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A decision support system for optimizing. The conversion of forest plantations to continuos cover forest stands

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Abstract

Continuous cover forestry (CCF) management is being increasingly popular all around the globe. Its popularity rises from the ecological and silvicultural advantages for some species, specially those with medium to low growth rates compared to traditional even-aged management. In addition, CCF offers more environmental services than traditional even-aged management, whose demand is also every day higher. The Decision Support System (DSS) described in this paper optimizes a thinning schedule for converting a forest plantation stand to CCF. The system integrates a transition matrix growth and yield model for Pinus pinaster Ait. with a non linear optimization routine which maximizes net present benefits derived from thinning the forest stand as well as benefits derived from additional environmental services which could not be generated through a traditional even-aged management. The system can be used to analyze different stand initial conditions, market and environmental services interrelationships as well as conversion periods. This last feature can be used to optimize simultaneously the harvest schedule and the conversion period to CCF. Optimization constraints, growth model limitations and additional simulations and DDS's sensitivities are also described in the paper.

KEYWORDS: Non linear optimization, conversion, CCF, maritime pine, thinning scheduling

Resumen

El Manejo de Cobertura Forestal Continua (CCF) se ha hecho más popular alrededor del globo. Su popularidad surge de sus ventajas ecológicas y silvícolas para algunas especies, particularmente aquellas con tasas de crecimiento de bajas a medias, comparada con el manejo coetáneo tradicional. Adicionalmente, CCF ofrece más servicios ambientales que el tradicional manejo coetáneo, cuya demanda es cada día más alta. El Sistema de Apoyo a la Toma de Decisiones descrito en este documento optimiza una secuela de aclareo para convertir una plantación forestal a CCF. El sistema integra un modelo de crecimiento y rendimiento de matriz de transición para Pinus pinaster Ait. con una rutina de optimización no lineal que maximiza los beneficios actualizados derivados de aclarar el rodal, así como los beneficios derivados de servicios ambientales adicionales que podrían no ser generados a través del manejo coetáneo tradicional. El sistema puede ser usado para analizar diferentes condiciones iniciales del rodal, interrelaciones entre servicios ambientales y mercado, así como periodos de conversión. Esta última cualidad puede ser usada para optimizar simultáneamente el programa de cosecha y el periodo de conversión a CCF. Las restricciones de optimización, limitaciones del modelo de crecimiento, simulaciones adicionales y sensibilidades del DSS también son descritas en el documento.

PALABRAS CLAVE: Optimización no lineal, conversión, CCF, pino marino, secuela de aclareo.

Introduction

Currently two types of sustainable forest management can be distinguished: Rotation Forest Management (RFM) and Continuous Cover Forestry (CCF) systems. The RFM systems are characterized by a regeneration period (natural or through re-planting) followed by a succession of thinnings and a final clear-cut when the forest has reached the so called rotation age. CCF systems are characterized by shorter periods of selective harvesting (cutting cycles), the stand age is undefined and forest development does not follow a cyclic harvest-and-regeneration pattern (Gadow, 2001). In general, for most of the commercial species CCF management is relatively less economically efficient to produce timber since harvesting costs per unit of volume are greater (Kluender et al., 1998), and residual trees and high-grading could be damaged during logging operations (Stokes et al., 1993).

On the other hand, selective harvesting might be financially superior to RFM when rotation ages are too long or where landowners face high risk conditions or discount rates (Chang, 1990; Redmond and Greenhalgh, 1990). In addition, CCF management can be more suitable when the land ownership dimensions restraint an efficient RFM practice. Experience in Western Europe has shown that the CCF management can be applied on a large scale as well as on very small forest properties comprising only a few hectares. This is however, true only in areas with suitable growing conditions.

From the silvicultural perspective, CCF is seen as a mean to reduce the impact of clear cutting and the associated changes that this practice produces in forest landscapes and habitats (Mason et al., 1999). Moreover, these systems promote a very different kind of forest development and imply different cultural effects from all other management systems, namely: i) spontaneous renewal (i.e. without direct intervention) under cover; ii) form control by shading, because shade is a substitute for lateral competition and ensures that good tree form develops and that a fine branch structure is retained; iii) early individualisation of trees from the pole stage, without lateral competition leading to stem wise production (Schütz, 2001).

However, the main attraction of continuous cover forestry lies on the belief that this approach is more suited than RFM within a multi-purpose forestry framework where cultural, environmental, recreational, aesthetic and other objectives are as important as timber production. This feature becomes more attractive in a world where timber market is already adding a premium to those products derived from environmentally friendly forestry systems (eco-labelling). Hence, in recent years government agencies and even private non-industrial forest owners are increasingly interested in CCF management (Hill 1992, Gadow and Puumalainen, 2000) in contrast to the RFM.

This change in perspective of forestry systems is promoting not only a change in the management of natural forests but also a change in the management of some forest plantations. This transformation is currently occurring in those forest areas with low competitiveness in terms of timber yield or those located in regions where public society is willing to pay more money for the environmental services than for the timber yields (Gadow and Puumalainen, 2000). The transformation of even-aged stands to uneven-aged stands is an issue of changing from a structure that is very simple, homogeneous, and relatively well understood to one which is highly variable and with many complex interactions (O'Hara, 2001). The optimal conversion strategy problem for even-aged stands relates to the cutting schedule, which will take a particular stand form its current state to some desired optimal steady state (Gove and Fairweather, 1992).

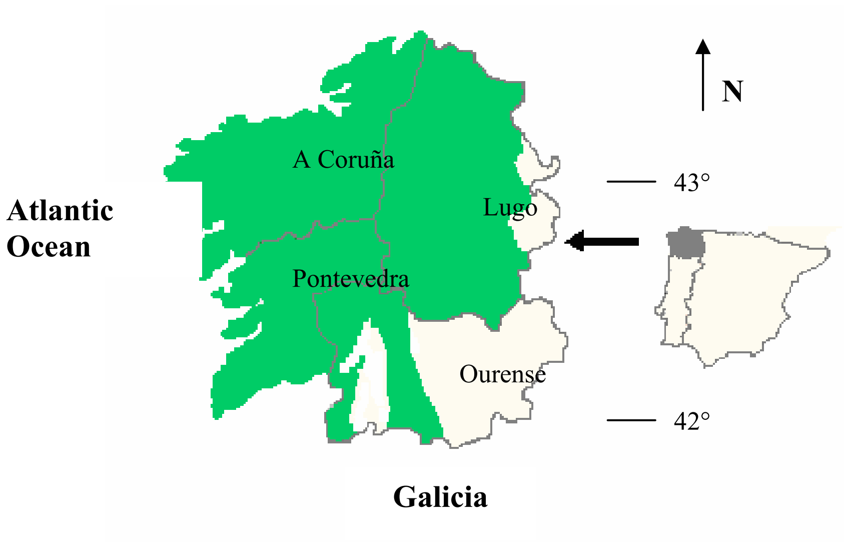
The optimization of selective harvests under an uneven-aged management system has been an old topic studied by several authors (Hool, 1966; Adams and Ek, 1974, Hartman, 1976; Buongiorno and Michie, 1980; Hyde, 1980; Chang, 1981, 1983; McConnell et al., 1983; Michie, 1985; Newman et al., 1985; Bare and Opalach, 1987; Haight and Getz, 1987; Haight, 1990a, 1990b; Haight and Monserud, 1990a, 1990b; Hotvedt and Ward, 1990; Gove and Fairweather, 1992; Anderson and Bare, 1994; Gan et al., 2001); however, the study of financial consequences of transforming even-aged stands to uneven-aged stands has been studied until recently (Buongiorno, 2001; Knocke and Plusczyk, 2001) and only few authors have approached the problem of optimizing the conversion from even to uneven-aged management (Hanewinkel, 2001; Hanewinkel and Pretzsch, 2000).

This paper describes a Decision Support System (DSS) developed to optimize conversion paths from even to uneven-aged stands of maritime pine (Pinus pinaster Ait.) growing in Galicia (North western Spain). The DSS can be applied under different stand structure, site and economical initial conditions and can be adjusted to different ending conditions on stand distribution and conversion period, as well as some additional constraints on the thinning scheduling along the conversion period. The paper is divided as follows. Next section shows the decision problem and emphasizes the need for this tool. Section three shows the structure of the DSS with a brief description of its components and the fourth section shows some statistics about its performance and limitations. Finally last section shows some simulations and conclusions about the system and its use.

Decision problem

Maritime pine (*Pinus pinaster* Ait.) is a natural species growing in Galicia mainly along the sandy coastal areas (Figure 1). The expansion of this species in the coastal areas and its naturalization was due to the reforestations carried out by the landowners from the 18th century, but the most important factor promoting its expansion were the reforestation programs developed by the *Forest Administration on Communal Lands* from 1940 to 1970, especially in the inland areas. Nowadays, these plantations cover close to 450,000 ha of pure maritime pine stands which are managed according to the *RFM* system.

FIGURE 1. DISTRIBUTION OF MARITIME PINE IN GALICIA

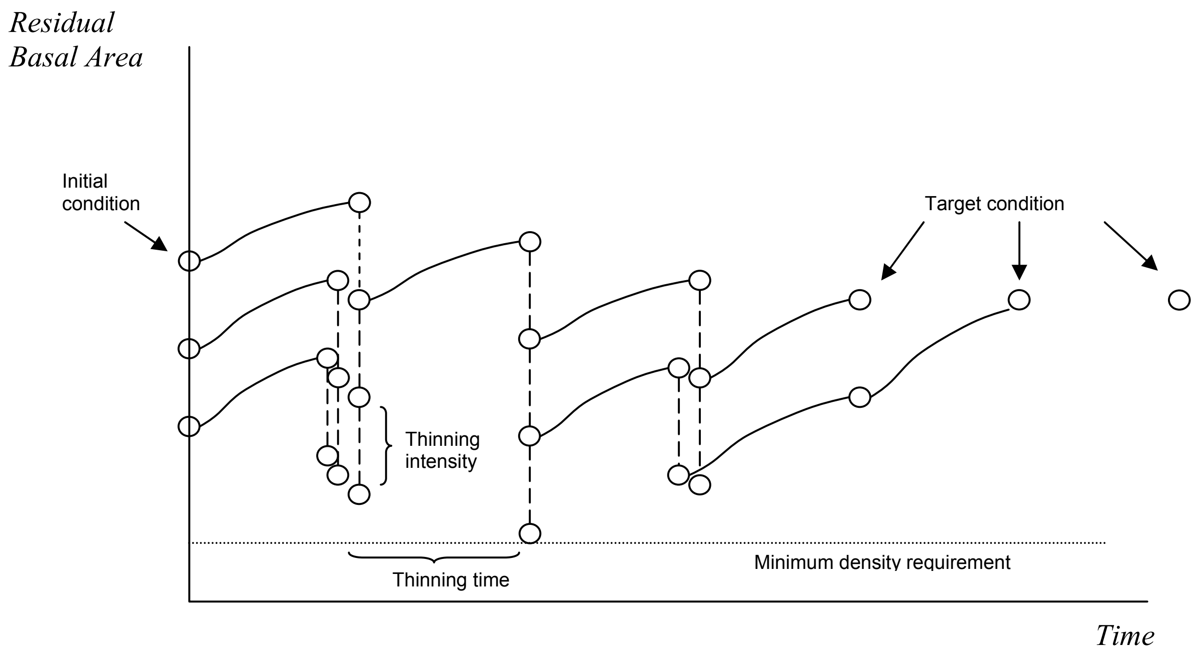


A special type of uneven-aged pine forest has developed in Galicia as a result of a low intensity *RFM* system. These forests are normally small non-industrial private forest, covering less than 1 ha on average. The management normally involves a kind of selective thinning from above, where only the best and the largest trees are harvested whenever cash income is required by owners. Residual trees are usually low quality and with low growth rate (Molina, 1988), yielding an uneven-aged forest usually under stocked and in many cases lacking commercially valuable trees (Romero, 1992). Hence, conversion of forest plantation has already been taking place in most parts of the region.

The potential for active management of these forest lands has not been explored completely. Guidelines to improve current selective harvesting practices as well as to define conversion patterns to *CCF* systems become important and necessary along the region. Hence the development of a tool that can provide easily these guidelines with a relatively high level of precision and in short time becomes a strategic support tool.

The conversion problem can be formulated as the problem to define an optimal path of thinnings starting from an initial condition (presumably an even-aged stand) to an ending goal condition (not a clear cut) within a given conversion period. Figure 2 shows a discrete example of the problem where many alternatives are feasible.

FIGURE 2. DISCRETE REPRESENTATION OF THE CONVERSION PROBLEM.



As can be observed, the problem can be formulated as a thinning optimization problem. This problem has been solved through various methods such as marginal analysis (Chappelle and Nelson, 1964), dynamic programming (Amidon and Akin, 1968), Nonlinear programming (Roise, 1986), special numerical methods (Valsta, 1990) and even neural networks (Chung and Roise, 1993), although the most used one has been dynamic programming.

Nonlinear programming was chosen as the tool to optimize the problem, since it offers a continuous variation on the state variables without the need to force the problem to be a state discrete problem and to explicitly define a thinning rule. In addition, it provides additional information about the relative cost (opportunity cost) of important constraints such as the minimum density requirements as well as the final conditions. The problem was formulated as:

$$max \sum_{t=1}^{T} 1 \Big/ (1+r)^t \sum_{i=1}^{n} p_i h_{it} \qquad (1)$$

st

(1.1) $NB_{it+1} = \beta_0 + \beta_1 NA_t + \beta_2 NA_{it} + \beta_3 NA_{it} BA_t + \beta_4 NA_{i-1t} BA_t + \beta_5 NA_{i-1t} BA_t \quad \forall i = 1,2,..,n \quad \forall t = 1,2,..,T-1$

(1.2) $NA_{it} = NB_{it} - h_{it} \quad \forall i = 1,2,..,n \quad \forall t = 1,2,..,T$

(1.3) $\sum_{i=1}^{n} NA_{it} = NA_t \quad \forall t = 1,2,..,T$

(1.4) $\sum_{i=1}^{n} k_i NA_{it} = BA_t \quad \forall t = 1,2,...,T$

(1.5) $\sum_{i=1}^{n} v_i h_{it} = V_t \quad \forall t = 1,2,...,T$

(1.6) $BA_t \geq \overline{BA_t} \quad \forall t = 1,2,...,T-1$

(1.7) $V_t \geq \overline{V_t} \quad \forall t = 1,2,...,T$

(1.8) $NB_{i0} = \overline{NB_{i0}} \quad \forall i = 1,2,...,n$

(1.9) $NA_{iT} = \overline{NA_{iT}} \quad \forall i = 1,2,...,n$

(1.10) $h_{it}, NB_{it}, NB_{it}, NA_t, BA_t \geq 0 \quad \forall i = 1,2,...,n \quad \forall t = 1,2,...,T$

where the objective function is to maximize the discounted value (at interest rate *r*) of the net returns (*p* represent the net price; *i.e.* unit price minus unit cost) derived from harvesting *h* trees in the *i-th* $(\forall i = 1,2,..n)$ diameter class during period *t* (h_{it}). The first set of constraints corresponds to the growth model. The model is a typical matrix stand growth model which predicts the number of trees before thinning for the *i-th* diameter class in period *t+1* (NB_{it+1}), from total number of trees after thinning in period *t* (NA_t), number of trees after thinning for the *i-th* diameter class in period *t* (NA_{it}) and basal area after thinning in period *t* (BA_t). More details about the data, methods used to fit the parameters as well as model limitations are described in Sánchez and Rodríguez (2002).

The second set of constraints represents the equilibrium constraints (*i.e.* residual trees are the result of standing trees before thinning minus harvested trees). The third, fourth and fifth sets of constraints represent respectively the accounting constraints for total number of trees (NA_t), basal area (BA_t) after thinning and harvested volume (V_t) at period t. The sixth and seventh sets of constraints represent minimum requirements of residual basal area and minimum harvest volume per entry at each period (if any[1]). The eighth and ninth sets of constraints represent initial and final stand table requirements. This last set of constraints was added in order to use recommendations on optimal residual growing stock and cutting cycles derived in Sanchez *et al.* (2003). Finally, the last set of constraints corresponds to the no negativity constraints. As can be observed the problem is nonlinear just because of the matrix growth model, otherwise the formulation can be completely linear.

A solution to this problem provides an optimal thinning schedule (timing and intensity) that maximizes discounted net returns over the conversion period. Thinning type can also be optimized by constraining harvest on certain diameter classes to be zero.

Decision support system structure

The *DSS* was designed to provide a thinning schedule given a user's provided initial stand condition and a flexible combination of ending conditions. The system has five interrelated main components as described in figure 3. Each one of these components was built as an independent subprogram and called by the INTERFACE. The characteristics of each one of the components are as follows:

Interface

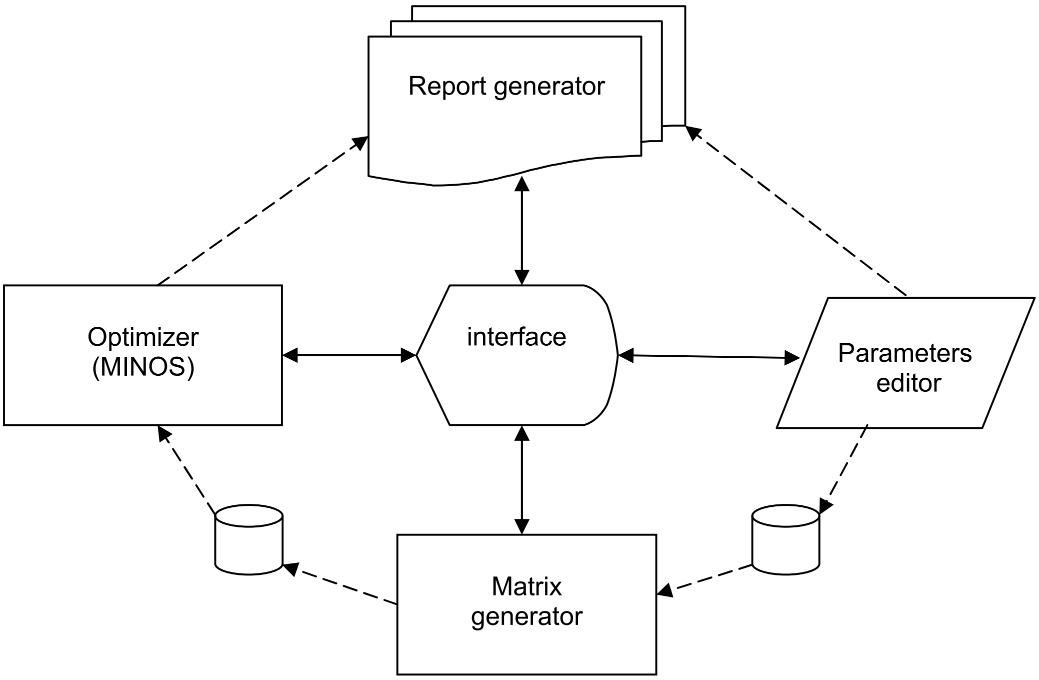
It was designed to call up all other subroutines. It organizes the sequence of calls to the other subprograms as well as the follow up of each one of them. It is written in Visual Basic and writes down all data ASCII files.

Parameters editor

[1] This constraint set is associated with a turn on and off constraint set so fixed entry costs can be added whenever a harvest is conducted in a given period.

This editor is a subroutine within the INTERFACE. It provides all the call up menus to change initial conditions and additional parameters. The main editor screens are:

FIGURE 3. DECISION SUPPORT SYSTEM STRUCTURE



Economic conditions: Allows edition of variables such as interest rate (%), log prices (€/m3), grading system (range of diameter classes), variable thinning costs (€/m3), fixed entry cost (€/ha) and objective function value (Present Net Worth or Land Expectation Value).

Conversion parameters: Allows edition of variables such as cutting cycle (years), conversion period (years), goal distribution structure (stand table) or goal basal area (m2/ha), minimum entry harvest (m3/ha/period) and minimum basal area constraints (m2/ha/period).
Initial conditions: Allows edition of the initial stand table as well as the selection of site class and volume table.

In all cases, entries are checked before processed to satisfy growth model and optimization requirements and limitations.

Matrix generator

This matrix generator writes down the optimization problem in MPS format as described in problem (1) above. Such a problem can be generalized in matrix notation and subdivided as shown in problem (2).

$$\begin{aligned}&\max \quad \mathbf{c'x}\\&s.t.\\&\mathbf{f(y)} + \mathbf{A_1x} = \mathbf{b_1}\\&\mathbf{A_2y} + \mathbf{A_3x} = \mathbf{b_2}\\&l \le \begin{bmatrix}\mathbf{x}\\\mathbf{y}\end{bmatrix} \le u\end{aligned} \qquad (2)$$

where x represents a vector of linear variables, y represents the vector of non linear variables2, f(y) is a vector of functions (growth model) and the rest of sub matrices are either linear parts of a constraint (A1x) or sets of linear constraints. The matrix generator only generates matrices A1, A2 and A3 as well as the RHS values (b1 and b2) and the bounds on the decision variables (l and u) if required. The nonlinear parts of the constraints are formulated inside the optimization routines as well as the gradients of such functions which are used during the optimization process.

The mathematical programming formulation considers all the requirements defined by the user through the parameter's editor. Any inconsistence on the formulation is checked before the MPS file is closed. In addition, this routine estimates problem parameters such as number of linear and nonlinear variables and constraints, optimization parameters such as maximum number of iterations as well as additional characteristics of the problem according to the selected constraint sets. This information is used to write the SPECIFICATION (SPC) file used for MINOS optimization routines.

Optimizer

This part of the system integrates the set of optimization routines from the MINOS optimization system (Murtagh and Saunders, 1995). MINOS uses the projected augmented Lagrangian algorithm (Robinson, 1972) with all the features to specially treat linear constraints and bounds; however nonlinear constraints may not be satisfied until an optimal point is reached. Hence searching for an optimal solution might involve several changes in the optimization parameters. Therefore, each time MINOS reports and END of RUN, the INTERFACE checks for the details of the solution reached. If an optimal solution is not attained, then changes in the optimization parameters

[2] The nonlinear variables defined in problem (1) are: total number of trees after thinning in period t (NA_t), number of trees after thinning for the *i-th* diameter class in period t (NA_{it}) and basal area after thinning in period t (BA_t).

are performed and MINOS is called again. Such changes involve modifications in the SPECIFICATION file and writing an old basis. Sometimes these changes are not enough and small bounds must be allowed in the nonlinear constraints (these bounds range from -0.5 to 0.5 trees per hectare in diameter classes lower than 35 cm) in order to obtain a suboptimal solution.

Report generator

This routine organizes the MINOS output so it can be easily read without knowing the meaning of each variable. The output shows the number of trees before and after thinning at each one of the periods. An example of the output is shown in figure 4.

The system is flexible enough to test the effect of different economic and silvicultural parameters. Hence good practical recommendation can be derived to manage maritime pine stands with a high level of confidence. Sensitivity analyses may include variations in interest rate, price and cost information, cutting cycle, conversion period, site index class, goal stand table, minimum basal area or entry volume requirements as well as any combination of initial conditions, even regular diameter distributions.

FIGURE 4. EXAMPLE OF THE DSS OUTPUT.

STAND TABLE BEFORE THINNING IN PERIOD

DIAM CLASS	0	1	2	3	4	5
15	55.30	40.35	29.06	27.73	27.57	26.79
20	40.20	50.32	46.85	28.13	25.75	19.91
25	34.50	37.13	46.45	50.79	26.06	23.78
30	33.70	0.76	0.10	0.01	11.13	0.00
35	27.30	2.70	0.60	0.06	0.00	5.15
40	22.90	9.56	2.41	0.40	0.02	0.00
45	10.20	0.00	5.38	1.95	0.18	0.00
50	6.60	0.00	0.00	6.19	1.20	0.00
55	3.80	0.00	0.00	0.00	7.30	0.00
60+	3.60	6.30	6.34	6.38	6.42	15.14
Basal Area B T	16.66	7.41	7.28	7.25	7.18	7.04
Num Trees B T	238.10	147.12	137.19	121.63	105.64	90.77

STAND TABLE AFTER THINNING IN PERIOD

DIAM CLASS	0	1	2	3	4	5
15	55.30	40.35	29.06	27.73	21.14	0.00
20	40.20	50.32	46.85	28.13	25.75	19.91
25	0.86	0.12	0.01	4.94	0.00	0.00
30	3.20	0.76	0.10	0.01	0.00	0.00
35	8.89	2.70	0.60	0.06	0.00	0.99
40	0.01	4.82	2.41	0.40	0.02	0.00
45	0.05	0.00	5.38	1.95	0.18	0.00
50	0.37	0.00	0.00	6.19	1.20	0.00
55	2.25	0.00	0.00	0.00	7.30	0.00
60+	3.60	6.30	6.34	6.38	6.42	15.14
Basal Area A T	5.00	5.00	5.00	5.00	5.00	5.00
Num Trees A T	119.74	110.37	95.74	80.77	67.01	41.04

HARVEST VOLUME (Cub. mtrs.)	94.48576	17.28234	15.40126	15.20586	15.09851	14.01679
Present Net Worth (Euros)	12551.337					

FIGURE 5. EXAMPLE OF A SENSITIVITY ANALYSIS: VARIATION IN THE CONVERSION PERIOD.

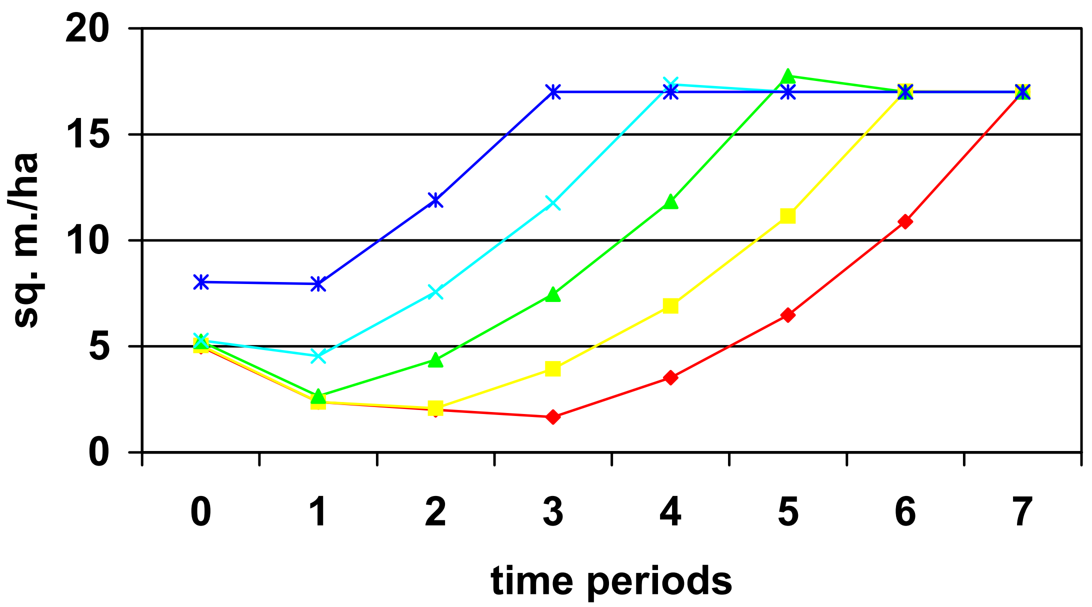


Figure 5 shows an example of sensitivity analysis where different residual basal areas obtained from thinning schedules constrained to meet final conditions (residual basal area = 17 m2/ha) at different time periods are plotted. Observe the expected trend of the residual basal area where the longer the conversion period the heavier the thinnings at the beginning of the conversion period in order to use as much as possible the surplus high value timber. Similar trends are derived even when no interest rate is considered or when initial stand density conditions are low.

System performance and limitations.

The problem formulation is totally referred to maritime pine. Hence, any change in species must involve a change in the parameters, perhaps the structure of the growth model as well as the optimization routines. Problem size is limited only by the memory available in the MINOS executable program since all routines are independent. Compilation of MINOS subroutines with a 32-bit Windows compiler takes approximately 918 KB and has enough memory to solve relatively large size problems (15 periods and all sets of constraints). To solve larger problems MINOS must be reconfigured and compiled again. The problem used as example in the last section is a seven periods problem which has around 264 variables (only 77 are non linear) and close to 200 constraints (only 77 are non linear); computing time for the solution of this problem ranges from 0.5-1.7 minutes (on a personal computer 1.2 GHz.) depending on the set of constraints selected.

Some of the technical limitations of the system are:

1. *Unfeasible solutions might be obtained because nonlinear constraints are not met. This problem rises when there are many constraints on the minimum basal area requirements (basal area is a non linear variable) close to the expected basal area. In these cases small bounds on the predicted number of trees must be allowed in order to reach a solution.*

2. *Growth and yield predictions out of the allowable range can not be controlled during the optimization process.*

3. *Simultaneous optimization of thinning schedule and conversion time is not available. Optimal conversion time must be estimated by simulating different conversion periods.*

4. *Marginal information such as reduced costs or dual variables values is not available in the main output. They must be checked in the MINOS output file.*

5. *Some desirable constraints like type of thinning (from below or from above) must be directly written in the MPS file either by setting the harvest of some diameter classes equal to zero or through a pricing mechanism where the value of such a harvest is less than or equal to zero.*

Evidently the practical use of this system must involve additional expert opinion about the dimension of constraints that can be used as well as their ranges of allowable variation. Future work on this system might include an expert interpretation of the output as well as practical recommendations on the way to handle the management options suggested by the system.

Conclusions

Integration of a matrix growth and yield model with an optimization tool has proven to be a handy tool to derive forest management recommendations for maritime pine stands growing in Galicia, Spain. The computer tool is especially useful to define conversion paths from forest plantations to CCF systems, although it can be used to optimize current stand conditions given a goal diameter distribution or density (measured as basal area) regardless the type of diameter distribution. Additional work must include expert's information as well alternative ways of valuing additional benefits derived from CCF systems as opposed to RFM, such as the production of environmental services, financial security for land owners and larger flexibility for the space and time constraints imposed by the RFM systems.

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