Assessing fire risk in stand-level management in Galicia (north-western Spain)

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Abstract

Forest fires are the most important threat that forest plantations have to face in Galicia. Due to both economic and ecological losses that fire cause in the region, fire risk must be integrated in forest management planning. Nevertheless, the complexity of forest fires and the dependence of their consequences on many uncontrollable factors (i.e., wind speed, fuel moisture, flame intensity, etc), makes it difficult to predict these consequences. Fire risk is the probability of occurrence multiplied by the proportion of damaged timber. The aim of this study is to analyse the effect of fire risk on the optimal management schedule of *Pinus radiata* stands under two different ways of assessing risk: endogenous and exogenous approach, both with and without timber depreciation. The results show that optimal rotation length shortens with increasing fire risk if there is timber depreciation. Without timber depreciation the trend is similar except for very high values of exogenous salvage rate and endogenous salvage; in these situations, rotation length increases when fire risk increases.
Keywords: optimisation, simulation, endogenous risk, exogenous risk, soil expectation value, salvage, timber depreciation.

1 Introduction

Fire can be considered the main hazard for forest stands in Galicia. More than half of the forest fires that took place in Spain in the last decade occurred in Galicia. (Ministerio de Medio Ambiente [1]). Among the reasons that can explain this high proportion of forest fires are the high fuel loads due to management that maximises biomass production. This kind of management is a consequence of high demand for disintegration wood in the region. The current management practise involves production of large amount of forest residues

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which often are left in the forest (Núñez-Regueira *et al* [2]). Another reason for high fire risk is the land abandonment that turns fragmented forest in continuous one and, therefore, eases the spread of forest fires (Moreira and Russo [3]).

With this background it seems necessary to integrate fire risk into forest planning. Fire risk has been proved to affect optimal management of forest stands (González-Olabarría *et al* [4], Pasalodos-Tato *et al* [5]) and, thus, it must be considered when developing forest management strategies in the region. With the development of new tools that can help forest managers to anticipate the evolution of forest stands, new approaches have been considered in the field of forest planning. These methodologies allow forest managers not only to anticipate the evolution of the stands in the future under a chosen management schedule (growth and yield models, simulators), but also to know which management schedule one should follow in order to fulfil the management objectives (optimisation methods).

There are many examples of the optimisation of forest management in order to obtain maximal productivity (see Pasalodos-Tato and Pukkala [6] for references). Risk has been integrated in the optimisation problem in many other studies (see Pasalodos-Tato *et al* [5] for references). Thorsen and Helles [7] considered the risk endogenous when it depends on the management decisions that affect stand characteristics (like timing and type of thinnings), approach that was adopted by some other authors when dealing with risk of fire (Amarcher *et al* [8], González-Olabarría *et al* [4], Pasalodos-Tato *et al* [9]). The general conclusion of these studies is that the optimal management under conditions of fire risk present different trends depending on whether the risk of fire is treated as endogenous or exogenous factor. The aim of this study is to find out how the way of treating fire risk affects the economically optimal management schedule of *Pinus radiata*.

In the present study the characterisation of fire risk is based on the definition adopted by Bachmann and Allgöwer [10], which implies that risk comprises the probability of an undesired event and its outcome, which can be translated to quantitative terms as the probability of occurrence multiplied by the outcome (or damage). Considering that the main cause of forest fires in Galicia is arson (Ministerio de Medio Ambiente [1]), which is not influenced by management, the probability of fire occurrence was considered as exogenous in this study. However, the salvage rate can be considered as a constant value (exogenous approach) or as an endogenous variable, which depends on stand characteristics. In the first case (exogenous approach) the salvage proportion is a constant over the whole rotation. In the endogenous approach the proportion of timber salvaged after a fire depends, in our case, on the breast height diameter, which means that it depends on the management when it affects the growth rate of the trees.

A decision support system was employed to seek for the optimal management of *Pinus radiata* stands under the risk of fire. It includes simulation and optimisation sub-systems. The simulation sub-system predicts the outcome of a certain management schedule in a certain stand with certain assumptions concerning fire risk, salvage percentage, timber price and management schedule and calculates the objective variable which, in our case, was the economic performance. Using the optimisations conducted with the system, the effect of the two different approaches to dealing with salvage on the optimal management schedule will be analysed.

2 Material and methods

2.1 Growth simulation

To simulate stand development in different management schedules, we used the model developed by Castedo-Dorado *et al* [11] for even-aged *P. radiata* stands in Galicia. In this model, the initial stand conditions are defined by three state variables (number of trees per hectare, stand basal area and dominant height), and are used to estimate the total and merchantable stand volume for a given projection age. The model uses three transition functions to provide the stand state at any point of time and also includes a function for predicting the initial stand basal area, that can be used to establish the starting basal area for the simulation. Once the state variables have been predicted for a specific moment, the Weibull distribution function is used to estimate the number of trees in each diameter class. By using a generalized height-diameter function to estimate the height of the average tree in each diameter class, combined with a taper function that uses diameter and height, the total and merchantable stand volume are calculated, which depend on specified log dimensions.

To calculate the stem volume extracted in thinning operations or clear cuttings, the following top diameters (d_{top}) were used: 35, 18 and 7 cm, corresponding to the following timber assortment: (I) $d_{top} \geq 35$ cm; (II) 35 cm > d_{top} > 18 cm; and (III) 18 cm > d_{top}. The following minimum piece lengths were assumed in this study: (I) 3.0 m; (II) 2.5 m; and (III) 1.0 m. If the piece was shorter, the volume was moved to the next (with a smaller minimum top diameter) timber assortment.

2.2 Objective function

The soil expectation value (*SEV*) was used as the objective variable. The *SEV* was calculated as the net present value (*NPV*) of all future net incomes:

$$SEV = \frac{NPV_f}{1 - \frac{1}{(1+r)^R}}. \tag{1}$$

where NPV_f is the net present value of the first rotation, r is the discounting rate and R is the rotation length (years).

The *SEV* can also be expressed as the sum of the *NPV* of the first rotation plus the *NPV* of all the subsequent rotations:

$$SEV = NPV_f + NPV_{allsubsequent}. \tag{2}$$

which is the same as:

$$SEV = NPV_f + \frac{NPV_f}{(1+r)^R}. \tag{3}$$

To integrate the risk of fire in the optimisations, the standard probabilistic approach developed by Bright and Price [12] was adopted. This method makes a risk valuation in three phases: (i) evaluate the NPV of different possible outcomes, (ii) weight each NPV by the probability of the outcome, and (iii) sum of the probability-weighted NPVs. The risk of fire was defined by means of three variables: probability of occurrence, salvage proportion and timber price reduction. The modified expression of the *SEV* was:

$$SEV = \sum_{t=1}^{R} p_t \times NPV_t + p_R \times NPV_R + \sum_{t=1}^{R}\left[p_t \times \frac{NPV_t}{(1+r)^t}\right] + p_R \times \frac{NPV_R}{(1+r)^R}. \tag{4}$$

where p_t is the probability that fire hits the stand and ends the rotation prematurely at an age t shorter than the full rotation (R) and survives the previous years ($p_t = (1 - p_{fire})^{t-1} p_{fire}$), where p_{fire} is the annual probability of fire), and p_R is the probability that there is no fire before the rotation age ($p_R = (1-p_{fire})^{R-1}$)).

NPV_t (and NPV_R) is calculated as follows:

$$NPV_t = \sum_{i=0}^{t} \frac{I_i - C_i}{(1+r)^i}. \tag{5}$$

where C_i are the costs and I_i the incomes in year i. The incomes are calculated by:

$$I_i = s_t \sum_{j=1}^{J}\left(n_j \sum_{k=1}^{3} v_{kj} \cdot P_k\right). \tag{6}$$

where s_t is the proportion of salvage (s_t = 1 when t = R), J is the number of diameter classes, n_j is the number of trees in diameter class j, P_k is the unit price of timber assorment k and v_{kj} is the volume of assortment k of a tree in diameter class j. In the exogenous approach salvage (s_t) is constant and in the endogenous approach it is calculated by:

$$s_t = 1 - 0.92^d. \tag{7}$$

where d is the diameter at breast height measured in cm. To develop the model we employed the information obtained from the Forest Service of the Galician Administration and corroborated the relationship by comparing it with the results obtained by Botelho *et al* [13] for similar stands in Portugal for *Pinus pinaster*.

In order to avoid too heavy thinnings, a penalty function was added to the objective function. A thinning intensity higher than 30% was assumed to make the stand sensitive to windthrow and snow breakage (Castedo-Dorado *et al* [14]). Therefore, the eventual objective function (*OF*) which was maximised was:

$$OF = SEV - \sum_{z=1}^{Z} Penalty_z. \tag{8}$$

$$Penalty_z = \begin{cases} 0 \quad \text{if} \quad TH\%_z \le 30 \\ 10000\dfrac{TH\%_z - 30}{70} \quad \text{if} \quad TH\%_z > 30 \end{cases} \tag{9}$$

where $TH\%_z$ is thinning intensity in percent of removed stand basal area in thinning z and Z is the number of thinnings. According to the penalty function, the penalty of harvesting too much at a time, increases from 0 to 10 000 € ha^{-1} when the harvest percentage increases from 30 to 100.

2.3 Decision variables

A management schedule is defined with decision variables (DV). Optimised management schedule means that the optimal values for DVs have been found (Mabvurira and Pukkala [15]).

Schedules with different numbers of thinnings have to be treated as separate optimization problems because the number of thinnings is not a continuous variable (Miina [16]). In this study, the number of thinnings was fixed at three based on preliminary analyses where three thinnings often produced the highest SEV and was never much worse than the best number of thinnings. Considering also that the thinnings simulated in this study were combinations of uniform and low thinning, the management regime was specified by the number of thinnings and the following DVs:

- For the first thinning
  - Stand age
  - Percentage of uniform thinning (% of number of trees)
  - Percentage of low thinning (% of trees removed after uniform thinning)
- For the other thinnings
  - Number of years since the previous thinning
  - Percentage of uniform thinning (% of number of trees)
  - Percentage of low thinning (% of trees removed after uniform thinning)
- For final felling
  - Number of years since the last thinning

The number of optimized decision variables was therefore $3 \times Z+1$ where Z is the number of thinnings (i.e. 10 DVs with three thinnings).

2.4 Optimisation method

The optimisation algorithm used was the direct search method of Hooke and Jeeves [17]. This method uses a form of coordinate optimization and does not require explicit evaluation of any partial derivative of the objective function. The direct search method compares each new trial solution with the best obtained up to that time. The search has two components, the exploratory search and the pattern search. For a given base point, the exploratory search examines points around that base point in the direction of the coordinate axes (decision variables). The pattern search moves the base point in the direction defined by the given (current) base point and the best point found in exploratory search. The convergence of this method to the global optimum is not guaranteed with objective functions which are neither convex nor differentiable (Miina [16]).

2.5 Economic parameters

The economic parameters needed for calculating the SEV were timber prices, discounting rate and treatment costs. For timber price data, different sources were consulted, such as the Association of Galician Private Forest Owners, the Galician Forest Administration and the study of Rodríguez *et al* [18]. The following prices were used: 90 € m^{-3} for grade I timber (top diameter ≥ 35 cm), 50 € m^{-3} for grade II timber (35 > d ≥ 18 cm) and 18 € m^{-3} for grade III timber (18 > d ≥ 7 cm). The discounting rate used was 3%.

The Galician Forestry Administration was consulted for silvicultural costs (table 1).

Table 1: Years and costs of tending operations. *N* is the number of planted trees per hectare.

Year	Operation	Cost (€/ha)
0	regeneration	500+1*N*
2	cleaning	150
4	cleaning	150
10	pruning	200
15	pruning	200

The regeneration cost (Table 1) was assumed to be a linear function with the constant part representing the cost of site preparation and the variable part representing the planting cost per tree.

The harvesting cost was calculated from (based on Ambrosio *et al* [19]):

$$HCost = ECost + V \cdot \left\lfloor FCost + (78 \cdot (S+3.3)^{0.30477} / \bar{v}^{0.972}) / 167 \right\rfloor \cdot \quad (10)$$

where *Hcost* is harvesting cost (€ ha^{-1}), *ECost* is entry cost (€ ha^{-1}), *V* is the total harvested volume ($m^3 ha^{-1}$), *FCost* is forwarding cost (€ m^{-3}), *S* is slope (%), and $\bar{v}$ is the mean volume of harvested trees (m^3). It was assumed that the entry cost of moving the machinery to the forest (*ECost*) is 200 € ha^{-1}. The forwarding cost was assumed to be 5 € m^{-3} and the slope was taken as 20%.

2.6 Study cases

We optimised the management of an initial stand of *Pinus radiata* under different conditions of fire risk. The age of the initial stand was fixed at 10 years, and the initial dominant height was calculated from stand age and site index. The site index chosen was 21 metres at 20 years and the stand density was 1500 trees per hectare. The initial stand basal area was calculated using the initialization equation of the model.

Fire risk conditions were varied using four different annual fire probabilities: 0%, 1%, 3% and 5%. When fire comes before the rotation age we assume that the landowner harvests any salvageable timber, and then replants and begins a new rotation. The outcome of fire is in our case measured by the amount of timber that can be salvaged after the fire. In the exogenous approach three different salvage proportions were considered, namely 10%, 50%, 75% and 90%. In the endogenous case the salvage proportion is calculated with eqn. (7).

Besides the fact that some timber is lost after a fire occurs, we also analysed the cases with and without timber depreciation. This depreciation corresponds to a decrease of timber price by around 25% according to the timber auction statistics in Galicia (Arenas and Izquierdo [20]). Timber prices were decreased by 25% when fire ended the rotation (i.e. salvaged timber was 25% cheaper).

3 Results

When there is no depreciation of timber prices the optimal rotation lengths decrease when the probability of occurrence increases for the cases in which salvage is exogenous and smaller or equal to 75% (fig.1). For salvage values larger than 75% rotation length increases with the probability of fire. This means that when the salvage proportion is high, it is worthwhile to increase rotation length. This is a way to postpone the risky situation, i.e. the beginning of next rotation; a young stand without commercial timber is totally lost even with a high salvage rate because fire was assumed to always end the rotation. When salvage is endogenous, the optimal rotation length increases with increasing probability of fire. The bigger the trees are, the less susceptible to fire they became. Moreover, there is no timber depreciation, so it is more profitable to prolong the rotation lengths.

When a price reduction of 25% of burned wood was assumed, the effect of salvage on optimal rotation length is smaller. In all cases the increase of the probability of occurrence decreases the rotation length. It can also be deduced that the smaller the salvage proportion is, the shorter the rotation length

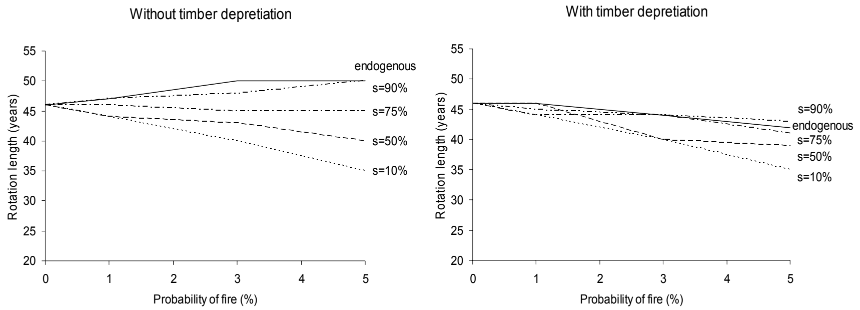

Figure 1: Relationship between the probability of fire occurrence and optimal rotation length when different salvage proportions are considered. On the right hand side figure a 25% depreciation in timber price is considered.

becomes. Now optimal rotation lengths decrease even when salvage percentage is higher than 75%. The same happens when salvage is endogenous.

4 Conclusion

The main conclusion that can be extracted from this study is that the results about optimal stand management depend on the information that we have about fire risk components and the manner in which these components are treated in optimisation. It is therefore important to acquire knowledge about salvage characteristics, not only the proportion of timber that can be harvested after the fire occurs but also its distribution among diameter classes and the price reductions of different timber assortments. When instruction for the optimal management of *Pinus pinaster* under risk of fire are developed using optimisation techniques, it is necessary to develop models for predicting the salvage and the influence of fire on timber prices. The most realistic way to characterise salvage is by using stand characteristics as predictors (endogenous approach). It would be especially useful to consider stand characteristics which are not only easy to obtain from forest inventories but also easily predicted in forest planning. Breast height diameter, stand basal area and number of trees per hectare are examples of these predictors.

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