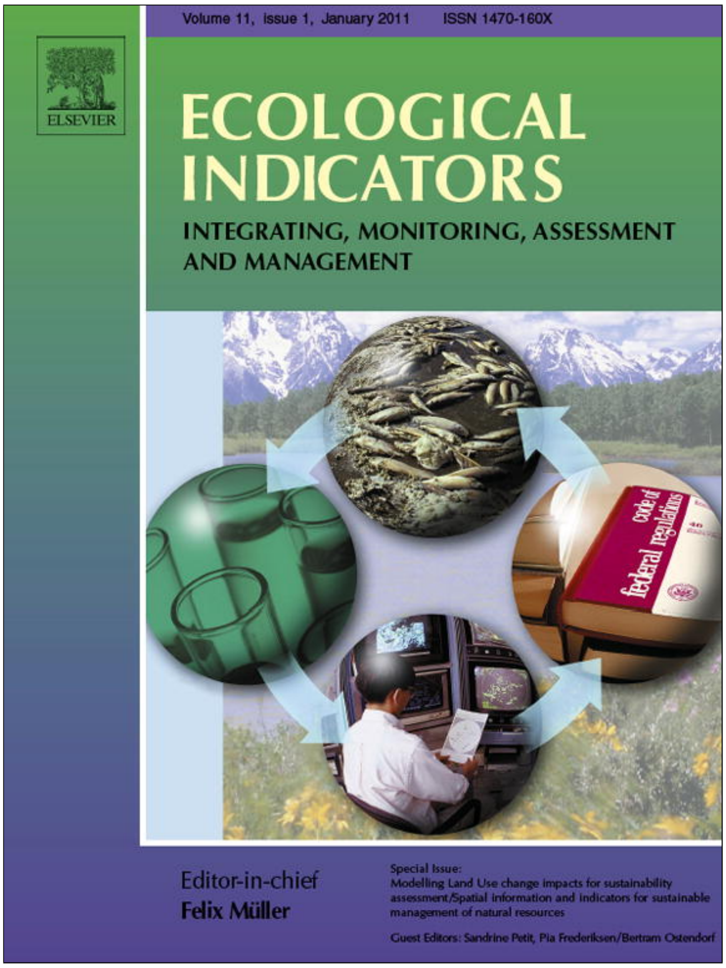
Volume 11, Issue 1, January 2011 ISSN 1470-160X
ELSEVIER
ECOLOGICAL INDICATORS
INTEGRATING, MONITORING, ASSESSMENT AND MANAGEMENT
code of federal regulations
Editor-in-chief
Felix Müller
Special Issue:
Modelling Land Use change impacts for sustainability assessment/Spatial information and indicators for sustainable management of natural resources
Guest Editors: Sandrine Petit, Pia Frederiksen/Bertram Ostendorf

Ecological Indicators 11 (2011) 36–45

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

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

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ARTICLE INFO

Article history:
Received 3 October 2008
Received in revised form 22 June 2009
Accepted 22 June 2009

Keywords:
Regional simulator
Eucalyptus
Carbon
Wood demand
Fire

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 and at long-term 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.

1. 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 in 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).

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doi:10.1016/j.ecolind.2009.06.015

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 bioenergy 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, not connected to a GIS, whose outputs are usually given by forest type, but focused on the whole region (Tome 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 modeling.

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 (Landesberg, 2003).

Given the numerous targets that can be pursued in forest management, there are 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 selected. 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 (Duncker et al, 2007). 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.

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.

2. Materials and methods

2.1. 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.

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

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 ($m^3\ ha^{-1}$)

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.

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, production costs and wages and salaries

The output_clt file includes the area distribution per age class contains the existing forest area per year 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.

2.2. 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 and the number of years to simulate, 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 other uses 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.

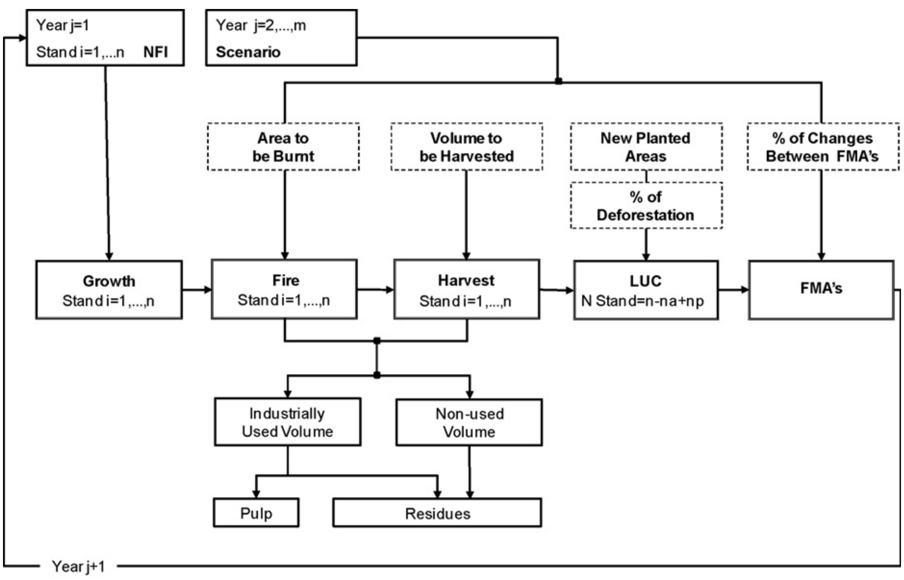

Fig. 1. Simplified structure of the simulator. The NFI box represents the base year plots' input file while the scenario box represents the scenario input file. The next level of boxes deriving from the scenario input file show the total amount of each driver needed as input for each of the drivers' 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.

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

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 will run 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 behavior is influenced by weather, in the short and the 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,b). 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 non-industrial 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 scenarios 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.

2.3. Growth and yield models

As mentioned before, SIMPLOT uses two growth models: the GLOBULUS 3.0 model for even-aged stands and the GYMMAnlin models for uneven-aged stands.

The GLOBULUS model (Soares et al, 2006; 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 (Antonio 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, 2008a,b). 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 GYMMAnlin model. As the GLOBULUS model it includes a projection and an initialization module that include the same variables as the GLUBULUS model. In the projection module the growth functions are formulated as age-independent growth functions (Tomé et al., 2006) with some of the parameters expressed as a function of climatic variables.

2.4. Case study

2.4.1. Input data

The 1995–1998 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 41.94×10^6 m^3. Fig. 2 shows the distribution of the eucalyptus area by age class and stand type.

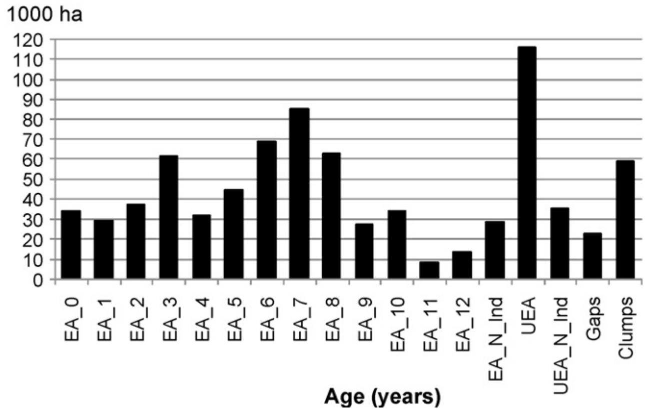

Fig. 2. Area of eucalyptus even-aged stands distributed in 1 year age classes (EA) and area of other stand types: non-industrial even-aged stands (EA_n_ind), uneven-aged stands (UEA_ind), non-industrial uneven-aged stands (UEA_n_ind), Gaps and Clumps.

2.4.2. 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'.

2.4.2.1. 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 introduce 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.

2.4.2.2. Wood demand. Three alternative wood demand scenarios have been defined. Until 2006 wood consumption by species can be found in the Portuguese statistics (Costa 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.

2.4.2.3. 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 (Costa 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 (Costa Pereira et al., 2009). It was considered that the deforestation of eucalyptus stands per year was constant over the simulation period.

2.4.2.4. 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.

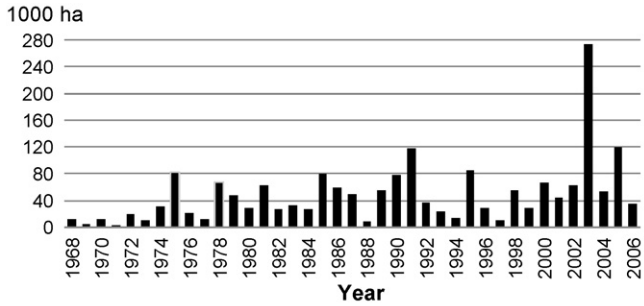

Fig. 3. Area of forest wildfires in a 1000 ha occurred in Portugal from 1968 until 2006.

The first three fire scenarios consider the eucalyptus forest burnt areas published in the statistics (Costa 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).

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.

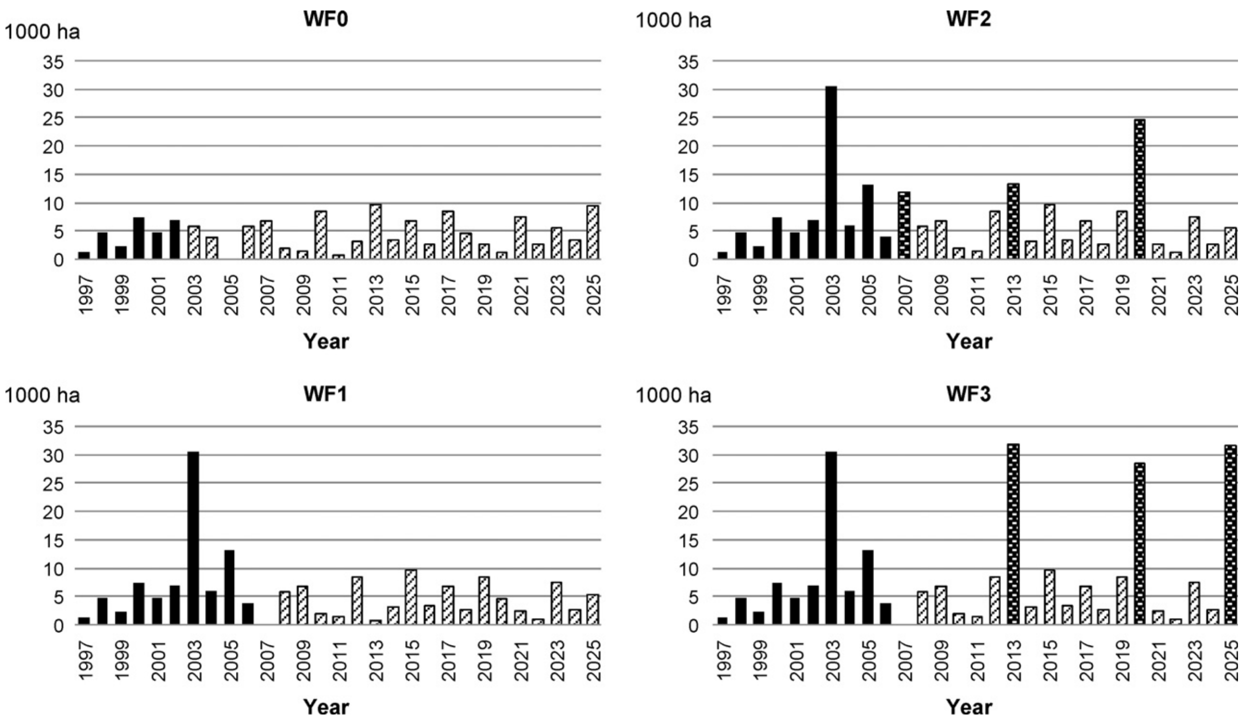

Fig. 4. Area of forest fires in hectares occurred in eucalyptus stands for each of the four scenarios: WF1, low intensity fire scenario; WF2, scenario with 3 medium intensity fires; WF3, scenario with 3 high intensity fires and WF0, hypothetical scenario with no severe fire occurrence.

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 up 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 wild fires that characterize scenarios WF3 and WF4, respectively.

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)

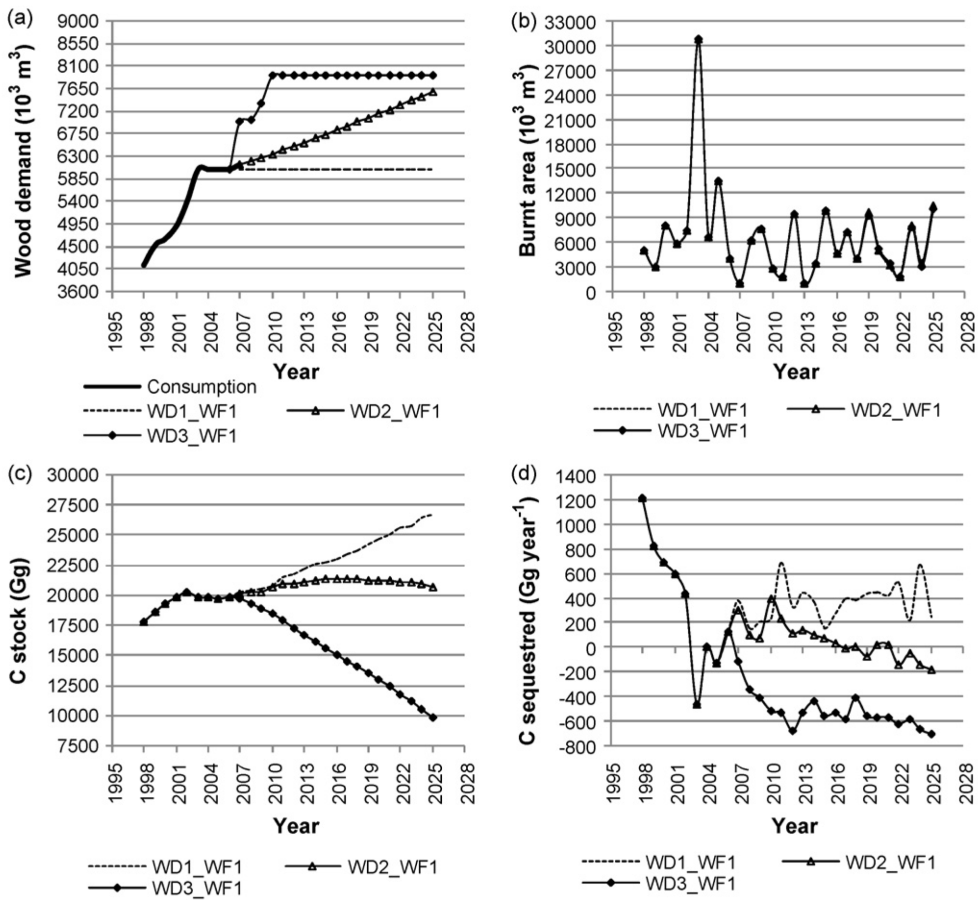

Fig. 5. Evolution of the main drivers and indicators: carbon stock and carbon sequestered characterizing the three scenarios in the wood demand scenario line: (a) evolution of wood demand driver, where WD1_WF2, WD2_WF2 and WD3_WF2 represent the wood demand defined in the three scenarios; (b) evolution of the burnt area driver for each scenario; (c) evolution of carbon stock and (d) evolution of carbon sequestered.

Table 4
Summary description of the scenarios studied.

Scenario	Land use changes		Wood demand	Hazards fire	FMAs
	Afforestation	Deforestation			
WD1_WF2	4800 (ha)	0.0012%	WD1	WF2	EAF
WD2_WF2	4800 (ha)	0.0012%	WD2	WF2	EAF
WD3_WF2	4800 (ha)	0.0012%	WD3	WF2	EAF
WD*i*_WF0	4800 (ha)	0.0012%	WD*i*	WF0	EAF
WD*i*_WF1	4800 (ha)	0.0012%	WD*i*	WF1	EAF
WD*i*_WF2	4800 (ha)	0.0012%	WD*i*	WF2	EAF
WD*i*_WF3	4800 (ha)	0.0012%	WD*i*	WF3	EAF

2.4.2.5. Wood demand scenario line. The first line contemplates 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 (WD*i*, where $i = 1$, 2 or 3).

2.4.2.6. 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.

3. Results

3.1. 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.

3.2. 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.

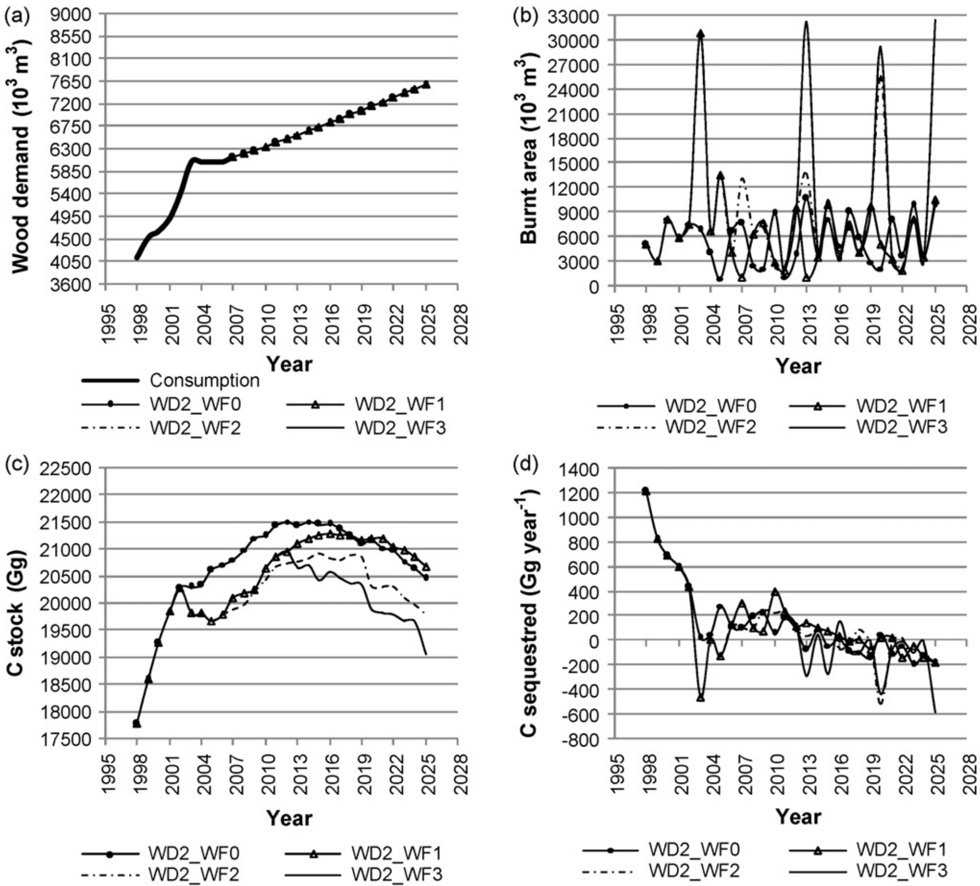

Fig. 6. Evolution of the main drivers and indicators: carbon stock and carbon sequestered characterizing the four scenarios in the wildfire scenario line: (a) evolution of wood demand driver, where WD2_WF0, WD2_WF1, WD2_WF2 and WD2_WF3 represent the wood demand defined in the four scenarios; (b) evolution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

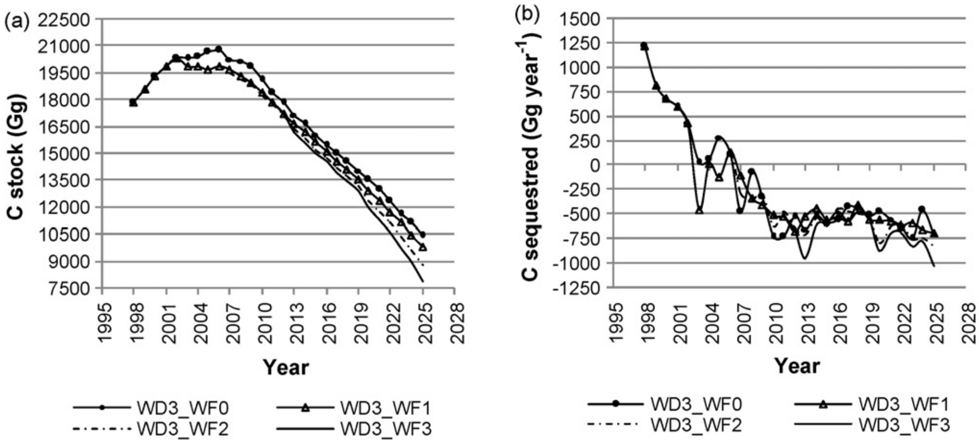

Fig. 7. Evolution of carbon stock (a) and carbon sequestered (b) for wood demands WD3 combined with the four wildfire scenarios.

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 behavior 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).

4. Discussion

The objective of the research presented here was to study the impact of different scenarios of intensity and frequency of forest fires 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 GYMMAnlin 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 would 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.

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 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 model 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 other forest management alternatives than even-aged forestry

5. 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.

Acknowledgements

The research reported here is part of the PhD of the first author supported by grant SFRH/BD/31239/2006 of the Portuguese Foundation for Science and Technology (FCT), and it was also supported by the EU FP6 EFORWOOD-IP project (contract 518128) and the national FCT CarbWoodCork project (POCI/AGR/57279/2004).

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