Using a study area based on real data can be considered a limitation, if general prescriptions for optimal allocation of treatments to reduce the risk of fire are required. However, it gives an insight into real-life problems met in forest planning. Comparing the results, using the proposed planning approach in different types of forest landscapes would be an interesting exercise to assess the role of the initial conditions of the landscape on the evolution of fire risk over the planning period. Another aspect that can be included in future studies is the integration of prescribed fires in the planning problem (Yoder, 2004) to reduce the potential fire-related losses within a forest compartment and to further enhance the control of fire spread. Using non-uniform fire ignition probability based for instance on the analysis of historical fire records would be an improvement. Adding the possibility of fire arriving from the surrounding forest lands would also improve the estimates for the probabilities of fire occurrence.

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