

**Dissertationes Forestales 102**

Optimising forest stand management in Galicia, north-  
western Spain

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Academic dissertation

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## **ABSTRACT**

The present thesis aims at developing instructions for the optimal management of pine stands in Galicia in order to maximise the economic profitability of these stands. Galicia is a Spanish region characterised by the high productivity of its forests, *Pinus pinaster*, *Pinus radiata* and *Pinus sylvestris* being Galicia's most important conifers. Analytical methods have not been effectively applied in Galician forest management. The main objective of the present thesis was to develop management tools that ease the management in Galician pine stands, thus enhancing the profitability of forestry. Employing stand growth and yield models in combination with an optimisation algorithm, models for the optimal management of pine stands were developed. Since optimal management is sensitive to market conditions, timber price and discounting rate were used as predictors in the models (studies I-III) in addition to other predictors such as site index and planting density. The main challenge for the development of Galician pine stands is the constant presence of forest fires that complicate both management and economic analyses. High risk of fire makes it necessary to include fire risk considerations in the analyses when developing instructions for the optimal management. Fire risk was characterised and analysed as an exogenous (study II) or endogenous (studies III-IV) factor, observing that the manner in which fire risk is characterised affects the conclusions about optimal forest management. Another novelty of this thesis was the analysis of silvopastoral systems as an alternative to mere timber-oriented schedules under conditions of high fire risk (study IV). The results (studies I-IV) showed that optimal management was highly sensitive to market and fire risk conditions, an increase in both discounting rate and fire risk shortening rotation optimal lengths. The models for optimal management developed in the thesis allow great flexibility for adapting the instructions to every possible economic and risk situation. Study IV showed that grazing in the forest improved profitability.

**Keywords:** stand-level optimisation, management instructions, discounting rate, Hooke and Jeeves' algorithm, fire risk, salvage.

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I would also like to thank my co-authors Dr Fernando Castedo-Dorado, Dr Alberto Rojo, Prof Antonio Rigueiro, Dr Rosa Mosquera and Dr Esther Núñez for the help provided in the research work and/or on the data acquisition. Prof. Jose G. Borges and Dr. Jordi García have been excellent hosts during my stayed in Lisbon and they are acknowledged for fruitful discussions that have influenced this thesis. With Dr José Ramón González, Dr Tero Heinonen, Dr Mikko Kurtilla and Dr Jouni Pykäläinen I have shared many lunch times and enriching conversations about forest planning, I learnt many things by listening to them. Dr Ulises Diéguez guided my steps to Finland and provided helpful comments this research. I would like to acknowledge also Dr Luis Díaz-Balteiro for his comments and for his constant interest on this thesis. Dr Aija Ryyppö was always willing to help me with the practicalities at the Faculty; I really thank her for making easier my life at the University. I express my deepest gratitude to Dr Jari Miina and Dr Marc Palahí who acted as the official pre-examiners of the thesis providing valuable and detailed comments that helped me to improve this thesis. I really thank them for the time and attention they put in this task.

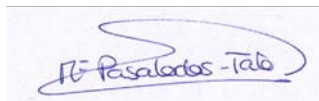
My former colleagues from the Forest Service of La Coruña (Spain) provided data about forest fires in Galicia and shared with me the first stage of this project. My workmates from INIA (Spain) made me feel a part of the group from the very first day and walked with me the last steps of this thesis. I want to thank all of them not only for these reasons but for been excellent colleagues. I would like to thank Dr Gregorio Montero for all the facilities provided to make it possible to finalize this thesis.

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Madrid, April 2010

María Pasalodos Tato

A handwritten signature in blue ink that reads "M. Pasalodos - Tato". The signature is written in a cursive style and is enclosed within a faint, hand-drawn oval border.

## LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following papers referred to in the text by the Roman numerals I-IV. The articles are reprinted with the kind permission of the publishers.

- I **Pasalodos-Tato, M.** & Pukkala, T. 2007. Optimising the management of even-aged *Pinus sylvestris* L. stands in Galicia, north-western Spain. *Annals of Forest Science* 64:787-798.  
doi: 10.1051/forest:2007059
  
- II **Pasalodos-Tato, M.**, Pukkala, T. & Castedo-Dorado, F. 2009. Models for the optimal management of *Pinus radiata* D. Don in Galicia (north-western Spain) under risk of fire. *Allgemeine Forst und Jagdzeitung*. 180 (11/12): 238-249.  
<http://www.sauerlaender-verlag.com/index.php?id=429>
  
- III **Pasalodos-Tato, M.**, Pukkala, T. & Rojo Alboreca, A. 2010. Optimal management of *Pinus pinaster* in Galicia (north-western Spain) under endogenous risk of fire. *International Journal of Wildland Fire*. In press.  
<http://www.publish.csiro.au/nid/114.htm>
  
- IV **Pasalodos-Tato, M.**, Pukkala, T., Rigueiro-Rodríguez, A., Fernández-Núñez, E. & Mosquera-Losada, M.R. 2009. Optimal design and economic analysis of silvopastoral systems established on abandoned agricultural soils. *Silva Fennica* 43(5): 831-845.  
<http://www.metla.fi/silvafennica/full/sf43/sf435831.pdf>

María Pasalodos-Tato was responsible for the data analysis, compiling the results and writing all the articles. Professor Timo Pukkala supervised the writing process and the analysis of all the papers and prepared the simulation-optimisation program employed in studies I-IV. The other co-authors of studies II-IV have helped to improve reporting by commenting the manuscripts.

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# 1 INTRODUCTION

## 1.1 Galicia

Galicia is located in north-western Spain. It is characterised by rugged orography and Oceanic climate with mild temperatures, low termic oscillation between winter and summer and frequent rainfalls. Galicia is a rural region, its important economic sectors being agriculture, fisheries and farms. Also forestry is one of the principal economic activities in Galicia, which is among the most important Spanish regions from the point of view of forestry production. With 3 million hectares, Galicia comprises 5.8% of the total area of Spain, 7.8% of the total forest land and 9.5% of the wooded forest land (DGCONA 2002a). It contributes to more than half of the timber production in Spain (Chas et al. 2002). The growth rates of forests are very high, up to  $30 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$  for the best site qualities of eucalyptus (DGCONA 2002b). Forests belong to individual land-owners (68%), communes (30%) and public institutions (2%) (Xunta de Galicia 2001). The average area owned by a person is only two hectares (Xunta de Galicia 1992), typically divided into 2 or 3 compartments, the small size of holding being a problem in forest planning.

The main tree species of Galicia are *Pinus pinaster* Ait. (384 000 ha), *Quercus robur* L. (188 000 ha) and *Eucalyptus globulus* Labill. (174 000 ha) which occur mainly in pure but also in mixed stands. From the economic point of view the most important species are *Eucalyptus globulus* Labill., *Pinus pinaster* Ait., *Pinus radiata* D.Don and *Pinus sylvestris* L. Around 6.5 million  $\text{m}^3$  are harvested every year, 46.5% corresponding to saw timber, 36.5% to particle wood and 17% to pulp wood. Of the harvested timber 61% is pine, 31% eucalyptus and 8% other broadleaves species. The statistics (DGCONA 2002b) claim that there is a lack of saw timber in the region. However, many plantations are oriented to the production of pulp and board wood. These are dense plantations managed to maximise biomass production.

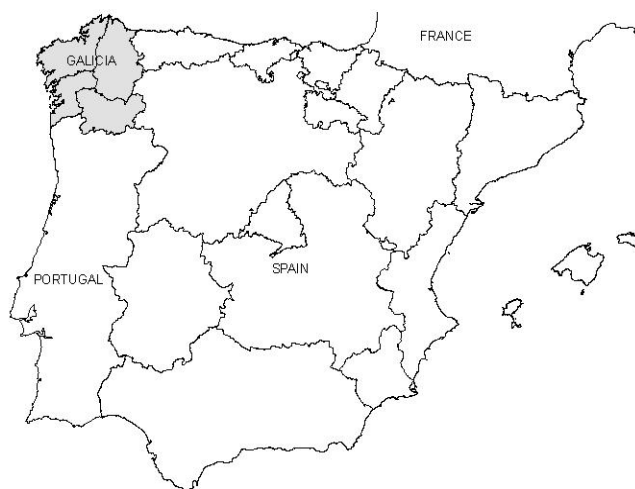
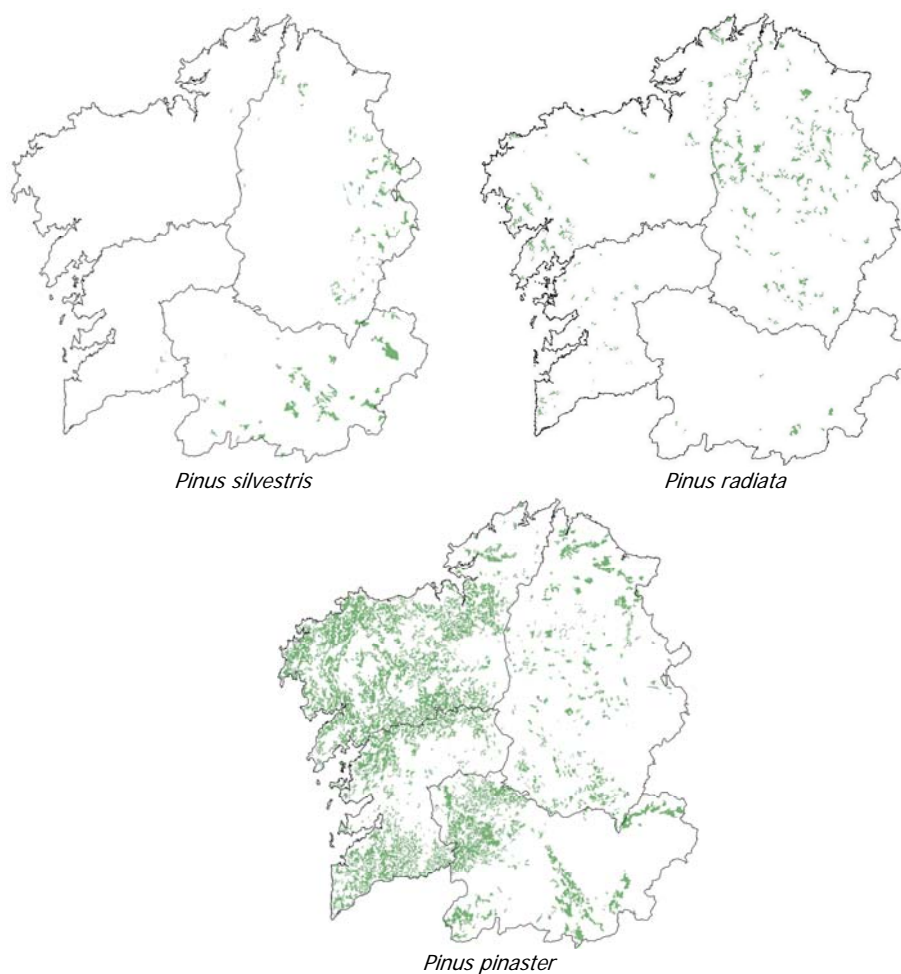


Figure 1. Location of Galicia.



**Figure 2.** Distribution of the three main conifer species in Galicia.

*Pinus pinaster* with 384 000 hectares of wooded forest land (Xunta de Galicia 2001) both in even-aged plantations and naturally regenerated stands, as well as mixed with *Eucalyptus* and *Pinus radiata*, is the most abundant and economically important conifer of Galicia. Other important conifers are *Pinus radiata* covering almost 60 000 ha of pure stands (Xunta de Galicia 2001) and 500 000 m<sup>3</sup> harvested annually (Xunta de Galicia 2006), and *Pinus sylvestris* stands of around 63 000 ha (Xunta de Galicia 2001) and an annual harvest of 78 000 m<sup>3</sup> (Xunta de Galicia 2006).

Another feature that characterises Galician forests is the abundance of forest fires. More than half of the forest fires in Spain during the last decade occurred in Galicia, most of them being deliberately caused (Seijo 2005, Ministerio de Medio Ambiente 2006). Although the trend in last years showed a decrease in forest fires compared to the former decades, in 2006 a wave of forest fires swept the region with 90 000 hectares of forest burnt (Chuvieco et al. 2006, Xunta de Galicia 2007, Ministerio de Medio Ambiente 2007) implying that fire is still a problem to be solved. Forest fires cause great ecological and



economic losses. Some of these losses are noticeable only gradually such as the influence of ashes on maritime ecosystems (BOCG 2006) but in the case of timber the losses are immediately noticed. Economic losses can be expressed in terms of timber lost in a fire and in terms of reduced price of the survived stems.

The damage caused by fires is enhanced by some factors that favour the propagation of fire, such as high stand densities, lack of intensive silviculture, and land abandonment. Lack of intensive silviculture translates into the low quality of the produced timber (Bermúdez and Touza 2000) and great fuel loads (Vega 2001, Núñez-Regueira et al. 2003). Fires spread easily due to the continuous structure of the landscape caused by the abandonment of the rural lands (Moreira and Russo 2007). This is more relevant in the interior provinces of Galicia, where summers are, in general, warmer and drier. Young plantations are much more susceptible to fire damage than the older stands (Botelho et al. 1998).

The most important reason of forest fires is arson (Seijo 2005, Ministerio de Medio Ambiente 2006). Pasture management is also significant since fire has been employed to eliminate understory shrub vegetation and to promote the growth of more palatable species suitable to feed the animals. However, if pastures are managed in a sustainable way grazing can reduce fire risk by reducing the fuel loads at the understory level (Rigueiro-Rodríguez et al. 2005, Rigueiro-Rodríguez et al. 2009). Since pasture production greatly depends on tree cover it is logical to integrate silvopastoral systems in forest planning tools in Galicia. Integration of timber production and grazing diversifies incomes from the forest and it may reduce the risk of fire by diminishing fuel loads.

## 1.2 Forest planning in Galicia

Despite the opportunities that Galicia shows regarding forestry, forest management is not very advanced. There is a heavy pressure by forest industries on conifer stands (Bermúdez and Touza 2000). For instance, the high productivity of *Pinus pinaster* and *Pinus radiata* forests allows profitable wood production for disintegration purposes with short rotation lengths leaving out management schedules that would produce more valuable products. This is noteworthy if we consider the lack of saw timber in the region (Bermúdez and Touza 2000). With a different management forest owners may have even more profit from their forests than now. Nowadays, silvicultural schedules are mainly based on experience instead of quantitative analyses. As a consequence, Galician forests are not managed optimally.

Lack of modern tools, easy to use in forest planning practice, has been an indirect reason for basing forest management on tradition. Special characteristic of forest crops are long rotations. The manager needs to anticipate the outcome of different management schedules in order to choose the best one. Growth and yield models provide this type of information. These models allow the manager to simulate any management schedule. In recent years, growth and yield models for the main conifer species of Galicia have been developed (Álvarez González et al. 1999, Diéguez-Aranda et al. 2006, Castedo-Dorado et al. 2007).

### *1.2.1 Growth and yield models*

According to Valsta (1993) growth and yield models can be classified on different grounds: (i) the unit of prediction; (ii) employment of spatial data, i.e. distance dependent vs. distance independent; (iii) stochasticity or determinism; and (iv) statistical-empirical vs. process-based models. Considering the first category, growth and yield models can be stand-based models, diameter distribution models and individual tree models. Since the models employed in this thesis are stand level models, more attention is given to them. Regarding the three other features that Valsta (1993) used to classify growth and yield models, the models employed in this thesis are distance independent, deterministic and empirical. In whole stand models the basic units of modelling are stand parameters, for instance basal area, stand density and stand volume (Vanclay 1994). Since the information provided by these models is rather general, more detailed approaches have been implemented in order to make them useful in forest planning. Among these approaches we have the whole-stand distribution models, state space models and whole stand transition matrices (Vanclay 1994). The models developed in Galicia employed the first two approaches (Álvarez González et al. 1999, Diéguez-Aranda et al. 2006, Castedo-Dorado et al. 2007). Whole stand distribution models provide additional information on the stand structure by estimating the diameter distribution. The state-space approach was developed by García (1984, 1994) to model plantations. In this approach the system is described by the specified state variables that summarize the historical events affecting the future development of the stand. Future values of state variables are derived by using a few transition functions (Vanclay 1994).

### *1.2.2 Stand level management*

Models provide information about the stand dynamics. They help managers in the decision making process by predicting the future development of the stands. According to Valsta (1993), five levels can be distinguished in forest management decision making, namely tree, stand, forest, enterprise, and region or sector. A forest stand is a geographically continuous parcel of land considered homogeneous in terms of tree vegetation (Davis et al. 2001). It is also the basic operational unit in forest management. The stand level management problem is to select the time and intensity to implement each activity in order to maximise or minimise the management objective (Roise 1986a). The stands that are considered in this thesis are even-aged stands established by planting. Decisions must be made regarding the number of thinnings, timing and intensity of thinnings as well as the time for clear felling. In forest planning, the decision of choosing the best management schedule involves the generation of multiple alternatives for each stand. Once they are generated, they need to be combined in the way that the objectives of the forest owner are fulfilled. In this type of stands that are plantations oriented to produce economic revenues, the most common goal is to maximise the economic profitability. Some studies have been carried out in Galicia by comparing the performance of different management schedules (Rodríguez et al. 2002, Bravo and Díaz-Balteiro 2004, Castedo-Dorado et al. 2004, Rojo et al. 2005a, Bravo et al. 2008). Since there are very many potential alternatives, optimisation techniques have been commonly used elsewhere to find the best management schedule (Pukkala and Mabvurira 1999, Rautiainen et al. 2000, Palahí and Pukkala 2003, Trasobares and Pukkala 2004, González et al. 2005). Optimisation methods are used for finding the optimal management alternative according to the goals set by the forest owner (Pukkala et

al. 1998). A common way to implement optimisation at the stand level is a combined use of a simulator of the stand dynamics and an optimisation algorithm (see Valsta (1993) and Hyytiäinen (2003)).

### *1.2.3 Integrating the risk of fire*

Due to the abundance of forest fires in Galicia it is important to integrate the risk of fire in forest planning. Fire risk is defined by two components: probability of the fire to occur multiplied by the damage caused (Jones 1992, Kumamoto and Henley 1996, Bachmann and Allgöwer 2000). The occurrence probability depends on the availability of fuel, the presence of a heat source for ignition, and oxygen (Hardy 2005). Oxygen is never a limiting factor, and the same is true for fuel availability in most Galician forests. Therefore, the main source of variation in fire occurrence is ignition. Since the majority of forest fires in Galicia are caused by arson (Seijo 2005, Ministerio de Medio Ambiente 2006), ignition probability does not depend on climatic factors.

The second component of fire risk is damage, which is measured in terms of the proportion of timber that is lost after a fire occurs. In the present thesis the term salvage is used. Salvage is the proportion of timber that can be harvested after fire takes place. Sometimes salvage is considered independent of the stand characteristics. In this case damage is exogenous to stand management. However, it is more logical to suppose that fire does not affect all stands in the same way. Younger stands are more susceptible to fire. When damage is related to e.g. diameter at breast height (Botelho et al. 1998, González et al. 2007) which can be affected by stand management, it is an endogenous factor.

### *1.2.4 Silvopastoral systems*

Silvopastoral systems in Galicia have proven to be effective in reducing the risk of fire (Rigueiro-Rodríguez et al. 2005). They also provide incomes sooner than timber-oriented schedules (Anderson and Sinclair 1993, Sharrow 1999). These are reasons that make it attractive to study these traditional production systems. Integrating silvopastoral systems in stand level planning would help us to enhance profitability. Nevertheless, little research has been done regarding the management of this kind of systems although they may be a good alternative when the risk of fire is high.

## **1.3 Aims of the thesis**

The main objective of this thesis was to find the optimal management of planted pine stands in Galicia. The stand level is useful because of generality of the results (Valsta 1990). The optimisation results were translated into management instructions. To elaborate these instructions, models for the optimal management schedules for pine plantations were developed. These models show the optimal management of a given stand as a function of states of nature. A state of nature was defined as a combination of variables that cannot be controlled by the forest manager or decision maker (Pukkala and Kangas 1996). In this thesis they were economic conditions and fire risk.

To attain the principal objective of this thesis, different sub-objectives were set:

- (i) Integrate the risk of forest fires in the optimisation of stand management.
- (ii) Develop models for the optimal management of pine stands in Galicia.

- (iii) Examine the performance of silvopastoral systems as an alternative to timber-oriented schedules.

The first objective consisted of the inclusion of fire risk in the analysis. Risk of fire was first treated as an exogenous factor (study II). To make the problem more realistic, the risk of fire was also treated as an endogenous factor (studies III and IV). Forest fires were assumed to reduce the price of the salvaged timber.

For developing management instructions for Galician pine stands different factors were integrated in the analysis. Economic parameters describing different market conditions as well as different stand types were incorporated in the optimisation process in order to analyse their influence on the optimal stand management (studies I, II, III and IV). The optimal management schedules of different stands under different market conditions were found and regression models were fitted to the results.

The last aim of the thesis consisted of providing information on silvipastoral systems to reduce the effects of forest fires and timber price fluctuations. Silvopastoral systems were considered as a potential tool for reducing fire risk and providing additional incomes (study IV).

The four studies aimed at providing information for forest owners to help them to manage their stands in an optimal way. Since the developed management instructions were expressed as regression models in which optimal management is a function of non-controllable variables, they can easily be adapted to changing market conditions and different fire risk situations.

## 2 STAND LEVEL OPTIMISATION

Stand level optimisation has been used with many different objective variables. Economic profitability has been widely studied in both even-aged (Valsta 1986, Miina 1996, Palahí and Pukkala 2003) and uneven-aged stands (Trasobares and Pukkala 2004, Pukkala et al. 2010) not only with timber as the only product but also when mushrooms (Díaz-Balteiro et al. 2003, Palahí et al. 2009), CO<sub>2</sub>-capture (Díaz-Balteiro and Romero 2003, Pohjola and Valsta 2007) or agricultural products (Muchiri et al. 2002) are considered together with timber. To illustrate the flexibility of objectives in stand-level optimisation, it is interesting to cite biodiversity (Wikström and Eriksson 2000) and recreational values (Koskela et al. 2008). The influence of the risk of fire on forest management has also been analysed when optimising management at the stand level, especially in the USA and Canada (Routledge 1980, Martell 1980, Reed 1984, Reed and Errico 1985, Caulfield 1988). These studies focus on the effect of the risk of fire on economically optimal forest management without considering thinning operations. Rotation length has been the only decision variable and the risk of fire has been assumed to be age-dependent (Martell 1980), constant over time (Routledge 1980) or a time-independent Poisson process (Reed 1984). Some years ago, thinnings have been integrated in optimisations problems that include risks (Thorsen and Helles 1998, Möykkynen et al. 2000, Amacher et al. 2005a, 2005b, González et al. 2005, González-Olabarria et al. 2008).

Optimisation techniques can be used to develop instructions for stand management. Stand level optimisation finds the best management schedule for a stand of trees without taking into account the dynamics of the neighbouring stands. The stand level management schedule is defined by the operations involved on the schedule. In this thesis the stands are

even-aged plantations. The optimised silvicultural operations include thinnings and a final clear cut (defined by the decision variables).

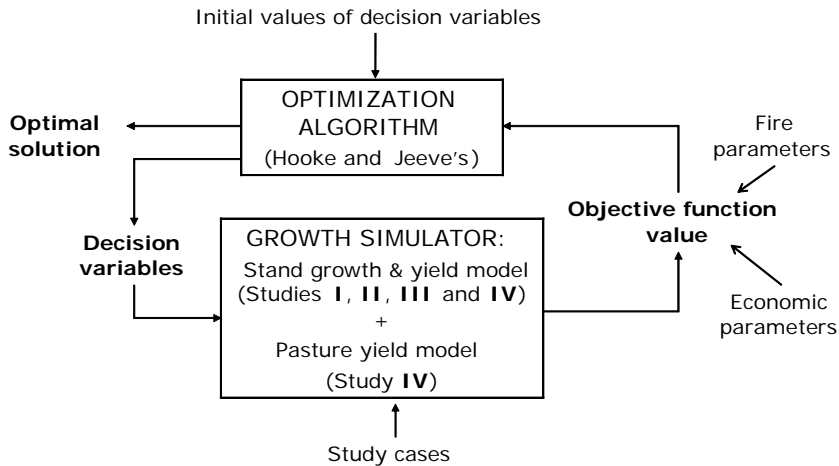
Different methods have been employed in stand level optimisation and various classifications of these methods have been done. In his doctoral thesis White (1988) classified the methods for solving stand level models into four categories: marginal analysis, control theory, comparative simulation and dynamic programming but pointing out the importance of the latter. Some years later Valsta (1992) considered that stand-level optimisation can be divided into deterministic and stochastic methods. Among the deterministic methods he distinguished (i) dynamic programming, (ii) optimal control theory, (iii) non-linear programming and (iv) random search. The stochastic group includes three methodologies: (i) adaptation and anticipation; (ii) stochastic dynamic programming and optimal stopping and (iii) stochastic non-linear programming. Bettinger (2005) distinguished four different categories as the more usable: Hooke and Jeeves (1961); heuristics and meta models; non-linear programming and dynamic programming. Some years later Bettinger et al (2008) generalized a bit more and distinguished three broad categories: Hooke and Jeeves; heuristics or meta models and dynamic programming. This latter classification can be completed by modifying one of the groups. Instead of considering Hooke and Jeeves method as a category by itself, Pukkala (2009) grouped it in the so-called direct search methods. Within this category there are methods that work with one solution, namely Hooke and Jeeves method, cyclic coordinate method and Rosenbrock method (see Bazaraa et al. 1993), and methods that operate with a population of solutions, namely differential evolution, particle swarm optimisation, evolution strategy and Nelder-Mead method (see Pukkala 2009). This thesis classifies the methods into (i) dynamic programming and (ii) direct search methods. The latter group divides into three types of methods: (i) direct search methods with one solution vector, (ii) population-based methods; and (iii) heuristics and meta models.

All these methods present advantages (+) and disadvantages (-) that make them more or less suitable to apply depending on the model they are aim to solve:

- Dynamic programming
  - (+) It finds the global optimum
  - (+) It is fast/efficient
  - (-) It is difficult to use with tree-level models
  - (-) It is difficult to use in stochastic optimization
- Direct search methods:
  - (-) They do not guaranteed to find the global optimum
  - (-) They are slow/inefficient
  - (+) They can be used with any type of models
  - (+) They are easy to use in stochastic optimization

The formulation of the optimisation problem depends on the method applied (see Valsta 1993). In this thesis, Hooke and Jeeves' direct search algorithm (non-linear programming) is employed. This method does not work with the state variables of the stand but with decision variables that define the change in the state variables generated by human actions. The problem is formulated as follows (Figure 3):

$$\max_{\{x \in C \subset R^m\}} f(x|w_0) \quad (1)$$



**Figure 3.** Structure of the simulation-optimisation system.

where  $f(\mathbf{x}|\mathbf{w}_0)$  is the value of the objective function generated by the stand simulator,  $\mathbf{x}$  is the vector of decision variables,  $\mathbf{w}_0$  ( $\mathbf{w} \in R^m$ ) is the vector of initial conditions for the stand simulator (initial stand) and  $C$  is the set of feasible decision variables. The state variables are not used by the optimisation algorithm but computed by the stand simulator based on the given initial state  $\mathbf{w}_0$  and the decision variables (Kao and Brodie 1980, Roise 1986b, Valsta 1993).

## 2.1 Dynamic programming

Dynamic programming (DP) is essentially an optimisation approach that simplifies complex problems by transforming them into a sequence of smaller simpler problems (Bradley et al. 1977). DP typically solves the problem in stages. The computations at the different stages are linked through recursive computations in a manner that yields a feasible optimal solution to the entire problem (Taha 1992).

The first study that employed DP to solve forestry problems was Arimizu (1958). Some years later Hool (1966) provided an application of DP to a forest production problem solving it as a Markov chain but restricted to a very small problem. Among the first studies in incorporating thinning decisions in the optimisation problem we find the study of Chapelle and Nelson (1964), who solved the problem employing marginal analysis. Some years later, Amidon and Atkin (1968) employed data from Chapelle and Nelson (1964) to solve the problem of the optimal stocking by DP. They set the problem as a multistage sequential process in the sense that the level of each thinning affects the intensity of all the subsequent thinnings as well as the magnitude of the final harvest. The interaction between thinnings may be due to either mensurational or economic forces. The number of thinning alternatives can increase rapidly. They obtained the same results as Chapelle and Nelson (1964). Amidon and Atkin (1968) used backward recursion, the most important outcome of

their study being the computational flexibility showed by DP when changing the basic parameters, which is important especially in sensitivity analysis.

Schreuder (1971) formulated the problem in a continuous way but, in order to use DP, he transformed it in a discrete form. The solution method used backward recursion and the model included the cost of the land. Brodie et al. (1978) employed forward recursion and developed a method for solving the problem of finding the optimal thinning schedule and rotation length. They concluded that forward recursion is more flexible for thinning analysis. One shortcoming of the model was that they did not take into account that more intensive thinnings accelerate diameter growth. This was solved by Brodie and Kao (1979) who used a biometric model instead of a yield table and developed an algorithm called DOPT.

Chen et al. (1980) optimised stand densities and rotation length in order to maximize the volume harvested over the rotation. They used also a growth model. Based on the work of Brodie and Kao (1979), many applications were carried out: Ritters et al. (1982) employed DP to optimise timber production and grazing; Hann et al. (1983) studied initial planting density and precommercial thinnings; Sleavin (1983) developed a similar model for a different simulator (DFSIM); Haight et al. (1984) employed single-tree simulator (instead of whole stand simulator as Brodie and Kao (1979) did) modifying the output in order to be able to use the same methodology as Brodie and Kao (1979) (Brodie and Haight 1985, White 1988).

While the integration of DP and stand growth and yield models has allowed the simultaneous determination of the timing and intensity of thinnings, the successful integration of the two requires one to limit the number of variables used to define thinning decisions (Haight et al. 1985). To solve this, Paredes and Brodie (1987) introduced a new programming algorithm called PATH (Projection Alternative THEory) that reduces the scheduling problem to a one-state one-stage DP problem. Yoshimoto et al. (1988) introduced the MS-PATH (Multiple Stage PATH) algorithm to incorporate all possible lookaheads in the optimisation instead of the one-stage lookahead of the algorithm PATH, but no significant gain was found. Yoshimoto et al. (1990) introduced RLS-PATH (Region Limited Strategies) for the multivariate control problem. This last algorithm has been successfully employed by Bettinger et al. (2005) in density-dependent forest stand level optimisation. Also Yoshimoto and Masurak (2007) employed the method in an optimisation problem where carbon sequestration was included.

Many other studies have dealt with the application of DP to the stand level optimisation problem, among them are Kilkki and Väisänen (1970), Adams and Ek (1974), Martin and Ek (1981), Valsta and Brodie (1985), Arhau and Pelkki (1996), Borges and Falcao (1999) and Díaz-Balteiro and Rodríguez (2006).

## **2.2 Direct search methods**

### *2.2.1 Direct search methods using one solution vector*

Direct search methods seek the optimal solution without using derivatives. This kind of methods is useful when the objective function is non-differentiable and non-linear, as it is the case in many stand management optimisation problems. The general structure of the direct search methods is that, given a function  $f$  of several variables, and given a vector  $\mathbf{x}$

(of decision variables), a suitable direction  $d$  is first determined and then  $f$  is minimized or maximized in the direction of  $d$  by employing one of the following methods:

**Cyclic coordinate method:** It uses the coordinate axes as the search directions and therefore changes one variable at a time.

**Method of Rosenbrock:** Originally, it was designed to take discrete steps along the search directions but it has been modified (Bazaraa et al. 1993) in order to employ it in a continuous way by utilizing line searches along  $m$  orthogonal and independent directions ( $m$  being the number of decision variables).

**Method of Hooke and Jeeves:** As in the case of the Rosenbrock method, as originally proposed, does not perform any line search but takes discrete steps along the search directions. The method uses two search modes: exploratory search in the direction of the coordinate axes (decision variables) and pattern search in directions other than the coordinate axes.

The Hooke and Jeeves method (1961) is the optimisation algorithm that was employed in this thesis. The method is called as “direct search” because of the sequential examination of trial solutions, which involves a comparison of each trial solution to the best obtained up to that time together with a strategy for determining (as a function of earlier results) what the next trial solution would be (Hooke and Jeeves 1961). It is an unconstrained optimisation method for minimizing or maximizing a function in the absence of restrictions. A constrained problem can be formulated by adding penalty and barrier functions, which has been done in this thesis. Moreover, within the unconstrained optimisation methods, we can categorize the method as “multidimensional search without using derivatives” (Bazaraa et al. 1993). The fact that these methods do not need any explicit derivative is an important advantage because it allows the employment of a wide range of objective functions (Roise 1986a).

The method of Hooke and Jeeves has also some shortcomings. It is usually repeated several times starting from different initial solutions, which increases solution time (Roise 1986b, Haight and Monserud 1990). When optimisation requires several decision variables, the non-convexity of the problem increases and the results become dependent on the starting solution. Thus, the number of decision variables that can be included in the process should not be higher than 10 (Haight and Monserud 1990) because the lack of stability of the results. Despite it has these deficiencies, it has proved to be a good method when some of the decision variables have upper and lower bounds (Miina 1996) as is the case when optimising stand management.

Since the first tests of this method were made (Kao and Brodie 1980, Roise 1986a), many other authors have employed it in forestry. Roise (1986b) employed the method to optimise the residual diameter distribution of an even-aged stand after a thinning operation. Haight and Moserud (1990) solved the problem for any-aged stands. The method has been employed also to integrate non-timber management goals with timber production (Haight et al. 1992). Valsta (1992a) based on Roise (1986a) developed an optimisation model that included different management goals and employed individual-tree growth and yield models. He solved the problem by grouping the diameter classes into three categories (Valsta 1992a). Pukkala and Miina (1997) utilized the algorithm to develop a method to integrate multiple objectives, risk and attitude towards risk, in the optimisation problem.

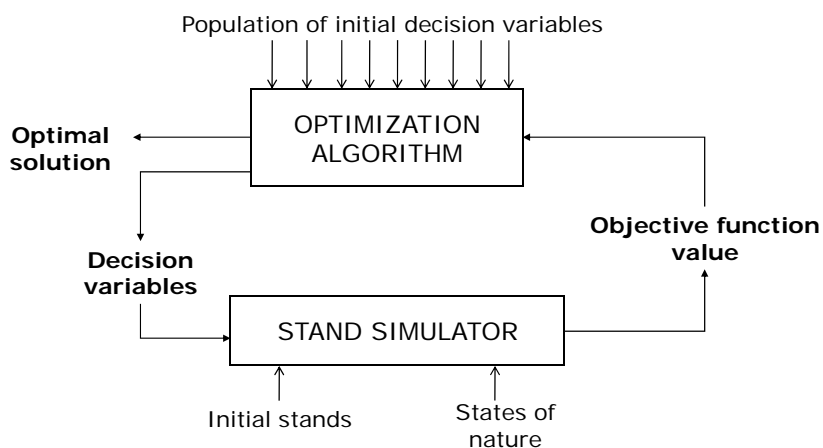


The method has also been employed to solve the optimisation problem when risk is involved (Thorsen and Helles 1998, Möykkynen et al. 2000, González et al. 2005), in spatial thinning problems (Pukkala and Miina 1998) and to optimise the management of agroforestry systems (Muchiri et al. 2002). These examples showed that Hooke and Jeeves' algorithm is an interesting and reliable technique to be applied in optimization at the stand level.

### 2.2.2 Population-based methods

According to Pukkala (2009) there is a new category of direct search methods namely, population-based methods or evolutionary computation methods, which work with a population of solutions instead of a single vector of decision variables (Figure 4). The main methods are differential evolution (Storn and Price 1997), particle swarm optimisation (Kennedy and Everhart 1995), evolution strategy (Beyer and Schwefel 2002) and the Nelder and Mead method, which is also called polytope search or amoeba search (Nelder and Mead 1965, Pukkala 2009).

**Differential evolution** (Storn and Price 1997): The method uses  $n$   $m$ -dimensional parameter vectors as a population for each generation. The initial population of vectors is chosen randomly and should cover the entire parameter space (Pukkala 2009). Two vectors from the population are randomly chosen, namely the target vector ( $\mathbf{x}_t$ ) and the base vector ( $\mathbf{x}_b$ ). Then, differential evolution chooses another two vectors and their weighted difference vector is computed. This weighted difference vector is added to the base vector (mutation) and a mutated vector ( $\mathbf{x}_m$ ) is obtained. The mutated vector is combined with the target vector and a trial vector is obtained ( $\mathbf{x}_g$ ). The trial vector is then compared to the target vector and if  $f(\mathbf{x}_g) < f(\mathbf{x}_t)$  the trial vector  $\mathbf{x}_g$  replaces  $\mathbf{x}_t$ . Each vector from the population has to serve as target vector at least once.



**Figure 4.** Structure of the population-based simulation-optimisation system.

**Nelder-Mead method** (Nelder and Mead 1965): It is based on evaluating a function at the vertices of a simplex. The worst ( $\mathbf{x}_w$ ), the second-worst ( $\mathbf{x}_s$ ) and best ( $\mathbf{x}_b$ ) solutions are found at the beginning of a new iteration. The worst solution is replaced by a new candidate solution which is a transformation of all other solutions. However, if the candidate solution is worse than the current worst ( $\mathbf{x}_w$ ), there is no replacement. Instead the algorithm iteratively shrinks the simplex until better points are found or some bound is obtained (Nelder and Mead 1965).

**Particle swarm optimisation** (Kennedy and Everhart 1995): Each particle of the population is characterized by the current solution ( $\mathbf{x}$ ), the current objective function value ( $f(\mathbf{x})$ ), the best solution found by the particle so far ( $\mathbf{x}_b$ ), objective function value of this best solution ( $f(\mathbf{x}_b)$ ), and a vector of  $m$  velocities ( $\mathbf{v}$ ) which determine the next movement of the particle. In addition, the whole population is characterized by the best solution found so far by the swarm ( $\mathbf{x}_g$ , called as “global best”) and the objective function value  $f(\mathbf{x}_g)$  of global best. The algorithm updates the velocity of a particle based on the current velocity, the best position it has found so far (cognitive component of the move), the best position found so far by the entire swarm (social component). The particle swarm optimisation process is iterated for a fixed number of times.

**Evolution strategy** (Beyer and Schwefel 2002): Given a population  $m$  of solutions, every solution of the population is characterized by the current solution ( $\mathbf{x}$ ) (vector of current values of decision variables),  $f(\mathbf{x})$  which is the objective function calculated for the solution and  $\mathbf{s}$  which is a vector of strategy parameters. The strategy parameters, one for each decision variable, determine how much the values of decision variables of a recombination, are mutated. During every generation, one offspring is produced as a mutated recombination of two parents from either the previous offspring population (comma-selection) or the offspring and parent selection (plus-selection). If the new offspring is better than the worst solution of the current population, the offspring replaces the worst solution. The best solution after the last generation is taken as the optimal solution.

### 2.2.3 Heuristics and meta models

Heuristics are techniques that seek good (i.e. near optimal) solutions at a reasonable computational cost without being able to guarantee either feasibility or optimality, or even in many cases to state how close to optimality a particular feasible solution is (Reeves 1993). Despite of not assuring the achievement of the best alternative, heuristics are very good methods because of their flexibility. They can mimic the problem (objective function and constraints) better than traditional exact algorithms. Another advantage is that they can deal with more complicated problems (Reeves 1993, Borges et al. 2002).

Heuristics have been traditionally employed in forest planning at the forest level, when the optimised variables are binary. Because stand level optimisation works with continuous variables some changes must be made to be able to utilize heuristics at the stand level. With the exception of genetic algorithms, most heuristics follow a local improvement methodology. The solution is improved gradually by changing it locally (this is called a move) (Pukkala 2006b). When continuous variables are employed, moves are done starting from the current point  $\mathbf{x}_i$  and generating a new random point  $\mathbf{x}_{i+1}$ :

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \Delta \mathbf{x} \quad (2)$$

where  $\Delta \mathbf{x}$  is the amount of change in decision variable (displacement). There are several ways to generate the move depending on the heuristic employed. For instance, Parks (1990) proposed a method for generating solutions when simulated annealing is employed:

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \mathbf{D}\mathbf{u} \quad (3)$$

where  $\mathbf{u}$  is a vector of uniform random numbers in the range  $(-1, 1)$  and  $\mathbf{D}$  is a diagonal matrix which defines the maximum change allowed in each variable. Every time a new solution is accepted,  $\mathbf{D}$  is updated based on previous step sizes.

$$\mathbf{D}_{j+1} = (1-\alpha)\mathbf{D}_j + \alpha\omega\mathbf{R} \quad (4)$$

where  $\mathbf{R}$  is a diagonal matrix where its elements are the magnitudes of the successful changes made to each decision variable:

$$R_{kk} = |D_{kk}u_k| \quad (5)$$

and  $\alpha$  and  $\omega$  control the rate at which information from  $\mathbf{R}$  is integrated into  $\mathbf{D}$ .

In many studies that have used simulated annealing in continuous optimisation problems, the moves (displacements) have been obtained from uniform distribution (Corana et al. 1987, Goffe et al. 1994, Wang and Chen 1996) or Cauchy distribution (Szu and Hartley 1986), among others. In these methods, the variation of these displacements (step size) needs to be reduced when the optimisation proceeds.

When the heuristic employed in continuous optimisation is tabu search,  $\mathbf{x}_{i+1}$  can be generated in the following way. The space neighbourhood is considered as a ball  $B(\mathbf{x}_i, s)$  with center  $\mathbf{x}_i$  and radius  $s$ . Considering a set of concentric balls with radii  $h_0, h_1, \dots, h_n$  the space is portioned into  $n$  concentric crowns. Hence  $n$  neighbours of  $\mathbf{x}_i$  are obtained by selecting one point randomly inside each crown and eliminating those neighbours that belong to the tabu list (Hajji et al. 2004, Zheng et al. 2005).

These two methods of producing moves can be employed not only with simulated annealing and tabu search, but also in great deluge and threshold accepting. In the case of genetic algorithms, continuous variables can be converted into binary ones after which normal genetic algorithm procedures can be used (Chelouah and Siarry 2000). Moreover, hybridation of heuristics has been also employed as a method to deal with continuous variables (Wikström and Eriksson 2000, Chelouah and Siarry 2005, Miettinen et al. 2006).

Heuristics can be deterministic (HERO developed by Pukkala and Kangas 1993) or stochastic (random ascent, simulated annealing, tabu search, threshold accepting, genetic algorithms, among others). They can also be classified according to the number of solutions that can process simultaneously: one solution at a time or a population of solutions (genetic algorithms). The most popular heuristics used in optimisation with continuous variables are simulated annealing, threshold accepting, great deluge, tabu search and genetic algorithm.

**Simulated annealing:** The initial solution is typically produced by generating random values for the decision variables. Moves that lead to an inferior solution may be accepted in order to try to avoid convergences to local optima. Moves that do not improve the value of the objective function are accepted with a probability of:

$$p = \exp\left(\frac{f(\mathbf{x})_{new} - f(\mathbf{x})_{old}}{T_i}\right) \quad (6)$$

The method mimics the cooling of metals and therefore uses the same nomenclature.  $T_i$  is the “current temperature” and  $f(\mathbf{x})$  is the objective function value. The temperature is a parameter of the method and defines the probability of accepting a candidate solution poorer than the current solution. During the process this parameter is gradually decreased so that at the end of the search the likelihood of accepting inferior moves is close to zero (Pukkala 2006b). A certain number of candidate moves are tested at each temperature. The search stops when a user-specified stopping temperature is reached or a certain number of consecutive temperatures results in no change in the solution.

**Threshold accepting:** This heuristic is similar to simulated annealing but it simplifies the decision of whether or not to accept a candidate solution. All the moves that produce a candidate equally good as or better than the current objective function value minus a threshold are accepted. The threshold is gradually reduced during the process and a certain number of moves is tested with every threshold. The process finishes when the threshold becomes very small or the solution does not improve anymore.

**Great deluge** (Dueck 1993): This method is also rather similar to simulated annealing and threshold accepting. It uses an initial solution. If the move improves the solution it is accepted and also the acceptance user-specified objective function value. If the move improves that value it is accepted and also the acceptance limit is increased. When the acceptance level reaches the best objective function value recorded so far, the search is stopped. After this, a certain number of random moves may be tested to check whether the solution can be further improved.

**Tabu search** (Glover 1986): Tabu search is based on searching the neighbouring solution space before accepting one change in the solution. The production of a set of candidate moves and accepting one of them is repeated for many iterations. Typical of tabu search are tabu lists. The most commonly used tabu lists memorize recent moves, and can be used to prohibit them for some time.

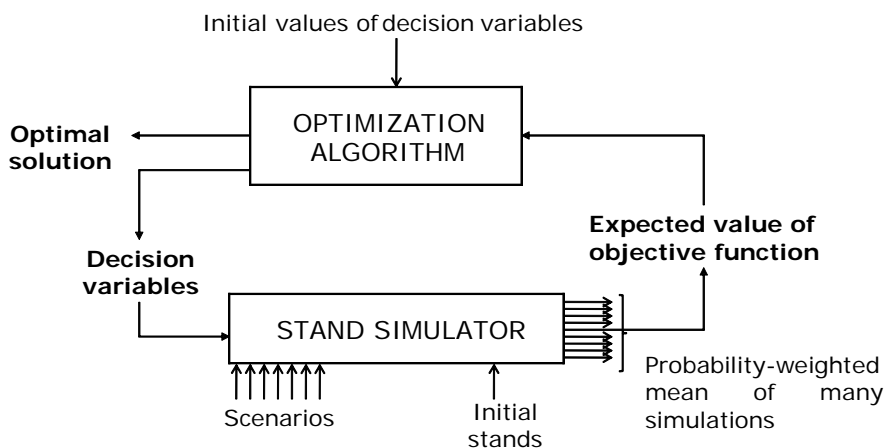
**Genetic algorithm:** The most characteristic feature of this heuristic is that its search process is based on an initial population of solution alternatives, their evaluation and their breeding. The initial solutions are called parent chromosomes, which are processed by crossing-over and mutation. These operations result in a new chromosome. Usually, at least one of the two parents of a new chromosome is selected with the probability proportional to its ranking. The second parent may be chosen randomly with an equal probability for all chromosomes. In the incremental genetic algorithm technique, the new chromosome replaces one chromosome of the initial population. The removed chromosome is selected based on its objective function value, the probability of removal being highest for chromosomes that have a low objective function value. The updated group of chromosomes is called generation.

### 2.3 Integrating risk: Stochastic scenario approach

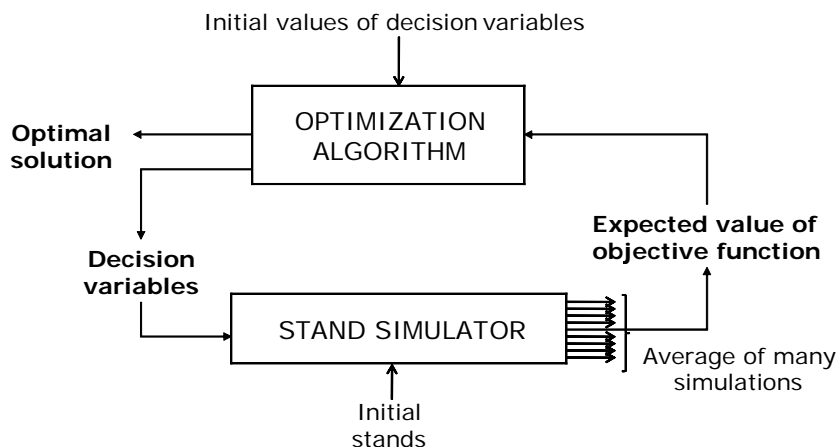
Many uncertainties are involved in forest management planning. Some of them come from the stochasticity of stand growth, others from natural risks, inaccurate information related to the present forest, preferences of decision makers, etc. When a probabilistic description of the unknown elements is available, it is logical to apply stochastic models. One of the most common methodologies employed to integrate uncertainty and risk is the scenario analysis technique (Rockafellar and Wets 1987, see Valsta 1992b). The stochastic components are introduced in the problem using scenarios (Figure 5). The first step is to define a set of scenarios  $S$  where each  $s^s$  is a joint realization of the stochastic processes over the planning horizon. The second step is to define the probability weights associated to each scenario ( $p_s$ ). Now the stochastic component has been recoded using scenarios and therefore the problem is again a deterministic one:

$$\max_{\{U \in C \subset R^n\}} \sum_{s \in S} p_s g(\mathbf{x}, s^s | \mathbf{w}_0) \quad (7)$$

In this approach (scenario technique) the simulation process is deterministic. Simulation is repeated under all scenarios and the objective function is calculated as a weighted outcome of the scenarios. This method has been employed by many authors to integrate classical sources of uncertainty and risk: stochastic timber prices, attitude towards risk (Pukkala and Kangas 1996) and preferences of the decision maker (Pukkala and Miina 1997). The decision to employ this deterministic approach is based on the fact that for developing predictive models for the optimal management of pine stands, output data coming from deterministic simulation was easier and more logical to model than stochastic simulations.



**Figure 5.** Structure of the stochastic simulation-optimisation system using the scenario technique.



**Figure 6.** Structure of the stochastic simulation-optimisation system using the stochastic simulation.

Another way to introduce risk and uncertainty is by stochastic simulation (Figure 6). This method is very flexible and can be adapted to different optimisation techniques. The key point of the methodology is to define the problem as a stochastic simulation model (Lohmander 2007). Some authors have implemented the simulation by means of random number generators (González et al. 2005), probability distributions (Pukkala 1998) or Monte Carlo techniques (Kaya and Boungiorno 1987). The method has been widely employed to integrate risk (Möykkynen et al. 2000; González et al. 2005, González et al. 2008, Hyytiäinen and Haigh 2009) and uncertainty (Pukkala and Miina 1997, Kaya and Boungiorno 1987).

### 3 MATERIAL AND METHODS

The methodology employed in studies I-IV is very similar and it is based on the combination of a stand simulator and an optimisation algorithm (see Figure 3). Starting from an initial solution, the optimisation algorithm searches for the optimal solution of the problem. The problem is formulated in terms of optimised decision variables which define the management schedule. The simulator gives feedback of each trial solution in terms of objective function value. This value is compared to the best solution obtained up to that time and if it improves the objective function value it is accepted. The process ends when the convergence criterion is achieved. Input data in the form of initial stands, economic conditions and fire risk are employed in order to be able to parameterize optimal management to make the results usable in different conditions.

### 3.1 Decision variables

Decision variables ( $\mathbf{x}$ ) define the management schedule: timing and intensity of thinnings and rotation length. These variables are the ones that are optimised. Since the number of thinnings is not a continuous variable, optimisation must be repeated for different number of thinnings (1-thinning schedule, 2-thinning schedule and so on). In all the studies, the thinnings were combinations of systematic and low thinning. The management regime was specified by the number of thinnings and the following decision variables:

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

The number of optimised decision variables was therefore  $3 \times N_{\text{thin}} + 1$  where  $N_{\text{thin}}$  is the number of thinnings.

### 3.2 Optimisation method

The direct search method of Hooke and Jeeves (1961) was used as the optimisation algorithm. The method needs a user-defined initial solution  $\mathbf{x}$  (vector of decision variables) to initialize the process. Given the coordinate directions  $\mathbf{d}_1, \dots, \mathbf{d}_m$ ;  $\mathbf{x}_1 = \mathbf{y}_1$  and  $k=j=1$ . The algorithm works in the following way:

#### *Exploratory search*

##### Step 1

If  $f(\mathbf{y}_j + \Delta \mathbf{d}_j) > f(\mathbf{y}_j)$  (success), let  $\mathbf{y}_{j+1} = \mathbf{y}_j + \Delta \mathbf{d}_j$  and go to Step 2.

Otherwise if  $f(\mathbf{y}_j - \Delta \mathbf{d}_j) > f(\mathbf{y}_j)$  (success), let  $\mathbf{y}_{j+1} = \mathbf{y}_j - \Delta \mathbf{d}_j$  and go to Step 2.

Otherwise let  $\mathbf{y}_{j+1} = \mathbf{y}_j$  and go to Step 2 (no improvement found in direction  $j$ ).

##### Step 2

If  $j < m$ , replace  $j$  by  $j + 1$  and repeat Step 1 (go to next decision variable).

Otherwise go to *Pattern search* (Step 3) if  $f(\mathbf{y}_{m+1}) > f(\mathbf{x}_k)$  (at least one successful change detected in the directions of coordinate axes).

If  $f(\mathbf{y}_{m+1}) \leq f(\mathbf{x}_k)$  go to *Step size reduction* (Step 4).

##### Step 3, *Pattern search*

Let  $\mathbf{x}_{k+1} = \mathbf{y}_{m+1}$  and let  $\mathbf{y}_1 = \mathbf{x}_{k+1} + \alpha(\mathbf{x}_{k+1} - \mathbf{x}_k)$ . Replace  $k$  by  $k + 1$ , let  $j = 1$ , and go again to *Exploratory search* (Step 1).

##### Step 4, *Step size reduction*

If  $\Delta \leq \epsilon$ , stop. Otherwise replace  $\Delta$  by  $\Delta / 2$ . Let  $\mathbf{y}_1 = \mathbf{x}_k$ ,  $\mathbf{x}_{k+1} = \mathbf{x}_k$ ,  $j = 1$ , replace  $k$  by  $k + 1$ , and repeat *Exploratory search* (Step 1).

The method has three parameters: initial steps size ( $\Delta$ ), stopping criterion ( $\epsilon$ ), and  $\alpha$ . Since the convergence of this method to the global optimum is not guaranteed, all the optimisations were repeated several times starting every time from a different initial solution.

### 3.3 Initial stands

An initial stand refers to a forest stand whose management is optimised. In Study I instructions for the optimal management of *Pinus sylvestris* in Galicia were developed maximising soil expectation value (SEV), i.e. the net present value of all future incomes. The stands were characterised by site index, planting density and stand age. Four site indices were chosen: 6, 12, 18 and 24 metres at 40 years. The planting densities were 1000, 1500, 2000 and 2500 trees per hectare. The initial stand age was 10 years. This resulted in sixteen initial stands which differed in terms of site index and planting density (4 site indices times 4 planting densities).

In study II, three site indices for *Pinus radiata* stands were chosen, namely 13, 19 and 25 metres at 20 years. The planting densities were 1000, 1500 and 2500 trees per hectare. Therefore, there were nine initial stands which differed in site index and planting density (3 site indices times 3 planting densities).

The initial stands of *Pinus pinaster* tested in study III comprised four site indices, namely dominant heights of 9, 13, 17 and 21 meters at the reference age of 20 years, with three different planting densities: 1100, 1500 and 2500 trees per hectare. Therefore, management was optimised for twelve different initial stands.

In study IV, *Pinus radiata* stands with site index 25 and 29 meters at 20 years were analysed. The planting densities ranged from the sparsest to the densest used in the region: 500, 1500 and 2500 trees per hectare. This resulted in six different initial stands.

### 3.4 Simulation

#### 3.4.1 Simulation of stand dynamics

Models developed earlier for the three conifer species in Galicia, *P. Pinaster* (Álvarez González et al. 1999), *P. sylvestris* (Diéguez-Aranda et al. 2006) and *P. Pinaster*(Castedo-Dorado et al. 2007) were used to simulate stand development in different management schedules. The models were rather similar in all cases; they were whole stand models with a diameter distribution incorporated as well as a taper function. In this way it was possible to predict the merchantable volumes as well as the volumes of different timber assortments. The three models function in the same way: the initial stand is defined by four state variables: stand age, dominant height, number of trees per hectare and stand basal area. Age and dominant height determine the site index (dominant height at 20 or 40 years). The models use three transition functions to provide the stand state at any point of time. Moreover, the model set includes a function for predicting the initial stand basal area, which can be used to establish the starting basal area for the simulation. The model for *P. pinaster* (Álvarez González et al. 1999) lacks the self-thinning model because mortality was rare on the plots used to develop the model. Therefore, in *P. pinaster* stand density was altered only by thinning operations.



The Weibull distribution was used to calculate the number of trees per hectare in 1-cm diameter classes. The simulation of thinnings was based on these frequencies. Both systematic and low thinnings were simulated. Systematic thinnings removed an equal percentage from every diameter class. When a low thinning was simulated, the remaining number of trees in diameter class  $i$  ( $n_i$ ) was calculated as follows:

$$n_i = N_{\text{before}} L \left[ (F(d_i))^{1/L} - (F(d_{i-1}))^{1/L} \right] \quad (8)$$

where  $N_{\text{before}}$  is the number of trees per hectare before low thinning,  $L$  is low-thinning intensity expressed as one minus the proportion of removed trees ( $1 - N_{\text{removed}}/N_{\text{before}}$ ) and  $F(d)$  stands for Weibull distribution function (showing the cumulative frequency at diameter  $d$ ).

The volumes of the removed trees were calculated by different taper models: for *Pinus sylvestris* the model developed by Dieguez-Aranda et al. (2006) and for *Pinus radiata* the model of Castedo-Dorado et al. (2007), both based on the function proposed by Fang et al. (2000); in the case of *Pinus pinaster* the model of Rojo et al. (2005b) based on the function proposed by Kozak (1988) was employed. These taper models were used to calculate the stem volume up to the following top diameters: 35, 18 and 7 cm. The timber assortments therefore correspond to the following over-bark stem diameters: (I)  $d \geq 35$  cm; (II)  $35 \text{ cm} > d \geq 18$  cm; and (III)  $18 \text{ cm} > d \geq 7$  cm. The following minimum piece lengths were required: (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.

### 3.4.2 Simulation of grass production

In study IV silvopastoral systems were analyzed and therefore, the simulation of these systems also required a grass yield model. Pasture production is highly dependent on the stand development, since pasture production is only possible when the canopy allows light to reach the understorey level. Site and stand characteristics were used as predictors in a model of pasture production:

$$\ln(\text{grass}) = 0.09SI - 0.12G - 1.25 \quad (9)$$

where *grass* is the annual pasture production ( $\text{t ha}^{-1}$ ), *SI* is the site index corresponding to the *Pinus radiata* stand (m) (dominant height at the reference age of 20 years) and *G* is the basal area ( $\text{m}^2 \text{ha}^{-1}$ ) of the *P. radiata* stand.

## 3.5 States of nature

The term state of nature is defined as a combination of variables that cannot be controlled by the forest manager or decision maker, i.e. the circumstances under which the stand management schedules were optimised. In this thesis the states of nature were determined by economic parameters (studies I, II, III and IV) and fire risk parameters (studies II, III and IV).

### 3.5.1 Economic parameters

The economic parameters needed for calculating the objective function (SEV) were discounting rate, treatment costs and timber prices. The cost parameters included regeneration and tending costs, and harvesting costs, which were all constant. Different timber prices were used for the three assortments: 90 €m<sup>-3</sup> for grade I timber (top diameter ≥35 cm), 50 €m<sup>-3</sup> for grade II timber (≥18 cm) and 18 €m<sup>-3</sup> for grade III timber (≥7 cm). In studies I, II and III, timber prices were varied ± 20% in order to have results for different market conditions.

In study IV, revenues from pasture were also analysed. These revenues were calculated employing the “unit value of grass production from pasture” which is the income that one ton of grass can produce after converting it into meat production. This value was varied from 0 to 400 € t<sup>-1</sup> to see its effect on the optimal management.

Several discounting rates were used: 0.5%, 1%, 2%, 3% and 5% in study I and 1%, 3% and 5% in studies II and III. In study IV, only one discounting rate was used (3%). In studies III and IV in which fire risk was included, the price of timber salvaged from a burned stand was reduced by 25%.

### 3.5.2 Fire parameters

The risk of fire was integrated in studies II, III and IV and it was described by means of two different variables: probability of occurrence and salvage. The probability of occurrence was considered in the three studies as an exogenous variable and it was assumed to remain constant over the rotation period. In study II the annual probabilities of fire were 0, 1, 3 and 5% covering a realistic range of the probability of fire occurrence for *Pinus radiata* stands in Galicia (with observed annual probabilities of 0.3% in 2002 and 2% in 2003). In studies III and IV the annual fire probabilities for *Pinus pinaster* stands were 0, 1 and 5%. In all studies it was assumed that when fire comes before the rotation age the landowner harvests any salvageable timber, and then replants and begins a new rotation.

The proportion of salvaged timber was calculated with two different ways. In study II the salvage was considered as a constant variable, independent of stand characteristics. Different salvage proportions were tested (0%, 40% or 80%) in order to analyse their effect on the optimal management schedule. In studies III and IV a different approach was adopted. It assumes that salvage is an endogenous variable to stand characteristics. Salvage ( $s_t$ ) depended on tree diameter according to the following equation:

$$s_t = 1 - 0.92^d \quad (10)$$

where  $d$  is the diameter at breast height in cm. This expression is based on literature (Botelho et al. 1998, González et al. 2007) and professional experience. Sensitivity analyses were carried to see the effect of salvage rate on the optimal stand management.

In study IV, a hypothesis that grazing may reduce fire risk was introduced. Several reduction factors were employed, namely 25, 50, 75 and 100% reduction in the probability of fire occurrence in every grazing year (when grass yield was ≥ 0.3 t ha<sup>-1</sup>).

### 3.6 Objective function

To find the optimal management schedules of the stands an objective function must be chosen. Because stands are established to produce economic profit, soil expectation value (SEV) was chosen as the objective function in the four studies. Many authors have called it land expectation value (LEV), but as Davis et al. (2001) mention, LEV and SEV mean the same. The SEV is defined as the net present value (NPV) of all future net incomes. The NPV of all the management operations during a rotation, discounted to the beginning of the rotation is:

$$NPV = \sum_{t=0}^R \frac{I_t - C_t}{(1+r)^t} \quad (11)$$

where  $C_t$  are the costs and  $I_t$  the incomes in year  $t$ ,  $r$  is discounting rate and  $R$  is rotation length (years). The  $NPV$  for an infinite number of rotations, i.e. the soil expectation value, can be expressed as:

$$SEV = \frac{NPV}{1 - \frac{1}{(1+r)^R}} \quad (12)$$

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

$$SEV = NPV_{first} + NPV_{allsubsequent} \quad (13)$$

which is the same as:

$$SEV = NPV_{first} + \frac{NPV_{first}}{(1+r)^R - 1} \quad (14)$$

In studies II, III and IV the risk of fire was integrated with the approach developed by Bright and Price (2000). This method calculates the sum of the possible outcomes, weighted by their probabilities. The modified expression for the expected  $SEV$  was:

$$SEV = \frac{NPV_{first}}{\left[ 1 - \left( \sum_{t=0}^{R-1} \frac{p_t}{(1+r)^t} + \frac{p_R}{(1+r)^R} \right) \right]} \quad (15)$$

where  $p_t$  is the probability that the stand burns in year  $t$  and survives the previous years, i.e.  $p_t = (1 - p_{fire})^t p_{fire}$ , where  $p_{fire}$  is the annual probability of fire occurrence, and  $p_R [p_R = (1 - p_{fire})^R]$  is the probability that there is no fire before the rotation age.  $NPV_{first}$  was calculated from:

$$NPV_{first} = \sum_{t=0}^{R-1} p_t \cdot NPV_t + p_R \cdot NPV_R \quad (16)$$

where  $NPV_t$  is the net present value when fire hits the stand at age  $t$  and ends the rotation prematurely and  $NPV_R$  is the net present value at the rotation age.

The incomes were calculated from:

$$I_t = s_t \sum_{j=1}^J \left( n_j \sum_{k=1}^3 v_{kj} \cdot P_k \right) \quad (17)$$

where  $s_t$  is the proportion of salvage which was constant in study II and calculated from Eq. 10 in studies III and IV ( $s_t = 1$  if there is no fire),  $J$  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 assortment  $k$  and  $v_{kj}$  is the volume of assortment  $k$  of a tree in diameter class  $j$ . If fire ended the rotation timber prices were decreased by 25% (i.e. salvaged timber was 25% cheaper) in studies III and IV. In study IV also incomes from grazing were added to the incomes obtained from timber.

As the Hooke and Jeeves algorithm (1961) is an unconstrained method, a penalty function was added to the objective function to avoid too heavy thinnings. A thinning intensity higher than 30% in basal area was penalised. Therefore, the eventual objective function ( $OF$ ) which was maximised was:

$$OF = SEV - \sum_{z=1}^Z Penalty_z \quad (18)$$

$$Penalty_z = \begin{cases} 0 & \text{if } TH\%_z \leq 30 \\ 10000 \frac{TH\%_z - 30}{70} & \text{if } TH\%_z > 30 \end{cases} \quad (19)$$

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<sup>-1</sup> when the harvest percentage increases from 30 to 100.

In study I some penalty was paid with the highest discounting rates, especially in the last thinnings (third and fourth) meaning that when the discounting rate was very high the opportunity cost of having the trees standing was higher than the penalty.

### 3.7 Modelling optimal management

The output from the optimisation-simulation process consisted of the optimal management schedules of many different initial stands under different states of nature. The number of optimal schedules generated was 2160, 6561 and 3888 in studies I, II and III, respectively. In studies I, II and III the results from the optimisation were employed to develop models for the optimal management of *Pinus sylvestris*, *Pinus radiata* and *Pinus pinaster*, respectively. Parameters describing stand characteristics (studies I, II and III), economic situation (studies I, II and III) and fire risk (studies II and III) were included as predictors.

Models were developed for the optimal rotation length and optimal prior and post-thinning basal area.

The way of using the models for optimal management is by comparison: the results provided by the models are compared to the actual state of a stand. If the stand is older than the optimal rotation age, the stand is to be clear-felled. Otherwise the stand basal area is compared to the pre-thinning basal area given by the model. If the stand basal area exceeds the model prediction, the stand should be thinned. The optimal post-thinning basal area is obtained from the model for the optimal basal area after thinning. In this thesis models are presented in the form of equations and diagrams but also software products can be prepared to make them easy to use in forest practise.

In study IV, so many variables affected the optimal management of the silvopastoral systems that building regression models for the optimal management was regarded impractical.

## 4 RESULTS

### 4.1 Models for the rotation length

Models that predict the optimal rotation length of *Pinus sylvestris*, *P. radiata* and *P. pinaster* were developed in studies I, II and III, respectively.

In study I the model obtained to predict the optimal rotation length of *Pinus sylvestris* has the following expression:

$$\ln(R) = 4.391 - 0.394 \ln(SI) + 0.195 \ln(N) - 0.101 \ln(r) - 0.009 P_{II} + 5.38 \times 10^{-5} (P_I \times P_{II}) - 0.001 (P_I \times r) \quad (20)$$

where  $R$  is rotation length (years),  $SI$  is site index (m),  $N$  is planting density (number of trees per hectare),  $r$  is discounting rate (%) and  $P_i$  is the price of grade  $i$  (I or II) in €m<sup>-3</sup>. According to the model, higher values of site indices and discounting rate lead to shorter rotation lengths. On the contrary, high planting densities lengthen rotations (Figure 7). The model also suggests that increasing price of grade II shortens optimal rotations, but this effect depends on the price of grade I, which is also influenced by discounting rate.

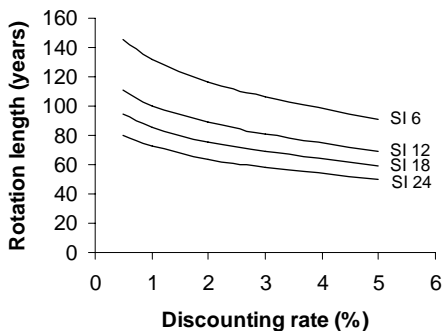
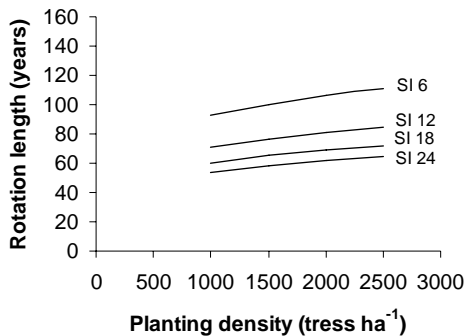
In the model for the optimal rotation length of *P. radiata* plantations, the equation fitted was:

$$R = 75.624 - 0.845 SI + 2.293 \times 10^{-3} N - 2.495 r - 2.107 p_{\text{fire}} + 0.026 (p_{\text{fire}} \times s) - 0.271 P_{II} + 1.239 \times 10^{-3} (P_I \times P_{II}) \quad (21)$$

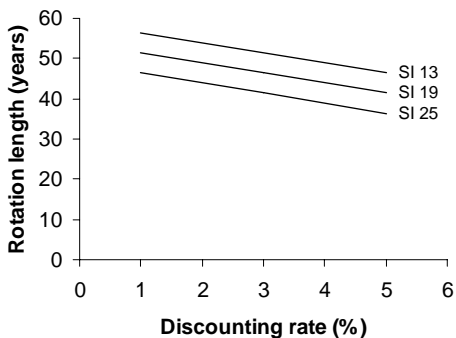
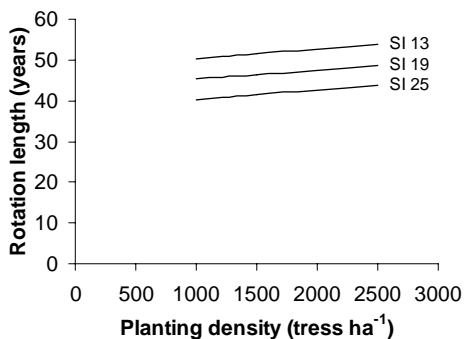
where,  $p_{\text{fire}}$  is the annual probability of fire occurrence (%) and  $s$  is the salvage percentage after a fire. As in study I, the model implies that better site indices and high discounting rates lead to shorter optimal rotation lengths while high planting densities lead to longer rotation lengths (Figure 7). Increasing probability of fire usually leads to shorter rotations (see Figure 8) but, since the probability of fire interacts with salvage percentage, which increases with stand age, the effect of fire probabilities is less clear when salvage rate is

assumed to depend on tree size (Figure 9). In study II price of grade II was the most significant price, and its increase decreased optimal rotation length.

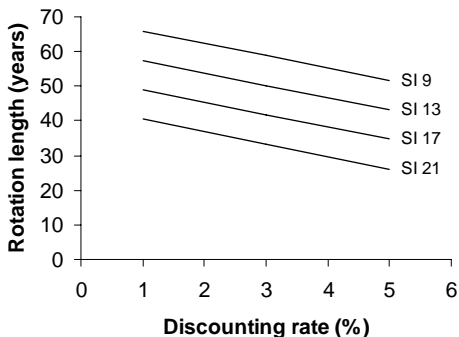
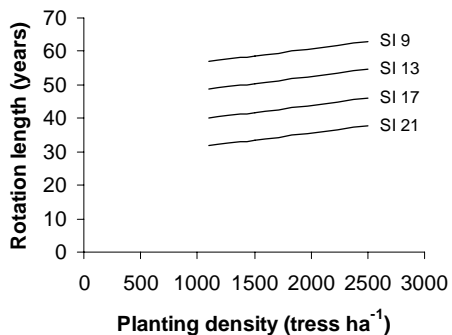
**STUDY I (*P. sylvestris*)**



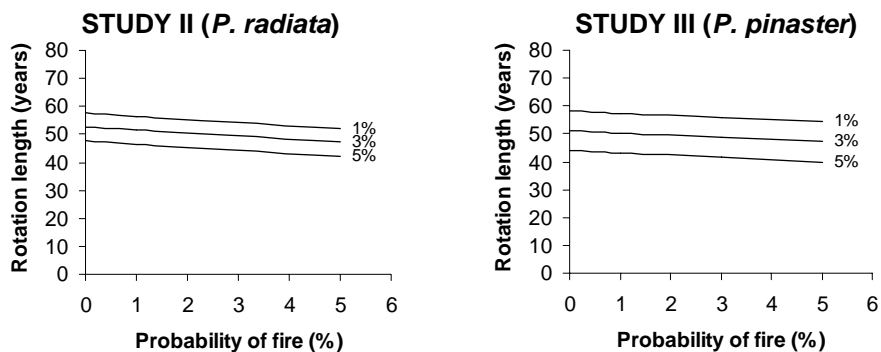
**STUDY II (*P. radiata*)**



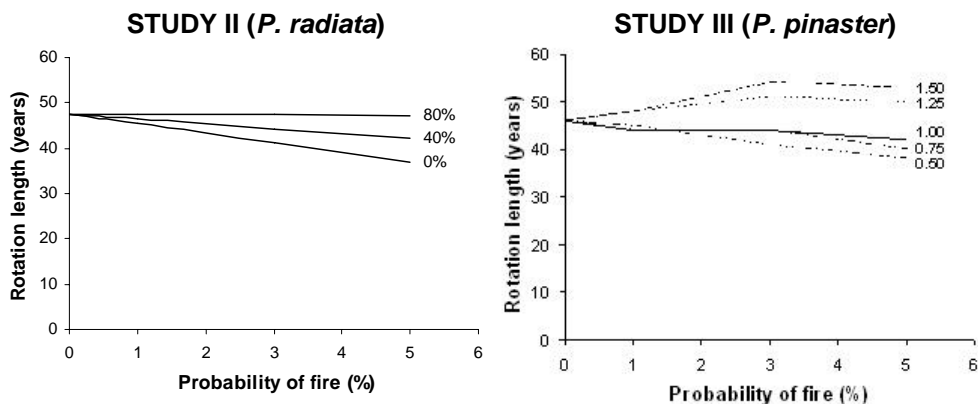
**STUDY III (*P. pinaster*)**



**Figure 7.** Effect of planting density, site index and discounting rate on the optimal rotation length in studies I, II and III when prices of timber grades I, II and III ( $P_I$ ,  $P_{II}$ ,  $P_{III}$ ) are 90, 50 and 18 € m<sup>-3</sup>, respectively. The index age is 40 years for *P. sylvestris* and 20 years for the other species.



**Figure 8.** Effect of discounting rate and probability of fire on the optimal rotation length in studies II and III when planting density is 1500 trees, site index 13 meters, salvage proportion 40% (in study II) and prices of timber grades I, II and III ( $P_I$ ,  $P_{II}$ ,  $P_{III}$ ) are 90, 50 and 18 € m<sup>-3</sup>, respectively.



**Figure 9.** Relationship between salvage proportion and optimal rotation length in studies II (exogenous approach) and III (exogenous approach) when site index is 13 meters, discounting rate is 3%, planting density is 1100 trees per hectare and prices of timber grades I, II and III ( $P_I$ ,  $P_{II}$ ,  $P_{III}$ ) are 90, 50 and 18 € m<sup>-3</sup>, respectively. In study II (left) different fixed salvaged rates (0, 40, 80%) were used, whereas in study III (right) the prediction of a salvage model was multiplied by 0.5-1.5.

The regression model obtained for the optimal rotation age in study III for *P. pinaster* follows the expression:

$$R = 99.519 - 2.114SI + 4.283 \cdot 10^{-3}N - 3.602r - 0.774p_{\text{fire}} - 0.261P_{\text{II}} - 0.198P_{\text{III}} \quad (22)$$

The most significant parameter affecting rotation length is site index, again with the same effect as in studies I and II, stands with poor site indexes having longer optimal rotation lengths than stands on better sites. Salvage was calculated as a function of diameter at breast height, i.e. it was endogenous. A sensitivity analysis was performed to analyse the influence of the salvage function on the optimal rotation length (Figure 9). Again high discounting rates led to shorter rotation lengths, and more densely planted stands had longer optimal rotation lengths.

The results follow the same trends as in studies I and II (Figure 7). Regarding the risk of fire, increasing probability of fire led to shorter rotation length (similar to study II) (see Figure 8) If the price of salvaged timber was reduced. If price was not reduced, increasing probability of fire led to longer optimal rotation length.

#### 4.2 Pre- and post-thinning basal area

The models for the pre and post-thinning basal area for *P. sylvestris* plantations (study I) were:

$$\sqrt{G_{\text{before}}} = -7.901 + 0.083 SI + 3.110 \ln(T) - 0.002 (T \times r) + 0.006 P_1 - 2.98 \times 10^{-5} (P_1 \times P_{\text{II}}) + 2.337 Fst + 1.548 Snd + 0.776 Trd \quad (23)$$

$$G_{\text{after}} = -20.719 + 0.132 SI + 3.717 \ln(T) + 0.830 G_{\text{before}} - 0.025 (T \times r) + 0.039 P_1 - 2.81 \times 10^{-4} (P_1 \times P_{\text{II}}) + 4.162 Fst + 3.039 Snd + 1.562 Trd \quad (24)$$

where  $T$  is stand age in years. Since the optimal basal area of pre- and post-thinning stand was influenced by the number of the thinning, indicator variables  $Fst$ ,  $Snd$  and  $Trd$  for the first, second and third thinning, respectively, were included in the models. Better site indices have higher optimal pre-thinning basal area (Figure 10). High discounting rate decreases optimal pre-thinning basal area this effect being enhanced by the age of the stand (Figure 11). Prices of grades I and II were significant predictors. Higher prices of grade I lead to higher optimal pre-thinning basal area, i.e. thinning takes place later. However, the effect of the price of grade I was influenced by the price of grade II. The optimal basal area after thinning was strongly dependent on the basal area before thinning, all the predictors being common to both models.

The models for the optimal pre- and post-thinning basal for *P. radiata* plantations (study II) were:

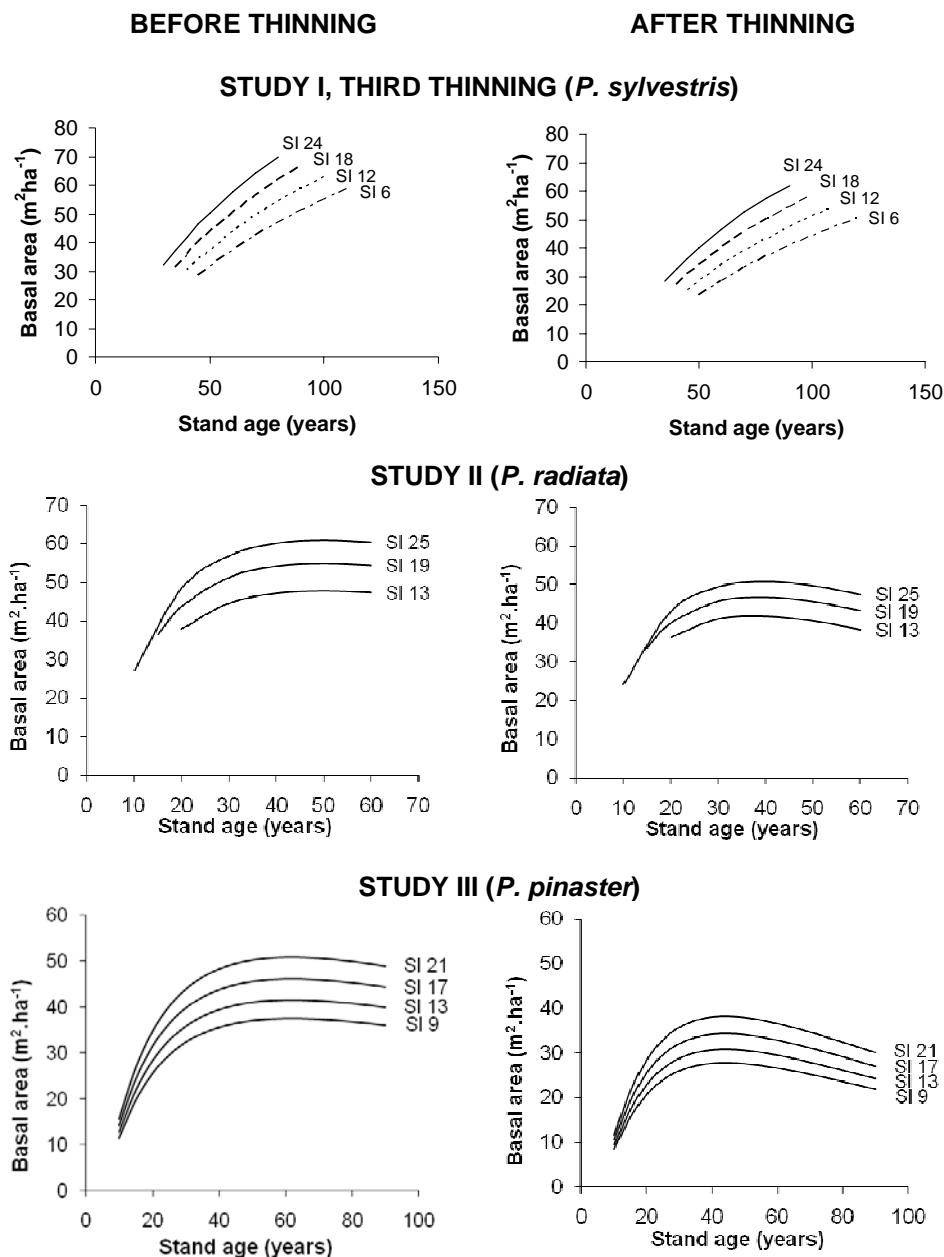
$$\ln(G_{\text{before}}) = 3.720 + 0.374 \ln(SI) - 12.635 (1/T) - 436.532 (1/N) - 0.031 p_{\text{fire}} - 1.414 \times 10^{-3} (T \times r) - 8.231 \times 10^{-4} (T \times p_{\text{fire}}) + 6.290 \times 10^{-4} (p_{\text{fire}} \times s) + 3.511 \times 10^{-4} (r \times P_1) - 7.359 \times 10^{-4} (r \times P_{\text{II}}) \quad (25)$$

$$G_{\text{after}} = 16.750 - 5.452 \ln(SI) - 0.450 p_{\text{fire}} + 0.972 G_{\text{before}} - 0.049 (T \times r) - 0.029 (T \times p_{\text{fire}}) + 0.010 (p_{\text{fire}} \times s) + 0.012 (P_1 \times r) - 0.020 (P_{\text{II}} \times r) \quad (26)$$

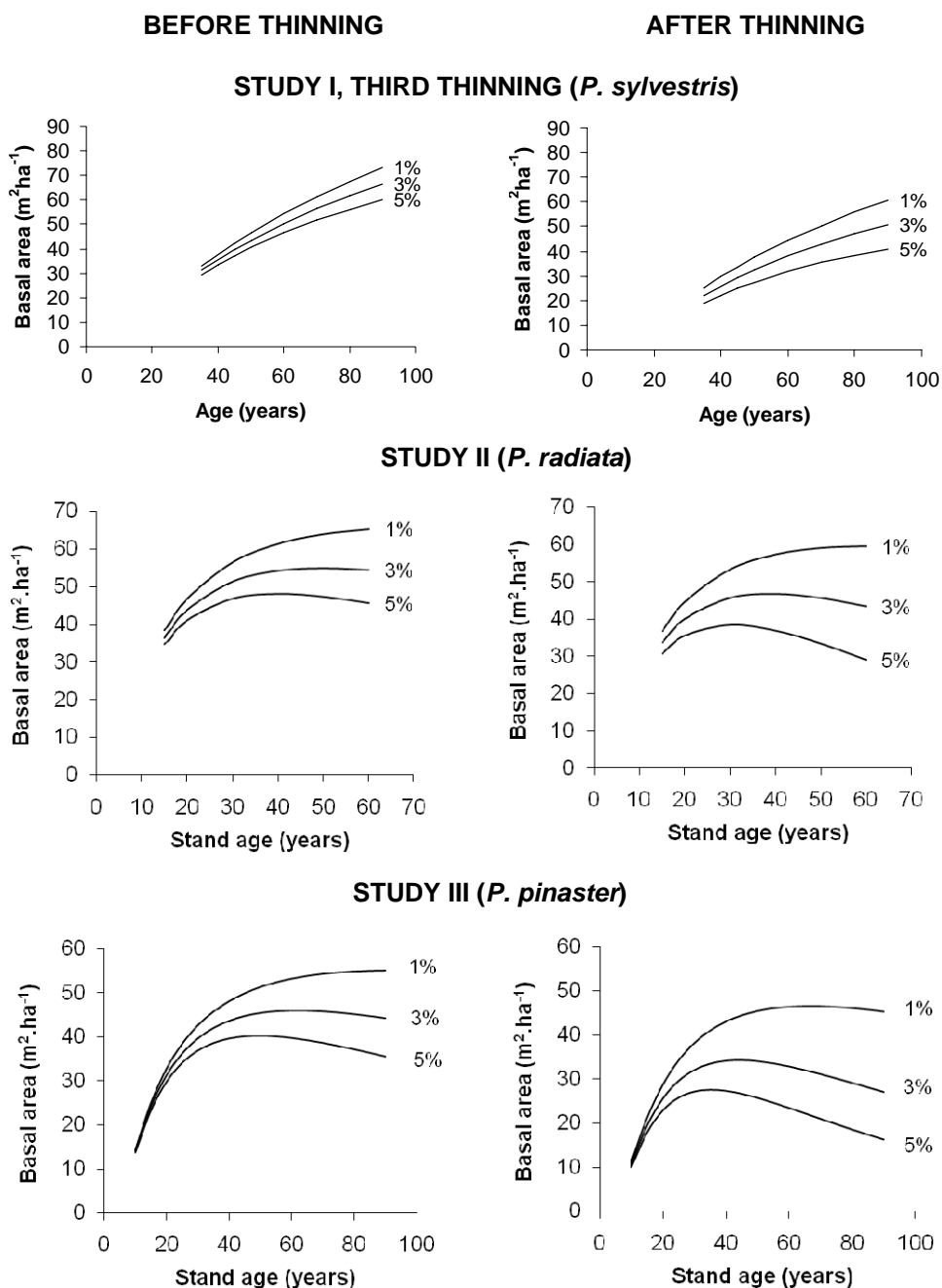
The model for the basal area before thinning suggests that better site indices have higher optimal thinning basal areas (Figure 10). The same occurs with high planting densities.



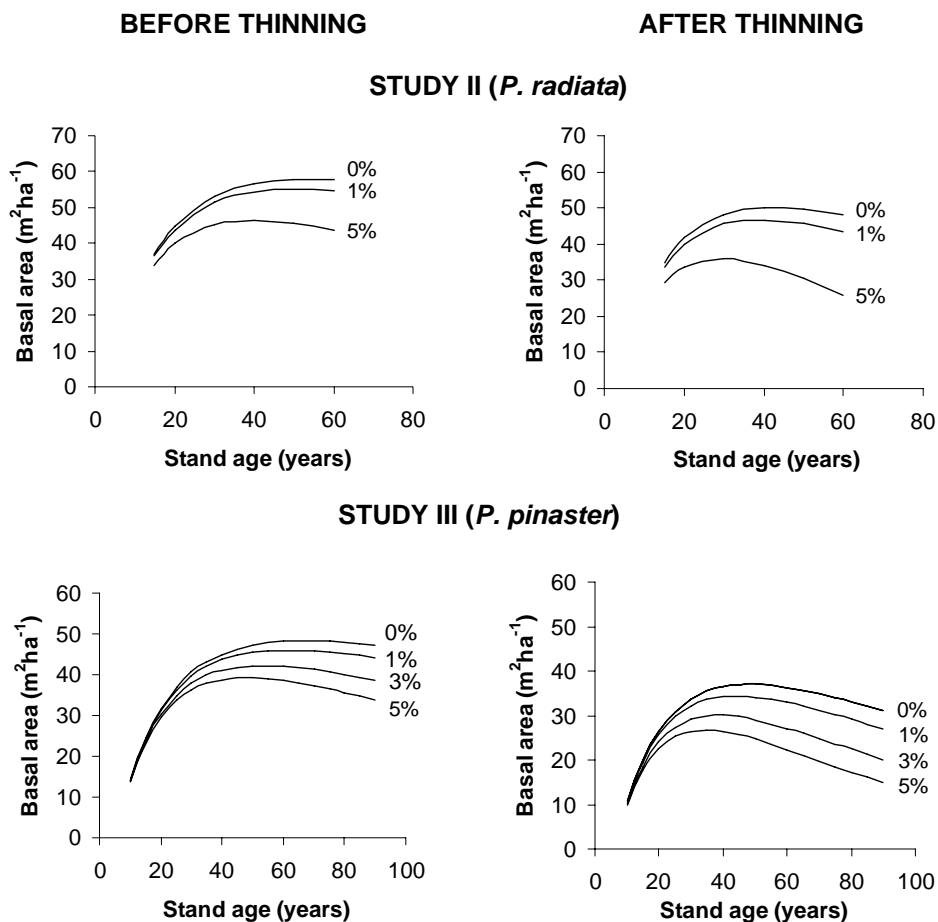
With higher discounting rates the optimal pre-thinning basal area begins to decrease after certain age (Figure 11). High probability of fire occurrence decreases the optimal pre-thinning basal area. However, the probability of fire interacts with stand age in the same way as discounting rate, i.e., increasing probability of fire decreases the optimal pre-thinning basal area more in older stands (Figure 12).



**Figure 10.** Effect of site index on the optimal pre- and post-thinning basal area in study I (third thinning), II and III when planting density is 1500 trees per hectare, discounting rate is 3% and prices of timber grades I, II and III ( $P_I$ ,  $P_{II}$ ,  $P_{III}$ ) are 90, 50 and 18 € m<sup>-3</sup>, respectively.



**Figure 11.** Effect of discounting rate on the optimal pre- and post-thinning basal area in study I (third thinning), II and III when planting density is 1500 trees per hectare and prices of timber grades I, II and III ( $P_I$ ,  $P_{II}$ ,  $P_{III}$ ) are 90, 50 and 18 € m<sup>-3</sup>, respectively.



**Figure 12.** Effect of the probability of fire occurrence on the optimal pre- and post-thinning basal area in studies II and III when planting density is 1500 trees per hectare and prices of timber grades I, II and III ( $P_I$ ,  $P_{II}$ ,  $P_{III}$ ) are 90, 50 and 18  $\text{€m}^{-3}$ , respectively.

As in study I, the model for the optimal basal area after thinning follows similar trends as the model for the optimal basal area before thinning due to the strong correlation between pre- and post-thinning basal area. According to the models, thinnings should be heavier with better site indexes and with high probabilities of fire occurrence. The probability of fire affects more in older stands but with high salvage percentages the influence of the probability of fire becomes less significant. Discounting rate affects in a similar way as the probability of fire. In general, high discounting rates lead to heavier thinnings.

The models for the optimal basal area before and after thinning for *P. pinaster* plantations (study III) were:

$$\ln(G_{\text{before}}) = 1.999 + 0.025SI - 16.827(1/T) + 0.277\ln(N) - 1.221 \times 10^{-3}(T \times r) - 7.453 \times 10^{-4}(T \times p_{\text{fire}}) \quad (27)$$

$$\ln(G_{\text{after}}) = -0.209 + 1.047\ln(G_{\text{before}}) - 2.158(1/T) - 1.571 \cdot 10^{-3}(T \times r) - 8.341 \cdot 10^{-4}(T \times p_{\text{fire}}) + 1.261 \cdot 10^{-3}P_{\text{II}} \quad (28)$$

As in studies II and III, stands of better site indices have higher optimal pre-thinning basal areas (Figure 10). Also high planting densities lead to high optimal pre-thinning basal area. With low discounting rate and fire probability, optimal basal area before thinning increases with stand age (Figures 11 and 12). However, higher discounting rates and fire probabilities decrease the optimal basal areas of older stands.

In the model for the optimal basal area after thinning site index and planting density were replaced by stand basal area before thinning. Stand age, discounting rate and probability of fire have similar effects as in the model for the pre-thinning basal area.

According to Figures 10 and 11, the shape of the pre- and post-thinning optimal basal area is very different for *Pinus sylvestris* (study I), on one hand, and *Pinus radiata* (study II) and *Pinus pinaster* (study III), on the other. The main reason for this is that in the model for *P. sylvestris*, the number of the thinning is a predictor, resulting in decreasing basal area in later thinnings although this cannot be seen from the curves drawn for a single thinning. This means that in fact there is no drastic difference in the optimal thinning of *P. sylvestris* and the other pines.

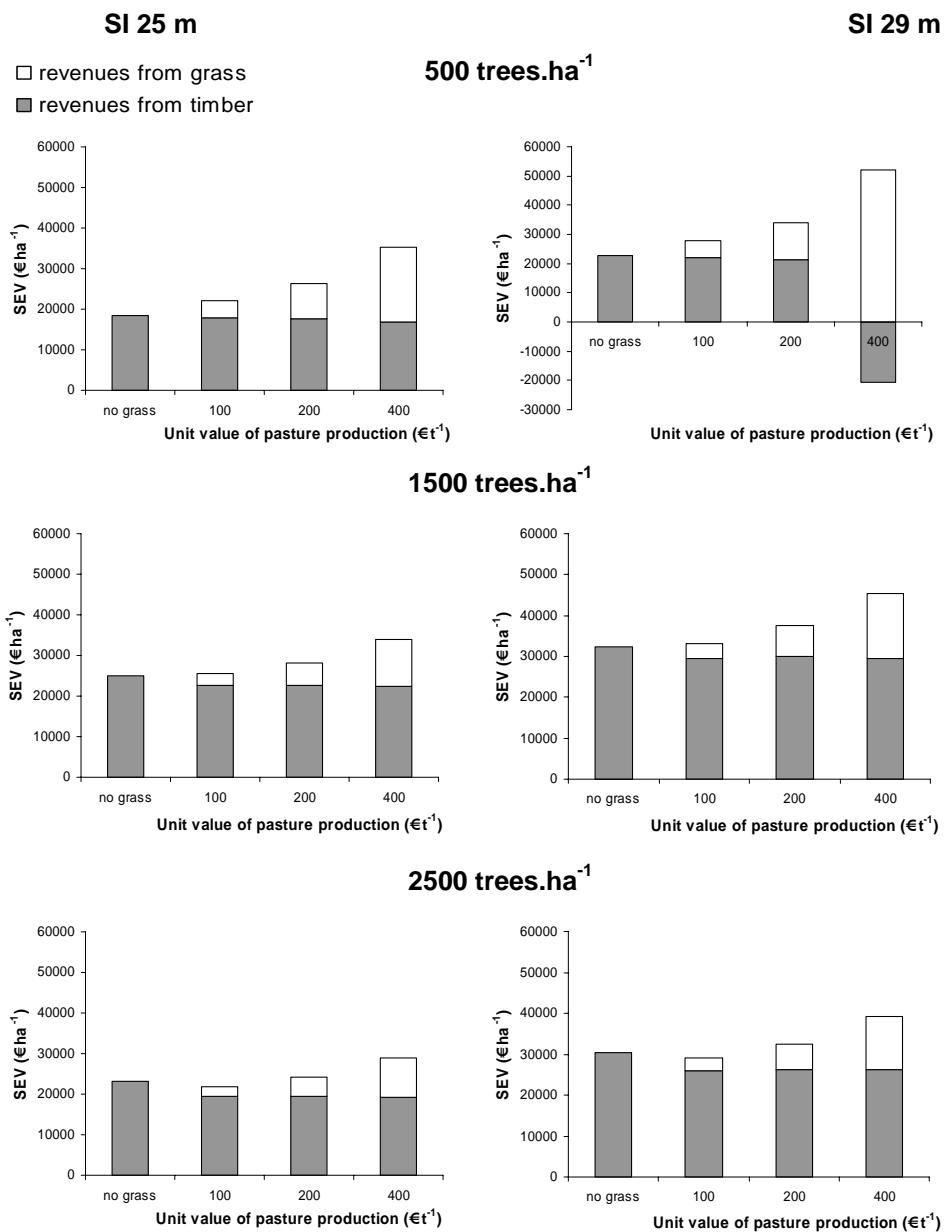
### 4.3 Optimal management of silvopastoral systems

The results of study IV showed that the optimal schedules for silvopastoral systems were a 1-thinning schedule for the lowest planting density (500 trees per ha) and 2-thinning schedule for planting densities of 1500 and 2500 trees per hectare, for both site indices 25 and 29. Silvopastoral systems were usually more profitable than sole timber production. Rotation lengths decreased with the inclusion of pasture, especially with lower planting densities.

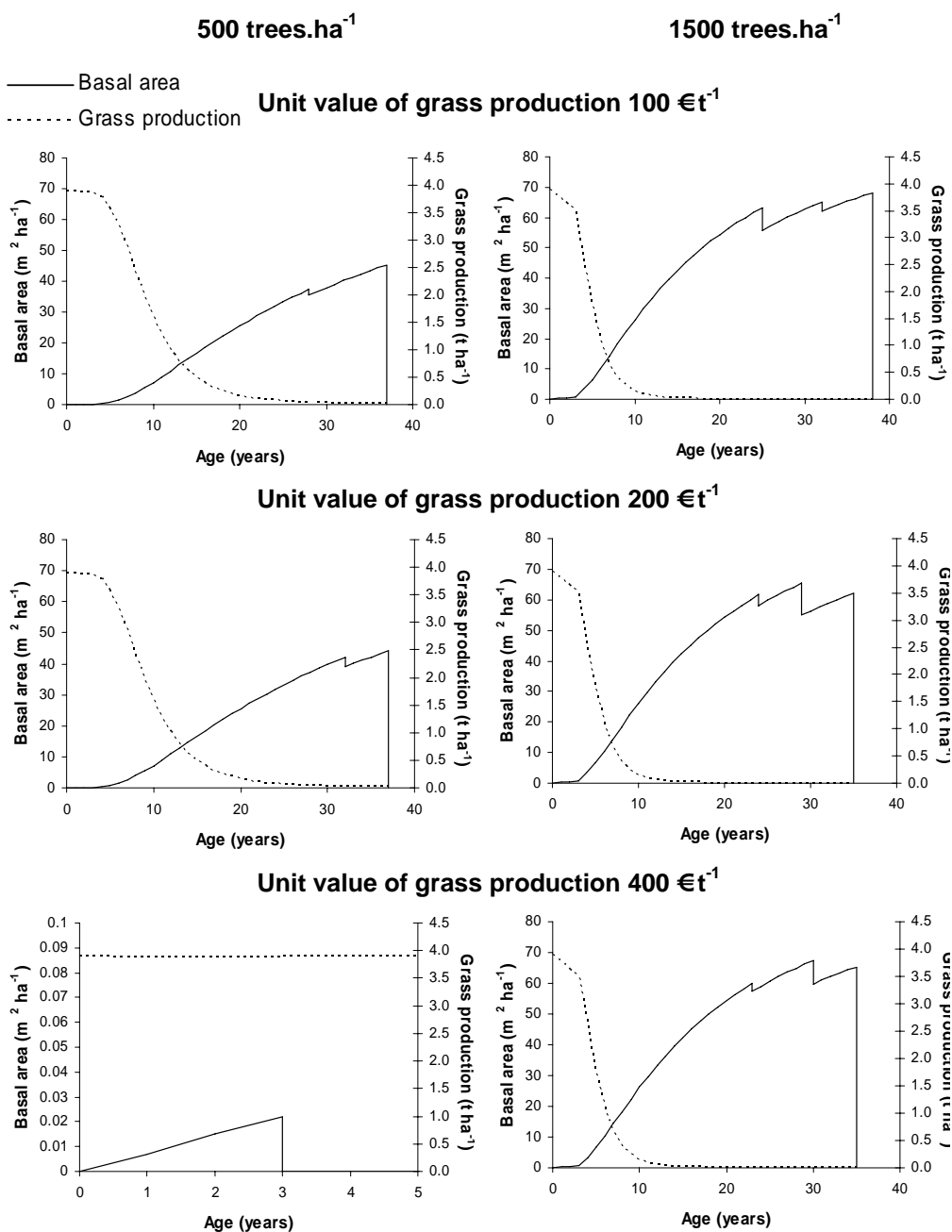
Increasing value of grass increased the profitability of low-density schedules (Figure 13), which became the most profitable alternative. Increasing grass value also shortened rotation lengths (Figure 14). With low unit values of grass dense tree plantations (2500 trees per hectare) without silvipasture became the best option.

When fire risk was integrated in the analysis, silvopastoral systems were always more profitable than mere timber production, following the trend that the higher the risk of fire was, the more profitable the silvopastoral schedules become in comparison to timber-oriented schedules.

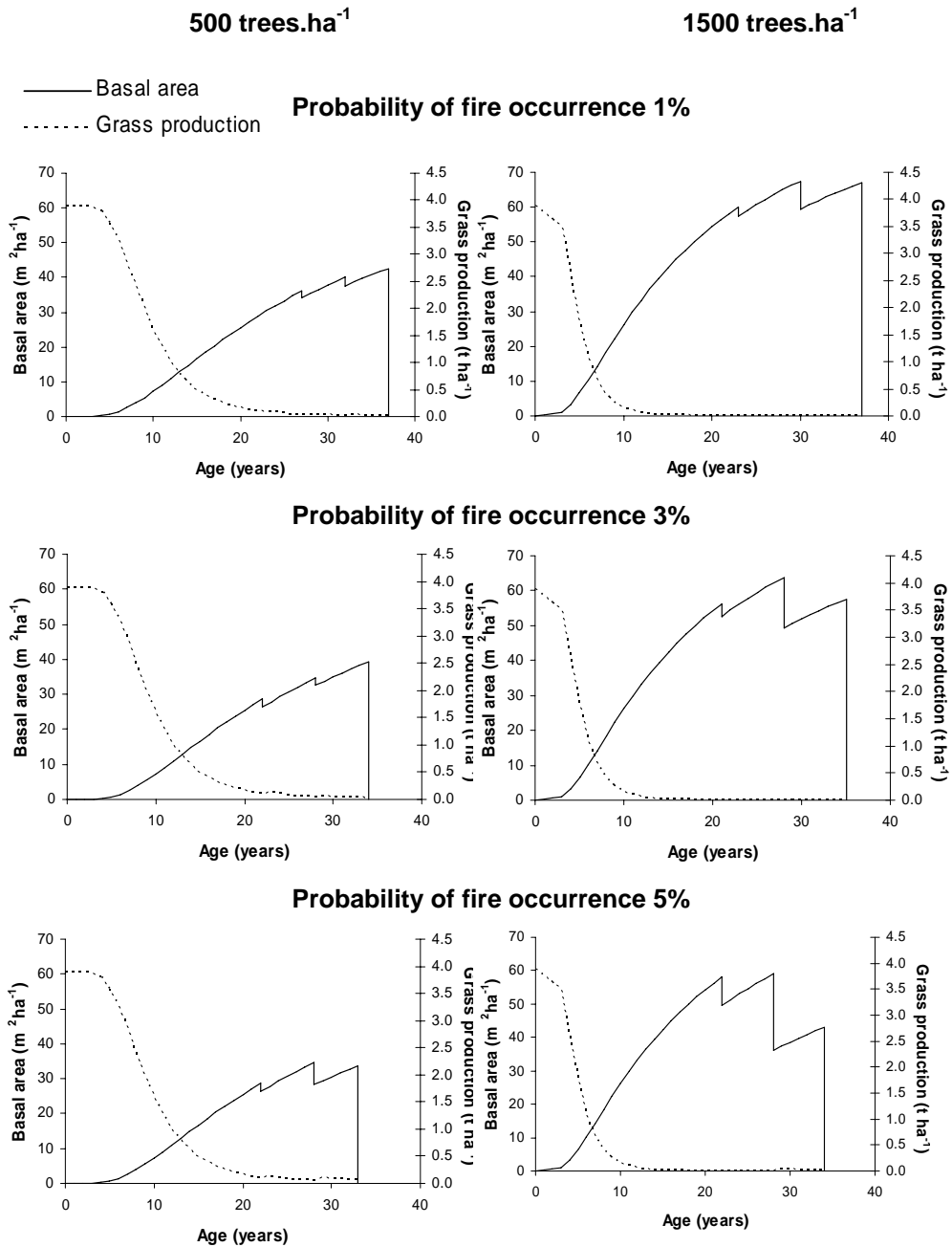
Optimal rotation lengths were shorter when fire risk was included and this decrease was more with increasing risk of fire (see Figure 15). Moreover, with increasing risk of fire the thinnings become heavier and earlier. When grazing was assumed to reduce the risk of fire, optimal thinnings were heavier and earlier. When the risk of fire was high (5%), this effect was so strong that grazing could continue much longer. Moreover, the higher was the risk reduction caused by grazing, the shorter were the optimal rotation lengths.



**Figure 13.** Soil expectation value of the optimal silvopastoral schedules for different planting densities when different unit values of grass production are considered.



**Figure 14.** Development of stand basal area and annual grass yield in the optimal management schedule for different silvopastoral systems when site index is 29 meters.



**Figure 15.** Development of stand basal area and annual grass yield in the optimal management schedule of silvopastoral systems when the unit value of grass production is 200 € t<sup>-1</sup>.



## 5 DISCUSSION

### 5.1 Significance of the research

The models for optimal stand management obtained in this thesis are helpful and simple tools to manage pine plantations in Galicia. So far, information that relates, in a systematic way, stand management to economic and risk conditions has been almost lacking in Galicia. Models obtained in studies I, II, III and IV allow stand management to be adapted to market conditions at each moment. Using the results of studies II, III and IV, management can also be adapted to the prevailing fire risk conditions. Forest manager can adjust the prescriptions based on the risk tendency of the area where the stand is located; in an area with high level of risk of fire he or she should shorten rotation lengths and carry out earlier and heavier thinnings. In study II the manager has to assign a salvage proportion to a burned stand. In studies III and IV this step is not necessary since salvage proportion was modelled as a functions of stand mean diameter.

To find the optimal operations for stand management, the models are used in the following way. The age of a stand is compared to the model for optimal rotation length, if the stand is older than the optimal rotation age it should be clear-felled. Else, the stand basal area is compared to the pre-thinning basal area given by the corresponding model and if it exceeds the model prediction, the stand should be thinned. The model for the optimal post-thinning basal provides the basal area to which the stand should be thinned. The models (study I-III) are easy to use, and at any time point the manager is able to find out whether the stand needs to be thinned or clearcut or nothing needs to be done. The models can be also employed to ease decision making at the forest level. At the forest level the manager can use the models to produce several near-optimal treatment alternatives for each stand. These alternatives are then combined, using combinatorial optimisation, to achieve the forest level objectives.

### 5.2 Validity of the results

All the results of the thesis were obtained from a simulation- optimisation system. Therefore the quality of results obtained is determined by the performance of both the growth and yield models and the optimisation algorithm. Growth and yield models present certain limitations, one of them being the fact that they have been developed without explicitly modelling the effect of thinning operations on the growth of stand basal area (Diéguez-Aranda et al. 2006, Castedo-Dorado et al. 2007). However, some studies conducted in pine stands suggest that this may not be a serious limitation (Pukkala et al. 2002). Another limitation of the models is the database employed in their constructions (Diéguez-Aranda et al. 2006, Castedo-Dorado et al. 2007). Sometimes it was necessary to pass the observed ranges of variables because, for instance, optimisations prescribed longer rotations than the maximum stand age in the data. This caused some uncertainty concerning the quality of the models. In Study IV the simulations were started at very young ages (less than 10 years) where the models may also be less reliable. Nevertheless, the growth and yield models (Álvarez-González et al. 1999, Diéguez-Aranda et al. 2006, Castedo-Dorado et al. 2007) are well established and reasonably simple and it may be expected that no drastic deterioration in simulation quality occurred when extrapolations were done. Despite

this, it is important to continue data collection and growth modelling to obtain improved models in the future. One important shortcoming was the lack of a self-thinning model in the maritime pine growth and yield model (study III). This is explained by the fact that no significant mortality was found in the plots that were used to build the models (Rodríguez Soalleiro 1997, Barrio-Anta et al. 2006).

In study IV there is also place for improvement. The main shortcomings are low amount of information regarding the dynamics of the understory vegetation and competition between trees and grass, or trees and bushes. Additional information on these factors would help to develop models for the dynamics of silvopastoral systems.

The optimisation algorithm also has weaknesses. As it is known, the algorithm does not assure to find a global maximum but a good solution instead (Bazaraa et al. 1993). The Hooke and Jeeves algorithm has been widely employed to solve optimisation problems at the stand level (Kao and Brodie 1980, Roise 1986a, 1986b, Valsta 1986, Haight and Monserud 1990, Valsta 1990, 1992a, 1992b, Pukkala and Mabvurira 1999, Pukkala 2006a, Hyytiäinen et al. 2005, 2006, González et al. 2005, González-Olabarría et al. 2008, Pasalodos-Tato and Pukkala 2008), but it has been object of some criticism. Because the results obtained with the method are not stable but may find different local optima, the optimisation must be repeated several times (Roise 1986a). Haight and Monserud (1990) found that with many decision variables the algorithm often converged to suboptimal solutions (Wikström 2001). Moreover, when there are many decision variables in the problem, the solution becomes dependent on the starting solution and, therefore, several repeated optimisation runs are needed (Valsta 1990). Despite these shortcomings, the Hooke and Jeeves algorithm has proved to be a good method when some of the decision variables have upper and lower bounds (Miina 1996) as it is the case in studies I, II, III and IV. Another fact that complicated the modelling of optimal management is that two or more quite different management schedules may lead to almost the same value of the objective function. This is the main reason why the optimal management schedules did not always agree with the regression models.

In studies I, II and III the instability of the results is not a very serious problem because optimisations were not used directly but as a means to provide modelling data. However, modeling had an averaging effect on the results on optimal management. In study IV the results obtained from optimisations were used directly and therefore it was necessary to repeat the optimisations several times in order to obtain robust results. Another possibility would be to try different optimisation algorithms, such as differential evolution, particle swarm optimisation, evolution strategy or Nelder and Mead method, which have been found to perform well in stand management optimisation (Pukkala 2009). However, at the time when studies I-IV were conducted there was no information available about the performance of these methods in stand level optimisation.

Another point worth of consideration is the type of models developed for the optimal basal area before and after thinning. In the models developed in studies I, II and III, pre- and post-thinning optimal basal area were fitted as independent equations. Although the models work satisfactory, some other modelling techniques more suitable for this type of analysis could have been employed, for instance simultaneous equation modelling. Nevertheless this could be object of further research.

### 5.3 Analysis of the results

In study I, rotations much shorter than traditionally used were often obtained. The manager not only obtains higher revenues when following the optimal management schedules, but also revenues are obtained earlier. Thinnings became heavier with the increment of the discounting rate but thinning intensity also increased with stand age. Discounting rate was always a predictor in the models for optimal management (studies I-III). With high discounting rates the optimal rotation lengths became shorter because the opportunity cost of the standing trees increased.

The optimal management schedule, especially the rotation length, varied a lot depending on discounting rate and timber price. Therefore, it is important to adapt management to changing conditions. To illustrate this, it would be interesting to compare the profitability of pine stands traditionally managed and optimally managed under different economic situations. This could be a matter of further studies.

### 5.4 Inclusion of risk of fire

In study II fire risk was integrated as an exogenous factor, meaning that both the probability of fire occurrence and the proportion of timber salvaged were constant and independent of stand variables (Pasalodos-Tato and Pukkala 2008). The results show that optimal rotation lengths decrease when the probability of fire occurrence increases. The best option is to prevent the valuable growing stocks from being exposed to high risk. The same reason explains why thinnings are heavier and earlier in presence of risk of fire. Fire risk has the same effect as discounting rate (Reed 1984) but the effect of fire risk is reduced by the increase in salvage proportion: the smaller the damage caused by fire, the less influential is fire risk. These same results have been achieved in previous research (Routledge 1980, Martell 1980, Reed 1984, Reed and Errico 1985, Caulfield 1988).

One improvement in the way to assess fire risk was made in study III by adopting an endogenous approach where salvage proportion depended on diameter at breast height (Botelho et al. 1998, González et al. 2007, Pasalodos-Tato and Pukkala 2008). Also a 25% reduction in the price of the salvaged timber was introduced. Study III gave some interesting results. When fire probability increases, rotation length decreases when the price of salvaged timber is reduced. However, when the price of salvaged timber is not reduced, rotation length increases. This last result, a priori quite illogical and opposite to previous studies (Routledge 1980, Martell 1980, Reed 1984, Reed and Errico 1985 and Caulfield 1988), is due to the fact that larger trees (and therefore older ones) survive fires much better than young trees, and they can be harvested and sold with a reasonable price. Therefore, in these conditions it is profitable to delay the clear cutting postponing the period of vulnerable stand stages. This agrees with the results achieved by other authors (Englin et al. 2000, Castedo et al 2004, Amacher et al. 2005a, González-Olabarría et al. 2008, Pasalodos-Tato and Pukkala 2008). However, price reduction of salvaged timber is the most realistic scenario and also the current practise (Arenas and Izquierdo 2007). Anyway, with smaller depreciation and higher relative salvage, the result would be the same, i.e., longer rotation with increasing probability of fire occurrence.

The results obtained in studies II and III illustrate how the optimal management varies depending on whether or not the risk of fire is included and also on the way this is done. Risk is many times considered exogenous or ignored (Thorsen and Helles 1998) due to the

lack of information about the factors affecting it. These assumptions can lead to suboptimal management strategies. Other examples of how the way to assess fire risk can influence the solution can be found in González-Olabarria et al. (2008) and in Pasalodos-Tato and Pukkala (2008). Therefore, accurate information about the effects of forest fires is needed to find truly optimal management schedules for risky situations.

However, the analysis of the effect of fire risk is not complete with the stand level since fire spreads from one stand to the neighbors and therefore has also a spatial component. In order to complete the integration of the risk of fire in forest planning it is necessary to model fire risk at the landscape level, too. Many authors have already studied this issue using different approaches (Van Wagner 1983, Cohan 1986, Reed and Errico 1986, Teeter and Dyer 1986, Gassman 1989, Martel 1994, Boychuck and Martell 1996, Hof and Omi 2003, Loehle 2004, González et al. 2005).

## 5.5 Silvopastoral systems

In this thesis, grazing in the forest was analysed as an alternative use for mere timber production. The grass production model developed in study IV, used in conjunction with a growth and yield model (Álvarez-González et al. 1999) that describes the pine stand dynamics allow the analysis of these systems in a quantitative and systematic way.

The developed model cannot be applied to all types of silvopastoral systems but only to those ones established by planting trees and sowing grass at the same time on abandoned agricultural lands (Mosquera-Losada et al. 2006, Fernández-Núñez et al. 2007). The model and the whole simulation-optimisation system can be improved with new information regarding the dynamics of the understory vegetation and the competition relationships among trees and bushes or herbaceous vegetation (Pollock et al. 1994, Chang et al. 2002, Peri et al. 2002, Ares et al. 2003) especially when both occupy the same strata (e.g., when tree plantations are young).

The results from this study showed that silvopastoralism can be a more profitable option in *Pinus radiata* plantations than mere timber production on good sites in Galicia. Former studies (Percival and Knowles 1988, Cossens and Crossan 1991, Cossens and Hawke 2000) recommended low plantation densities when implementing silvopastoral systems. However, the results of study IV showed that silvopastoral systems with high planting densities (1500 trees per hectare) are more profitable than sparser stands (500 trees per hectare) as long as fire risk is not considered. When fire risk is considered, sparse stands (500 trees per hectare) are the most profitable. Although the results are sensitive to changes in market and fire risk conditions, some conclusions could be drawn regarding the optimal way to manage these systems and the performance of silvopastoral systems as compared to timber-oriented management.

## REFERENCES

- Adams, D.M. & Ek, A.R. 1974. Optimising the management of unevenaged forest stands. *Canadian Journal of Forest Research* 4: 274–287.
- Álvarez González, J.G., Rodríguez Soalleiro, R. & Vega Alonso, G. 1999. Elaboración de un modelo de crecimiento dinámico para rodales regulares de *Pinus pinaster* Ait en Galicia. *Investigaciones Agrarias: Sistemas y Recursos Forestales* 8 (2): 319-334.
- Amacher, G., Malik, A. & Haight, R. 2005a. Don't get burned: the importance of fire prevention in forest management. *Land Economics* 81(2): 284-302.
- , Malik, A. & Haight, R. 2005b. Forest landowner decisions and the value of information under fire risk. *Canadian Journal of Forest Research* 35: 2603-2615.
- Amidon, E. & Atkin, G. 1968. Dynamic programming to determine optimal levels of growing stock. *Forest Science*. 14: 287-291.
- Anderson, L.S. & Sinclair, F.L. 1993. Ecological interactions in agroforestry systems. *Forestry abstracts* 54 (6): 489-523.
- Arenas, S.G. & Izquierdo, S. 2007. Estudio de los precios de la madera en pie de los montes gestionados por la administración forestal gallega en los años 2005 y 2006. *Montes* 90: 8-15.
- Ares, A., St Louis, D. & Brauer, D. 2003. Trends in tree growth and understorey yield in silvopastoral practices with southern pines. *Agroforestry systems* 59: 27-33.
- Arimizu, T. 1958. Regulation of the cut by dynamic programming. *Journal of Operations Research Society of Japan* 1(4):175–182.
- Arthaud, G.J. & Pelkki, M.H. 1996. A comparison of dynamic programming and A\* in optimal forest stand management. *Forest Science* 42: 498–503.
- Bachmann, A. & Allgöwer, B. 2000. The need for a consistent wildfire risk terminology. In: Neuenschwander, L., Ryan, K. & Golberg, G. *Crossing the Millennium: Integrating Spatial Technologies and Ecological Principles for a New Age in Fire Management*. The University of Idaho and the International Association of Wildland Fire, Moscow. p. 67-77.
- Barrio-Anta, M., Balboa-Murias, M.A., Castedo-Dorado, F., Diéguez-Aranda, U. & Álvarez-González, J.G. 2006. An ecoregional model for estimating volume, biomass and carbon pools in maritime pine stands in Galicia (northwestern Spain). *Forest Ecology and Management* 223: 24-34.
- Bazaraa, M.S., Sherali, H.D. & Shetty, C.M. 1993. *Nonlinear programming. Theory and algorithms*. Second edition. John Wiley & Sons, Inc., Hoboken. 639 p.
- Bermúdez, J. & Touza, M. 2000. Las cifras del Tercer Inventario Forestal Nacional en Galicia y su incidencia en la industria de transformación de la madera. *Revista del Centro de Innovación y Servicios Tecnológicos de la Madera*, 4.
- Bettinger, P., Graetz, D. & Sessions, J. 2005. A density-dependent stand-level optimisation approach for deriving management prescriptions for interior northwest (USA) landscapes. *Forest Ecology and Management* 217 (2-3): 171-186.
- , Boston, K., Siry, J.P. & Grebner, D.L. 2008. *Forest Management and Planning*. Academic Press 2008. 331 pages.
- , Boston, K. & Sessions, J. 1999. Intensifying a heuristic forest harvest scheduling procedure with 2opt decision choices. *Canadian Journal of Forest Research* 29: 1784-1792.

- , Graetz, D., Boston, K., Sessions, J. & Chung, W. 2002. Eight heuristic planning techniques applied to three increasingly difficult wildlife planning problems. *Silva Fennica* 36: 561–584.
- Beyer, H.G. & Schwefel, H.P. 2002. Evolution Strategies: A Comprehensive Introduction. *Journal Natural Computing*, 1(1): 3-52.
- BOCG. 2006. Boletín oficial de las cortes generales. Congreso de los Diputados. Num. 461. 13 noviembre 2006. Pag.6.
- Borges, J. G. & Falcão, A. 1999. Programação dinâmica e gestão de povoamentos com estrutura regular e composição pura. Aplicação à Mata Nacional de Leiria. *Revista Florestal XII* (1/2): 69-82.
- , Hoganson, H. & Falcao, A. 2002. Heuristics in multi-objective forest management. In: Pukkala, T. (ed.). *Multi-objective forest planning*. Kluwer Academic Publishers, Netherlands. p. 119-151.
- Botelho, H.S., Rego, F.C. & Ryan, K.C. 1998. Tree mortality models for *Pinus pinaster* of Northern Portugal. In: *Proceedings of the 13<sup>th</sup> Conference of Fire and Forest Meteorology*. p. 235-240.
- Bradley, S.P., Hax, A.C. & Magnanti, T.L. 1977. *Applied Mathematical Programming*. Addison-Wesley Publishing Company. Reading, Mass.
- Bravo, F. & Diaz-Balteiro, L. 2004. Evaluation of new silvicultural alternatives for Scots pine stands in northern Spain. *Annals of Forest Science* 61: 163-169.
- , Bravo-Oviedo, A. & Diaz-Balteiro, L. 2008. Carbon sequestration in Spanish Mediterranean forests under two management alternatives: a modeling approach. *European Journal of Forest Research* 127: 225–234.
- Bright, G. & Price, C. 2000. Valuing forest land under hazards to crop survival. *Forestry* 73 (4): 361-370.
- Brodie J.D. & Haight, R. 1985. Optimisation of silvicultural Investment for several types of stand projection systems. *Canadian Journal of Forest Research* 15: 188-191.
- & Kao, C. 1979. Optimising thinning in Douglas fir with three descriptor dynamic programming to account for accelerated diameter growth. *Forest Science* 25: 665-672.
- , Adams, D. & Kao, C. 1978. Analysis of economic impacts on thinning and rotation for Douglas-fir using dynamic programming. *Forest Science* 24: 513-522.
- Bullard, S.H, Sherali, H.D & Klemperer, W.D. 1985. Estimating optimal thinning and rotation for mixed-species timber stands using a random search algorithm. *Forest Science* 31(2): 303-315.
- Castedo-Dorado, F., Rodríguez Soalleiro, R., Rojo, A. & Álvarez González, J.G. 2004. Valuating Standard treatment options for *Pinus radiata* D. Don plantations in Galicia including the risk of fires. *Proceedings of the International I.U.F.R.O. 4.04.06 Meeting. The Economics and Management of High Productivity Plantations*. Lugo, Spain.
- , Diéguez-Aranda, U. & Álvarez González, J.G. 2007. A growth model for *Pinus radiata* D. Don stands in north-western Spain. *Annals of Forest Science* 64: 453-465.
- Caulfield, J.P. 1988. A stochastic efficiency approach for determining the economic rotation of a forest stand. *Forest Science* 34 (2): 441-457.
- Chang, S.X., Amatya, G., Beare, M.H. & Mead, D.J. 2002. Soil properties under a *Pinus radiata*-ryegrass silvopastoral system in New Zealand. Part I. Soil N and moisture availability, soil C, and tree growth. *Agroforestry systems* 54: 137-147.
- Chas, M.L., Lorenzo, M.C., Pérez, J., Rodríguez, D., Mesías, A., Torres, S. & Villar, J. 2002. Socioeconomía forestal. IEFCA: Contribución de la región Galicia. Eurosilvasur.

- Chapelle, D. & Nelson, T. 1964. Estimation of optimal stocking levels and rotation ages of loblolly pine. *Forest Science*. 10: 421-502.
- Chelouah, R. & Siarry, A. 2000. A continuous genetic algorithm designed for the global optimisation of multimodal functions. *Journal of Heuristics* 6(2): 191-213.
- & Siarry, P. 2005. A hybrid method combining continuous tabu search and Nelder-Mead simplex algorithms for the global optimisation of multimodal functions. *European Journal of Operational Research* 161 (3): 636-654.
- Chen, C., Rose, D. & Leary, R. 1980. How to formulate and solve optimal stand density over time problems for even-aged stands using Dynamic Programming. General Technical Report 56. USDA Forest Service, North Central Forest Experiment Station. St Paul, Minnesota.
- Chuvieco, E., Rodríguez, F., Nieto, H. & Martín, P. 2006. Evaluación de superficies quemadas en Galicia. Universidad de Alcalá, Departamento de Geografía y C.S.I.C., Instituto de Economía y Geografía Unidad Asociada GEOLAB.
- Corana, A., Marchesi, M., Martini, C. & Ridella, S. 1987. Minimizing multimodal functions of continuous variables with the 'simulated annealing algorithm', *ACM Transactions on Mathematical Software* 13: 262-280.
- Cosens, G.G. & Crossan, G.S. 1991. Akatore Agroforestry Trial. Results from 1974-1990. Agroforestry Research Collaborative. Report No. 12.
- & Hawke, M.F. 2000. Agroforestry in Eastern Otago: results from two long-term experiments. *Proceedings of the New Zealand Grassland Association* 6: 93-98.
- Davis, L.S., Johnson, K.N., Bettinger, P.S. & Howard, T.E. 2001. Forest management to sustain ecological, economic, and social values. McGraw-Hill, 4<sup>th</sup> ed., New York.
- DGCONA. 2002a. Plan Forestal Español. Secretaria General de Medio Ambiente. Ministerio de Medio Ambiente, Madrid.
- 2002b. Tercer Inventario Forestal Nacional (1.997-2.006): Galicia. Dirección General de Conservación de la Naturaleza. Ministerio de Medio Ambiente, Madrid.
- Díaz-Balteiro, L. & Romero, C. 2003. Forest management optimisation models when carbon captured is considered: a goal programming approach. *Forest Ecology and Management* 174: 447-457.
- & Rodríguez, L.C.E. 2006. Optimal rotations on *Eucalyptus* plantations including carbon sequestration - a comparison of results in Brazil and Spain. *Forest Ecology and Management* 229: 247-258.
- , Álvarez Nieto, A. & Oria de Rueda Salgueiro, J.A. 2003. Integración de la producción fúngica en la gestión forestal. Aplicación al monte "Urcido" (Zamora), *Investigación Agraria Sistemas y Recursos Forestales* 12 (1): 5-19.
- Diéguez-Aranda, U., Castedo Dorado, F., Álvarez González, J.G. & Rojo Alboreca, A. 2006. Dynamic growth model for Scots pine (*Pinus sylvestris* L.) plantations in Galicia (north-western Spain). *Ecological Modelling* 191: 225-242.
- Dueck, G. 1993. New Optimisation Heuristics The Great Deluge Algorithm and the Record-to-Record Travel. *Journal of Computational Physics* 104 (1): 86-92.
- Fang, Z., Borders, B.E. & Bailey, R.L. 2000. Compatible volume-taper models for loblolly and slash pine based on a system with segmented-stem form factors. *Forest Science* 46: 1-12.
- Fernández-Núñez, E., Mosquera-Losada M.R. & Rigueiro-Rodríguez, A. 2007. Libro de Actas de la XLVI Reunión Científica de la Sociedad Española para el Estudio de los pastos.pp: 89-94. <http://www.neiker.net/neiker/seep07/Datos/Libro%20Actas/R.%20Silvopastorales/RECURSOS%20SILVOPASTORALES.pdf>

- García, O. 1984. New class of growth models for even-aged stands: *Pinus radiata* in Golden Downs Forest. *New Zealand Journal of Forest Science* 14: 65–88.
- . 1994. The state-space approach in growth modelling. *Canadian Journal of Forest Research*. 24 (9): 1894-1903.
- Glover F. 1986. Future paths for Integer Programming and Links to Artificial Intelligence, *Computers and Operations Research* 5: 533-549.
- Goffe, W.L., Ferrier, G.D. & Rogers, J. 1994. Global optimisation of statistical functions with simulated annealing. *Journal of Econometrics* 60: 65-99.
- González, J.R., Pukkala, T. & Palahí, M. 2005. Optimising the management of *Pinus sylvestris* L. stand under risk of fire in Catalonia (north.east of Spain). *Annals of Forest Science* 62: 493-501.
- , Trasobares, T., Palahí, M. & Pukkala, T. 2007. Predicting stand damage and tree survival in burned forests in Catalonia (North-East Spain). *Annals of Forest Science* 64: 733-742.
- González-Olabarria, J.R., Palahí, M., Pukkala, T. & Trasobares, A. 2008. Optimising the management of *Pinus nigra* Arn. Stands under endogenous risk of fire in Catalonia. *Investigación Agraria: Sistemas y Recursos Forestales* 17 (1): 10-17.
- Haight, R.G. & Monserud, R.A., 1990. Optimising any-aged management of mixed-species stands: II. Effects of decision criteria. *Forest Science* 36: 125-144.
- , Brodie, J.D. & Dahms, W. 1985. A dynamic programming algorithm for optimisation of lodgepole pine management. *Forest Science* 31: 321-330.
- , Monserud, R.A. & Chew, J.D., 1992. Optimal harvesting with stand density targets: managing Rocky Mountain conifer stands for multiple forest outputs. *Forest Science* 38: 554–574.
- Hajji, O., Brisset, S. & Brochet, P. 2004. A new tabu search method for continuous parameter optimisation: application to design problems in electromagnetic. *European Transactions on Electrical Power* 15 (6): 527-540.
- Hann, D., Brodie, J.D. & Riitters, K. 1983. Optimum Stand Prescriptions for Ponderosa Pine. *Journal of Forestry* 81: 595-598.
- Hardy, C.C. 2005. Wildland fire hazard and risk: Problems, definitions and context. *Forest Ecology and Management* 211: 73-82.
- Heinonen, T. & Pukkala, T. 2004. A Comparison of One- and Two-Compartment Neighbourhoods in Heuristic Search with Spatial Forest Management Goals. *Silva Fennica* 38 (3): 319-332.
- Hooke, R. & Jeeves, T.A. 1961. “Direct Search” solution of numerical and statistical problems, *J. Assoc. Comput. Mach.* 8: 212-229.
- Hool, J. 1966. A dynamic programming-Markov chain approach to forest production control. *Forest Science. Monograph* 12, 26 p.
- Hyytiäinen, K. 2003. Integrating economics and ecology in stand-level timber production. *Finnish Forest Research Institute, Research Papers* 908: 42p.+ pp.
- & Haight, R. 2009. Evaluation of forest management systems under risk of wildfire. *European Journal of Forest Research* in press.
- , Tahvonen, O. & Valsta, L. 2005. Optimum juvenile density, harvesting and stand structure in even-aged Scots pine stands. *Forest Science* 51(2): 120–133.
- , Ilomäki, S., Mäkelä, A. & Kinnunen, K. 2006. Economic analysis of stand establishment for Scots pine. *Canadian Journal of Forest Research* 36: 1179-1189.
- Jones, D.A. 1992. Nomenclature of hazard and risk assessment in the process industries. *Institution of Chemical Engineers. Rugby, Warwickshire, UK.*



- Kao, C. & Brodie, J.D. 1980. Simultaneous optimisation of thinning and rotation with continuous stocking and entry intervals. *Forest Science* 26 (3): 338-346.
- Kaya, I. & Buongiorno, J. 1987. Economic Harvesting of Uneven-Aged Northern Hardwood Stands Under Risk: A Markovian Decision Model. *Forest Science* 33(4): 889-907.
- Kennedy, J. & Eberhart, R. 1995. Particle swarm optimisation, In: Proceedings of the IEEE International Conference on Neural Networks. Piscataway, NJ, pp. 1942–1948.
- Kilikki, P. & Väisänen, U. 1970. Determination of the optimum cutting policy for the forest stand by means of dynamic programming. *Seloste: Metsikön optimihakkuuohjelman määrittäminen dynaamisen ohjelmoinnin avulla. Acta Forestalia Fennica* 102:1–23.
- Koskela, E., Ollikainen, M. & Pukkala, T. 2008. Biodiversity policies in commercial boreal forests: Optimal design of subsidy and tax combinations. *Forest Policy and Economics* 9(8): 982-995.
- Kozak, A. 1988. A variable-exponent taper equation. *Canadian Journal of Forest Research* 27: 619-629.
- Kumamoto, H. & Henley, E.J. 1996. Probabilistic risk assessment and management for engineers and scientists. IEEE New York, USA.
- Lohmander, P. 2007. Adaptive optimisation of forest management in a stochastic world. In: Handbook of operations research in Natural Resources. Andres Weintraud, Carlos Romero, Trond Bjørndal, Rafael Epstein(eds.). Springer US.
- Martell, D. L. 1980. The optimal rotation of a flammable forest stand. *Can. J. For. Res.* 10: 30-34.
- Martin, G.L. & Ek, A.R. 1981. A dynamic programming analysis of silvicultural alternatives for red pine plantations in Wisconsin. *Canadian Journal of Forest Research* 11: 370–379.
- Miettinen, K., Mäkelä, M.M. & Maaranen, H. 2006. Efficient hybrid methods for global continuous optimisation based on simulated annealing. *Computers and Operations Research* 33 (4): 1102-1116.
- Miina, J. 1996. Optimising thinning and rotation in a stand of *Pinus sylvestris* on a drained peatland site. *Scandinavian Journal of Forest Research* 11 (1): 182 – 192.
- Ministerio de Medio Ambiente. 2006. Los incendios forestales en España. Decenio 1996-2005. Dirección General para la Biodiversidad.
- . 2007. Los incendios forestales en España. Año 2006. Dirección General para la Biodiversidad.
- Mosquera-Losada, R., Fernández-Núñez, E. & Rigueiro-Rodríguez, A. 2006. Pasture, tree and soil evolution in silvopastoral systems of Atlantic Europe. *Forest Ecology and Management* 232: 135-145.
- Moreira, F. & Russo, D. 2007. Modelling the impact of agricultural abandonment and wildfires on vertebrate diversity in Mediterranean Europe. *Landscape Ecology* 22: 1461-1476.
- Möykkönen, T., Miina, J. & Pukkala, T. 2000. Optimising the management of a *Picea abies* stand under risk of butt rot. *Forest Pathology* 30: 65-76.
- Muchiri, M., Pukkala, T. & Miina, J. 2002. Optimising the management of maize-*Grevillea robusta* fields in Kenya. *Agroforestry systems* 56 (1): 13-25.
- Nelder, J.A. & Mead, R. 1965. A simplex method for function minimization. *Computer Journal* 7: 308-313.

- Núñez-Regueira, L., Rodríguez-Añón, J., Proupín, J. & Romero-García, A. 2003. Energy evaluation of forest residues originated from pine in Galicia. *Bioresource Technology* 88: 121-130.
- Palahí, M. & Pukkala, T. 2003. Optimising the management of Scots pine (*Pinus sylvestris* L.) stands in Spain based on individual-tree models. *Annals of Forest Science* 60: 105-114.
- , Pukkala, T., Bonet, J.A., Colinas, C., Fischer, C. & Martínez de Aragón, J.R. 2009. Effect of the inclusion of mushroom values on the optimal management of even-aged pine stands of Catalonia. *Forest Science* 55 (6): 503-511.
- Paredes, V.G.L. & Brodie, J.D. 1987. Efficient specification and solution of the evenaged rotation and thinning problem. *Forest Science* 33 (1): 14-29.
- Parks, G.T. 1990. An intelligent stochastic optimisation routine for nuclear fuel cycle design. *Nuclear Technology* 89: 233-246.
- Pasalodos-Tato, M. & Pukkala, T. 2008. Assessing fire risk in stand-level management in Galicia (north-western Spain). In: de las Heras, J., Brebbia, C.C., Viegas, D. & Leone V. (ed.). *Modelling, monitoring and management of forest fires*. Witpress, p. 89-97.
- Percival, N.S. & Knowles, R.L. 1988. Relationship between radiate pine and understorey pasture production. In: McLaren, J.P. (ed.). *Proceedings of Agroforestry symposium*, pp. 153-164. Forest Research Institute and New Zealand Ministry of Forestry. Rotorua, New Zealand.
- Peri, P.L., Mason, E.G., Pollock, K.M., Varella, A.C. & Mead, D.J. 2002. Early growth and quality of radiate pine in a silvopastoral system in New Zealand. *Agroforestry systems* 55: 207-219.
- Pohjola, J. & Valsta, L. 2007. Carbon credits and management of Scots pine and Norway spruce stands in Finland. *Forest Policy and Economics* 9: 789-798.
- Pollock, K.M., Lucas, R.J., Mead, D.J. & Thomson, S.E. 1994. Forage-pasture production in the first three years of an agroforestry experiment. *Proceedings of the New Zealand Grassland Association* 56: 176-185.
- Pukkala, T. 1998. Multiple risks in multi-objective forest planning: integration and importance. *Forest Ecology and Management* 111:265–284.
- . 2006a. Puun hinta ja taloudellisesti optimaalinen hakkuun ajankohta, *Metsätieteen aikakauskirja* 1/2006: 33-48.
- . 2006b . The Use of Multi-Criteria Decision Analysis and Multi-Objective Optimisation in Forest Planning. In: Hasenauer H. (ed.). *Sustainable Forest Management– Growth Models for Europe*. Springer, Berlin– Heidelberg, p. 263–284.
- . 2009. Population-based methods in the optimisation of stand management. *Silva Fennica* 43 (2): 261–274
- & Heinonen, T. 2006. Optimising heuristic search in forest planning. *Nonlinear Analysis: Real World Applications* 7: 1284-1297.
- & Kangas, J., 1993. A heuristic optimisation method for forest planning and decision making. *Scandinavian Journal of Forest Research* 8: 560-570.
- & Kangas, J. 1996. A method for integrating risk and attitude toward risk into forest planning, *Forest Science* 42(2): 198-205.
- & Mabvurira, D. 1999. Optimising the management of *Eucalyptus grandis* plantations in Zimbabwe. In: Pukkala, T. & Eerikäinen, K. (ed.). *Growth and yield modelling of tree plantations in South and East Africa*. University of Joensuu. Faculty of Forestry. Research notes 97, p. 113-123.

- & Miina, J., 1997. A method for stochastic multiobjective optimisation of stand management. *Forest Ecology and Management* 98: 189–203.
- & Miina, J. 1998. Tree-selection algorithms for optimising thinnings with a distance-dependent growth model. *Canadian Journal of Forest Research* 28: 693-702.
- , Miina, J. & Rautiainen, O. 1998. Dependence of stand management on management goal, in: Pukkala, T. & Eerikäinen, K. (ed.). *Tree seedling production and management of plantation forest*. University of Joensuu. Faculty of Forestry. Research notes 68, p.165-180.
- , Miina, J. & Palahí, M. 2002. Thinning response and thinning bias in a young Scots pine stand. *Silva Fennica* 36(4): 827-840.
- , Lähde, E. & Laiho, O. 2010. Optimizing the structure and management of uneven-sized stands of Finland. *Forestry Advance Access published January 6, 2010*.
- Rautiainen, O., Pukkala, T. & Miina, J. 2000. Optimising the management of even-aged *Shorea robusta* stands in southern Nepal using individual tree growth models. *Forest Ecology and Management* 126: 417-429.
- Reed, W.J. 1984. The effect of risk of fire on the optimal rotation of a forest. *Journal of Environmental Economics and Management* 11: 180-190.
- & Errico, D. 1985. Assessing the long-run yield of a forest stand subject to the risk of fire. *Canadian Journal of Forest Research* 15 (4): 680-687.
- Reeves, C.R. 1993. *Modern heuristic techniques for combinatorial problems*. John Wiley & Sons, Inc. 1<sup>st</sup> ed. New York 320p.
- Rigueiro-Rodríguez, A., Mosquera-Losada, M., Romero-Franco, R., González-Hernández, M.P. & Villarino-Urtiaga, J.J. 2005. Silvopastoral systems as a forest fire prevention technique. In: Mosquera-Losada, M.R., McAdam, M.J. & Rigueiro-Rodríguez, A. (ed.). *Silvopastoralism and Sustainable Land Management*. CAB International. Wallingford. p. 380–387.
- , Fernández-Núñez, E., González-Hernández, P., McAdam, J.H. & Mosquera-Losada, M.R. 2009. Agroforestry Systems in Europe: Productive, Ecological and Social Perspectives. In: Rigueiro-Rodríguez, A., McAdam, J. & Mosquera-Losada, M.R. (ed.). *Agroforestry in Europe*. Springer. p. 43-65.
- Ritters, K., Brodie, J.D. & Hann, D. 1982. Dynamic programming for optimisation of timber production and grazing in ponderosa pine. *Forest Science* 28: 517-526.
- Rockafellar, R.T. & Wets, R. 1987. Scenarios and policy aggregation in optimisation under uncertainty, HASA Working Paper, WP-87-119.
- Rodríguez, R., Sánchez, F., Gorgoso, J., Castedo, F., López, C. & Gadow, K.v. 2002. Evaluating standard treatment options for *Pinus radiata* plantations in Galicia (north-western Spain). *Forestry* 75 (3): 273-284.
- Rodríguez Soalleiro, R. 1997. Crecimiento y producción de masa forestales regulares de *Pinus pinaster* Ait. en Galicia. Alternativas selvícolas posibles. Doctoral Thesis. (Universidad Politécnica, Madrid).
- Roise, J.P. 1986a. A nonlinear programming approach to stand optimisation. *Forest Science*. 32: 735-748.
- . 1986b. An approach for optimising residual diameter class distributions when thinning even-aged stands. *Forest Science* 32: 871-881.
- Rojo, A., Diéguez-Aranda, U., Rodríguez Soalleiro, R. & Gadow, K.v. 2005a. Modelling silvicultural and economic alternatives for Scots pine (*Pinus sylvestris* L.) plantations in north-western Spain. *Forestry* 78 (4): 385-401.

- , Perales, X., Sánchez-Rodríguez, F., Álvarez-González, J.G. & Gadow, K.v. 2005b. Stem taper functions for maritime pine (*Pinus pinaster* Ait) in Galicia (Northwestern Spain). *European Journal of Forest Research* 124: 177-186.
- Rosenbrock, H.H. 1960. An automatic method for finding the greatest or least value of a function. *The Computer Journal* 3: 175-184.
- Routledge, R.D. 1980. The effect of potential catastrophic mortality and others unpredictable events on optimal forest rotation policy. *Forest Science* 26 (3): 389-399.
- Schreuder, G. 1971. The simultaneous determination of optimal thinning schedules and rotation for an even-aged forest. *Forest Science*. 17: 333-339.
- Seijo, F. 2005. The politics on fire: Spanish forest policy and ritual resistance in Galicia, Spain. *Environmental Politics* 14 (3): 380-402.
- Sharrow, S.H. 1999. Silvopastoralism: competition and facilitation between trees, livestock and improved grass-clover pastures on temperate lands. In: Buck, L.E., Lassoie, J.P. & Fernández, E.C.M. (ed.) *Agroforestry in Sustainable Agricultural Systems*. Lewis, Boca Ratón, USA. p. 111-130.
- Sleavin, K. 1983. Searching the response surface of stand simulators under different objectives and constraints. DFSIM as a case of study. In: *Proceedings of the National Silviculture Workshop Economics of Silvicultural Investments*. USDA Forest Service. Timber Management Branch. Washington, D.C. p 106-128.
- Storn, R. & Price, K. 1997. Differential Evolution - a Simple and Efficient Heuristic for Global Optimisation over Continuous Spaces. *Journal of Global Optimisation* 11: 341-359.
- Szu, H. & Harley, R. 1986. Fast simulated annealing with Cauchy probability densities. Naval Research Laboratory. Washington. DC, Preprint.
- Taha, H.A. 1992. *Operations Research: An Introduction*. 5<sup>th</sup> edition. New York. MacMillan.
- Trasobares, A. & Pukkala, T. 2004. Optimising the management of uneven-aged *Pinus sylvestris* L. and *Pinus nigra* Arn. mixed stands in Catalonia, north-east Spain. *Annals of Forest Science* 61: 747-758.
- Thorsen, B.J. & Helles, F. 1998. Optimal stand management with endogenous risk of sudden destruction. *Forest Ecology and Management* 108: 287-299.
- Valsta, L.T. 1986. Mänty-rauduskoivusekametsikön hakkuuhjelman optimointi. Summary: Optimising thinning and rotation for mixed, even-aged pine-birch stands. *Folia Forestalia* 666. 23p.
- . 1990. A comparison of numerical methods for optimising even-aged stand management. *Canadian Journal of Forest Research* 20: 961-969.
- . 1992a. An optimisation model for Norway Spruce management based on individual-tree growth models. *Acta Forestalia Fennica* 232. 20 p.
- . 1992b. A scenario approach to stochastic anticipatory optimisation in stand management. *Forest Science* 38(2):430-447.
- . 1993. Stand management optimisation based on growth simulators. The Finnish Forest Research Institute. *Research Papers* 453: 51-81.
- & Brodie, J.D. 1985. An economic analysis of hardwood treatment in loblolly pine plantations—a whole rotation dynamic programming approach. In: Dress, P.E. & Field, R.C. (ed.). *The 1985 symposium on system analysis in forest resources*. Georgia Center for Continuing Education, Athens, p. 201-214
- Vanclay, J.K. 1994. *Modelling forest growth and yield. Applications to mixed tropical forests*. CAB International, Wallingford, UK.

- Vega, J.A. 2001. Efectos del fuego prescrito sobre el suelo en pinares de *Pinus pinaster* Ait. de Galicia. PhD Thesis. Universidad Politécnica de Madrid, ETSIM, Madrid.
- Wang, P.P. & Chen, D.S. 1996. Continuous Optimisation by a Variant of Simulated Annealing. *Computational Optimisation and Applications* 6: 59-71.
- White, W.A. 1988. A dynamic programming approach to optimal forest stand management regimes in coastal British Columbia. PhD thesis. Simon Fraser University
- Wikström, P. 2001. Effect of decision variable definition and data aggregation on a search process applied to a single-tree simulator. *Canadian Journal of Forest Research* 31: 1057-1066.
- & Eriksson, L.O. 2000. Solving the stand management problem under biodiversity-related considerations. *Forest Ecology and Management* 126: 361-376.
- Xunta de Galicia. 1992. Plan Forestal de Galicia. Consellería de Agricultura, Gandería e Montes, Santiago de Compostela.
- . 2001. O monte galego en cifras, Dirección Xeral de Montes e Medio Ambiente Natural, Santiago de Compostela.
- . 2006. Anuario de Estatística Agraria 2003, Consellería de Medio Rural, Santiago de Compostela.
- Yoshimoto, Y. & Marušák, R. 2007. Evaluation of carbon sequestration and thinning regimes within the optimisation framework for forest stand management. *European Journal of Forest Research* 126 (2): 315-329.
- , Paredes, V.G.L. & Brodie, J.D. 1988. Efficient optimisation of an individual tree growth model. In: Kent, B.M. & Davis, L.S. (ed). The 1988 symposium on systems analysis in forest resources. USDA Forest Service. General Technical Report RM-161, p. 154-162
- , Haight, R.G. & Brodie, J.D. 1990. A Comparison of the Pattern Search Algorithm and the Modified PATH Algorithm for Optimising an Individual Tree Model. *Forest Science* 36(2): 394-412.
- Zeng, R.T., Ngo, N.Q., Shum, P., Tjin, S.C. & Binh, L.N. 2005. A staged continuous tabu search algorithm for the global optimisation and its application to the design of fiber bragg gratings. *Computational optimisation and applications* 30: 319-335.