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ORIGINAL PAPER

A decision support system for management planning of Eucalyptus plantations facing climate change

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Abstract
• *Context* Climate change studies in Portugal point to warming winters and increase in the dry season length, impacting growth of plants. New tools are needed to increase the effectiveness of forest management planning under climate change.
• *Aims* To develop research tools that may help forest managers cope with climate change challenges to long-term planning. These tools should help assess the impact of climate change on the timing and location of forest management options as well as on forest products flows.
• *Methods* The proposed tools are based on information system architecture approaches that suggested a “Decision Support System” (DSS) with a modular structure to integrate (1) a management information module; (2) a prescription generator module that integrates a process-based model (Glob3PG); (3) a decision module; (4) a solution report module. To demonstrate the usefulness of the DSS, a eucalyptus forest with 1,722 stands (6,138 ha) in Portugal was considered. Two climate scenarios were used.
• *Results* Potential wood supply decreased from 2.35 to 2.19 million m^3, land value depreciated from 81.1 to 74.7 million Euro and total carbon stock decreased from 228 to 212 tons.
• *Conclusions* The DSS demonstrated that the design of optimal management plans should take into account climate change.

Keywords Climate change · Decision support system · Management planning · Eucalypt · Forestry

1 Introduction

Climate change may impact substantially the forest sector in Portugal. Several studies point to the warming of winters and to the increase of both the length of the dry season and the frequency of extreme events like forest fires (Christensen et al. 2007). This will impact the growth and survival of plants as well as their geographical distribution and the composition of plant communities. As empirical models are not suitable for estimating growth under different conditions from those observed during the period for which the plots were measured (Landsberg and Waring 1997), they are inadequate as a means to support decision-making under climate change. Thus, forest managers need new tools to increase the efficiency and the effectiveness of forest management under changing environmental conditions. Namely, they need decision support systems (DSS) with growth and yield models sensitive to environmental change.

According to the Portuguese Forest Inventory, eucalyptus represents about 23 % of the forest cover in Portugal, totalling about 739×10^3 ha. Eucalypt is the main source of raw material used by the pulp and paper industry—a leading Portuguese export-driven industry. For this reason in Portugal, forestry growth and yield research has focussed mostly in eucalypt forest ecosystems and basically on empirical models (Fontes et al. 2006; Tomé et al. 2006).

In Portugal, most eucalypt stands are even-aged stands intensively managed under a coppicing system with 11–

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12 year rotations. Therefore it is expected that climate change will have a strong impact on short-term productivity. Since empirical growth and yield models are based on past inventories, they are based on the assumption that future environmental conditions will be similar to those of the past. Therefore, they lack flexibility and the capacity to assess the impacts of environmental changes, such as droughts, on eucalyptus growth. Process-based models, which are based on physiological processes controlled by climatic and edaphic factors (e.g. Kellomäki et al. 1997) may overcome the shortcomings of empirical models. Examples of process-based modelling research in Portugal include the calibration of MAESTRO for *Eucalyptus globulus* (Tomé 1997) and the examination of the potential for application of PROMOD (Battaglia and Sands 1997) to Portuguese conditions. Yet the structure of these models is complex and a detailed ecosystem description is needed to initialise growth and yield projections. This constrains the use of these models in management planning contexts.

Landsberg and Waring (1997) developed the 3-PG model in a deliberate attempt to bridge the gap between conventional growth and yield models and detailed process-based models. 3PG is a simple process-based stand-level model requiring few parameter values and readily available input data. This model has been used for *Eucalyptus globulus* growth projections in Australia. Further, it has been successfully calibrated for a wide range of species and site conditions (e.g. Fontes et al. 2006).

On the other hand, the linkage between process-based models and empirical models aimed at combining the strengths of both is a good alternative (Mäkelä et al. 2000). For example, in Portugal, Tomé et al. (2004) presented a methodology to hybridise a version of 3-PG parameterised for Portugal with the empirical model GLOBULUS to obtain Glob3PG. More recently, J. Garcia-Gonzalo et al. (manuscript submitted) presented a methodology to integrate this hybrid model (Glob3PG) with optimisation techniques in order to analyse climate change impacts on forest management plans. This methodology would overcome shortcomings of its predecessors in supporting management planning of Eucalypt stands under scenarios of climate change.

Addressing climate change is a challenge to forest managers. Although some forest simulators that address climate change exist, they have not yet been implemented in decision support systems with decision aid capabilities (Gordon et al. 2004). In this area, a limited number of studies have been devoted to optimise forest management under climate change (e.g. Garcia-Gonzalo et al. 2008). Vacik et al. (2010) developed ClimChAlp, a system with multi-criteria-decision analysis tools to help forest owners design adaptive strategies at stand level. Nevertheless there is no experience of automating the use of process-based models with optimisation techniques, and this is key for its usefulness in forest management planning. In order for models to be used effectively, they must be programmed and integrated within computer-based decision systems (Reynolds et al. 2005; Gordon et al. 2004). Stimulated by developments in business administration and industry, these systems have been improving the quality and transparency of decision-making in natural resource management (Reynolds et al. 2005).

In Portugal, there is considerable experience of developing DSS to enhance the efficiency and effectiveness of forest management planning and scenario analysis (e.g. Garcia-Gonzalo et al. 2013; Borges et al. 2003; Ribeiro et al. 2004; Falcão and Borges 2005). Yet these DSS do not include process-based models. This prompted research to develop, incorporate and test the use of a process-based model, Glob3PG, and of multi-objective optimisation techniques in a DSS. Emphasis was placed on demonstrating the applicability of a process-based model to support management planning processes under changing environmental conditions.

In this article, we investigate the effects of climate change on eucalypt management. Our hypothesis is that forest management plans must be adapted, as forests will grow more slowly due to climate change. For this purpose, we develop a DSS—SADfLOR v ecc 1.0—to address eucalypt forest management planning under climate change scenarios. The proposed approach is described and applied to a case study located in central Portugal. Results from test computer runs are discussed for application of the proposed approach to eucalypt forest management planning problems.

2 Materials and methods

2.1 The DSS structure and modules

The development of the DSS architecture encompassed consultation with several forest stakeholders (e.g. forest owners, forest industry, local and central public administration, non-governmental organisations). This architectural approach was based on the extension by Marques et al. (2011) and Marques et al. (2013) of the four-stage Enterprise Architecture methodology presented by Spewak and Hill (1992) to actively incorporate forest practitioners and decision makers in the development of forest management systems. The reader is referred to Marques et al. (2013) for details of the architecture process, which highlights the need for tools that might address climate change impacts on forest management.

Based on this information, and taking advantage of former decision support systems architecture (Borges et al. 2003; Falcão and Borges 2005), an innovative DSS (SADfLOR v ecc 1.0) was developed to incorporate and test the use of a process-based model that is sensitive to environmental conditions, Glob3PG, as a vegetation growth projection tool.

This novel DSS thus extended the SADfLOR platform (Borges et al. 2003; Falcão and Borges 2005; Reynolds et al. 2005) to include new tools that might support eucalypt forest management planning under climate change scenarios.

This DSS integrates four independent and compatible modules, encapsulated in one single graphical interface (GUIfLOR) (Fig. 1). The four modules are: (1) a management information module offering an interface to a comprehensive relational database that stores all relevant information about the target forest (e.g. inventory); (2) a prescription generator module including a set of routines and growth and yield functions (GLOB3PG process-based model) that allows the users to generate and explore the outcomes of different forest prescriptions; (3) a decision module to assemble these alternative prescriptions into a consistent mathematical model which is solved; (4) a reporting module REPfLOR, which allows viewing and reporting of the results generated by the decision module. Following the SADfLOR concept developed by Borges et al. (2003), the modular structure allows the use of the modules in other systems as well as to use input data from other sources (e.g. simulations from external growth and yield simulators).

The user can interact with the system taking two basic steps. First, they may check spatial and non-spatial inventory data in order to select a forest area. Immediately thereafter, they may define parameters (e.g. rotation lengths) to generate acceptable forest prescriptions at stand level and simulate them. Thereafter, they may define and parameterise goals (e.g. management objectives and constraints) needed for developing the mathematical models and solve the landscape planning problems. The solution is reported in tabular format and in maps. Both stand-level decisions (e.g. prescriptions) and landscape-wide results (e.g. eucalypt pulpwood yield carbon stocks over the planning horizon) are accessible through the user interface.

The DSS was designed to facilitate model use, and was implemented in Visual Studio 2008 (Visual Basic) while certain parts of the system were programmed in FORTRAN (e.g. the Glob3PG model, which was encapsulated within the SADfLOR v ecc 1.0). Visual Basic was chosen due to its simplicity to develop prototypes, robust interface design, and extensive graphics capabilities. The integrated programming environment further contributed to reducing the development cycle.

2.1.1 Management information module

A management information module (MIS)—INfLOR 2.1—(Miragaia et al. 1998; Marques and Borges 2007) stores spatial and non-spatial information, including administrative attributes of land units (e.g. forest stands or land units). In addition, it stores topological data to allow spatial recognition of land units within the landscape. Further, it stores financial and economic data, which will allow financial analysis for strategic management planning. One of the specific requirements of this system is the need for monthly climatic data (i.e. radiation, temperature, precipitation), which are used by the process-based model to predict stand development under different climate scenarios. For this reason a climate picker tool, existing under SIMFLOR—a platform for Portuguese forest simulators (Faias et al. 2012)—was programmed to interact with the forest growth model to provide the closest climatic data available to each forest area considered. Further, interfaces were programmed to upload inventory data from text (txt) or comma separated values (csv) files and to allow the user to introduce timber prices and operations costs when these are not readily available in a relational model format. These formats can be generated easily by widely used software packages (e.g. Excel or Access databases). In this case, an XML file is associated to each csv or txt file describing its contents to facilitate the processing of very large files.

2.1.2 Prescription generator module

The prescription generator module includes the prescription writer and the growth and yield model. It serves to project conditions and outcomes in each land unit over time. The success of the DSS depends on the availability of these projections. The projections are instrumental for building resource capability and policy models. The structure of the module is flexible and independent of the other components of the system in order to allow updates, changes or even substitutions in the growth and yield model without affecting the rest of the system.

A prescription writer (Fig. 1) generates prescriptions (silvicultural operations to perform along the planning horizon) based on the simulation parameters and silvicultural practices specified by the user. Thus, the user interface encompasses a set of input forms were the user can define ranges of feasible values for parameters such as: (1) planning horizon, (2) number of rotations, (3) possible cutting ages, (4) number of stools after stool selection, (5) planting density.

The current version of Glob3PG combines the strengths of a process-based model (3PG) and of an empirical model (GLOBULUS 3.0). Specifically, Glob3PG takes advantage of the flexibility and ability of 3PG to predict the effects of changes in growing conditions (e.g. climate change, fertilisation) and of GLOBULUS 3.0's prediction capacity under current conditions (Barreiro 2011). Glob3PG has been validated recently against permanent plots, and its performance has been compared to an empirical growth and yield model; in this validation the model showed a good performance (Barreiro 2011).

The use of this process-based model allows: (1) simulation of the effect of intensive silviculture practices (i.e. initial stand

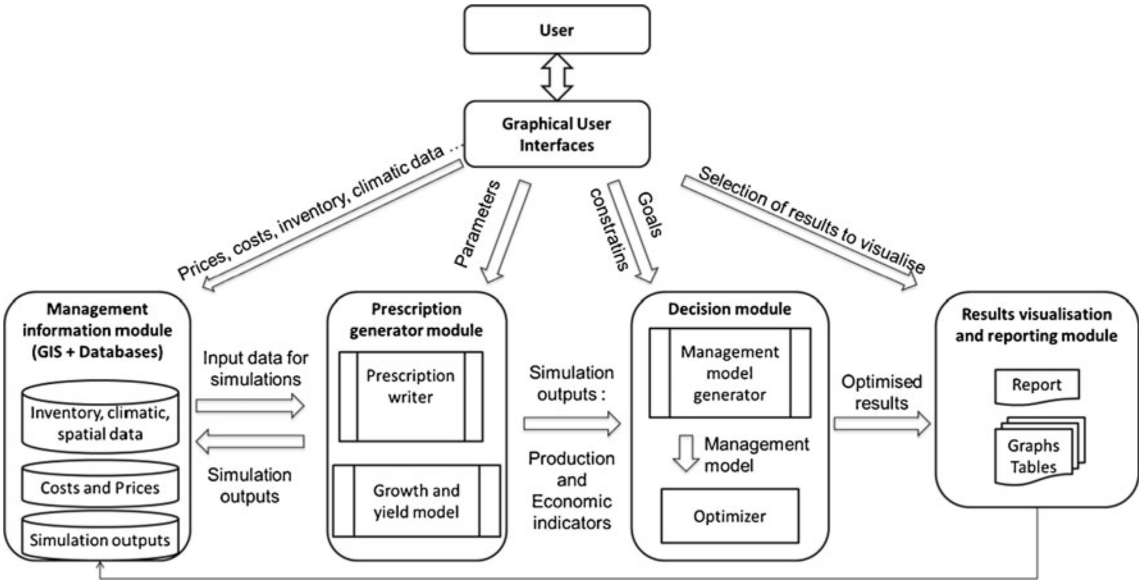

Fig. 1 Structure of the decision support system showing the different modules: (1) management information module, (2) prescription generator module, (3) decision module and (4) solution report module. *Arrows with text* indicate information flow

density, stool selection), (2) simulation of growth under climate change, and (3) provision of detailed stand structure information (diameter distribution, merchantable volumes to any top diameter). The growth and yield simulator interprets inventory data and applies prescriptions to each management unit.

2.1.3 Decision module

Generally, management models require the generation of matrices to describe the decision problem. The decision module provides linkages to a set of management problem types [e.g. unconstrained forest value (FV) optimisation, forest value optimisation subject to harvest flow constraints, unconstrained carbon stock and forest value optimisation…]. These problem types may be formulated in the linear programming (LP), mixed integer programming (MIP) and goal programming (GP) format, which allows the use of metaheuristics (e.g. simulated annealing).

In order to generate the mathematical formulations, the management model generator reads outputs from growth and yield simulations (e.g. harvest volumes, carbon stocks) and, together with the financial information (i.e. interest rate, prices and costs), generates the coefficients for all the equations needed in the problem formulation. The structure of the output files has thus been designed to incorporate the requirements of several optimisation techniques. In addition, links with external solvers (i.e. commercial software CPLEX and the freeware GLPK) were programmed in the optimisation module in order to solve the mathematical models. Alternatively, the system may use a metaheuristic to solve the problem without the need to use any external solver.

2.2 Case study

A eucalypt test forest extending over 6,138 ha located in Central Portugal was the subject of study. Mean annual rainfall is 826 mm, but less than 20 % occurs between May and September (130 mm). Soils are of low fertility, with low organic carbon content (0.23–0.28 %) with an average of 395 mm (range between 242 and 737 mm) of water holding capacity. Soils are mostly sandy and may be classified as Arenosols (FAO/UNESCO) (Madeira and Ribeiro 1995). Environmental and biometric data from the study area were stored in a relational database. The forest landscape was classified into 1,722 stands with areas ranging from 4.8 to 18 ha. The current distribution of stand area by age class is very even, with ages ranging from 0 to 16.5 years, with an average age of 8 years.

The management problems for decision-making in this area were characterised during interviews with forest owners in the frame of the consultation process described by Marques et al. (2013). During the interviews, stakeholders highlighted the importance of analysing possible adaptation options like rotation lengths. In addition they defined objectives as maximisation of economic returns and regulation of harvest flows.

The prescription writer was used to generate possible management options that provide the flexibility needed by forest owners to adapt their management to changing environmental conditions. There is no unique definition of what is meant by adaptive management. For example, a review published by Bolte et al. (2009) explained that one case of “Active Adaptation” is the realisation of thinnings earlier than usual in order to avoid windthrow damages.

Therefore, options used in our study were developed based on information gathered in the literature review (Lindner et al. 2010; Bolte et al. 2009) and on adaptive options highlighted by stakeholders during interviews. During these interviews, stakeholders (e.g. forest owners and industry) explained which were the typical options they used and which parameters may be adapted to cope with climate change. Among the parameters specified, some were not implemented as there is no empirical/numerical knowledge of their impact in forest growth. In this case study, a typical eucalyptus rotation may include up to two or three coppice cuts, each coppice cut being followed by a stool thinning that may leave an average number of shoots per stool ranging from one to two. Harvest ages ranged from 9 to 14 years with a 1-year interval. Initial density was 1,400 trees per hectare. A modified version of the prescription writer in SADfLOR (Borges et al. 2003) was programmed to generate all possible management alternatives for all stands in the test forest, over a planning horizon of 30 periods of 1-year each. In total, 198, 000 prescriptions were used.

For testing purposes, two climate scenarios were selected using the climate picker tool under the SIMFLOR umbrella (Faias et al. 2012). These scenarios are based on the ENSEMBLES project (http://www.ensembles.eu.org), which provided climate datasets (Scenario A1B) developed by the Hadley Center that are considered the most appropriate for Portuguese conditions (Soares et al. 2012). Using Scenario A1B, the weather data for the period 1971–2000 were assumed to represent the "current climate" over a temporal horizon of 30 years, and the period 2001–2030 was considered as the future climate change (CC) scenario. For CC, the scenario predicts a reduction in precipitation of 6 %, an increase in the minimum temperature of 4 % and an increase of the maximum temperature of 7 % during the growing season (May–September) (Table 1).

2.2.1 Mathematical formulations for the case study

The proposed DSS automates the quantification of outcomes associated with all management regimes produced by the prescription writer. The growth estimates by the process-based model provide the information needed to assess the impact of each prescription on results and conditions of interest. For testing the applicability of the process-based model, both timber flow and carbon stock objectives were considered. Further economic objectives (e.g. maximisation of net present value using a 4 % discounting rate) were also addressed by the test problem.

The eucalypt test forest with over 1,722 stands extended over 6,138 ha. The test problems encompassed a 30-year planning horizon and two climate scenarios. Model building involved the generation of over 96500 Model I type (Johnson and Scheurman 1977) binary decision variables. In order to assess the impact of climate change on net revenues, timber production, and carbon stocks, the model includes several accounting variables. Moreover, timber volume flow constraints are used. All constraints were annual.

If we follow a Model I formulation as defined by Johnson and Scheurman (1977), the test problem may be described as:

$$\text{Max FV} = \sum_{i=1}^{N}\sum_{j=1}^{M_i} fv_{ij}x_{ij}A_i \tag{1}$$

Subject to:
stand integrity

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

accounting variables

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} w_{ijt}x_{ij}A_i = W_t, t = 1, \ldots, T \tag{3}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} carb_{ijt}x_{ij}A_i = CARB_t, t = 1, \ldots, T \tag{4}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} npv_{ijt}x_{ij}A_i = NPV_t, t = 1, \ldots, T \tag{5}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} nr_{ijt}x_{ij}A_i = NR_t, t = 1, \ldots, T \tag{6}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{J_i^{ACI_{it}}} A_i x_{ij} - ACutAge_{kt} = 0, \forall_t, \forall CAge_k, k = 9\ldots15, t = 1, \ldots T \tag{7}$$

volume control (for period t)

$$W_{t+1} \geq (1-alpha)\cdot W_{t=1}, t = 1, \ldots, T-1 \tag{8}$$

$$W_{t+1} \geq (1-alpha)\cdot W_{t=1}, t = 1, \ldots, T-1 \tag{9}$$

binary decision variable

$$x_{ij} \in \{0, 1\}, \forall i, j \tag{10}$$

Where,

FV	total net present forest value (includes value of the ending inventory)
N	Number of stands (1,722)
A_i	Area of the stand i.
x_{ij}	binary variable that is set equal to 1 if alternative j is chosen for stand i and to 0 otherwise.
T	Number of periods during the planning horizon (30)

Table 1 Monthly average for different variables needed for the simulations for control climate scenario (Current climate) and climate change scenario (CC) data. *T* Temperature (°C), *P* precipitation (mm), *Rad* radiation (MJ m^{-2}), *FrostDays* number of frost days ($T_{\min}$ <0 °C), *RainDays* number of days with precipitation >1 mm

	Month	$T_{\max}$	$T_{\min}$	P	Rad	Frost days	Rain days
Current climate	1	13.5	4.8	91.5	6.2	3.3	17.4
	2	15	5.3	68.5	9.1	1.2	15.2
	3	17	6.1	58	13.4	0.5	15.1
	4	19.8	8.1	59.4	17.3	0.1	16.2
	5	23.3	10.1	32.5	21.6	0	11.8
	6	29.8	14.2	17.3	23.8	0	7.3
	7	33.9	16.5	5.6	23.9	0	4.6
	8	33.2	16	2.3	21.4	0	4.2
	9	30.8	14.9	25.1	16.7	0	9
	10	23.5	11.6	66.6	10.8	0	14.3
	11	17.5	8.7	97.9	6.8	0.1	17.7
	12	14.8	6.7	97.1	5.3	1.4	17.6
CC	1	14.2	5.7	105.1	6	2.6	17.2
	2	15.7	5.7	49	9.4	0.9	14.8
	3	17.8	6.7	39.1	13.8	0.4	14
	4	20	8.2	45.1	17.6	0.1	14.7
	5	24.7	11.2	35.2	21.4	0	12.1
	6	30.8	15	13.7	24	0	7
	7	34.9	17.5	5.1	23.9	0	4.9
	8	34.9	17.4	3.2	21.4	0	4.3
	9	31.5	15.9	20.9	16.5	0	9.1
	10	24.5	12	49.5	11.3	0	12.2
	11	18.1	8.8	107	6.7	0.1	18
	12	14.7	6.7	119.7	5.2	1.7	18

M_i	Number of prescriptions for stand i.
$J_i^{ACI_{kt}}$	Set of prescriptions for stand i that harvest the stand at age k in period t.
fv_{ij}	FV per hectare associated with prescription j and stand i. Forest value includes the net present value (NPV) of management costs and revenues of the current rotation plus the NPV of all management costs and revenues in perpetuity when starting with bare land.
w_{ijt}	Harvested eucalypt pulpwood flow per hectare in period t that results from assigning prescription j to stand i.
$carb_{ijt}$	Average carbon stock per hectare in stand i in period t if prescription j is selected.
nr_{ijt}	Net revenue per hectare in period t associated to prescription j in stand i.
npv_{ijt}	Discounted net revenue per hectare in period t associated to prescription j in stand i.
$ACutAge_{kt}$	Total area cut in the study area at age k in period t.
alpha	Deviation allowed from target level (e.g. 15 % variation)

Equation (1) defines the objective of maximising FV. Equation (2) ensures that one and only one prescription is assigned to each stand. Equations 3, 4, 5 and 6 account for eucalypt pulpwood yield, the average carbon stock, net revenue and discounted revenue in each planning period. Equation 7 accounts for the number of hectares cut for each cutting age. Equations 8 and 9 force the eucalypt pulpwood volume levels to meet the flow targets in each period. They reflect concerns with the sustainability of eucalypt pulpwood supply. Equation 10 defines the domain of the variables for the mixed integer programming (MIP) formulation.

2.2.2 Case study methodology

The steps followed to address the case study management problem defined by the stakeholders are as follows (Fig. 2):

1. Selection of geographical and biometric data for the 1, 722 stands (6,138 ha), which are stored in the MIS for further use in the simulations
2. Selection of the climate change scenarios to use in the simulations.*
3. Generation of prescriptions based on parameters set by the user (e.g. rotation length, planting density).
4. Simulating all prescriptions in all the stands of the forest over the planning horizon (i.e. 30 years).

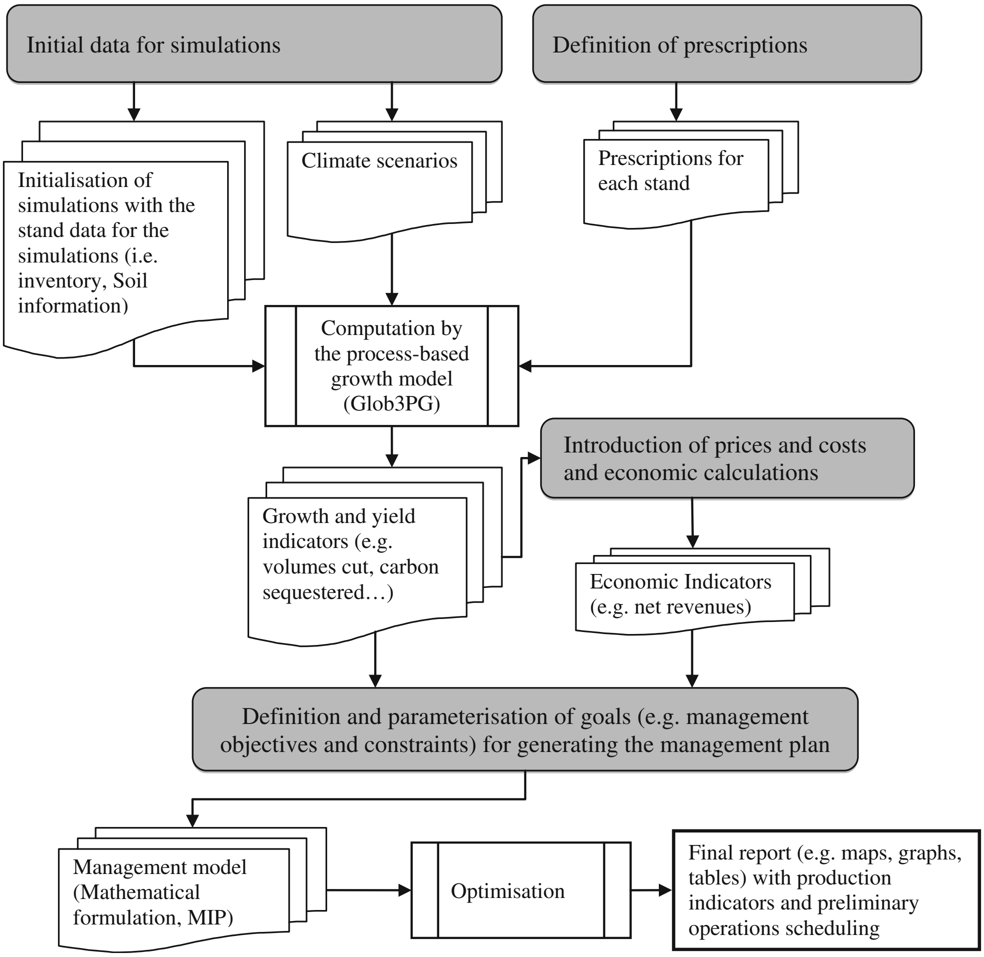

Fig. 2 Scheme of the simulation-optimisation process. *Grey rectangles* Specific forms for carrying out actions

5. Introducing prices and costs of operations and calculating economic indicators as net revenues, net present value and FV. Prices and costs of operations used in this study are from statistical data provided by the Forest Service.
6. Generating management models based on objectives (e.g. maximisation of forest value), constraints (e.g. even flow) and parameters (e.g. planning horizon) set by the user. The coefficients for the management models (LP, MIP and GP models) are produced based on the information from projections and economic indicators.
7. After generating the management models, an external application (CPLEX) is run for solving the models and for generating information.
8. Interpreting the optimiser solution file, by filtering the simulation dataset for the prescription found for each stand. As the solution file has already accounting variables (Eqs. 3–6), these are gathered to supply information to the report.
9. Finally, the report with the strategic management plans is produced.
10. This report is provided to the stakeholders for further analysis and input adjustments (e.g. criteria targets, constrains, prescription parameters,...) if needed

*Steps 2–10 are repeated until a strategic management plan is accepted.

For the simulations, the price of wood depending on the age of the trees and a 4 % rate was used to discount costs and revenues. Report building was done with a linkage to Microsoft Excel to generate graphs and tables.

The case study was solved with a desktop computer (CPU Duo P8400 with 3GB of RAM) and IBM ILOG CPLEX Optimization Studio.

3 Results

The proposed approach was first used to assess the climate change effect on the potential eucalypt pulpwood yield and carbon stock over the whole study area over a 30-year time horizon. The unconstrained optimal solution for the “current climate” showed that the maximum eucalypt pulpwood yield was 2.35 million m^3, the corresponding forest value was € 81.13 million and total carbon stock was 228.3 Mg C. Under the "climate change" scenario the harvests were reduced to 2.19 million m^3 the forest value was reduced to €74.7 million and carbon stocks decreased to 212.7 Mg C. (Table 2). To illustrate the changes in stand-level growth, simulations under both climatic scenarios for a random stand were selected (Fig. 3).

The model was further used to assess the opportunity costs associated with the timber flow constraints. This allows the evaluation of trade-offs between strategic landscape-wide pulpwood supply and carbon storage objectives. The comparison between the unconstrained forest value optimisation solution and the constrained solutions provided that information. The impacts of enforcing pulpwood even-flow policies are substantial. For example, if a 15 % maximum variation between 2 consecutive years is allowed under the current climate, the pulpwood yield and the soil expectation value would decrease up to € 3 million.

A GIS visualisation tool may be used to analyse landscape-wide impacts of the treatment schedules, especially if spatial constraints are considered. The geographical reporting may show the harvest scheduling as well as the harvested volume (and NPV) for each period. The tool also allows the visualisation of the growth projection in each management unit, superimposed on top of Google maps. The unconstrained financial optimum concentrate cuttings into only a few years; consequently, the harvest flow is very uneven. Conversely, regular flow constraints scenarios propose a more even distribution of cuttings over the planning horizon (Fig. 4).

The proposed approach was further used to check what would happen if the optimal management plans under the current climate scenario were implemented and climate change of the magnitude assumed here did occur. This would provide information about the cost of not adapting the management plan to climate change. Thus, if climate change of the magnitude assumed here does occur and the forest management plans obtained for current climate conditions are implemented, the pulpwood yield would be slightly reduced (Table 3). In addition, this plan would violate pulpwood flow objectives (Fig. 5). This is the "cost" of not adapting management.

The proposed approach was further used to check how cuttings at stand level might change due to climate change. If the total area cut at different ages is accounted for, results show that, under climatic change conditions, a delay in the year of cuttings is observed. For example, the constrained problem (i.e. maximisation of FV with 15 % even-flow constraints) shows that, when switching from current climate scenario to the climate change scenario the area cut when the stands are 9 to 11 years old is reduced by up to 20 %. On the other hand, under climatic change conditions, the area cut when the stands are 12 and 14 years old increases by 12 and 13 %, respectively (Fig. 6). This clearly shows a delay in harvest age.

4 Discussion

Climate change may threaten the capacity of forests to provide services and may substantially impact the forest sector in Portugal. Moreover, climate change adds uncertainty to future forest productivity projections and thus empirical models become unsuitable as a means of making decisions about the future. For this reason, forest managers need new tools to increase the efficiency and effectiveness of forest management under changing environmental conditions. In this work, we used a new process-based model easy to use in a DSS. This was instrumental in developing a management model and software to support timber flows and carbon stocks for regional scenario analysis.

The development of the DSS encompassed consultation with several forest stakeholders (e.g. forest owners, forest industry, local and central public administration, non-governmental organisations) following the architecture approach described by Marques et al. (2013). This active involvement of forest practitioners and decision makers in the development of the forest management system gives an indication of willingness to use the system and of the importance given to the problem of planning under uncertainty.

Process-based models are valuable tools for studying forest growth and dynamics under climate change. In recent years, several process-based models have been used to study the

Table 2 Simulation outputs for different climate scenarios. Constraints refer to deviations of eucalypt pulpwood yields, net returns carbon stocks between consecutive planning periods over the 30-year planning horizon.

CC Climate change, *FV* Forest value, *CStock* carbon stock in the forest ecosystem, *VH* Harvested timber volume

Objective	Constraint	Climate scenario	FV (M€)	Cstock (Mg C)	VH (Mm^3)
MaxFV	–	Current	81.1	228	2.35
		CC	74.7	213	2.20
MaxFV	15%vol	Current	78.5	205	2.47
		CC	72.4	193	2.32

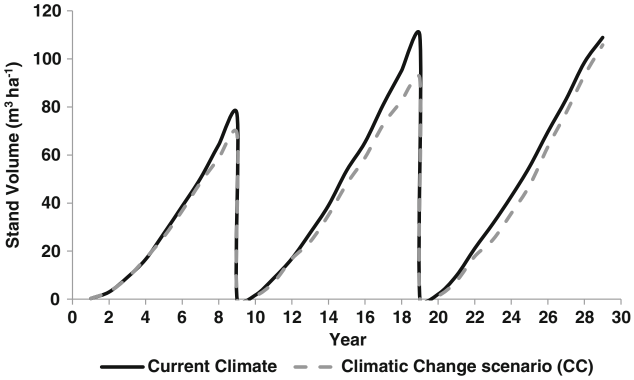

Fig. 3 Example of stand development when applying the same prescription under current climate (*Current*) and climate change (*CC*) scenario (Scenario A1B) when simulating a prescription involving two coppice cuts, each coppice cut being followed by a stool thinning that leaves an average number of shoots per stool of 1.5. Even flow constraints indicate that for any period of the planning horizon a maximum variation of harvests level achieved on planning period 1 is allowed

impact of climate change on forest growth (e.g. Austin 2007; Seidl et al. 2011). However, most of these studies have focussed on the assessment of forest growth under climate change by applying the current stand-level management practices. At the landscape level, a limited numbers of studies have focussed on optimising management plans under climatic changing conditions (Garcia-Gonzalo et al. 2008). On the other hand, there is no experience of automating the use of process-based models in DSS and this is key for its usefulness in forest management planning (Reynolds et al. 2005). The main constraints for using these kind of models in DSS have been their complex structure and the need for detailed ecosystem description to initialise growth and yield projections.

In this context, the novelty of this study is the implementation of a new process-based model, Glob3PG, for Portuguese conditions into a DSS. This, together with multi-objective optimisation techniques, may allow policy

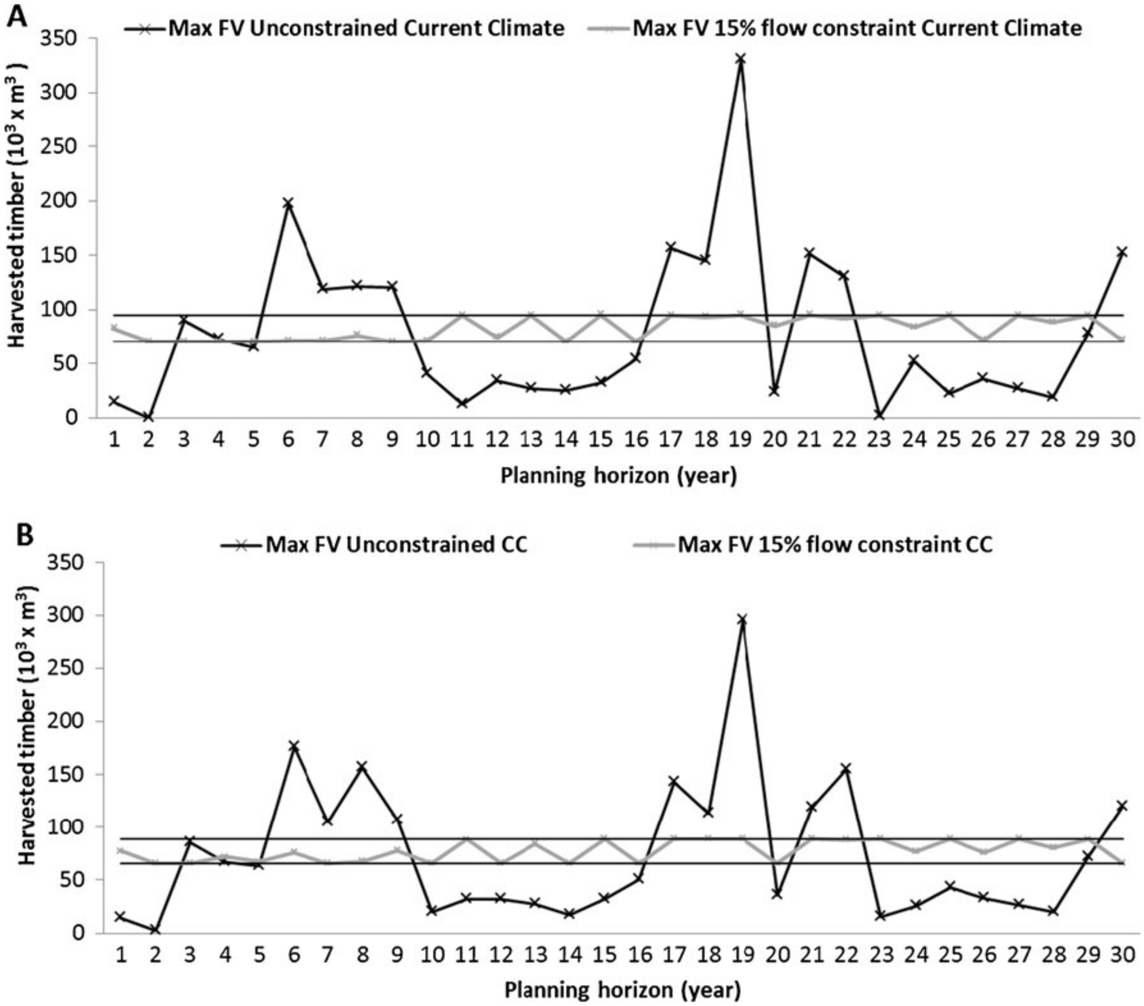

Fig. 4 Pulpwood flows (m^3) associated with the unconstrained forest value (FV) maximisation and the solution using 15 % even flow constraints under current climate (Current) (**a**) and climate change (CC) scenarios (**b**). *Horizontal lines* Limits for the15% even-flow of harvests constraints

Table 3 Results of applying the optimised management plan for a certain climate scenario in the other climate scenario

Scenario used	FV (M€)	Cstock (Mg C)	VH (Mm^3)
Optimal solution for CC used under Current Climate conditions	78.7	208	2.49
Optimal solution for current climate used under CC conditions	71.8	190	2.31

analysis as well as adapting forest management to climate change.

An ideal DSS would require capabilities from different systems to work together. In this context, the so-called interoperability is the ability of two or more software components to cooperate by exchanging services and data with one another, despite the possible heterogeneity in their language, interface and hardware platform (Heiler 1995). In our system, we developed a modular structure that may evolve over time by adding new components. For example, the optimisation module may work as stand-alone software that is able to read an external file and may construct a mathematical model that may be solved either with the programmed metaheuristic, with freeware included in the system (GLPK), or by a commercial solver (e.g. in this case we have a link to CPLEX 12.2). In addition, the present modules may be updated or replaced easily (e.g. the growth and yield model). Also, other functionalities may be added easily to the system (e.g. wildfire risk models, post-fire mortality models).

In order to demonstrate the applicability and the use of the DSS, a test study was presented where a multi-objective planning problem under changing climatic conditions was addressed. The eucalypt test forest with over 1,722 stands each had on average up to 56 prescriptions per stand. Thus the number of possible management plans made it impractical to compare and evaluate all possible alternatives. Instead, one relies on efficient numerical tools to search the decision space for feasible solutions. Since we wanted to track not only the amount of resource produced by stands over the planning area but also the exact location of the prescriptions, integer solutions were needed. This means that a very large volume

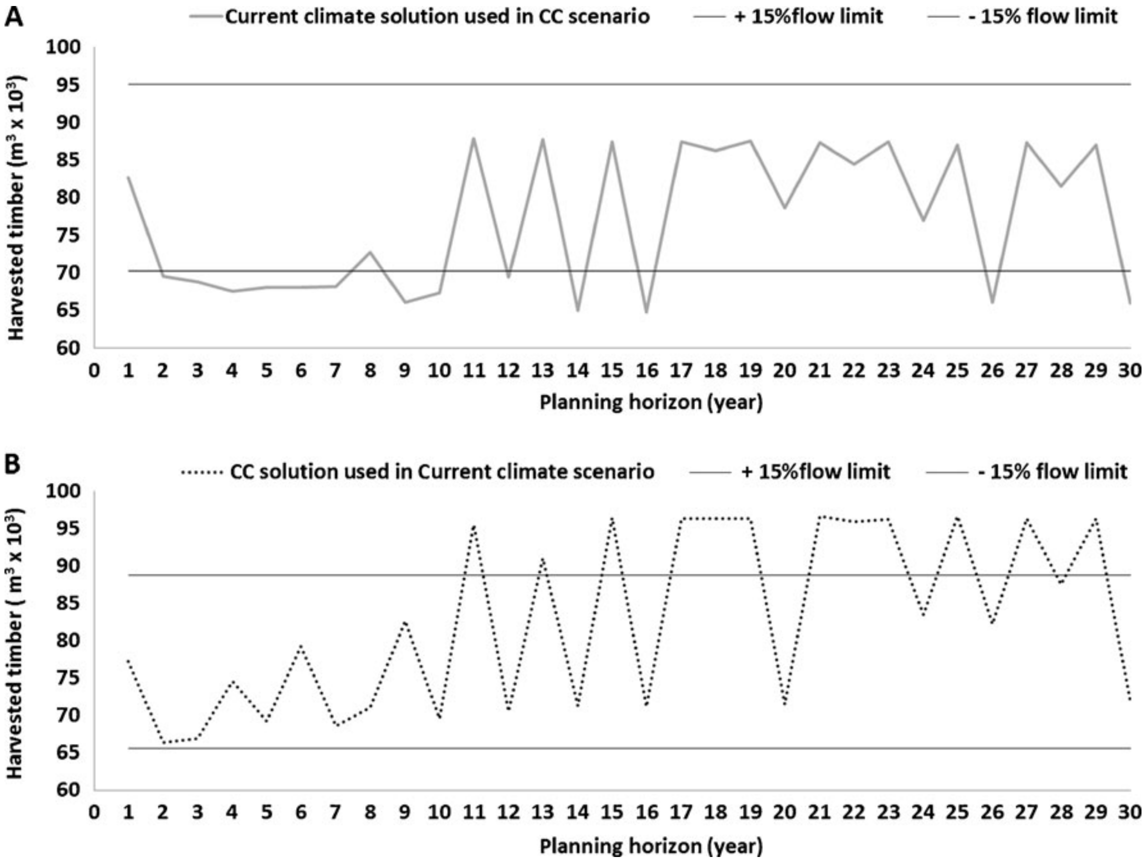

Fig. 5a,b Total harvested timber (m^3) flows associated with the constrained solution (i.e. 15 % even flow of harvests) found when using current climate and the result of using this management plan under climatic change (CC) conditions for the first 30 year simulation period under current climatic conditions. *Horizontal lines* Even flow of harvests (15 %) limits calculated for the optimized solutions found for each specific climate scenario. **a** Climate change, **b** current climate

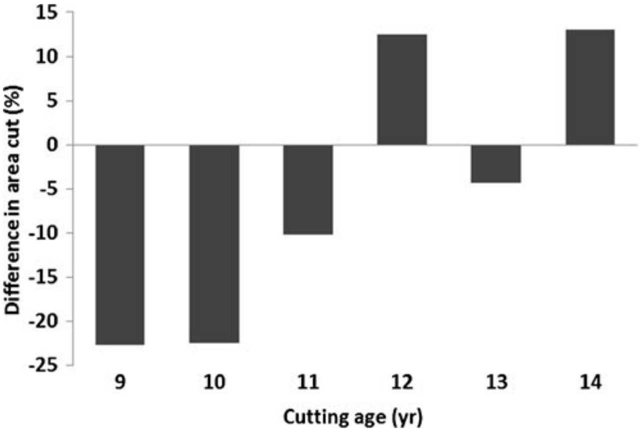

Fig. 6 Percentage of change in the total harvested area (%) per age class when comparing the optimal solution under the climate change scenario assumed here (CC) compared to the solution found for current climate conditions. Results associated to the maximisation of forest value (Max FV) under 15 % even flow of harvest constraints

of information needs to be processed and tracked and that the size of the combinatorial problem becomes very large (Weintraub and Murray 2006). In order to solve this kind of problem, both heuristic methods (e.g. Borges et al. 2002) and mathematical programming techniques have been used (e.g. Weintraub and Murray 2006). The advantage of using a mathematical programming technique instead of using a heuristic method is that we guarantee finding the optimal solution as opposed to heuristics that find a near-optimal solution. For this reason, a mixed integer programming model was used to ensure the spatially explicit solution (i.e. integer solutions) and to find the optimal distribution of stand treatment programmes over the study area.

The prescription writer developed in this study allows the user to define parameters in order to develop prescriptions (e.g. number of rotations, possible cutting ages, number of stools after stool selection, planting density…). These options provide the flexibility needed by forest owners to adapt their management to changing environmental conditions. These options were developed based on information gathered in the literature review (Lindner et al. 2010; Bolte et al. 2009). Moreover, the DSS provides information about how to adapt the distribution of silviculture models over the landscape to climate change.

As the objective of the study was to test a process-based model in the context of forest management planning, we did not include another interesting issue, i.e. solving integer forest management scheduling models that incorporate addition spatial constraints (e.g. adjacency constraints, maximum open gap area). However, it should be relatively easy to include spatial constraints in the formulation. Future research will also address wildfire and pest risks and their interaction with climatic change conditions. These interactions were felt to be outside the scope of this study so they were not included.

The solution of the test problem demonstrated that the system performed well and was able to find optimal solutions under different constrained conditions. Moreover, the proposed test problem shows the usefulness of using a process-based model to tackle changing climatic conditions. In addition, the current implementation is an extensible system because it allows for the updating and the insertion of timber growth and yield models. The use of process-based models sensitive to climate change that can be calibrated easily for different species makes this modelling approach suitable for forest planning under environmental changing conditions.

As expected, a climate change scenario will have a substantial impact on forest area. The climatic change scenario used predicted less precipitation over the growing season. This impacts the wood supply with a reduction in incomes of around 8 % (i.e. around € 7 million in the unconstrained problem and € 6 million in the even flow constrained problem). These findings are in line with previous research in Mediterranean climate area, where many authors agree that increased drought is likely to lead to reduced plant growth and primary productivity (e.g. Peñuelas et al. 2007). Climate change invalidates optimal management plans developed for control climates, especially regarding target or even-flow constraints. When analysing the effects of not adapting forest management decisions to climate change (i.e. using optimal management plans developed for current climate in climate change scenario used in this article), timber yield would be reduced and the even flow of harvests constraints would be violated. This is especially important when minimum target productions are not met, which would have an impact on pulp and paper mills. This again shows the necessity of adapting plans to climate change. Of course, the magnitude of the impact of climate change on forest productivity and management plans may vary depending on the climate change scenario. However, analysis of uncertainty in the climate change scenarios was out of the scope of this article. In the light of these findings, it is recommended that possible future climatic changes be included in forest planning. Thus, this study demonstrates that the use of DSS that combine process-based growth models and multi-objective optimisation techniques are an efficient tool to support forest planning and decision making including climate change uncertainty.

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