Designing decision support tools for Mediterranean forest ecosystems management: a case study in Portugal

André O. Falcão, José G. Borges

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Designing decision support tools for Mediterranean forest ecosystems management: a case study in Portugal

André O. FALCÃO[a]*, José G. BORGES[b]

[a] Departamento de Informática, Edifício C6, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, 1700 Lisboa, Portugal
[b] Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

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Abstract – The effectiveness of Mediterranean forest ecosystem management calls for the conceptualization and implementation of adequate decision support tools. The proposed decision support system encompasses a management information system, a prescription simulator, a constraint generator and a set of management models designed to solve decision problems. Emphasis is on the architecture of the prescription simulator and its linkage to the three other modules, as well as on methods for reporting and visualizing solutions. Results are discussed for a real world test case – Serra de Grândola, a management area with about 18 600 ha comprising 860 cork oak (*Quercus suber* L.) land units. Cork oak silviculture adds complexity to the traditional forest management problem. Results show that the devised system is able to address effectively the integration of ecosystem data, silviculture, growth-and-yield and management models. They further suggest that the proposed system architecture may help address the complexity of Mediterranean ecosystem management problems.

forest management / Mediterranean ecosystems / prescription simulation / decision support systems / cork oak

Résumé – Concevoir des outils de support de décision pour la gestion des écosystèmes forestiers méditerranéens : une étude de cas au Portugal. L'efficacité de gestion de l'écosystème méditerranéen requiert la conception et l'implantation d'outils de support à la décision adaptés. Le système d'aide à la décision proposé comprend un système de gestion de l'information, un simulateur de prescriptions, un générateur de contraintes et un ensemble de modèles de gestion conçus pour la résolution de problèmes de décision. L'accent est mis sur la description de l'architecture du simulateur de prescriptions et de ses liens avec les trois autres modules. Sont également décrites les méthodes de présentation et de visualisation de scénarios alternatifs. Les résultats obtenus sur un cas réel, la Serra de Grândola, située au sud du Portugal (qui correspond à la gestion d'une superficie de 18 600 ha dont 860 unités de gestion de chêne liège (*Quercus suber* L.)) sont discutés. Le chêne liège est une espèce dont la spécificité engendre une gestion complexe. Les résultats montrent que le système est capable de résoudre avec succès l'intégration des données, des modèles de sylviculture, croissance et développement ainsi que des modèles de gestion. L'analyse des résultats suggère que le système proposé permet de traiter la complexité de gestion de l'écosystème méditerranéen.

gestion forestière / écosystème méditerranéen / simulation / système de décison / chêne liège

1. INTRODUCTION

Management alternatives, activities or prescriptions consist of a schedule of cultural treatments for a specific management area within a given planning horizon. According to Davis et al. [10] developing, evaluating and applying prescriptions is the central activity of professional forestry. Ecosystem management objectives determine the number and the complexity of prescriptions. As the diversity of objectives increases, demand grows for comprehensive natural resources inventories and for new land classification schemes with more detailed, land-unit prescriptions [2]. Automated simulation of prescriptions is thus a key functionality of an ecosystem management decision support system [1].

A decision support system (DSS) is an interactive and flexible set of computer-based tools that integrate the insights of the decision maker with information processing capabilities in order to improve the quality of decision-making [19, 47, 48]. The prescription simulator is a key component of an ecosystem management decision support system (EMDSS), as it allows the automated generation of all management options available to the decision maker. Other modules of the system include a management information system (MIS) that stores both spatial and aspatial data from Mediterranean ecosystems to provide

* Corresponding author: afalcao@di.fc.ul.pt

information appropriate for planning, and a set of models to address specific ecosystem management problems. [5, 8, 20, 23, 25, 34, 38, 39, 41, 45] present examples or applications of prescription simulators. Nabuurs and Paivinen [29] further compare several decision support tools for large-scale forestry modeling. [31–33, 46] report the development of decision support modules for some Mediterranean ecosystems.

In this paper we present a cork oak prescription simulator and we further discuss a common framework for conceptualizing and implementing decision support tools for Mediterranean forest ecosystem management. Research on the basic components of decision support tools specific to the Mediterranean region is discussed. Both the specificity of Mediterranean prescription simulation and its integration within an EMDSS are emphasized. The description of a scalable and interactive EMDSS will address (a) database interaction; (b) linkage to growth and yield models; (c) interactive silviculture modeling; and (d) linkage to management models – mathematical representations of ecosystem management scheduling problems. The proposed system architecture is implemented and an application is presented.

Dry and hot summers and rainy winters characterize the Mediterranean ecosystem climate and contribute to fire risk and ecosystem fragility [40]. Although this biome represents less than 2% of the continental area, it encompasses about 20% of the world's floristic richness [26, 35]. This biodiversity is reflected in Mediterranean human-forest ecosystems with contrasting silviculture models. Cork oak (*Quercus suber* L.) is a characteristic species of the Mediterranean basin and its main product (cork) is one of the most important assets in the Portuguese forest sector. According to the Portuguese Forest Inventory [11], it represents about 22% of the forest cover in Portugal, totalling about 713 000 ha. Further, the specificity of cork oak management turns out to be a challenge for natural resource management modeling and information systems development. Serra de Grândola, a cork oak management area located in Southern Portugal was thus used to test the proposed EMDSS. Its ability for automating the simulation of a large number of prescriptions for cork oak stands was assessed. The EMDSS capabilities to help decision-makers evaluate and select simulated prescriptions and to provide information for scenario analysis were assessed by solving three cork oak ecosystem management example problems.

2. MATERIALS AND METHODS

2.1. The test problem

Serra de Grândola, a management area with about 18 600 ha comprising 860 cork oak land units located in Southern Portugal was used to test the proposed EMDSS. The ecological importance of Serra de Grândola is highlighted by its classification as a CORINE Biotope (C-108) and its integration in the set of sites proposed to be part of the EU network Natura 2000. The main cover types are dominated by cork oak and umbrella pines (*Pinus pinea* L.). These species may occur in pure or mixed composition, and in even-aged or uneven aged stands [37]. Spacings also vary. Higher densities are generally found at higher altitudes. In the past, land use has led to erosion and soils are generally thin. Agro-forestry activities, namely range management, are conducted in most stands [37].

The 'montado' ecosystem is generally managed as an agro-forestry system. Most stands are uneven-aged and have densities of 70 to 150 trees per ha when mature. The first debarking cannot take place until the tree perimeter at breast height reaches 70 cm. Thus cork oak debarking usually starts at the age of 30 years. Current legislation further prescribes a minimum tree debarking cycle of 9 years. A land unit debarking cycle usually ranges from 1 to 9 years as trees in the same uneven-aged stand often distribute unevenly between "years since debarking" classes. In some cases, a land unit debarking period may encompass more than one year, i.e., a debarking entry in a land unit may last for more than one year. Thinnings occur in debarking years and remove recently debarked trees. Trees may live up to about 150 years or more. Cork oak ecosystem management modeling is a particularly complex task, for both tree growth and cork production must be taken into account.

A local development organization and a forest landowners association set up the Mediterranean ecosystem management problem for decision-making at Serra de Grândola. These non-governmental organizations (NGO) provide both technical and management assistance to landowners and information to develop policy instruments for sustainable practices to central and local government agencies. The intelligence phase of decision analysis concluded that natural resources inventory and assessment in both areas were priorities [37]. Further, it pointed out the importance of estimating cork production potential in Serra de Grândola over short to medium terms. Previous efforts to model cork oak ecosystem management used either classical methods (e.g. [7]) or assignment models (e.g. [2]). In order to comply with the NGO information requirements and to test the proposed architecture for a prescription simulator and its integration within an EMDSS, the system is used initially to simulate a set of management prescriptions and the generated simulated information is then used by a set of management models. These, will define the appropriate management plan to each land unit selected, according to a set of user specifications.

2.2. Architecture requirements for a prescription simulator for Mediterranean forests

An automated prescription simulator is a key module of an EMDSS. Its design should take into account both efficiency and effectiveness issues. First, the simulator should be able to retrieve data from several ecosystem types stored in MIS. Second, the system should be fully scalable, i.e. capable of dealing with different cover types and growth models without compromising ease and efficiency of use, thus simulating prescriptions according to user-defined silviculture models. Finally, the output of every prescription simulation should be in a format compatible with alternative management models (e.g. linear programming matrix format) so that the system may be used to address different Mediterranean ecosystem management problems.

2.2.1. Linkage to a management information system

A MIS within a typical EMDSS stores physical, vegetative, development and administrative attributes of land units (e.g. forest stands). It also stores topological data to allow spatial recognition and analysis of land units within the landscape, thus integrating Geographic Information System (GIS) functionalities. Further, it stores financial and economic data. The linkage between a MIS and a prescription simulator should take into account efficiency and effectiveness considerations. First, it should provide easy access to a set of spatial and aspatial data from the MIS so that the user may select the ecosystem area where decisions are to be made. The system should thus enable the user to select land units in the ecosystem area either by querying the database for specific attributes (e.g. region, management area name, cover type, major forest use, species, site index, date of last inventory) or by direct

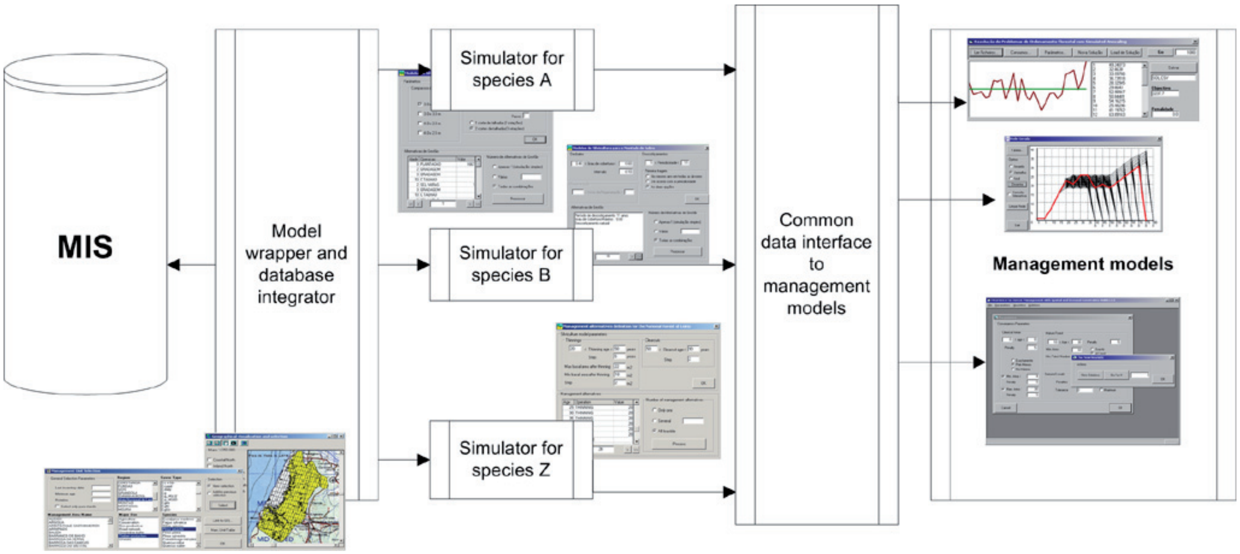

Figure 1. Integration of decision support tools within the EMDSS.

selection through a GIS. The latter allows the user to select land units based solely on geographical and topological characteristics (e.g. location, adjacency or proximity).

Second, the system must provide a capability for interpreting data from a land unit. This interpretation is a prerequisite for selecting and applying an adequate production or conservation function (e.g. growth and yield models, wildlife and habitat models) for both simulating prescriptions and computing resource flows. For example, some models may need site index and stand age as inputs while others may require individual tree information and specific ecological data. Third, an additional capability for linking financial and economic data, i.e. unit costs and prices, to cultural treatments is key for estimating revenue and cost flows associated with each prescription in each land unit. This capability ensures that thinnings, harvests, fertilizations and other cultural treatments' economic returns are computed based on the characteristics of the land units where they occur. The development of the proposed Mediterranean prescription simulator addressed these three major MIS linkage issues. It is a standalone module that can link to a MIS with the required data model. Currently, it accesses a MIS [27, [37] that stores data from the most important Portuguese forest ecosystem types. Ecosystem areas encompass over 85 000 ha and are classified into over 12 000 land units. Access to ecosystem data is performed through a set of internal queries that organize the information needed by the growth models within the prescription simulator.

2.2.2. Prescription simulation and system adaptability

The success of prescription simulation depends on the availability of models to project conditions and outcomes in each land unit over time [10]. Growth and wildlife models are constantly being changed and improved. Furthermore, the storage of data from other Mediterranean ecosystems in the MIS may induce the insertion of new models in the system. Thus, the architecture of a prescription simulator should be flexible to allow for model updating and insertion. The simulator should encapsulate models so that its coding is independent of the implementation of other components of the system. Further, interface with the user is provided through input forms that allow for the specification of simulation parameters and silvicultural practices (Fig. 1). For example, the user interface encompasses a set of forms with ranges of feasible values for parameters such as rotation age or cutting cycle based on the interpretation of data from the land units. This interface is key for interactive definition of adequate cultural treatments in each land unit in a Mediterranean ecosystem.

The development of the proposed Mediterranean prescription simulator addressed these issues. Both stand-level and individual-tree-growth models were implemented within the system. Currently, it encompasses six main models:

(a) The GLOBULUS 1.0.1. [43] stand-level growth model, a growth model for eucalypt (*Eucalyptus globulus,* Labill) plantations in Portugal;
(b) The DUNAS [12] a stand-level growth model for maritime pine stands (*Pinus pinaster*, Ait) on the Portuguese northern coastal region;
(c) The Oliveira [30], stand-level growth model for maritime pine stands (*Pinus pinaster*, Ait) on Portuguese inland regions;
(d) The SUBER 1.0.0. [44] individual-tree model used for cork oak simulations;
(e) The MONTADO [14] hybrid individual-tree-stand-level model is also implemented;
(f) The HORTAS [18] stand-level model to assess growth and yield for several species (e.g. *Quercus robur* L., *Castanea sativa* L. *Betula pubescens* L., *Pseudotsuga menziesi* Franco) in the Portuguese central mountainous region.

Each model is connected to a model wrapper through a data-centric interface. The wrapper provides access to the MIS and supplies each model with the required input information in a standardized format (Fig. 1). Wildlife habitat concerns (e.g. wild boar (*Sus scrofa* L.)) are further addressed by the system through an adequate use of landscape metrics [16].

2.2.3. Linkage to management models

Model building to address ecosystem management problems requires utilities (e.g. matrix generators) that translate prescription data into adequate input files that may be read by management models in the EMDSS. The solution proposed involves the definition of three data structures:

MAS – (for Management AlternativeS) stores general data for each prescription (land unit ID, prescription ID, net present value resulting from applying the prescription (it includes the sum of individual operations discounted values and the bare land value) and age at the ending inventory).

PRODS – (for PRODuctS) stores data that describes operations and outputs resulting from the application of each prescription to each land unit. Several product types can be considered.

CONS – (for CONStraints) stores data related to user requirements for each product in each planning period.

These data structures complement each other thus facilitating model building to address several ecosystem management problems. The prescription simulator identifies each product with a unique code and the second data structure may thus record several types of outputs that may result from a prescription in a planning period. The simulator output structure follows the definition of a relational model in the third normal form ([9], pp. 288–312). It is therefore capable of future extensions without affecting current applications ([9], pp. 79–100). It is possible, for example, to add one extra field to the data structure PRODS (e.g. cost resulting from one operation), with no impact on the basic system structure. Notwithstanding, there are some product types that cannot be included within this data structure. Examples include spatial outputs such as patch size or edge length. Yet, providing topological information to management models can circumvent this limitation, for these product types may be calculated dynamically as the optimisation process runs (e.g. [3, 13]). In addition to prescription data, the simulator is then able to provide topological information and other pertinent data required for building management models [17]. Another optional data structure provides additional information required to link prescription simulation information to a real time 3D-visualiser.

Generally, management models require the generation of matrices to describe the decision problem (e.g. [5, 22]). The system includes a module that allows the generation of formulations in the LP format [21]. It can also produce output files with the forest topological structure so that spatially constrained models may be solved (e.g. [13, 15, 16]). The structure of the output files has thus been designed to incorporate the requirements of several optimisation and heuristic techniques. Further, the simulated data produced by the models is exported to the wrapper through a common data format (Fig. 1). This framework facilitates the introduction of other management models in the system.

The current system provides linkages to a set of management problem types (e.g. unconstrained timber net present value optimization, timber net present value optimisation subject to flow constraints, timber net present value optimization subject to adjacency constraints, timber net present value optimization subject to flow constraints and to minimum harvest patch size constraints). The system further enables the selection of specific models to solve a management problem type. For example, for timber net present value optimisation subject to flow constraints the user may select simulated annealing, tabu search, evolution programs or Lagrangean relaxation.

2.2.4. Implementation of the basic interface

The current implementation of the prescription simulator has an extensible modular structure. The program was developed in Visual Basic 6.0, under Windows 2000. Yet the compiled program runs in any Win32 platform (Windows 95/98, Me, 2000 or XP). Visual Basic was chosen due to its rapid prototyping capabilities, robust interface design, and extensive graphics capabilities. The integrated programming environment further contributed to reduce the development cycle. The systems architecture allows for easy linkage to GIS interfaces thus facilitating information interpretation by the end users. The prescription generator is able to display simple maps that can be used for interactive selection of management units or to depict accomplished management plans. These geographical visualization tools were incorporated in the system through an integrated ActiveX [6] component (ESRI's MapObjects LT). As the tool produces simple ArcView files, the outputs can be further analysed and interpreted in a desktop GIS, such as ESRI's ArcView

Table I. Intervention periods for a sample management alternative generation using simultaneous debarking for a 20-year planning horizon.

Prescription	1st Debark	2nd Debark	3rd Debark
1	1	10	19
2	1	10	20
3	1	10	
4	1	11	20
...	...	...	...
31	9	20	

2.3. Cork oak prescription simulation

The simulation of cork oak prescriptions encompasses the definition of both the debarking cycle for each tree in the land unit and the thinning regime. The prescription simulator may consider three debarking models. The inputs to the first model (Model A) are both the minimum and the maximum number of years of a land unit debarking cycle and the timing of the first debarking for each land unit. In order to run this model the prescription simulator interprets inventory data to estimate the "number of years since debarking" for all trees in all land units. Afterwards it simulates land unit debarking cycles starting in the year when the first debarking is to take place. Trees with a "number of years since debarking" lower than 9 at that year will not be debarked. Their debarking will be delayed until the next debarking in that land unit starts. From then on all trees in a land unit will be debarked in the same year. For example, if land unit debarking cycles range from 9 to 11 years, as many as 31 prescriptions may be simulated over a 20-year planning horizon (Tab. I).

The inputs to the second model (Model B) encompass the minimum number of years in a tree debarking cycle, the range of years in a debarking period and the number of levels of periodic land unit cork yield intensities. Again, in order to run this model the prescription simulator interprets inventory data to estimate the "number of years since debarking" for all trees in all land units. It further estimates the maximum and the minimum periodic cork yields for each land unit over the planning horizon. Intermediate yield values are defined by interpolation. Afterwards, debarking operations are simulated according to a simple rule. Trees in each land unit are sorted in descending order according to the "number of years since debarking", and debarked in that order, until one of two situations occurs: (a) the required land unit periodic yields are reached or (b) there are no more trees in the land unit with the "number of years since debarking" equal or larger than the minimum of years in a tree debarking cycle. In the latter case, despite debarking all available trees, the required periodic land unit yields may not be satisfied. For example, consider a case with a range of 1 to 3 years debarking period, with three levels of periodic land unit cork yield intensities. If the prescription simulator estimates that the land unit minimum and maximum periodic yields are 250 and 300 kg, respectively, then the program may simulate up to 9 different options:

1. Every year harvest 250 kg of cork;
2. Every year harvest 275 kg of cork;
3. Every year harvest 300 kg of cork;
4. Every two years harvest 500 kg of cork;
5. Every two years harvest 550 kg of cork;
6. Every two years harvest 600 kg of cork;

7. Every three years harvest 750 kg of cork;
8. Every three years harvest 825 kg of cork;
9. Every three years harvest 900 kg of cork.

The third model (Model C) takes as input a range of years to define the tree debarking cycle. The prescription generator checks all trees in each period and if the "number of years since debarking" is equal or larger than the years in that cycle the tree is debarked; otherwise it is not debarked.

The simulator and prescription generator let the user select three land unit density target levels (sparse, normal and dense). Users are asked too to define the minimum number of years between harvest entries. The thinning regime is then simulated according to the interpretation of inventory data and selected target levels. In order to reduce cork production losses, the prescription simulator only allows for thinnings in debarking years – only recently debarked trees may be harvested in a thinning operation.

In general, the output of a cork oak ecosystem management problem may encompass up to 7 cork types. Each type is characterized by its evenness and thickness. Yet, due to the limitations of the growth model and scarce inventory information, only one cork type was considered for testing purposes.

2.4. Simulated annealing as a solution method

Usually management models are based on a typical Model I formulation [22]:

$$\text{Max NPV} = \sum_{i=1}^{N} \sum_{j=1}^{M_i} c_{ij}\, x_{ij} \tag{1}$$

subject to,

$$\sum_{j=1}^{M_i} x_{ij} = 1, \ \forall i \tag{2}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{M_i} v_{ijpt}\, x_{ij} \geq (1 - d_{pt}) V_{pt}, \ p = 1,2,\ldots, P \wedge t = 1, 2, \ldots, T \tag{3}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{M_i} v_{ijpt}\, x_{ij} \leq (1 + d_{pt}) V_{pt}, \ p = 1,2,\ldots, P \wedge t = 1, 2, \ldots, T \tag{4}$$

$$x_{ij} = 1 \vee x_{ij} = 0, \ \forall i, \ \forall j = 1, \ldots, Mi \tag{5}$$

where,

N = the number of land units;

M_i = the number of alternatives for land unit i;

P = the number of products;

T = the number of planning periods;

x_{ij} = binary variable that is set equal to 1 if alternative j is chosen for land unit i and to 0 otherwise;

c_{ij} = net present value associated with alternative j for land unit i. It includes the value of the ending inventory;

v_{ijpt} = yield of product p in period t that results from assigning alternative j to land unit i;

d_{pt} = deviation allowed from target volume level of product p in period t;

V_{pt} = target volume level of product p in period t.

Equation (1) defines the objective of maximizing net present value (NPV). Equation (2) states that there must be one, and only one prescription per stand. Equations (3) and (4) define the maximum and minimum yields per product and planning period. Finally, equation (5) ensures that the solution is integer. Strategic estimates of cork production do not require an integer solution. Yet the anticipation of future ecological goals other than cork production prompted the development of an integer formulation that might better address new strategic management concerns. The integer requirements generally preclude the use of linear programming packages to solve the generated problems, thus a heuristic strategy is frequently used, generally providing near optimal results [15].

The simulated annealing meta-heuristic has been used extensively to solve integer formulations (e.g. [4, 16, 24, 28, 42]). Its basic mechanism can be described as follows:

1. An initial solution is generated randomly. That is, a random prescription is assigned to each land unit and the solution is evaluated (Z_1);
2. A modification of the previous solution is proposed (by changing randomly the prescription assigned to a randomly selected land unit) and this solution is evaluated (Z_2);
3. If Z_2 is larger than Z_1, the proposed modification is accepted, and the procedure jumps to step 5;
4. If Z_2 is lower than Z_1, the proposed modification will be accepted if a randomly generated value (within a 0.1 bound) is lower than $\exp((z_1 - z_2)/temp)$, where *temp* is a control parameter. If it is not accepted then jump to step 6, else continue to step 5;
5. Change the current solution with the proposed modification and make $Z_1 = Z_2$;
6. After a fixed number of iterations, lower the *temp* parameter by a given factor (cooling schedule);
7. If the number of iterations has not reached the maximum go to step 2, else end and report the final solution.

Thus, the probability of accepting inferior solutions increases with temperature (*temp*) and decreases with magnitude of the inferior move. Pham and Karaboga [36] report that factors that lead to successful algorithm implementation are choices regarding the solution data structure, the fitness evaluation function and the cooling schedule. In general, the latter involves a careful choice of the initial temperature (*temp*), of the cooling schedule and of the maximum number of iterations. Another issue when using meta-heuristics is the incorporation of constraints in the evaluation function. This is usually accomplished through the use of penalty functions that penalise the objective value the further the solution is from the required constraints.

The implementation of simulated annealing for this type of problems has used a default set of parameters (temperature and cooling schedule) that usually provide good results for a large spectrum of situations. The evaluation function encompassed the net present value and a penalty function (Eq. (6)):

$$\sum_{i=1}^{N} \sum_{j=1}^{M_i} c_{ij}\, x_{ij} - \sum_{c} \lambda_c(d_c, V_c) \tag{6}$$

where λ_c represents a penalty function dependent of the demand levels and deviation values for each constraint c in the set of equations (3) and (4). Previous efforts [15] showed that a parabolic function, with parameters derived from the problem and the constraint values, provided a reliable and flexible approach to this problem, so this method is used uniformly in the simulated annealing implementation.

3. RESULTS

The proposed architecture for a prescription simulator and its integration within an EMDSS were used successfully to address the test problem. The prescription simulator considered all three debarking models. In the case of the first model, the minimum and the maximum number of years of a land unit debarking cycle were set to 9 and 11 years, respectively. The

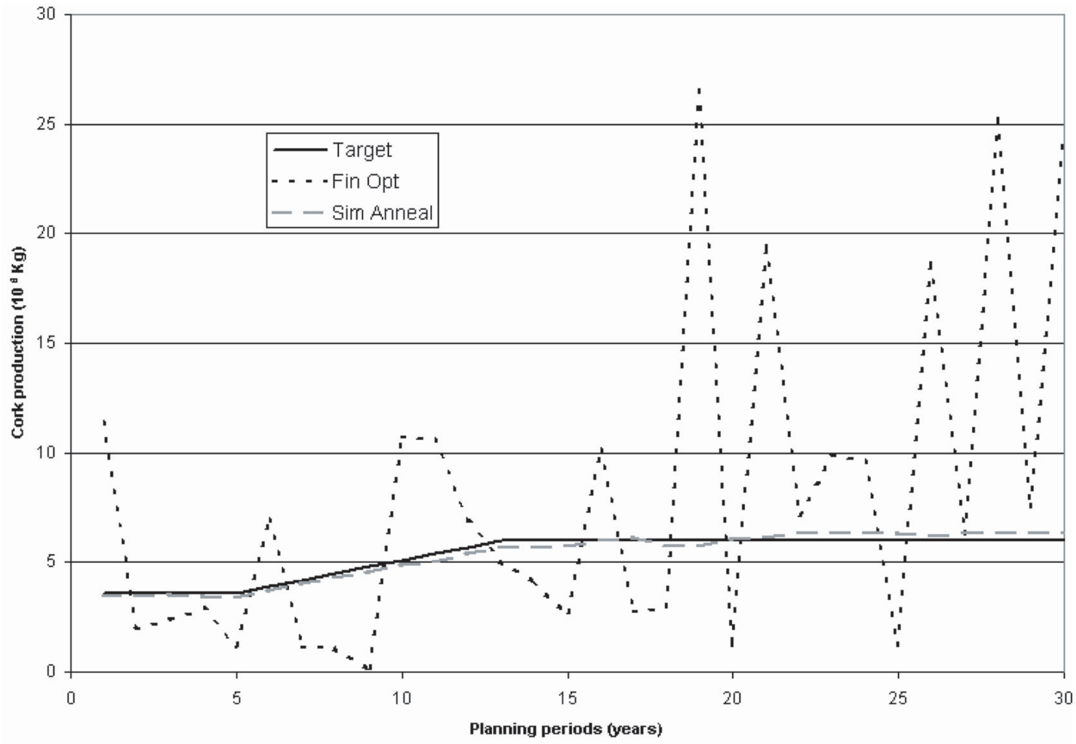

Figure 2. Cork flows associated with the unconstrained net present value maximization and the simulated annealing solutions.

second model considered a minimum tree debarking cycle of 9 years, a debarking period ranging from 2 to 9 years and three levels of periodic land unit cork yield intensities. The third model considered tree debarking cycles ranging from 9 to 11 years. The minimum number of years between harvest entries was set to 9 years. Only one land unit density target level was considered. The prescription simulator interpreted efficiently the ecosystem data from each of the 860 cork oak land units in the MIS and used effectively the three debarking models and the thinning model to generate 209 840 prescriptions over a thirty 1-year periods planning horizon. Users may use the system to simulate prescriptions over longer planning horizons. Yet for current testing purposes it was not necessary to do so. The proposed system generated an average of about 244 decision variables for each land unit. Adequate management flexibility may be achieved by considering a lower number of options for each land unit. Thus extending the planning horizon will not impact the effectiveness of this decision support tool.

The interpretation of inventory data demonstrated the effectiveness of the linkage between the MIS and the prescription simulator. It further showed that most land units were occupied by fairly young cork oaks. Current cork production in Serra de Grândola is below potential production levels in the area. Unconstrained financial optimization and several LP model solutions were used to estimate potential production levels over the 30-year planning horizon. Based on this information, the decision model (Eq. (1) to (5)) to address the NGOs requirements and to test the linkage between the prescription simulator and the management models assumed a yearly production target of 3 600 t of cork in the first five 1-year periods. This value was gradually increased over an 8-year period to a maximum of 6 000 t of cork per year. Deviations from these target levels of up to 5% were allowed.

The results of the prescription simulation and the management model parameters were organized into the three data structures – MAS, PRODS and CONS –, to generate the management model matrix. The latter was used as input by both a linear programming solver (CPLEX 8.1.) and the simulated annealing algorithm thus demonstrating the effectiveness of the linkage between the prescription simulator and the management models.

In order to provide useful information to the NGOs, the system was further used to assess the opportunity costs associated with the cork even-flow constraints. This information helped evaluate tradeoffs between strategic objectives of cork production in Serra de Grândola and financial objectives for each land unit. The comparison between the unconstrained net present value optimization solution and the solutions of the linear programming and the simulated annealing algorithms provided that information. The former net present value was 3.484×10^8 EUR. The LP optimal solution was 2.774×10^8 EUR, while the simulated annealing solution was 5.3% below this value (2.628×10^6 EUR). The last two approaches provided an estimate of strategic sustainable cork flows over the 30-year planning horizon (Fig. 2). Cork even-flow constraints further impact the selection of debarking models. Unconstrained net present value optimization selected models A and C for about

Table II. Debarking models selected by the unconstrained net present value maximization (UNPVM) and the simulated annealing (SA) solutions.

Solution method	Debarking model	No. land units	(%)
UNPVM	A	426	49.53
	B	25	2.91
	C	409	47.56
SA	A	199	23.14
	B	524	60.93
	C	137	15.93

97% of land units while simulated annealing selected Model B for most land units (Tab. II). Further comparison between the LP and the simulated annealing solutions provided a first estimate of opportunity costs of other strategic ecological objectives that may require integer solutions. These costs reached about 784 EUR per ha as a consequence of prescription value variability in each land unit. Several land units show differences above 1 100% between the maximum and minimum NPV and over 82% of land units have differences greater then 300% between prescription values.

A GIS visualization tool may be used to analyze landscape wide impacts of the treatment schedule (Fig. 3). For example, the unconstrained financial optimum scenario concentrates treatments and it proposes that over 90 percent of the total area is debarked in 2018 and 2033 (Fig. 3). Conversely, the regular flow constraints scenario proposes a more even distribution of debarking over the planning horizon. Moreover, it proposes that only about 30% of the total area is debarked. It is also interesting to analyze the type of prescriptions selected in each scenario. The regular flow constraints scenario selected mostly management option B to address sustainability concerns (Fig. 4). The unconstrained financial optimum scenario assigned to each land unit the most lucrative method, which was, for the more productive area (the south-eastern plateau), management option C. Northern and western areas in Serra de Grândola area characterized by higher altitudes, steeper slopes and lower productivity. In these areas, the unconstrained financial optimum criterion assigned to most land units management option A to enforce a regular and simultaneous debarking periodicity for all trees, thus minimizing the costs (Fig. 4).

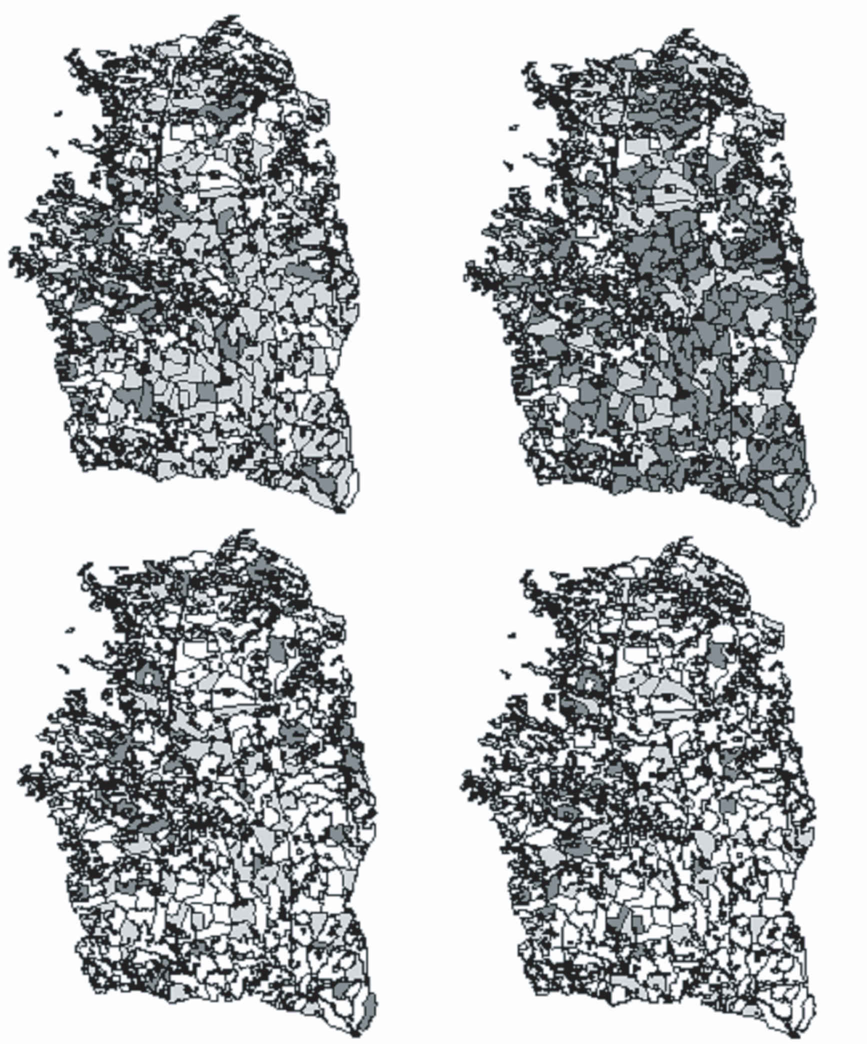

Figure 3. Maps of Serra de Grândola presenting the unconstrained net present value maximization (top) and the simulated annealing (bottom) solutions in 2018 (left) and 2033 (right). Dark gray - debarking; Light gray - debarking and thinning; White - do nothing.

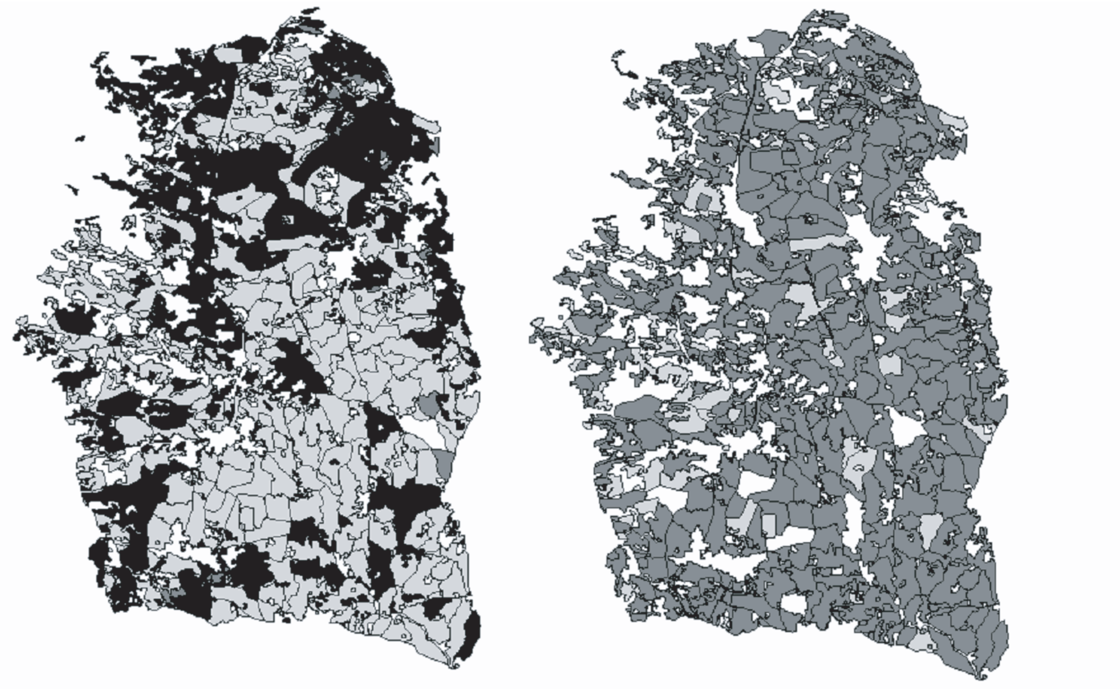

Figure 4. Maps of Serra de Grândola presenting the debarking models selected by the unconstrained net present value maximization (left) and the simulated annealing (right) solutions. Black - Model A; Dark gray - Model B; Light gray - Model C.

4. DISCUSSION

Database interaction, linkage to growth and yield models, interactive silviculture modeling, GIS integration and linkage to management models are key aspects of the architecture for a prescription simulator. All have been discussed in the framework of the development of an effective and efficient simulator that might interface with other components of an EMDSS. A cork oak management problem was used to test the system functionality. The problem was defined according to end users (a local development organization and a forest landowners association) objectives. Results showed that the proposed prescription simulator architecture did successfully address end users objectives.

The current implementation is an extensible system because it allows for the updating and the insertion of timber growth and wildlife models. Currently, the system includes models for the most common forest species in Portugal (*Pinus pinaster*, *Eucalyptus globulus*, and *Quercus suber*) plus a general model for other less important species. New growth and yield models for other species (e.g. *Pinus pinea*, *Pinus nigra* or *Quercus ilex*) may be integrated in the system thus extending the usability of the system to support other Mediterranean forest ecosystems. Further, the system does not incur in excessive computational costs.

The solution of the test problem demonstrated that the system acted effectively as an interface between the models, the (geo-referenced) database thus simulating adequate cork oak prescriptions for each land unit. It further demonstrated the effectiveness of the simulator data structures that provide the linkage to management models. They facilitate model building to address several forest ecosystem management problems. It was also shown that the prescription simulator is fully integrated with a geographical information system thus producing data needed by state-of-the-art ecosystem management heuristics. The user friendliness of the interface, namely its visualization capabilities, connection to popular tools (e.g., Microsoft Excel, ESRI ArcView), and its overall architecture define a powerful and easy to use tool.

The current system still does not allow conversions between cover types, yet a new prototype is being developed that aims at overcoming this shortcoming. Research work will also focus on integrating other production and conservation functions and on enhanced interfacing with other multiple criteria ecosystem management models. Finally, further research is needed to include fire risk considerations and models within the EMDSS.

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