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Development of forest simulation tools for assessing the impact of different management strategies and climatic changes on wood production and carbon sequestration for Eucalyptus in Portugal

TESE APRESENTADA PARA OBTENÇÃO DO GRAU DE DOUTOR EM ENGENHARIA FLORESTAL E DOS RECURSOS NATURAIS

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“Na vida há que ter a serenidade necessária, para aceitar as coisas que não podemos modificar, coragem para modificar aquelas que podemos e sabedoria para distinguirmos umas das outras.”

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Susana Miguel Barreiro

Abstract

The present work had as main objective developing tools capable of simulating the evolution of *Eucalyptus globulus* forests in Portugal taking into account disturbance factors, such as market demands, hazards occurrence, land use changes, forest management and/or climate changes.

Some conceptual work was done concerning the definition of different forest management alternatives while at the same time the *E. globulus* current management was described. SIMPLOT, a regional simulator based on national forest inventory plots was developed and validated. This simulation tool, mainly driven by wood and biomass demands, takes into account the occurrence of hazards, land use changes and the changes between different forest management alternatives allowing accessing its long-term impacts, namely on wood production and carbon sequestration. Some of the empirical growth models available for this species in Portugal were integrated into this simulator. However, the need to forecast the growth of highly stocked stands managed for bioenergy lead to the development of a new model. In order to account for climate changes, a process-based model was required. Therefore, the applicability of 3PG process-based model at a regional scale was tested for planted and coppice stands. Two forest level simulators, 3PG-Out+ and GLOBULUS, were developed along this study.

Key-words: forest simulators, *Eucalyptus globulus*, SIMPLOT, GLOBULUS, 3PG-Out+, climatic scenarios, management alternatives, long-term forecasts

Resumo

Esta tese teve como objectivo principal o desenvolvimento de ferramentas para simular a evolução das florestas de eucalipto em Portugal tendo em conta factores externos tais como as procuras de mercado, a ocorrência de riscos, as alterações de uso do solo, a gestão florestal e/ou as alterações climáticas.

A gestão actual dos povoamentos de *E. globulus* foi descrita e estes classificados de acordo com os conceitos desenvolvidos. O simulador regional SIMPLOT, baseado nas parcelas do inventario florestal nacional, foi desenvolvido e validado. Este simulador é movido pela procura de madeira para pasta e biomassa para energia e tem em conta a ocorrência de riscos, as alterações de uso de solo e as alterações na gestão florestal, permitindo avaliar os seus impactes na produção de madeira e no sequestro de carbono a longo prazo. O SIMPLOT inclui modelos empíricos disponíveis para esta espécie em Portugal. A necessidade de prever o crescimento de povoamentos com elevadas densidades (produção de bioenergia) levou ao desenvolvimento de um novo modelo. O modelo de base fisiológica 3PG que permite contabilizar as alterações climáticas foi testado para alto fuste e talhadia a uma escala regional. Foram desenvolvidos os simuladores do povoamento GLOBULUS e 3PG-Out+.

Palavras-chave: simuladores florestais, *Eucalyptus globulus*, SIMPLOT, GLOBULUS, 3PG-Out+, cenários climaticos, alternativas de gestão, simulações a longo prazo

Preamble

This thesis is composed of several scientific articles. Some of the articles have already been published; others are being edited; while others are ready for submission. The manuscript encloses detailed descriptions of some of the simulators, containing explanations of procedures, decisions and assumptions made throughout this study.

The motivation and the work conducted for the thesis are explained in the general introduction (**Chapter I**). The articles are integrated as chapters of this document and have a Roman numeral assigned (II – VII). The thesis is the compilation of the articles and the manuscript included as chapters of this document:

Chapter	***Title***
II	Dunker, P., **Barreiro**, S., Hengeveld, G.M., Lind, T., Mason, W.L., Ambrozy, S., Spiecker, H.. Classification of Forest Management Approaches: a new Conceptual Framework and its Applicability to European Forestry. Ecology and Society. (Under revision)
III	**Barreiro**, S., Tomé, M., SIMPLOT: Simulating the impacts of fire severity on sustainability of eucalyptus forests in Portugal. Ecological Indicators 11 (2011) 36–45.
IV	**Barreiro**, S., Tomé, M., Analysis of the impact of the use of eucalyptus biomass for energy on wood availability for eucalyptus forest in Portugal. A simulation study. Ecology and Society. (Under revision)
V	**Barreiro,** S., Tomé, M., Using consecutive National Forest Inventories to validate regional forest simulators. An application to the regional simulator SIMPLOT in Portugal. (In preparation for 2012)
VI	**Barreiro**, S., Tomé, M. Modelling biomass production in highly stocked Eucalyptus stands in Portugal. (In preparation for 2012)
VII	**Barreiro**, S. Crous, J., Tomé, J.A. and Tomé, M. Evaluating 3PG and Glob3PG models for planted and coppice stands using long-term *Eucalyptus globulus* Labill. permanent plots. (In preparation for 2012)

Susana Miguel Barreiro had the main responsibility for the entire work in articles for which is the first author. Concerning the article that makes up **Chapter II**, as a co-author, the candidate helped writing and formatting the document and was responsible for the eucalyptus management description for Portugal that is part of the Appendix. **Chapter VIII**, contains the final remarks, summarizing the conclusions of the work and also describing some tasks that were essential to move forward but that were not included in the articles.

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EFORWOOD - Sustainability Impact Assessment of the Forestry Wood Chain	EU 6th Framework Program	2005 - 2009
MOTIVE - MOdels for AdapTIVE Forest Management	EU 7th Framework Program	2009 - 2012
AFORE - Forest bio-refineries: Added-value from chemicals and polymers by new integrated separation, fractionation and upgrading technologies	EU 7th Framework Program	2009 - 2013

The candidate attended the following courses during the period of her research:

ECTs	***Hours[1]***	***Course***	***Organization***
2		Spring School 2011 – Modelling Forest Ecosystems	Cost Action FP0603
	35	Visual Basic.net (2009)	Galileu, Lisbon
7.5		2008 NOVA International Ph.D. course on Ecology, silviculture and economics of multi-functional forestry	Copenhagen University
3.5		Statistics Applied to forest modelling	School of Agriculture, Technical University of Lisbon.

[1] Indicated for courses not directly providing ECTs.

During the PhD the candidate cooperated in parallel projects resulting in three publications:

Type	***Title***
Book chapter	**Barreiro**, S., Godinho, P.F. and Azevedo. A., 2009. National Forest Inventories reports: Portugal In: Tomppo, E., Gschwantner, Th., Lawrence, M. & McRoberts, R.E. (eds.). National Forest Inventories - Pathways for common reporting. Springer, p. 437-464. ISBN 978-90-481-3232-4.
Article	Dunger, K., Petersson, H., **Barreiro,** S., Cienciala, E., Colin, A., Hylen, G., Kusar, G., Oehmichen, K., Tomppo E., Tuomainen, T., Ståhl, G.,. Harmonizing greenhouse-gas reporting from European forests – case examples and implications for EU level reporting. Forest Science. (Under revision)
Article	Faias, S.P., Palma J.H.N., **Barreiro** S., Paulo J.A., Tomé, M., 2012. sIMfLOR – Platform for the Portuguese forest simulators. (In preparation for 2012)

The work described in this manuscript was presented by the PhD candidate at several national and international conferences either as oral presentation or in poster format:

Oral Presentations Title *(Just as first author)*

Barreiro, S., Tomé, M., 2008. Estimating future forest sustainability indicators at national/regional level using NFI data: the impact of data aggregation. In proceedings of the International conference on Impact Assessment on Land Use Changes, 6-9 April 2008, Humboldt University, Berlin, Germany.

Barreiro, S., Tomé, M., Faias, S., Palma, J., 2009. SIMPLOT: Regional Simulator for the Portuguese Forest Resources. In proceedings of the EFORWOOD Final Conference: Shape your sustainability tools and let your tools shape you. 23-24 September 2009. Uppsala, Sweden.

Barreiro, S., Tomé, M., 2009. Simulador de Eucalipto baseado em parcelas de inventário. Seminário CarbWoodCork – Modelos e Simuladores para Estimação de Sequestro de Carbono e Produção de Madeira, 17 February 2009, Lisbon Portugal.

Barreiro, S., Tomé M., Soares, P., 2009. Simulação de povoamentos de eucalipto para a produção de biomassa. In proceedings of 6º Congresso Florestal Nacional, a Floresta num Mundo Globalizado. 6–9 October 2009. Ponta Delgada, Açores, Portugal.

Barreiro, S., Faias, S., Palma, J., Tomé, M., 2010. Long-term simulation of forest sustainability under a multifunctionality context. In proceedings of XXIII IUFRO WORLD CONGRESS, International Union of Forest Research Organizations, Parrotta, J.A., Carr, M.A. (Eds.), 23-28 August 2010, Seoul, Republic of Korea.

Barreiro, S., Faias, S., Palma, J., Tomé, M., 2010. Simulation of long-term forest condition assessed by sustainability indicators using Simplot a regional simulator. In proceedings of IV Reunión de Jóvenes Investigadores en Conservación y Uso Sostenible de Sistemas Forestales. Programa de Máster y Doctorado en "Conservación y Uso Sostenible de Sistemas Forestales. 18-19 February 2010, CENEAM Valsaín, Segovia, Spain.

Barreiro, S., 2011. Simulation tools – models and simulators. Cost Action FP1001: "USEWOOD: Improving Data and Information on the potential supply of wood resources – A European Approach from Multisource National Forest Inventories", 10-11 March 2011, Vienna, Austria.

Posters Titles *(Just as first author)*

Barreiro, S., Tomé, M., Coelho, M. B., Tomé, J., Soares, P., 2007. Estimating future carbon sequestration at national/regional level using NFI data: the impact of data aggregation. In proceedings of the IUFRO Forest Growth and Timber Quality: Crown Models and Simulation Methods for Sustainable Forest Management, 7-10 August 2007, Portland, Oregon, United States.

Barreiro, S., Tomé, M., 2009. SIMPLOT: simulador regional de eucalipto baseado em parcelas de inventário. In proceedings of 6º Congresso Florestal Nacional, a Floresta num Mundo Globalizado. 6–9 October 2009. Ponta Delgada, Açores, Portugal.

Barreiro, S., Tomé, M., 2010. SIMPLOT – Simulador Regional de Eucalipto Baseado em Parcelas de Inventário. Workshop 'Novas Tecnologias em Gestão Florestal Sustentável' - NOVTEC2010. ISA, Lisboa.

Barreiro, S., Tomé, M., 2011. SIMPLOT: regional forest simulator based on inventory plots developed for eucalyptus in Portugal. AFORE Conference "Nordic Wood and Biorefinery", March 2011, Stockholm, Sweden.

Barreiro, S., Tomé, M., 2011. SIMPLOT: regional forest simulator based on inventory plots developed for eucalyptus in Portugal. In proceedings of COST FP0603 Spring School 2011 - Modelling Forest Ecosystems. Concepts data and application, 8-14 May 2011, Kaprun, Austria.

CHAPTER I

General Introduction

General Introduction

I.1 Background

Eucalyptus globulus Labil. was introduced into Portugal in the second half of the 19th century as an ornamental species. From then onwards, it has increased its range from around 70 thousand hectares in 1965 (DGSFA 1966a, DGSFA 1966b) to 740 thousand hectares (AFN 2010). The expansion, achieved at the expense of a reduction of uncultivated land and marginal agriculture, was promoted by pulp and paper industries in an attempt to secure their raw-material supply (Borges and Borges 2007). Nowadays, 23% of the Portuguese forests are covered with *E. globulus* which is the second most representative species in area (AFN 2010) and one of the most important ones for the economy. Over the last decade, the incidence of severe forest fires, which had drastic consequences for the Portuguese forests, combined with the recent increase in production capacity registered in the pulp and paper industries led to an increase in wood demand. In 2009, around 20% of the wood used to supply the industry was imported (CELPA 2010). The increase in imported wood observed after 2006 can be seen as indicative of the harvesting pressure on eucalyptus forest in Portugal.

Even though forests have always been used with multiple purposes, over the last decades the expectations regarding forest use have increased. Forestry wood production with profitable purposes is no longer the unique objective of forestry. This fact has led to changes in forest management and has set new challenges to forest managers that have to find a balance between alternative forest uses. Meanwhile, carbon sequestration in forests started being seen as an extremely valuable forest service. For this reason, managers will have to account more and more for the impacts that different management alternatives, combined with a general global change context, namely climatic changes, might have on forest growth, and consequently on forest policies.

Along with carbon sequestration, the use of biomass for energy has also become an attractive and important topic in the last years. Under the scope of energetic diversification and of profitable exploitation of bio-fuels for energy production, biomass from forest residues might play a major role in reducing both carbon emissions and the consumption of fossil energy. Many European governments consider forest biomass as an important motor in meeting the Kyoto Protocol commitments (United Nations 1998). In Portugal, the construction of new thermoelectric plants supplied by forest biomass was supported by the Portuguese Energy Strategy (DRE 2005a). The energy produced in these plants is competitively priced (109€/MWh), only bettered by photovoltaic energy (DRE 2005b). As a matter of fact, forestry wood chain (FWC) industries have been using biomass to produce thermo and electrical energy. In 2008, 74% of the energy consumed by the pulp and paper industry was derived from bio-fuels; of these 81% of the energy produced from biomass derived from a sub-product of pulp production (black liquor), 17% was produced from *E. globulus* and *Pinus pinaster* bark, and the remaining 2% from shrubs and agro-industrial residues (CELPA 2009). Until now, mainly eucalyptus forest residues have been used with energetic purposes in Portugal. Nevertheless, bio-energy plantations could contribute as extra revenue for the forest sector. For this reason, the establishment of eucalyptus plantations with energetic purposes must not be disregarded in a near future. On the other hand, pulp and paper industries play a major role in the Portuguese economy and are responsible for the sustainable management of 154 thousand hectares of eucalyptus forest (CELPA 2011). Even though, sustainable forest management is difficult to achieve at the national level. Despite the Portuguese Energy Strategy has recommended financing research related to the use of forest biomass for energy production (DRE 2006), no results from studies on the potential use of eucalyptus for bioenergy have been published so far. Notwithstanding, the competition for areas managed for pulp and bio-energy is likely to occur in a near future considering the current market pressure to supply pulp mills with wood and bio-energy plants with biomass. In fact, the competition for the use of eucalyptus wood has already started since private forest owners have already started selling wood from pulp managed stands for bio-energy purposes because it pays off. Nevertheless, from the standpoint of the pulp and paper chain given biomass energetic efficiency, and despite the climatic impact policies that encourage the use of biomass for energy, it should only be used for heat production and cogeneration instead of dedicated electricity production (CELPA [s.d.]). Moreover, the use of wood in industries results in added value and higher employment in the forest sector than if used for energy production.

With all the external factors that affect long-term wood availability in mind, such as the impacts of fluctuations in market demands, occurrence of disturbance events, such as fires, as well as changes in land use, forest management and climate, it became urgent to develop all-embracing methods for estimating forest growth. Several long-term scenario simulators have been and/or are being developed in Europe to evaluate the large-scale impacts of external drivers on the evolution of forests. EFISCEN is a good example of a large scale simulation tool. This simulator, based on an age-volume transition matrix was conceived to be used at European scale and has been used by the European Forest Institute (EFI) to predict the evolution of European forests under different scenarios (Pussinen et al. 2001, Schelhaas et al. 2004, Nabuurs et al. 2003). Despite being a useful tool applicable to over 30 countries, EFISCEN works on a base of 5-year interval time-steps, which results in some limitations in terms of simulating the evolution of species explored in short-rotations like is the case of eucalyptus in Portugal.

Until recently, Portuguese forest managers aiming for wood production have seen their requirements met by empirical growth and yield models. Because of *E. globulus*'s importance for the pulp industry, Portugal has a long history in developing empirical growth models for this species (Amaro 2003, Amaro et al. 1998, Tome and Ribeiro 2000, Tomé et al. 2001, Soares and Tomé 2003, Barreiro et al. 2004, Tomé et al. 2006). Universities and pulp and paper industries embraced the challenge of developing a growth model for eucalyptus that could be applied to the whole country. The first version of this model was Globulus 2.1 (Tomé et al. 2001). Under the scope of the GlobLand project, a new version of Globulus empirical growth model was developed (Tomé et al. 2006). Now in its 3rd version Globulus 3.0 is the model in use for estimating eucalyptus growth in Portugal. Because empirical models have the inconvenient of being based on measurements lacking the flexibility and capacity to simulate environmental stresses, process-based models gained an extreme importance over the last years. 3PG was conceived to be a simple process-based model using only readily available data as input (Landsberg and Waring 1997, Sands and Landsberg 2002). 3PG has been parameterized for several species in different countries. The first studies to assess 3PG's ability to simulate growth for *E. globulus* in Portugal also intended to identify needs for improvement (Tomé et al. 2004a). The model was hybridized with the Globulus model in an attempt to strengthen the week points of both models, resulting in the Glob3PG model, (Tomé et al. 2004b), and parameterised for *E. globulus* in Portugal (Fontes et al. 2006). Forest growth and yield models are essential to support forest management planning. However, they should be integrated into simulators with user-friendly interfaces in order to maximize their full potentialities. Out of the forest growth models available in Portugal, few had been implemented in individual interfaces making them non-user-friendly tools. In 2001, interfaces were developed for the main tree species' models in Portugal (FPPF 2001). The interface developed for E*. globulus* integrated the Globulus 2.0 model (Tomé and Ribeiro 2000). This stand simulator was based on a closed rigid structure that required ordering new programs to integrate any updates to the models. Furthermore, the simulation of different forest management alternatives was quite reduced.

I.2 Objectives and Outline

The main objective of this PhD study was to develop tools that allowed simulating the impacts of different management and climate change scenarios on eucalyptus carbon stocks and wood production in Portugal at stand, forest and/or regional level, with particular emphasis on the latest one.

One of the first steps in order to account for changes in management was developing a classification of forest management approaches (FMA). This classification was based on an intensity gradient of silvicultural operations described using specific sets of basic principles which enable comparison across European forests. A set of 5 FMA's was described according to which, the current management practiced for *E. globulus* in Portugal was classified as Intensive even-aged forestry. However, given the present situation on the eucalyptus wood-chain in Portugal, short-rotation forestry, the most intense FMA, was also considered. The definition of alternative FMAs and the concept behind this classification is presented in **Chapter II**.

At the same time, under the scope of this thesis, a regional forest simulator was built for eucalyptus in Portugal. SIMPLOT was conceived to simulate eucalyptus stand growth in a region producing as output a whole variety of forest characteristics and a set of sustainability indicators. Based on national forest inventory (NFI) information as input it updates forest resources using growth models in order to predict the evolution of forest condition taking into account external drivers. The first version of the simulator, mainly driven by wood demand, but also accounting for hazards, more specifically fire occurrence and land use changes is described in detail in **Chapter III**. In this chapter, the conclusions of a long-term analysis of the impact of fire severity on the Portuguese forest are discussed.

The next step was making SIMPLOT secondarily driven by biomass demand, which required structural changes in SIMPLOT. So far, SIMPLOT's growth module only included growth models developed for projecting the growth of stands managed for pulp. In order to simulate the growth of bioenergy plantations, some correction factors, to be applied to Globulus 3.0 estimates, were developed and integrated into the growth module. Also, biomass modules were integrated into SIMPLOT in order to account for different sources of biomass used for energy. The updated version of the simulator was used to assess the impact of different biomass demands for bioenergy, combined with different afforestation alternatives on the wood available for the pulp and paper industry in Portugal (**Chapter IV**).

At this stage, the simulator's second version covered all types of stands taking into account several external drivers such as wood and biomass demands, fire occurrence and land use changes. Notwithstanding, because projections obtained from running regional simulators are often used by policy makers to assist and support their decision making process, these tools need to be validated to increase credibility and gain sufficient confidence about its outputs. Therefore, SIMPLOT was initialized with data from 1995-1997 NFI, with historic data used to define the drivers, and the resulting projections were compared with 2005-2006 NFI data. The methodology applied in the validation process and the results obtained can be found in **Chapter V.**

In the meantime, the need to simulate short-rotation stands for bio-energy production more accurately led to another study. At present, no results from studies about the development of this species under short-rotation management are available. Thus, in a first step, Globulus growth estimates for highly stocked stands were evaluated. In a second step, new functions for bio-energy production stands were developed. The results from Globulus evaluation and the process of developing the growth model for highly stocked stands, GlobEP, are presented in **Chapter VI**.

Empirical models, apart from being site specific and highly dependent on the concept of site index, are also known to be limited when it comes to simulating the effects of environmental stresses, conversely process-based models are expected to overcome these limitations. In order to make SIMPLOT sensitive to new management practices and climate changes, process-based models must integrate the simulator's growth module. However, these models are demanding in terms of soil input, which are not available from the Portuguese NFI surveys, although there is the possibility to use soil information derived from soil maps. To test whether this was feasible, 3PG and Glob3PG were run using soil characteristics estimated from cartography complemented with stand measurements, as input. Their projections were compared to Globulus empirical model, which was used as a benchmark (**Chapter VII**). In order to test the performances of the process-based models, two stand/forest level simulators were developed, one based on empirical models and the other based on process-based ones: GLOBULUS and 3PG-out+, respectively. Similarly to GLOBULUS, 3PG-out+ is driven by management and at the same time it accounts for weather and soil characteristics. Brief descriptions of these stand level tools are included in **Chapter VIII**.

All simulators were programmed in FORTRAN language and are organized in modules and subroutines that are called by the main program in a proper order. Some modules integrate several subroutines, while others are composed of a single subroutine.

The programming process was progressive and followed by the development of a common platform that integrates different simulators for the Portuguese forest – sIMfLOR. A lot of efforts have been made to make sIMfLOR as user friendly as possible. A visual interface was developed and programmed in VB.net to facilitate generating and/or importing the simulators required inputs. The conception of sIMfLOR is not part of this thesis despite the PhD candidate was involved in it.

Finally, **Chapter VIII** apart from stressing the importance to the forest sector of the tools developed and studies conducted also summarizes the main results of this research. Moreover, this chapter also covers some topics that despite essential to this work would have passed unnoticed given the structure of the thesis, such as the problems related to data needs and sources, the underlying assumptions respecting to silvicultural systems, forest management approaches and prescriptions.

I.3 Literature Cited

Amaro, A., 2003. SOP model. The SOP Model: the Parameter Estimation Alternatives. In: Amaro, A., Reed, D. and Soares, P.(Eds.), Modelling Forest Systems. CABI Publishing, USA.

Amaro, A., Reed, D., Tomé, M., Themido, I., 1998. Modeling Dominant Height Growth: Eucalyptus Plantations in Portugal. Forest Science, 44 (1): 37-46.

Associação da Indústria Papeleira (CELPA). [s.d.]. A Indústria papeleira no contexto das alterações climáticas. [online] URL: http://www.celpa.pt/Default.aspx?PageId=207&ContentId=22&ChannelId=113

Associação da Indústria Papeleira (CELPA). 2009. *Boletim Estatístico 2008* da Associação da Indústria Papeleira. CELPA Editores. Lisbon, Portugal.

Associação da Indústria Papeleira (CELPA). 2010. *Boletim Estatístico 2009* da Associação da Indústria Papeleira. CELPA Editores. Lisbon, Portugal.

Associação da Indústria Papeleira (CELPA). 2011. *Boletim Estatístico 2010* da Associação da Indústria Papeleira. CELPA Editores. Lisbon, Portugal.

Autoridade Florestal Nacional (AFN). 2010. *Inventário Florestal Nacional. IFN 2005-2006. Portugal Continental*. Autoridade Florestal Nacional, Ministério da Agricultura do Desenvolvimento Rural e das Pescas, Lisbon, Portugal.

Barreiro, S., Tomé, M., Tomé, J., 2004. Modeling growth of unknown age even-aged eucalyptus stands. In: Hasenauer, H., Makela, A. (Eds.), Modeling Forest Production.

Scientific Tools—Data Needs and Sources. Validation and Application. Proceedings of the International Conference, Wien, pp. 34–43.

Borges J.G., Borges G.C., 2007. Impactes socioeconómicos da expansão do eucaliptal. In: Monteiro Alves A., Pereira, J.S., Silva, J.M.N. (Eds.), O Eucaliptal em Portugal. Impactes Ambientais e Investigação Científica, ISA Press, Lisboa.

Direcção Geral dos Serviços Florestais e Aquícolas (DGSFA), 1966a. Inventário ao Norte do Tejo - 1965-66. Direcção Geral dos Serviços Florestais e Aquícolas, Lisboa, Portugal.

Direcção Geral dos Serviços Florestais e Aquícolas (DGSFA), 1966b. Inventário ao Sul do Tejo - 1965-66. Direcção Geral dos Serviços Florestais e Aquícolas, Lisboa, Portugal.

Diário da República (DRE). 2005a. Diário da República Electrónico, PRESIDÊNCIA DO CONSELHO DE MINISTROS, Resolução do Conselho de Ministros nº 169/2005, DIÁRIO DA REPÚBLICA-I SÉRIE-B, nº 204 -24 de Outubro de 2005, Lisboa, Portugal. [online] URL: http://dre.pt/pdf1sdip/2005/10/204B00/61686176.pdf

Diário da República (DRE). 2005b. Diário da República Electrónico, Ministério das Actividades Económicas e do Trabalho, Decreto-Lei nº 33-A/2005 de 16 de Fevereiro, DIÁRIO DA REPÚBLICA -I SÉRIE-A nº 33-16 de Fevereiro de 2005, Lisboa, Portugal. [online] URL: http://dre.pt/pdf1sdip/2005/02/033A01/00020009.pdf

Diário da República (DRE). 2006. Diário da República Electrónico, PRESIDÊNCIA DO CONSELHO DE MINISTROS, Resolução do Conselho de Ministros nº 115/2006, Diário da República, 1.a série - nº 180-18 de Setembro de 2006, Lisboa, Portugal. [online] URL: http://dre.pt/pdf1sdip/2006/09/18000/68356881.pdf

Fontes, L., Landsberg, J.J., Tomé, J., Tomé, M., Pacheco, C.A., Soares, P., Araújo, C., 2006. Calibration and testing of a generalized process-based model for use in Portuguese eucalyptus plantations. Canadian Journal of Forest Research, 36: 3209-3221.

FPFP. 2001. Globulus v2.0. Modelo de produção para o Eucalipto. Manual do utilizador. Edição da Federação dos Produtores Florestais de Portugal. 35 pp.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency. Carbon balance and partitioning. Forest Ecology and Management, 95: 209-228.

Nabuurs, G.J., Päivinen, R., Pussinen, A., Schelhaas, M.J., 2003. Development of European Forests until 2050 - a projection of forests and forest management in thirty countries, EFI Research Report, vol. 15. European Forest Institute.

Pussinen, A., Schelhaas, M.J., Verkaik, E., Heikkinen, E., Liski, J., Karjalainen, T., Päivinen, R., Nabuurs, G.J., 2001. Manual for the European Forest Information Scenario Model (EFISCEN 2.0), EFI Internal Report, vol. 5. European Forest Institute.

Sands, P., Landesberg J.J., 2002. Parameterisation of 3PG for plantation grown *Eucalyptus globulus*. Forest Ecology and Management, 163: 273-292.

Schelhaas, M.J., Cerny, M.I., Buksha, F., Cienciala, E., Csoka, P., Galinksi, W., Karjalainen, T., Kolozs, L., Nabuurs, G.J., Pasternak, V.P., Pussinen, A., Sodor, M., Wawrzoniak, J., 2004. Scenarios on Forest Management in Czech Republic, Hungary, Poland and Ukraine, EFI Research Report, vol. 17., European Forest Institute.

Soares P., Tomé, M., 2003. GLOBTREE: an Individual Tree Growth Model for Eucalpytus globulus in Portugal. In: Amaro, A., Reed, D., Soares, P. (Eds.), Modelling forest systems. CAB International, pp. 97-110.

Tomé, M., Soares P., Oliveira, T., 2006. O modelo GLOBULUS 3.0. Dados e equações. Publicações GIMREF RC2/2006. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.

Tomé, J., Tomé, M., Fontes, L., Soares, P., Pacheco, C.A., Araújo, C., 2004a. Testing 3PG with irrigated and fertilized plots established in *Eucalyptus globulus* plantations in Portugal. In: Hasenauer, H., Makela, A. Modeling forest production. Scientific tools - data needs and sources. Validation and Application. Proceedings of the International Conference, Wien, pp. 382-390.

Tomé, M., Faias, S.P., Tomé, J., Cortiçada, A., Soares, P., Araújo, C., 2004b. Hybridizing a stand level process-based model with growth and yield models for *Eucalyptus globulus* plantations in Portugal. In: Borralho, N.M.G., Pereira, J.S., Marques, C., Coutinho, J., Madeira, M., Tomé, M. (Eds.), Eucalyptus in a changing world. Proceedings of the IUFRO International Conference, Aveiro, pp. 290-297.

Tomé, M., Borges, J.G., Falcão, A., 2001. The use of Management-Oriented Growth and Yield Models to Assess and Model Forest Wood Sustainability. A case study for Eucalyptus Plantations in Portugal. In: Carnus, J.M., Denwar, R., Loustau, D., Tomé, M., Orazio, C. (Eds.), Models for Sustainable Management of Temperate Plantation Forests, European Forest Institute, Joensuu, pp. 81-94.

Tomé, M., Ribeiro, F., 2000. GLOBULUS 2.0, um modelo de aplicação nacional para a simulação da produção e crescimento do eucalipto em Portugal. Relatórios técnico-científicos do GIMREF nº 1/2000, Centro de Estudos Florestais, Instituto Superior de Agronomia, Lisboa, Portugal.

United Nations. 1998. *Kyoto protocol to the United Nations framework convention on climate change.* United Nations Climate Change Secretariat, Bonn, Germany. [online] URL: http://unfccc.int/resource/docs/convkp/kpeng.pdf

CHAPTER II

Classification of forest management approaches: a new conceptual framework and its applicability to European forestry

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Classification of Forest Management Approaches: a new Conceptual Framework and its Applicability to European Forestry

II.1 Abstract

The choice between different forest management practices is a crucial step in short, medium and long-term decision-making in forestry and when setting up measures to support a regional or national forest policy. Some conditions such as biogeographically determined site factors, exposure to major disturbances and societal demands are pre-determined, whereas operational processes such as species selection, site preparation, planting, tending or thinning can be altered by management. In principle, the concept of a forest management approach provides a framework for decision-making including a range of silvicultural operations which influence the development of a stand or group of trees over time. These operations vary between silvicultural systems and can be formulated as a set of basic principles. Consequently, forest management approaches are essentially defined by coherent sets of forest operation processes at a stand level.

Five ideal forest management approaches (FMAs) representing a gradient of management intensity are described using specific sets of basic principles which enable comparison across European forests. Each approach was illustrated by a regional European case study. The observed regional variations resulting from changing species composition, stand density, age structure, stand edges and site conditions could be interpreted using the FMA framework.

Despite being arranged along an intensity gradient, the forest management approaches are not considered to be mutually exclusive, as the range of options allows for greater freedom in selecting potential silvicultural operations. As derived goods and services are clearly affected, the five forest management approaches have implications for sustainability. Thus, management objectives can influence the balance between the economic, ecological, and social dimensions of sustainability.

II.2 Introduction

Sustainable forest management (SFM) is a key concept that underpins modern forestry forests, as outlined in Europe in the principles agreed through the Ministerial Conference on the Protection of Forests in Europe (MCPFE 2003a). However, assessing the overall sustainability of different types of forestry practice is complicated because of variation both in the nature of the forest resource and in the impacts of different management measures in space and over time (Kimmins 1992). For example, European forests cover a wide range of climatic zones and forest types ranging from the spruce-pine forests of boreal Scandinavia to the mixed oak and pine forests of Mediterranean Europe (EEA 2006). In addition, there are extensive plantation forests of conifers in Atlantic Europe and broadleaved plantations in Hungary and other Central European countries. In each of these forest types, a range of silvicultural operations can be applied from intensive systems based on clear felling and artificial regeneration to the fostering of irregular stand structures based on natural regeneration. Each coherent set of silvicultural operations applied to a given forest forms a silvicultural system which may be defined as ‘the process by which the crops constituting a forest are tended, removed, and replaced by new crops, resulting in the production of stands of distinctive form’ (Matthews 1989).

Therefore, the informed choice of a silvicultural system is a crucial step in forest planning which can have major consequences for sustainability. The selection has to be made in a wider context that can only be partially influenced by a forest manager. Some conditions are predetermined or are beyond the control of forest management, e.g. biogeographically determined site conditions, current tree species composition, climate, but also economic and market circumstances and the formal and informal demands made by society at large. Other conditions are under direct control of forest management through the application of silvicultural operations at a stand level, such as site preparation, tree species selection, planting, tending, thinning, and final harvest regime. The wide range of forest types coupled with a variety of silvicultural systems can make it difficult to carry out a comparative sustainability analysis of different methods of forest management at either a regional or a continental scale.

Various studies have tried to classify silvicultural systems, usually along one out of two main axes: an economic axis where systems are categorized according to production factor utilization and economic return (Speidel et al. 1969, Dummel 1970, Arano and Munn 2006), or an ecological axis where the categories depend on the degree of modification of natural conditions (Seymour et al. 1999, Pro Silva 1999, MCPFE 2003c, Gamborg and Larsen 2003). Most classifications of this type have tended to adopt a three category system which contrasts non-intervention reserves with intensively managed plantations and with a more extensive form of management which may seek to emulate natural disturbances or to practice close-to-nature forestry (Montigny and MacLean 2006, Gamborg and Larsen 2003). One problem with this structure is that it ignores the variety of silvicultural systems which can be used in management of plantations, which can have consequential impact on biodiversity and other criteria of sustainability (Carnus et al. 2006).

Current attempts to assess the sustainability of forest management practices in Europe, whether as part of a set of land uses (Helming et al. 2008) or as the first part of a forestry wood chain (Paivinen et al. 2010), require a standard classification that can be linked to criteria and indicators of sustainability at local or national level, yet which is sufficiently flexible to be capable of application across a wide range of forest types.

In this paper we present a new framework for classifying silvicultural systems and practices in relation to management intensity. Unlike existing classifications that are generally centered on two dimensions of sustainability, this framework is designed to be used with criteria and indicators reflecting the full range of economic, ecological and social components of sustainability. Irrespective of the particular aims of forest management, the actions taken (including a decision to take no action) will have consequences for forest ecosystem status and processes. Such actions will affect, to some degree, the goods and services derived from forests. Thus, the provision of goods and ecosystem services can be considered to be both a consequence as well as a driver of forest management. As such, our framework can serve as the foundation of any analysis wishing to explore the effect of changing policies and silvicultural operations upon criteria and indicators of sustainability, and upon the provision of ecosystem services. A suite of Forest Management Approaches (FMAs) is proposed, defined by the silvicultural operations practiced and the intensity of human manipulation of the processes of natural forest development. The FMAs are characterized by a coherent set of objectives and supporting practices, which results in a framework that should allow transnational, cross-regional and within-region comparisons of different silvicultural systems. This framework includes the detail of local technological, economic and ecological situations, while still being insightful for policy at the regional and cross-regional level. We illustrate the potential utility of this framework of FMAs by applying it to five European regions with different tree species and varying silvicultural regimes.

II.3 Basic Decisions and Principles in Forest Management

The implementation of a silvicultural system involves a number of decisions on the type of operations to employ at the various phases of the development of a stand or group of trees. These operations can affect one or more key stand variables, such as tree species composition, stand density and age structure, stand edges, or site conditions, which in turn influence the provision of a range of ecosystem services. Further, within any given FMA, a particular criterion of sustainability (e.g. aspects of biodiversity, public preference for forest landscapes) may vary with different stages of tree growth. Therefore we have classified the development of a stand or group of trees into four “phases of development” according to their height and diameter: Regeneration (I), Young (II), Medium (III) and Adult (IV). The phases are not mutually exclusive in space or over time since, under certain conditions, they may occur together in the same stand, e.g. in the complex stand structures characteristic of ‘close-to-nature’ forestry. However, defining these phases is a means of arranging silvicultural operations and decisions along management cycles (**Table 1**). The value of being able to combine FMAs with their constituent phases is shown by Edwards et al. (submitted) and Jactel et al. (submitted). The first phase refers to the period from the start of establishing young trees naturally or artificially until the stand has reached 2 to 3 m height (Helms 1998). The second phase lasts until trees have reached pole size, i.e. 7 cm diameter at breast height (DBH). The third phase covers the period from trees having a DBH equal to 7 cm until the age/size when they have attained most of their potential height growth. The fourth phase is reached when height growth has largely ceased although diameter growth may continue, this phase includes the onset of senescence and eventual tree death. Although the phases are defined by tree size/health they differ slightly from development stages sensu Oliver and Larson (1996). While “Regeneration” corresponds to the ‘stand initiation’ stage, their ‘stem exclusion’ stage is split here into “Young” and “Medium” phases which are typically characterised by pre-commercial or thinning operations respectively. While the beginning of the “adult” phase and their ‘understorey re-initiation’ stage are quite similar, no separate ‘old growth’ stage is distinguished in our classification. **Table 1** summarizes the 12 critical decisions chosen for defining FMAs, the phases of stand or tree group development to which they predominantly refer and the key variables they affect as well as some associated silvicultural operations. This summary partly reflects criteria previously developed and discussed by Winkel et al. (2005). Having identified these essential decisions to be considered in the framework, clear differences have to be defined for each decision that will allow one to distinguish between FMAs. We call these limits the ‘basic principles’ of a

FMA which reflect the objective of the particular FMA and which identify the set of silvicultural operations appropriate for each decision.

Table1. Major decisions involved in forest management, the associated silvicultural operations, and the link to sustainability indicators.

Decision and subsidiary elements (and phase of development[†])	**Silvicultural operation**	**Affected stand variable and sustainability criteria**
1. Naturalness of tree species composition (I-IV[‡]) Species composition in relation to the potential natural vegetation Share of site-adapted tree species Share of introduced tree species	Selection of tree species	Biological diversity Tree species composition
2. Tree improvement (I) Use of genetically improved material Use of genetically modified organisms	Selection of tree genotypes	Biological diversity Stand genetic diversity
3. Type of regeneration (I) Planting, seeding, natural regeneration or coppice	Stand establishment	Stand density (growing stock) Age structure/ diameter distribution Tree species composition
4. Successional elements (I-IV) Tolerance of successional elements, i.e. pioneer and nurse species or accompanying secondary tree species	Stand establishment Tending Thinning	Tree species composition Density pattern
5. Machine operation (I-IV) Machine movement/driving on forest soils Extent of forest opening for machine access	Fertilizing Liming Soil preparation Thinning Final harvest	Forest ecosystem health and vitality Site condition
6. Soil cultivation (I) Mechanical, physical and chemical site preparation Drainage	Soil preparation Drainage	Site condition
7. Fertilisation / Liming (I-IV) Fertilization to increase yield (amelioration) Compensate for nutrient extraction and re-establishment of natural biogeochemical cycles	Fertilisation Liming	Site condition
8. Application of chemical protective agents (I-IV) Extent of application of pesticides, herbicides	Pest control	Tree species composition
9. Integration of nature protection (I-IV) Tolerance of biotope/habitat trees Tolerance of deadwood Biotope protection within stands	Thinning Final harvest	Biological diversity Tree species composition Density pattern Age structure
10. Tree Removals (III-IV) Extent of tree components extracted in thinning or harvesting operations	Thinning Final harvest	Site condition Carbon stock
11. Final harvest system (III-IV) Extent of area cleared by a final harvest operation	Final harvest	Density pattern Age structure/ diameter distribution
12. Maturity (III-IV) Felling age in relation to the potential life span of a given tree species	Final harvest	Biological diversity Age structure

[†] Phase of stand development the critical decision predominantly refers to., [‡] I “regeneration”, II “young”, III “medium” and IV “adult”.

II.4 Forest Management Approaches

Using these twelve decisions and their associated basic principles, we are able to describe five FMAs arranged along a gradient of intensity of resource manipulation (from 'passive' to 'intensive'). The intensity of manipulation associated with a particular FMA results from the deliberate alteration of key stand variables through utilization of production factors. Therefore, the degree of naturalness of forest ecosystems is indicative of the intensity of human intervention. Different levels of intensity can be characterised not only by changing stand structures but also by different species communities and, thus influence the biological diversity of an area (MCPFE 2003b). **Table 2** shows how the decisions and their basic principles relate to the five FMAs proposed arranged along a scale of intensity of intervention. We also show how the different FMAs relate to traditional silvicultural systems used in European forests (e.g. Matthews 1989). In the following sections, the management objectives and basic principles of the five FMAs listed in **Table 2** are described.

II.4.1. Passive - Unmanaged forest nature reserve

Management objective: An unmanaged forest nature reserve is an area where natural processes and natural disturbance regimes are tolerated to develop without management intervention and where ecological and societal goals are given primacy. The aim is to maintain ecologically valuable habitats and their dependant biodiversity, while also providing a reference for the development of close-to-nature silviculture (see below). Depending upon the dominating stand or tree group development phase within this FMA, the area may be more or less valuable for these objectives. Furthermore, as an important landscape feature, the reserve may serve as a backdrop to forest recreation, and be used for basic and applied research (Parviainen et al. 2000). These areas may be protected by an ordinance or forest act (IUFRO 2007).

Basic principles: No operations are allowed in a forest reserve that might change the nature of the area. Stands have a history of development without direct management or exploitation resulting in various qualities of naturalness (Peterken 1996, Sprugel 1991). Permissible operations (with limitations) can be the building of a trail so that people can visit these places of high ecological value. Other treatments may be allowed if the future of the area is compromised by external factors such as heavy browsing by deer or other animals. Such control measures must be limited and their only purpose is to protect the reserve from destruction, because in Europe these habitats are often very limited in size, and therefore do not have the resilience against major disturbances that a larger area would have. A further reason for taking control measures would be to prevent major threats to adjacent stands managed under one of the four other approaches (Michalski et al. 2004, Popiel and Karczewski 2006).

II.4.2 Low - Close-to-nature forestry

Management objective: Close to nature is a “classification of stands or forest according to how closely they resemble nature. This classification is based on the impact of man, for which naturalness is defined as the extent to which man’s impact is absent or hidden” (IUFRO 2007). The objective of close-to-nature forestry is to manage a stand with the emulation of natural processes as a guiding principle. Economic outturn is important, but must occur within the frame of this principle. Any management intervention in the forest has to enhance or conserve the ecological functions of the forest. Timber can be harvested and extracted during these activities, but some standing and fallen dead wood has to remain in the forest, which may reduce productivity (FAOTERM 2007).

Basic principles: Only native or site adapted tree species are chosen. The preferred method of regeneration is natural regeneration. Planting can be used to re-introduce native species into a devastated forest, but genetically improved planting material cannot be used. Species mixtures follow the typical composition for the stand type. Guidance on natural processes to be emulated and the patterns produced by various disturbance mechanisms is often based on findings from areas treated as ‘unmanaged forest nature reserves’ (e.g. Brang 2005). Soil cultivation or fertilization can only be done to restore the “naturalness” of the forest, if for example the sites have been so intensively managed in the past that these treatments are necessary to initiate any potential natural vegetation. Chemical pest control can only be applied during major events which spread from the surrounding stands. Small outbreaks should not be treated so that natural control processes are promoted. Concepts such as rotation length are of limited value and the decision on which tree(s) to harvest is often based on target diameters and stem quality rather than age. Biological legacies and natural biotopes should be promoted inside the stands. The final harvesting system should simulate the natural disturbance mechanisms, and therefore clear-cuts are not allowed unless stand replacing natural disturbances are characteristic of this forest type. Extraction of biomass is limited to the removal of the stems. Machine operations should be limited to a minimum with an emphasis on the protection of the natural structures during the activities. The use of appropriate machines, which suit the structure and features of the forest (Pro Silva 1999) is restricted to a strip road system (with an extensive rack system).

II.4.3 Medium - Combined objective forestry

Management objective: This FMA is an approach that assumes that various management objectives can be combined in a manner that satisfies diverse needs better than through zoning where individual objectives are maximised in separate areas. Generally economic and ecological concerns play a major role in this FMA. Additional objectives to timber production can be: habitat, water and soil protection; mushroom production, game management and nature protection, avalanche and fire prevention, and recreation. Due to the great variability within combined objective forestry, it is often easier to define the limits of a combined objective forestry approach than the strategy itself. This allows for optimal adaptation to the local situation.

Basic principles: Native or introduced tree species suitable for the site can be chosen. The preferred method of regeneration is natural regeneration but planting or seeding is acceptable to introduce native or desired species that would not otherwise occur. Products of tree breeding can be planted, but genetically modified planting material cannot be used. Tree species mixtures are typical for the forest type. Site cultivation and/or fertilization can be carried out to enhance the development of the forest, provided that these treatments are necessary to restore vegetation cover. Chemical pest control can be used in major outbreaks which are either introduced from the surrounding stands or placed the latter at risk. Minor outbreaks should not be treated with pesticides while natural measures are preferred for pest control as well as to increase resilience (e.g. greater use of mixed species stands). The rotation length is often longer than the age of maximum mean annual volume increment (MMAI) provided that financial criteria do not dictate otherwise. Biological legacies and natural habitats should be promoted inside the stands. The final harvesting system should be compatible with the chosen regeneration method. The intensity of harvesting is generally limited to solid wood volume, i.e. stem and branches with a diameter larger than 7 cm. Vehicle movement is restricted to a strip road system (with an intensive rack system), so that machine operations protect the residual stand and soil.

II.4.4 High - Intensive even-aged forestry

Management objective: The intensive even-aged classification is characterised by stand or forest types, in which no or relatively small age differences occur among individual trees (IUFRO 2007). The age differences are usually less than 20% of rotation length. Typical stands consist of even-aged monocultures (sometimes with a small percentage of admixed species). The main objective of intensive even-aged forestry is to produce timber. If ecological aims can be achieved without much loss of revenue, they are normally incorporated. In many European countries, national guidelines outline the best practices for ensuring that operations in this approach are compatible with sustainability and environmental protection.

Basic principles: Any non-invasive tree species suitable for the site can be chosen. Planting, coppice, seeding and natural regeneration are all possible regeneration methods. Economic factors are used to decide between the alternative methods. Planting/seeding material can be genetically improved, but not genetically modified. Typically, monocultures with small percentages of mixed-species stands (admixed species preferably also produce merchantable timber) are used to implement this strategy. Admixed species are generally only used if some parts of the stand fail, and/or if no economic loss is associated with their use. Site preparation is often used to enhance establishment success and remedial fertilization is used to increase growth rates. Chemical control of pests and diseases is kept to the minimum necessary. The rotation length depends mainly on the economic return and is normally similar to or shorter than the age of MMAI. Biological legacies can be incorporated to improve the ecological values of the stand, as long as the economic return is not substantially reduced. Biomass extraction is commonly limited to solid wood volume but might include whole tree extraction e.g. for bio-energy. Machine operations are not limited, as long as they do not harm the environment. The final harvest system is preferably clear cut or a combination of shelterwood and clear-cut if natural regeneration is preferred to reduce the costs of establishment.

II.4.5 Intensive – Short-rotation forestry

Management objective: The main objective of short-rotation forestry is to produce the highest amount of merchantable timber or wood biomass. Economic objectives are given priority while ecological concerns play a minor role in this approach.

Basic principles: The tree species selection depends mainly on the economic return. The planting material can be genetically improved and/or genetically modified. No natural colonisation by other tree species is permitted, if it reduces the growth of the chosen tree species. Sites are mechanically cultivated and can also be drained or irrigated if needed. Fertilization and liming are applied to the stands to enhance growth. Chemicals are used to treat pests and diseases and also for weed control. The rotation length only depends on the economic return, is often 20 years or less, and no biological legacies are included. No other habitats are maintained within the stand. The intensity of machine operations is at a maximum compared to the other approaches and is only limited by national environmental laws. The final harvesting system is a clear-cut combined with removal of all woody residues if there is a suitable market for these.

II.5 Using FMAs to Classify Forest Management in Different European Regions

To illustrate the potential utility of the framework proposed in **Table 2**, current forest management practices from five forest types in different European case studies (see **Appendix**) were described and classified. These practices were taken from the best practice guidelines for the relevant country or region. The classification process was based on evaluating each decision in the forest management cycle for each forest type according to the basic principles for the FMA. This provided a rating for the 12 basic decisions, and gave a quick overview of the intensity of the silvicultural practices described in each case study (**Fig. 1**).

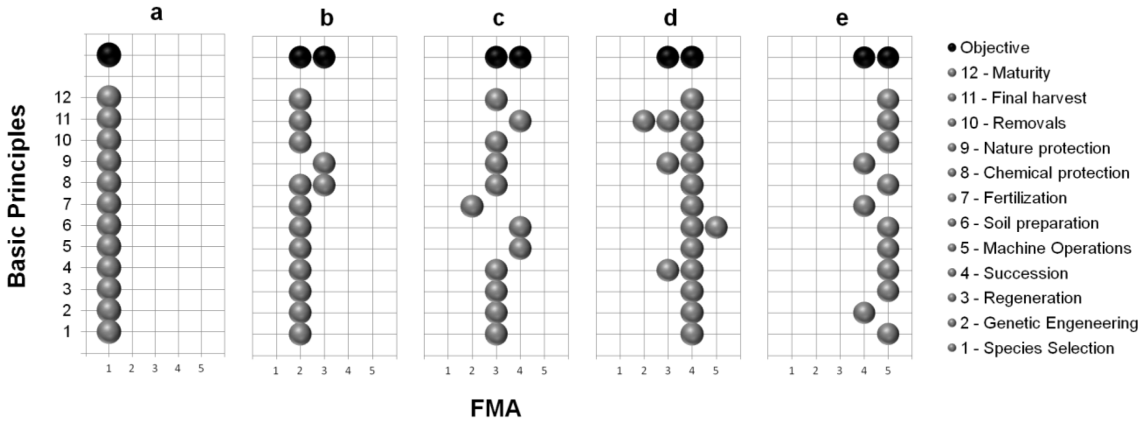

Fig. 1. Classification of the case studies along the intensity gradient where a) Forest nature reserve in Białowieża National Park, Poland, b) European beech management in Baden-Württemberg, Germany, c) Norway spruce management in the county of Västerbotten in Sweden, d) Sitka spruce management in Scotland and e) Eucalyptus management in Portugal.

Table 2. A list of the 12 major decisions, the basic principles used to distinguish between the 5 Forest Management Approaches (FMAs) and the main silvicultural systems associated with FMAs.

	Basic principles by FMA intensity scale				
Decision	**Passive** "Unmanaged forest nature reserve"	**Low** "Close-to-nature forestry"	**Medium** "Combined objective forestry"	**High** "Intensive even-aged forestry"	**Intensive** "Short-rotation forestry"
1. Naturalness of tree species composition	Only species characteristic of the potential natural vegetation	Native or site adapted species	Tree species suitable for the site	Tree species suitable for the site	Any species (not invasive)
2. Tree improvement†	No	Not genetically modified or derived from tree breeding programmes	Planting material can be derived from tree breeding but not genetically modified	Planting material can be derived from tree breeding but not genetically modified	Planting material can be derived from tree breeding or produced via genetic modification
3. Type of regeneration	Natural regeneration / natural succession	Natural regeneration (planting for enrichment or change in tree species composition)	Natural regeneration, planting and seeding	Natural regeneration, planting, seeding and coppice	Planting, seeding and coppice.
4. Successional elements	Yes	Yes	Temporarily	No	No
5. Machine operation	No	Extensive	Medium	Intensive	Most intensive
6. Soil cultivation	No	No (only to introduce natural regeneration)	Possible (mainly to promote natural regeneration)	Possible	Yes
7. Fertilisation / Liming	No	No (only for devastated soil‡)	No (only for devastated soil‡)	Possible	Yes
8. Application of chemical agents	No	No	Possible as a last resort	Possible	Possible
9. Integration of nature protection	High	High	High	Medium	Low
10. Tree removals	No	Stem (solid volume)	Stem and crown (solid volume)	Up to whole tree	Whole tree and residues
11. Final harvest (and main silvicultural) system	No	Mimics natural disturbances: Single stem or Group selection And Irregular shelterwood	All possible: Seed tree, Strip, Group and Uniform shelterwood	All possible: Clear fell (long rotation) preferably used	All possible: coppice clear fell (shorter rotation)
12. Maturity	No intervention	Long rotation length ≥ age of max. MAI or target diameter according to tree species and stem quality	Medium rotation length ≈ age of max. MAI or target diameter according to tree species and stem quality	Short-rotation length ≈ age of max. financial return (low interest rate)	Shortest rotation length ≤ age of max. MAI or ≈ age of max. financial return (high interest rate)

† In this decision element, the definitions might need to be adjusted in future if the principle of genetic modification became more widely accepted in forestry. For example, planting stock produced through genetic modification might be accepted in 'Intensive even-aged forestry'. **‡** Devastated soil = soil that needs measures to get in an acceptable condition.

The Bialowieza National Park reserve in Poland exemplifies the Unmanaged Forest Nature Reserve FMA for which the main objective is to allow natural processes and natural disturbance regimes to develop without human intervention (**Appendix a**). The next FMA along the intensity scale, Close-to-Nature, is represented by the European beech management practiced in Baden-Württemberg, Germany (**Appendix b**) where the emphasis on use of native species, natural regeneration, limited site disturbance and no chemical inputs are all characteristic of this FMA. However, the intensity of timber removal in this approach is more characteristic of 'combined objective forestry', which is here exemplified by the management of mixtures dominated by Norway spruce forests in Sweden (**Appendix c**). In the latter case site preparation, machine operation and final harvest are more intensive than would be expected while fertilisation is less intensive. In Scotland, the management of Sitka spruce forests is generally representative of intensive even-aged forestry, but there are components such as the acceptance of successional elements and the provision for nature protection which are indicative of less intensive FMAs (**Appendix d**). Finally, eucalyptus stands in Portugal grown on short-rotation under coppice regimes represent one of the most intensive levels of management found in European forests (**Appendix e**).

II.6 Discussion

In this paper, a framework is presented which classifies of forest management according to the degree of interference with natural processes resulting from the silvicultural systems employed. Based on this framework, five forest management approaches (FMAs) have been defined along a gradient of management intensity. This framework defines forest management intensity as the manipulation of natural processes (i.e. along an ecological axis) but at the same time includes cost and yield objectives in the classification scheme (i.e. along an economic axis). This allows grading and comparison of various types of forest management with different objectives both between and within regions. The gradient of management intensity covered by our framework is illustrated through the application to five case studies (**Fig. 1**).

The intensity of forest management is often either described using economic or ecological considerations. In managerial economics, intensity addresses the extent to which the production factors such as soil, labour, energy and capital are utilized (Martin 1991). The intensity is set in relation to the management objectives to define the optimal input of production factors. On this basis, classes in forest management intensity were defined in relation to net-return criteria (Speidel et al. 1969) and production costs have been used as a measure to evaluate management intensity (Arano and Munn 2006). These proposals imply that management intensity primarily reflects the productive function of forests while other non-market goods and services only justify maintenance of management costs not covered by wood sales (Kroth et al. 1969). This has provoked discussion whether the approach is acceptable for long-term forest planning (Möhring 1969, Speidel 1969, Dummel 1970). Further, because production costs are the product of a production factor price and the utilized factor quantity, they are of limited use if intensity is to be defined in a wider operational dimension (Sagl 1990). Forest management implies purposeful manipulation of stand and site which can result in a changed ecosystem. The more natural conditions are controlled and modified through operational processes, the more intensive a management approach might be considered. Various factors such as controllability, the amount of usage (i.e. extracted volume of biomass) and the degree of modification of natural conditions required to achieve management objectives differentiate approaches in forestry (Seymour et al. 1999, Pro Silva 1999, Gamborg and Larsen 2003) or serve to group forested areas (MCPFE 2003c). Where the classifications along the economic axis focus on the productive function, the classifications along the ecological axis tend to focus on the protective functions of forests and are usually policy driven. Our framework combines both considerations through the formulation of critical decisions (**Table 1**) and basic principles (**Table 2**) and thus allows grading and comparison of various types of forest management with different objectives as illustrated with five case studies.

The selected case studies (**Fig. 1**) describe management based on the manipulation intensity associated to each basic principle. As a result, a silvicultural system is classified under a particular FMA depending on how the basic principles are distributed across the gradient of management intensity. Moreover, the distribution of basic principles across the intensity gradient shows the separation between FMAs and also indicates the possibility of conversion between FMAs. If management objectives for a forest change, then the balance of the various decisions and elements (**Table 1**) used to determine which FMA is prevalent in a given forest may also be affected. Therefore, over time, the classification of a forest may alter from one FMA to another, for example, if Norway spruce forests managed under FMA 4 are converted to close-to-nature forestry due to ecological considerations (e.g. Kulhavý et al. 2004). In such cases a transition period should be defined and the length of time required for this transition will vary with forest type and region. The duration of this period is likely to be longer when moving between FMAs that are wide apart on the intensity scale (**Table 2**) than for those that are close together. For example, even under favourable conditions, conversion of an existing forest to close-to-nature forestry requires decades (Spiecker et al. 2004). Less flexible situations (e.g. forests in areas with a high risk of fire or wind damage) often limit the conversion of older stands and more natural stand structures cannot be developed before the regeneration phase of the next generation of stands. It is generally quicker to implement a move to a more intensive FMA than the reverse because aspects such as the establishment of young trees are faster when achieved through cultivation and planting than through natural regeneration.

The identification of five different FMAs offers greater flexibility in evaluating impacts of forest management on sustainability indicators than is the case when using the Triad zonation approach (Seymour and Hunter 1999) whereby forests are separated into protected areas (equivalent to our FMA 1), multifunctional areas under ecosystem management (FMAs 2 and 3), and intensive plantations (FMA 4 and 5) (see **Table 3**). The value of this framework is underlined by comparing the forestry principles proposed by the European federation of foresters who advocate forest management on natural processes (Pro Silva 1999) against our decision criteria. Their preference for “responsible forest management following natural processes” would be graded as a ‘low’ intervention forest management approach according to our framework, although some operations of ‘medium’ intensity occur.

It is also possible to relate our FMAs to other forest classification systems developed by European conservation and environment agencies. For instance, the FMAs can be compared to the five classes of protected and protective forest and other wooded land in Europe (MCPFE 2003c) (see **Table 3**). MCPFE Class 1 covers areas with “Biodiversity” being the main management objective and has three subclasses according to the restrictions on intervention. The first two subclasses 1.1 and 1.2 with no active and minimum intervention match our passive ‘unmanaged forest nature reserve’ FMA. MCPFE subclass 1.3 with active interventions to achieve specific conservation goals only excluding silvicultural measures detrimental to the management objective might be assigned to our low intensity ‘close-to-nature’ approach. For a proper assignment of MCPFE-Class 2 “Protection of Landscapes and Specific Natural Elements” and Class 3 “Protective Functions” to FMAs, the specific conservation goal of the protected area needs to be known. However, judging by the definitions, MCPFE Class 2 still relates to our ’close-to-nature’ approach while the ‘combined objective’ FMA might well maintain the protective functions characteristic of MCPFE Class 3 through combination of protection and timber production in a holistic, integrative concept (Parviainen and Frank 2003). While not coping with the detail of subclasses in the MCPFE system, our FMAs are compatible with the major MCPFE Classes and have the advantage of going beyond that classification system to include production forestry.

Table 3. Comparison of MCPFE Classes of protected and protective forest and other wooded land in Europe , Forest Management Approaches (FMAs) and separated forest areas according to the Triad zonation approach.

MCPFE Classes[†] ***(main management objective)***	**FMA**	**Triad zonation approach**[‡]
1. “Biodiversity”		
1.1 “No Active Intervention” 1.2 “Minimum Intervention”	FMA 1: Passive – Unmanaged forest nature reserve	Protected areas
1.3 “Conservation Through Active Management”	FMA 2: Low - Close-to-nature forestry	Multifunctional areas under ecosystem management
2. “Protection of Landscapes and Specific Natural Elements”	-	-
3. “Protective Functions”	FMA 3: Medium – Combined objective forestry	-
No equivalent MCPFE classes defined	FMA 4: High - Intensive even-aged forestry FMA 5: Intensive – Short-rotation forestry	Intensive plantations

[†] MCPFE 2003c, [‡] Seymour and Hunter 1999

Because FMAs are defined by their objective and basic principles, there is some flexibility to allow adaptation to local situations within one FMA. Since FMAs are arranged along an ordinal scale they allow reasonable categorizing of forest management intensity but do not provide a measure for absolutely quantifying the magnitude of interference with natural processes nor the effects on ecological services. Inevitably, there is some overlap between FMAs as an examination of the framework used to evaluate the case studies in **Fig. 1** has shown. If, in a hypothetical example, the allocation of decision criteria appears to be evenly split between one FMA and another, then we suggest that a more detailed examination of the subsidiary elements listed in **Table 1** will allow allocation to the most appropriate FMA. Nevertheless, with the current state of forest resource and ecology modelling this flexible framework can enable comparison of different forest management approaches at a single stand or landscape level or of the same FMA in different forest types or regions, and with evaluation of potential effects over time. This comparison can not only involve economic production, but can also consider ecological criteria like biodiversity, water quality and carbon stocks (Duncker et al. submitted), the recreational use of the forest (Edwards et al. submitted), or the risks from hazards like biological pests, fire or windthrow (Jactel et al. submitted). Furthermore this methodology can provide a uniform framework for quantifying forest management in European wide forest resource models (Hengeveld et al. submitted). By combining the use of one management objective and one set of basic principles within one FMA with the flexibility of applying silvicultural operations that are specific to local circumstances and traditions, the framework of FMAs proposed in this paper is expected to provide a useful tool for facilitating communication between forestry policy and practice. For instance, Mason et al. (2009) have used this methodology to explore the implications of current forest policy in Great Britain upon future carbon sequestration and carbon stocks in British forests. Pizzirani et al. (2010) employed the framework to explore the effect of four different scenarios upon the management of Scots pine forests in northern Scotland and the consequent effects upon a range of sustainability indicators.

II.7 Conclusions

Forest management approaches can be characterized based on an objective and a set of basic principles reflecting decisions on operations that occur at various stages during the development of a stand. The FMAs form a gradient that reflects the intensity of manipulation of natural processes and structures, so that the methodology can be applied flexibly to classify a range of regional examples as shown here for diverse European forest management approaches. The five FMAs defined in this paper provide an extension of the MCPFE forest classes by including more intensive forest management strategies. They can be applied for evaluating existing forest management strategies, for comparing the effects of different silvicultural options on stand or landscape levels, or can be used for facilitating communication between forestry policy and practice.

The case studies selected illustrate the value of the FMA framework when it comes to discriminating between contrasting silvicultural systems. Nevertheless, to demonstrate the wider applicability of this method, further tests of the FMA classification should be carried out. The wider relevance of this classification will only be confirmed after being trailed in a wider range of European countries and silvicultural systems, as well as being used for within-region comparisons.

II.8 Literature Cited

Arano, K.G., Munn, I.A., 2006. Evaluating forest management intensity: A comparison among major forest landowner types. Forest Policy and Economics, **9**: 237-248.

Brang, P. 2005. Virgin forests as a knowledge source for central European silviculture: reality or myth. Forest Snow and Landscape. Research, **79**: 19-32.

Carnus, J.M., Parrotta J., Brockerhoff, E., Arbez, M., Jactel, H., Kremer, A., Lamb, D., O'Hara, K., Walters B., 2006. Planted forests and biodiversity. Journal of Forestry, **104**(2): 65–77.

Dummel, K. 1970. Intensitätsstufen sind praxisreif! Zur Diskussion über die Bildung von Intensitätsstufen. Allgemeine Forst Zeitschrift **25**: 636-640.

Duncker, P., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., De Jong, J., Ravn, H.P., Smith, M., Eckmüllner, O., Spiecker, H.. Synergies and trade-offs between production, land expectation values and ecological services in relation to forest management. Ecology and Society, submitted.

Edwards, D., Jay, M., Jensen, F.S., Lucas, B., Marzano, M., Montagné, C., Peace, A., Weiss, G.. Public Preferences Across Europe For Different Forest Stand Types As Sites For Recreation. Ecology and Society, submitted.

EEA (European Environment Agency), 2006. European forest types. Categories and types for sustainable forest management reporting and policy. Technical report No. 9, Copenhagen, Denmark.

*Ellenberg, H. 1996. Vegetation Mitteleuropas mit den Alpen in ökologischer, dynamischer und historischer Sicht. (The vegetation of central Europe and the Alps from the ecological standpoint) Ulmer, Stuttgart, Germany.

FAOTERM data base. 2007.
[online] URL: ttp://www.fao.org/faoterm/index.asp?lang=EN)

Gamborg, Ch., Larsen, J.B., 2003. 'Back to nature'-a sustainable future for forestry? Forest Ecology and Management **179**: 559-571.

Helms, J.A. 1998. The dictionary of forestry. CABI Publishing, Wallingford, USA.

Helming, K., Bach, H., Dilly, O., Hüttl, R.F., König, B., Kuhlman, T., Perez-Soba, M., Sieber, S., Smeets, P., Tabbush, P., Tscherning, K., Wascher, D., Wiggering, H., 2008. Ex ante impact assessment of land use change in European regions—the SENSOR approach. In Helming, K., Perez-Soba, M., Tabbush, P., (Eds). Sustainability impact assessment of land use changes. Springer, Berlin, Germany. pp 77-105

Hengeveld, G.M., Nabuurs, G.J., Didion, M., van den Wyngaert, I., Clerckx, A.P.P.M., Schelhaas, M.J.. A forest management map of European Forests. Ecology and Society, submitted.

International Union of Forest Research Organizations (IUFRO). 2007. SilvaTerm data base.
[online] URL: http://www.iufro.org/science/special/silvavoc/silvaterm/

Jactel, H., Branco, M., Duncker, P., Gardiner, B., Grodzki, W., Långström, B., Moreira, F. Netherer, S., Nicoll, B., Orazio, C., Piou, D., Schelhaas, M.J., Tojic, K.. A multi-criteria risk analysis to evaluate impacts of forest management alternatives on forest health in Europe. Ecology and Society, submitted.

Kimmins, H., 1992. Balancing Act: Environmental issues in Forestry. UBC Press, Vancouver, Canada.

Kroth, W., Kreutzer, K., Franz, F., Köstler, J.N., Frank, A., 1969. Entscheidungshilfe zur Abgrenzung von Intensitätsstufen in der Forsteinrichtung. (Aids to decision-making in the delimitation of intensity classes in forest management). Allgemeine Forst Zeitschrift, **24**: 543-560.

Kulhavý, J., Berger, T., Čaboun, V., Gottlein, A., Grunda, B., Heitz, R., Kantor, P., Klimo, E., Lomský, B., Niemtur, S., Rehfuess, K.E., Slodičák, M., Sterba, H., Vesterdal, L., 2004. Ecological Consequences of Conversion. In Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J.P., Sterba, H., von Teuffel, K., (Eds). Norway spruce conversion – options and consequences. European Forest Institute Research Report 18, Brill, Leiden, Boston, USA. pp 165-195.

*Landesforstverwaltung Baden-Württemberg. 1999. Richtlinie Landesweiter Waldentwicklungstypen. Stuttgart, Germany.

Martin, O., 1991. Intensität und Wirtschaftsziele der Forstwirtschaft - ein Diskussionsbeitrag. (Intensity and the objects of management in forestry – a discussion). Forstarchiv, **62**: 225-229.

*Mason, W.L., 2007. Silviculture of Scottish forests at a time of change. Journal of Sustainable Forestry, **24**: 41-57.

Mason, W.L., Nicoll, B.C., Perks, M.P., 2009. Mitigation potential of sustainably managed forests. Pages 100-118 in Combating Climate Change – a role for UK forests: main report. The Stationery Office, London, UK.

Matthews, J.D., 1989. Silvicultural Systems. Clarendon Press, Oxford, U.K.

*McIntosh, R.M., 1995. The history and multi-purpose management of Kielder forest. Forest Ecology and Management, **79**: 1-11.

Ministerial Conference on the Protection of Forests in Europe (MCPFE). 2003a. Improved Pan-European Indicators for Sustainable Forest Management as adopted by the MCPFE Expert Level Meeting 7-8 October 2002, Vienna, Austria.
[online] URL: http://www.mcpfe.org/files/u1/publications/pdf/improved_indicators.pdf.

Ministerial Conference on the Protection of Forests in Europe (MCPFE) 2003b. State of Europe's Forests 2003. The MCPFE Report on Sustainable Forest Management in Europe.
[online] URL: http://www.mcpfe.org/files/u1/publications/pdf/forests_2003.pdf.

Ministerial Conference on the Protection of Forests in Europe (MCPFE). 2003c. Fourth Ministerial Conference on the Protection of Forests in Europe, 28 – 30 April 2003, Vienna/Austria. Vienna Resolution 4 Conserving and Enhancing Forest Biological Diversity in Europe.
[online] URL: http://www.mcpfe.org/system/files/u1/vienna_resolution_v4.pdf.

Michalski J., Starzyk, J.R., Kolk, A., Grodzki, W., 2004. Threat of Norway spruce caused by the bark beetle *Ips typographus* (L.) in the stands of the Forest Promotion Complex "Puszcza Bałowieska" in 2000-2002. Leśne Prace Badawcze - (Forest Research Papers), **3**: 5-30.

Möhring, K., 1969. Zu: Intensitätsstufen in der Forstwirtschaft. Ein Diskussionsbeitrag zu der Abhandlung von Speidel-Dummel-Mayer-Vollmer in Heft 11/1969. (To: Intensity classes in forest management. A contribution to the discussion paper by Speidel-Dummel-Mayer-Vollmer in issue 11/1969). Allgemeine Forst Zeitschrift, **24**: 738.

Montigny, M.K., MacLean, D.A., 2006. Triad forest management: Scenario analysis of forest zoning effects on timber and non-timber values in New Brunswick, Canada. Forestry Chronicle, **82**: 496-511.

* Moore, J.R., Mochan, S.J., Brüchert, F., Hapca, A.I., Ridley Ellis, D.J., Gardiner, B.A., S. Lee J., 2009. Effects of genetics on the wood properties of Sitka spruce growing in the UK: bending strength and stiffness of structural timber. Forestry, **82**: 491-501.

* Moore, S.E., Lee Allen, H., 1999. Plantation Silviculture. Pages 400 – 433. In Hunter, M.L. (Ed). Maintaining Biodiversity in Forest Ecosystems. Cambridge University Press, Cambridge, Great Britain.

Oliver, C.D., Larson, B.C., 1996. Forest stand dynamics. Wiley, New York, USA.

Paivinen, R., Lindner, M., Rosen, K., Lexer, M.J., 2010. A concept for assessing sustainability impact of forestry wood chains. European Journal of Forest Research, DOI 10.1007/s10342-010-0446-4.

Pizzirani, S., Gardiner, B., Edwards, D. (2010) Analysing forest sustainability under various climate change scenarios: a case study in northern Scotland. Proceedings of the Eighteenth Commonwealth Forestry Conference, Edinburgh.
[online] URL:{ahref="http://www.cfc2010.org/papers/session7/Pizzirani-s7.pdf%20.%20Accessed%20May%202"target="_blank"}http://www.cfc2010.org/papers/session7/Pizzirani-s7.pdf.

Parviainen, J., Frank, G., 2003. Protected forests in Europe approaches - harmonising the definitions for international comparison and forest policy making. Journal of Environmental Management, **67**: 27-36.

Parviainen, J., Bucking, W., Vanderkerkhove, K., Schuck, A., Paivinen R., 2000 Strict forest reserves in Europe: efforts to enhance biodiversity and research on forests left for free development in Europe. Forestry, **73**: 107-118.

Peterken, G.F., 1996. Natural woodland. Ecology and conservation in northern temperate regions. Cambridge University Press, Cambridge, UK.

Popiel J., Karczewski A., 2006. Active nature protection In Białowieża National Park on example of Hwoźna Protection Circle. Proceedings of R. 8, z. 1, **11**: 85-102.

Pro Silva, 1999. Brochure PRO SILVA.
[online] URL: http://www.prosilvaeurope.org/docs/doc153.pdf.

Sagl, W., 1990. Grundsätzliche Fragen zum methodischen Hintergrund des Intensitätsproblems. Forst und Holz **45**: 228-232.

Seymour, R.S., Hunter, M.L., 1999. Principles of ecological forestry. In Hunter, M., (Eds). Maintaining Biodiversity in Forested Ecosystems. Cambridge University Press, Cambridge, UK. pp 22-61.

* Soares, P., Tomé, M., Pereira, J.S. 2007. A produtividade do Eucaliptal. In: Alves, A.M., Pereira, J.S., Silva, J.M.N., (Eds). Impactes Ambientais e Investigação Científica. Instituto Superior de Agronomia. ISA Press, Lisboa, Portugal. pp 27-59.

Speidel, G., 1969. Zu: Intensitätsstufen in der Forstwirtschaft. Stellungnahme zu dem Diskussionsbeitrag von K. Möhring, in Nr. 38/1969. Allgemeine Forst Zeitschrift **24**: 774-775.

Speidel, G., Dummel, K., Mayer, R.W., Vollmer, U., 1969. Die Bildung von Intensitätsstufen als Mittel zur Rationalisierung der Forstbetriebe. Allgemeine Forst Zeitschrift **24**: 191-198.

Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J.P., Sterba, H., von Teuffel, K., 2004. Norway spruce conversion – options and consequences. European Forest Institute Research Report 18, Brill, Leiden, Boston.

Sprugel, D.G., 1991. Disturbance, Equilibrium, and Environmental Variability: What is 'Natural' Vegetation in a Changing Environment? Biological Conservation, **58** :1-18.

*Skogstyrelsen, 2010. Skogsvårdslagstifningen.
[online] URL: http://www.skogsstyrelsen.se.

* Willoughby, I., Evans, H., Gibbs, J., Pepper, H., Gregory, S., Dewar, J., Nisbet, T., Pratt, J., McKay, H., Siddons, R., Mayle, B., Heritage, S., Ferris, R., Trout, R.. 2004. Reducing pesticide use in forestry. Forestry Commission Practice Guide, Forestry Commission, Edinburgh, UK.

Winkel, G., Schaich, H., Konold, W., Volz, K.R., 2005. Naturschutz und Forstwirtschaft: Bausteine einer Naturschutzstrategie im Wald. Schriftenreihe Naturschutz und Biologische Vielfalt des Bundesamts für Naturschutz. Band 11. Landwirtschaftsverlag, Münster-Hilstrup, Germany.

* cited in the Appendix

II.9 Appendix

A. Forest nature reserve in Białowieża National Park, Poland

This description corresponds to the best preserved fragment of forest in Białowieża National Park in North-Eastern Poland, which is under strict protection. The beginning of Białowieża National Park can be traced back to 1921, when the "Reserve" forest was created at the place currently occupied by the Park. In 1932, this "Reserve" was transformed into "National Park in Białowieża" and in 1947 this unit was reinstated as Białowieża National Park by an ordinance of the Cabinet[1]. The Białowieża National Park covers the last natural forest in the European lowlands which retains a primeval character, with stands characterized by large amounts of deadwood at various stages of disintegration and very high biodiversity of plants and animals. According to the "Ordinance of the Cabinet about Establishment of Białowieża National Park, 1947", the main objective of an unmanaged forest nature reserve is to allow natural processes and natural disturbance regimes to develop without management intervention to create natural ecological valuable habitats and biodiversity, in the last primeval forest in lowland Europe. Furthermore it serves as a field laboratory for basic and applied research.

Tree species selection, genetic engineering, regeneration type, and succession elements

According to the "Ordinance of the Cabinet about Establishment of Białowieża National Park, 1947" in an unmanaged forest nature reserve under strict protection no management to favour particular tree species takes place. The forest is naturally regenerated.

Machine operation, soil preparation, fertilisation and liming

There is no machine operation, soil preparation, fertilisation and liming.

Application of chemicals or protective agents, integration of nature protection

There is no application of chemicals or protective agents. Maintenance of undisturbed nature has the highest priority.

Tree removals, final harvesting system, and maturity

There are also no tree removals.

According to the strict protection by the ordinance of the Cabinet Białowieża National Park is to be classified as an unmanaged forest nature reserve (see **Fig. 1.a**).

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[1] Rozporządzenie Rady Ministrów z dnia 21 listopada 1947 r. o utworzeniu Białowieskiego Parku Narodowego (Dziennik Ustaw Nr 74, pozycja 469) - (Ordinance of the Cabinet of 21. November 1947 establishing the Białowieża National Park (Official Gazette No. 74, item 469))

B. European beech management in Baden-Württemberg, Germany

The following description of current management of European beech refers to the forest type “European beech forest with coniferous admixture” of the corresponding regional directive (Landesforstverwaltung Baden-Württemberg 1999) in Germany. This forest type is widely distributed in the sub-mountainous temperate zone of Baden-Württemberg. European beech (*Fagus sylvatica*) grows naturally on most sites in the region, except on organic or heavy clayish soils, sites with highly fluctuating water availability, wet sites, floodplains and steep sites with moving rocks. Current beech forests are said to represent the natural forest vegetation and can be assigned to the climax forest communities of Galio- and Lonicera-Fagetum (Ellenberg 1996). Here, beech is highly competitive, thus admixed tree species only compete outside the natural range of beech.

The long-term forest development objective is semi-natural, well structured European beech stands with significant admixtures of conifers (20-50 %) and limited amounts of other broadleaved species (0-20 %). The admixed tree species are distributed either as single trees or in small groups. On small areas the stand structure is multi-storied during the regeneration phase. Apart from this, where not dominant itself, beech can form an understory under the conifer admixture. Beech trees and the partly pruned conifers produce valuable stem wood. The target diameter for European beech is 60cm or more depending on stem quality and the risk of economic losses through red heartwood formation.

Tree species selection, genetic engineering, regeneration type, and succession elements

European beech is only favoured on adequate sites where it generally is part of the potential natural vegetation. Most European beech stands are naturally regenerated with planting on spots where no sufficient regeneration is available. If there is insufficient natural regeneration, beech is planted at a spacing of approximately 2x1 m (~5000 seedlings/ha) with additional planting of site adapted mixed species in patches (~20%). The planted material may originate from seed stands. Currently no genetically improved material is being used. Admixed tree species and especially light demanding ones are to be maintained in the stand.

Machine operation, soil preparation, fertilisation and liming

The directive does not discuss site cultivation, fertilization or liming. However, it is mentioned that soil fertility is well preserved under mixed beech stands. Again, machine operation is not directly addressed in the directive. Vehicle movement is restricted to racks with a minimum distance apart of 20 or 40 m depending on soil vulnerability.

Application of chemicals or protective agents, integration of nature protection

Forest protection is regulated by the forest law and plant protection act and not by the directive itself. Within the rationale of integrated plant protection approach the application of protective chemical agents is seen as a last resort. The directive requires maintenance of the forest community with site adopted flora and fauna.

Tree removals, final harvesting system, and maturity

After selection of 60 - 80 future crop trees per hectare, when natural pruning reaches 25-35% of expected final tree height, the main competitors (1-3) for these trees are removed in 5- to 10-year intervals with no more than 80 m3 ha-1 removed per thinning. Even though this is not stated in the directive, generally only solid wood is removed. The rotation length is chosen according to target diameter and is not defined by age. According to the growth dynamics and the risk of red heartwood formation, production time might be in the range of 80 to 150 years. The final felling system is mostly harvesting trees that have reached the target diameter, or uses group cuttings in order to promote natural regeneration.

Management recommendations for European beech can be classified as “low intensity category” with some “medium intensity” measures (see **Fig. 1.b**).

C. Norway spruce management in the county of Västerbotten in Sweden

The following description of Norway spruce management refers to the forest type “Mixed forests dominated by Norway spruce," i.e. where more than 70% of growing stock consists of Norway spruce (*Picea abies* [L.] Karst.). Other common tree species in the mixed forest are birch (*Betula pubescens* or *B. pendula*) and Scots pine (*Pinus sylvestris*). About 22% of the forest area corresponds to this type. Norway spruce grows naturally on most sites except on dry soils dominated by lichens and on mires. The main objective is to produce wood to obtain a good profit. Additional objectives are typically water protection, habitat protection, nature protection, and recreation. The magnitude and importance of additional objectives depends on the local situation.

Tree species selection, genetic engineering, regeneration type, and succession elements

The preferred methods of regeneration are planting of Norway spruce after clear-cut or natural regeneration with a shelterwood system. Normally, the planting material is genetically improved but not genetically modified. The number of plants depends on site index but on average about 2000- 2500 per ha. Birch and/or pine seedlings almost always occur on the regeneration sites. Biological legacies and natural biotopes should be promoted inside the stands. If necessary, pre-commercial thinning is carried out to reduce the number of trees at 1.5 - 4 m medium height.

Machine operation, soil preparation, fertilisation and liming

Machine operations are not limited, as long as they do not harm the environment. Site cultivation is applied to sites when necessary. Fertilization can be an option, but is not widespread.

Tree removals, final harvesting system, and maturity

The rotation period of a stand is chosen by the potential natural vegetation as well as economic interests. Additional to this, the Swedish Forestry Act (Skogsstyrelsen 2010) has a lowest allowable clear-cut age depending on site index and geographical location. The final harvest system is preferably clear-cut or a combination of shelterwood and clear-cut if natural regeneration is preferred to reduce the costs of reforestation.

Summarizing, the management recommendations result in “medium intensity” measures (see **Fig. 1.c**).

D. Sitka spruce management in Scotland

The forest area of Scotland comprises about 1.4 M ha of which some 530,000 ha is composed of forests of Sitka spruce (*Picea sitchensis (Bong.) Carr.).* These plantation forests are fast growing in European terms with an average productivity of 14 $m^3ha^{-1}yr^{-1}$ and better sites yielding more than 20 $m^3ha^{-1}yr^{-1}$. All forests are managed to conform to principles of sustainable forest management with a commitment to meeting multi-purpose objectives (McIntosh 1995). In practice, the balance between timber production, conservation, recreation and amenity will depend upon local conditions. Stands are generally managed so that pulpwood and small roundwood is produced in early thinnings while sawtimber is provided by later thinnings and final fellings.

Tree species selection, genetic engineering, regeneration type, and succession elements

The commonest method of regeneration is by planting at density of 2500-2700 trees ha-1. About 20 per cent of other species are planted along with Sitka spruce to increase diversity (Mason 2007). Genetically improved material derived either from seed orchards or from propagation of controlled cross mixtures, is widely planted and is expected to give increased timber yields over first generation stands (Moore et al. 2009). No genetically modified material is planted. Natural regeneration of spruce, pine, larch and various broadleaves is accepted when it occurs but the other species rarely survive beyond canopy closure because of the fast growth of the spruce stands. Re-spacing (pre-commercial thinning) is carried out in dense natural regeneration when trees are 2-3 m tall.

Machine operation, soil preparation, fertilisation and liming

Machine operation is not limited provided the guidance on soil conservation and maintaining water quality is observed. Site cultivation is standard practice when replanting occurs while fertilisation is much reduced compared to the earlier afforestation phase (Mason 2007). No liming is carried out.

Application of chemicals or protective agents, integration of nature protection.

Under the certification process, there is an aim to reduce levels of chemical input to the forest system but the use of chemical herbicides and pesticides is permitted where no practical cost-effective alternatives exist (Willoughby et al. 2004). Conservation considerations are incorporated through the forest design process (McIntosh 1995).

Tree removals, final harvesting system, and maturity

The customary rotation period is between 35 and 50 years depending upon site productivity and the risk of windthrow. A non-thin regime is used on more exposed sites: elsewhere 3-4 intermediate thinnings are carried out on a 5-year cycle followed by clear felling. In some locations of high amenity or recreational value, attempts are being made to introduce continuous cover forestry into the management of Sitka spruce forests.

Summarizing the management measures (see **Fig. 1.d**) suggests that most are of high-moderate intensity although there are current tends to reduce the intensity.

E. Eucalyptus management in Portugal

Eucalyptus (*Eucalyptus globulus*) is an exotic species that grows exceptionally well in Portugal. Eucalyptus is a fast growing species for which the maximum net increment occurs before the age of 5, although high productivities do not persist for a long time (Soares et al. 2007). Most of the stands are planted and plantations are mainly managed as short-rotation coppice systems, with an average cutting cycle of 10- to 12-years to benefit from its productivity. The main objective is to produce high quality wood for pulp and paper production.

Tree species selection, genetic engineering, regeneration type, and succession elements

Eucalyptus first rotation stands are usually planted with a density of 1250 seedlings per ha. A beating up operation is performed 6 months after planting to replace dead trees (15%). Its fast growth rate makes this species quite competitive and intolerant to succession elements, which reduces the regeneration of natural vegetation resulting in pure even-aged stands. Due to this species high coppicing ability, a first cycle of planted seedlings is usually followed by 2 to 3 cycles of coppiced stands. To increase productivity, improved genotypes resulting from tree breeding can be used and genetically modified material may be used in the future.

Machine operation, soil preparation, fertilisation and liming

There is a set of mechanised silvicultural operations that are performed. Whenever replanting is considered, stump removal and harrowing for woody debris incorporation are performed. Site preparation can be carried out through harrowing, ploughing or ripping operations. It is common to fertilize at planting with a NPK slow release fertilizer plus a phosphorus fertilizer. Additional mechanical fertilizations with NPK fertilizer can take place when the soil proves to be deficient in some specific nutrient(s). One or more mechanical weed control operations can be done in order to eliminate competition and decrease the risk of fire. Usually, weed control and mechanical fertilizations are done at the same time in a single operation reducing costs and compaction problems caused by machine movement on forest soil. In high fire risk areas weed control can be more frequent and/or more intense forest and building of forest roads' conducted to improve access.

Tree removals, final harvesting system, and maturity

In coppice stands, the number of sprouts per stool is reduced down to 1.2 to 1.6 by motor-manual cutting of shoots selected according to the intensity of mortality occurred in the transition from planted to coppice stands. Management is conducted in order to minimize the effects of natural hazards: stands showing any sign of being infected with any pest or disease may be submitted to chemical/biological control, pruning (after intense night frosts and/or Botrytis cinerea attacks) or even pre-commercial thinning (after insects or fungi attacks), Normally, only cut stems are removed from the stand although the extent of components extracted in thinning and final harvest operations can go up to the whole tree. A clear-cut is carried out at the age of 12 years producing 400-600 m3 ha-1. The size of the clear felling area depends upon the landscape.

The basic principles behind the current forest management of planted and coppice Eucalypt stands are very similar, differing only in the type of regeneration and in specific silvicultural operations associated with it such as soil preparation and tree removals (see **Fig. 1.e**).

CHAPTER III

SIMPLOT: Simulating the impacts of fire severity on sustainability of eucalyptus forests in Portugal

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SIMPLOT: Simulating the impacts of fire severity on sustainability of eucalyptus forests in Portugal

III.1 Abstract

SIMPLOT is a forest simulator for eucalyptus mainly driven by wood demand. It was developed to predict the evolution of the eucalyptus plantations in Portugal by combining forest inventory data with growth models taking into account the effect of different drivers such as wood demand, hazards occurrence and percentage of land use changes. The use of simulators for scenario analysis can be a powerful tool to explore policy options and to illustrate the consequences of different management alternatives. In the past years Portugal has been marked by extremely severe forest fires of great environmental impact. This paper shows simulation runs for two main scenario lines: the wood demand line and the wildfires line. In the first one, the simulator is used to identify a reasonable wood demand out of three different wood demands combined with a low/medium intensity fire scenario. The selected wood demand combined with three fire scenarios of increasing severity and a fourth one disregarding the existence of recent severe wildfires builds the second scenario line. The purpose of this study is to evaluate the impact of different magnitudes of forest fires occurrence on the sustainability of eucalyptus plantations starting with NFI data gathered in 1997 during a horizon of 28 years. The simulations reflect a constant level of afforestation and deforestation and assume that no changes took place between different management alternatives. These simulations provide some insight on the impact of different wood demand and different magnitudes/frequency of severe wildfires: it is not only the number and magnitude of severe wildfires that make a difference, but it is also the number and magnitude of medium wildfires that follow an extremely severe one. Furthermore, the inter-annual variability of wildfire occurrence affects carbon stock and carbon sequestration in a different way. The occurrence of severe wildfires has an immediate effect on carbon sequestration. The lower values are registered in the same year in which the most severe wildfires occur. On the other hand, the occurrence of severe wildfires has more permanent consequences on carbon stocks than on carbon sequestration. The more severe and numerous are the wildfires the more difficult will be to recover the carbon stocks in the forest. Results have also shown that if a higher wood demand compatible with the expected increase of pulp industry capacity

would have been considered this would have had drastic impacts on eucalyptus forest sustainability due to overharvesting in order to meet the desired wood demand.

III.2 Introduction

Forests have always been used with multiple purposes, although in the latest years expectations concerning forest use have increased. Profitable wood production is no longer forestry's main purpose, which has led to changes in forest management. At present, finding an acceptable balance between different forest uses has become a challenge for forest managers. Carbon sequestered in trees and in forest soils is one of the most important services expected from forests. Another paradigm that forest managers have to face nowadays is that different forest management alternatives along with climatic changes are expected to have significant impacts on forest growth.

In Europe, large-scale scenario simulators have been developed to evaluate the impacts of changes in forest management and environmental conditions at national level (Lämås and Eriksson 2003, Lindner and Cramer 2002, Eid et al. 2002, Nuutinen and Kellomäki 2001, Hoen 1996, Lundström and Söderberg 1996, Sallnäs 1990). There is also the EFISCEN, a large-scale matrix transition model developed to be used at European scale (Pussinen et al. 2001). This model is the tool used by the European Forest Institute (EFI) to predict European forest tendencies based on input information individualized by country (Schelhaas et al. 2004; Nabuurs et al. 2003).

These simulators are used to assess future forest resources combining growth models that use forest inventory data as input under the assumption that the uncertainty in forest growth is small and forest management remains the same (Mohren 2003).

Even though a wide variety of forest products and services are expected from forests, wood availability in the long-term is still considered to be a problem. According to Nabuurs et al. (2006) this concern is driven by a set of factors such as an expected increase in the demand for pulp and paper, together with a larger increase in consumption in certain Central European countries, as well as new trends in forest management resulting from nature oriented forest management tendencies, EU policies on energy (extra demand for bio-energy uses) and the Kyoto Protocol. Forest simulators provide examples of what can happen in reality being able to guide decision making either in research or management.

Technical studies focusing on timber supply and carbon stocks have been made, although not taking into account value driven aspects of forest management strategies that might allow achieving comprehensive scenarios for future developments (Mohren 2003). The need to include more detailed forest functions might lead to the development and use of more complex ecosystem models capable of dealing with changing environmental conditions, for instance. On the other hand, including this kind of information becomes complicated because simulation with complex models is time consuming and a large number of runs may be requested.

The objective of this paper is to describe SIMPLOT, a regional simulation tool (not spacialized) developed for eucalyptus in Portugal with the ability to integrate multiple influential factors within a single framework. Regional simulators are focused on the simulation of a large region based on forest inventory data, without individualizing each stand, whose outputs are usually given by forest type, but focused on the whole region (Tomé et al. 2008). SIMPLOT is designed for large-scale and long-term analysis being suitable for assessments of the future state of the forest under assumptions of future wood demand, hazards occurrence and land use changes. By allowing simulations under alternative scenarios it provides flexibility for improved regional modelling. The simulator potential users can be grouped in pulp and paper industries, broader public communities that may include landowners' associations, politicians in organizations such as local and regional governments and academic and scientific communities composed of people in universities and research institutions. These different groups can use SIMPLOT as a tool in decision making. Simulation results do not necessarily need to be used in quantitative terms; in many cases, they can be used as guides in a way to explore different options and alternatives (Landsberg 2003).

Given the numerous targets that can be pursued in forest management, there is a large number of possible alternatives that could be considered. Thus, for simplification, under the scope of the EFORWOOD project (EU FP6 EFORWOOD-IP project contract 518128), five forest management alternatives (FMA) were considered. The FMAs can be arranged along a two axis gradient of management intensity with wood/biomass production on one side and non-wood goods and services on the other. Biomass production is considered to be the most intensively managed FMA, while non-wood goods and services become more important as one moves towards the unmanaged forest reserve FMA, passing through: intensive even-aged forestry, combined objective forestry and close-to-nature forestry FMAs (**Chapter II**). Since eucalyptus is not a native species in Portugal, unmanaged forest nature reserves and close-to-nature forestry were not considered possible FMAs for this species. Combined objective forestry was not considered either.

The objective of this paper is to evaluate the impact of different magnitudes of forest fires occurrence on the sustainability of eucalyptus plantations based on the results of a forest regional simulator using NFI data gathered in 1997 as input. Sustainability of the eucalyptus forest is assessed by standing stock (volume and biomass) and by C sequestration.

III.3 Materials and Methods

III.3.1 Concept and structure of the simulator

SIMPLOT has been conceived to simulate the development of all the eucalyptus stands in a region, providing as output several forest characteristics and sustainability indicators. When running the simulator for different scenarios, it starts with forest inventory information at plot level to characterize the forest resources in a region. Once forest resources have been characterized for the first year of simulation, it uses forest growth models to predict long-term development of forest resources in the region taking into account the influence of a certain number of external variables - the drivers: wood demand, hazards occurrence, land use changes and management alternatives’ changes. The basic simulation unit is a ‘‘fictitious’’ stand from here on designated by stand. Each stand has the characteristics of a NFI plot and represents an area corresponding to the total area of eucalyptus stands in the country divided by the number of NFI plots that coincided with eucalyptus stands. Mixed stands are taken into account splitting the stand area among the species accordingly to the ratio between the volume per hectare of the eucalyptus in the stand and the total stand volume per hectare, thus obtaining a stand area equivalent to the area of a pure stand. This assumption seems reasonable due to the small representativeness of mixed stands with low proportion of eucalyptus. The stand can be divided in as many parts as desired in order to adjust the area to which harvest, fire and forest operations are applied.

There are different types of input files:

Base year plot input file - characterizing the forest resources for the first year of simulation.

- Simulation parameters input file - giving the values for several parameters/variables used in the simulations.

- Scenario input file - describing the total amount of each driver for the scenario to be simulated.

- FMA input file - describing the different forest management alternatives and respective options.
- Economy input file - listing costs and prices.

The base year plot input file contains the list of forest inventory plots to be simulated. The file structure requires descriptive information on each plot as well as the stand variable's information listed in **Table 1** (principal variables). All these variables can be predicted in the initialization module.

Table 1. List of stand variables needed as input for the simulator.

Stand variable information	
hdom	dominant height (m)
Nst	Number of trees (ha^{-1}) in planted stands and number of stools in coppice stands
N	Number of sprouts in coppice stands (Nst=N in planted stands)
G	Stand basal area (m^2)
Vu	Stand volume under-bark with stump (m^3 ha^{-1})
Vb	Stand volume of bark (m^3 ha^{-1})
Vs	Stand volume of stump (m^3 ha^{-1})

Fig. 1 illustrates the structure of the simulator. It starts by running the growth module for all the stands at year j in order to update forest resources to year j+1. After growth has been updated the fire module runs and analyses all the stands in order to decide if they burn. Stands will burn according to a probability function until the Afire defined in the scenario file is met. The amount of wood to be used by industry is "stored" in a V_harvest variable. The harvesting module is the next one to run. A stand can be harvested or not according to a probability (P_harv) depending on stand age and type defined in the simulation parameters file. If harvesting takes place the volume will be "stored" in the V_harvest variable.

After each stand is analyzed by the harvest module, V_harvest will be compared to the wood demand and in case it is greater or equal, the simulator is ready to move to the next year of simulation j+1. Before moving to the next year, the simulator runs the land use changes module (LUC) comprising both the afforestation and deforestation modules which will plant and abandon as many stands as the total amount of afforestation and deforestation defined in the scenario file. The last module to run is the forest management alternatives (FMAs). This module defines the percentage of changes that occur from 1 year to another between different management alternatives/options. Both the fire and the harvest modules produce harvested volume. Part of this volume is intended to Industry, while part of it is not. In case the industrial harvested volume is greater than the wood demand, the exceeding volume is stored to be used in the next year of simulation.

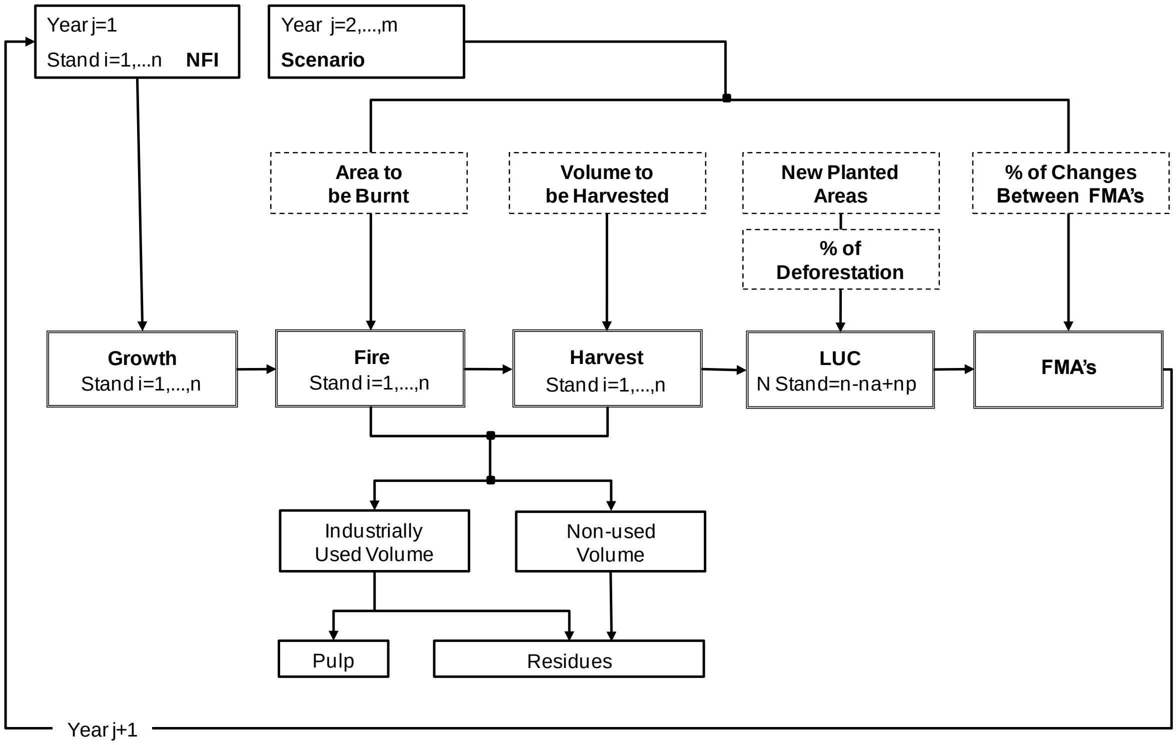

Fig. 1. Simplified structure of the simulator. The NFI box represents the base year plots' input file while the scenario box represents the scenario input file. The next level of boxes deriving from the scenario input file show the total amount of each driver needed as input for each of the drivers' modules. The arrows indicate the order by which each of the modules run: first the growth module followed by the modules corresponding to the drivers.

The simulator has 3 types of outputs: output of sustainability indicators per year (output_year.prn), output of area distribution per age class and year (output_clt.prn) and output per plot and year (output_plot.prn).

The main output is given in the file output_year that encloses the simulation results. It allows to compare the volume of wood that is planned to be harvested in each year (total amount of wood demand) with the total volume that was available to be harvested in that year under the user defined restrictions (the actual harvested volume). It shows the total standing volume before and after running the drivers' modules and the total volume harvested due to fire occurrence as well as equivalent information regarding biomass can also be found in this output file. It also holds information on areas, such as the existing forest area before and after running the drivers' modules, the area that corresponds to the actual harvested volume and the area that was burnt per year as well as other sustainability indicators such as those related to C stock and C sequestered in the trees/stands, production costs and wages and salaries. The output_clt file includes the area distribution per age class and contains the existing forest area allocated to 1-year age classes. This output is an area transition matrix that illustrates the evolution of forest area between different age classes along the simulation period.

The output_plot file allows tracking the history of each stand throughout the simulation period by analyzing the values of several stand variables.

III.3.2 Simulation parameters, drivers and scenarios

Simulation runs depend on a series of parameters that can be modified by the user. The parameters include the first year of simulation, the number of years to simulate and other information needed to run the different modules. Top-diameter (TopDiameter) considered in the computation of merchantable wood and the percentage of death occurring between rotations (%deathRot) are simulation parameters of the growth module. The fire module simulation parameters are the minimum age that allows the industrial use of trees after a fire (tminFire) and the percentage of salvage wood used by the industry (%UseFire), while the parameter for the harvest module is the minimum age that allows a stand to be harvested (tminHarv). The percentages of non-industrial stands (%HarvNI) and uneven-aged stands (%HarvUEA) that can be harvested are also simulation parameters that can be user defined. The probability of an even-aged stand to be harvested (P_harv) is defined as a function of age and stand type, while the probability of a stand to be abandoned (P_aband) is function of stand productivity.

The influence of the drivers is expressed through the scenario described in the input scenario file. The simulator comprises four types of drivers: (i) the wood demand which has implications on the amount of harvest per year; (ii) the occurrence of hazards that takes into account the burnt area per forest type; (iii) the land use changes (LUC) to and from forest use representing the afforested area per year and the deforested area per year and (iv) the percentage of change between different forest management alternatives and or options.

The implementation of the drivers takes into account two main points: the total amount of each driver and the probability of occurrence of the event for each stand. The driver's total amount for each year can be given as an area, a volume or a proportion of an existing area, whereas the probability of occurrence of the event is estimated according to a fixed probability (simulation parameter) or a probability function and implemented with Monte Carlo simulation. In case the event occurs, the simulator takes a specific action depending on the event.

The simulator is organized in different modules and the scenario file contains the input information per year to run the modules for the drivers: the total amount of area expected to burn (Afire), the total amount of volume that has to be harvested (V_harvest) so that the wood demand will be met, the total amount of new planted areas (AnewPlant) and the total amount of abandoned areas given as a proportion of the eucalyptus forest area (%LandChange). The file has the structure shown in **Table 2**.

Table 2. Structure of the scenario input file for the SIMPLOT simulator for a simulation period of 15 years.

Year	VHarvest	AFire	ANewPlant	%LandChange
1997	3524	4817	4800	0,0012
1999	3891	2353	4800	0,0012
2000	3985	7326	4800	0,0012
2001	4222	4837	4800	0,0012
2002	4618	6954	4800	0,0012
2003	5312	30526	4800	0,0012
2004	5593	6054	4800	0,0012
2005	6083	20000	4800	0,0012
2006	5938	7000	4800	0,0012
2007	5938	7000	4800	0,0012
2008	5938	7000	4800	0,0012
2009	5938	7000	4800	0,0012
2010	5938	7000	4800	0,0012
2012	5938	7000	4800	0,0012
2013	5938	7000	4800	0,0012

The hazards occurrence (fire) is the first module of the drivers to run. The total amount of area burned every year (Afire) is provided in the scenarios input file. The simulator starts with a burnt area equal to zero and selects the stands that are burned by Monte Carlo simulation assuming an equal probability of being burnt for all stands (P_fire). The burnt area is added to the so far existing one and the fire algorithm runs until the burnt area meets the total amount of burnt area defined in the scenario for that year. If the stand burns, it is assumed that the whole stand will be harvested. The conditions under which it is possible to use salvage wood are defined by the simulation parameters. For the computation of wood coming from industrial harvest after fire occurrence it is assumed that the fires occur when half of the growth has been attained. This assumption is reasonable as most fires occur during the growing season.

Wildfire behaviour is influenced by weather, in the short- and long-term, as well as by topography and fuels. Therefore, forest conditions combined with extreme weather conditions can lead to high severity fires (USDA 2004). The fact that an equal probability of burning is assumed for every stand might seem unrealistic, but it has been shown that a very high percentage of the burnt area per year results from big fires of high intensity which occur concentrated in only a few days (Oliveira 2008a). When this type of fire occurs there are no characteristics related to the stand (slope, age, vertical structure, species, management, etc.) or the landscape (species mixture, proximity to populated areas) that can be said to regulate the fire, therefore in reality the burnt area is almost randomly set. An alternative to assuming an equal value of P_fire for all the stands is to use a logistic function that uses the distance of the stand to the nearer different land uses as well as the stand’s azimuth as predictors (Vasconcelos et al. 2001).

As the harvesting unit is a stand, with a fixed area, the volume harvested is usually slightly higher than the wood demand. The difference is kept for the following year as a volume stock (Vstock). Eucalyptus stands can be harvested during all year, therefore to make the harvest module more realistic it is assumed that stands are harvested after half of the growth has occurred. Before the wood demand driver runs, the harvested volume is already greater than the Vstock because there is a percentage of the burnt stands (%UseFire) that will be used by the industry.

Similarly to what has been described for the fire driver, the total amount of volume harvested in each year of simulation (V_harvest) is defined in the scenario input file. Just like for hazards, there is also a simulation parameter that defines the age threshold that keeps non burnt stands under a certain age from being harvested (tminHarv) and another one that defines the percentage of harvest in nonindustrial stands (%HarvNInd) and uneven-aged stands (%HarvUEA).

The harvesting module, according to the simulation parameter P_harv, gives an increasing harvesting priority to older stands up to the age limit for harvesting (tminHarv) and keeps on harvesting until wood demand is met (Vharvest). A random number is drawn for each stand and compared to the harvesting probability (P_harv) which is defined in the scenario input file to decide whether the stand is harvested or not (Monte Carlo simulation).

The land use changes module includes an algorithm for the new planted areas in lands that were not forested before. These areas represent the afforestation per year. The other algorithm in this driver is the one for the abandoned areas per year (which correspond to deforestation). The simulator assumes that part of the forest area is abandoned and converted to other land uses.

The first step in the afforestation module is to determine the number of stands that correspond to the total amount of new planted areas per year of simulation (APlant) that is defined in the scenario file. Afterwards, a random number is drawn for each of the new stands in order to set them with a climatic region (Ribeiro and Tomé 2001). Once the climatic region is set, this module simulates the stands' site index according to the climatic region previously set and the observed distribution of site indices for each particular climatic region. After this, the new planted stands are ready to be simulated.

The main input information in the deforestation algorithm is the total amount of eucalyptus forestland converted to a different land use (%LandChange) given as a proportion of the forest area. Thus, the next step is to determine the abandoned area in hectares and the number of stands that correspond to that same area. Only harvested stands are allowed to be abandoned. To decide which stands are abandoned, the simulator uses a probability function (P_aband), implemented by Monte Carlo simulation, depending on the climatic region where it occurs (closely related to productivity regions).

At present all even-aged stands are managed as even-aged forestry (EAF), but there is the possibility to originate a certain number of options (silvicultural model - series of silvicultural operations during the stand's life) to each stand. Uneven-aged and non-industrial stands (that can be considered as being close to combined objective forestry - COF) are simulated in a very simple way with the same growth models as the stands managed as even-aged forests. This type of forest management is expressed by the small level of harvest occurring in these stands.

III.3.3 Growth and yield models

As mentioned before, SIMPLOT uses two growth models: the Globulus 3.0 model for even-aged stands and the $\text{GYMMA}_{\text{nlin}}$ model for uneven-aged stands.

The Globulus model (Tomé et al. 2006b, Tomé et al. 2001) is a stand level growth and yield model developed for pure even-aged stands. It integrates all the available information on eucalyptus growth and yield in Portugal and represents the combined efforts between industry and universities, which have been involved in several co-operative research projects over the past decades.

Globulus 3.0 includes two types of variables and two main modules. The variables that define the state of the stand over time (state variables) can be divided into principal variables in case they are directly predicted from a growth function or derived variables when their values are predicted from allometric or other equations that relate them to the principal variables and other previously predicted derived variables. On the other hand, the external variables control the development of the state variables and can be of three different sub-types: environmental, related to the management regime or intrinsic to the stand. The present version of this model has some of the parameters expressed as a function of climatic and site variables: the number of days with rain, the altitude, the total precipitation, the number of days with frost and the temperature. The greatest achievements in relation to previous versions is that: (i) it allows simulating the transition between rotations, by simulating growth for coppice stands before the thinning of the shoots usually occurring during the third year after the final harvest, and (ii) it includes improved biomass equations. A system of compatible equations to estimate tree aboveground biomass and biomass per tree component (António et al. 2007) were used to obtain tree level biomass estimates that were afterwards used to develop stand level compatible aboveground biomass and biomass per tree component equations (Oliveira 2008b). The model has two modules, the initialization and the projection module. The initialization module predicts each principal variable as a function of the control variables that characterize the stand and is used to estimate the values of the principal variables in stands younger than 3 years that are not measured in the NFI (just visited and characterized). The initialization module is also essential because it allows initializing a new stand either by planting or coppice. The projection module consists of a system of compatible functions for each principal variable as a function of its starting value and control variables. All the functions of the growth module are growth functions formulated as first order non-linear difference equations. On the other hand, derived variables are predicted as a function of principal variables as well as of control variables and previously predicted derived variables.

To simulate the growth of uneven-aged stands a growth and yield model independent of age was used (Barreiro et al. 2004), the GYMMA$_{nlin}$ model. As the Globulus model, it includes a projection and an initialization module that include the same variables as the Globulus model. In the projection module the growth functions are formulated as age-independent growth functions (Tomé et al. 2006a) with some of the parameters expressed as a function of climatic variables.

III.3.4 Case study

III.3.4.1 Input data

The 1995–1997 NFI provided the eucalyptus input data for the simulator. In the case study presented here all eucalyptus stands were taken into account: pure even- and uneven-aged stands as well as stands with eucalyptus as the main and/or secondary species. Stand evaluation in terms of structure, production and vitality was achieved through field work on 786 inventory plots. All trees holding a diameter at breast height greater or equal to 7.5 cm were measured and the trees below this threshold were counted. The total area of eucalyptus stands was 805,546 ha (area equivalent to pure stands equal to 674,908 ha) and held a standing volume of 41.94 x 10^6 m^3. **Fig. 2** shows the distribution of the eucalyptus area by age class and stand type.

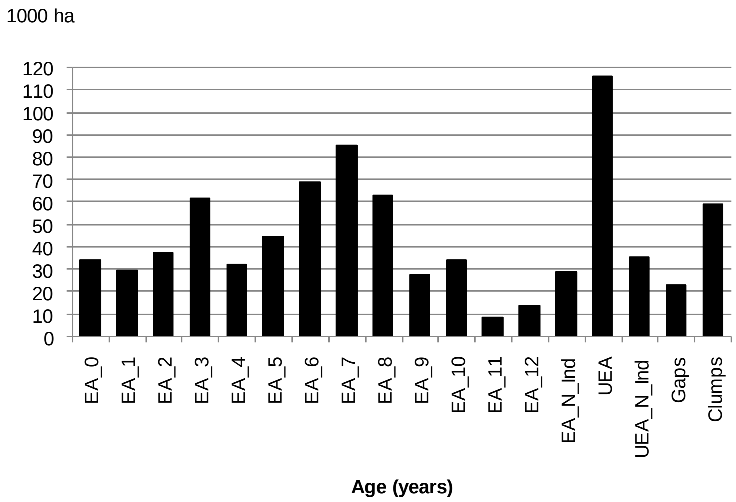

Fig. 2. Area of eucalyptus even-aged stands distributed in 1-year age classes (EA) and area of other stand types: non-industrial even-aged stands (EA_n_ind), unevenaged stands (UEA_ind), non-industrial uneven-aged stands (UEA_n_ind), Gaps and Clumps.

III.3.4.2 Scenarios

Two main scenario lines showing the impact of wildfire severity on the potential volume available to be harvested are considered. The scenarios in each line are mainly characterized by the total amount of the drivers and by a set of simulation parameters. All underlying assumptions are described in the following sections: ‘Forest Management Alternatives’, ‘Wood Demand’, ‘Land Use Changes’, ‘Hazards-fire’, and ‘Simulation Parameters’.

Forest management alternatives. Eucalyptus stands are managed as planted stands followed by two coppice stands with a rotation length around 12 years each. Out of the different forest management alternatives considered for eucalyptus in Portugal, in this study of the impacts of wildfire severity all the even-aged stands were simulated assuming even-aged forestry (EAF) FMA. The main reasons for this are two. First, the fact that at present there are no eucalyptus stands planted specifically for biomass production and second, the difficulty of classifying stands as combined objective forestry (COF) stands. Rather old or uneven-aged stands - these last simulated with a different growth model - of low density, close to urban areas and easy to access can be appointed as potential COF stands oriented to the recreational and social use of forests in case proper management measures are undertaken (like making improvements to existing facilities and introducing new facilities). Despite this fact, these types of stands have only been treated as non-industrial stands and therefore set with a smaller harvesting probability.

Wood demand. Three alternative wood demand scenarios have been defined. Until 2006 wood consumption by species can be found in the Portuguese statistics (Pereira et al. 2009). The official numbers correspond to volume of wood including bark and the corresponding driver used by SIMPLOT is wood without bark, thus to define the scenarios bark was discounted out of the wood demand published figures. Bark corresponds to 18% of the wood demand (Tomé et al. 1996). The scenarios can be distinguished by the wood demand evolution from 2006 onwards. In the first scenario (WD1) wood demand is admitted to have reached its maximum in 2006 and to remain constant until the end of the simulation period (Fig. 5a). On the second scenario wood demand is considered to increase at a rate of 1.2% per year (WD2) based on an analysis of the evolution of consumption and fellings in 30 Western and Central European Countries from 1964 up to year 2000 (Nabuurs et al. 2006). Finally, the third scenario with wood demand evolution set based on the announced production capacity increase (WD3). Recent changes in production processes, transforming unbleached softwood pulp mills into bleached eucalyptus kraft pulp producers, have resulted in a production capacity increase. In addition to this, one of the most efficient pulp mills in Portugal, with a present annual production capacity of 300,000 t/year has just announced to be able to double its annual production capacity by 2010 (Celbi 2009). Apart from the capacity increases in pulp production, also non-pulp and paper national consumption and exports were considered. The first ones were considered to be constant along the simulation period as well as the exports based on the average of the exports of the last 3 years as reported in the Eurostat statistics (Eurostat 2009). This value was discounted of a percentage representing bark smaller than the usual 18% since the reported exports of eucalyptus refer to a mix of wood with or without bark. These announced changes are expected to have a positive impact on the evolution of wood demand until 2013 but assumed to remain constant until the end of the simulation period.

Land use changes. The total amount of new planted areas (Aplant) was considered constant throughout the simulation period based on the average of new eucalyptus areas planted during a 5-year interval from 1995 to 2000 (Pereira et al. 2009). The total amount of abandoned eucalyptus forest (P_Aband) is given as a proportion of the existing total forest area in each year. The proportion was set based on the average value of deforestation occurring between 1986 and 2000 (Pereira et al. 2009). It was considered that the deforestation of eucalyptus stands per year was constant over the simulation period.

Hazards - fire. In this study four alternative fire scenarios have been compared. Three of the fire scenarios are based on the real wildfire occurrences until 2006, while the fourth is a completely hypothetical scenario which ignores the existence of the extremely severe wildfires occurred in 2003 and 2005. The first three fire scenarios consider the eucalyptus forest burnt areas published in the statistics (Pereira et al. 2009) from 1997 until 2006. From 2006 onwards, the burnt areas were simulated (**Fig. 3**) based on the analysis of historical data on forest burnt areas since 1968 (DGRF 1991).

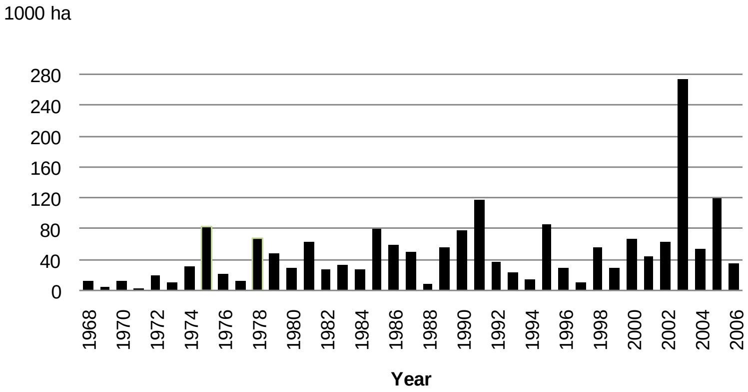

Fig. 3. Area of forest wildfires in a 1000 ha occurred in Portugal from 1968 until 2006.

The historical analysis of the burnt area series allowed concluding that the probability of occurrence of two severe wildfires in two consecutive years is very low, a severe wildfire being usually followed by a series of less severe wildfires for the next years. Therefore, three fire dimension classes were defined (low, medium and high) and the historical data was used to: first, set the probability of occurrence of a medium dimension fire after a medium or high dimension one had occurred; and second, to study the distribution of burnt areas by each fire dimension class. With these elements it is possible, using Monte Carlo simulation, to obtain a time series of burnt areas. The total burnt areas obtained were then reduced to the corresponding eucalyptus forest area in Portugal. The reduction was based on the average percentage of eucalyptus representativeness in the forest area between the years 2000 and 2006.

The first scenario is characterized by the official burnt areas until 2006 and the simulated burnt areas for low and medium fires until the end of the simulation period were established by Monte Carlo simulation as described above (WF1). The second scenario (WF2) is established based on the real burnt areas until 2006 and three wildfires of medium/high dimension until the end of the simulation period intercalated with the simulated burnt areas for low and medium fires used in the previous scenario. Monte Carlo simulation was used to define the years of occurrence (2007, 2013 and 2020) of these medium high dimension fires and to set them with the burnt areas according to the fire dimension class. The third scenario (WF3) is set in a similar way to the second one. The only difference lies in the years of occurrence of the big fires (2013, 2020 and 2025) and the burnt areas values randomly set according to the limits of the high fire dimension class.

The reason for including a fourth scenario (WF0) that disregards the severe fires of 2003 and 2005 intends to show the impact of fires of such magnitude in wood demand and in the future condition of forests. In 2003 forest fires consumed over 274,000 ha in Portugal and this catastrophe had a major repercussion in terms of carbon stocks and carbon sequestered. Thus, 2003 and 2005 real burnt areas were deleted and its values replaced by the ones from years 2004 and 2006, respectively. The remaining areas are those used in first scenario (WF1) shifted back 2 years. **Fig. 4** shows the difference between these scenarios in terms of number of severe wildfires and their intensity, reflected in terms of burnt area. The black bars represent real fires that have actually occurred in the past, while the dashed ones represent the simulated burnt areas for low and medium/low fires until the end of the simulation period established by Monte Carlo simulation. The dark dotted bars represent the 3 medium and severe wildfires that characterize scenarios WF3 and WF4, respectively.

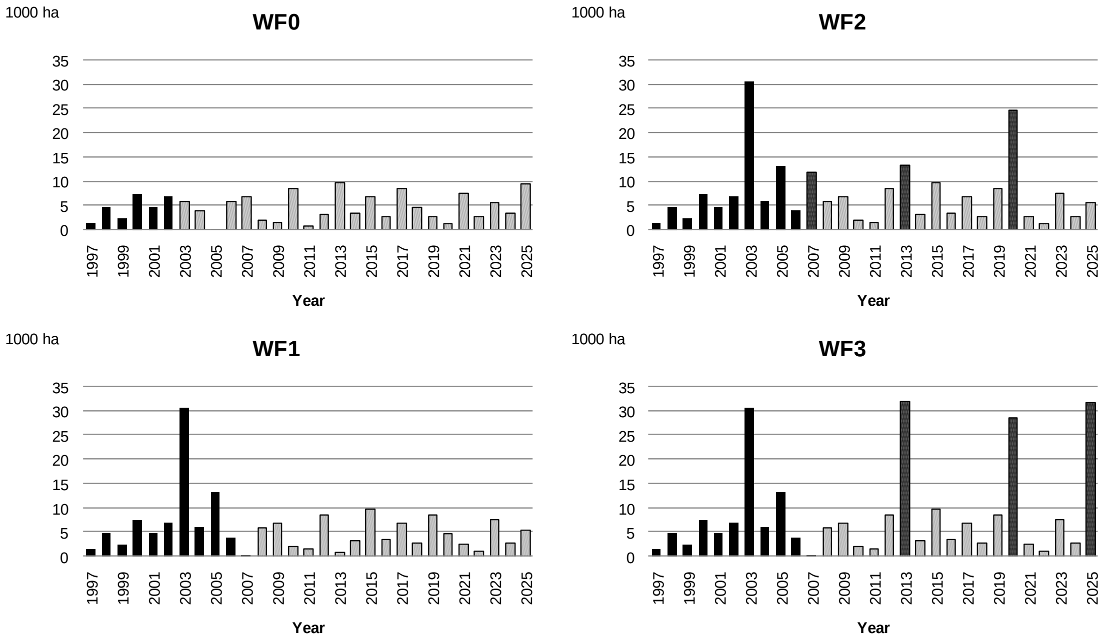

Fig. 4. Area of forest fires in hectares occurred in eucalyptus stands for each of the four scenarios: WF1, low intensity fire scenario; WF2, scenario with 3 medium intensity fires; WF3, scenario with 3 high intensity fires and WF0, hypothetical scenario with no severe fire occurrence.

As mentioned before, apart from the total amounts of each of the drivers described in the scenario file, the simulator depends on several parameters for which there are default values that can be modified by the user. The simulation runs in this study have been made with the set of default values for the simulation parameters (**Table 3**).

Table 3. Simulation parameters default values.

Top-diameter (TopDiameter)	5 cm
Percentage of death occurring between rotations (%deathRot).	20%
Minimum age that allows the industrial use of trees after a fire (tminFire)	5 years
Percentage of salvage wood used by the industry (%UseFire)	60%
Minimum age that allows a stand to be harvested (tminHarv) unless they have burnt	8 years
Percentages of non industrial stands that can be harvested (%HarvNI)	10%
Percentages of uneven-aged stands that can be harvested (%HarvUEA)	10%
Probability of a stand being harvested (P_harv)	F (age, stand type)
Probability of a stand being abandoned (P_aband)	F (productivity)

Wood demand scenario line. The first line integrates three alternative wood demand scenarios (WD1, WD2 and WD3) combined with the moderate fire scenario (WF1). The objective of this line of scenarios is to identify a reasonable demand scenario to be applied to the forest fire driven scenario's line (WDi, where i = 1, 2 or 3).

Forest fire driven scenarios. This line is composed of the most sustainable and reasonable wood demand scenario selected from the previous line combined with the three different fire intensity scenarios previously described: WF1, WF2 and WF3. To provide a more clear view of the impacts of the severe wild fires registered in 2003 and 2005 the hypothetical scenario WF0 was also combined with the selected wood demand scenario in a total of seven scenarios. **Table 4** shows a summary of all the scenarios studied.

Table 4. Summary description of the scenarios studied.

Scenario	Land Use Changes		Wood Demand	Hazards Fire	FMAs
	Afforestation (ha)	**Deforestation (%)**			
WD1_WF1	4800	0.0012	WD1	WF1	EAF
WD2_WF1			WD2	WF1	EAF
WD3_WF1			WD3	WF1	EAF
WDi_WF0			WDi	WF0	EAF
WDi_WF1			WDi	WF1	EAF
WDi_WF2			WDi	WF2	EAF
WDi_WF3			WDi	WF3	EAF

III.4 Results

III.4.1 Wood demand scenario line

Fig. 5 summarizes the results of the wood demand scenario line. The results show that when keeping the levels of wood demand stable and assuming a fire occurrence of low intensity (WD1_WF1) the carbon stock rises above 26000 Gg by the end of the simulation period (**Fig. 5c**). On the other hand, for the wood demand considered in scenario WD3_WF1 carbon stocks decrease drastically in about 9000 Gg from 2009 until the end of the simulation period. Even though wood demand is met in scenario WD3_WF1, this is only possible because overharvesting is allowed. If a more severe fire scenario is combined with such levels of supply, overharvesting is expected to occur even more severely leading to an unsustainable forest. Being so, the wood demand in this scenario makes it unsustainable and therefore the wood demand increase of 1.2% per year (WD2) seemed to be the reasonable choice to apply in the fire scenarios line.

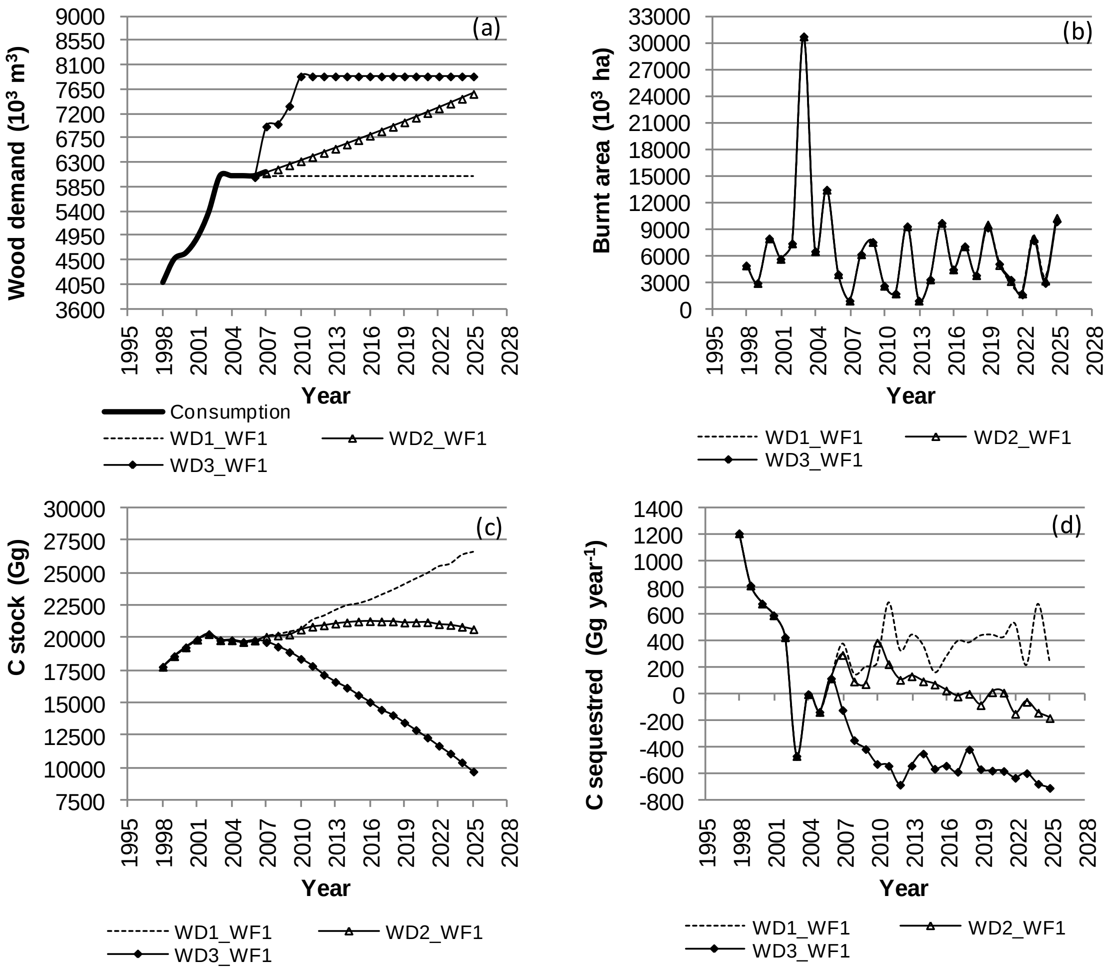

Fig. 5. Evolution of the main drivers and indicators: carbon stock and carbon sequestered characterizing the three scenarios in the wood demand scenario line: (a) evolution of wood demand driver, where WD1_WF1, WD2_WF1 and WD3_WF1 represent the wood demand defined in the three scenarios; (b) evolution of the burnt area driver for each scenario; (c) evolution of carbon stock and (d) evolution of carbon sequestered.

III.4.2 Wildfire scenario line

The results of the simulations combining the wood demand selected out of the wood demand scenario line and the different intensities of wildfires can be seen in **Fig. 6** Despite the severe fire scenarios considered the harvested volume is always enough to cover for the wood demand (**Fig. 6a**). The more intense the fire scenario the more drastically carbon stocks decrease. This is clearly shown by the impact of the big wildfire of 2003, which lead to a considerable loss of carbon from 2002 to 2003, nearly 500 Gg/year.

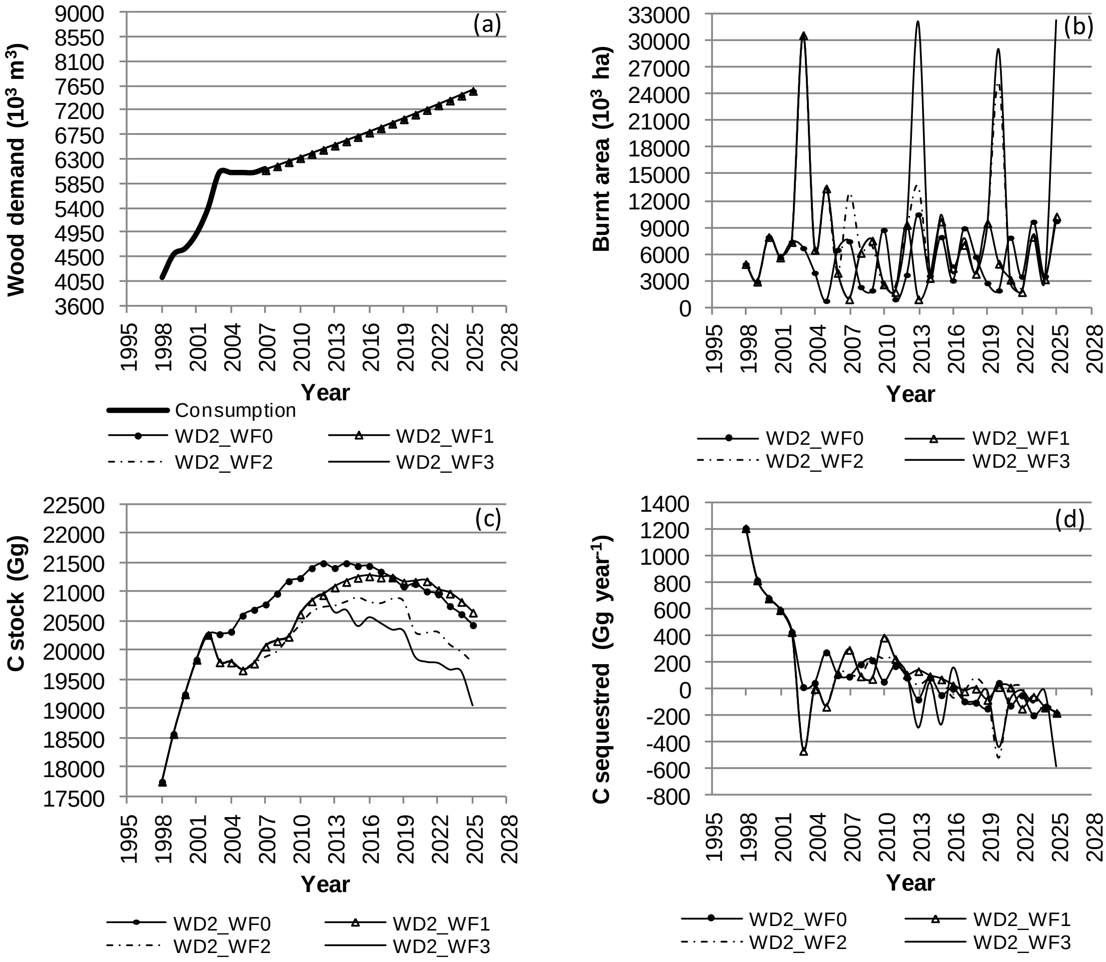

Fig. 6. Evolution of the main drivers and indicators: carbon stock and carbon sequestered characterizing the four scenarios in the wildfire scenario line: (a) evolution of wood demand driver, where WD2_WF0, WD2_WF1, WD2_WF2 and WD2_WF3 represent the wood demand defined in the four scenarios; (b) evolution of the burnt area driver for each scenario; (c) evolution of carbon stock and (d) evolution of carbon sequestered.

The consequences of a severe wildfire can be even worse if the number of consecutive medium sized wildfires is high. This is expressed by the behaviour of the lines of scenarios WD2_WF2 and WD2_WF3 in **Fig. 6c**. Since WD2_WF3 is characterized by having three wildfires of severe magnitude it could be expected that carbon stocks in WD2_WF2 would be higher, but this only happens after 2012. From 2006 until 2012, WD2_WF2 has less carbon stocked because the severe fires of 2003 and 2005 were followed by another medium wildfire in 2007 causing 12924 ha to burn against 991 ha in scenario WD2_WF3 (**Fig. 6b**). It takes the first severe wildfire WD2_WF3 to occur in 2013 to invert the tendency of carbon storage in the two scenarios.

The severe wildfires of 2003 and 2005 are responsible for the carbon stock depletion registered over the next decade, although when comparing scenarios WD2_WF0 and

WD2_WF1 after 2018, the evolution of carbon stock reversed. Despite these two fires have been neglected in scenario WD2_WF0 this scenario holds for some years bigger burnt areas than scenario WD2_WF1 (2007, 2010 and 2013), this can be the reason why in the long run carbon stock ends up being higher for WD2_WF1 (**Fig. 6c**).

III.5 Discussion

The objective of the research presented here was to study the impact of scenarios of different forest fires intensity and frequency on the sustainability of the eucalyptus forests in Portugal. This analysis was done by implementing existing growth and yield models - the Globulus 3.0 model for even-aged stands and the $\text{GYMMA}_{\text{nlin}}$ model for uneven-aged stands – into the regional simulator SIMPLOT.

As a first step, SIMPLOT was used in order to select a realistic wood demand scenario that was compatible with the long-term sustainability of the eucalyptus forests. In the process of selecting a sustainable realistic wood demand to be combined with the wildfire's scenarios it was realized that results change considerably when wood demand is replaced by the one reflecting increased production capacity (WD3) down to the one corresponding to 1.2% increase (WD2). **Fig. 7** shows the negative impact of the highest wood demand on carbon stocks and carbon sequestered (compare **Figs. 7a** and **b** with **Figs. 6c** and **d**). Such a scenario would have drastic impacts on the Portuguese eucalyptus forests. Abundant supply is only possible while resources increase at the same level (it is even desirable that growth overcomes harvest), but under WD3 this would only be possible with the increase of the eucalyptus plantations rate. Restrictive measures on exports could be put to practice nonetheless with no guarantees that even so the resulting supply of wood would be enough to meet the level of wood demand in WD3. Imports may have to be done. Harvesting has to take place in a sustainable way over time. In order to achieve this, there might be needed to regulate wood demand. These results clearly show the importance of a tool as SIMPLOT for industry planning and for the definition of forest policies.

Not only SIMPLOT has proven to be sensitive to wood demand, it has also shown to be susceptible to the evolution of burnt areas. The results point out the importance of the number of consecutive medium wildfires as well as their magnitudes. In the long run, the consequences of a few severe wildfires can nearly be compared to those of a set of consecutive medium wildfires when it comes to carbon stock. Although, carbon sequestered as proven to be less affected by sets of severe wildfires showing the greater impacts of severe fires in the exact same year in which they occur. This result is extremely important for the industry specially if the pulp and paper industries can not handle the inter-annual variability deriving from wildfires occurrence.

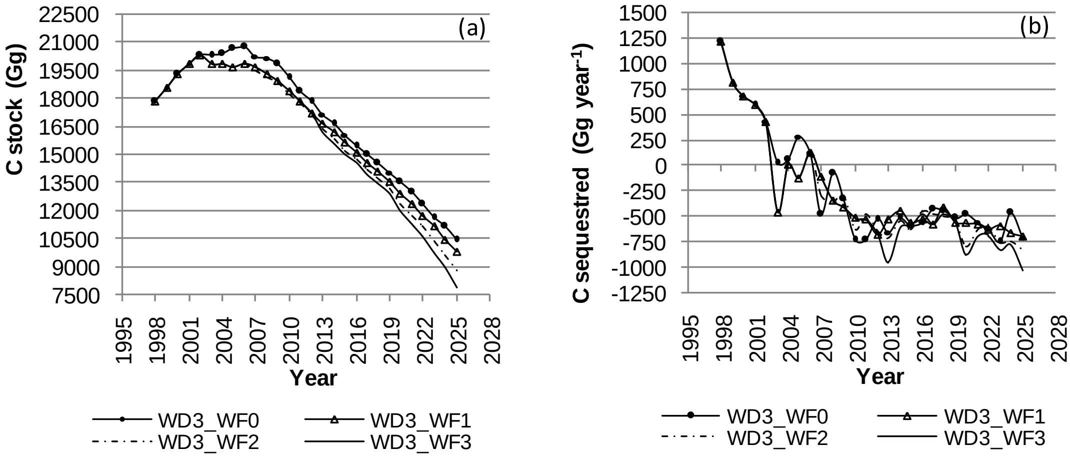

Fig. 7. Evolution of carbon stock (a) and carbon sequestered (b) for wood demands WD3 combined with the four wildfire scenarios.

This type of analysis is only possible with this kind of tool. With a stand simulator like Globulus 3.0 the impacts of wildfire occurrence at a regional level and different wood demand levels would have never been possible. SIMPLOT allows the use of Globulus 3.0 at regional level.

The simulator is under constant development at Instituto Superior de Agronomia (ISA). This paper describes the first prototype of the simulator. The only hazard taken into account by this first version of the simulator is forest fire but it is planned to add the impact of the most important pests and diseases that affect the eucalyptus in Portugal. Another characteristic that will be added very soon is the possibility to simulate forest management alternatives other than even-aged forestry.

III.6 Conclusions

The regional simulator described in this paper – SIMPLOT – was developed for eucalyptus stands in Portugal to investigate the potential impacts of wood demand, wildfire magnitude and occurrence, land use and forest management changes on the future forest resources at a regional level. With the previously existing simulator (stand level simulator), simulation results could only be obtained for a given stand, while SIMPLOT allows a global analysis of the simulation results for a set of stands integrating the influence of several factors that have no expression at stand level, such as wood demand.

Simulations were conducted to forecast the impact of wildfire occurrence on standing volume and carbon stock of eucalyptus plantations, therefore on the sustainability of such forests, under alternative scenarios combining different levels of wood demand with different levels of wildfires occurrence. One important conclusion is that the impact of the very large fires on carbon sequestration coincides mainly with the year of occurrence of the large fire, but does not have a long-term impact, except if the forest becomes unsustainable. On the other hand the impact on carbon stock is much more durable.

The simulator has the advantage of not being too demanding in terms of input data. It requires inventory data usually available from National Forest Inventories (NFI) as is the case of eucalyptus in Portugal. The basic output of the model consists of the state of the forest in 1-year intervals: growing stock, harvested area and volume, burnt area and a wide set of social, economic and environmental indicators.

III.7 Literature Cited

António, N., Tomé, M., Tomé, J., Soares, P., Fontes, L., 2007. Effect of tree, stand and site variables on the allometry of *Eucalyptus globulus* tree biomass. Canadian Journal of Forest Research, 37: 895–906.

Barreiro, S., Tomé, M., Tomé, J., 2004. Modeling growth of unknown age even-aged eucalyptus stands. In: Hasenauer, H., Makela, A. (Eds.), Modeling Forest Production. Scientific Tools—Data Needs and Sources. Validation and Application. Proceedings of the International Conference, Wien, pp. 34–43.

Celbi, A., 2009. [online] URL: http://www.altri.pt/Display.aspx?MasterId= 6ecbd958-13a3-4f6f-bdd0-cc23c7cae917&NavigationId=832 (accessed: 06/05/2009).

Direcção Geral dos Recursos Florestais (DGRF), 1991. Perfil Florestal, Direcção Geral das Florestas. Divisão de Estudos, Lisboa.

Eid, T., Hoen, H.F., Øksæter, P., 2002. Timber production possibilities of the Norwegian forest area and measures for a sustainable forestry. Forest Policy and Economics, 4: 187–200.

Eurostat, 2009. [online] URL: http://epp.eurostat.ec.europa.eu/portal/page?_pageid= 1090,30070682,1090_33076576&_dad=portal&_schema=PORTAL (accessed: 06/05/2009).

Hoen, H.F., 1996. Forestry scenario modelling for economic analysis—experiences using the GAYA-JLP model. In: Päivinen, R., Roihuvuo, L., Siitonen, M. (Eds.), Large-Scale Forestry Scenario Models: Experiences and Requirements. European Forest Institute, Joensuu, pp. 79–88.

Lämås, T., Eriksson, L.O., 2003. Analysis and planning systems for multi-resource, sustainable forestry—the Heureka research programme at SLU. Canadian Journal of Forest Research, 33: 500–508.

Landsberg, J., 2003. Physiology in forest models: history and future. For. Biom. Modell. Inf. Sci. 1, 49–63.

Lindner, M., Cramer, W., 2002. German forest sector under global change: an interdisciplinary impact assessment. Forstwiss. Centralblatt. 121 (1), 3–17.

Lundström, A., Söderberg, U., 1996. Outline of the Hugin system for long-term forecasts of timber yields and possible cut. In: Päivinen, R., Roihuvuo, L., Siitonen, M. (Eds.), Large-Scale Forestry Scenario Models: Experiences and Requirements. European Forest Institute, Joensuu, pp. 63–77.

Mohren, G.M.J., 2003. Large-scale scenario analysis in forest ecology and forest management. Forest Policy and Economics, 5: 103–110.

Nabuurs, G.J., Pussinen, A., van Brusselen, J., Schelhaas, M.J., 2006. Future harvesting pressure on European forests. European Journal of Forest Research, 136 (3): 391–400.

Nabuurs, G.J., Päivinen, R., Pussinen, A., Schelhaas, M.J., 2003. Development of European Forests until 2050 - a projection of forests and forest management in thirty countries, EFI Research Report, vol. 15. European Forest Institute.

Nuutinen, T., Kellomäki, S., 2001. A comparison of three modelling approaches for large-scale forest scenario analysis in Finland. Silva Fennica, 35: 299–308.

Oliveira, S.L., 2008a. Análise da frequência do fogo em Portugal Continental (1975-2005), com a distribuição de Weibull. Master Thesis. Lisbon Technical University, Lisbon.

Oliveira, T., 2008b. Sistema para a predição de biomassa aérea total e por componentes em povoamentos puros regulares de *Eucalyptus globulus* Labill. Master Thesis. Lisbon Technical University, Lisbon.

Pereira, T.C., Seabra, T., Maciel, H., Torres, P., 2009. Portuguese National Inventory Report on Greenhouse Gases, 1990-2008 Submitted under ARTº 3.1.(f) of Decision No.280/2004/EC of the European Parliament and the Council. Portuguese Environmental Agency, Amadora, Portugal.

Pussinen, A., Schelhaas, M.J., Verkaik, E., Heikkinen, E., Liski, J., Karjalainen, T., Päivinen, R., Nabuurs, G.J., 2001. Manual for the European Forest Information Scenario Model (EFISCEN 2.0), EFI Internal Report, vol. 5. European Forest Institute.

Ribeiro, F., Tomé, M., 2001. Classificação climática de Portugal. Revista de Ciências Agrárias, XXIII (2): 39–50.

Sallnäs, O., 1990. A matrix model of the Swedish forest. Stud. For. Suec. 183, 23.

Schelhaas, M.J., Cerny, M.I., Buksha, F., Cienciala, E., Csoka, P., Galinksi, W., Karjalainen, T., Kolozs, L., Nabuurs, G.J., Pasternak, V.P., Pussinen, A., Sodor, M., Wawrzoniak, J., 2004. Scenarios on Forest Management in Czech Republic, Hungary, Poland and Ukraine, Research Report, vol. 17. European Forest Institute, EFI.

Tomé, M., Coelho, M.B., Meridieu, C., Cucchi, V., 2008. Framework for the Description of Forest Modelling Tools Currently Available with Identification of Their Ability to Estimate Sustainability Indicators, EFORWOOD Project deliverable PD 2.5.2.
[online] URL: http://87.192.2.62/eforwood/Partnersonly/Module2/ WP21SustainableForestManagementStrategies/tabid/156/Default.aspx

Tomé, J., Tomé, M., Barreiro, S., Paulo, J.A., 2006a. Modelling tree and stand growth with growth functions formulated as age independent difference equations. Canadian Journal of Forest Research, 36: 1621–1630.

Tomé, M., Soares, P., Oliveira, T., 2006b. O modelo Globulus 3.0. Dados e equações. Publicações GIMREF RC2/2006. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.

Tomé, M., Borges, J.G., Falcão, A., 2001. The use of management-oriented growth and yield models to assess and model forest wood sustainability. A case study for eucalyptus plantations in Portugal. In: Carnus, J.M., Denwar, R., Loustau, D., Tomé, M., Orazio, C. (Eds.), Models for Sustainable Management of Temperate Plantation Forests. European Forest Institute, Joensuu, pp. 81–94.

Tomé, M., Ribeiro, F., Soares, P., Pereira, H., Miranda, I., Jorge, F., Pina, J.P., 1996. Efeito do compasso na quantidade e qualidade da madeira de *Eucalyptus globulus*, Análise da 1 rotação de um ensaio, Actas do congresso da Tecnicelpa. Aveiro 150–159.

USDA Forest Service, 2004. Science Basis for Changing Forest Structure to Modify Wildfire Behaviour and Severity. Rocky Mountain Research Station, RMRS-GTR-120, Missoula, MT.
[online] URL: http://www.fs.fed.us/rm/pubs/ rmrs_gtr120.pdf).

Vasconcelos, M.J., Silva, S., Tomé, M., Alvim, M., Pereira, J.M.C., 2001. Spatial prediction of fire ignition probabilities: comparing logistic regression and neural networks. Photogrammetric Engineering & Remote Sensing, 67 (1): 73–81.

CHAPTER IV

Analysis of the impact of the use of eucalyptus biomass for energy on wood availability for eucalyptus forest in Portugal. A simulation study

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Analysis of the impact of the use of eucalyptus biomass for energy on wood availability for eucalyptus forest in Portugal. A simulation study.

IV.1 Abstract

In the scope of energy diversification and profitable forest resources exploitation, increasing the use of biomass residues for energy can play an important role. The use of local sources of energy, reduce carbon emissions and fossil energy use, providing additional revenue for the forest sector and also reducing the risk of forest wildfires. Regional simulators can help forecast available wood and biomass and allow evaluation of possible future conflicts of interest and its consequences for society. This paper focuses on improving an existing regional forest simulator (SIMPLOT) so that it can be applied to study research questions related to increasing the use of eucalyptus biomass for bioenergy and the related consequences for wood available for pulp.

Biomass modules were integrated into SIMPLOT so that different sources of biomass used for energy could be accounted for. The updated version of the simulator was used to assess the impact of different biomass demands for bioenergy, combined with different afforestation alternatives on the wood available for the pulp and paper industry in Portugal. SIMPLOT's forecasts indicated that eucalyptus forest is unable to satisfy wood demand even when pulp afforestation areas are doubled regardless of the biomass demand considered. Also, the simulation results showed that, with the tested afforestation rates, eucalyptus forest cannot meet high increases in demand for wood.

IV.2 Introduction

Eucalyptus globulus was introduced into Portugal in the second half of the 19th century, but only recently, has it increased its range from around 70 thousand hectares in 1965 (DGSFA 1966a, DGSFA 1966b) to 739.515 hectares, making it the second most important species in the country (AFN 2010). *E. globulus* has assumed an important role not only in terms of forest area, but also in terms of the economy, providing the raw-material for the pulp and paper industry, one of the most important industries in the country. Eucalyptus plantations have emerged as an alternative to other land uses, competing with grasslands, rain-fed agriculture, shrublands, maritime pine forest, and, more recently, as an alternative to land abandonment (Soares et al. 2007).

In recent decades, the use of biomass for energy has become a common topic. Short-rotation forestry, as part of short-rotation coppice crops, has become extremely important because biomass is seen by many European governments as having an important role in meeting commitments under the Kyoto Protocol (United Nations 1998). By 2010, Europe was expected to obtain 12% of its power production from renewable resources (Abell 2005).

The role of biomass in energy production is high in Brazil, where huge investments made in the pulp and paper industry resulted in intensive selection programs using cloning, controlled hybridization and micro-propagation of eucalyptus (*Eucalyptus grandis* and *Eucalyptus saligna)* (Abell 2005).

In 2005, the Portuguese Energy Strategy pointed out the need to increase the power infrastructure by building 15 new thermoelectric plants supplied by forest biomass (DRE 2005a). Energy produced by these plants is competitively priced (109€/MWh) only bettered by photovoltaic energy (DRE 2005b). The strategy also recommended financing research into new technologies that use forest biomass for localized energy production (DRE 2006).

Over the last three decades, forestry wood chain (FWC) industries have been using biomass to produce thermo and electrical energy in Portugal. In 2008, 74% of the energy consumed by the pulp and paper industry was derived from bio-fuels; of these 81% of the energy produced from biomass derived from a sub-product of pulp production (black liquor), 17% was produced from *E. globulus* and *Pinus pinaster* bark, and the remaining 2% from shrubs and agro-industrial residues (CELPA 2009).

The first biomass plant, Mortágua, started operating in 1999 with a 63 GWh capacity and a biomass consumption of 109 000 Mg/yr. This plant was followed by another three plants installed in 2007 and 2009, amounting to a total power of 380 GWh/yr and a consumption of 700 000 Mg/yr. In 2010, four other biomass plants were planned to come online.

In Portugal, *E. globulus* stands have mainly been managed for pulp production. Unlike what happens for other species managed with other purposes, *E. globulus* does not have restrictions on wood dimensions provided that tree tops are eliminated according to a predefined top diameter being possible to use them for bioenergy. Rotation age is usually set by the development of mean and current annual volume increment, although it is difficult to set a fixed rotation age because stand growth depends on stand density and site quality. Therefore, rotation age can vary from 8 up to 14 years or more, depending on wood demand. Over the years, spacing trials have determined that ideal density is around 1200 trees, compromising between stand density and silvicultural operation costs (Ribeiro et al. 1997). Although this species has always been managed for pulp, the recent interest in bioenergy requires considering in this study a different forest management approach (FMA). Species used for bioenergy purposes are usually chosen for their resprouting ability, good biomass quality (low water content) and high productivity. Thus, high densities and shorter rotations (but not too short, in order to give it time to grow and reduce the amount of foliage) are preferred for this type of management. To date, no studies examining *E. globulus* potential to be used for bioenergy have been published in Portugal.

Given current market pressure to supply pulp mills with wood and future pressure to supply bioenergy plants with biomass, it is interesting to study possible competition and conflicts between both uses for the same raw-material. The main objective of this paper is to investigate the impacts of increasing biomass demands on wood available to be used in pulp production. In order to do so, the SIMPLOT regional simulator, described in Barreiro and Tomé (2011), was improved to simulate the two most intensive FMAs considered under the scope of the EFORWOOD project: intensive even-aged forestry and short-rotation forestry (**Chapter II**). Consequently, improvements to the simulator can be seen as a secondary objective of this paper.

Several alternative combinations of new annual plantation areas for wood-production for pulp (WP) and for bioenergy production (BP) were studied, combined with two scenarios of biomass demand: one considering no biomass demand and the other characterized by an annual percentage increase.

IV. 3 Methods

Before describing the modifications made to the SIMPLOT simulator, a brief description of the original version is presented. The description of the updated version of the model and its overall structure follows a brief introduction to biomass sources.

IV.3.1 Simulator description

IV.3.1.1 Overview of the original SIMPLOT simulator

SIMPLOT's previous version has been described in detail by Barreiro and Tomé (2011). It is a non-spatially explicit regional simulator conceived to use national forest inventory plots as input. It was designed to simulate the development of all types of eucalyptus stands in 1-year time-steps by using growth models. For the simplicity of the simulator's growth module, the area of mixed stands, not very significant compared with the area of pure stands, is converted into area of pure stands, based on the ratio between eucalyptus volume in the stand and the total stand volume. The evolution of forest resources is mainly driven by wood demand, also considering other drivers: fire occurrence, land use changes (LUC) and forest management changes. Drivers are organized in separate modules and implemented in two steps: the total amount of the drivers, which represents the module's inputs; and the probability of occurrence of the event for each stand, usually set by a probability function and implemented with Monte Carlo simulation. If an event occurs, the simulator takes a specific action depending on the event. The influence of the drivers is expressed through the scenario, and simulation runs depend on a series of user-defined parameters. The simulator assumes beforehand that only stands that have reached the number of rotations defined by the user can be either abandoned, replanted under the same FMA or changed to a different one. Furthermore, SIMPLOT works based on a set of implicit assumptions, namely, burned stands are harvested, salvage wood is considered, and surplus harvested biomass is left on site to offset nutrients removal.

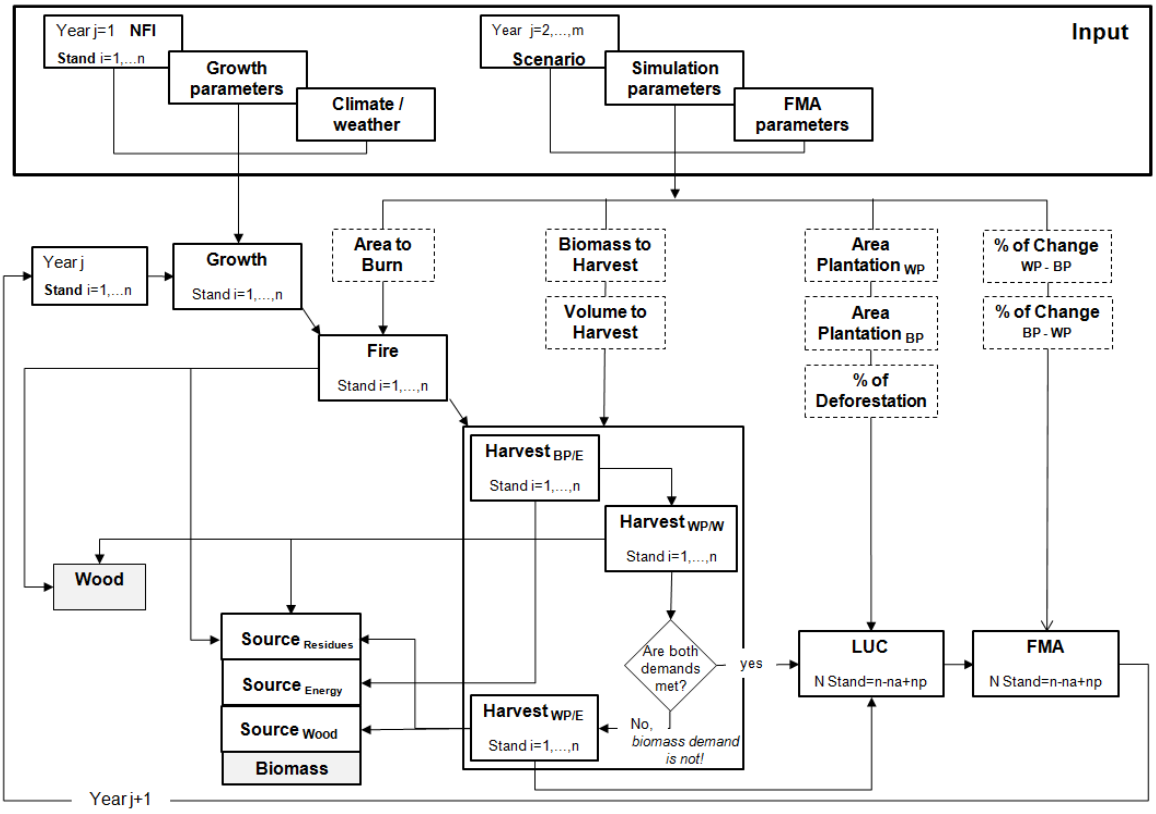
IV.3.1.2 Improvements made to SIMPLOT

The previous version of SIMPLOT did not consider the use of biomass. Biomass can be allocated from different sources: forest residues ($\text{Source}_{\text{Residues}}$), bioenergy plantations ($\text{Source}_{\text{Energy}}$) and wood-production forests for pulp ($\text{Source}_{\text{Wood}}$). Forest residues are composed of biomass deriving from burned stands not used by the pulp industry, biomass from tree tops, branches and bark resulting from harvesting depending on the harvesting method, and biomass resulting from shoot selection operations in coppice stands. To integrate these three sources of biomass for energy in the simulator, different methodologies were applied, depending on the source.

So that SIMPLOT could simulate the use of biomass, several significant improvements were made: (1) biomass demand and annual plantation of areas for energy purposes were included as drivers in the scenario, and simulation parameters mostly concerning short-rotation forestry were added; (2) biomass ratio functions, which predict the biomass of a tree component below a given height (and therefore to a certain diameter), were integrated so that biomass residues could be accounted for; (3) an adaptation of Globulus growth model was added to simulate the growth of stands used for bioenergy production; (4) two harvesting modules were created to harvest stands for bioenergy.

It was necessary to include an assumption concerning the harvesting of wood-production plantations for energy: if biomass demand is not met using biomass from $\text{Source}_{\text{Residues}}$ and $\text{Source}_{\text{Energy}}$, wood-production forests can be harvested for energy as long as wood demand has been met. Another assumption was made, this one related to fire: biomass of leaves is totally destroyed, but bark and branches are damaged, suffering biomass reductions of 40% and 25%, respectively.

After the improvements, SIMPLOT now includes two demands to be met for the horizon of simulation: wood demand for pulp and paper production and biomass demand for bioenergy production. **Fig. 1** shows the current structure of the simulator, including the new modules and each module's contribution to meet the wood and biomass demands. The first three boxes represent the input files. The next level of boxes deriving from the scenario and simulation parameters input files show the total amount of each driver needed as input for each of the drivers' modules. The cascade boxes represent the modules, and the arrows indicate the order in which each of the modules run: first, the growth module, followed by the modules related to the drivers: fire, harvest bioenergy plantations (BP/E), harvest wood-production forests for pulp production (WP/W), harvest wood-production forests for energy production (WP/E), LUC, and changes in FMAs.



With BP/E, WP/W and WP/E representing bioenergy plantations used for energy, wood-production plantations used for wood and wood-production plantations used for energy, respectively.

Fig. 1. Simplified overall structure of SIMPLOT simulator.

IV.3.1.3 Simulation parameters, drivers, and scenarios

The scenario input file containing the information to run the driver's modules has been restructured. Inclusion of the short-rotation FMA was followed by a need to specify the total amount of biomass for bioenergy production to be harvested in each year of simulation (representing the biomass demand for energy) and the area of new bioenergy plantations. Apart from these changes, the proportions of area related to the conversion of even-aged (WP) to short-rotation (BP) and the inverse one have also been included. **Fig. 2** gives a more detailed overview of the present functioning of the simulator.

The new user defined parameters concerning short-rotation forestry are: rotation length, starting density and number of rotations. The assortments and the harvesting system have also increased the previous list. At present, apart from top diameter it also integrates log length and four dummy variables that are used to define the possible harvesting systems: 1) top (over bark wood); 2) branches (of the whole tree including leaves); 3) bark (of the whole tree except top bark); and 4) top with branches (the whole top including bark, branches and leaves).

IV.3.1.4 Biomass ratio functions

In the previous version of the simulator, there was an amount of biomass residues resulting from harvested stands, but this material was not accounted for. In the present version, this material is estimated and assumed to be used for bioenergy production representing one of the three sources of biomass. In order to calculate the percent biomass, tree biomass ratio equations depending on the top diameter were used (Fontes et al., submitted). The biomass of tops is estimated per tree component: wood, bark, branches and leaves. The equations are applied to the mean tree and the total biomass of residues is then estimated from the number of trees per hectare. In order to implement the biomass ratio equations, height of the mean tree (Tomé et al. 2007b), height up to the crown base (Soares and Tomé 2003), diameter of the dominant trees (Tomé et al. 2007a) and top height need to be determined. In this study, logs 2 meters long were considered. The diameter at the base of each log (di) along the stem is calculated until the top diameter planned for harvesting is surpassed. The diameters (di) were calculated over bark with existing taper equations (Tomé et al. 2007b). The height of the last log was selected from the bottom or the top of the previous log so that a top diameter as close as possible from the one planned could be obtained. All equations used can be found in **Table 1**.

This improvement allows considering different harvesting systems from more to less intensive biomass removal, depending on the amount of residues removed from the site.

Table 1. Equations used in the calculation of *E. globulus* residues biomass.

(Tomé et al. 2007a):

$$\mathrm{ddom}=0.4164+0.9416\ \mathrm{dg}+0.3008\ \mathrm{hdom}$$

$$\mathrm{h} = \mathrm{hdom}\ \ \mathrm{e}^{\left[\left(-1.7701\ (1-cop)-1.7291\ cop-0.0233\ hdom+0.5488\ \frac{N}{1000}-0.0553\ dg\right)\ \left(\left(\frac{1}{\mathrm{d}}\right)-\left(\frac{1}{\mathrm{ddom}}\right)\right)\right]}$$

(Soares and Tomé 2003):

$$\mathrm{h_c} = \mathrm{h}\ \left(1-\left(\frac{1}{1+\mathrm{e}\ \left(-\left(-5.7611-0.1754\ \ \mathrm{hdom}-0.2718\ \ \frac{\mathrm{N}}{1000}+12.3341\ \ \frac{1}{\mathrm{t}}-0.2056\ \ \mathrm{d}\right)\right)}\right)^{\frac{1}{6}}\right)$$

(Tomé et al. 2007b):

$$\mathrm{d_i} = \mathrm{dg}$$

$$\mathrm{d_i}=\left(1.4409+0.3535\ \ \ln\left(1-\left(\frac{\mathrm{hi}}{\mathrm{h}}\right)^{\frac{1}{7.7840}}\left(1-\mathrm{e}^{\frac{-1.4409}{0.3535}}\right)\right)\right)$$

(Fontes et al. submitted):

$$\frac{\mathrm{W_{w\ di}}}{\mathrm{W_w}} = 1-\left(1-\left(\frac{\mathrm{h_i}-\mathrm{h_{st}}}{\mathrm{h}-\mathrm{h_{st}}}\right)^{1.0430}\right)^{2.4545}$$

$$\frac{\mathrm{W_{b\ di}}}{\mathrm{W_b}} = 1-\left(1-\left(\frac{\mathrm{h_i}-\mathrm{h_{st}}}{\mathrm{h}-\mathrm{h_{st}}}\right)^{0.8507}\right)^{2.0807}$$

$$\frac{\mathrm{W_{br\ di}}}{\mathrm{W_{br}}} = 1-\left(1-\left(\frac{\mathrm{h_i}-\mathrm{h_c}}{\mathrm{h}-\mathrm{h_c}}\right)^{1.7933}\right)^{2.3417}$$

$$\frac{\mathrm{W_{l\ di}}}{\mathrm{W_l}} = 1-\left(1-\left(\frac{\mathrm{h_i}-\mathrm{h_c}}{\mathrm{h}-\mathrm{h_c}}\right)^{2.1388}\right)^{2.6899}$$

$$\mathrm{Wa_{di}} = \mathrm{W_{w\ di}}+\mathrm{W_{b\ di}}+\mathrm{W_{br\ di}}+\mathrm{W_{l\ di}} \qquad \text{If } \mathrm{h_i} \leq \mathrm{h_c} \text{ then } \frac{\mathrm{W_{i\ di}}}{\mathrm{W_i}} = 0 \quad \text{where } \mathrm{i} = \mathrm{br}, \mathrm{l}$$

where **N** is the stand density (ha^{-1}); **hdom** is the dominant height (m); **ddom** is the average diameter of the dominant trees (cm), **t** is the stand age (years); **d** is the diameter at breast height (cm), **dg** is the quadratic mean d (cm); **cop** is a dummy variable for coppice, assuming the value 0 for planted stands and 1 for coppice stands; **h** is the total tree height of the average tree (m); **h_{st}** is the stump height considered 0.15 m; **h_c** is the tree height up to the base of the crown (m); **h_i** is the top height (m); **d_i** is a top diameter (cm); **$w_{i\ di}$** is the biomass of the component below diameter d_i (Mg ha^{-1}); where **i** represents: w for wood, b for bark, br for branches and l for leaves; **Wa_{di}** is the aboveground biomass below a top diameter d_i.

IV.3.1.5 Growth module update

In SIMPLOT's previous version, the growth module integrated growth models for uneven-aged stands and for pure even-aged stands (wood-production forests). This version comprises an adaptation of Globulus 3.0 (Tomé et al. 2006) model in order to produce more accurate estimates for highly stocked pure even-aged stands (**Chapter VI**), which is used to simulate the growth of stands used for bioenergy production.

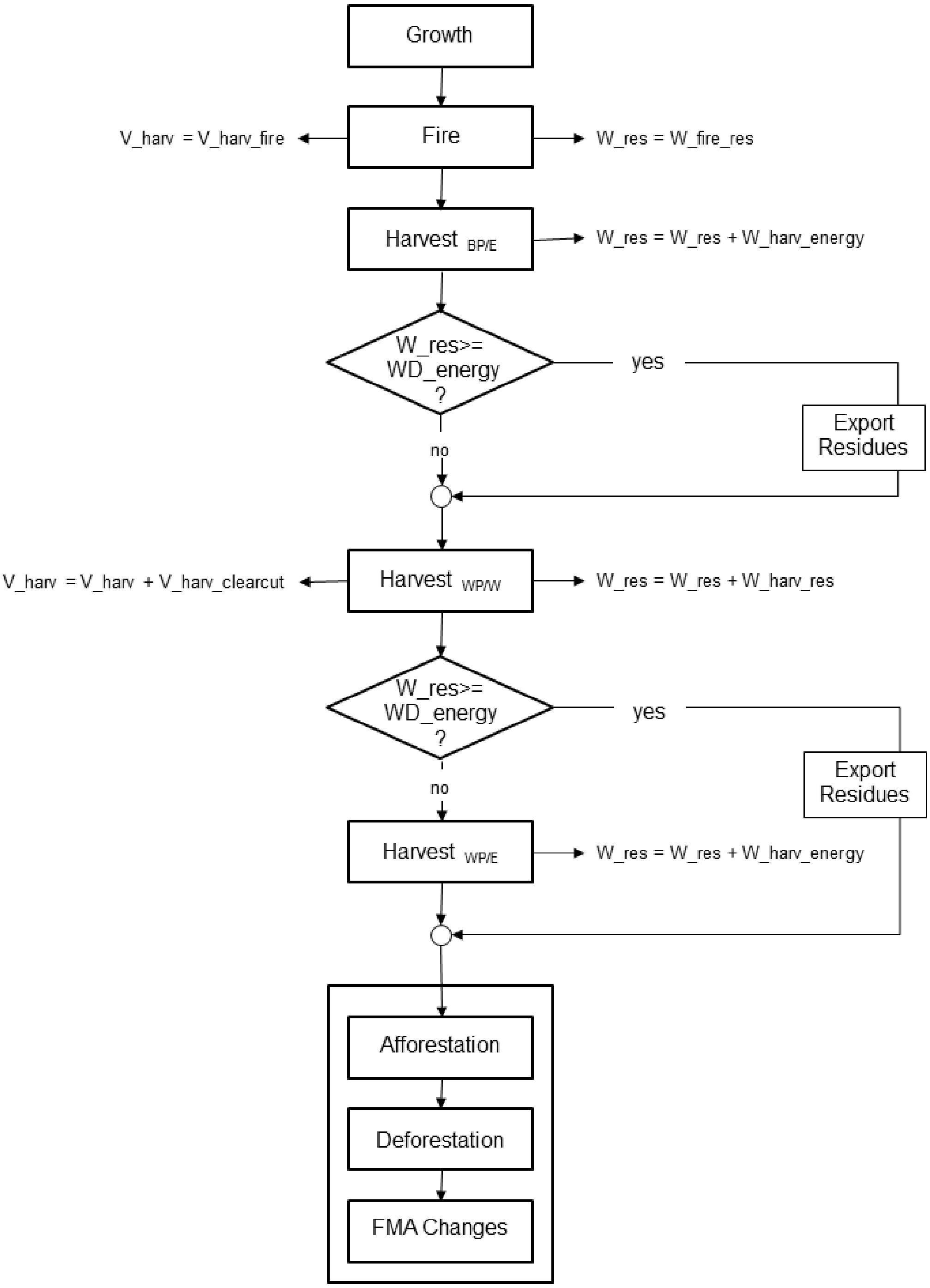


Fig. 2. Schematic view of SIMPLOT's functioning.

IV.3.1.6 Running the simulator

After updating stand growth with the growth module, the first driver module to run is “hazards-fire”. This module was updated in order to produce two different outputs. After deciding which stands are burned (Monte Carlo simulation), it separates the volume of salvage wood to be used for pulp from the biomass of residues for bioenergy production. The biomass of residues resulting from harvesting a certain proportion of burned wood for industrial use, combined with the total biomass from the stands with no industrial use, is summed, contributing to the first source of biomass for energy.

The next three modules in **Fig. 1** are harvesting modules. The first one (harvest BP/E), is responsible for harvesting bioenergy stands consisting of the second source of biomass for energy. This module harvests all stands planted for energy production that have reached the rotation length defined as a simulation parameter, regardless of the biomass demand defined in the scenario. The aboveground biomass resulting from this harvest operation is summed up to the burned biomass previously harvested, and compared with the biomass demand. If biomass demand has been met, the surplus biomass is considered to be available for export. If not, the harvested biomass will continue being increased by biomass outputs from subsequent modules until the corresponding demand is met.

This module is followed by the one responsible for harvesting stands for pulp production (harvest WP/W). It produces two outputs: harvested volume, which is added to the volume of salvage wood that resulted as an output from the fire module, and biomass of residues, including shoot selection biomass. This last biomass output also contributes to the first source of biomass if biomass demand still needs to be met. Alves (1996) determined that, in one spacing trial (500 to 1667 trees/hectare), the amount of biomass removed during this operation when compared to the total standing dry biomass ranges between 47.57% and 57.41%, with an average value of 53.24% and no pattern in variation from the higher to the lower densities. In the absence of other information, and after discussion with forest experts, this value was used for the whole country to account for this pool of biomass. Harvesting takes place based on an age dependent probability, selecting stands with Monte Carlo simulation. The module runs until wood demand is met, and as it runs, biomass residues are produced. This biomass output, together with the biomass resulting from burned stands, contributes to the first source of biomass.

At this point, the total harvested biomass is compared with the biomass demand, and if it has not reached the amount defined in the scenario, another harvesting module can be run. Module harvest WP/E is responsible for harvesting pulp stands for energy production. Running this module will depend on whether wood demand has been met and biomass demand has not. Thus, it ensures that pulp stands will only be used for energy if there is enough wood to supply the wood demand. This module is based on the same principles as the previous one, with the difference that the whole harvested material is used for bioenergy. The product of this module makes up the third source of biomass.

After running the modules responsible for meeting the two demands, the modules responsible for land use are run: afforestation and deforestation. Presently, the afforestation module has to take into account two different kinds of stands to be planted: wood-production stands (WP) and short-rotation bioenergy production stands (BP). This module runs under the same principles described in Barreiro and Tomé (2011), but it has been updated so that new bioenergy plantations are set according to the areas defined in the scenario for each FMA. The deforestation module has not been modified.

Finally, the last module to run is the changes between FMAs, which defines the percentage of change between FMAs for each year of the simulation period. The main input information in the FMAs algorithm is the percentage of transition from one FMA to another. Thus, the next step is to determine the area in hectares and the corresponding number of stands that are converted from WP to BP and from BP to WP for each year of simulation. Monte Carlo simulation is used to decide which stands are converted to a different management approach.

It is important to stress that, if biomass demand is met at any point during the simulation for a given year, biomass from shoot selection and harvesting residues is assumed to be left on site to minimize nutrient removal.

IV.3.2 Methods used for testing the simulator

IV.3.2.1 Input data

The simulations were done using the national forest inventory (NFI) eucalyptus plots from NFI1995-97 as input. This case study includes a total of 786 plots, representing pure-even and uneven-aged stands and also eucalyptus mixed stands, covering an area of 805,546 ha (area equivalent to 674,908 ha of pure stands). All plots were classified as wood-production forest (WP). Biomass production (BP) stands will be represented by bioenergy plantations simulated based on the area of new plantations defined in the scenarios for each year of simulation.

IV.3.2.2 Scenarios and simulation parameters description

In order to facilitate the analysis, the total amount of the drivers' wood demand, hazards-fire, and deforestation are considered equal for the different scenarios. From 1998 to 2008 wood consumption, burned areas and LUC are based on the national forest statistics (Pereira et al. 2010). Changes between different FMAs were considered null throughout the simulation period. The underlying assumptions related to each of the drivers are described below.

Wood demand evolution from 2008 onward is based on the production capacity increase announced until year 2010 by the pulp and paper mills (Altri 2010). From 2010 onward, there is a 0.3% increase per year. As for hazards-fire, the simulation of burned areas from 2008 onward was based on the analysis of historical data from 1963 on forest fires (excluding the very large fires of 2003 and 2005), and Monte Carlo simulation was used to generate a time series of eucalyptus burned areas with two medium-high severity fires occurring in this period (**Fig. 3**). Deforestation is defined as a proportion of the total forest area. This proportion, considered constant for the simulation period, was determined by multiplying the average deforestation registered for the period of 1986-2000 (Pereira et al. 2010) by the total annual forest area.

Until 2015, biomass consumption was estimated based on the capacity of the biomass plants operating or planned to be operating in a near future (Campilho, personal communication). After 2015, an annual increase of 0.9% was applied (BD1). A scenario considering no biomass demand (BD0) was also studied (**Fig. 3**). Because there is no information on the amount of biomass consumed per species by bioenergy plants, it was considered that 50% of the raw material came from eucalyptus. This option relates to the fact that *E. globulus* and *Pinus pinaster* together cover 51% of total forest area and are the species used for bioenergy. The harvesting system considered in this study is characterized by removal of bark, branches and tree tops. Because the objective was to assess the maximum biomass available, a removal efficiency of 100% was assumed, as well as total use of the material resulting from the shoot selection operation.

Total afforestation results from the sum of new plantations for energy and new plantations for pulp. Afforestation scenarios were based on the average of new eucalyptus areas planted between 1995 and 2000 (Pereira et al. 2010): 4833.3 ha year^{-1}. Another three levels of new plantations were considered: 33%, 66% and 100% increases over this amount. Within each of the four afforestation levels, four different bioenergy plantation amounts were tested (**Fig. 4**), resulting in 16 alternative scenarios that were run with a 0.9% increase in biomass demand (BD1). Additionally, four plantation scenarios excluding bioenergy plantations were combined with a no biomass demand scenario (BD0). A total of 20 scenarios were identified and named after the biomass demand combined, the plantation scenario for pulp and the plantation scenario for bioenergy.

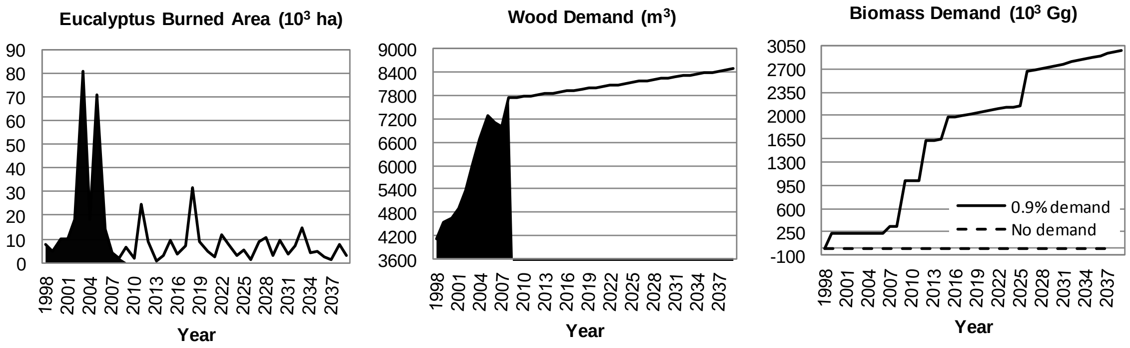


Fig. 3. Evolution of wood and biomass demand and burned area drivers.

Details on each FMA with a summary of the silvicultural operations can be found in **Table 1** in the **Appendix**. All scenarios were tested with the simulation parameters described in **Table 2** in the **Appendix**.

SIMPLOT was stochastically run in an attempt to illustrate natural variability through multiple simulation runs performed for each scenario. Outputs were averaged by scenario.

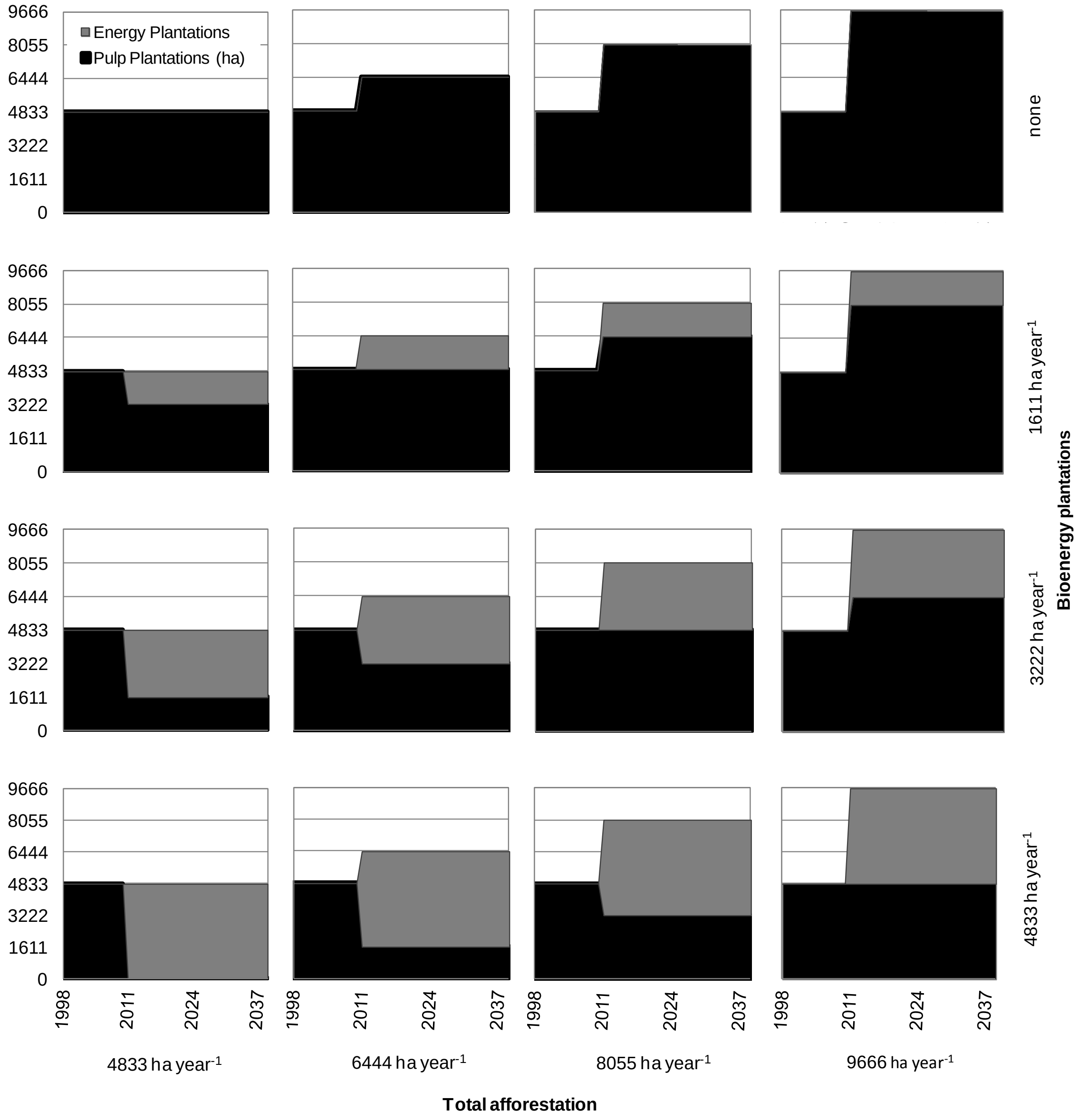


Fig. 4. Evolution of the alternative afforestation scenarios resulting from the combination of 4 bioenergy production planted areas (0, 1611, 3222 and 4833 ha) with different levels of wood-production planted areas varying between 0 and 9666 ha in order to achieve total afforestation levels of 4833, 6444, 8055 and 9666.

IV.4 Results

Applying SIMPLOT to the scenarios with different levels of new wood-production and bioenergy plantations allowed plotting wood volume available for harvest against wood demand for the two biomass demand scenarios (**Fig. 5** and **6**).

According to the projections, the potential wood volume between years 2018 and 2021, depending on the scenario, is not enough to satisfy wood demand. The amount of wood harvested is unstable and presents a cyclic behaviour.

For the no biomass demand scenario (BD0), four pulp plantation levels were combined with the null bioenergy plantation level. None of these scenarios succeeded in meeting wood demand. However, as the area of new wood-production plantations increased, the volume deficit was reduced (**Fig. 5**).

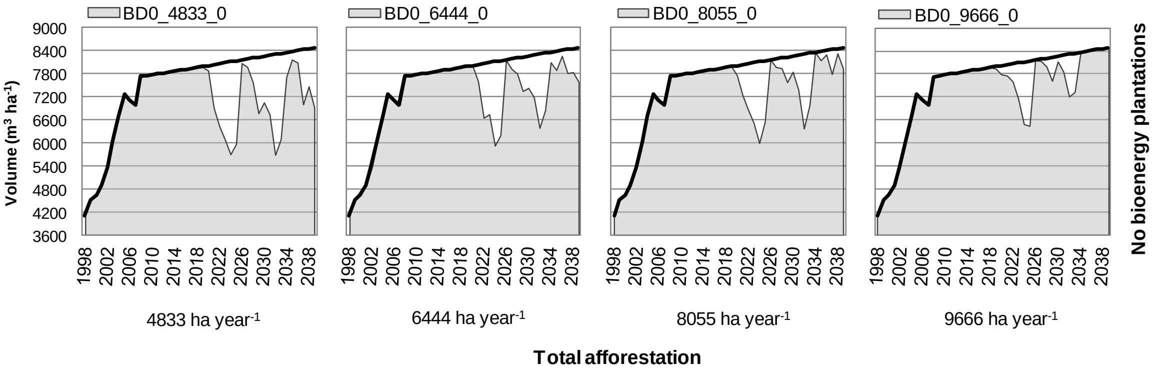


Fig. 5. Evolution of wood demand and harvested volume under the no biomass demand scenario combined with the four pulp afforestation scenarios considering no plantations for bioenergy.

The simulated harvested volume under BD1 for the same combination of plantation levels used in the BD0 scenario indicated a similar pattern throughout the simulation period (**Fig. 6**). Nevertheless, volume deficits are more severe under BD1 because the wood-production forest was responsible for supplying wood and partially bioenergy demands.

The remaining 12 afforestation levels combined with BD1 showed the same cyclical behaviour, with peaks of harvested volume nearly reaching wood demand after 2018 for some of the scenarios (**Fig. 6**). The highest levels of new wood-production plantations increased the potential volume to be harvested; in fact, the scenarios that allowed getting closer to meeting wood demand were those with areas of new wood-production plantations greater than 6444 ha year^{-1}. Moreover, for the same level of new pulp planted areas, the amount of wood available for pulp increased with the areas planted for bioenergy. This was mainly because the use of pulp planted stands for bioenergy was avoided when biomass deriving from bioenergy plantations was available.

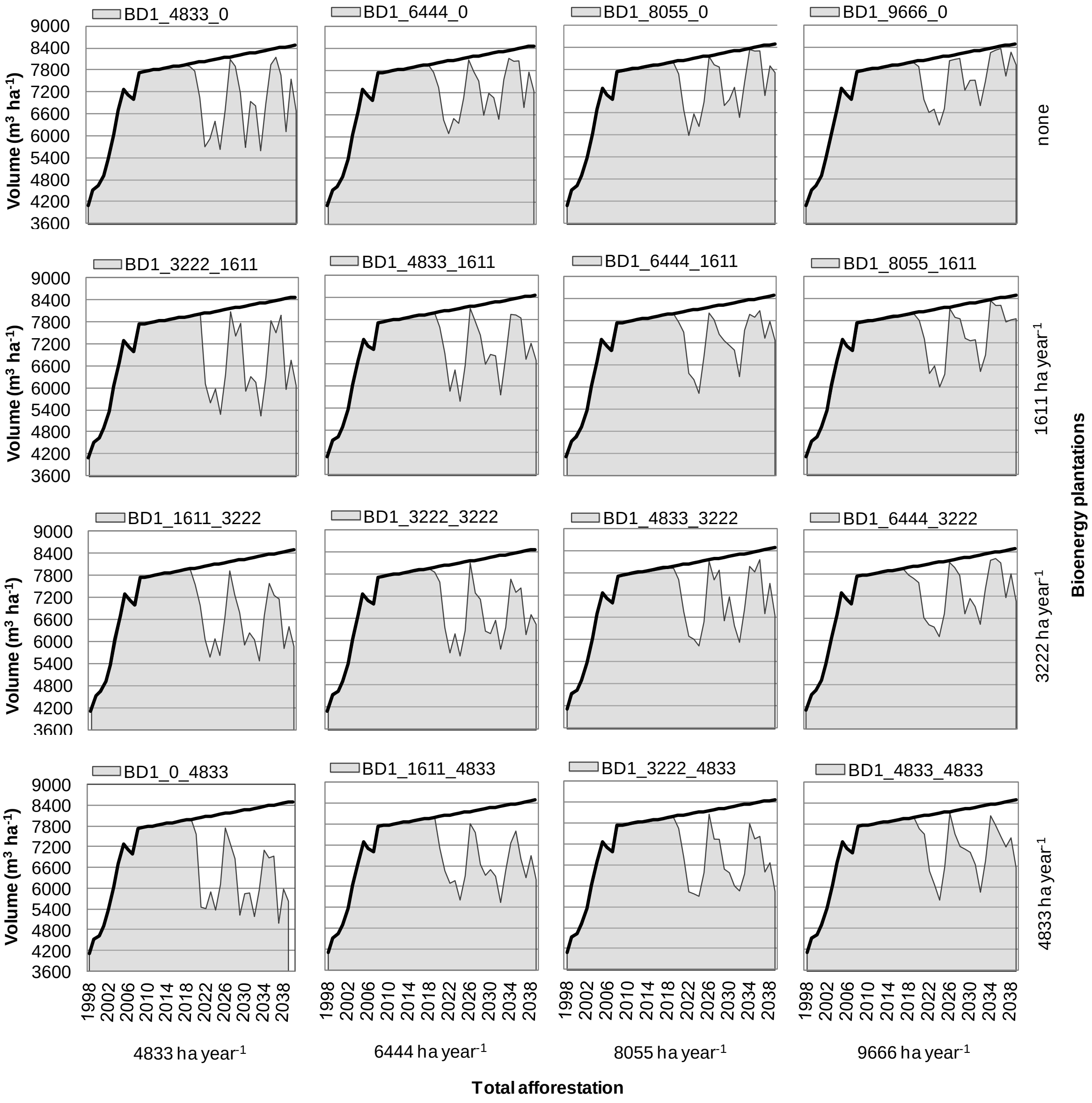


Fig. 6. Evolution of wood demand and harvested volume under the 0.9% biomass demand scenario combined with 16 afforestation scenarios varying in the proportion of wood-production and bioenergy plantations.

The cyclical behaviour of simulated harvested volume results from the forest area fluctuations by age class combined with forest productivity. After 2011, a reduction in forest area for the older age classes can be observed. Consequently, from 2021 onward, just the area from age class 8 is harvested, except for the years of 2026 and 2036 (**Fig. 9**). For these years, the distribution of forest area by age class allows going back to harvesting again in age class 9, which justifies the peaks of harvested volume observed in **Fig. 6**. The distribution of eucalyptus area by age class, together with an average yield of around 10 m^3 ha^{-1}year^{-1} at age 10 supports the idea that forest resources were being depleted.

The use of biomass for energy was graphically analyzed by source of biomass (**Fig. 7**).

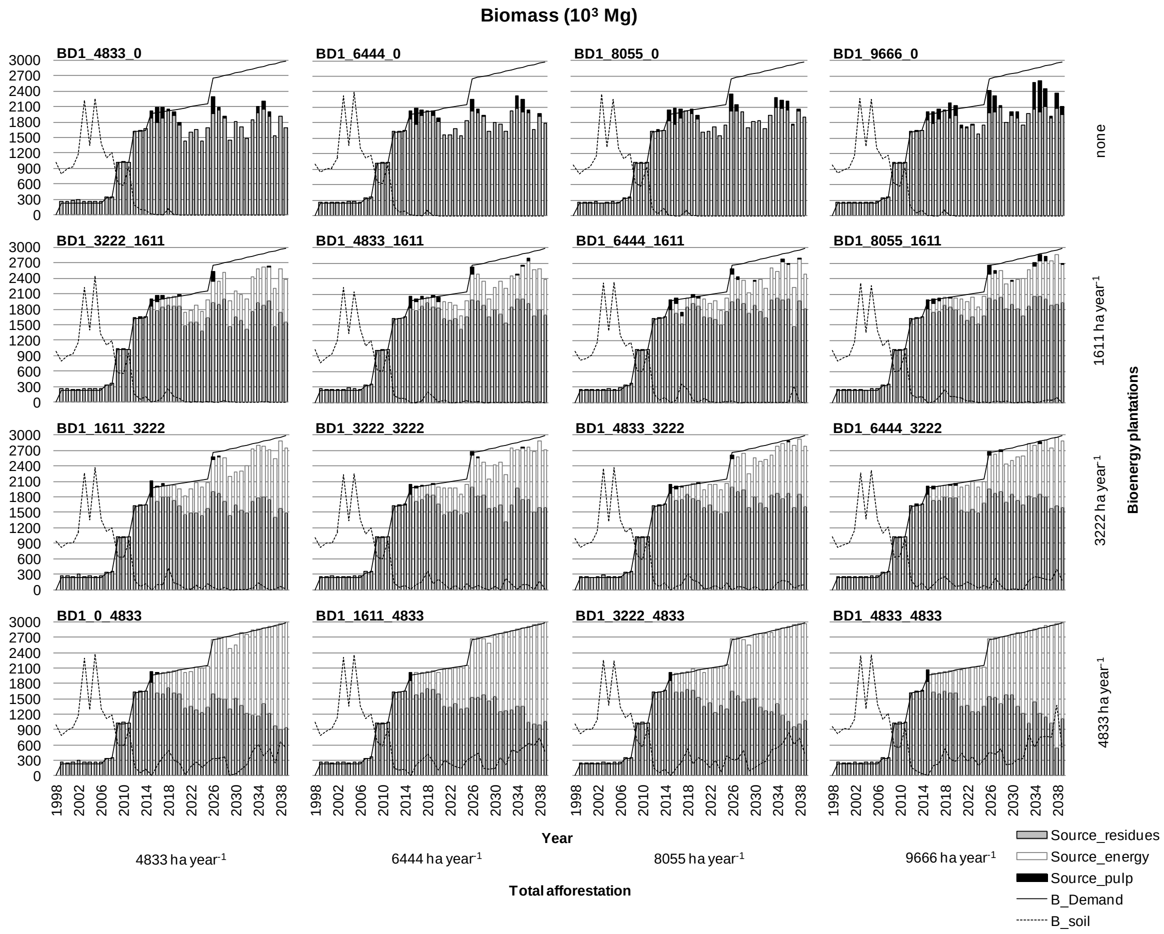


Fig. 7. Evolution of harvested biomass by biomass source: Source$_{\text{Residues}}$; Source$_{\text{Energy}}$ and Source$_{\text{Pulp}}$. B_demand is the biomass demand and B_soil is the biomass of the residues that left on the soil.

Forest residues (Source$_{\text{Residues}}$) that comprise burned and harvesting plus thinning residues proved to be the biggest contributor for bioenergy supply. This justifies the problem of meeting biomass demand when wood demand in no longer secure because, if there were no stands to be harvested for wood supply, no residues would be produced to increment the Source$_{\text{Residues}}$.

Results showed a high amount of soil residues present during the first decade of simulation. On one hand, this reflected the reduced consumption given the small number of bioenergy plants operating at that time, and on the other hand, the high amount of biomass residues resulting from severe forest fires. The two soil biomass peaks represent the severe forest fires of 2003 and 2005. Also, simulated soil residues showed a drastic drop as biomass demand increased, indicating the use of residues as a biomass source.

Whenever there was not enough biomass in the $\text{Source}_{\text{Residues}}$, new wood-production plantations for pulp were responsible for securing biomass supply, which was highlighted under the scenarios of no plantations for bioenergy. This explains the more negative impacts in terms of available volume registered for the no bioenergy plantations scenarios under BD0 and BD1. Also, wood-production plantations helped satisfying biomass demand whenever biomass deriving from $\text{Source}_{\text{Residues}}$ and $\text{Source}_{\text{Energy}}$ was unable to cope with the needs.

For a given pulp plantation area the negative impact of using biomass for energy can be partially offset by the increase in bioenergy plantations (BD1_4833_0, BD1_4833_1666, BD1_4833_3222 and BD1_4833_4833).

Simulations showed that the BD1 harvested volumes were considerably lower than the ones from BD0, which indicated the negative impact of bioenergy demand on the potential volume to be harvested for pulp. Volume deficits are considerably smaller for higher pulp plantation levels. So, in terms of wood demand, the best scenario is the one considering the highest pulp plantation level, BD1_9666_0. However, if the objective is to maximize the two demands, the choice would fall upon a scenario combining a favourable pulp plantation level with a reasonable bioenergy plantation, such as 6444 ha of wood-production areas combined with 3222 ha for bioenergy (BD1_6444_3222).

IV.5 Discussion

The objective of this simulation study was to assess the impact of using biomass for energy on wood available for the pulp industries. In this sense, some of the assumptions and constrains were established in order to guarantee maximum biomass removal. In this study, the different scenarios were forecast based on several assumptions and some constraints that must be accounted for when explaining the results obtained. The most important points to note are the lack of statistics related to biomass demand, specially the lack of knowledge about the quantity of eucalyptus consumed by the bioenergy plants.

It was considered that as bioenergy demand increased, more harvesting residues were removed from the forest soil, contributing for the $\text{Source}_{\text{Residues}}$. This is shown by the decline in soil residues as biomass demand increases (**Fig. 7**). In reality, the removal of soil residues is usually less intensive in stands managed for pulp, as was observed in this study. First, the most intensive harvesting method, responsible for the removal of tops, bark and branches of the whole tree, was considered, whereas it is common for bark or tops to be left on the soil. Second, the biomass resulting from the shoot selection operation was considered to fully integrate the $\text{Source}_{\text{Residues}}$, whereas in most cases it is left on the soil because of high transportation costs. Finally, when harvesting residues are removed, the efficiency of the operation is always less than 100%. However, if some biomass components had been left on the site, bigger contributions would have had to come from other sources to satisfy biomass demand, namely from stands planted for bioenergy or even from those planted specifically for pulp. If harvesting residues are left on the soil, nutrient removal is reduced, and they also help protect against soil erosion. Even though recent studies have shown that, for Mediterranean conditions, retaining harvest residues on the soil surface does not increase tree growth compared with removing it (Jones et al. 1999, Madeira et al. 2010). Only the incorporation of harvest residues, despite the negative effects caused by harrowing, show a positive effect on tree growth (Madeira et al. 2010). In turn, bioenergy plantations ($\text{Source}_{\text{Energy}}$) were assumed to be more intensively managed than pulp stands (see **Table 2** in the **Appendix**) based on the type of management practiced for willow (*Salix* sp.) and poplar (*Populus* sp.) in northern Europe, removing all aboveground biomass from the site without any environmental concerns.

However, these assumptions have no implications for productivity projections because SIMPLOT, being based on empirical growth models, does not have the flexibility to adequately account for nutritional issues. Furthermore, the assumption did not have a negative effect on biodiversity as the removal of harvesting residues has been proven not to reduce understory species diversity (Carneiro et al. 2007).

Most Portuguese forests (73%) are privately owned, with privately owned eucalyptus forests belonging to two types of ownerships: (1) those who make the investment without maintenance concerns and collect the profits of final felling; and (2) those who make the investment, manage the forest, and cut it whenever an unexpected need arises (Baptista and Santos 2005). In this context, and despite the pulp and paper industries being responsible for the sustainable management of 154.45 thousand ha of eucalyptus forest (CELPA 2011), sustainable forest management is difficult to achieve at national level without negative consequences on forest productivity. Furthermore, some forest owners have started selling their wood for bioenergy purposes because it pays off. However, given biomass energetic efficiency, and despite the climatic impact policies that encourage the use of biomass for energy, biomass should be used for heat production and cogeneration instead of dedicated electricity production. Moreover, the use of wood in industries brings about more added value and higher employment in the forest sector than if it were used for energy production (**Fig. 8**). For the above-stated reasons, this study also assumed that pulp stands could be harvested for bioenergy production ($\text{Source}_{\text{Pulp}}$) when wood demand had already been satisfied. As a consequence of this assumption, biomass deriving from $\text{Source}_{\text{Pulp}}$ was used to satisfy the corresponding demand for scenarios with bioenergy plantations of less than 1611 ha year^{-1} (**Fig. 7**).

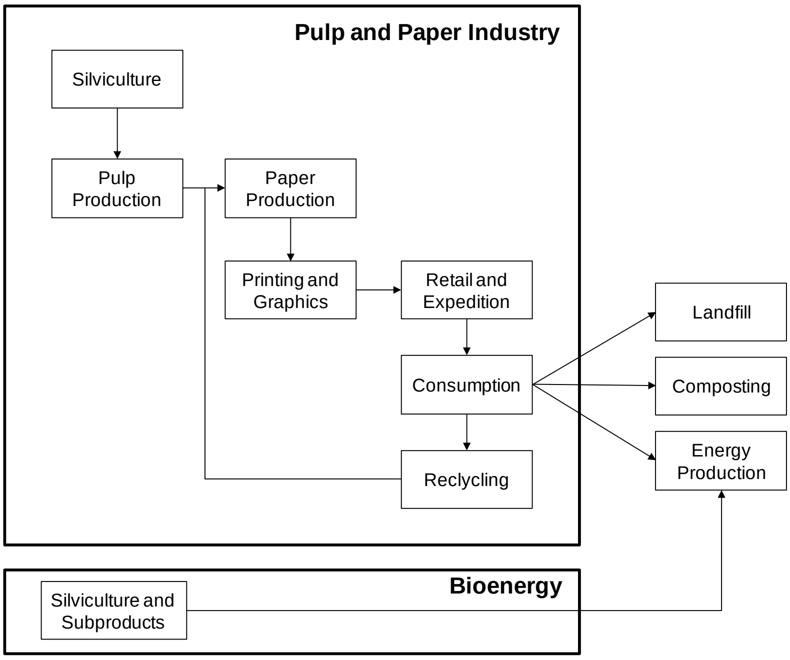


Fig. 8. Compared added value and employment related to the pulp and paper industry and bioenergy (adapted from CELPA (2006)).

Apart from the assumptions on which SIMPLOT was based, a few constraints set by simulation parameters should also be discussed, such as the minimum age for harvesting and the harvesting probabilities, as well as the harvesting method. Portuguese eucalyptus forests are experiencing an overharvesting situation that has been mentioned in other studies (Nabuurs et al. 2007). When wood demand is not met, this means that not enough volume, or no volume at all, was harvested for that year. Analyzing the distribution of areas by age classes, BD1_6444_3222 scenario as an example (**Fig. 9**), it is clear that stand structure has suffered an enormous change that started with the big fires of 2003 and 2005 and was thereafter accentuated by the harvesting pressure to satisfy wood demand. After 2021 there was not enough volume available to meet wood demand because there was no area in the age classes older than 8 years. This can be explained by the minimum age for harvesting assumed in the simulations that was set at the age of 8 years and by a higher harvesting priority that was established for older stands.

As long as forests ensure meeting wood demand the first source of biomass is guaranteed up to some extent, otherwise there might be the need to plant specifically for energy. In this case, it might be wise to choose a different eucalyptus variety or even a different species. According to some studies there are eucalyptus species other than *E. globulus* with better coppicing ability and higher yields (Sims et al. 1999).

Bioenergy production stands were simulated with an adapted version of the Globulus model developed from spacing trials data to simulate WP stands. To provide more trustworthy simulation results for highly dense stands, research on the productivity of bioenergy plantations is needed to provide data for a new model to be developed for this purpose based on *E. globulus* trials, or any other variety/species.

Increasing new pulp plantation areas could be an answer to satisfying wood demand. However, when discussing the potential conflict between bioenergy and pulp, it has to be taken into account the fact that eucalyptus is an exotic species and that the Nature and Biodiversity Conservation Institute (ICNB) has made efforts to classify it as an invasive species. Eucalyptus is considered by many not to fit local natural ecosystems. Given this pressure, eucalyptus forest area is not likely to increase much more in the future. A solution may be the intensification of silviculture to improve productivity and an improvement of management in a large proportion of the privately owned eucalyptus stands.

Apart from this, the situation of the pulp industries in Portugal has to be considered. In 2008 wood imports represented 13.1% of wood consumption, while in 2010 the number raised up to 26.8%, this is partly due to severe fires that occurred in the past which have depleted forest resources (CEPA 2009, CELPA 2011). Moreover, after the investment made by pulp and paper industries to double production capacity while facing a 52.6% decline of raw material when compared to 2008 (CELPA 2010), it is expected that imports will grow even more so that wood demand can be meet in the future. At the same time, in 2010 exports of pulp and paper have increased 3.1% when compared to 2009.

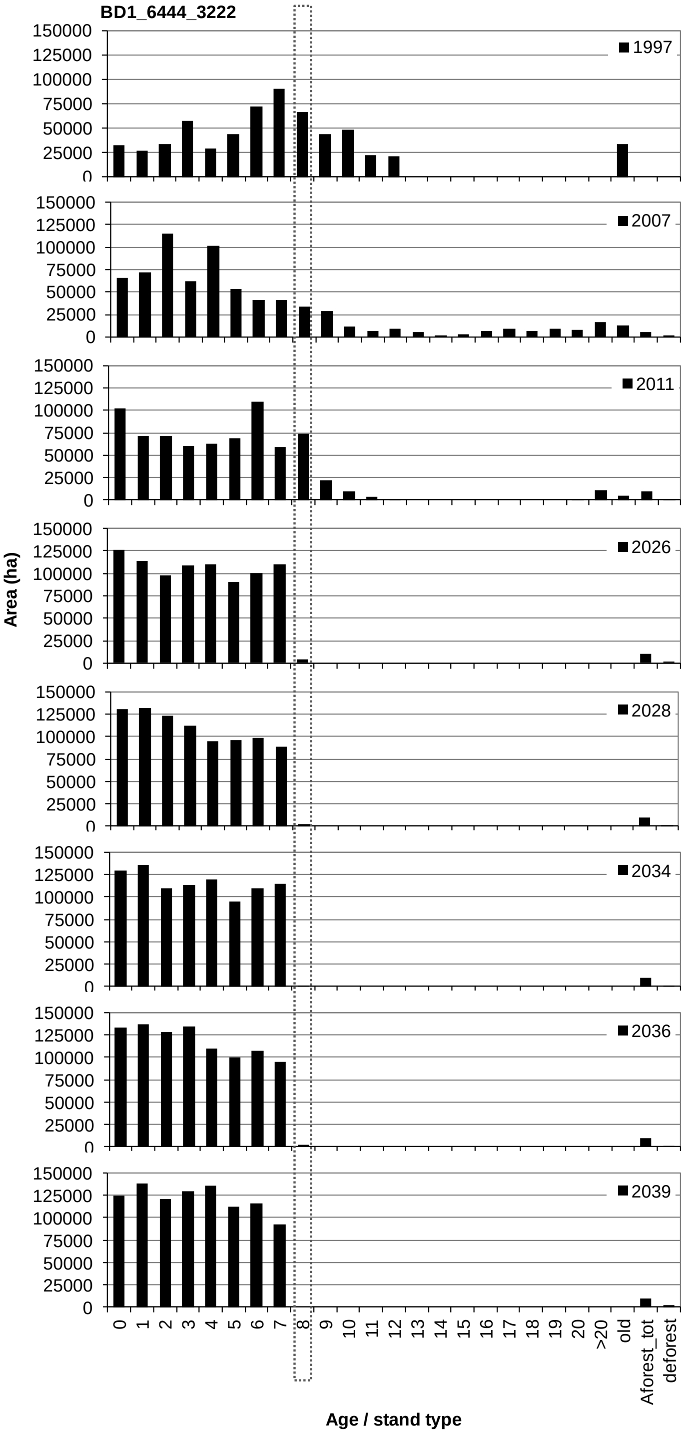


Fig. 9. Evolution of area by age class and stand type for a scenario considering 6444 ha of new plantations for pulp combined with combined with 3222 of new bioenergy plantations (BD1_6444_3222) for some years of simulation (at the end of the year and after harvesting has occurred).

IV.6 Conclusions

The simulations show that under the current situation in Portugal, and assuming that biomass demand is satisfied before bioenergy demand, increasing biomass demand up to the considered level will not have a major impact on wood available for pulp production, as long as bioenergy plantations are established to secure the supply of biomass demand avoiding wood from being used as energy. However, forest was not capable of satisfying wood demand even when biomass demand was disregarded. This situation could be less problematic if higher afforestation levels were considered. However, eucalyptus is a controversial species and a big expansion in terms of area might be excluded. Therefore, pulp and paper industries will have to focus on alternative measures to increase productivity and wood quality in order to satisfy wood demand and reduce or maintain their level of imports, such as the use of improved genetic material and sustainable forest management practices and also by enforcing fire prevention in order to reduce burned areas.

Some of the assumptions and constraints that were used resulted from the deficient information regarding the present situation of bioenergy production in Portugal. This lack of reporting resulted in several assumptions that cannot be demonstrated for the time being and that were deliberately exaggerated, in order to explore the future biomass availability, such as the amount of eucalyptus consumed in each plant and the exact number and capacity of future plants to be set. However, the simulation results under the different scenarios showed that the simulator can be used to forecast wood available for pulp and paper industries and the potential biomass deriving from forests to supply both demands. Furthermore, it allows assessing the contribution of each biomass source to meet biomass demand, but also set up a landmark to evaluating future scenarios. SIMPLOT’s predictions have been evaluated using data from consecutive inventories and the results have proven its accuracy (**Chapter V**). This gives more credit to the results making the simulator an extremely valuable tool for eucalyptus in Portugal as well as for any other species provided that the new species-specific growth functions are introduced into the growth module.

IV.7 Literature Cited

Abell, T.M., 2005. Forestry and Biomass Production. Lessons from the temperate regions and the tropics. International Conference on the Issues for Sustainable use of Biomass Resources for Energy. Colombo, Sri Lanka.
[online] URL: www.nri.org/projects/biomass/conference_proceedings_p2.htm

Altri, SGPS, S.A. (Altri)., 2010. Relatório do Conselho de Administração - Contas Consolidadas 2009.
[online] URL: http://en.altri.pt/pulpandpaper/

Alves, G.R., 1996. Estimação de biomassa total e de madeira em eucaliptais jovens de segunda rotação. Dissertation. Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Lisbon, Portugal.

Associação da Indústria Papeleira (CELPA). 2006. Contribuição para a politica das alterações climáticas. CELPA, Associação da Indústria Papeleira.
[online] URL: http://www.celpa.pt/images/pdf/art213_brochura_contribuicao.pdf

Associação da Indústria Papeleira (CELPA). 2009. Boletim Estatístico 2008 da Associação da Indústria Papeleira. CELPA Editores. Lisbon, Portugal.

Associação da Indústria Papeleira (CELPA). 2010. Boletim Estatístico 2009 da Associação da Indústria Papeleira. CELPA Editores. Lisbon, Portugal.

Associação da Indústria Papeleira (CELPA). 2011. Boletim Estatístico 2010 da Associação da Indústria Papeleira. CELPA Editores. Lisbon, Portugal.

Autoridade Florestal Nacional (AFN). 2010. Inventário Florestal Nacional. IFN 2005-2006. Portugal Continental. Autoridade Florestal Nacional, Ministério da Agricultura do Desenvolvimento Rural e das Pescas, Lisbon, Portugal.

Baptista, F.O., Santos, R.T., 2005. Os Proprietários Florestais. Celta Editora, Lisbon, Portugal.

Barreiro, S., Tomé, M., 2011. SIMPLOT: Simulating the impacts of fire severity on sustainability of eucalyptus forests in Portugal. Ecological Indicators, **11**: 36–45.

Carneiro, M., Fabião, A., Martins, M.C., Cerveira, C., Santos, C., Nogueira, C., Lousã, M., Hilário, L., Fabião, André, Abrantes, M., Madeira, M., 2007. Species richness and biomass of understory vegetation in a *Eucalyptus globulus* Labill. coppice as affected by slash management. European Journal Forest Research, **126**: 475–480.

Diário da República (DRE). 2005a. Diário da República Electrónico, PRESIDÊNCIA DO CONSELHO DE MINISTROS, Resolução do Conselho de Ministros nº 169/2005, DIÁRIO DA REPÚBLICA-I SÉRIE-B, nº 204 -24 de Outubro de 2005, Lisboa, Portugal. [online] URL: http://dre.pt/pdf1sdip/2005/10/204B00/61686176.pdf

Diário da República (DRE). 2005b. Diário da República Electrónico, Ministério das Actividades Económicas e do Trabalho, Decreto-Lei nº 33-A/2005 de 16 de Fevereiro, DIÁRIO DA REPÚBLICA -I SÉRIE-A nº 33-16 de Fevereiro de 2005, Lisboa, Portugal. [online] URL: http://dre.pt/pdf1sdip/2005/02/033A01/00020009.pdf

Diário da República (DRE). 2006. Diário da República Electrónico, PRESIDÊNCIA DO CONSELHO DE MINISTROS, Resolução do Conselho de Ministros nº 115/2006, Diário da República, 1.a série - nº 180-18 de Setembro de 2006, Lisboa, Portugal.

[online] URL: http://dre.pt/pdf1sdip/2006/09/18000/68356881.pdf

Direcção Geral dos Serviços Florestais e Aquícolas (DGSFA). 1966a. Inventário ao Norte do Tejo - 1965-66. Direcção Geral dos Serviços Florestais e Aquícolas, Lisbon, Portugal.

Direcção Geral dos Serviços Florestais e Aquícolas (DGSFA). 1966b. Inventário ao Sul do Tejo - 1965-66. Direcção Geral dos Serviços Florestais e Aquícolas, Lisbon, Portugal.

Fontes, L., Tomé, M., Tomé, J., Coelho, M.B. Equations to predict aboveground biomass per tree component to a merchantable height for *Eucalyptus globulus* Labill. in Portugal, submitted.

Jones H.E., Madeira, M., Herraez, L., Dighton, J., Fabião, A., González-Rio, F., Fernandez Marcos, M., Gomez, C., Tomé, M., Feith, H., Magalhães, M.C., Howson. G., 1999. The effect of organic-matter management on the productivity of *Eucalyptus globulus* stands in Spain and Portugal: tree growth and harvest residue decomposition in relation to site and treatment. Forest Ecology and Management, **122**: 73-86.

Leal, L.A Indústria papeleira no context das alterações climaticas. CELPA, Associação da Indústria Papeleira
[online] URL: http://www.celpa.pt/images/pdf/art211_alteracoes.pdf

Madeira A.C., Madeira, M., Fabião, A., Marques, P., Carneiro, M., 2010. Impact of harvest residues, fertilisers and N-fixing plants on growth and nutritional status of young *Eucalyptus globulus* plantations, under Mediterranean conditions. European Journal of Forest Research, **129**: 591–601.

Nabuurs G.J., Pussinen, A., van Brusselen, J., Schelhaas, M.J., 2007. Future harvesting pressure on European forests. European Journal Forest Research, **126**: 391–400 DOI 10.1007/s10342-006-0158-y.

Pereira, T.C., Seabra, T., Maciel, H., Torres, P., 2010. Portuguese National Inventory Report on Greenhouse Gases, 1990-2008. Agência Portuguesa do Ambiente, Ministério do Ambiente e do Ordenamento do Território, Amadora, Portugal.

Ribeiro, F., Soares, P., Tomé, M., Cadete, D., Pina, P., 1997. Determination of initial stand density that optimizes the system production of *Eucalyptus globulus* Labill. in Portugal. In Proceedings of IUFRO Conference on Silviculture and Improvement of Eucalypts. Embrapa, Centro Nacional de Pesquisa de Florestas Colombo, Brazil. Vol 3, pp. 125-129.

Sims, R.E.H., Senelwa, K., Maiava, T., Bullock, B.T., 1999. Eucalyptus species for biomass energy in New Zealand - Part II: Coppice performance. Biomass and Bioenergy, **17**: 333-343.

Soares, P., Tomé, M., 2003. GLOBTREE: an Individual Tree Growth Model for Eucalpytus globulus in Portugal. In Amaro, A., Reed, D., Soares, P. (Eds.). Modelling forest systems. CABI Publishing, Cambridge, USA. pp. 97-110.

Soares, J., Leal, L., Canaveira, P., Goes, F., Fialho, A., 2007. Porquê cultivar o eucalipto? In Público comunicação Social, SA and Fundação Luso-Americana para o Desenvolvimento Editores. Árvores e Florestas de Portugal. Pinhais e Eucaliptais – A floresta cultivada. Lisbon, Portugal. pp. 185-219.

Tomé, M., Meyer, A., Ramos, T., Barreiro, S., Faias, S.P., Cortiçada, A., 2007a. Relações hipsométricas desenvolvidas no âmbito do tratamento dos dados do Inventário Florestal Nacional 2005-2006. Publicações GIMREF. RT 3/2007. Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Lisbon, Portugal.

Tomé, M., Tomé, J., Ribeiro, F., Faias, S.P., 2007b. Equação de volume total, volume percentual e de perfil do tronco para *Eucalyptus globulus* Labill. em Portugal. Silva Lusitana, **15**(1): 25-29.

Tomé, M., Soares, P., Oliveira, T., 2006*.* O modelo GLOBULUS 3.0. Dados e equações*.* Publicações GIMREF RC2/2006. Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Lisbon, Portugal.

United Nations. 1998. Kyoto protocol to the United Nations framework convention on climate change. United Nations Climate Change Secretariat, Bonn, Germany.
[online] URL: http://unfccc.int/resource/docs/convkp/kpeng.pdf

IV.8 Appendix

Detailed description of the simulation parameters and forest management approaches considered in the case study**.**

Wood-production stands (WP) are managed as a planted stand followed by two coppice stands before replanting occurs with final harvest, whereas bioenergy production stands (BP) are managed as a planted stand followed by three coppiced stands. All rotations in BP stands are characterized by a rotation length of 5 years. **Table 1** summarizes the silvicultural operations practiced for each FMA, rotation and age.

Table 1 Detailed description of the forest management approach considered in the case study.

FMA	Rotation	Age	Silvicultural operations
WP	1	1	Planting (1250 trees/ha) and fertilization at planting
		2	Weed control and beating up
		4, 7 and 11	Weed control and fertilization
		16, 22 and 28	Weed control
	2 and 3	3	Weed control and shoot selection (1.6 sprouts per stool)
		5 and 8	Weed control and fertilization
		12, 17, 23 and 29	Weed control
BP	1	1	Planting (5000 trees/ha) and fertilization at planting
		2	Weed control and beating up
		4	Weed control and fertilization
		5	Final harvest
	2 until 3	1	Fertilization
		2	Weed control and fertilization
		4	Weed control

For WP final harvest can occur at any stand stage as long as the stand is older than the minimum age for harvesting defined by the simulation parameter.

The usual age for even-aged stands final felling was considered to be 12 years, but it can vary according with the need for wood. The harvesting method/system consists in removing tops, bark and branches. **Table 2** contains the simulation parameters used in the simulations.

Table 2 Simulation parameters considered in the case study.

Number of years to project	42	
Minimum age for industrial use of wood after a fire (years)	5	
Proportion wood industrially used after fire	0.6	
Proportion of old/sparse non-industrial stands harvested	0.1	
Proportion uneven-aged stands harvested	0.1	
Minimum age for harvesting	8	
Nr of age classes	6	
Even-aged stands harvesting probability:		
Age= 8	0.1	
Age= 9	0.2	
Age=10	0.3	
Age=11	0.4	
Age=12	0.5	
Age>12	0.95	
Harvesting system:		
Bark	1	
Branches	1	
Top	1	
Tops and branches	0	
Assortments:		
Number of assortments	1	
Id	1	2
Label	Pulp	biomass
Top diameter (cm)	5	-
Log length (m)	2	-
Value (€/m^3)	45	25
FMA:		
Number of FMA	2	
FMA Id	1	2
Number of rotations	3	4
Maximum age of rotation	30	5

CHAPTER V

Using consecutive National Forest Inventories to validate regional forest simulators. An application to the regional simulator SIMPLOT in Portugal

Title: Using consecutive National Forest Inventories to validate regional forest simulators. An application to the regional simulator SIMPLOT in Portugal.

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Using consecutive National Forest Inventories to validate regional forest simulators. An application to the regional simulator SIMPLOT in Portugal.

V.1 Abstract

In the past few years in Portugal, the losses caused by severe forest fires on *Eucalyptus globulus* plantations in conjunction with the increase of wood demand for the pulp and paper industries emphasised the need for a tool capable of evaluating the impacts of disturbance factors at a national level. SIMPLOT regional simulator was conceived to simulate eucalyptus stand growth in a region. The simulator is initialized with NFI plots and forest resources are updated using growth models in order to predict the evolution of forest condition. The simulator is mainly driven by wood and biomass demands, but fire occurrence, land use changes and changes in management are also considered.

The main objective of this study was to validate SIMPLOT's projections running the simulator with historic data and, secondly, to identify existing aspects of the tool that might need to be improved. SIMPLOT was initialized with data from the 1995-1997 NFI and a business as usual scenario based on official statistics reflecting reality for the period of 1997 to 2007 was run. Subsequently, simulation results for standing volume and forest area distribution by age classes were compared to forest inventory data conducted between 2005 and 2007. Results of validation showed that SIMPLOT is capable of making reliable large scale projections for standing volume. In terms of the distribution of forest areas by age classes, simulation results were reasonable for all stand types except for the uneven-aged ones for which simulated areas were under-estimated.

V.2 Introduction

Over the last decades eucalyptus forest area in Portugal has increased from 70 thousand hectares in 1965 (DGSFA 1966a, DGSFA 1966b) to around 740 thousand hectares in 2005 (AFN 2010). The expansion was achieved at the expense of a reduction of uncultivated land and marginal agriculture, but greatly promoted by pulp and paper industries in an attempt to secure their raw-material supply (Borges and Borges 2007). Presently, 23% of the Portuguese forests are covered with *Eucalyptus globulus* which is the second most representative species in the country in terms of area, being of extreme importance to the Portuguese pulp and paper industry (AFN 2010). The contribution of the Portuguese forest sector to the gross value-added in percentage of the gross domestic product is 1.7%, which places Portugal above the average European contribution (Castro Rego 2011). Over the last decade, the incidence of severe forest fires combined with the recent increase in production capacity registered in the pulp and paper industries led to an increase in wood demand that implied an increase in imported wood. In 2009, around 20% of the wood used to supply the industry was imported (CELPA 2010). The increase in imported wood observed after 2006 can be seen as indicative of the harvesting pressure on eucalyptus forest in Portugal. In 2010, the forest sector represented 10.3% of the national exports with pulp and paper leading the sub-sectors representativeness with 5.7% (Honório 2011). The inability of eucalyptus forest to supply wood demand and its extreme importance for the national economy emphasized the need to predict future productions accounting for the effects of markets, disturbance factors and management providing more than just stand development. The present needs and the current flow of information in forestry practice can only be met by more complex computerized models or simulators with the capacity to respond to this wide range of factors (Pretzsch et al. 2002). SIMPLOT, a eucalyptus regional simulator based on National Forest Inventory (NFI) plots as input, was created to forecast the evolution of eucalyptus forests in order to assist forest managers and policy makers in their decisions (Barreiro and Tomé 2011). SIMPLOT covers all types of stands taking into account several external drivers such as wood demand, fire occurrence and Land Use Changes (LUC) allowing predicting the evolution of forest resources under different scenarios. Projections obtained from running regional simulators are often used by policy makers to assist and support their decision making process. For this reason, before models and simulators are used there is the need to validate these tools to increase the credibility and gain sufficient confidence about its outputs (Soares et al. 1995, Vanclay and Skovsgaard 1997, Yang et al. 2004).

The aim of this study was to validate SIMPLOT's results in order to show how faithfully its outputs represent reality and help identify potential problems or weaknesses of this tool. Projections were made under a scenario based on the official statistics available so that reality was illustrated as best as possible for the period in question. The study was enriched by testing different sets of harvesting probabilities by age classes under the same scenario to see which reflects more accurately the average harvesting criteria applied during the 1995-2005 decade.

V.3 Methods

V.3.1 Overview of SIMPLOT regional simulator

The SIMPLOT simulator has been described in detail elsewhere (Barreiro and Tomé 2011, Barreiro and Tomé, in press). It starts with forest inventory information at plot level and uses a set of forest growth models to predict long-term development of forest resources in the region taking into account the influence of wood and biomass demands, fire, land use changes (LUC) - afforestation and deforestation - and changes in forest management. SIMPLOT's growth module is composed of stand level models: Globulus 3.0 (Tomé et al. 2006a) and GYMMA$_{nlin}$ (Barreiro et al. 2004) models that update forest resources before the drivers are applied. The drivers are implemented in two steps: 1) the total amount of each driver is given as input through the scenario file; 2) the probability of occurrence of the event for each stand and the selection of stands to be affected, which, depending on the driver, maybe estimated according to a fixed probability (simulation parameter) or according to a probability function and implemented with Monte Carlo simulation. In case the event occurs, the simulator takes a specific action depending on the event (Barreiro and Tomé 2011).

Simulation runs depend on a series of simulation parameters defined by the user. SIMPLOT is organized in several modules and operates based on a set of assumptions such as: all burnt stands are harvested and a certain percentage of salvage wood is always considered; fire causes leaves, bark and branches biomass reductions of 100%, 40% and 25%, respectively; only stands that have been harvested can be either abandoned, replanted under the same FMA or under a different one; and that wood-production stands can be harvested to meet biomass demand for energy in case wood demand has been met. It also assumes that fire occurs after half of the annual growth has been attained, which is a reasonable assumption because fires usually occur during most of the growing period. As for harvest, it is assumed that it takes place when half the annual growth has been achieved because eucalyptus stands can be harvested during the whole year. Assumptions concerning stand structure are also considered: the areas of gaps and clumps are assumed to be maintained throughout the simulation period while the areas of uneven-aged stands tend to be reduced because after harvest stands are replanted as even-aged stands and no conversion from even- to uneven-aged stands is considered.

After growth has been updated, the fire module runs using Monte Carlo simulation to select which stands will be burnt. The annual probability of burning is assumed to be equal for all stands and computed using the total area affected by fire for each particular year defined in the scenario. The percentage of salvage wood for pulp is a simulation parameter. As the module runs, burnt area is accumulated until the area defined in the scenario for each year of simulation is met. It is assumed that after a fire occurs, the stand is harvested and part of its wood is used as salvaged wood. Non-burnt stands are selected for harvesting with Monte Carlo simulation and the harvesting probabilities associated to each age are defined by the user. Harvested volume is added to the volume of salvage wood. The sum is compared with the wood demand defined in the scenario and harvesting goes on until wood demand is met. Before the simulation of the next year starts, afforestation and deforestation are taken into account. A site index is assigned to each new stand to initiate the simulation process. New stands are planted until the total area of new plantations meets the area in the scenario. In respect to deforestation, a probability function depending on the stands' climatic region was implemented by Monte Carlo simulation and is used to decide which stands are abandoned. The last drivers' module to run is the FMA's one which defines the percentage of changes that takes place in each year of simulation between the different FMA's.

In Portugal eucalyptus mixed stands represent a small percentage of the eucalyptus forest area. There are no growth models available for mixed stands. So, one way of forecasting the evolution of mixed stands is correcting the areas of the mixed stands converting them into pure stands and using sand level growth models developed for pure stands. Due to the small area of mixed stands, the methodology applied to contour mixed stands' simulation is not considered to have a large influence on the results. In order to make results comparable to the area of the validation dataset the area of mixed stands for year 2007 was also corrected.

V.3.2 Evaluation of models and simulators – the SIMPLOT case

Growth and yield models are essential tools for forest management planners. However, decisions are always influenced by the accuracy of projections provided by the models. Because models and simulators are simplifications of reality they should always be evaluated before being used. Stage (2003) states that a model used for supporting decisions should have the bias and the precision of its forecasts quantified. The same is valid for simulator's validation. Validating a model or a simulator can be considered as a way to define a certain level of confidence in its forecasts providing information on whether it is adequate for a particular use (van Horn 1971).

The evaluation of a model or a simulator can be achieved by testing the tool using verification and validation procedures (**Fig. 1**). Verification consists of checking that the model or simulator is carrying out its instructions correctly, while the validation process is responsible for comparing projections to "real world" observations through the use of subjective or objective approaches (Cawrse et al. 2010).

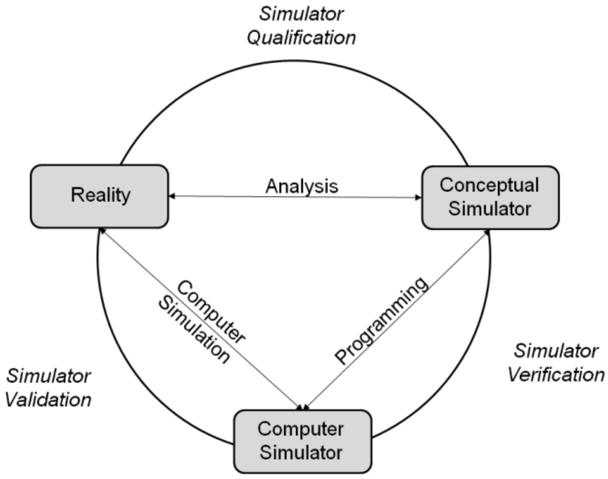

Fig. 1. The evaluation process of simulation models (adapted from Schlesinger 1980).

The first step in the process of developing a simulator consists of conceptually designing the structure and the functioning of the simulator in a conceptual form so that it can mimic reality (simulator qualification*)*. Despite based on growth models, a simulator also has to account for other issues such as the inclusion of the drivers and the set of assumptions on which the simulator's functioning is based that are independent of the growth models' accuracy but also affect the simulators accuracy. Afterwards, there is the need to assess whether the programming instructions are given correctly and if the algorithms are capable of expressing the conceptual form of the simulator that was previously defined (simulator verification). Finally, the simulator needs to be validated which consists of comparing the simulator's outputs to reliable data. Different approaches can be used to validate long-term forest projection simulators (Nabuurs et al. 2000): 1) validation of the component growth functions by comparison with real data or with growth functions of another models; 2) comparing its projections with projections from other simulators carried out for the same forest, region and period; and 3) running the simulator using historic data as input and comparing the simulated results with real data from some point in the future.

The first approach was not considered for SIMPLOT because the simulator already integrates the most commonly used growth models developed for eucalyptus in Portugal and these have already been thoroughly validated. Moreover, just validating the growth functions would not allow validating the application of the drivers/scenario. The second approach could not be applied as at present there is no other regional simulator to use for comparison.

The validation approach applied in this study was running the simulator initialized with data from NFI 1995-1997 (historic data plus published statistics for defining the scenarios) and compare the projections with the NFI data from 2005-2006. The ideal would be to have long time series of data with detailed information on stand level to validate models and simulators. However, in the particular case of validating regional simulators using national forest inventory data as input was the solution because no long term series of data from permanent plots were available for the whole country. The same approach was used to validate EFISCEN (Thürig and Schelhaas 2006, Nabuurs et al. 2000), and had also been used before for other situations (Manley 1998, Clawson 1979). When compared to other approaches, using historic data to define the drivers and predict the actual state of forests from a previous state has the advantage of allowing validating the simulator as a whole accounting for all its modules' interactions.

V.3.3 Data

Portuguese National Forest Inventory was initiated in the 1960s. Thereafter, periodic NFIs have been conducted, more or less every 10-years, based on different sampling designs (Barreiro et al., 2010). NFI 1995-1997 (NFI4) started in 1995 with aerial photography production followed by the photo-interpretation of 136836 photo-point. Photo-interpretation was conducted in 1996-1997 and the forest areas were evaluated by qualitative sampling. A grid was laid over each aerial photograph for photo-interpretation purposes and field plots were systematically selected by stratum in proportion to the number of photo-points in the stratum. Field work was undertaken in 2211 concentric fixed area circular plots (783 eucalyptus plots) between July 1997 and April 1998. For this reason, field work is assumed to characterize forest resources by the end of 1997 (Tomé et al. 2010). All trees with a diameter at breast height (dbh) greater or equal to 7.5 cm were measured. Trees below this threshold were counted in a satellite of 5 small plots located inside the field plot (50 m^2 in total). Afterwards, standing volume was calculated for the most important tree species including eucalyptus.

Ten years later new aerial photography was produced for NFI5 that was to a great extent motivated by the 2003 and 2005 severe wildfires that jeopardized the viability of the Portuguese forest. It was crucial to obtain area and volume information for the main wood production species, maritime pine and eucalyptus. Unlike the previous forest inventory, NFI5 was based on a regular 2km x 2km dot grid covering the whole country. The coordinates of each NFI field plot matched a photo-point in the finer dot grid (500m x 500m) used for photo-interpretation. Forest area was estimated based on the photo-interpretation of 355737 points. Field measurements took place between December 2005 and December 2006 in 8860 field plots. Most of the field work was finished before June 2006, thus it is assumed to represent forest resources by the end of 2005 (Tomé et al. 2010). Eucalyptus production was assessed in 1765 fixed area circular plots with areas of 500 m^2 or 2000 m^2 for strata where cork or holm oaks were dominant. Eucalyptus with a dbh greater than 5 cm were measured (the diameter threshold for all other tree species was 7.5 cm). With respect to structure, vitality, biodiversity and production an evaluation was carried out for the plots classified as forest, other wooded land or shrubland. Trees below the diameter threshold were counted like in the previous NFI (Barreiro et al. 2010).

According to the national forest service - DGF statistics (2001) eucalyptus stands in 1995/1997 were mainly pure even-aged stands (573,231 ha), although some mixed, both dominant and dominated eucalyptus stands, and uneven-aged stands could also be found (**Table 1**). Stands for which eucalyptus is responsible for less than 75% of the total forest cover are classified as mixed eucalyptus stands. These stands can be designated as dominant if eucalyptus is the most abundant species or dominated otherwise.

Age is one of the most important variables for growth and yield modelling in even-aged stands. However, for stands composed of trees that differ markedly in age and sometimes in species at stand level, age cannot be used to predict growth and yield. Despite its importance, age is often a variable of difficult determination in National Forest Inventories being especially hard to assess for fast growing species with no well-defined tree rings like is the case of Eucalyptus (Tomé et al. 2006b). Unfortunately, field crews involved in NFI5 were not specifically trained to visually estimate the age of eucalyptus which resulted in deficient age estimates.

Table 1. Area and volume of eucalyptus stands by stand composition for 1997 and 2005.

		Pure Stands	**Dominant Stands**	**Dominated Stands**	**Total**
1997	**Area (ha)**	573231	98918	133397	805546
	Volume (10 m^3)	24985	6571	3341	34897
2005	**Area (ha)**	646543	92972	86926	826441
	Volume (10 m^3)	32990	5711	4167	42868

The NFI4 plot data was used as input in SIMPLOT and the output projections of standing volume were compared to the present state of the forests (NFI5). However, the poor age estimates resulting from NFI5 were inappropriate for validating the distribution of forest area by age classes. The alternative was using the Pulp and Paper Industry Association (CELPA) database containing the NFI plots that were revisited and measured in 2007 by field crews specifically trained for estimating age in eucalyptus stands. In accordance with the information provided by CELPA database, stand structure was characterized and forest area was distributed by age classes (**Table 2**).

Table 2. Area in hectares of eucalyptus stands distributed by stand structure.

	Even-aged Stands						**Uneven-aged Stands**	**Gaps and Clumps**
	<4	**[4-8[**	**[8-12[**	**[12-16[**	**[16-20[**	**Old**		
2007	209,423	218,320	125,669	36,360	984	6,084	157,222	65,398

V.3.4 SIMPLOT application

V.3.4.1 Input data

The data used as input to run SIMPLOT was the set of 786 eucalyptus plots from the National Forest Inventory of 1995-1997 (NFI4). A study carried out before NFI5 (Paulo 2001) showed that the eucalyptus volume equations used in NFI4 were biased leading to an underestimation of stand volume. As a consequence of Paulo's study, new volume equations were used in the NFI5. In order to harmonize volumes from NFI4 and NFI5, NFI4 volumes were recalculated using the same volume equations (Tomé et al. 2007). SIMPLOT growth module integrates the growth models available in Portugal. Pure even aged stands are projected with Globulus 3.0 model (Tomé et al. 2006a), while $\text{GYMMA}_{\text{nlin}}$, developed for projecting stands of unknown age, is applied to project uneven-aged stands (Barreiro et al. 2004). The area of eucalyptus mixed stands (232315 ha) was converted into an equivalent area of pure stands. This was achieved by assuming that each plot in a mixed stand, usually with *E. globulus* and *Pinus pinaster*, is equivalent to two even-aged plots with an area estimated according to the percent contribution of the species volume to the total volume in the plot. The conversion resulted in a reduction of the eucalyptus forest area down to a total of 674,908 ha of pure stands with a corresponding standing volume of 41.94x10^6 m^3, area that was considered in the simulation. This methodology was applied to NFI4 and to CELPA data from 2007 in order to allow validating the distribution of forest area by age classes. Because harvesting operations are not concentrated in any particular period of the year two annual simulated volumes were compared, one corresponding to the beginning of the year and the other to the end of the year.

V.3.4.2 The scenario used

The scenario, characterized by the total amount of the drivers and by a set of simulation parameters, was defined for a planning horizon of 10 years. Eucalyptus wood demand and burnt areas were obtained from the Portuguese official statistics (Pereira et al. 2010). **Fig. 2** shows the evolution of these drivers for the period between 1997 and 2007.

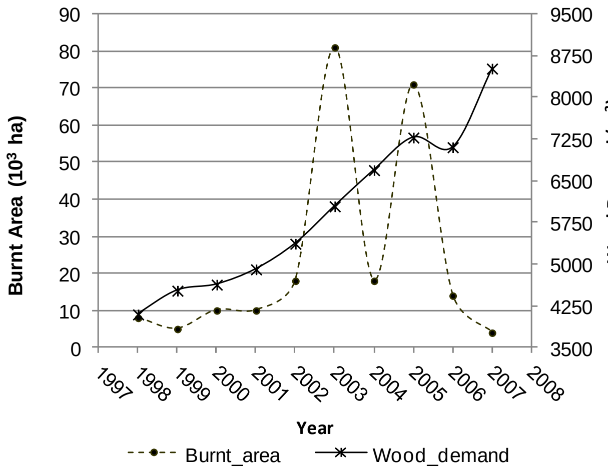

Fig. 2. Evolution of wood demand (volume under-bark) and burnt area for the eucalyptus forest during the simulation period.

The total area of new plantations was obtained by the difference of the eucalyptus forest areas registered in NFI4 and NFI5. Until 2000, the annual area of new plantations for pulp was considered constant and it was based on the average of new plantations reported in the statistics for the period of 1995 to 2000 (Pereira et al. 2010), the last period for which this information was available. From 2000 onwards, the afforestation up to 2000 was discounted of the forest area balance from NFI4 to NFI5. The remaining area of new plantations was equally distributed over 2001 and 2007.

Deforestation was set as a proportion of the existing total forest area. The proportion was based on the average value of land whose use changed from forest to other uses reported for the period from 1986 to 2000 in each year (Pereira et al. 2010).

Biomass demand and new planted areas for bio-energy purposes were not considered for the period from 1997 to 2007. At the same time, no significant changes were registered in forest management for this period so the transitions between forest management approaches were disregarded (**Table 3**).

Table 3. SIMPLOT's scenario for the period between 1997 and 2007.

Year	**W_demand (10^3 m^3)**	**ABurnt (10^3 ha)**	**APlantW (ha)**	**Aband (%)**
1998	4096	8	4833	0.0012
1999	4523	5	4833	0.0012
2000	4632	10	4833	0.0012
2001	4907	10	913	0.0012
2002	5368	18	913	0.0012
2003	6041	81	913	0.0012
2004	6692	18	913	0.0012
2005	7278	71	913	0.0012
2006	7104	14	913	0.0012
2007	8519	4	913	0.0012

Where, W_demand represents Wood demand, ABurnt the burnt area, APlantW the area of new plantations for wood production and Aband the area that used to be forest and has been changed to a different use.

V.3.4.3 Simulation parameters

It was established that 50% of the wood coming from burnt eucalyptus stands older than 5 years was salvaged (Pereira et al. 2010). It was also defined that stands younger than 8 years were not harvested and that the harvesting probability increased with age. Three sets of harvesting probabilities were defined: the first ascribing almost equally high harvesting probabilities to all age classes (Prob$_1$); a second one that clearly set higher probabilities for the older age classes (Prob$_2$); and finally an intermediate set of probabilities (Prob$_3$). **Table 4** shows the simulation parameters used in the case study.

Table 4. Simulation parameters considered in the case study describing the three sets of harvesting probabilities.

Number of runs under the stochastic mode	25		
Number of years to project	10		
Minimum age for industrial use of wood after a fire (years)	5		
Proportion wood industrially used after fire	0.5		
Proportion of old/sparse non-industrial stands harvested	0.1		
Proportion uneven-aged stands harvested	0.1		
Minimum age for harvesting	8		
Nr of age classes	6		
Even-aged stands harvesting probability:	Prob$_1$	Prob$_2$	Prob$_3$
Age= 8	0.70	0.10	0.30
Age= 9	0.75	0.20	0.35
Age=10	0.80	0.30	0.40
Age=11	0.85	0.40	0.45
Age=12	0.90	0.50	0.50
Age>12	0.95	0.95	0.95

The simulator was run several times which lead to different results as a consequence of the application of the drivers being based on Monte Carlo simulation. This allowed the computation of confidence intervals that were compared for each simulation run considering a confidence of 95%.

V.4 Results

V.4.1 Simulator qualification

SIMPLOT's structure and functioning were conceived based on the analysis of the forest sector in Portugal and on discussions with forest managers in order to deliver a tool capable of meeting their requests. Risk modelling, namely fire occurrence, is a good example of the interaction between the simulator designers and the forest managers. The susceptibility of the Portuguese forest to fires combined with the possibility of the pulp industry to use a considerable percentage of salvaged wood determined that the first external driver to run would be the driver fire, despite SIMPLOT is mainly driven by wood demand (Barreiro and Tomé 2011). In this way, after an extremely severe fire, if the harvested salvage wood is enough to meet wood demand, non-burnt stands are saved from being harvested.

V.4.2 Simulator verification

SIMPLOT was programmed in a modular form with the growth models integrating the growth module and each of the drivers being represented by one module or several sub-modules. The growth module was verified comparing the simulation results obtained for a few randomly selected plots with the same simulations performed in an excel file. However, the growth models' projection accuracy was assumed to have already been done by the models' developers. Consequently, no validation was performed to the growth models. All the drivers' modules and sub-modules were verified by exporting the outputs at plot level and confirming whether the simulator was following the instructions given to harvest, burn, plant and abandon according to what was conceptually defined.

V.4.3 Simulator validation

V.4.3.1 Standing volume

Applying the simulator to NFI4 data for the period between 1997 and 2007 resulted in a concave simulated volume curve that decreases continuously after 2002. The results of the validation – comparison of NFI and simulated volumes for 2005 - showed that SIMPLOT was capable of making reliable regional projections for the considered period (**Fig. 3**).

Projected volume for the beginning of year 2005 falls inside the NFI5 confidence interval (AFN 2010) regardless of the harvesting probability tested except for $Prob_2$ being always close to the upper bound of the interval. Whilst, volumes predicted for the end of the year 2005 of the simulation period tend to be closer to the lower bound of the interval. On the other hand, prediction errors observed for the three harvesting probabilities were higher for the beginning of the simulation, when stand growth has not been updated yet, than for the end. However, the best results are obtained when simulated volumes in the beginning of the simulation year and the ones from the end of the simulation year are averaged which corresponds well with reality because the forest inventory took place for a long period throughout the year (**Fig. 5**).

Volume projections show that SIMPLOT is sensitive to harvesting probabilities set for the different age classes. Examining the effect that the distribution of the three harvesting probabilities over the age classes had on standing volume (**Fig. 3** and **5**), it was clear that the sets of probabilities responsible for applying lower harvesting pressures for ages less or equal to 11 years produced the less accurate results (Prob$_2$ and Prob$_3$).

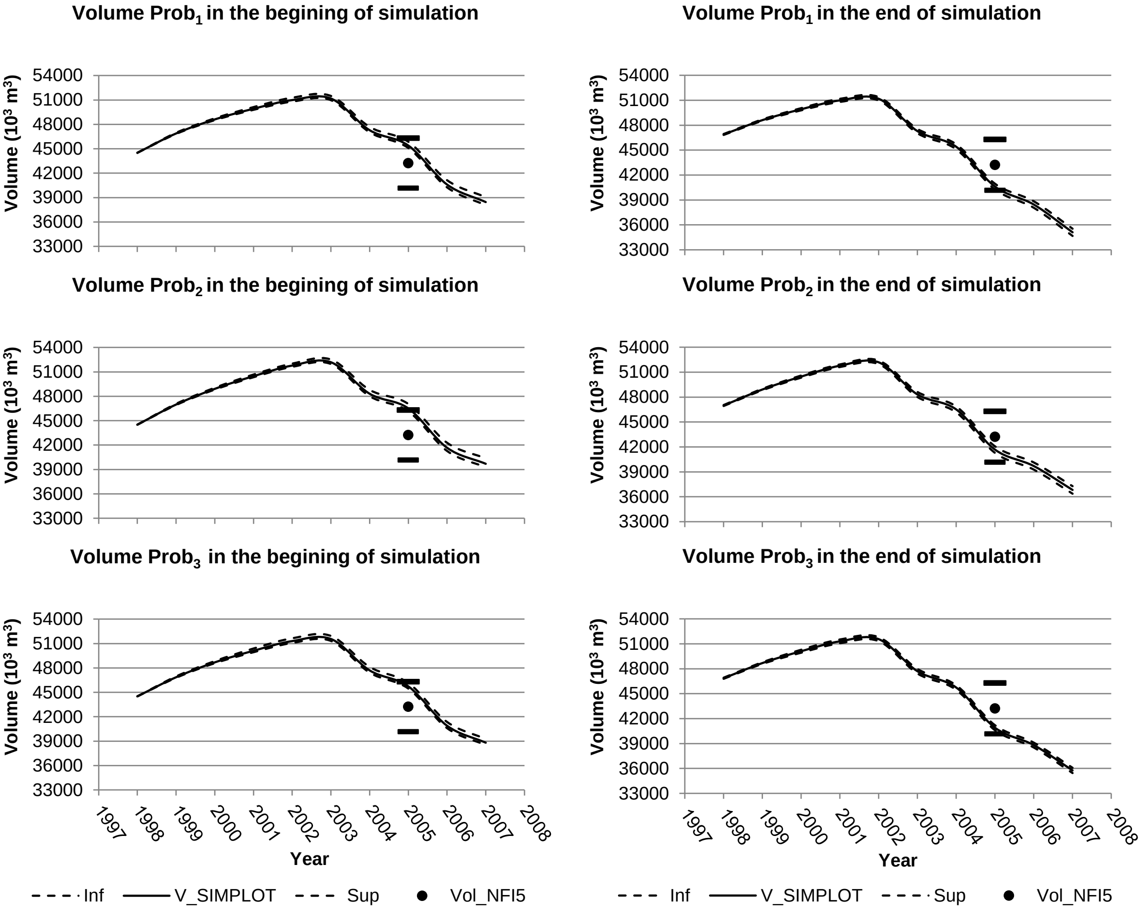

Fig. 3. Comparison between SIMPLOT simulated volume and NFI5 volume for the three harvesting probabilities under the real scenario line. Standard deviations are represented by the dashed lines.

V.4.3.2 Distribution of area by age classes

After the areas of mixed stands were corrected (*see section VII.2.4.1 Input data*), the same age classes considered for the area validation dataset were applied to the simulation outputs. The distribution of forest area for the three different sets of harvesting probabilities was compared (**Fig. 4**). Simulation results more or less follow the tendency registered for the validation data set apart from the age class older than 16 and for the uneven-aged class.

In general terms, the graphical analysis indicates that the three sets of harvesting probabilities seem to produce quite similar area distributions except for the age class containing the harvesting threshold. The sum of squared residues divided by the predicted forest area in each age class was calculated in order to illustrate possible differences between the three sets of probabilities and the results indicate that the values obtained for $Prob_1$ are considerably higher than under $Prob_2$ and $Prob_3$. Results show that the three harvesting probabilities' sets over-estimate the forest area for class [16-20[and [20,…[, while the area of uneven-aged stands is under-estimated in more than 110 x 10^3 ha.

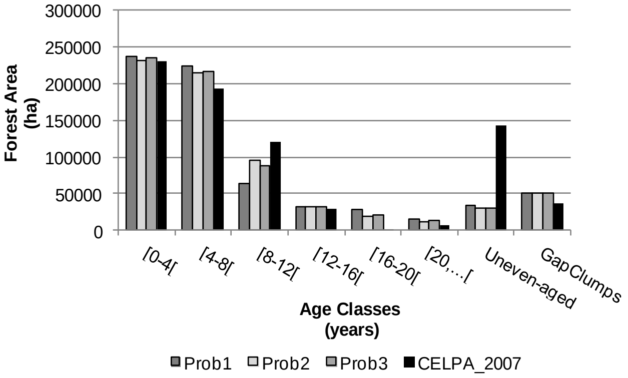

Fig. 4. Simulated distribution of forest area by age class for the three alternative sets of harvesting probabilities compared to CELPA's areas.

Higher harvesting pressures ($Prob_1$) resulted in bigger shifts to the youngest age classes (below the harvesting threshold) at the expense of a reduction in the areas of harvestable age classes.

V.5 Discussion

This research presents a comparison between SIMPLOT's projections for standing volume and forest area distribution by age classes with real data (obtained in the period 2005-2007) when initialized with the information from a previous forest inventory. The validation approach selected, running the model on historic data, allowed validating SIMPLOT's growth module as well as the interactions between the modules responsible for implementing fire, harvest, new plantations and deforestation. Portuguese NFI5 data was used to validate standing volume. However, the validation data set was completed by

CELPA's remeasurements to the NFI5 plots in order to minimize the errors in age estimation.

V.5.1 Standing volume

One of the simplifications of SIMPLOT is the way that was used to simulate the growth of mixed stands. An area correction is applied resulting in the conversion of mixed to pure stands, whose growth is afterwards projected using pure stands' growth models. Despite the straightforward approach, the evolution of eucalyptus total volume for 2005 was simulated quite accurately. The reason for this might be related to the small representativeness of eucalyptus mixed stands. However, more precise results would be expected if tree level growth models were integrated in SIMPLOT's growth module for the simulation of mixed stands.

The input and validation NFI data sets were obtained with two different methodologies (including different sample sizes), however, volumes were realistically estimated. Neither assumptions nor structural issues have apparently interfered with the simulation ability shown by SIMPLOT, proving its robustness. On the other hand, it is important to stress the difference in time between the two consecutive NFI's. An 8-years simulation period might not be long enough for rising out conceptual deficiencies.

Volumes computed for the end of the simulation year were closer to NFI5 estimated volume, which supports the fact, that for the beginning of the year neither growth nor the external drivers that characterize the scenario have been accounted for yet. In reality, forest fires have a higher probability to occur in the middle of the year and new areas are more often planted during spring, while stands can be harvested and abandoned throughout the year. Therefore, it is not unrealistic to consider that the average of the volumes predicted for the beginning and the end of the simulation year should agree quite well with the NFI data (**Fig. 5**).

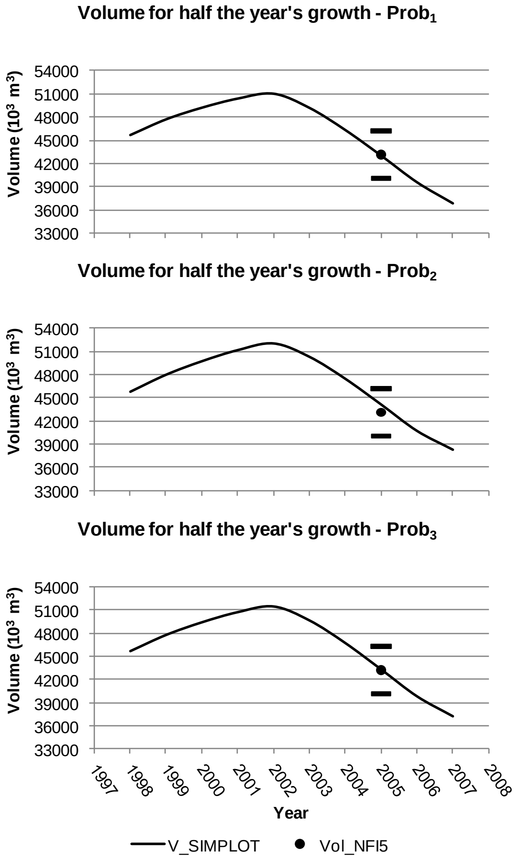

Fig. 5. Comparison of NFI5 volume with SIMPLOT's estimated volumes for half the year's growth period for the three harvesting probabilities.

Under Prob$_1$, estimated volumes decreased faster than for the other probability sets. Furthermore, results pointed to a situation for which the higher and the more equally distributed by age classes the harvesting probabilities were, the bigger the deviation between the simulated volume and the inventory data was. This information seemed to indicate that the harvesting pressure on the younger age classes is not very high. This makes sense as practitioners know that it should be avoided in order to minimize depleting forest resources caused by overharvesting.

It is clear that the evolution of simulated volume from 2002 onwards can reflect the sensitivity of SIMPLOT to the severe forest fires occurred in 2003 and 2005, but it might also be the consequence of the combination of the severe fire scenario and wood demand increase between 2002 and 2005.

A comparative look at a simulation run for which the 2003 and 2005 severe wildfires were replaced by fires of smaller area is shown in **Fig. 6**.

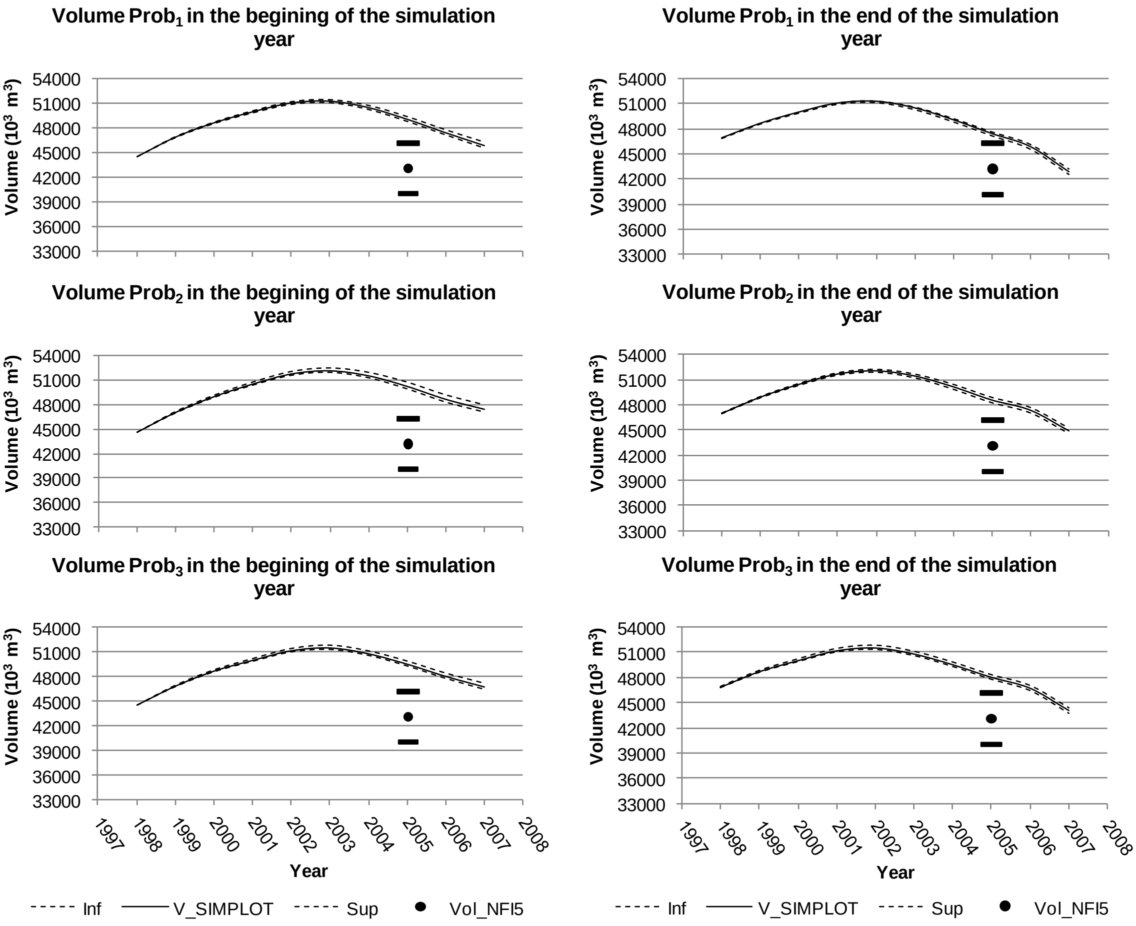

Fig. 6. Comparison between SIMPLOT simulated volume and NFI5 volume for the three harvesting probabilities under a hypothetical scenario without the severe forest fires. Standard deviations are represented by the dashed lines.

This simulation used the burnt areas considered for years 2003 and 2005 reduced from 81 and 71 thousand hectares to 21 and 11 thousand hectares, respectively. The set of simulation parameters was maintained. Despite the decreasing tendency remained due to the increase of wood demand, the results obtained for the hypothetical scenario with no severe forest fires presented less accentuated decreases in terms of standing volume after year 2002, causing simulation results to drift from the NFI5 confidence interval. Moreover, the differences registered for the beginning of the year and the end of the year of simulation were less evident as well as the differences between the three probability distribution sets. This can be indicative of the high pressure eucalyptus forests have been under after the severe fires occurred over the last decade that drastically affected the distribution of growing stocks by the different age classes. SIMPLOT has shown before that the severe wildfires of 2003 and 2005 are responsible for the carbon stock depletion registered over the next decade and that the more intense the fire scenario the more drastic consequences are (Barreiro and Tomé 2011). Therefore, it is clear that the results found in this study concerning SIMPLOT's sensitivity to severe forest fires correspond well to previous findings. Overall, it can be concluded that the simulated standing volume was in good agreement with the NFI5 data used for validation.

V.5.2 Distribution of area by age classes

The simulated area distribution's present a decreasing tendency with age class for even-aged stands that corresponds well with the behavior found in the validation dataset.

The most striking deviation of SIMPLOT's predictions was on the simulation of areas for uneven-aged stands. This finding is not surprising considering that the regional simulator assumes no conversion of even-aged to uneven-aged stands and that these stands can be burnt or harvested as any other stand over the simulation period. Despite, this simplification could be the most important a reason to explain the results, another possible cause could be the harvesting probability defined as a simulation parameter (**Table 4**). To test for this hypothesis, alternative simulation runs were made with null harvesting probability for uneven-aged stands and old stands to see if this could compensate for the fact that SIMPLOT disregards that some even-aged stands are converted to uneven-aged stands during the simulation period. The graphical analysis showed an increase in the simulated area of uneven-aged stands, but projections for the other age-classes became worse (**Fig.7**). In fact, setting the harvesting probability of uneven-aged stands to zero proved to minimize the difference between observed and projected areas in this class. However, a substantial difference can still be found because these stands have the same probability of burning as other stands being subsequently harvested after a fire.

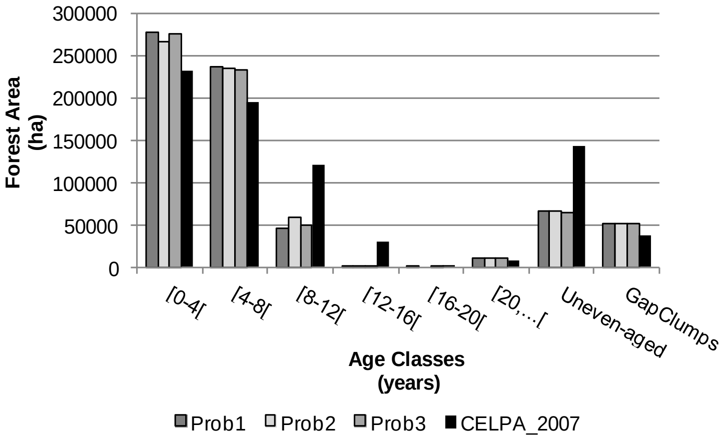

Fig. 7. Simulated distribution of forest area by age class for the three alternative sets of harvesting probabilities compared to CELPA's areas considering a harvesting probability of zero for uneven-aged-stands.

V.5.3 Limitations

Similarly to EFISCEN, SIMPLOT was created to be applied to forests experiencing stand replacing disturbances like fire and harvesting by clear-cut events which tend to originate even-aged stands. Despite eucalyptus is mainly managed as even-aged forest to be used by the pulp and paper industry, Portuguese forests are also characterized by a small percentage of old uneven-aged stands and by sparse stands defined as non-industrial due to its reduced management. Estimating age is particularly difficult for free growth species such as eucalyptus and should be seen as an important uncertainty to be accounted for in the validation process. In an attempt to minimize the consequences of age being poorly estimated an alternative dataset was used to validate the distribution of forest area by age-classes despite age also being estimated in this dataset. Additionally, the limited comparability between the two inventories (NFI4 and NFI5), because of the use of different definitions and methodologies, represented another uncertainty.

Apart from all the uncertainties related to data and scenarios that should always be considered when validating regional scenario simulators, the results obtained for simulated standing volume were very similar to the forest inventory ones.

The failure to accurately project the area for some of the age classes could be due to a particular fault or to an association of problems like the lack of adequacy of the growth models chosen to integrate the simulator and also on flaws deriving from assumptions or simplifications in the underlying structure of the simulator. SIMPLOT is based on the assumption that even-aged stands are not converted to uneven-aged stands which is known to occur in real life. Stands can be thinned for sanitary purposes and the resprouting of the harvested stems originates an uneven-aged stand. In other cases, smaller trees are left at harvest and become older in the following coppice stands. If the percentage of occurrence of these and other events leading to uneven-aged stands will be available as a result of forest inventories focusing on the remeasurement of the same plots, SIMPLOT can be improved in order to better reproduce the observed area distribution by age classes. Another simplification in SIMPLOT is that the area of gaps and clumps is assumed to remain constant throughout the simulation period. This assumption did not seem to have major consequences in the short-term, although it might not hold true for longer simulation periods. As shown in the present study, validation helped to identify features of the simulator that need to be improved.

SIMPLOT's module responsible for implementing percentual changes between different FMA needs to be improved by coupling an even-to-uneven-aged transition algorithm that will be responsible for simulating the events, such as sanitary thinnings or incomplete final harvest that can originate uneven-aged stands. Such an algorithm was not included in the present version of this tool because there are no single tree growth models and also no statistics on the conversion between these stands exist.

The growth functions integrating the growth module are biologically meaningful and the parameter values are derived from a complete dataset covering the entire country. Thus, growth projections are reasonably reliable. On the other hand, results could be improved and area corrections could be avoided if the stand level growth models were replaced by tree level models. Notwithstanding, projections should always be seen as possible future scenarios instead of predictions because there are always errors associated to it (Nabuurs et al. 2000). Therefore, it is important to underline the need to always interpret forest resource projections with caution and to account for different error sources (Kangas 1997, 1998), namely measurement and sampling errors in the data used as input for the simulation runs and/or for the validation data set, the accuracy of the growth models integrated in the simulator as well as the simulation's assumptions.

V.6 Conclusions

The evolution of a forest at the regional level is not only influenced by the species response to the environment but it is also extremely affected by exogenous disturbance regimes. The main objective of this study was to validate the accuracy of the regional simulator's predictions and SIMPLOT has proven to be able to reflect the forests' behavior to the occurrence of disturbances and secondly, to identify the improvements required to perfect the projection ability of the simulator.

The overall results demonstrate the ability of SIMPLOT to simulate the evolution of the eucalyptus forest. Because the model incorporates the effects of the drivers, apart from simulating growth, it can also serve as a tool to help decision making for addressing issues such as market pressures, hazards impacts or even policies to support reforestation.

The ability of the model to simulate harvest as a response to wood demand allows assessing the impacts of applying different harvesting probabilities. However, the consequences of different harvesting intensities proved to be more evident for forests under a higher pressure, which corresponds well with empirical findings that point to unstable forests being more sensitive to disturbances.

In the process of validating the simulator, SIMPLOT showed a less accurate precision to simulate the distribution of areas by age-classes, namely for the class representing uneven-aged stands. This finding helped identifying an important improvement required in terms of forest management affecting stand structure.

Further validation studies should be conducted for longer-term simulation periods. Also, under future scenarios with smaller proportions of pure stands, area corrections should be avoided for mixed stands. Instead, different modeling approaches should be integrated into SIMPLOT to better predict the growth of mixed forests.

V.7 Literature Cited

Associação da Indústria Papeleira (CELPA), 2010. Boletim Estatístico 2009. Indústria papeleira Portuguesa. CELPA Editores. Associação da Indústria Papeleira, Lisboa, Portugal.

Autoridade Florestal Nacional (AFN), 2010. Inventário Florestal Nacional Portugal Continental IFN5, 2005-2006. Autoridade Florestal Nacional, Lisboa, Portugal. 209 p.

Barreiro, S., Tomé, M., 2011. SIMPLOT: Simulating the impacts of fire severity on sustainability of eucalyptus forests in Portugal. Ecological Indicators, **11**: 36–45.

Barreiro, S., Godinho, P. F., Azevedo, A., 2010. National Forest Inventories reports: Portugal. In: Tomppo, E., Gschwantner, Th., Lawrence, M., McRoberts, R.E. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, New York, US. pp. 437-464.

Barreiro, S., Tomé, M., Tomé, J., 2004. Modeling Growth of Unknown Age Even-aged Eucalyptus Stands. In: Hasenauer, H., Makela, A. (Eds.), Modeling forest production.

Scientific tools – data needs and sources. Validation and application. Proceedings of the International Conference, Wien, pp. 34–43.

Borges J.G., Borges G.C., 2007. Impactes socioeconómicos da expansão do eucaliptal. In: Monteiro Alves A., Pereira, J.S., Silva, J.M.N. (Eds.), O Eucaliptal em Portugal. Impactes Ambientais e Investigação Científica, ISA Press, Lisboa, Portugal. pp. 437-464.

Castro Rego, F., 2011. A Floresta Portuguesa. Academia das Ciências de Lisboa. Instituto de Estudos Académicos Para Seniores 2º Ano – Ciclo de Conferências: A Floresta.

Clawson, M. 1979. Forestry in the long sweep of American history. Science **204**: 1168–1174.

Cawrse, D., Keyser, C., Keyser, T., Meador, A. S., Smith-Mateja, E. and Dyck, M. van 2010. Forest Vegetation Simulator. Model Validation Protocols. Internal Rep. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center.

Direcção Geral das Florestas (DGF), 2001. Inventário Florestal Nacional Portugal Continental, 3ª Revisão, 1995-1998, Lisboa. Portugal.

Direcção Geral dos Serviços Florestais e Aquícolas (DGSFA), 1966a. Inventário ao Norte do Tejo - 1965-66. Direcção Geral dos Serviços Florestais e Aquícolas, Lisboa, Portugal.

Direcção Geral dos Serviços Florestais e Aquícolas (DGSFA), 1966b. Inventário ao Sul do Tejo - 1965-66. Direcção Geral dos Serviços Florestais e Aquícolas, Lisboa, Portugal.

Honório, J., 2011. O Papel de Portugal no Mundo é mais importante do que imagina! Congresso das Exportações - Industria Florestal.
[online]
URL:http://www.portugalglobal.pt/PT/geral/Documents/PORTUCEL_SOPORCEL.pdf

Kangas, A.S. 1998. Uncertainty in growth and yield projections due to annual variation of diameter growth. Forest Ecology and Management. **108**: 223–230.

Kangas, A.S. 1997. On the prediction of bias and variance in long-term growth projections. Forest Ecology and Management, **96**: 207–216.

Manley, B. 1998. Forest scenario analysis in New Zealand. In: Nabuurs, G.J., Nuutinen, T., Bartelink, H., Korhonen, M. (Eds.), Forest scenario modelling for ecosystem management at the landscape level. European Forest Institute. EFI Proceedings **19**: 73–88.

Nabuurs, G. J., Schelhaas, M. J., Pussinen, A., 2000. Validation of the European Forest Information Scenario Model (EFISCEN) and a projection of Finnish forests. Silva Fennica, **34**(2): 167–179.

Paulo, J.A., 2001. Impacto de diferentes equações de volume na avaliação do volume existente de *Eucalyptus globulus* no Inventário Florestal Nacional. Dissertation. Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Lisboa.

Pereira, T.C., Seabra, T., Maciel, H., Torres, P., 2010. Portuguese National Inventory Report on Greenhouse Gases, 1990-2008 Submitted under ARTº 3.1.(f) of Decision No.280/2004/EC of the European Parliament and the Council. Portuguese Environmental Agency, Amadora, Portugal.

Pretzsch, H., Biber, J., Ďurskỷ, K., von Gadow, K., Hasenauer, H., Kändler, G., Kenk, G., Kublin, E., Nagel, J., Pukkala, T., Skovsgaard, J.P., Sodtke, R., Sterba, H., 2002. Recommendations for Standardized Documentation and Further Development of Forest Growth Simulators. Forstw. Cbl. **121**: 138-151.

Schlesinger, S., 1980. Terminology for Model Credibility. Simulation **34**: 101-105.

Soares, P., Tomé, M., Skovsgaard, J.P., Vanclay, J.K. 1995. Validating growth models for forest management using continuous forest inventory data. Forest Ecology and Management, **71**: 251-266.

Stage, A.R., 2003. How forest models are connected to reality: evaluation criteria for their use in decision support. Canadian Journal of Forest Research, **33**: 410-421.

Thürig, E., Schelhaas, M.J., 2006. Evaluation of a large scale forest scenario model in heterogeneous forests: a case study for Switzerland. Canadia Journal of Forest Research, **36**: 671-683.

Tomé, M., Coelho, M.B., Soares, P., 2010. Carbon Stock Changes in Portuguese Forests. Forchange Thecnical Report, CEF, Lisbon, Portugal.

Tomé, M., Tomé, J.A., Ribeiro, F., Faias, S.P., 2007. Equação de volume total, volume percentual e de perfil do tronco para *Eucalyptus globulus* Labill. em Portugal. Silva Lusitana, **15**(1): 25-29.

Tomé, M., Soares, P., Oliveira, T., 2006a. O modelo GLOBULUS 3.0. Dados e equações. Publicações GIMREF RC2/2006. Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Lisbon, Portugal.

Tomé, J., Tomé, M., Barreiro, S., Paulo, J.A., 2006b. Modelling tree and stand growth with growth functions formulated as age independent difference equations. Canadian Journal of Forest Research, **36**: 1621-1630.

van Horn, R. L. 1971. Validation of simulation models. Management Science, **17**: 247-258.

Vanclay, J.K., Skovsgaard, J.P., 1997. Evaluating Forest Growth Models. Ecological Modelling, **98**: 1-12.

Yang, Y., Robert A. Monserud, R.A., Huang S., 2004. An evaluation of diagnostic tests and their roles in validating forest biometric models. Canadian Journal of Forest Research, **34**: 619–629.

CHAPTER VI

Modelling biomass production in highly stocked eucalyptus stands in Portugal

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Modelling biomass production in highly stocked Eucalyptus stands in Portugal

VI.1 Abstract

Eucalyptus globulus has been mainly managed for pulp in Portugal. Stands are planted with an average stand density of 1100 - 1300 trees per hectare and harvested between 10 and 12 years with plantation followed by one or two coppices. *E. globulus* increased in area and its economic importance lead to the development of growth models, such as Globulus 3.0 (Tomé et al. 2006), capable of predicting the evolution of these stands. In the meantime, biomass for energy became an appealing topic. In the scope of energetic diversification and profitable forest resources exploitation, increasing the use of forest biomass can play an important role. Up till now, the studies conducted to assess this species development under higher stand densities have not produced results.

This work had the objective of developing a growth model to estimate the productivity of highly stocked stands using data from a set of spacing trials available in the country. These data were firstly used to analyze the existing model, developed for stands managed for pulp production (smaller number of trees per hectare at planting). The results of this preliminary analysis showed the need to develop new basal area and mortality sub-models in order to improve the aboveground biomass estimates for highly stocked stands. Simplified versions of the Globulus 3.0 basal area and mortality functions were developed using the spacing trial's data set. Additionally, a new equation, essential to initialize coppice stands, was developed to estimate the average number of sprouts per stool.

The growth of highly stocked stands was simulated with Globulus 3.0 and the new developed sub-models. Results showed that the new basal area and stand density sub-models were less biased and more precise than the ones of Globulus 3.0 model. Biomass production was estimated for a silvicultural system corresponding to planting 5000 trees per ha^{-1}, followed by 4 coppices, all harvested at 5 years. To achieve this, the new developed sub-models were combined with Globulus 3.0 dominant height and biomass sub-models. The resulting woody biomass estimates ranged from 3.33 to 31.88 Mg ha^{-1} year, depending on site quality (11 to 27 m at 10 years). If using highly productive clones, a biomass production greater than 30 Mg ha^{-1} year^{-1} can be expected in the best sites.

VI.2 Introduction

Eucalyptus globulus was introduced in Portugal in the second half of the XIX century and occupies now the second largest area in the country providing raw-material for the pulp and paper industry. The economic importance of this species led pulp production stands to be thoroughly studied in Portugal and to supporting the development of growth and yield models. The Globulus model, at present at the third version known as Globulus 3.0 (Tomé et al. 2006), resulted from the combined efforts of Universities and Pulp and Paper companies, is the most commonly used growth model.

Over the last decades, the use of biomass for energy became a common topic setting an important role to short-rotation forestry in meeting Kyoto commitments. In Europe, short-rotation forests are being used for energy production. Willow and poplar are the preferred tree species, but experiments with other species as *Robinia spp* and eucalyptus have also been established. In Portugal, eucalyptus has been mainly managed for pulp production with stand densities around 1100-1300 trees per hectare, whereas densities found in short-rotation forestry can range from 8000 trees per hectare (Manzone et al. 2009) up to 18000 for poplar (Labrecque and Teodorescu 2005), 20000 for *Eucalyptus nitens* (AFG 2007) or even 20400 trees per hectare for willow (Noronha-Sannervik and Kowalik 2005).

In 2005, the Portuguese Energy Strategy proposed the construction of thermoelectric plants to add value to forest biomass (DRE 2005). The first plant started operating in 1999. At present, 19 biomass plants (combined heat and power generation plants and dedicated plants) are operating in Portugal. Another 19 plants are expected to become operational in the future (Sousa, personal communication). Until now, few studies have been conducted to find the best tree species for bioenergy or even to assess the potential of the more representative species in the country currently being used for wood production. However, green-policy measures might result in stimulus being granted to increase energy production by using forest biomass. At present, forest owners, despite managing their stands for pulp production, have already started selling their eucalyptus wood to bioenergy plants because it pays off. If they decide to change management towards bioenergy production by increasing stand density and reducing rotation length this could lead to substantial changes in the wood market, namely rising imports of wood to cope with wood demand for pulp having undesired consequences for the economy. In order to make growth projections into the future and assess the impact of intensive short-rotation management versus the current management for pulp production, a growth model for stands planted with very high densities is required. The data set used to develop the

Globulus model did not include plots in highly stocked stands; therefore its ability to simulate bioenergy stands is doubtful.

This study aimed to develop a growth model for eucalyptus stands with densities at planting closer to the ones appropriate for energy production. It started by checking the ability of the Globulus 3.0 model for this purpose. This was tested using mainly highly stocked plots from spacing trials, which allowed determining which of Globulus 3.0 sub-models that needed to be improved. Finally, new required sub-models were developed using the same data set.

VI.3. Materials and Methods

VI.3.1 Data

Globulus 3.0 growth model was developed using a large data base containing records of forest inventory plots, permanent plots and research trials. In Portugal, *E. globulus* is mainly managed for pulp; therefore stands used to develop Globulus 3.0 have average stand densities of 1200 trees with a standard deviation of 504. A few plots with densities ranging from 2500 up to 5000 trees ha^{-1} were included representing only about 2% of the data set (Tomé et al. 2006). With respect to coppice stands, the data set used derived from first or second coppices, but data were only collected after the thinning of the shoots that occurs around the age of 3 leaving about 1.6 shoots per stool, therefore there was no representation of coppices younger than 3 years.

In the 90s several spacing trials were installed in Portugal either by pulp companies, by Universities or by the joint effort of both (Soares and Tomé 2000). The data set available for validating Globulus 3.0 for extremely dense stands and developing a model for highly stocked plantations is composed of 6 spacing trials including planting densities up to 10000 trees per hectare. The data set was completed with coppice stands data from permanent sample plots (*PSP*) prior to the thinning of the shoots.

TAV trial is a spacing trial consisting of 2 blocks with 5 plots each in which five different spacings were distributed without previous randomization: 3x2 m, 3x3 m, 4x3 m, 4x4 m and 5x4 m. The stand was planted in 1975 and the first measurement took place in 1981. Measurements were repeated at approximately annual intervals. In March 1993 the trial was harvested and it was decided to split each plot in two with the objective of keeping one part of the plot thinned and the other unthinned. Measurements before the thinning of the sprouts, that took place around the age of 3 years, were made in smaller subplots on an annual base. After the thinning of the sprouts, measurements covered the whole plots with an approximately annual periodicity.

TQP trial was established as a randomized complete block design (with some restrictions in the randomization of the two closer spacings) with 2 replicates and 5 treatments (spacings): 2x1 m, 2x2 m, 3x1 m, 3x2 m and 3x3 m. It was established in 1992 and annually measured until 2003.

TVL trial followed a randomized block design with factorial combination of row and between-row spacings resulting in plots of unequal size with the same number of trees. It is characterized by 3 blocks of 12 plots corresponding to spacings 1, 2, 3 and 4 m within the row, with 3 and 4 m between rows. This trial was initially set in 1993 and was measured at least once a year over a decade.

TN spacing and fertilization trial was also established as a split-plot with 2 blocks divided in 2 main plots corresponding to fertilized and non-fertilized treatments. Each main plot contains 7 sub-plots representing different spacings - 1x1 m, 2x1 m, 2x2 m, 3x3 m, 4x1.5 m, 4x2 m, 4x4 m - resulting in different stockings ranging from 625 up to 10000 trees per hectare. Each sub-plot was divided in 3 sub-sub-plots, each with a different clone, totalizing a number of 84 plots of 35 trees (5x7) including a buffer row. The first measurement took place in 1995 and measurements were annually repeated until 2003.

TA experimental design in T5 trial is a split-plot with 3 blocks with 5 unequal sized plots with the same number of trees, each representing a different spacing: 3x0.5 m, 3x1 m, 3x2 m, 3x3 m and 3x4 m. Each of these plots was sub-divided in 4 sub-plots planted with a different clone. Two guard rows of trees were left between sub-plots to serve as a buffer and four between plots. The first measurement took place in 1997 when trees were 8 months old and it was measured every 6 months until 1999. From this point onwards measurements were made on an annual basis until 2006 except for the year 2001.

TT trial considered 3 factors: irrigation, spacing and clone and was designed as a split-split-plot. Irrigation was the main factor and was implemented in three levels: total irrigation, complement irrigation and control. Only control plots were used in the present study. Two clones and four different spacings were considered: 2x1 m, 4x1 m, 4x2 m, 4x4 m. Each block was divided into 3 plots corresponding to the different irrigation treatments, which were sub-divided in four different sub-plots, one per spacing. Each sub-plot had 2 sub-sub-plots each, one with a different clone. This trial was installed in 1998 and measured every year until 2004. As in the previous trial the use of clones guarantees that genetics is not confounding the effect of spacings.

The objective of using clones was to avoid genetic material impacts.

There is a large set of permanent sample plots (*PSP*) describing the growth of *E. globulus* in Portugal. For this study, only coppice plots with measurements before the thinning of the shoots were considered. A total of 5 PSP, planted between 1958 and 1959 and harvested for the first time from 1971 to 1976 depending on the plot were added to the data set. The selected *PSP* were remeasured at least once a year from the age of 2 until the shoots selection that took place between the ages of 3 and 5 years. The chosen plots were initially planted with densities around 2580 trees ha^{-1} and no clonal material was used.

Data from spacing trials *TAV*, *TQP* and *TVL* were part of the data set used to develop the Globulus 3.0 model with the exception of the data prior to the shoots selection in *TAV* plots.

For the evaluation of Globulus and fitting the growth models, a total of 906 growth periods were used for ages younger than 10 years (**Table 1**).

Table 1. Summary statistics for the data set used in the study, where rotations 1 and 2 represent planted and coppice stands, respectively.

Trial/PSPs		TAV		TQP	TVL	TN	TA	TT	PSP	total
Rotation		1	2	1	1	1	1	1	2	-
Growing periods		20	55	60	220	350	161	32	8	906
Stand age	Min.	7.8	3.0	2.6	2.0	1.5	1.6	1.6	1.9	1.5
	Avg.	8.4	5.9	5.2	5.0	5.5	5.7	4.5	2.6	5.4
	Max.	9.9	9.2	9.5	9.1	9.7	8.5	6.3	5.0	9.9
Site index	Min.	20.21	18.51	25.71	19.58	11.34	9.65	18.89	20.14	9.65
	Avg.	21.74	20.51	27.29	23.96	19.59	15.94	22.42	21.39	20.73
	Max.	23.70	22.60	29.81	28.09	25.59	25.22	26.14	23.24	29.81
Stand density	Min.	481	1500	924	488	778	542	625	2528	481
	Avg.	902	2492	2275	1754	2775	2696	3097	3346	2438
	Max.	1602	3611	4464	4922	6667	10000	5000	3776	10000
Density at planting	Min.	500	500	1111	625	833	625	625	2517	500
	Avg.	947	931	2722	1822	2767	2857	2949	2583	2404
	Max.	1667	1667	5000	5000	6667	10000	5000	2654	10000
Dominant height	Min.	18.50	8.89	11.13	6.33	2.70	2.19	4.60	7.38	2.19
	Avg.	19.84	15.55	18.88	16.07	12.31	10.05	13.78	9.37	13.65
	Max.	23.59	21.85	29.19	26.58	24.40	19.20	20.00	16.60	29.19
Basal area	Min.	11.75	4.51	6.64	1.09	0.19	0.11	1.90	3.21	0.11
	Avg.	16.49	15.31	19.46	13.08	9.67	7.09	18.38	6.34	11.46
	Max.	24.39	28.60	33.64	32.54	39.51	22.80	40.17	18.55	40.17

Fig. 1 illustrates the relationship between stand density and a few stand variables. The graphics show that the proportion of highly stocked stands is not very large and that site indices (base age 10 years) are less well represented for stand densities over 6000 trees ha^{-1} at planting. A better distribution of plots was desirable, however because Globulus model has been shown not to be biased with site index (Tomé et al. 2001), this drawback of the data set was not considered to be a serious inconvenience for the study.

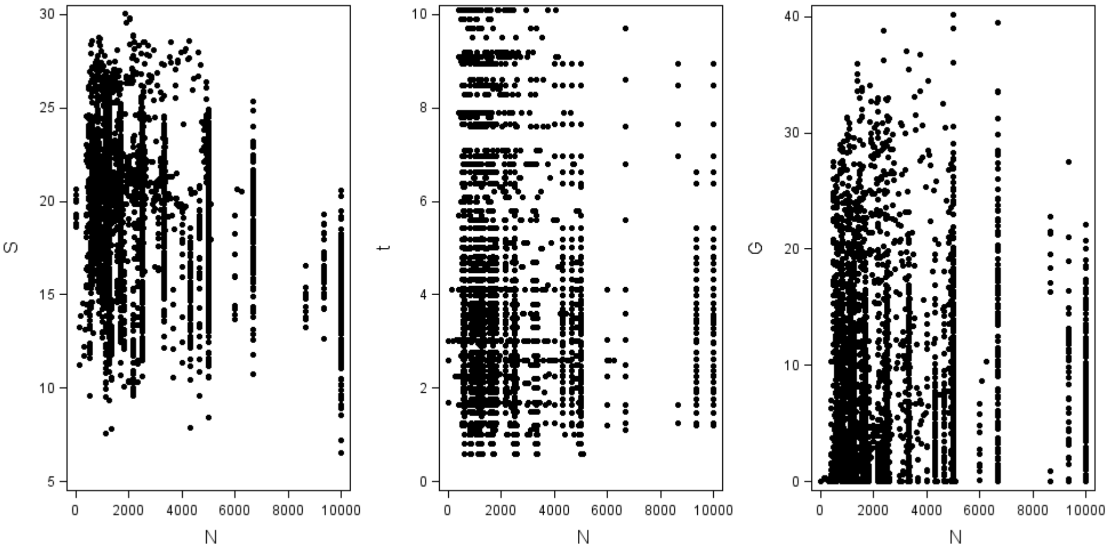

Fig. 1. Relationship of site index (S), stand age (t) and stand basal area (G) with stand density (N) shown for the data set used in this study. Each dot can represent several measurements.

VI.3.2 Evaluation of Globulus 3.0 model for highly stocked stands

Plots were initialized at each measurement age using the observed values and projected to the next measurement (the performance of initialization functions was not evaluated). Estimates of dominant height, basal area and stand density were compared against the observed data. Residuals were calculated as the difference between observed and estimated values and analyzed for the short-term (1-year projection length intervals). In order to detect possible tendencies with stand density residuals were plotted by density class. It was assumed that reasonable biomass predictions would depend on good estimates of stand basal area and stand density. For this reason, the short-term evaluation was conducted for the dominant height, basal area and stand density projection sub-models.

VI.3.3 Development of new functions for highly stocked stands

VI.3.3.1 Modelling approaches

New initialization and projection functions were developed for the Globulus 3.0 stand variables that did not perform well for highly stocked stands, leading to residuals correlated to stand density. The modeling work previously done for Globulus 3.0 growth and yield model (Tomé et al 2006) was used as the basis for this study.

Concerning the data set used for fitting the models, one alternative could have been to restrict it to the highly stocked stands. However, the amount of data would have been greatly reduced. On the other hand, it was desirable that the model to be developed would give reasonable estimates for the stand densities more commonly used, in order to guarantee compatibility in the estimation of productivities of stands with the usual densities practiced while managed for pulpwood. For these reasons, it was decided to develop the new functions using all the data from the spacing trials, including no so highly stocked plots.

Additionally, a set of functions was developed to estimate the number of shoots per stool in order to improve stand density estimates before the thinning of the shoots.

Globulus model represents the forest through a set of state variables, at stand level, that are projected over time. Some of these variables are directly projected with growth functions, the principal variables; while others, the derived variables, are indirectly predicted from the principal variables, the control variables and, eventually, other derived variables. The model includes a sub-model for each one of the state variables. Each sub-model for principal variables includes a growth function formulated as a difference equation that projects the variable over time.

Difference equations estimate stand variables in an instant (t_2) based on the values of stand variables and control variables in the previous instant (t_1). If the objective is to simulate the growth of a stand for which no measurements have been made or of a stand after harvesting (coppice) it is necessary to estimate the initial conditions. This is achieved by using the growth function in its integral form which includes at least one additional parameter in relation to the respective difference formulation. The formulation of the difference equation functions was made by ensuring the compatibility between the initialization and prediction functions of each principal variable. In turn, derived variables are predicted using prediction functions, for instance allometric equations, to estimate the value of the variable for a given instant in time based on other stand variables and control variables for the same instant.

The formulation of a growth function as a difference equation assumes a family of curves with all parameters common except one, the free parameter. The common parameters may be expressed as a function of stand and/or site characteristics.

Basal Area

The Lundqvist function (Lundqvist 1957) was used for modeling basal area in Globulus 3.0 model:

$$G = Ae^{-k\left(\frac{1}{t}\right)^{n}} \tag{1}$$

Where G represents basal area and t represents age. A is the asymptote, k and n are the shape parameters.

Basal area projection was modeled with the following difference formulation (Lundqvist-k):

$$G_2 = A\left(\frac{G_1}{A}\right)^{\left(\frac{t_1}{t_2}\right)^{n}} \tag{2}$$

Where G_2 and G_1 represent the G variable at t_2 and t_1 ages, respectively, A is the asymptote and n is the shape parameter. The resulting family of curves obtained with this function is defined by the parameters A and n and each curve is defined by a specific k value (free parameter).

Parameters k and n are related to the growth rate and, being k the free parameter, it makes sense that n is related to stand density. The initial condition, represented by k, can be determined knowing G at a certain time t. In order to ensure the compatibility between the initialization and projection modules, the growth function from which the difference equation is derived needs to be used as the prediction equation used in the initialization module. Thus, the initialization and projection functions were developed using Lundqvist and Lundqvist-k functions, respectively.

Stand Density

Because some of the stands from the spacing trials were highly stocked, there was the need to explore the occurrence of self-thinning in order to decide for the best method to model mortality. Self-thinning can be described as the decrease in the number of trees in a stand as the size of the trees increases with age resulting from the death of competing trees in an unfavorable hierarchical situation within the canopy. The relationship of the logarithm of the number of trees per hectare over the logarithm of mean stand diameter was used to define the average maximum stand density (Reineke 1933).

Based on the self-thinning analysis, the function used to project stand mortality corresponds to the one used in Globulus 3.0 (Tomé et al. 2006):

$$N_2 = N_1\, e^{-am(t_2 - t_1)} \qquad (3)$$

Apart from projecting the number of trees in the stand, this model can be used to initialize planted stands assuming that N_1=Npl is the density at planting and t_1=0. Whilst for coppices, it can be used to project the number of sprouts as soon as ingrowth ceases by assuming N_1=N_0 (the number of shoots after ingrowth) and t_1=t_0 (age at which ingrowth ceases, assumed to be 3 years). The following expressions were therefore used to initialize stands regenerated by planting and coppice, respectively:

$$N = Npl\, e^{-am(t)} \qquad (4)$$

$$N = N_0\, e^{-am(t - t_0)} \qquad (5)$$

Several expressions were tested for the am parameter in order to express the effects of stand density and site index.

For coppice stands, stand density during the ingrowth stage or before the age t_0 was modeled through the average number of sprouts per stool. This model was developed based on the evolution of the number of shoots per stool observed in *PSP* and the unthinned *TAV*. A preliminary graphical analysis was first undertaken to analyze possible effects of stand density and/or site index and also to help defining the age when the ingrowth phase could be assumed as finished as well as the type of function(s) that should be tested to model this variable. This graphical analysis (**Fig. 6**) and the data available suggested the development of a model to estimate the number of shoots at an age t_0, complemented with a model to predict the ingrowth till the age (t_0-1).

In order to simulate the growth and yield of *E. globulus* plantations for Energy Production, the new basal area and stand density functions have to be combined with the dominant height and biomass functions of Globulus 3.0, therefore the resulting model will be henceforth designated as GlobEP.

VI.3.3.2 Parameter estimation

Parameters were estimated by non-linear least squares using the PROC MODEL procedure of the SAS statistical software (SAS Institute Inc. 2011). In regression analysis, model errors are assumed to follow some underlying assumptions: independent with a mean of zero, homogeneous variance and a normal distribution. If these assumptions hold, the estimators achieve minimum variance in the class of all unbiased estimators (UMVU); if the Gaussian assumption is relaxed, the estimators achieve minimum variance of all linear unbiased estimators (BLUE). However, in the case of non-linear models the least squares estimators do not have these properties. Unless samples are large, properties are only asymptotic properties; therefore estimators are not unbiased in general, but they are asymptotically unbiased and minimum variance estimators. Thus, the asymptotic variance-covariance results obtained can be used to determine confidence intervals and built t-statistics on the parameters (Myers 1990).

Permanent plots and trials are often observed at different time points, thus the resulting growth and yield data are expected to be correlated over time. In such cases, temporal correlation between the model errors may be observed, violating the assumption of the independence of errors. Studentized residuals (*rstd*) were plotted against lagged *rstd* to evaluate the order of the autoregressive structure. These residuals were obtained with the PROC MODEL procedure of the SAS statistical software combined with the new functionality of SAS 9.3 designated by ODS Statistical Graphics (SAS Institute Inc. 2011) before expanding the error term. A stationary autoregressive structure of order *p* (AR(*p*)) was applied to model error autocorrelation according to the structure:

$$\varepsilon_{ij} = \varphi_1 \varepsilon_{ij-1} d_1 + \cdots + \varphi_p \varepsilon_{ij-p} d_p + u_{ij} \tag{6}$$

Where ε_{ij} is the error of the j^{th} measurement on the i^{th} plot, φ_q (q=1,…, p) are the q parameters to be estimated for the autoregressive process of p order, d_q is a dummy variable equal to 1 if $j>q$ and equal to zero if $j\leq q$, and u_{ij} is white random noise.

Studentized residuals were plotted against predicted values to assess the homogeneity of the errors' variance. Weighted OLS estimates were used to override the heterogeneity of the variance of model errors when needed (Parresol 1999).

To examine possible violations of the normality assumption, QQ-probability plots were analyzed. The non-normality of errors observed was corrected by applying the Huber

(1973) influence function (Myers 1990) reweighting the least squares regression in order to reduce the influence of data points containing large errors on fit (Myers 1990).

In a first step, the common parameters of the growth function were estimated by fitting its difference formulation to pairs of successive observations. In a second step, the parameters associated with the *k* parameter of the initialization function were estimated by using the common parameter estimates obtained in the first step. Finally, the initialization and projection functions were simultaneously fitted through iterated seemingly unrelated regression estimation using the estimates obtained in the previous steps as the initial values for the parameters.

The procedures for fitting the mortality model were similar to the ones described for basal area except for the simultaneous fit.

The subset of data composed of *PSP* and the unthinned coppice stands from *TAV* up to the age t_0 was used to model the number of shoots per stool. The evolution of the number of shoots was studied in order to find the best function shape. The parameters for the average number of shoots per stool were estimated using the PROC NLIN procedure of SAS statistical software (SAS Institute Inc. 2011).

VI.3.3.3 Evaluation of the new functions

The short-term model evaluation took several aspects into consideration as recommended by Soares et al. (1995): 1) the quality of fit, 2) the biological consistency, 3) the predictive ability, and finally 4) the behavior of the model when operationally used.

The different models fitting ability was evaluated using adjusted modeling efficiency, a statistic equivalent to the adjusted R-square in linear regression (MEF_{adj}):

$$MEF_{adj} = 1 - \frac{(n-1)\ \sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)\ \sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{7}$$

Where *p* is the number of parameters in the model, *n* is the number of observations, y_i is the observed value of the variable, $\bar{y}$ is the respective average value, $\hat{y}_i$ corresponds to the predicted value.

The biological consistency of the models was analyzed through the observation of the magnitude and sign of the estimated parameters.

No data set was available to assess the models prediction ability, therefore PRESS residuals (e.g. Myers 1990) were used for this purpose. The PRESS residuals were calculated via the programmed code in SAS/ETS PROC MODEL (SAS Institute Inc 2011). Several statistics were computed with the PRESS residuals to characterize model error.

The mean value of PRESS residuals ($\overline{pr}$) produced information on bias. Precision was evaluated with the absolute value of PRESS residuals ($\overline{apr}$) and the prediction sum of squares (*SSEp*) evaluated in comparison to the model sum of squares (SSE).

$$\overline{pr} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i^*)}{n} \tag{8}$$

$$\overline{apr} = \frac{\sum_{i=1}^{n}|y_i - \hat{y}_i^*|}{n} \tag{9}$$

$$SSEp = \sum_{i=1}^{n} w_i(y_i - \hat{y}_i^*)^2 \tag{10}$$

$$SSE = \sum_{i=1}^{n} w_i\left(y_i - \hat{y}_i\ \right)^2 \tag{11}$$

Where $\hat{y}_i^*$ is the predicted value calculated with the model fitted with the observation i deleted from the original data set; *wi* is the weight for observation *i* and all the variables as defined before.

To validate the new growth functions in the short-term (1-year projection intervals), PRESS residuals of basal area and stand density were plotted by classes of stand density (CN) in order to detect possible relationships. All classes were defined based on percentiles to ensure a similar number of observations per class.

VI.3.3.4 Long-term evaluation of the new functions

Plots were initialized at each measurement age using the observed values and projected until their last measurement. Likewise to the short-term evaluation initialization functions were not analyzed. Classes of projection length were defined based on percentiles to ensure a balanced distribution of observations per class. Box-plots of the residuals (observed – estimated) and of the absolute residuals by classes of projection length were used to illustrate the long-term performance of the new basal area and stand density sub-models.

VI.3.4 Comparison of Globulus 3.0 and GlobEP productivities

Globulus and GlobEP were used to simulate stands with different initial stand densities, considering a range of site indices representative of those found in the country. Five site index classes were defined based on the range of site index values observed in the data set. The performance of the models was compared for two situations: plantation initiated with 1111 and 5000 trees ha^{-1}, representing the common densities for which Globulus was developed and the densities expected in bioenergy stands, respectively. For the simulation, it was assumed that planted stands were followed by 4 coppices and that all rotations were harvested at the age of 5 years. No shoots selection operation was considered. The productivities were expressed by woody biomass, calculated as the sum of the biomass of stem, bark and branches.

VI.4 Results

VI.4.1 Evaluation of Globulus 3.0 model for highly stocked stands

Accurate projections were obtained for dominant height residuals and no evidence of correlation of residuals with stand density was found showing that dominant height growth estimates are not affected by high densities. On the other hand, for basal area and stand density strong tendencies were found with stand density, particularly for the highest density class (**Fig. 2**).

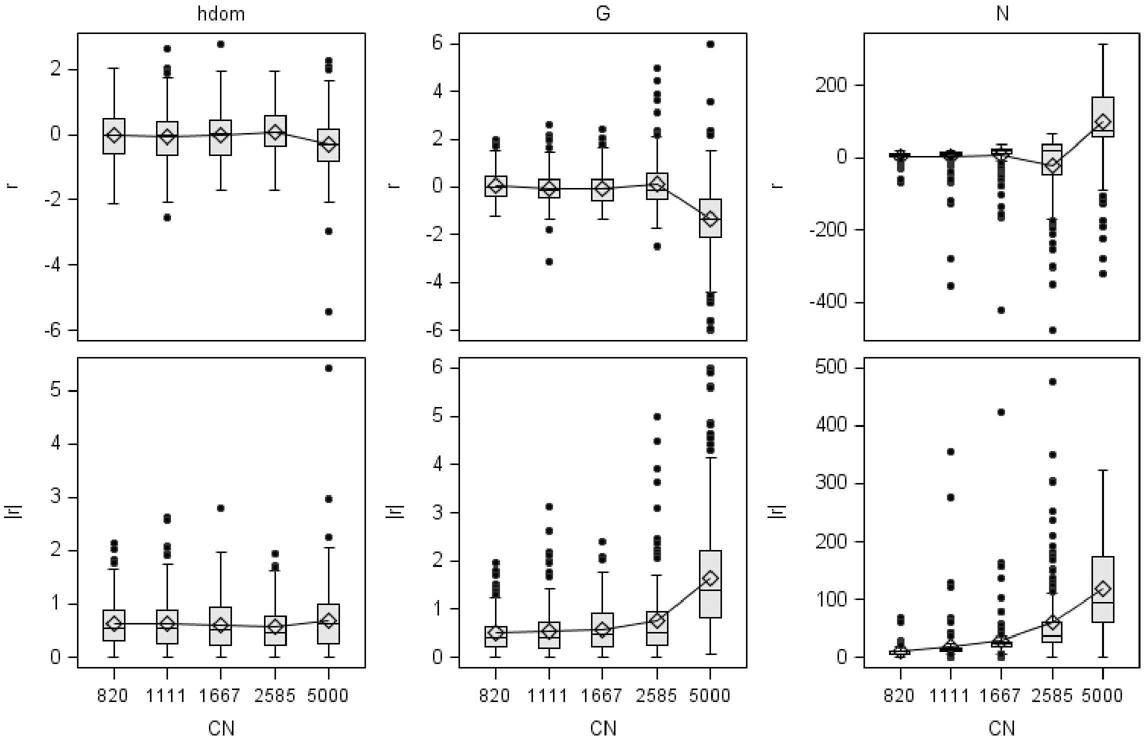

Fig. 2. Box-plots of the residuals (r) and the absolute residuals (|r|) by density class (CN) for dominant height (hdom), basal area (G) and stand density (N) projected with Globulus 3.0 (1-year projection length intervals).

VI.4.2 Development of new functions for highly stocked stands

Based on the results of the Globulus 3.0 model evaluation, new equations for initializing and projecting basal area and stand density were developed.

Basal Area

Following the Globulus 3.0 model, the Lundqvist-k equation was chosen to simulate basal area growth. The asymptote was expressed as function of site index and the parameter n as a function of stand density and stand rotation. The graphical analysis of the plots of studentized residuals (*rstd*) versus the lagged *rstd* showed that a first-order autoregressive structure (AR1) was suitable for modeling the error term for both the initialization and projection functions. Non-normality and heteroscedasticity of the model errors were also corrected during the fitting procedure. All parameters of the final model were significantly different from zero ($p<0.0001$) and presented consistent magnitudes and appropriate signs to model biological growth. **Table 2** presents the parameter estimates after the simultaneous fit and the statistics resulting from the fitting of the initialization and projection functions of the basal area sub-model.

Table 2. Basal area sub-model for highly stocked eucalyptus stands. Parameter estimates and fitting statistics obtained in the simultaneous fit of the equations.

initialization

projection

Parameters Estimates						
Ag_0	Ng_0	ng_r	ng_n	kg_0	kg_n	kg_s
2.6086	0.5684	0.1162	0.0484	7.5178	-0.1287	-0.1092
Fitting Statistics						
	n	**MEFadj**	$\overline{pr}$	$\overline{apr}$	***SSE***	***SSEp***
Initialization	906	0.9341	0.1000	1.4292	3041.5	3085.1
Projection	906	0.9806	0.0098	0.7909	953.5	980.8

Figs. 3 and **4** show the box-plots of the PRESS residuals (pr) and the respective absolute values by class of stand density for basal area initialization (G) and projection (G_2) functions. No undesirable trends were detected and results were less biased and more precise than the ones obtained when applying the Globulus 3.0 growth model (compare

Figs. 2 and **4**). The mean absolute errors were also within very reasonable values, indicating the precision of the new functions.

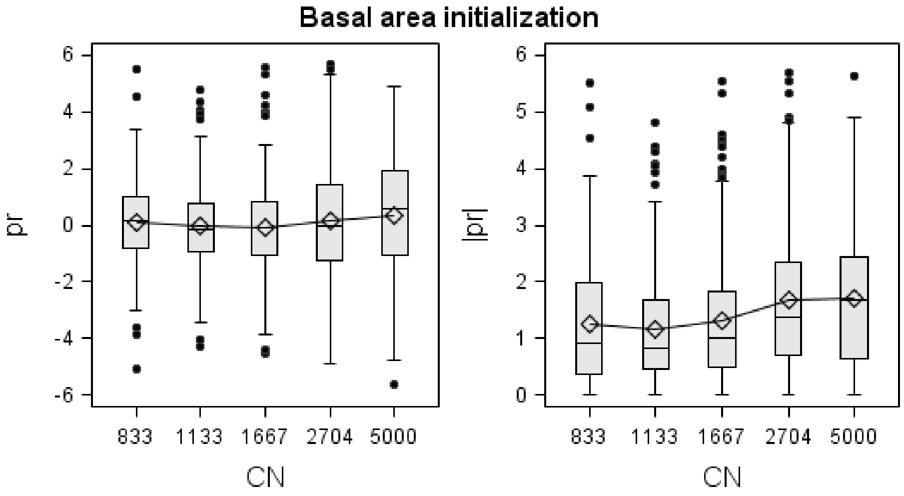

Fig. 3. Box-plots of the PRESS residuals (pr) and absolute PRESS residuals (|pr|) for the stand basal area initialization function (G) by stand density class (CN).

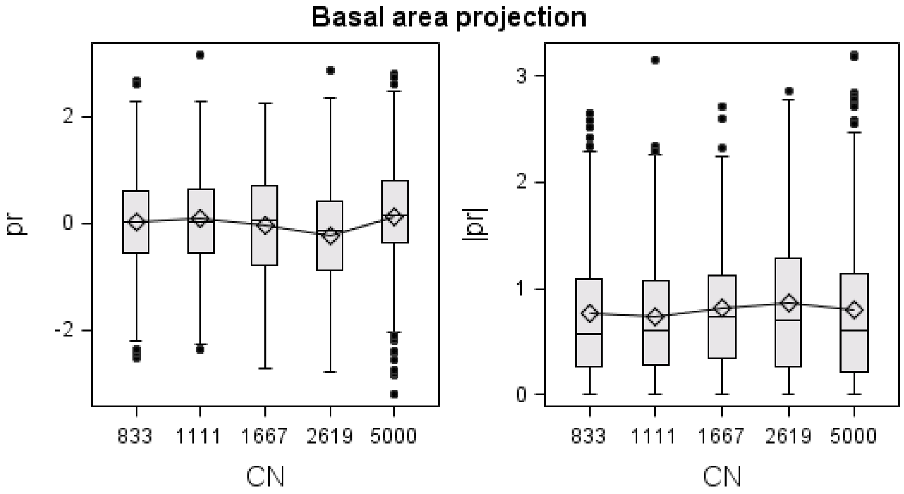

Fig. 4. Box-plots of the PRESS residuals (pr) and absolute PRESS residuals (|pr|) for the stand basal area projection function (G_2) by stand density class (CN).

Stand Density

Fig. 5 shows the relationship between ln(dg) and ln(N) for the stands used in this study together with the line of maximum density (slope=-1.6) proposed by Landsberg and Waring (1997) and used by Tomé et al. (2004) for this species, which assumes that a stand with 1000 trees per hectare has a dg=24.53 cm. This graphic shows that the stands used to develop the GLOBEP model, and thus future stands for biomass production, have not yet reached the onset of self-thinning at harvesting age. Therefore, stand density can be modeled with a mortality function. On the other hand, despite far from self-thinning, coppice stands evidenced some mortality for younger ages. This mortality can be explained by the increasing competition between the shoots registered during ingrowth.

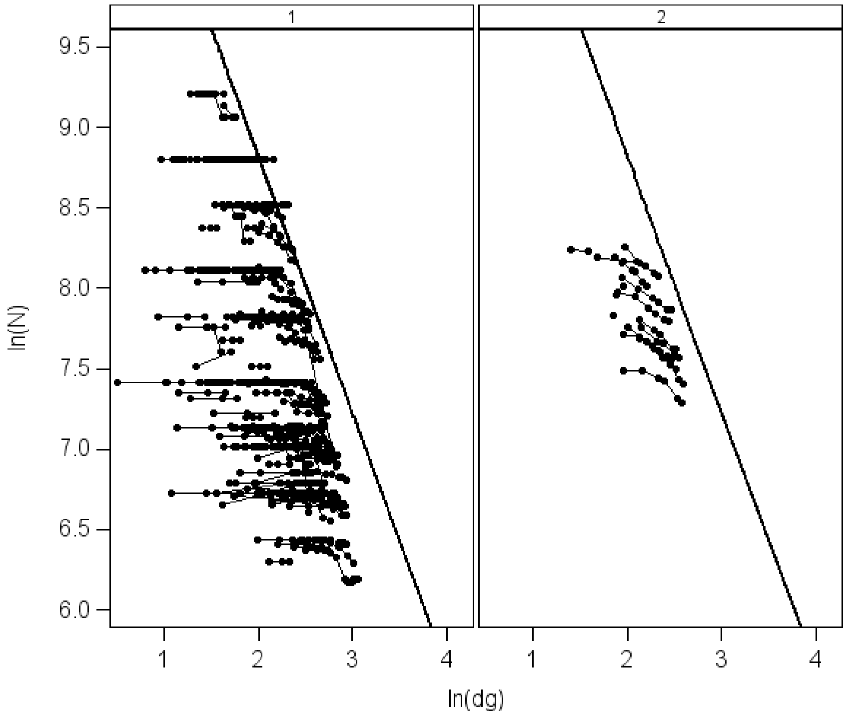

Fig. 5. Representation of Reineke maximum size-density relationship for the data set used for fitting GlobEP functions where the solid bold line represents the maximum density line with a slope=-1.6. The rotation is represented by 1 and 2 indicating planted and coppice stands, respectively.

Further graphical analysis for the unthinned stands showed differences between the *TAV* trial and the *PSP*, and also, the diversity in the number of shoots per stool over time showing some evidence of being related to the various starting densities and eventually to site index (**Fig.6**). Additionally, it indicated that after ingrowth, the number of shoots per stool decreased for all the plots from *TAV* trial around the age of 3 years, whereas it maintained approximately constant for the *PSP*. For this reason, the age of 3 years was assumed as the age at which ingrowth ceases. From this age onward, the mortality function can be applied to project stand density. The number of shoots at age 3 is designated, in the Globulus and GlobEP models, as N_0.

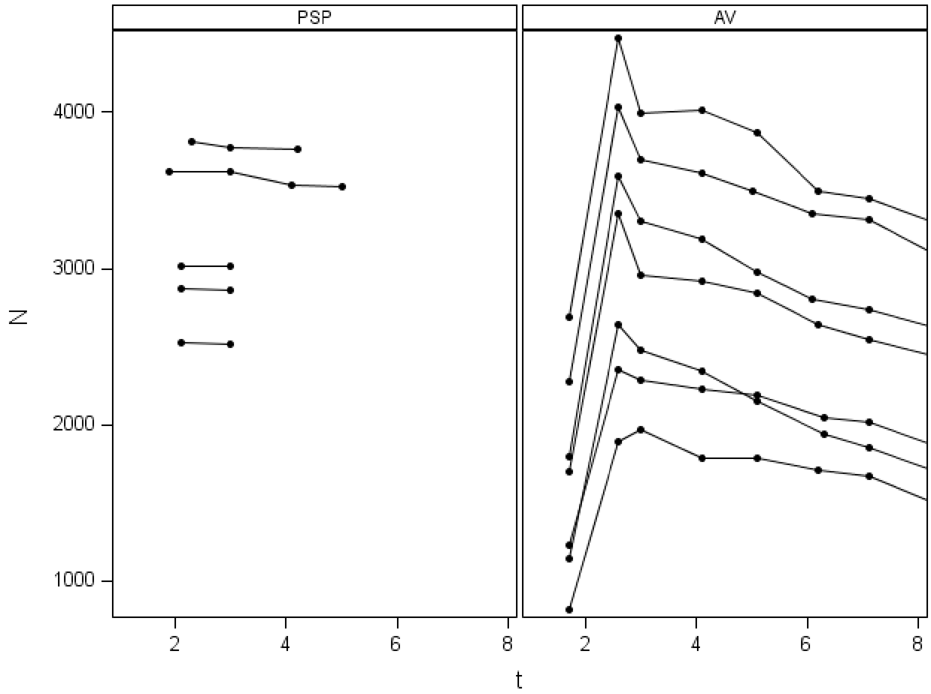

Fig. 6. Evolution of the number of shoots per hectare in the *PSP* and in trial *TAV* unthinned coppice stands.

Out of the tested expressions for the am parameter in the mortality function, the one selected expressed the effect of starting density (Npl or N_0 for coppices) and site index (S). Parameter estimates and the fitting statistics for the stand density sub-model are found in **Table 3**.

Table 3. Stand density sub-model for highly stocked eucalyptus stands, respective parameter estimates and fitting statistics.

$N = Npl\ \ e^{(-Am(t))}$ *initialization planted*

$N\ \ = N_0\ \ e^{(-Am(t-3))}$ *initialization planted* $\qquad Am = amn\ \ \frac{Npl}{1000} + ams\ \ \frac{S_1}{10}$

$N_2 = N_1\ \ e^{(-Am(t_2-t_1))}$ *projection planted and coppice*

Parameters Estimates

amn	***ams***
-0.0016	0.0075

Fitting Statistics

	n	**MEFadj**	$\overline{pr}$	$\overline{apr}$	***SSE***	***SSEp***
initialization /projection	906	0.9998	-0.2438	13.20	602407.2	608532.0

The stand density PRESS residuals and respective absolute values plotted as a function of stand density are displayed in **Fig. 7** that shows consistent results for all classes.

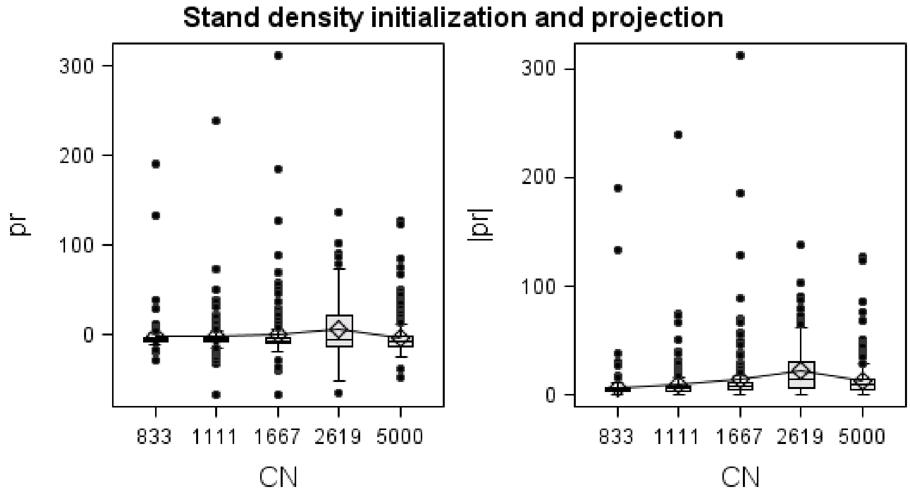

Fig. 7. Box-plots of the PRESS residuals (pr) and absolute PRESS residuals (|pr|) for the projection function of stand density (N) by stand density.

As mentioned in the methods section, two models were developed in order to simulate the evolution of the number of shoots till the age of 3 years. A linear function on age (t) with the slope depending on initial number of stools alive was chosen to predict the evolution of the number of shoots per stool before the age of 3. Graphical analysis of the average number of shoots per stool at 3 years of age as a function of the number of living stools (**Fig. 8**) clearly showed the dependence of the first variable on the second.

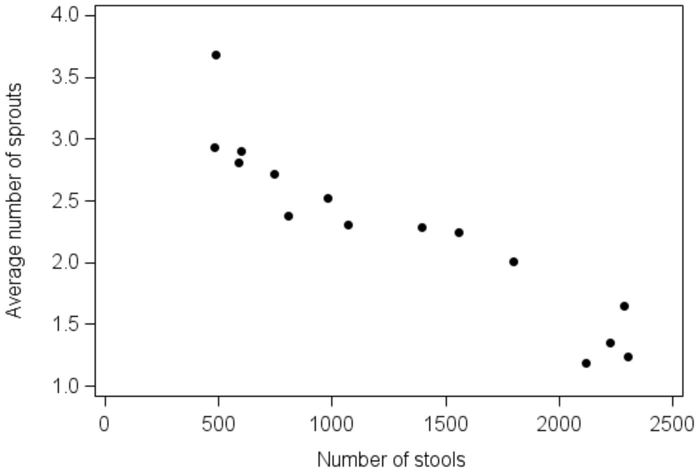

Fig. 8. Relationship of the average number of sprouts per stool and the number of living stools for *AVT* and *PSP*.

A few functions were tested and a hyperbolic function with a positive asymptote was chosen for performing better. This fact justifies the form of the equation used for the prediction function for the number of shoots per stool at age 3 (**Table 4**).

Table 4. Prediction model for the mean number of shoots per stool, parameter estimates and the model fitting statistics.

$$n_{Shoots\,t<3} = a0 + at \quad t + atn \quad t \quad \frac{Nstools}{1000} \qquad\qquad n_{Shoots\,t=3} = 1 + bn \quad \frac{1}{\mathrm{Nstools}}$$

Parameters Estimates

	a0	***at***	***atn***	***bn***
	1.0478	1.0198	-0.3833	1186.1

Fitting Statistics

	n	**MEFadj**	$\overline{pr}$	$\overline{apr}$	***SSE***	***SSEp***
Nshoots t<3	*31*	0.6918	-0.0092	0.4022	6.3283	7.5655
Nshoots t=3	*15*	0.8032	0.0329	0.2886	1.3646	1.6189

VI.4.3 Evaluation of the new functions for long-term projections

Results for the long-term analysis showed no important bias or loss of precision for projection lengths up to 5 years (**Fig. 9**). Basal area estimates show no tendency with projection length, whereas stand density estimates get slightly biased and less precise as projection length approaches 5 years (**Fig. 9**). Despite the outliers, the average estimates obtained with GlobEP show a considerable improvement when compared to Globulus, justifying the development of the new sub-models.

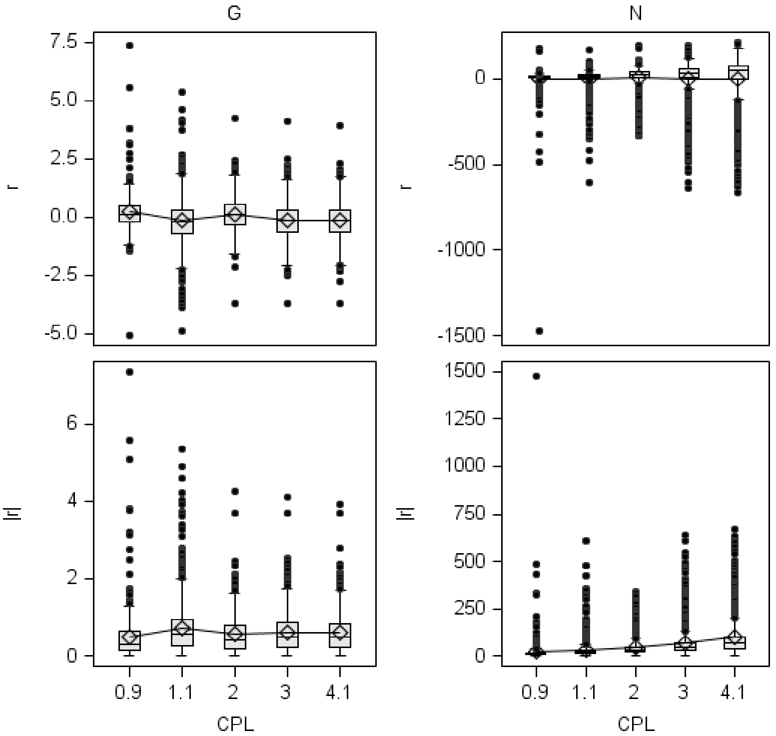

Fig. 9. Box-plots of GlobEP residuals (r) and absolute residuals (|r|) for stand basal area (G) and stand density (N) projection functions by projection length interval (CPL).

VI.4.4 Comparison of productivities estimated with Globulus 3.0 and GlobEP

The average productivities obtained with Globulus and GlobEP for 25 years (5 consecutive 5-year rotation cycles) show that the two models estimate similar productions for all site index classes for 1111 trees ha^{-1} starting densities (3x3 spacing), whereas for highly stocked stands, Globulus predictions are higher than those from GlobEP (**Fig**. **10**). According to GlobEP estimates, if planted at 5000 trees ha^{-1}, *E. globulus* can produce between 3.33 and 31.88 Mg ha^{-1}, depending on the site (**Fig**. **10**).

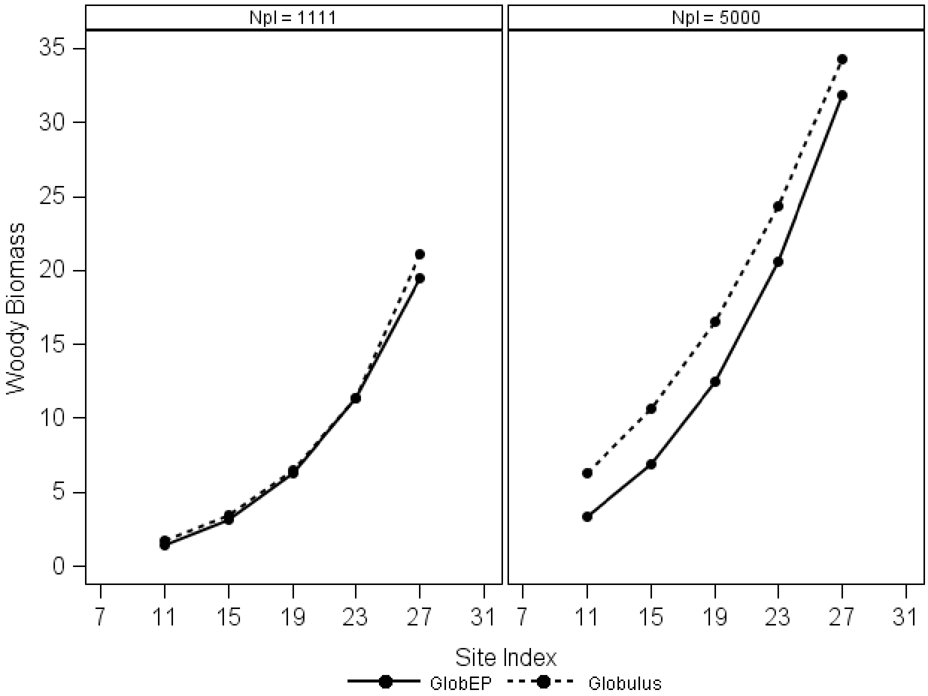

Fig. 10. Simulated productivities (Mg ha^{-1} year^{-1}) using GlobEP and Globulus growth models for a range of increasing site indices and initial stand densities (Npl) of 1111 and 5000 trees ha^{-1}.

VI.5 Discussion

The objective of the present research was to develop a growth model to predict biomass production in highly stocked stands to be used as a tool to evaluate the potential of *E. globulus* for energy production. At present, there is no data available from this type of plantations; therefore the model was built based on data from spacing trials and a few permanent plots. The data set was limited, namely the percentage of plots with stand densities greater than 2500 trees per hectare was not very large as well as the percentage of data from unthinned coppice stands. Nevertheless, it was useful for the purpose of the study.

The evaluation of the Globulus 3.0 model, developed to estimate the growth of stands planted for wood/pulp production, for stands with higher stockings showed that there was no need to refit the dominant height growth function. This result is in accordance with the theory of forest production that assumes the independence of dominant height from stand density (Assman 1961). On the contrary, the evaluation of the basal area and the stand density functions of the Globulus 3.0 model showed clear bias when used outside the range of densities present in the plots used for its development. Overall, these results demonstrated Globulus 3.0 model inadequacy to simulate growth for highly stocked stands supporting the development of new growth functions for basal area and stand density.

The known positive relationship of basal area growth rate with stand density was taken into account while developing the new basal area sub-model by expressing the growth rate parameter as a function of stand density.

The stand density sub-model, conceived to be applied to project the number of trees per hectare in planted stands as well as the number of sprouts after the age of 3 in coppice stands, presented an acceptable behavior. Despite all the efforts during the fitting stage, the residuals for stand density showed a non-normal distribution. This result is a consequence of some stands evidencing higher mortality than the mortality estimated with the model despite not being approaching self-thinning, which is unlikely to occur since the plantations to be managed and operationally used for bioenergy will be harvested several years before this occurs. The idea to develop a function to predict the average number of shoots per stool had the objective to improve the simulation of stand density for younger ages in coppice stands, accounting for ingrowth, as well as to obtain a function to initialize the number of shoots at the age the ingrowth has stopped.

The long-term validation of GlobEP showed the robustness of the model for the simulation of biomass production in bioenergy stands managed as short-rotations, assuming a 5-year rotation length.

The comparison of Globulus and GlobEP productivities showed that the two models give similar estimates for stand densities commonly practiced for pulp production. By contrast, for higher stockings, Globulus presented higher estimates than those of GlobEP. Because the latest model used higher stockings in its development it is expected that its estimates are closer to the ones to be obtained in highly stocked plantations than those provided by Globulus. In the evaluation of the two models, the big whiskers observed in GlobEP box-plot analysis are the result of the different productivities found in the data set used to develop stand basal area and stand density new functions. A close analysis of the data set evidenced the differences between the four clones: V, C, P and M when compared with each other and with the seminal origin material (S). For highly stocked stands (density class of 5000 trees ha^{-1}) around the age of 5, basal area values vary from 3 to 36 m^2 ha^{-1}. **Fig. 11** shows that the 4 clones that are planted on the same sites, lead to very different productivities. Clones V and M do not seem to be substantially different from seminal material, whereas clone C appears to be slightly more productive than all others. However, it is clone P that most distances from all the others for its lowest productivities.

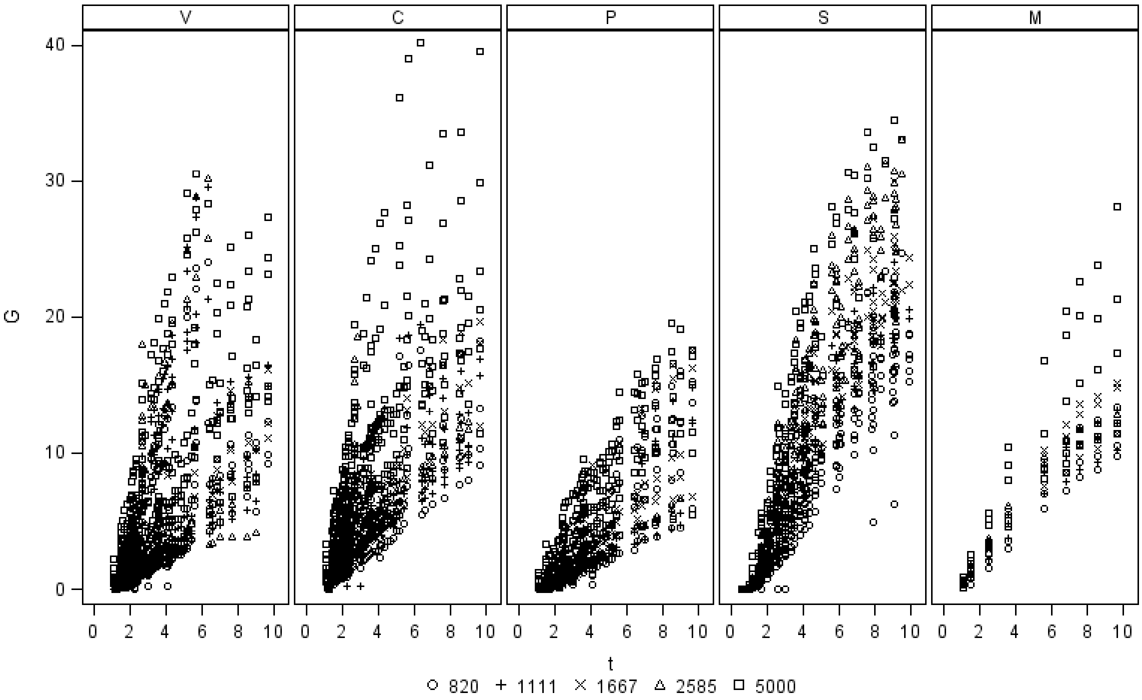

Fig. 11. Comparison of stand basal area (G) for the different clones (V, C, P and M) and seminal (S) by stand density classes.

As mentioned before, the data set used in this study had some limitations. In face of these restrictions, it is essential to continue investigating the potential of *E. globulus* for bioenergy production. The establishment of highly stocked trials to be managed as several consecutive coppice rotations, with no shoots selection and reduced rotation lengths would be extremely beneficial, not only for validating GlobEP model identifying limitations, but also for integrating the refiting data set.

VI.6 Conclusions

This study allowed several interesting conclusions:

- The evaluation of the Globulus 3.0 model using spacing trials data allowed confirming that dominant height was not affected by stand density (Assman 1961);
- Applying Globulus 3.0 model to spacing trials data resulted in less precise and biased estimates of basal area and stand density for highly stocked stands, outside the range of densities present in the data used to develop it. Therefore, it was concluded that Globulus 3.0 basal area and mortality sub-models were not suitable for projecting the growth of highly stocked stands. With GlobEP new sub-models, forecasting growth of these stands became more precise and less biased for high stand densities when

compared with the results obtained with Globulus 3.0. Furthermore, the general results obtained for the 5 consecutive rotation cycles showed the models performed equally for commonly practiced densities, although for higher stockings Globulus estimates were over GlobEP;

- This study showed that no self-thinning is likely to occur in short-rotation forests managed for bioenergy;
- Simulation of a new stand by coppice, after harvesting, was successfully achieved using two models, a first model to predict the evolution of the number of shoots per stool during the two first years and a second model to predict the same variable at the age of 3, assumed to be the age at which the ingrowth no longer takes place. From then on, a mortality function is appropriate to simulate the evolution of the number of shoots per hectare;
- According to GlobEP estimates, *E. globulus*, if planted at 5000 trees ha^{-1}, can produce from 3.33-31.88 Mg ha^{-1} year^{-1}, depending on the site.

In spite of the validity of the above conclusions, the small size of the data set used in this research indicates the need to obtain more data on growth for this type of stands by establishing trials specifically for this purpose.

VI.7 Literature Cited

Asociación Forestal de Galicia (AFG) 2007. ECAS: cultivos energéticos en el espacio atlântico – oportunidades de implantación a gran escala. Asociación Forestal de Galicia (Eds.).
[online] URL: http://www.enersilva.org/publicaciones.php (Available at 13/10/09)

Assman, E., 1961, Waldertragskunde. BLV Bayerischer Landwirtschaftsverlag Gmbtt, Muncchen. (Trad. Inglês: S.M. Gardiner, 1970. The principles of Forest Yield Study. Studies in the Organic Production, Structure, Increment and Yield of Forest Stands. Pergamon Press, Oxford).

Diário da República (DRE), 2005. Diário da República Electrónico, PRESIDÊNCIA DO CONSELHO DE MINISTROS, Resolução do Conselho de Ministros nº 169/2005, DIÁRIO DA REPÚBLICA-I SÉRIE-B, nº 204 -24 de Outubro de 2005, Lisboa, Portugal.
[online] URL: http://dre.pt/pdf1sdip/2005/10/204B00/61686176.pdf

Huber, P.J., 1973. Robust regression: asymptotics, conjectures, and Monte Carlo. Annals of Statistics, **1**: 799–821.

Labrecque, M., Teodorescu, T.I., 2005. Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). Biomass and Bioenergy, **29**(1): 1-9.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency. Carbon balance and partitioning. Forest Ecology and Management, **95**: 209-228.

Lundqvist, B., 1957. On the height growth in cultivated stands of pine and spruce in Northern Sweden. Medd. fran Statens Skogforsk. band **47**(2): 64.

Manzone, M., Airoldi G., Balsari, P., 2009. Energetic and economic evaluation of a poplar cultivation for the biomass production in Italy. Biomass and Bioenergy, **33**(9): 1258-1264.

Myers, R., 1986. Classical and Modern Regression with Applications. Duxbury Press, Boston, MA.

Noronha-Sannervik, A., Kowalik, P., 2005. Annual variations in the solar energy conversion efficiency in a willow coppice stand. Biomass and Bioenergy, **25**: 227-233

Parresol B.R., 1999. Assessing tree and stand biomass: a review with examples and critical comparisons. Forest Science, **45**(4): 573-593.

Reineke, L.H., 1933. Perfecting a stand-density index for even-aged forest. Journal of Agricultural Research, **46**: 627-638.

SAS Institute Inc., 2011. SAS/STAT 9.3 User's Guide. SAS Institute Inc, Cary, NC

Soares P., Tomé, M., Skovsgaard, J.P., Vanclay, J., 1995. Evaluating a growth model for forest managment using continuous forest inventory data. Forest Ecology Management, **71**: 251-265.

Soares, P., Tomé, M., 2000. Adequacy of different experimental designs for eucalyptus spacing trials in Portuguese environmental conditions in Integrated tools for natural resources inventories in the 21st century eds.: Hansen, M.; Burk, T. General Technical Report NC-212. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station. 744 p.

Tomé, M., Soares P., Oliveira T., 2006. O modelo Globulus 3.0. Dados e equações. Publicações GIMREF RC2/2006. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.

Tomé, M., Faias, S.P., Tomé, J., Cortiçada, A., Soares, P., Araújo, C., 2004. Hybridizing a stand level process-based model with growth and yield models for *Eucalyptus globulus* plantations in Portugal. In: Borralho, N.M.G., Pereira, J.S., Marques, C., Coutinho, J., Madeira, M., Tomé, M. (Eds.), Eucalyptus in a changing world. Proceedings of the IUFRO International Conference, Aveiro, pp. 290-297.

Tomé, M., Soares, P., Ribeiro, F., 2001. O modelo GLOBULUS 2.1. Relatórios técnico-científicos do GIMREF, nº 1/2001. Centro de Estudos Florestais, Instituto Superior de Agronomia, Lisboa.

CHAPTER VII

Evaluating 3PG and Glob3PG models for planted and coppice stands using long-term *Eucalyptus globulus* Labill. permanent plots

Title: Evaluating 3PG and Glob3PG models for planted and coppice stands using long-term *Eucalyptus globulus* Labill. permanent plots.

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Evaluating 3PG and Glob3PG models for planted and coppice stands using long-term *Eucalyptus globulus* Labill. permanent plots

VII.1 Abstract

According to the most recent National Forest Inventory, the Portuguese forest area comprises about 3.4 M ha of which some 7.4 thousand ha is composed of eucalyptus (*Eucalyptus globulus* Labill.*)*. This exotic species, mainly managed as even-aged plantations followed by coppice, covers approximately 23% of the forests in the country, and of this 59% of the stands are managed as coppice. Given the importance of this species to the national pulp and paper industries, a regional simulator was developed to project eucalyptus growth. At present, forecasts result from combining National Forest Inventory (NFI) data with empirical growth models. However, to be able to assess forest resources accounting for different management practices under changing environmental conditions, the regional simulator should also integrate process-based models. These models are more demanding in terms of inputs, namely soil inputs, which are not available from the Portuguese NFI.

The main objective of this study is to evaluate 3PG and Glob3PG models to project the growth of coppice stands as well as the transition from plantation to coppice and between subsequent coppices. The possibility to integrate these models into a NFI-based regional simulator was evaluated by using soil inputs deriving from the European soil database and using Globulus empirical model as a benchmark.

A set of 22 permanent plots measured throughout consecutive rotations was used. Model evaluation consisted mainly on the characterization of model error. Modelling efficiency was calculated as well as prediction errors. The quantitative evaluation was performed by density, site index and initial age of simulation classes for the short-term. Long-term evaluation was also undertaken to analyze the effect of projection length.

Glob3PG model behaved similarly to the empirical model with modelling efficiencies higher than 95%. Furthermore, no clear differences were observed between the performance of the model when applied to planted and coppice stands. In general terms, results seem to indicate that the use of information from soil maps combined with stand information as input did not compromise simulation results.

VII.2 Introduction

Eucalyptus globulus Labill. planted forest is of crucial importance for the Portuguese economy. The quality of *E. globulus* fibres for high quality paper production made this species the main source of raw material for the Portuguese pulp and paper industry. In 2009, Portugal was the fourth biggest pulp producer in Europe. The constantly increasing demand for *E. globulus* wood was a motor for the expansion of this introduced species that now is the second most representative forest species in Portugal covering nearly 740 thousand hectares (AFN 2010). According to information provided by the last NFI, 59% of the eucalyptus forests are represented by coppice stands.

Over the last decade, the occurrence of severe forest fires had a great environmental impact resulting in negative consequences for the ecosystems and the economy. Adding to this, the increasing expectations concerning the use of forests has led to changes in forest management that, along with climate changes, are expected to have significant impacts in forest growth. However, wood availability in the long-term is still a problem whose solution will have to account for increases in wood consumption combined with extra demand for bio-energy, new trends in management as well as energetic and environmental policy measures. In Portugal, a regional simulator was developed to explore policy options guiding decision making for research and management purposes. The current version of this tool combines national forest inventory (NFI) data with empirical growth models taking into account the effect of different drivers such as wood and biomass demands, hazards occurrence and land use changes (Barreiro and Tomé 2011, **Chapter IV**).

Since the 90's, several empirical growth models have been developed to simulate *E. globulus* growth in the country (Amaro 1998, Amaro 2003, Tomé et al. 2001a, Tomé et al. 2001b, Soares and Tomé 2003, Barreiro and Tomé 2004, Tomé et al. 2006). At present, the third version of Globulus, referred to as Globulus 3.0 (Tomé et al. 2006), is the most commonly used model. Despite process-based models projections' are very often based on input data that is not readily available from forest inventory at present, they are considered to be more appropriate to assess forest resources in a multiple objectives' management context under changing environmental conditions (Tomé et al. 2004b). Therefore, 3PG (Landsberg and Waring 1997, Sands and Landsberg 2002) is increasingly being used for *E. globulus* plantations in Portugal. Over the last decade, its applicability for the Portuguese conditions was studied (Tomé et al. 2004a) and the model was parameterized for Portuguese data covering planted stands (first rotation) (Fontes el al.

2006). In an attempt to benefit from the strengths of empirical and physiological models, 3PG and Globulus were hybridized using allometric equations between stand variables to establish the link between the models resulting in the Glob3PG model (Tomé et al. 2004b). Similarly to the parameterization study, this study also covered stands from seed. As coppice stands represent more than half of the eucalyptus area, it is of crucial importance to evaluate 3PG and Glob3PG performance for coppice stands as well as to simulate the transition between rotations. Throughout this paper, the term rotation is used to define he period that goes from stand regeneration, either by plantation or coppice, until harvesting. Process-based models are more demanding in terms of input, namely in soil information that is not available from the Portuguese NFI surveys. A possible solution is to use soil information collected or estimated from available soil maps and complement it with stand data available from the NFI. Inputs regulate the quality of forecasts which have the purpose of helping foreseeing long-term implications of forest management under a given climate. Thus, the accuracy of decisions depends on how reliable their growth projections are, being essential to evaluate the models in use.

The objective of this study is to evaluate the performance of 3PG and Glob3PG models for long-term prediction of planted and coppice stands using soil inputs deriving from the European Soil database (EU 2004) combined with stand information available from the NFI.

VII.3 Methods

VII.3.1 Study area and plots

Over the years, a large amount of information on eucalyptus growth has been compiled into a database integrating inventory data, permanent plots and experimental trials. This collection of data represents a great diversity of stands over the country and has been used to develop the Globulus models (Tomé and Ribeiro 2000, Tomé et al. 2001a, Tomé et al. 2006) and the link functions in Glob3PG model (Tomé et al. 2004b). A total of 22 plots were selected for the present research (**Table 1**). Data selection was based on the following requirements: 1) stands must have been measured throughout consecutive rotations as planted and coppice; 2) their geographical distribution should cover coastal and inland areas (**Fig. 1**); 3) at least one of the rotations had to have three measurements at minimum; and 4) average stand densities should neither be lower than 950 nor higher than 1500 trees/ha, in order to be representative of the stand densities most commonly found in the existing stands.

Table 1. Summary statistics for the plots used in the study. Data for each plot were organized as pairs of successive re-measurements (t_1, t_2). Statistics refer to t_1. N represents the stand density at the age of the first measurement and S the site index – dominant height at the age of 10. Location indicates whether the plot is located inland (I) or by the coast (C).

Plot	**N**	**S**	**Location**	**Nr of re-measurements**	
				Planted	**Coppice**
P1	1104	24.11	C	14	12
P2	1114	23.28	C	6	12
P3	1103	17.28	C	14	12
P4	1099	15.65	C	14	12
P5	1125	24.83	C	13	5
P6	1111	21.34	I	12	5
P7	1091	19.71	I	11	11
P8	1185	19.77	I	10	13
P9	1274	18.66	I	10	13
P10	1112	23.75	C	10	12
P11	1112	21.08	C	10	12
P12	1093	13.14	I	12	10
P13	1094	19.68	I	11	10
P14	1366	21.83	I	20	7
P15	975	19.28	I	9	11
P16	1111	21.49	C	12	12
P17	1111	21.70	C	12	12
P18	1306	23.08	C	10	11
P19	1122	27.64	I	10	14
P20	1111	17.43	C	10	4
P21	1111	22.48	C	8	5
P22	1433	17.15	C	8	5
Min.	975	13	-	6	4
Average	1148	21	-	11	10
Max.	1433	28	-	20	14

The stand variables used for each repeated measurement are: stand density, dominant height, basal area, volumes under and over bark, with and without stump, and biomass per component.

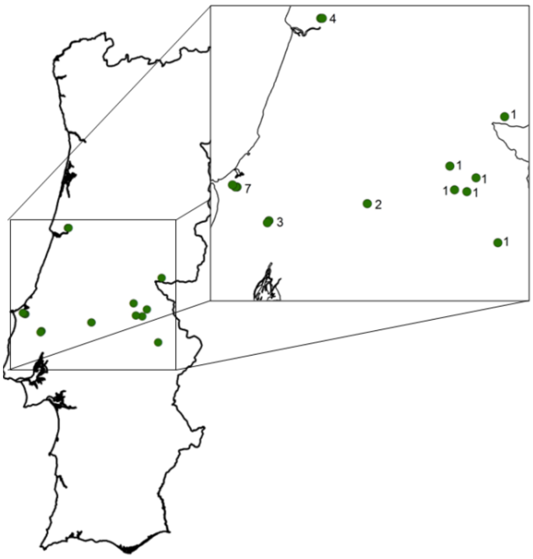


Fig. 1. Location of the permanent plots used in the present research. The numbers indicate the number of plots in each location.

VII.3.2 Initialization and management regime

For the evaluation of the models, data were organized as pairs of successive re-measurements (t_1, t_2). Stand level inputs comprising biomass starting values and stand age, among other variables, were obtained in the eucalyptus database. Each plot was simulated by defining a management regime according to the management practices observed in historic data.

VII.3.3 Climate data

The weather data required as input was obtained from the Portuguese Meteorological Institute and consisted of monthly information for: minimum, mean and maximum temperature, number of days with rain, number of frost days, precipitation, solar radiation and vapor pressure deficit. The nearest meteorological station to the stand was always selected provided it had a similar climate. For example, in case the nearest station was at a different altitude and significant differences in climatic variables could be found, the second nearest station would be preferred. Data was used as the averages for the time period available for each station.

VII.3.4 Soil data

A digital elevation model (DEM) was used to obtain the plot altitudes. As mentioned before, the European Soil DataBase (ESDB v2) was used to obtain soil characteristics (EU 2004) for the 22 plots used in this study. According to soil maps the 22 plots are distributed over four soil types: HorticLuvisoils (8 plots), EutricCambisoils (7 plots), DistricRegosoils (4 plots) and HorticPodzoils (3 plots). Only 2 plots had a medium texture, whereas all others were classified as coarse (clay <18% and sand >65%). However, soil water available to plants (SWAP) is not directly available in the database. Therefore, it was estimated according to Thomasson (1995) and King et al. (1995). The maximum available soil water (ASW_{max}), required by 3PG as input, was assumed to be the sum of the maximum available soil water content in the topsoil layer (30 cm thick) and the subsoil layer (to the depth to rock), whereas the minimum (ASW_{min}), was assumed to be 0.5 mm. In order to determine the available soil water (ASW) in the beginning of the simulation, 3PG was run for 50 years starting with $ASW=ASW_{max}$. The ASW values for each plot were averaged per month for the latest 40 years of simulation. The ASW in the beginning of the simulation was selected according to the initial month of measurement of each plot.

Fertility rating (FR) is used by the 3PG and Glob3PG models to rank soil fertility. The approach adopted to estimate this empirical index was to run the model for FR values varying between 0 (non-fertile soils) and 1 (extremely fertile soils) with increments of 0.05 and calculating prediction errors (observed minus predicted) for a set of stand variables. The FR that allowed obtaining the best growth prediction per plot based on the normalized sum of the errors was selected. The idea for using the 3PG model in regional simulations is to find the FR value that, under current climate, leads to a productivitiy closer to the one obtained with empirical models for a given age, for example 10 years, the standard age for eucalyptus (**Fig. 2**). In this research, instead of using the productivity estimated with the Globulus model, the observed values of stand variables were used instead. In this way, results would not be dependent on the empirical model. Also, in this study the best FR value was the one that minimized the sum of the differences between the observed values and 3PG estimates for all the measurement ages (Min sum $|Wobs_t - W3PG_t|$.

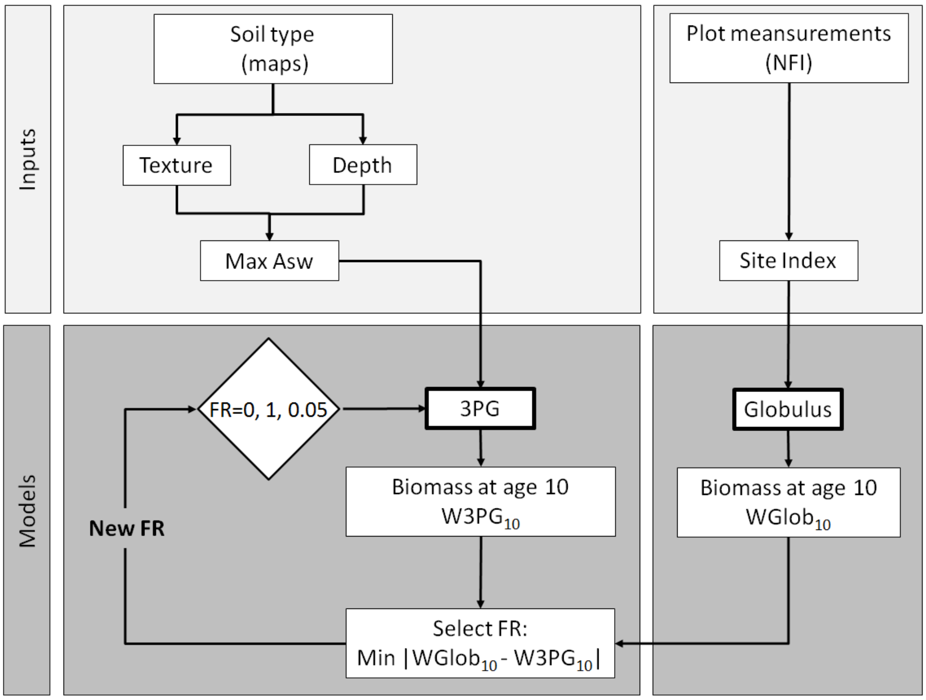
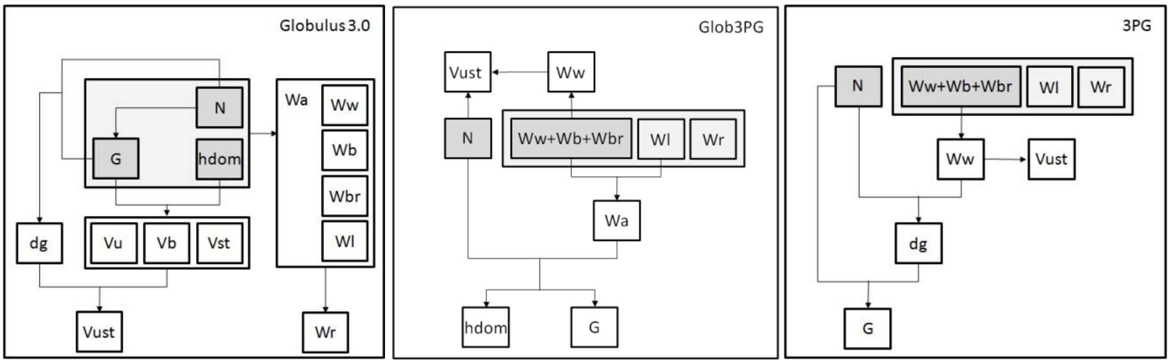


Fig. 2. Methodology for determining fertility rating (FR) based on European soil database inputs when using 3PG integrated in a regional simulator, where $W3PG_{10}$ is the total biomass estimated for age 10 with the 3PG model and $WGlob_{10}$ is the total biomass estimated for the same age with the Globulus model.

VII.3.5 Simulators overview

With the purpose of evaluating the performance of the three different models for planted and coppice stands, two stand/forest level simulators were developed: GLOBULUS and 3PG-Out+.

The differences between the two simulators are mainly related to the type of growth models used; and consequently to the input requirements and the time-step applied. **Fig. 3** shows the principal variables directly predicted by each model and how the derived variables (predicted from the principal variables) are obtained for each growth model.



Where: N, stand density; Wa, aboveground biomass; Wl, biomass of leaves; Wwy, woody biomass i.e. the biomass of stem wood, stem bark and branches; Ww, biomass of stem wood; Wb, biomass of stem bark; Wbr, biomass of branches; Wr, biomass of roots; hg, height of the average tree; hdom; dominant height; G, stand basal area; dg, quadratic mean diameter; Vu, volume underbark with stump; Vb, volume of bark; Vst, volume of stump; Vu_st, volume under-bark without stump.

Fig.3. Schematic view of the core and derived variables in Globulus 3.0, 3PG and Glob3PG growth models. The grey boxes contain the principal variables, whereas derived variables are the ones in the white boxes.

3PG and Glob3PG models work on monthly time-steps instead of 1-year time-steps like Globulus. Another difference between the two types of models lies in the external drivers considered: Globulus 3.0 is only driven by site index and management whereas the other two models also account for climate and soil characteristics. For this reason, Globulus 3.0 is implemented in a specific simulator (GLOBULUS), whereas 3PG and Glob3PG are both implemented in the same simulator (3PG-out+). The two simulators run in the same way and are programmed to allow applying a different management to the different stands along the different cutting cycles throughout the planning horizon. The transition between rotations is achieved by initializing all stand variables for the next rotation before the thinning of the shoots is done. Stand density is crucial for initializing stand growth. In the case of coppices, resprouting is accounted for using a prediction function based on the number of stools, while the number of stools is initialized with the number of living trees/stools harvested in the previous rotation and assuming a fixed mortality rate. After the shoots selection, usually done during the third year after final harvest, the number of sprouts has to be reinitialized based on the number of living stools at that moment and the number of shoots left per stool that is defined by management. After all inputs have been imported and stand variables initialized, the growth module projects growth until stands are harvested, simulates the transition between rotations and the thinning operation (selection of the shoots). Some simulation parameters like model variants (3PG or Glob3PG), type of weather data (annual values or monthly averages per year), planning horizon, number of rotations, harvesting age and removals have to be provided by the user.

VII.3.6 Evaluating the growth models

Model evaluation is a crucial step in model building, and should be carried out along with the model development, from the model design phase to its implementation as well as during the fitting stage (Soares et al. 1995, Vanclay and Skovsgaard 1997, Tomé and Soares 1999). It should comprise two distinct processes: model verification, or qualitative evaluation; and model validation, or quantitative evaluation. Model verification consists of checking the logics behind the structure of model components searching for inconsistencies and how biologically realistic the model outputs are. It is usually the modeler's responsibility to perform this type of evaluation. Several procedures can be applied for forest growth models validation or quantitative examinations of the models. One way of accomplishing the quantitative evaluation of a model is through the comparison of predictions with real data (Soares et al. 1995).

Real data are needed for characterizing model error so that model performance can be tested by comparing model predictions with the evaluation data set. The quantitative evaluation was conducted in several steps. The next step consisted of preparing the dataset as pairs of successive re-measurements, in order to initialize the simulators using each measurement to evaluate model bias and precision as a whole and in relation to site index, stand density and initial age.

Prior to running the simulators, the dataset was prepared so that simulations could be initiated for each plot from each measurement age of the planted stand until the last measurement before the coppice was harvested. In this way, the impact of the projection interval could be assessed and the transition between rotations and the thinning of the shoots could also be validated.

For the Globulus model, the principal variables, or the variables directly projected by the model are dominant height, basal area and stand density, whereas in 3PG total biomass is the principal variable which is then allocated to roots leaves and woody components (Wwy). Root biomass was not available in the dataset and it is well known that the prediction of leaf biomass in not straightforward. Therefore, it was decided to focus the evaluation on dominant height, basal area and woody biomass. Under-bark volume without stump was also considered because of its importance for forest managers. Because of the reduced mortality registered in the permanent plots used in this study, stand density was not considered here.

Prediction errors were calculated as the difference between (observed – estimated) values. The predictive ability of models was assessed using modeling efficiency (ef):

$$ef = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{1}$$

where *n* is the number of observations, y_i is the observed value of the variable, $\hat{y}_i$ is the respective predicted value calculated with the model and $\bar{y}$ is the mean value of the variable. Mean residuals ($\bar{r}$) and absolute mean residuals ($|\bar{r}|$) were used for evaluating model bias and precision, respectively:

$$\bar{r} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \tag{2}$$

$$|\bar{r}| = \frac{\sum_{i=1}^{n}|y_i - \hat{y}_i|}{n} \tag{3}$$

with the symbols as described before.

For the short-term analysis, modeling efficiency, mean and absolute mean residuals were calculated for 1-year projection intervals. Box-plots of prediction errors were built by density, site index, initial age of simulation and location (coastal versus inland) classes in order to see if any correlation could be found between the residuals and these variables. The classes were always built based on the percentiles of the variable in question.

To assess the performance of the models in the long-term, the analysis of the residuals was made by classes of projection length also built based on percentiles. Two analysis were carried out, one *within-rotation* and another *across-rotations*. *Within-rotation* analysis included residuals from simulations initialized and finalized within the same rotation, either planted or coppice, whereas *across-rotations* analysis used residuals resulting from simulations across rotations, i.e. integrating the simulation of the transition between rotations.

VII.4. Results

The modeling efficiency, bias and precision for the estimates of dominant height, basal area, under-bark volume without stump and woody biomass obtained with the three models, differentiating rotations, are presented in **Table 2**. The three models presented similar performances in predicting woody biomass. Gobulus is slightly less biased and more precise than Glob3PG for dominant height, whereas for basal area and volume, Glob3PG approaches Globulus estimates and 3PG distances from the other models showing evidence of an overestimating tendency.

Table 2. Validation statistics for dominant height (hdom), basal area (G), volume under-bark without stump (Vu_st) and woody biomass (Wwy) for the three models. Results are presented separately for planted and coppice stands with the empirical model in bold.

Growth function	**model**	ef		$\bar{r}$		$\overline{\lvert r \rvert}$	
		Planted	Coppice	Planted	Coppice	Planted	Coppice
hdom	Glob3PG	0.9472	0.9635	-0.5956	-0.2184	1.3133	0.9693
	Globulus	**0.9817**	**0.9838**	**0.2879**	**-0.0415**	**0.6749**	**0.5587**
G	3PG	0.9179	0.8911	-0.4563	-1.2351	1.7252	1.9197
	Glob3PG	0.9760	0.9767	0.4433	-0.1021	1.0863	0.9324
	Globulus	**0.9948**	**0.9867**	**0.2089**	**-0.0055**	**0.5264**	**0.5734**
Vu_st	3PG	0.8796	0.8877	-32.4325	-24.6042	33.0688	25.6123
	Glob3PG	0.9899	0.9905	-0.4886	-1.0398	7.4729	6.5302
	Globulus	**0.9910**	**0.9941**	**4.0246**	**0.2521**	**6.8507**	**4.8381**
Wwy	3PG	0.9908	0.9937	1.8051	0.0863	5.0110	3.5812
	Glob3PG	0.9908	0.9937	1.8089	0.0965	5.0143	3.5788
	Globulus	**0.9907**	**0.9943**	**2.3060**	**0.1672**	**4.8430**	**3.3867**

The short-term evaluation of the models was performed with resort to box-plots. The relationship of residuals with stand variables is described in the next paragraphs.

Stand density. This analysis confirmed that, for dominant height, Glob3PG is less precise than Globulus, although reasonably unbiased (**Fig. 4**). 3PG is not shown in **Fig. 4** as it does not provide dominant height predictions. For basal area and volume 3PG performance was worse than the one evidenced by the other two models, whereas Glob3PG was nearly as good as the empirical growth model. The graphical analysis for basal area evidenced that 3PG is biased and less precise for the denser stands (**Fig. 5**). Similar results were observed for volume (not shown). As for woody biomass, the three models presented reasonably good estimates with no clear relationship between the residuals and stand density.

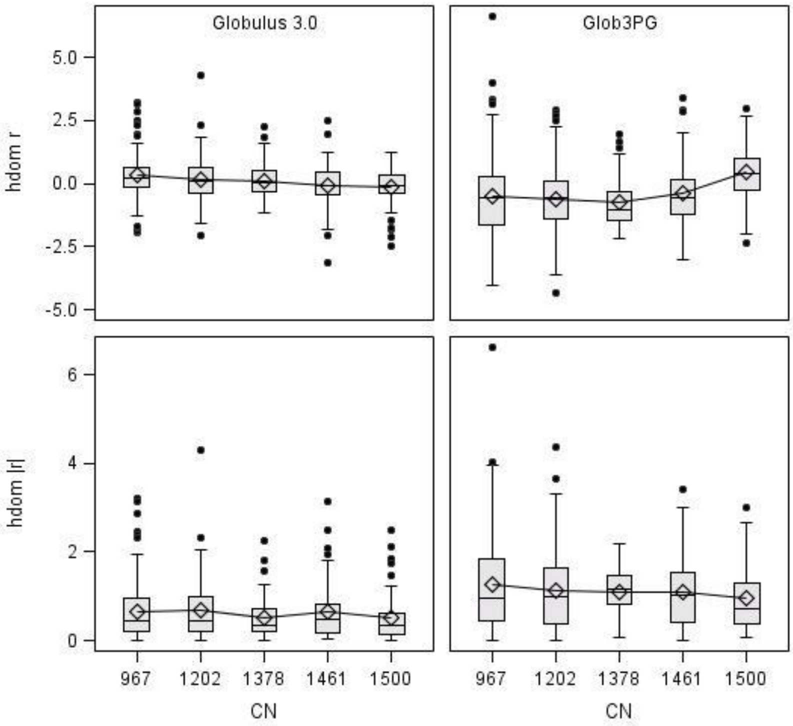


Fig.4. Box-plots for dominant height (m) residuals (hdom r) and absolute residuals (hdom |r|) by density class (CN).

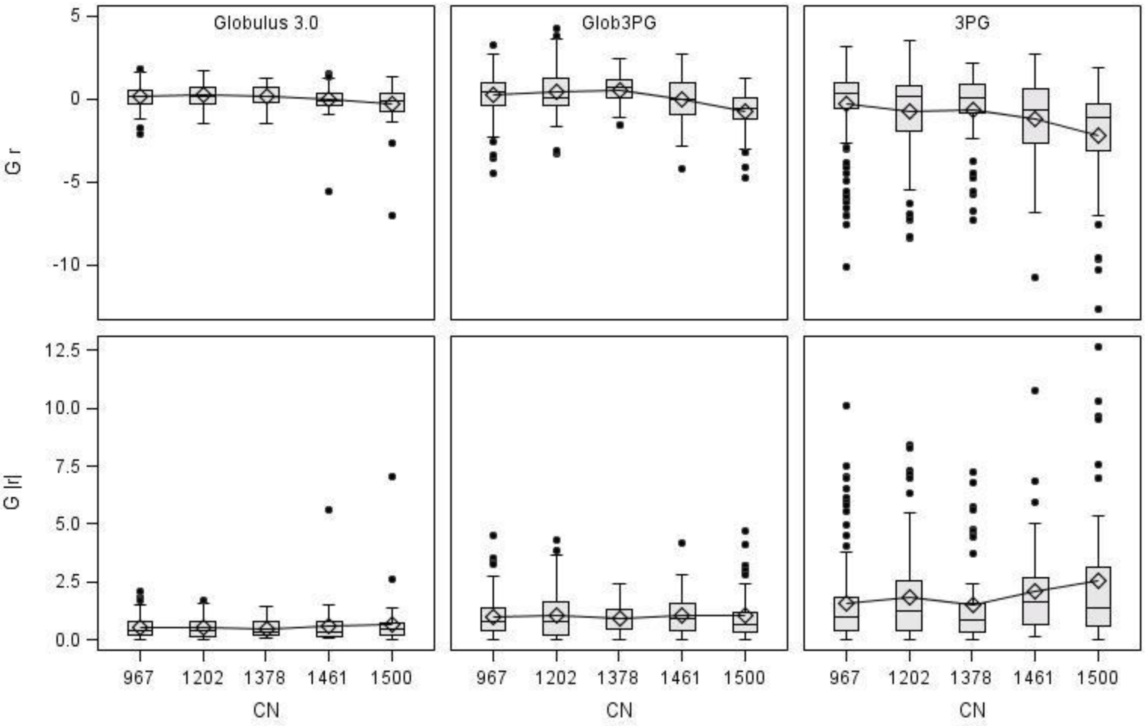


Fig.5. Box-plots for stand basal area (m^2 ha^{-1}) residuals (G r) and absolute residuals (G |r|) by density class (CN).

Site quality. The relationship between dominant height residuals and site quality showed that Glob3PG was slightly more biased than Globulus for the lower site qualities (results not shown). On the other hand, for stand basal area, Glob3PG was slightly less precise than Globulus with the loss of precision increasing with the site index; whereas for 3PG, the basal area residuals indicated that this model was strongly biased and less precise for higher site quality when compared to Globulus (**Fig. 6**). The same tendencies observed for the basal area residuals were found for volume for the three models (not shown), with 3PG estimates highly influenced by site quality presenting residuals and absolute residuals varying from -162.7 to 13.36 m^3ha^{-1} and 0.20 to 162.7 m^3 ha^{-1}, respectively. With regard to woody biomass, residuals and absolute residuals showed no tendency with site quality for the three models.

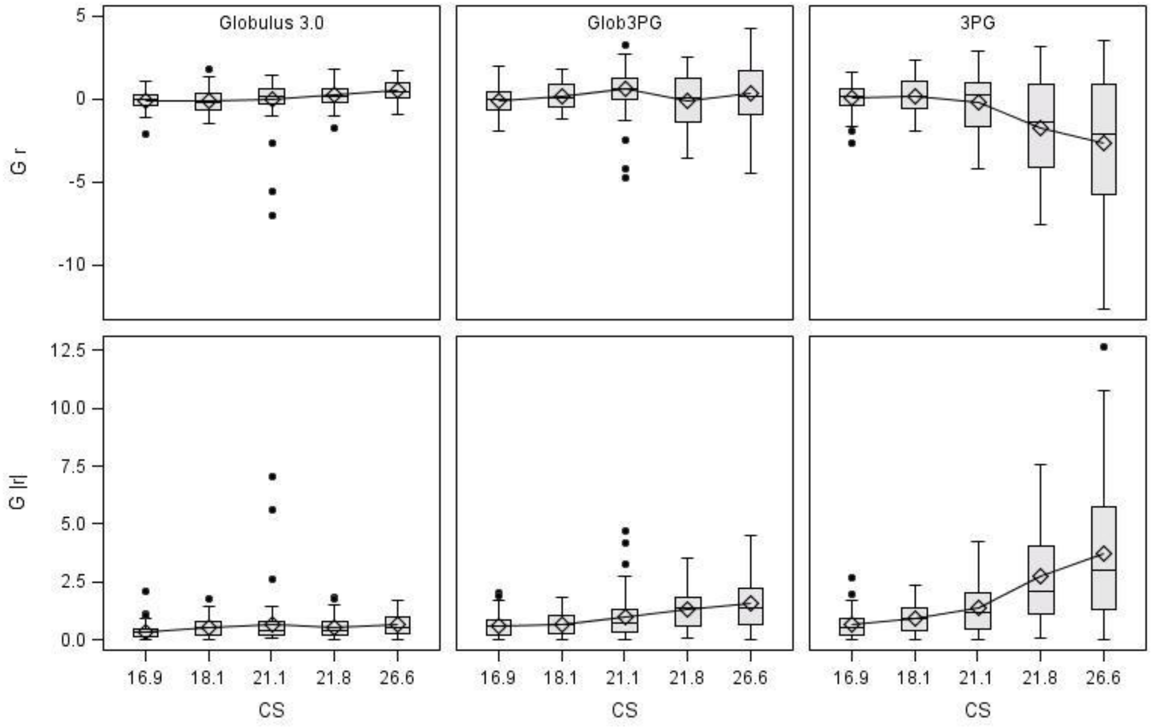


Fig. 6. Box-plots for stand basal area (m^2 ha^{-1}) residuals (G r) and absolute residuals (G |r|) by site index class (CS).

Initial age of simulation. The results agree with the ones obtained for the site index analysis, with Glob3PG benefiting from the hybridization when compared to 3PG. As for the site index analysis, the same overestimation tendency was observed for the 3PG process-based model whenever stands were initialized at older ages.

Stand location. The analysis of the stand variables by location (coastal versus inland) for the three models did not show ssubstancial differences between coastal and inland stands.

Stand rotation. The three models were compared for planted and coppice stands and graphical results confirmed what had been already shown in **Table 2**, the performance of the models is similar for both rotations showing that 3PG and Glob3PG can also be used to simulate coppice stands.

The long-term analysis made *within rotation* showed that the Globulus and Glob3PG models behaved similarly for all variables, while 3PG did not perform so well for basal area and volume. **Fig. 7** shows the results for basal area. A similar behaviour of Glob3PG and Globulus residuals was observed for dominant height, volume and biomass evidencing a soft tendency for more negatively biased and less precise estimates for projection lengths over 5 years. On the other hand, 3PG estimates for basal area and volume were consistently biased for all projection lengths and a slight tendency for increasing bias with projection length was observed for biomass.

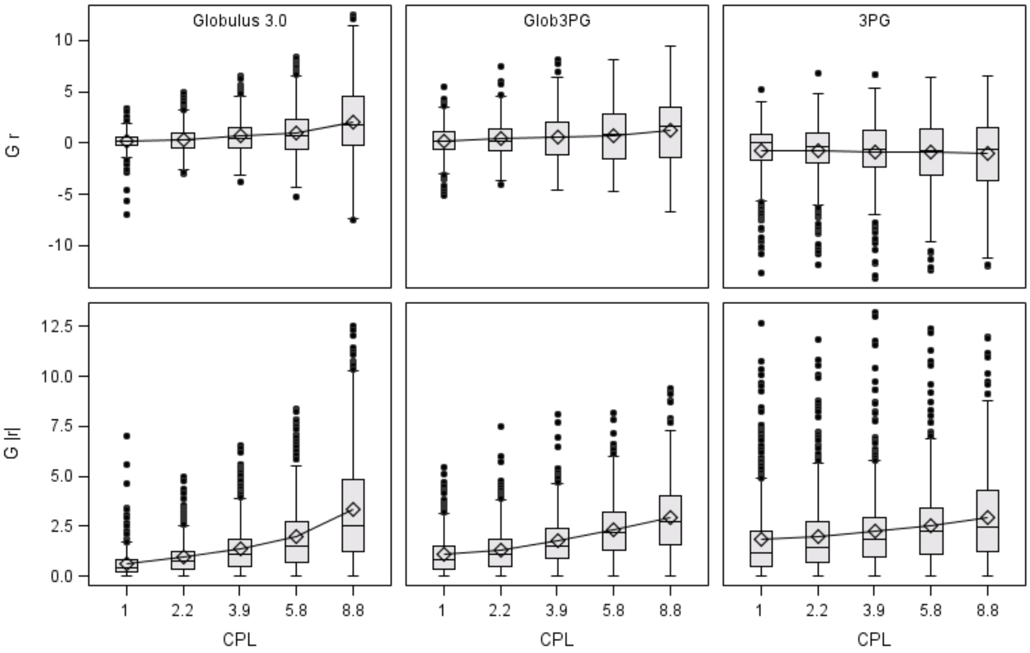


Fig. 7. Box-plots for stand basal area (m^2 ha^{-1}) residuals (G r) and absolute residuals (G |r|) for the *within rotation* long-term analysis, where CPL represents the class of projection length.

When compared to *within rotations*, the *across rotations* analysis showed a different outcome. **Fig. 8** illustrates the results for basal area. Similar results were obtained for dominant height, volume and biomass.

Globulus presented for all the variables a soft overestimation tendency for short projection lengths that evolved towards underestimation as projection length increased. With respect to Glob3PG, for dominant height the model presented an overestimation tendency that progressively decreased with the projection length interval, while for the other variables the model was unbiased, although less precise as the projection length increased. Compared to Globulus, 3PG presented for all variables a slight increase in bias for the longer projection lengths, except for biomass for which it evidenced no tendency with projection length. When compared to the process-based models, Globulus showed for all the variables big whiskers usually accompanied by outliers.

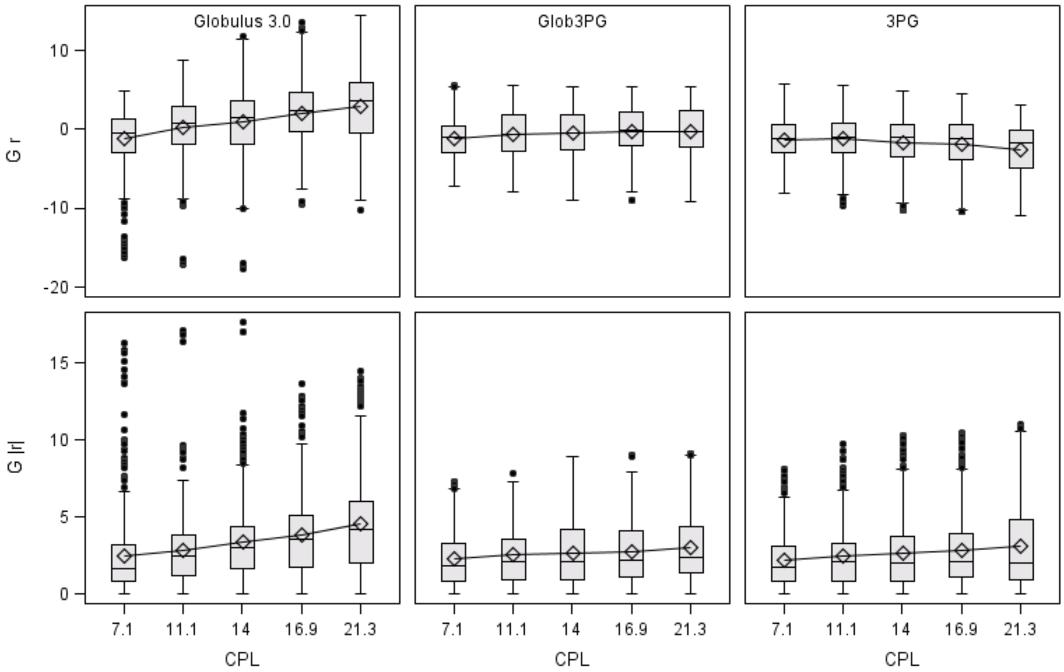


Fig. 8. Box-plots for stand basal area (m^2 ha^{-1}) residuals (G r) and absolute residuals (G |r|) for the *across rotations* long-term analysis, where CPL represents the class of projection length.

VII.5 Discussion

In this study, the Globulus 3.0 empirical model was used as benchmark in the evaluation of 3PG and Glob3PG process-based models. Empirical models, developed based on large field data sets, describe the best relationship between the measured data and the growth variables using specific mathematical functions (Peng 2000). Despite describing behaviors without trying to identify the causes, they provide biologically realistic predictions (Vanclay 1994). Nevertheless, these models have the inconvenient of being based on measurements which results in a lack of flexibility (Landsberg 2003, Landsberg and Sands 2011). Therefore, empirical models are not suitable for estimating growth under new silvicultural management treatments or climate conditions different from those observed during the period for which their measurements were made (Landsberg 2003). The limitations intrinsic to empirical models might be behind the results evidenced by the Globulus 3.0 model in this study. Because all the plots used in this study were used for fitting the model, better results would be expected in the evaluation. Notwithstanding, the model still lacks the ability to accurately simulate some of them (**Fig. 9**). This became evident after analyzing the residuals that caused the long whiskers and the outliers observed in the long-term analysis when compared to the results of the process-based models.

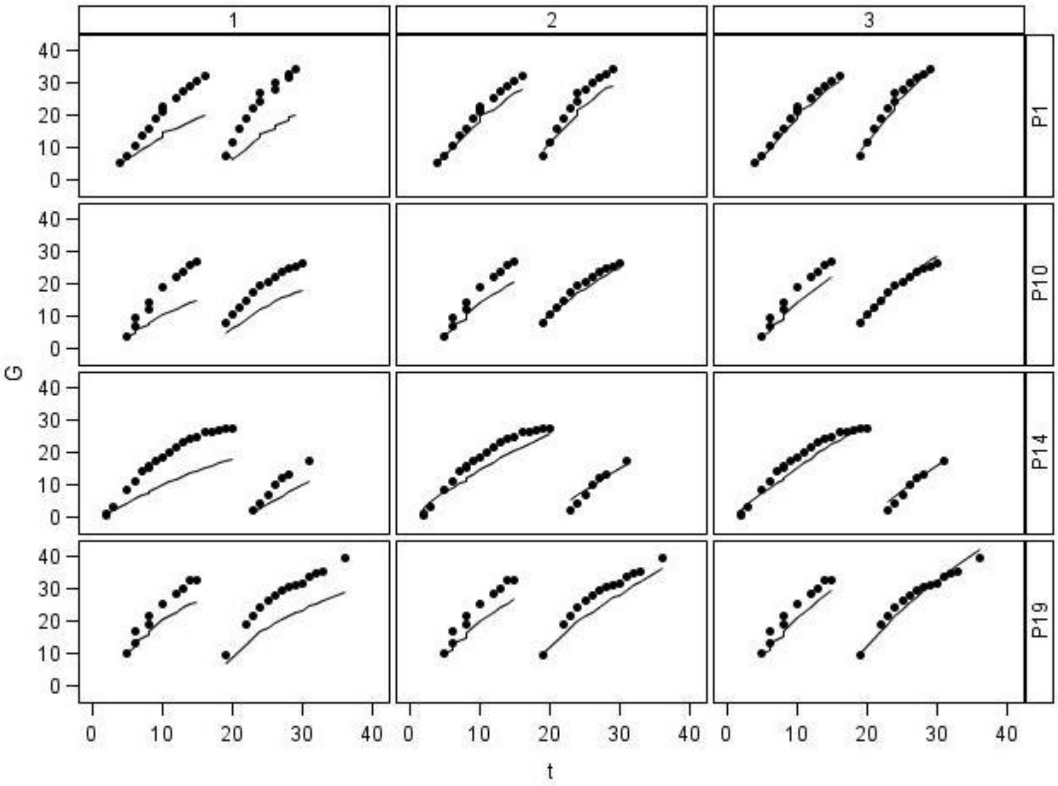


Fig. 9. Comparison of the observed and estimated values of basal area (G), obtained with 1) Globulus 3.0, 2) Glob3PG and 3) 3PG models for some plots for which the Globulus performance was not very good.

Over the years, 3PG's applicability to the Portuguese conditions has been subjected to several studies. The first, carried out by Tomé et al. (2004a), intended to assess 3PG ability to simulate the growth of *E. globulus* in Portugal and identify needs for improvement. Later on, Fontes et al. (2006) parameterised 3PG for *E. globulus* planted stands in Portugal (no coppice stands were considered). In the meantime, the empirical model was updated resulting in Globulus 3.0 version (Tomé et al. 2006). Now, with some of its parameters expressed as a function of climatic variables and a new set of aboveground biomass equations the model produces woody biomass estimates very close to the ones obtained with the process-based models. This study showed that 3PG is biased and has low precision for basal area and volume, which agrees with previous findings (Tomé et al. 2004b). Additionally, the present results show an overestimation tendency for basal area and volume that increases with site index and initial age of simulation. The results for basal area and volume could be evidencing a conceptual problem in 3PG estimates. Perhaps the methodologies used to derive volume and basal area estimates from woody biomass needed to be improved what has been done with success in the Glob3PG model.

For forest management purposes, it is a common place to consider the outputs of process-based models less detailed as the ones produced by empirical models. Thus, in an attempt to benefit from the strengths of empirical and process-based models, 3PG was hybridized with Globulus 2.1 using basal area to establish the link between the models (Tomé et al. 2004b). The results obtained with Glob3PG in this study were remarkably positive corroborating previous findings. Considerable improvements were obtained with Glob3PG by estimating volume and basal area from allometric relationships with stem biomass and aboveground biomass, respectively.

One of the most interesting results of this research was the performance of 3PG and Glob3PG for coppice stands. Despite 3PG had never been parameterized for coppices, both models showed no significant differences between planted and coppice stands which also validates the transition between rotations and the thinning of the shoots algorithms. In fact, the results from the *across-rotations* long-term analysis show that, in general terms, Globulus was more biased and less precise when compared to the process-based models.

Soil water available for plants and soil fertility are extremely important to most process-based models. Available soil water can be directly measured in the field using a calibrated neutron moisture meter (Almeida et al. 2010), estimated by analyzing a soil pit or more expeditious methods based on the fine earth fraction in collected soil samples can be applied (Domingo Santos et al. 2006). However, when the objective is integrating process-based models into a regional simulator using NFI data as input and sometimes this information is not available. The use of soil maps (for instance the European soil database) is an alternative to direct measurements. This study tried to test the effectiveness of this approach for a set of plots located in central Portugal. Despite using soil inputs derived from cartography combined with stand information, the overall results indicated a good accuracy of Glob3PG for all stand variables regardless of the rotation period considered along the simulation.

Concerning the differences between the methodology used in this study to contour the absence of soil information in NFI surveys and the methodology proposed for the integration of the models into the regional simulators a few points need to be discussed. First, the Globulus model was not used in the process of assessing soil fertility to the study plots to ensure its aptitude as a benchmark, otherwise 3PG and Glob3PG results would be dependent of the empirical model estimates. Second, all measurements were used in the process of selecting the FR that minimized the differences between the observed and estimated biomass, which represents an unreal advantage since the evaluation of the process-based models was performed for an optimal situation. However, when integrated in the regional simulator, soil fertility will be not only determined based on Globulus estimates as it will also be based on a single measurement age, 10-years, maybe with some influence on the reliability of the prediction which need to be further studied.

The overall results confirm previous findings: process-based models, when conveniently linked to empirical models, can produce as accurate estimates for forest managers as empirical models (Tomé et al. 2004b). According to our results, this holds true, even if using soil maps information combined with stand measurements as input.

VII.6 Conclusions

Growth models and simulators are essential tools in decision making processes. The accuracy of the models integrated into regional simulators is reflected in the quality of its forecasts. With the objective of making long-term large-scale forecasts sensitive to climate and management changes, 3PG and Glob3PG models performances were tested with data from existing permanent plots that had been part of the dataset used to fit the Globulus model.

The accuracy of the models was analyzed for the short- and long-term. Results showed that Glob3PG model behaved similarly to the empirical model with modelling efficiencies higher than 95%. In the long-term, Glob3PG proved to be unbiased and slightly less precise as the projection length increased. With respect to 3PG, basal area and volume estimates were biased and less precise, particularly for volume. Moreover, 3PG residuals showed a tendency for an increasing bias and loss of precision for the higher site qualities, initial ages of simulation and stand densities, less evident for the latest. At the same time, 3PG was slightly biased for longer projection lengths.

Furthermore, no clear differences were observed in the performances of any of the models for planted and coppice stands and the stand rotation at which each simulation was initiated did not compromise the results. This is a very important conclusion because confirms the ability of the models to simulate the transition between rotations as well as the thinning of the shoots.

In general terms, the comparison between simulation results seems to indicate that the use of soil information derived from soil maps as input did not compromised simulation results. It would be preferable that the NFI would gather more information on soils. However, using soil maps information combined with stand measurements makes possible to use the 3PG or Glob3PG models in regional simulators.

VII. 7 Literature Cited

Almeida, A.C, Siggins A., Batista, T.R., Beadle, C., Fonseca S., Loos, R., 2010. Mapping the effect of spatial and temporal variation in climate and soils on Eucalyptus plantation production with 3-PG, a process-based growth model. Forest Ecology and Management, **259**: 1730–1740.

Autoridade Florestal Nacional (AFN), 2010. Inventário Florestal Nacional. IFN 2005-2006. Portugal Continental. Autoridade Florestal Nacional, Ministério da Agricultura do Desenvolvimento Rural e das Pescas, Lisbon, Portugal.

Amaro, A., 2003. SOP model. The SOP Model: the Parameter Estimation Alternatives. In: Amaro, A., Reed, D., Soares, P. (Eds.), Modelling Forest Systems. CABI Publishing, USA.

Amaro, A., Reed, D., Tomé, M., Themido, I., 1998. Modeling Dominant Height Growth: Eucalyptus Plantations in Portugal. Forest Science, **44** (1): 37-46

Barreiro, S., Tomé, M., 2011. SIMPLOT: Simulating the impacts of fire severity on sustainability of eucalyptus forests in Portugal. Ecological Indicators, **11**: 36–45.

Barreiro, S., Tomé, M., Tomé , J., 2004. Modeling growth of unknown age even-aged eucalyptus stands. In: Hasenauer, H., Makela, A. (Eds.), Modeling Forest Production. Scientific Tools - Data Needs and Sources. Validation and Application. Proceedings of the International Conference, Wien, pp. 34-43.

Domingo Santos, J.M. , Fernández de Villarán San Juan, R., Corral Pazos de Provens, E., Rapp Arrarás, Í., 2006. Estimación de la capacidad de retención de agua en el suelo: revisión del parámetro CRA. Investigacion Agrária: Sistemas Recursos Forestales, **15**(1): 14-23.

European Commission (EU), 2004. The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004.

Fontes, L., Landsberg, J.J., Tomé, J., Tomé, M., Pacheco, C.A., Soares, P., Araújo, C., 2006. Calibration and testing of a generalized process-based model for use in Portuguese eucalyptus plantations. Canadian Journal of Forest Research, **36**: 3209-3221.

King, D., Le Bas, C., Daroussin, J., Thomasson, A.J., Jones, R.J.A., 1995. The EU map of soil water available for plants. In: King, D., Jones, R.J.A., Thomasson, A.J. (Eds.). European Land Information Systems for Agroenvironmental Monitoring. EUR 16232 EN, Office for Official Publications of the European Communities, Luxembourg. pp. 131-142.

Landsberg, J., Sands, P., 2011. Physiological Ecology of Forest Production. Principles, Processes and Models. Volume 4 in the Academic Press. Terrestrial Ecology Series. pp 331.

Landsberg, J., 2003. Modelling forest ecosystems:state of the art, challenges, and the future directions. Canadian Journal of Forest Research, **26**: 1174-1186.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency. Carbon balance and partitioning. Forest Ecology and Management, **95**: 209-228.

Peng, C., 2000. Growth and yield models for uneven-aged stands: past, present and future. Forest Ecology and Management, **132**: 259-279.

Sands, P., 2004. Adaptation of 3PG to novel species: guidelines for data collection and parameter assignment. Technical Report 141. Cooperative Research Centre for Sustainable Production Forestry and CSIRO.

Sands, P., Landesberg J.J., 2002. Parameterisation of 3PG for plantation grown *Eucalyptus globulus*. Forest Ecology and Management, **163**: 273-292.

Soares P., Tomé, M., 2003. GLOBTREE: an Individual Tree Growth Model for Eucalpytus globulus in Portugal. In: Amaro, A., Reed, D., Soares, P. (Eds.), Modelling Forest Systems. CAB International, pp. 97-110.

Soares, P. Tomé, M., Skovsgaard, J.P., Vanclay, J.K., 1995. Evaluating a growth model for forest management using continuous forest inventory data. Forest Ecology and Management, **71**: 251-265

Thomasson A.J., 1995. Assessment of soil water reserves available for plants (SWAP): a review. In: King D., Jones R.J.A., Thomasson A.J. (Eds.), European Land Information Systems for Agro-environmental monitoring,. CEC, Luxembourg. pp 286.

Tomé, M., Soares P., Oliveira, T., 2006. O modelo GLOBULUS 3.0. Dados e equações. Publicações GIMREF RC2/2006. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.

Tomé, J., Tomé, M., Fontes, L., Soares, P., Pacheco, C.A., Araújo, C., 2004a. Testing 3PG with irrigated and fertilized plots established in *Eucalyptus globulus* plantations in Portugal. In: Hasenauer, H., Makela, A. (Eds.), Modeling forest production. Scientific tools - data needs and sources. Validation and Application. Proceedings of the International Conference, Wien, pp. 382-390.

Tomé, M., Faias, S.P., Tomé, J., Cortiçada, A., Soares, P., Araújo, C., 2004b. Hybridizing a stand level process-based model with growth and yield models for *Eucalyptus globulus* plantations in Portugal. In: Borralho, N.M.G., Pereira, J.S., Marques, C., Coutinho, J., Madeira, M., Tomé, M. (Eds.), Eucalyptus in a changing world. Proceedings of the IUFRO International Conference, Aveiro, pp. 290-297.

Tomé, M., Borges, J.G., Falcão, A., 2001a. The use of Management-Oriented Growth and Yield Models to Assess and Model Forest Wood Sustainability. A case study for Eucalyptus Plantations in Portugal. In: Carnus, J.M., Denwar, R., Loustau, D., Tomé, M., Orazio, C. (Eds.), Models for Sustainable Management of Temperate Plantation Forests, European Forest Institute, Joensuu, pp. 81-94.

Tomé, M., Ribeiro, F., Soares, P., 2001b. O modelo Globulus 2.1. Departamento de Engª. Florestal. Instituto Superior de Agronomia. Universidade Técnica de Lisboa. Lisboa. Portugal.

Tomé, M., Ribeiro, F., 2000. GLOBULUS 2.0, um modelo de aplicação nacional para a simulação da produção e crescimento do eucalipto em Portugal. Relatórios técnico-científicos do GIMREF nº 1/2000, Centro de Estudos Florestais, Instituto Superior de Agronomia, Lisboa, Portugal.

Tomé, M., Soares, P., 1999. A Comparative Evaluation of Three Growth Models for Eucalypt Plantation Management in Coastal Portugal. In: Amaro, A., Tomé, M. (Eds), Empirical and Process-Based Models for Forest Tree and Stand Growth Simulation, Edições Salamandra, Novas Tecnologias, Lisboa, Portugal, pp. 517-533.

Vanclay, J.K., 1994. Modelling Forest Growth and Yield - Applications to Mixed Tropical Forests. CAB International, Oxon, UK.

Vanclay, J.K., Skovsgaard, J.P. 1997. Evaluating forest growth models. Ecological Modelling, **98**(1): 1-12

CHAPTER VIII

Final remarks

Final Remarks

VIII.1 Contribution of this research to the forest sector

There is little point in developing growth models unless they are to be used. Thus models should provide information required for forest management, in a form useful to forest managers and decision makers (Vanclay 1994). This does not necessarily mean that all simulation results should be directly used, but they can surely serve as guidelines when exploring alternatives, evaluating the consequences of specific actions or evaluating the system's sensitivity to a certain disturbance (Landsberg 2003). Modern forestry, besides requiring accurate growth prediction instruments, has to be able to give response to the different demands from the public, the effects of regional disturbance factors and new management practices while accounting for the consequences of climate change. Such complex responses can only be provided by elaborated computerized tools (Pretzsch et al. 2002).

The development of the forest simulation tools presented in the previous chapters of this manuscript resulted from the need to develop simulators integrating several and more updated versions of the available *E. globulus* growth models in Portugal and implementing it into user-friendly interfaces. The main objective of this work was to design a more ambitious tool capable of long-term large-scale simulations accounting for disturbance factors, which cannot be achieved with the management unit level tools available by the time this research work was initiated.

It is common to find some confusion between growth model and simulator in literature. Those terms were defined under the scope of COST Action FP0603 (Tomé et al. 2007). A growth model is a dynamic representation of the forest and of the forest behavior. Growth models are based on a set of sub-models or modules that as a whole determine forest behavior, according to the values of a set of state variables as well as the forest responses to changes in the driving variables. On the other hand, a forest simulator is a computer tool that, based on a set of forest models, makes long-term predictions of the status of a forest under a certain scenario of climate, forest policy and management. Forest simulators usually predict wood and non-wood products from the forest, at each point in time.

This manuscript describes the work involved in the development of forest simulation tools for eucalyptus in Portugal. A regional simulator integrating a set of empirical growth models and two stand/forest simulators, one integrating empirical growth models and the other based on the process-based models 3PG and Glob3PG were created. The three simulators were integrated into a common user-friendly interface, sIMfLOR.

VIII.1.1 Regional level simulator

SIMPLOT, described in detail in **Chapters III** and **IV**, has been conceived to simulate the development of all the eucalyptus stands in a region, providing as output several forest characteristics and sustainability indicators while taking into account the influence of a certain number of drivers. The potential users of this decision support tool are the pulp and paper industries and other industries using forest residues, politicians at local and regional governments as well as universities and research institutions.

SIMPLOT has been used for assessing the effects of fire occurrence in Eucalyptus forests and for analyzing the consequences of concurrent uses of eucalyptus wood, such as bio-energy. This long-term simulator permits to conduct a wide range of analysis, such as testing the impacts of applying different distributions of harvesting probabilities, alternative options of residues removals resulting from harvesting or thinning operations as well as alternative combinations of planted areas along the simulation period. The analysis performed using SIMPLOT led to interesting conclusions, namely that fire occurrence has an immediate effect on carbon sequestration, while a more durable effect is registered for carbon stocks. The more severe and numerous the wildfires are the more difficult will be to recover carbon stocks in the forest (**Chapter III**). Another interesting conclusion resulted from a different study where the consequence of using eucalyptus biomass for energy on wood available for pulp was tested. Projections considering a scenario reflecting historical management indicated that the Portuguese forests are being overharvested in comparison to increment. Moreover, under this scenario, forests proved to be unable to satisfy wood demand even when pulp afforestation areas were increased to a reasonable level (**Chapter IV**).

Projections obtained from running regional simulators are often used by forest managers and policy makers to assist and support their decision making process. As the potential application of forest simulators is intimately related to how accurate these tools are when compared to reality, it is essential to evaluate them, assessing the validity and logic relations between its different modules. In the course of validation, results showed that

SIMPLOT is able of making reliable large-scale projections for standing volume. The results for the distribution of forest areas by age classes were reasonable for all stand types except uneven-aged stands. This conclusion was important because it evidenced the need for an algorithm to simulate the transition between even and uneven-aged stands (**Chapter V**).

VIII.1.2 Stand level simulators

In order to conduct the work documented in **Chapter VII**, two forest level simulators were developed. In the referred chapter, these tools were only briefly described therefore a more detailed description is presented in this section.

GLOBULUS and 3PG-Out+ stand level simulators allow assessing the impacts of different forest management approaches. GLOBULUS stand level simulator was conceived to simulate either new stands (creating a yield table) or existing stands (a single or several stands) considering forest management as its only driver. On its turn, 3PG-out+ stand simulator has been created to simulate the evolution of stands managed according to different forest management alternatives under different climatic scenarios. 3PG-out+ can be run for one or several stands under different management regimes over the planning horizon. Climate change impacts can be assessed comparing different climate scenarios. Unless the user has a particular interest in a specific event (e.g. droughts) or evaluating the impact of climate change, the normal option will be running the simulator using monthly averages of the climate variables, although it can also use monthly weather (Sands 2004).

GLOBULUS stand level simulator integrates the Globulus empirical growth model that was conceived to project the growth of pure even-aged eucalyptus stands. The last version of the model, Globulus 3.0 (Tomé et al. 2006), includes some novelties: the use of climatic variables to express differences in growth among regions in a gradual way (Globulus 2.1 model used a categorical variable for the 8 climatic regions considered), the possibility of simulating the transition between rotations and the inclusion of improved stand level biomass equations. The growth model includes several sub-models or modules for the simulation of the state variables. The principal state variables include initialization and projection. The simulator predicts the transition between rotations, including the growth of coppice stands before and after the shoots selection operation. Because the growth model has some growth parameters expressed as a function of climatic variables, a climate input file containing the average values for the meteorological stations closer to the stand is also required.

3PG-out+ stand simulator has been developed to simulate the evolution of stands managed according to different forest management alternatives under different climatic scenarios. Growth projections are based on the Portuguese parameterization of 3PG process-based model (Fontes et al. 2006). 3PG is composed of a set of sub-models or modules for predicting: biomass production, biomass allocation, stem mortality, soil water balance and stand characteristics. This simulator allows selecting one of two modelling variants of 3PG growth model: 3PG or Glob3PG. Compared to GLOBULUS, this simulator requires more detailed information in terms of input, namely on soil and site characteristics. In 3PG-out+, growth is driven by intercepted radiation, resulting in distinct routines integrated in the initialization and in the projection modules. The initialization module is responsible for initializing new stands and predicting the variables that will serve as input to the growth module. Stand level variables estimation will depend on the selected variant of the growth. A detailed description of 3PG growth modules is presented elsewhere (see Sands 2004).

Both simulators were programmed to allow applying a different management to the different stands. This flexibility is extended to the management practiced for the same stand along the different rotation cycles throughout the planning horizon. The set of silvicultural operations is selected by picking out of a vast list of operations the ones that make up the management approach and then determining when in time and how often they occur. A set of simulation parameters is required to run the simulators; namely, rotation length (age for harvesting), starting density, beating up (%) and the age at which it occurs, the number of shoots left per stool and the age at which this selection is made and the number of rotations. 3PG-out+ requires extra inputs: model variants (3PG or Glob3PG), type of weather data (annual values or monthly averages per year).

Despite the differences, the two simulators run basically in the same way. After all inputs have been imported, the growth module computes the derived variables for the base year of simulation. At this point, all stand variables for the base year will be used as input by the projection module until the simulation period ends or harvesting age is reached. If a stand is harvested before the planning horizon is met the next rotation is initialized or a new stand is planted according to the prescription in the management defined for each rotation cycle until the planning horizon is met (*see section VIII.3*).

The integration of 3PG and Glob3PG process-based models into a regional simulator had two major limitations: it required detailed soil input information not available from the NFI surveys and it had to simulate coppice stands for which it was neither developed nor parameterized. The study conducted to assess these models applicability at a regional scale allowed concluding that using soil maps information combined with stand measurements allow the use of 3PG and Glob3PG models in regional simulators. Furthermore, the study also showed that the quality of the predictions obtained for coppice stands were no worse than the quality achieved for planted stands (**Chapter VII**).

VIII.2 Data needs and sources

VIII.2.1 National forest inventory data

Across Europe, the main purpose of National Forest Inventory (NFI) varies from providing accurate information to forest management and forest industry investment planning, to monitoring the sustainable use of forests. The changing roles of forests have substantially altered demands for forest information. Initially focusing mainly on timber supply, forest health emerged when acid depositions lead to declines of local forests. In urbanized societies, over the recent years, the role of forests in producing non-wood products and services like wildlife habitats, recreational and protective possibilities has become more interesting; while, at the same time, monitoring forest sustainability became more common. At present, in addition to timber information, most NFIs embrace a multitude of outputs including ground vegetation, biodiversity, deadwood and soil information. The increasing use of fossil fuels combined with deforestation and farming raised CO_2 and other greenhouse gas emissions creating new expectations for both forests and forest inventories (Tomppo et al. 2010). Portugal has tried to keep up with the tendencies, but a number of aspects have yet to be improved so national forest inventories' can represent the status of forests at a national and sub-national scale by providing trustworthy information.

"*Inventory serves many purposes, but different procedures are required to satisfy various needs of different data users in an efficient way*" (Vanclay 1994). In the same manner, the data needed to develop; test and use models and simulators are of different nature. By the time SIMPLOT started being programmed, the data from NFI5, the last national survey, were still being processed. Despite results were made available during this research, the NFI4 dataset was maintained throughout the study for two reasons: first, the inadequate estimation of eucalyptus stand age in NFI5 and second because, by doing so, these results could be used to validate the simulation results of SIMPLOT.

In the course of building SIMPLOT, one of the first steps was learning about the dataset used as input. To better understand NFI4 outputs the NFI database was analyzed and the measurement procedures and protocols for each variable were studied. A bibliographic research was conducted resulting in an historical overview of the evolution of the Portuguese NFIs with a more detailed description of the last two national surveys (Barreiro et al. 2010). Out of the national set of variables and measurements resulting from NFI, SIMPLOT requires qualitative variables such as land use, stand type, tree species composition and stand structure, apart from the quantitative ones. The use of both types of information allowed detecting some inconsistencies in reporting mainly due to the inadequate documentation describing procedures and techniques, but also to, what is believed to be, the light training of field crews.

So far, NFI data collection was not planned to serve as input to regional simulators, thus some adjustments can be expected. However, the discrepancies found in reporting compromise all purpose NFI uses, and consequently its credibility. Some modelers say that it might take years before a modeler can gather the ideal data to develop a model (Vanclay 1994). For this reason, most modeling attempts often start with the data sets available at the time. In the process of developing SIMPLOT, a similar situation was experienced. The long list of errors led to time-consuming cross-checks followed by data harmonization and correction, sometimes supported by expert guessing, before NFI4 and NFI5 data could be used to run and validate SIMPLOT, respectively. Inconsistent information is an important problem to NFI based simulators, whose functioning is set on rules defined based on the knowledge provided by the NFI plots representing major drawback in the process of developing such a tool.

Despite the inconsistencies, most of required information to run SIMPLOT can be provided by the Portuguese NFI. Nevertheless, the same is not true when it comes to stand/forest level simulators like 3PG-out+ that requires soil inputs which so far are not collected by the Portuguese NFI.

Quality reporting should be secured by consistent measurement procedures, extensive crew training and independent checks. The existence of a complete and consistent field manual is decisive for quality data collection. The inconsistencies found in the course of this research highlighted the need for the field manual to comprise clear descriptions of

NFI concepts such as the definition of tree, forest, even-and uneven-aged forest, pure and mixed forest, gaps and clumps.

The most common problem derived from the inexistence of instructions concerning stands in transitory conditions such as young, burnt and harvested stands; which was aggravated when several of these conditions occurred simultaneously. For instance, according to the field manual, there is no young stand class so stands had to be classified as mature. However, in some plots, being all trees under the diameter threshold no trees were measured, which originated *empty* plots, impossible to be used as input in a simulator. Young trees are simply counted in 5 circular satellite plots, in a total area of 50 m^2, which is totally inappropriate to evaluate plantations, such as eucalyptus. The methodology applied to assess young trees was in fact conceived to evaluate natural regeneration; therefore an all-embracing method ensuring that all trees were counted and an average tree height estimated should be proposed for plantations. To reduce data collection efforts increased by the resprouting ability of coppices, a suggestion is that only one out of 5 stools (or some other number) should be evaluated or the plot area reduced. The information on stand regeneration should also be complemented with details about the regeneration method: natural regeneration, plantation, seeding or coppice.

Concerning harvested stands, two situations were found: stand age prior to harvest imputed to the harvested stand when it should have been zero and harvested stands that were not classified as such but to which the age of zero was ascribed. These kinds of errors could be easily avoided by an alert displayed in the data collection software. Moreover, stumps were not measured by some field crews because the field manual was remiss. Considering that it is not mandatory to report harvest to Portuguese official entities, stump measurements could be used to develop models to predict the volume of harvested trees.

Gaps and clumps also caused some confusion. A sample plot should be a gap if and only if no trees of any species were inside the plot. Unfortunately, there were several gaps containing measured trees. Likewise, the concept of clump was often misunderstood, with plots defined as clumps while having the same composition (and structure) as the surrounding stratum. The inverse was also found. Furthermore, it was quite common for sampled plots to be classified as pure stands of a given species, while containing several different species in a high proportion.

Stand structure, in particular the classification of stands as uneven-aged, was also an issue. The considerable increase of this type of stands in NFI5 suggested that field crews classified stands as uneven-aged as long as some trees were found below or above the average canopy level. It would be beneficial to create an extra class for even-aged stands with some trees of a different age. Moreover, field crews have proved to be unable to provide accurate stand age estimates. As NFIs are only repeated every 10 years, remote sensing techniques, such as satellite images, could be used to assess stand age by determining when the stand was last harvested.

The Portuguese NFI data collection is structured in 3 levels of observations: stand-level observations including the characterization of stand type, stand structure, tree species composition, management regime and recent silvicultural operations; plot-level observations, comprising most of the previous level evaluations plus additional information on accessibility, topography, hazards occurrence, and natural regeneration and biodiversity assessments; and finally, tree-level observations that comprehend tree measurements and classification in terms of form, condition and health.

In the field manual, the description of procedures to be accounted for under each of the 3 levels needs to be presented and described in a complete and clear way anticipating difficulties and emphasizing common mistakes. However, despite a clear and organized field manual will reduce inconsistencies, it will not solve all the problems. Field crews should receive more than one week training, being tested afterwards and certified for their ability to satisfy the NFI requirements. Additional on-the-job training can be provided, if new crew members are paired with experienced crew members. Portable data recorders programmed with data checks and alert messages whenever data are illogical or outside standards should be tested and validated before the field season is initiated; and as soon as transmitted to the office, further checks should be made. These can be complemented by on-time inspections of the crew’s performance, re-measurement of some plots by experienced crews with access to the original crew data and/or blind-checks by independent crews without the original crew data (McRoberts et al. 2010).

VIII.2.2 Scenario data sources

The decisions about how, when and where to take specific actions are usually based on what is expected for the future. A scenario is a description of a possible future and SIMPLOT gives the users the ability to use contrasting scenarios to explore the future consequences of a decision. Scenarios are expressed, for each year, in terms of changes in the total amounts of the drivers: wood and biomass demands, area expected to be burnt, and land use changes. When simulations intent to represent the past evolution of forests up to the present it is likely, and desirable, to find the total amount of the drivers published in the official statistics, for instance: amount of m^3 of wood consumed and burned, newly planted and abandoned areas. On the other hand, when simulating into the future the direct use of statistics is no longer possible. Under these circumstances, scenarios should be preferably built by a diverse group of people. In such cases, scenarios can be based on percent variations (market demands) of a given value or simulated based on historic data analysis (fire occurrence).

Concerning official statistics, in some cases various sources are available, most times providing contradictory figures; while in other situations, a complete absence of information is find, the solution being using expert guesses. The use of SIMPLOT evidenced how statistical information concerning the forest sector is difficult to obtain.

VIII.3 Forest management

Many classifications of silvicultural systems can be found in the literature and it is difficult to set limits to the high number of various sets of treatments that can be considered. For Matthews (1989), the concept of silvicultural system is based on how the tree canopy is removed and on the regeneration pattern. According to this classification, *E. globulus* is managed as a 'Clear-cutting system' for first rotations and as a 'Coppice system' for the subsequent ones. In this manuscript, an alternative classification was used based on the framework presented in **Chapter II**. Accordingly, two forest management approaches (FMA) were considered for this species: 'Intensive even-aged forestry' and 'short-rotation forestry', designated throughout the manuscript as Wood Production and Bioenergy Production forests, respectively. Wood Production forests refer to plantations that are mainly used by the pulp and paper industry. These stands are managed as a planted stand followed by coppice rotations with an average cutting cycle of 10-12 years and a thinning carried out in coppice stands around the age of 3 to eliminate some of the shoots. After the second coppice the stand is usually replanted. Bioenergy Production forests represent highly stocked areas (around 5000 trees ha^{-1}) managed to maximize the biomass production potential of eucalyptus stands to be used for energy. At present, these stands are hypothetical and their management described by 5 consecutive 5-years rotation cycles with no thinning of the shoots. The above describe variables can be considered as management driving variables, however for the same FMA different sets of silvicultural operations (FMA options) can be carried out. In order to be able to simulate the growth of bioenergy Production forests a new model was developed, GlobEP (**Chapter VI**).

SIMPLOT gives the user the possibility to run plots under different FMAs provided that all plots of the same FMA are simulated according to the driving variables defined for that specific FMA. On the other hand, a greater flexibility is granted to stand/forest simulators for which it is possible to prescribe a sequence of different FMA/options combinations to be applied throughout the planning horizon. Thus, an FMA can be defined as the set of silvicultural operations performed from regeneration to the final cut, while a prescription is the combination of different, or not, FMA/options carried out until the end of simulation. Therefore, the prescription allows for a greater flexibility by changing between options under the same FMA, changing to a different FMA, changing the species, rotation length, the number of coppice stands that follow a plantation from one rotation cycle to another until the end of the simulation period. At present, this flexibility is only permitted for the stand level simulators.

VIII.4 Sustainability indicators

Forest management affects the status and dynamics of the ecosystem affecting derived goods and services. For this reason, FMAs have implications on all dimensions of sustainability: social, environmental and economical. Under the scope of the EFORWOOD project a list of social, economic and environmental indicators was compiled. Out of this list, a smaller subset was chosen to integrate SIMPLOT. Those indicators are described in the next points.

At the economic level, production costs from inside and from outside the Forestry Wood Chain (FWC), labour costs as well as total production costs are calculated in the regional simulator. Production costs from inside the FWC are defined as the cost of any wood raw material proceeding from FWC processes, such as, for instance, plants used for planting. On the other hand, production costs from outside the FWC include fertilizers, plastic tree protectors, etc. Labor costs are the costs of remunerating workers for the work performed in a silvicultural operation. It includes: payments for the time paid for but not worked, bonuses and gratuities, the cost of food, drink and other payments in kind, cost of workers’ housing borne by employers, employers’ social security expenditures, etc. Total costs result from summing up the previous costs. The input data to calculate the indicators derives from the consumable costs and the costs of the silvicultural operations listed in the Portuguese statistics (CAOF 2010). This information combined with the FMA descriptions listing the operations that occur allows calculating materials and labor costs.

At the social level wages and salaries were considered. This indicator reflects the gross earnings classified by gender and expertise. Wages and salaries are the rates paid for normal time of work, comprising: basic wages and salaries, cost-of-living allowances and other guaranteed and regularly paid allowances. Overtime payments, bonuses and gratuities, family allowances, other social security payments made by the employer directly to employees are disregarded.

The group of environmental indicators is the most complete one providing information on forest resources (standing volume, harvested volume and biomass), GHG balance (carbon stock, carbon sequestration and carbon sequestered in forest products) and forest areas (by age classes, new planted area, abandoned area, burnt area and so on). Unlike the indicators in the previous classes, which depend on statistics to be calculated, the evolution of environmental indicators depends on the evolution of forests simulated with SIMPLOT.

VIII.5 Future Perspectives

Regional simulators are ever-improvable tools. SIMPLOT can be used to gain insight into the future development of the Portuguese eucalyptus forest. Its functioning is based on several empirical growth models, on a set of implicit assumptions and on a series of programming algorithms responsible for implementing the drivers expressing disturbance factors. SIMPLOT was designed to be applicable to all types of stands and its reliability has been corroborated. However, a number of future improvements can be proposed to amend the accuracy of results either in terms of growth models or of improvements required on the drivers' modules:

- Improve SIMPLOT growth projections for highly stocked stands by replacing the correction factors currently applied to Globulus 3.0 model with GlobEP model developed to simulate the growth of these stands
- Implement GLOB3PG process-based model to allow making long-term projections under different climate scenarios

- Integrate tree level models to allow simulating all types of stands *per si* avoiding the simplification of converting mixed stands into pure stands
- Develop an algorithm to accomplish a realistic transition of even- to uneven-aged stands so that the area of uneven-aged stands will be more accurately estimated (at present under-estimated).
- Conduct SIMPLOT validation for the long-term.
- Perform a complete sensitivity analysis to better understand the relative importance of the different simulation parameters.
- Integrate the use of remote sensing data to implement in a more accurate way some of the drivers, such as afforestation and deforestation
- Spacialize the fire algorithm

VIII.6 Literature Cited

Barreiro, S., Godinho, P. F., Azevedo. A., 2010. National Forest Inventories reports: Portugal. In: Tomppo, E., Gschwantner, Th., Lawrence, M., McRoberts, R.E. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, New York, US. pp. 437-464.

Comissão de Acompanhamento das Operações Florestais (CAOF), 2010. Matriz de Referência com Custos Minimos e Maximos para as Principais Operações (Re)Arborização e Execução de Infraestruturas para 2010. ANEFA.
[online] URL: http://www.anefa.pt/servicos/representatividade.html

Fontes, L., Landsberg, J.J., Tomé, J., Tomé, M., Pacheco, C.A., Soares, P., Araújo, C., 2006. Calibration and testing of a generalized process-based model for use in Portuguese eucalyptus plantations. Canadian Journal of Forest Research, 36: 3209-3221.

Matthews, J.D., 1999. Silvicultural Systems. Oxford University Press.

Landsberg, J., 2003a. Modelling forest ecosystems: state of the art, challenges, and the future directions. Canadian Journal of Forest Research, 26: 1174-1186.

McRoberts, R.E., Hansen, M.H., Smith, W.B., 2010. National Forest Inventories reports: United States of America. Pages: 567-581 in: Tomppo, E., Gschwantner, Th., Lawrence, M., McRoberts, R. E. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, New York, US.

Pretzsch, H., Biber, J., Ďurskỷ, K., Gadow, K. Von, Hasenauer, H., Kändler, G., Kenk, G., Kublin, E., Nagel, J., Pukkala, T., Skovsgaard, J. P., Sodtke, R., and Sterba, H. 2002. Recommendations for Standardized Documentation and Further Development of Forest Growth Simulators. Forstw. Cbl, **121**: 138-151.

Sands, P., 2004. Adaptation of 3PG to novel species: guidelines for data collection and parameter assignment. Technical Report 141. Cooperative Research Centre for Sustainable Production Forestry and CSIRO.

Tomé, M., Coelho, B.C., Meredieu, C., Cucchi, V., 2007. Framework for the description of forest modelling tools currently available with identification of their ability to estimate sustainability indicators. Deliverable 2.5.2 from the EFORWOOD Project.
[online] URL: http://87.192.2.62/eforwood/Partnersonly/Module2/WP21SustainableForestManagementStrategies/tabid/156/Default.aspx

Tomé, M., Soares P., Oliveira, T., 2006. O modelo GLOBULUS 3.0. Dados e equações. Publicações GIMREF RC2/2006. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.

Tompo, E., Schadauer, K., McRoberts, R.E., Gschwantner, T., Gabler, K., Stahl, G., 2010. National Forest Inventories reports: Introduction. In: Tomppo, E., Gschwantner, Th., Lawrence, M., McRoberts, R.E. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, New York, US. pp. 1-18.

Vanclay, J.K., 1994. Modelling Forest Growth and Yield - Applications to Mixed Tropical Forests. CAB International, Oxon, UK.