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Optimising the management of *Pinus nigra* Arn. stands under endogenous risk of fire in Catalonia

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Abstract

The present study considers the risk of fire as an endogenous component in a stand management optimisation problem for even-aged *Pinus nigra* Arn. stands in Catalonia (North-east Spain). A simulation-optimisation system, RODAL, was used to determine the optimal stand management when maximal soil expectation value (SEV) was the objective. This system was modified to include fire occurrence and post-fire tree survival models. The fire occurrence and post-fire survival models used in the study have been developed for forest planning purposes using explanatory variables that relate the probability of fire occurrence and the expected loss to such stand variables which can be affected by management actions. Non-linear stochastic optimisation was used to find the optimal stand management schedule. The rotation length as well as the timing and intensity of thinnings were optimised. The inclusion of the risk of fire had a clear effect on the optimal stand management schedule, especially on the regime of thinnings which tended to include early thinnings as means of reducing the risk and expected loss. The regeneration cuts tended to be earlier with increasing fire risk.

Key words: forest fire, endogenous risk, non-linear stochastic optimisation.

Resumen

Optimización de la gestión de rodales de *Pinus nigra* Arn. bajo riesgo endógeno de incendio en Cataluña

El presente estudio, presenta como optimizar la gestión selvícola de masas regulares de *Pinus nigra* Arn. en Cataluña cuando se incluye el riesgo endógeno de incendios. Para ello, se utilizó el sistema de simulación-optimización RODAL con el fin de determinar la gestión óptima del rodal, considerando como objetivo de gestión el valor esperado del suelo. El sistema RODAL actualmente incluye modelos para predecir la probabilidad de ocurrencia de un incendio en una masa determinada y la probabilidad de supervivencia de los árboles afectados en caso de producirse el incendio en dicha masa. Estos modelos fueron desarrollados para ser utilizados en la planificación forestal, por lo tanto utilizan variables independientes regularmente utilizadas y obtenidas en el proceso decisorio de la planificación de la gestión forestal. Con el fin de encontrar el plan de gestión óptimo a nivel de masa se utilizó un proceso de optimización estocástica no linear. El plan de gestión óptimo queda definido por la combinación óptima del turno de corta y el momento e intensidad de las claras. La inclusión del riesgo de incendios tiene un claro efecto sobre la gestión óptima del rodal; las claras tienden a ser más tempranas para reducir el riesgo de incendios y el turno de corta también tiende a acortarse para reducir las perdidas esperadas.

Palabras clave: incendios, riesgo endógeno, optimización estocástica no lineal.

Introduction

Forest area in Catalonia (north-east of the Iberian Peninsula) involves 47% of total area. Black pine (*Pinus nigra* Arn. *salzmanii* var. *pyrenaica*) occupies an area of 134,000 ha, which represents 12% of the forested surface (Palahí and Grau Corbí, 2003). In Catalonia, most black pine forests are found in the central region, in the Pre-Pyrenees mountain range and to a less extent in other mountain ranges (Meya *et al*., 2001). Black pine forests in Catalonia are usually privately owned in the form of small-size holdings. Silviculture has been traditionally based on selective cuttings which

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extract trees with diameters appropriate for poles (approx. 25 cm). This kind of management often leads to uneven aged and multilayered stand structures.

In Catalonia, fires are considered as the main environmental problem (Tábara, 1996) causing enormous economic and ecological damages. During the last three decades the problem of forest fires has taken a new dimension in the region with the appearance of larger and more destructive forest fires (González and Pukkala, 2007), like the ones occurring in 1994 and 1998 when over 95 000 ha were affected by fire in Catalonia. Comparing data from the 2nd and 3rd Spanish National Forest Inventory (IFN), recent studies (González *et al.*, 2006, 2007) observed that 23% of the Black pine dominated forests were affected by fire during the period 1991-2002, the percentage of dead trees in the burned forest being approximately 42%. One reason to be considered as a precursor for the change in the regime of fires is the lack of proper forest management. This is caused, into some extent, by the abandonment of rural areas and the low profitability of forest practices, such as low thinnings and even-aged forestry, that lead to less vulnerable stand structures. At the same time, the high risk of forest fire in the region further decreases the profitability of forestry, creating a vicious circle of bad management, decreasing profitability and increasing risk of fire. In order to break such circle, new approaches must be taken. The integration of the risk of fire into forest planning and other analytical calculations is a step towards the solution of the problem. Tools for analysing management options under fire risk enable the manager to properly adjust management to prevailing fire risk conditions. Analytical tools may also show how management actions can be used to reduce the risk level.

Stand compartment is a relevant level where the risk of fire may be analysed when comparing alternative forest management strategies. Several studies have addressed the problem of finding the optimal stand management under risk of fire (Martell, 1980; Routledge, 1980; Reed, 1984; Reed and Errico, 1985; Cauldfield, 1988; Englin *et al.*, 2000; Kuboyama and Oka, 2000, etc.). However, these studies have been focused on the effect of the risk of fire on the optimal rotation length, considering the risk of fire as constant through the whole rotation or dependent on the age of the stands, and ignoring the effect of management on the risk of fire. Considering a management-dependent or endogenous fire risk therefore brings a new perspective into the stand management optimisation problem.

The risk of forest fire, in terms of occurrence probability and potential tree mortality, has been reported to be dependent on variables easily controllable through forest management such as stand density, species composition, and distribution of tree sizes (Van Wagner, 1977; Finney, 1994; Pollet and Omi, 2002; González *et al.*, 2006). Based on the hypothesis that the risk of fire can be predicted from variables related to the forest management, a set of models have been developed to predict the probability of fire occurrence (González *et al.*, 2006) and the potential damage caused by fire (González *et al.*, 2007). These models were specifically developed with the intention of integrating the risk of forest fire into forest management planning problems and stand level optimisations.

In the present study we use a stochastic simulation-optimisation system, RODAL, to examine the effect of endogenous risk of forest fire on the optimal management of an even-aged *P. nigra* stand in Catalonia. The use of such optimisation techniques can provide useful information about how the forest should be managed under risk of fire.

Material and Methods

The stand-level management support system RODAL (Palahí and Pukkala, 2003) was used to find the optimal stand management schedule under risk of fire. The system consists of a stand growth and yield simulator based on individual-tree growth and mortality models. The other module of the system is an optimisation algorithm, which finds the optimal management schedule, defined by a combination of decision variables, for a given objective function (Fig. 1). The system considers the risk of fire by generating fires stochastically and allocating the damage caused by those fires according to models developed for this purpose (González *et al.*, 2006, 2007).

The simulation-optimisation system in the RODAL software is able to find the optimal management schedule for different levels of fire risk using soil expectation value (SEV) as the objective function (Faustmann, 1894).

Initial stand

To initialise a simulation, the RODAL system requires the tree diameters of a young plot (prior to onset of

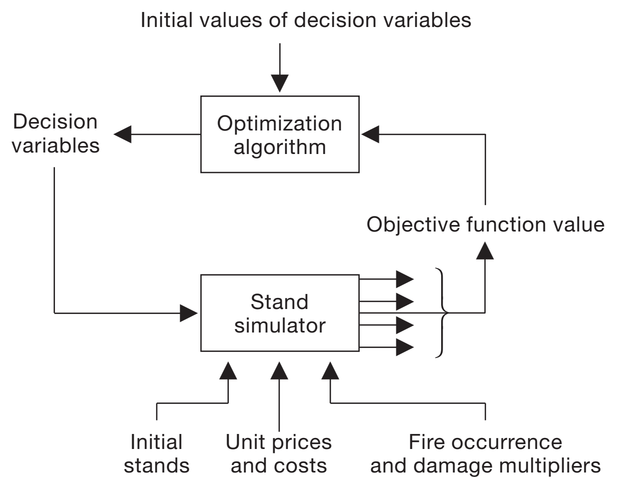

Figure 2. Structure of the stochastic simulation-optimisation system.

commercial thinnings), or the frequencies (number of trees per hectare) of different diameter classes. In addition, the stand age and the site index (dominant height at 60 years) of the forest stand are needed. The initial stand data used in this study came from a 30 years old pure even-aged *P. nigra* stand in Catalonia, representing medium site fertility (Site index 17 m) and located 700 meters above the sea level on a slope of 15% (Fig. 2).

Simulation of growth

The simulation uses a dominant height model, an individual-tree diameter growth model, an individual tree height model, and a survival function to simulate stand development (Palahí and Grau Corbí, 2003). The simulation of one five-year time step consisted of the following steps:

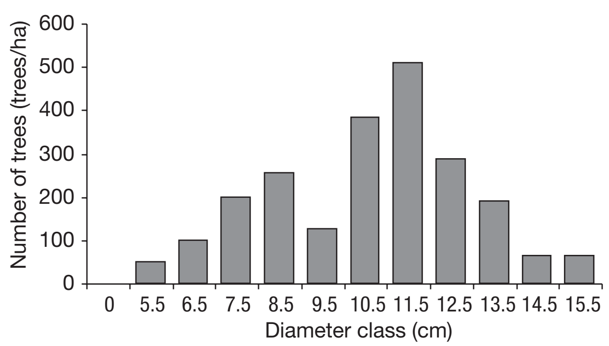

Figure 2. Diameter distribution of the initial stand.

1. For each tree, increment age by 5 years and add the corresponding five-year diameter increment to the initial diameter of the tree.
2. Multiply the frequency of each tree (number of trees per hectare that a tree represents) by the five-year survival probability.
3. Calculate stand dominant height, from the site index and incremented stand age, and calculate the dominant diameter from incremented tree diameters.
4. Calculate tree heights and volumes.

Simulation of thinnings and regeneration cuttings

The RODAL system allows for the simulation of thinnings and regenerative cuts. However, thinnings of even-aged stands are restricted to thinnings from below since the growth simulation is driven by the dominant height development (a thinning treatment must not alter dominant height). When a thinning is simulated, the program removes half of the thinned basal area equally from all diameter classes, and the other half as a low thinning. The simulation of regeneration cuttings was conducted in the present study by mimicking the *uniform shelter wood method*, which includes three successive cuts during the 20 last years of the rotation.

Fire occurrence and damage

For each five-year step simulation, the probability of fire occurrence is predicted using Equation [1] and converted later into 5-year probability (González *et al.*, 2006).

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

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).

Fires are generated in a stochastic way, the exact year of occurrence being generated randomly (0 to 5 years are added to the first year of the simulation step). If a fire is generated during a 5-year simulation step the proportion of trees that die due to fire is predicted using the following stand-level damage model (González *et al*., 2007):

$$y = -6.131 - 0.329G + 0.60\,Slope + 2.266\,Pine + \\ + 4.319\left(\frac{G}{D_q + 0.01}\right) + 6.718\left(\frac{s_d}{D_q + 0.01}\right) + e \quad [2]$$

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 residual term of the model with mean cero and standard deviation of 3.434. In order to mimic the true variation in stand-level damage, a stochastic component corresponding to the residual variation of the model was added to the prediction.

Once the proportion of dead trees is estimated, the next step is to identify the surviving trees by diameter classes. For this purpose, the following model is used to estimate the survival probability of each tree diameter:

$$P_{sur} = \left(1 + e^{-(2.224 + 0.110d - 7.117P_{dead})}\right)^{-1} \quad [3]$$

where P_{sur} is the probability of surviving the fire, d is the diameter of the tree at the breast height (cm), and P_{dead} is the proportion of dead trees obtained from Equation [2]. The probability is converted into number of surviving trees per diameter class, i.e. the total number of trees present in the diameter class is multiplied by the survival probability of the class midpoint tree.

If the estimated damage is superior to a subjectively pre-defined threshold (in this study, 50% of the stand basal area), the fire is considered as a stand replacing one and the stand becomes a zero-year old stand. If the threshold is not reached the stand continues its development. The simulation of stand development is continued until the stand accomplishes a full rotation without being replaced by a fire. The SEV calculated for such a simulation is one stochastic outcome of the management regime.

In the present study, two different regeneration scenarios were considered and their effect on the optimal management analyzed. In one scenario the stand regenerates naturally without any delay and without causing regeneration cost. In the other scenario, artificial planting was assumed after every stand-replacing fire with an additional cost of 1,500 € ha^{-1} (Espelta *et al*., 2003). Additionally, to study the effect of varying levels of fire risk on the optimal stand management, the predictions of the occurrence and damage models were multiplied by 0, 0.5, 1 and 2. Multiplier 0 represents a no risk scenario, multiply them by 1 represents the current level of risk of fire, predicted with the models, and multiplier 2 represents a scenario where the risk has been doubled.

Optimization

A management regime was specified with the following decision variables (DVs):

— For a thinning:
- Stand age when the first thinning occurs.
- Years since previous thinning for the other thinnings.
- Remaining basal area.

— For the final cutting:
- Years since the last thinning to the first regenerative cut.

The direct search method of Hooke and Jeeves (1961) was used to search the optimal combination of these decision variables. The optimisation algorithm calls the simulation module with the current decision variables and fire risk level (Fig. 1). The simulator calculates the value of the objective function, which is passed back to the optimisation algorithm. The optimisation sub-system alters the values of the DVs by using exploratory and pattern search modes (see e.g. Bazaraa *et al*., 1979), and the simulation system recalculates the objective variable after every change. The optimal management schedule is eventually found after repeating the two search processes for many times. The parameters of the Hooke and Jeeves algorithm were the same as in González *et al*. (2005). In the present study, the objective variable was the SEV with 2 % discounting rate.

Results

Effect of fire risk on SEV

When different levels of fire risk were applied in the optimization of stand management some trends were

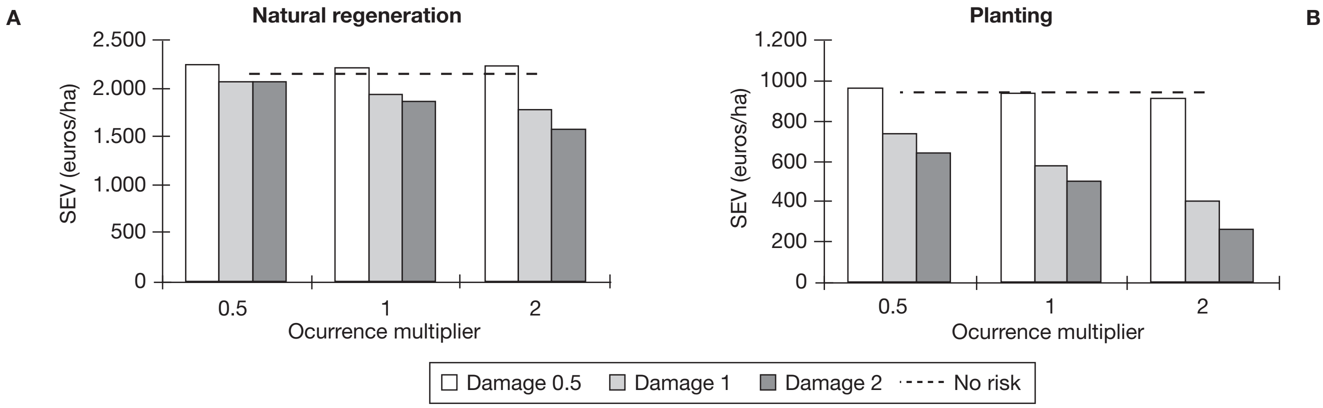

Figure 3. Effect of different levels of risk of fire on SEV of the optimal management schedules (4A, 4B). Occurrence and fire damage multipliers, multiplied to values predicted by each the models (Eq. [1] and [2]), obtaining 9 different risk levels, plus the no risk level.

observed (Figs. 3A and 3B): the higher the risk, the lower was the SEV, especially when the increasing risk of fire came from an increase in the degree of damage rather than fire occurrence. As expected, the additional planting cost increased the relative effect of the risk of fire on the SEV. An exception to the general trend occurred when the damage was halved from the model prediction and no regeneration cost was considered. In this case the SEV was higher than the one obtained without considering any risk of fire indicating that «light thinnings» by fire improve profitability (Fig. 3A).

Effect of fire risk on rotation length

The effect of different levels of risk on the stand's rotation length was not as clear as on the SEV (Figs. 4A and 4B). Generally, rotations shortened with increasing fire occurrence and damage. However, if the fire risk was very high (occurrence or damage, or both, multiplied by two), the optimal rotations started to increase with respect to lower levels of risk (not if compared with a 0 risk level) (Fig. 4B).

Effect of fire risk on thinnings

The inclusion of the risk of fire had a clear effect on the optimal regime of thinnings (Fig. 5) which tended to include an immediate low thinning as a means of reducing the risk. Apart from the effect of fire risk on the time of the first thinning, only changes in the timing of the first regeneration cut were observed (which determines the rotation length). Those first

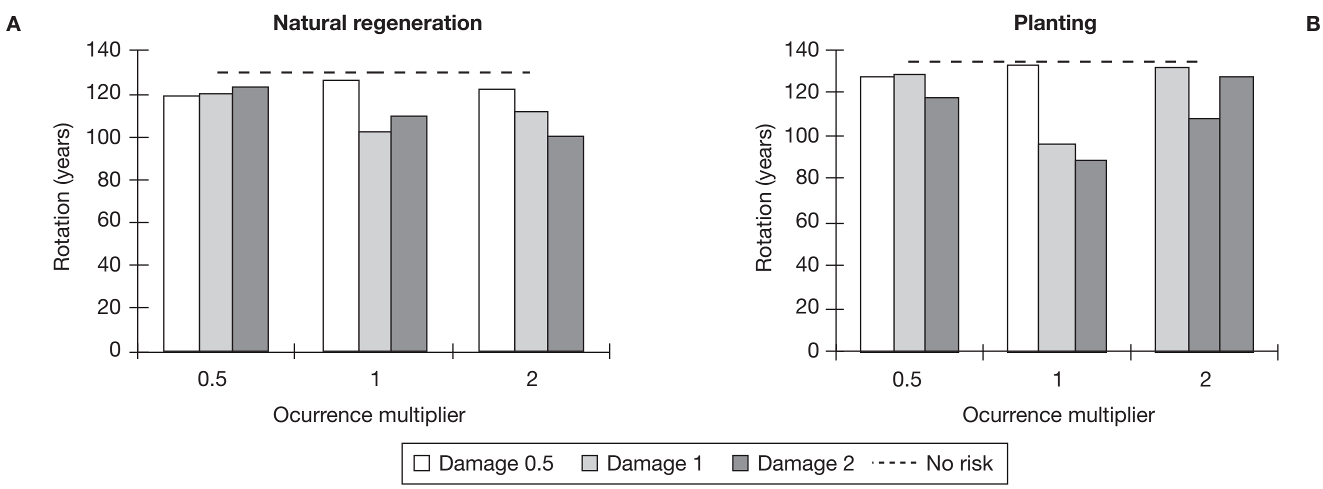

Figure 4. Effect of different levels of risk of fire on the optimal rotation of the optimal management schedules (3A, 3B).

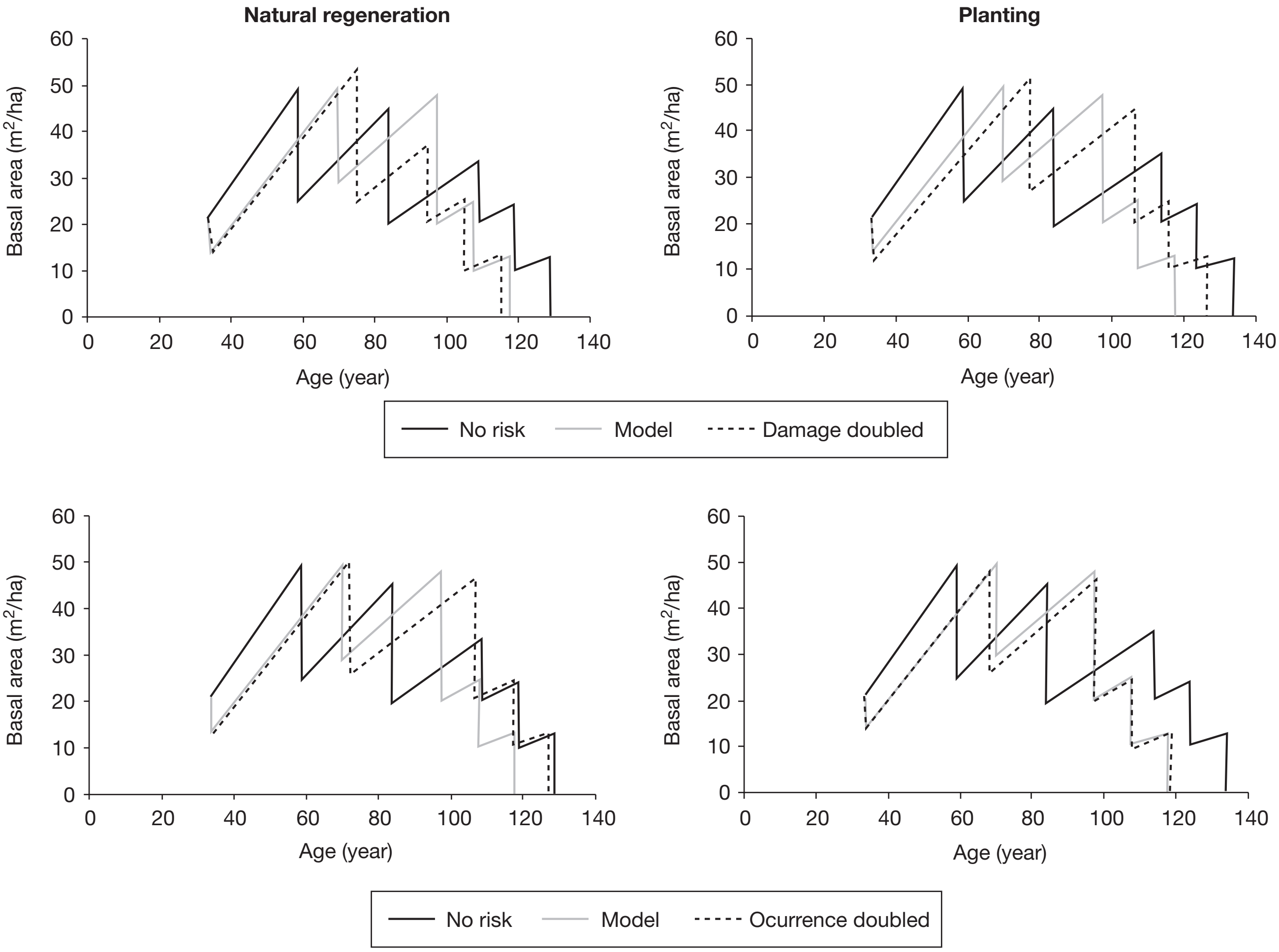

Figure 5. Optimal management schedule for stands under different levels of risk of fire (model means that the occurrence and damage models have been used without modificaton, occurrence doubled or damage doubled means that the predictions of one of the models have been doubled).

regeneration cuttings were applied, in most cases, earlier if a level of risk of fire different than 0 was considered. No other DVs were observed to be systematically affected by the level of fire risk.

Discussion

The inclusion of stochastic models for assessing the occurrence of fires and the potential damage caused by the fires into the stand simulation-optimisation system, enables the forest manager to consider the risk of fire in stand-level forest management optimisation. The presented approach differs from most previous studies in two aspects. It considers the risk of fire (both occurrence and damage) to be dependent on stand structure, and it optimises thinnings in addition to rotation length. These two aspects have a significant effect on the optimisation results. Different thinning regimes have different effects on the stand development, by changing competition included in the growth and yield models. Thinnings also modify the risk of fire (occurrence and damage) by changing the stand structure. Finally, thinnings allow part of the timber to be collected earlier, being exposed during less time to risk of fire.

Considering endogenous risk of fire on the stand management optimisation problem provides interesting results that in some cases differ to those obtained using more classical approaches (Martell, 1980; Routledge, 1980; Reed, 1984; Reed and Errico, 1985; Cauldfield, 1988; Englin *et al*., 2000; Kuboyama and Oka, 2000, etc.). For example, in the present study the optimal rotation length may eventually increase if risk increased, due to the endogenous nature of fire risk. This can be explained by the high resistance to fire of sparse stands containing large trees, and these conditions can be obtained by increasing rotation lengths (and conducting early thinnings). Another reason for increasing rotation lengths under severe risk conditions (occurrence and damage doubled in Fig. 4B), can be the low profitability of forest management, especially if an additional planting cost is necessary. In such case the system trends to minimize this extra cost by increasing the rotation length.

Another example that may represent quite well the effect of taking into account the thinnings as decision variables and including the endogenous risk of fire in the optimisation problem can be observed when the management of the stand was optimised under different levels of fire occurrence probability and the damage was half of the model prediction (Fig. 3A). In this case, the SEV obtained from the optimisations exceeds the one obtained when no risk of fire was applied. Although these results may seem contradictory, they have an explanation when observing the models used in the simulation system. Those fires (halved damage) will unlikely reach the threshold set for stand replacing fires (50% of basal area), and the small number of dying trees will be mainly within the smallest diameter classes of the stand. Fires that remove some small trees from the stand may be an advantage since they reduce thinning costs by removing trees with a negative roadside value. They also reduce the future risk of fire because small trees, that most increase the risk, are removed. In addition, a light fire reduces competition of the remaining trees which will therefore grow faster. As can be observed, a positive effect of fire on the economy of stand management is not impossible or illogical. However, the total economic effect of fire depends on several variables such as the amount and allocation of damage, limit of admissible damage (replacing fire threshold), and the regeneration costs.

The effect of fire on the forest stand, predicted from the damage and mortality models, did not include explicit information about the location of the dead trees, assuming the damage is uniformly distributed across the stand. Fire may also cause damage following diverse spatial patterns due to specific site conditions. For this reason assuming damage to be uniform across the stand, and in some cases having the same effect than a uniform low thinning can be considered as an oversimplification of the problem. Future studies aiming to include the effect of fire damage on the optimal stand management, should try to include explicit information about the spatial features of damage.

Considering the risk of fire as dependent on stand management can be justified especially in a large uniform forest which is managed in the same way. If this is not the case, an additional analysis on the effect that the surrounding conditions have on the stand's risk of fire should be done. The lack of knowledge on other important issues, such as post-fire regeneration, damage threshold (economic and ecologic) that makes the stand replacement necessary, effect of fire on the development of surviving trees etc., made it necessary the use of some assumptions. In order to make future studies more realistic, it would be necessary to provide the system with reliable information that fill these gaps of knowledge. Using different scenarios (levels of risk of fire, type of regeneration, etc.) is a way to overcome partially this problem, and it gives an idea about the flexibility of the system. This system flexibility provides strength to the system, as it allows forest managers to include site specific considerations.

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References

BAZARAA M.S., SHETTY C.M., 1983. Nonlinear Programming: theory and algorithms. Wiley, New York.

CAULFIELD J.P., 1988. A stochastic efficiency approach for determining the economic rotation of a forest stand. For Sci 34, 441-457.

ENGLIN J., BAXALL P., HAUER G., 2000. An empirical examination of optimal rotations in a multiple-use forest in the presence of fire risk. J Agric Res Econ 25(1), 14-27.

ESPELTA J.M., RETANA J., HABROUK A., 2003. An economic and ecological multi-criteria evaluation of reforestation methods to recover burned *Pinus nigra* forest in NE Spain. For Ecol Manage 180, 185-198.

FAUSTMANN M., 1849. Calculation of the value which forest land and immature stands possess for forestry. Allgemaine forst-und jagdzeitung 15, 441-55.

FINNEY M.A., 1994. Modeling the spread and behaviour of prescribed natural fires. Proc 12th Conf Fire and Forest Meteorology. pp. 138-143.

GONZÁLEZ J.R., PUKKALA T., PALAHÍ M., 2005. Optimising the management of *Pinus sylvestris* L. stand

under the risk of fire in Catalonia (north-east Spain). Ann For Sci 62, 493-501.
GONZÁLEZ J.R., PALAHÍ M., TRASOBARES A., PUKKALA T., 2006. A fire probability model for forest stands in Catalonia (north-east Spain). Ann For Sci 63, 169-176.
GONZÁLEZ J.R., PUKKALA T., 2007. Characterization of wildfire events in Catalonia (north-east Spain). Eur J Forest Res 126(3), 421-429.
GONZÁLEZ J.R., TRASOBARES A., PALAHÍ M., PUKKALA T., 2007. Predicting stand damage and tree survival in burned forests in Catalonia (North-East Spain). Ann For Sci 64, 733-742.
HOOKE R., JEEVES T.A., 1961. «Direct search» solution to numerical and statistical problems. J Assoc Comput Mach 8, 212-229.
KUBOYAMA H., OKA H., 2000. Climate risks and age-related damage probabilities-effects on the economically optimal rotation length for forest stand management in Japan. Silva Fenn 34(2), 155-166.
MARTELL D.L., 1980. The optimal rotation of a flammable forest stand. Can J For Res 10, 30-34.
MEYA D., GONZÁLEZ J.M., AUNÓS A., 2001. Evolución del crecimiento radial en un rodal adulto de *Pinus nigra* Arn. de la provincia de Lleida. Invest Agrar: Sist Recur For 10(1), 95-110.
PALAHÍ M., GRAU CORBÍ J., 2003. Site index model and individual-tree growth and mortality models for Black pine (*Pinus nigra* Arn.) in Catalonia (Spain). Invest Agrar: Sist Recur For 12(1), 137-148.
PALAHÍ M., PUKKALA T., 2003. Optimising the management of Scots pine (*Pinus sylvestris* L.) stands in Spain based on individual-tree models. Ann For Sci 60, 105-114.
POLLET J., OMI P.N., 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. Int J Wildland Fire 11(1), 1-10.
REED W.J., 1984. The effects of the risk of fire on the optimal rotation of a forest. J Environ Manage 11, 180-190.
REED W.J., ERRICO D., 1985. Assessing the long-run yield of a forest stand subject to the risk of fire. Can J For Res 20, 961-969.
ROUTLEDGE R.D., 1980. The effect of potential catastrophic mortality and other unpredictable events on optimal forest rotation policy. For Sci 26(3), 389-399.
TÁBARA D., 1996. La percepció dels problemes del medi ambient. Beta Editorial, Barcelona, Spain.
VAN WAGNER C.E., 1977. Conditions for the start and spread of crown fire. Can J For Res 7, 23-34.