EFORWOOD
Tools for Sustainability Impact Assessment

Report describing version 1 of the regional simulators and of the European simulator

Margarida Tomé and Sónia Faias

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Preface

This report is a deliverable from the EU FP6 Integrated Project EFORWOOD – Tools for Sustainability Impact Assessment of the Forestry-Wood Chain. The main objective of EFORWOOD was to develop a tool for Sustainability Impact Assessment (SIA) of Forestry-Wood Chains (FWC) at various scales of geographic area and time perspective. A FWC is determined by economic, ecological, technical, political and social factors, and consists of a number of interconnected processes, from forest regeneration to the end-of-life scenarios of wood-based products. EFORWOOD produced, as an output, a tool, which allows for analysis of sustainability impacts of existing and future FWCs.

The European Forest Institute (EFI) kindly offered the EFORWOOD project consortium to publish relevant deliverables from the project in EFI Technical Reports. The reports published here are project deliverables/results produced over time during the fifty-two months (2005–2010) project period. The reports have not always been subject to a thorough review process and many of them are in the process of, or will be reworked into journal articles, etc. for publication elsewhere. Some of them are just published as a “front-page”, the reason being that they might contain restricted information. In case you are interested in one of these reports you may contact the corresponding organisation highlighted on the cover page.

Uppsala in November 2010

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EFORWOOD

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EFORWOOD
Sustainability Impact Assessment
of the Forestry - Wood Chain

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Report describing version 1 of the regional simulators and of the European simulator

Editores: Margarida Tomé, Sónia Faias

Abstract:

This report describes forest simulators that were developed under EFORWOOD. According to the terminology agreed in PD2.5.2 "Framework for the description of forest modelling tools currently available with identification of their ability to estimated sustainability indicators" (Tomé et al., 2007) a forest simulator is a computer tool that, based on a set of forest models, makes long term predictions of the status of the forests within a well defined region under a certain scenario of climate, forest policy and/or management alternatives. Forest simulators usually predict, at each point in time, wood and non-wood products from the forest. An objective of EFORWOOD is that simulators include in the output a list of selected sustainability indicators. There are several simulators being developed/used under EFORWOOD, from stand simulators to a European simulator: i) sIMfLOR, a stand and regional simulator for the Portuguese forests; ii) EFISCEN-space, the spatialized European forest simulators; iii) RegWise, a regional simulator for Swedish forests; iv) ESCEN, a simulator of the Catalan forests; v) SYLVOGENE, simulator of the Maritime pine forests in Aquitaine (South West France); vi) PrognAus, a distance independent individual tree growth simulator for the Austrian Forests; vii) MOSES, a distance dependent tree growth model for the Austrian Forests; viii) BIOME-BGC, a large scale ecosystem model. This report presents a detailed description of each one of these simulators as well as their present status of development. Each simulator is presented as a working paper with the respective authors, and some flexibility was allowed in the descriptions so that each authors team was able to organize the description of the simulator in a way appropriate to the specificity of the simulator.

Keywords: Forest models, forest simulators, stand simulators, regional simulators, and sustainability indicators

CONTENT

1 INTRODUCTION

This report describes forest simulators that were developed under EFORWOOD. According to the terminology agreed in PD2.5.2 “Framework for the description of forest modelling tools currently available with identification of their ability to estimated sustainability indicators” (Tomé et al., 2007) a forest simulator is a computer tool that, based on a set of forest models, makes long term predictions of the status of the forests within a well defined region under a certain scenario of climate, forest policy and/or management alternatives. Forest simulators usually predict, at each point in time, wood and non-wood products from the forest. An objective of EFORWOOD is that simulators include in the output a list of selected sustainability indicators.

There are several types of forest simulators depending on the spatial scale to which they apply and to the connection/or not to geo-referenced information:

1. Stand simulator
   Forest simulator focused on the simulation of a stand
2. Landscape simulator
   Forest simulator focused on the simulation of all the stands included in a certain well defined region in which the stands are spatially described in a GIS. The simulation is made on a stand by stand basis but outputs for the whole landscape are also provided, namely sustainability indicators. It allows for the testing of the effect of spatial restrictions such as maximum or minimum harvested areas or maximization of edges.
3. Regional/National simulator – not spatialized
   Forest simulator focused on the simulation of a large region, based on forest inventory data, without individualizing each stand, not connected to a GIS. Outputs are usually given by forest type but focused on the whole region.
4. Regional/National simulator – spatialized through a grid
   Forest simulator focused on the simulation of a large region, based on forest inventory data aggregated according to a spatial grid connected to a GIS. Outputs are also usually given by forest type but focused on the whole region. Due to the connection to a GIS it is possible to compute indicators that include spatial relationships. It is also possible to include spatial conditions in the implementation of the drivers, for instance to include distance to the mills in the harvesting algorithms or ecological conditions in the areas that are abandoned or planted.

There are several simulators being developed/used under EFORWOOD, from stand simulators to a European simulator. Table 1 lists and briefly describes all these simulators. The following chapters present a detailed description of each one of these simulators as well as their present status of development.

Each simulator is presented as a working paper with the respective authors, and some flexibility was allowed in the descriptions so that each authors team was able to organize the description of the simulator in a way appropriate to the specificity of the simulator.

Table 1.1. Forest simulators that are being used/developed under EFORWOOD.

Name	Type of simulator	Partner responsible	Applicability			
			Region	Species	Stand types	FMAs[1]
sIMfLOR	Stand + Regional	ISA	Portugal	Eucalyptus	Pure even and uneven-aged	DB EAF COF
				Maritime pine	Pure even and uneven-aged	DB EAF COF CN
EFISCEN-space	European	ALTERRA	Europe	Several species[1]	Pure and mixed, even- and uneven-aged	DB EAF COF CN NC
RegWise	Regional/ National	SLU	Sweden	Scots Pine, Norway Spruce, Birch, Oak, Beech, Aspen, Other Deciduous	Even and uneven-aged	EAF COF CN NC
ESCEN	Regional	CTFC	Catalonia (Spain)		Pure and mixed, even- and uneven-aged	
Sylvogene	Stand + Regional	INRA FCBA	South West France	Maritime pine	Pure even aged	DB EAF (COF)
PROGNAUS	Regional/ National	BOKU	Austria	Norway spruce, silver fir, Scots pine, Austrian black pine, Stone pine, Larch, common beech, Oaks and other broadleaved	Pure and mixed, even- and uneven-aged	DB EAF COF CN NC
MOSES	Stand simulation model	BOKU	Austria, Switzerland, Southern Germany	Norway spruce, Fir, Scots pine, Larch, Stone pine, Common Beech, Oapk spp. Other needle trees, Other broadleave trees	uneven aged mixed species stands with any management	DB EAF COF CN NC
BIOME-BGC	large scale / stand	BOKU	Austria / Europe	Norway spruce (two variants), socts pine, Larch, stone pine beech oak,	pure stands (managed undmanged)	DB EAF CN NC
W+	Stand + regional	FVA ALUFR	Baden-Württemberg	Norway spruce, common beech	Pure even-aged	EAF COF CN NC

[1] Abies spp., Alnus spp., Betula spp., Carpinus betulus, Castanea sativa, Eucalyptus spp., Fagus sylvatica, Fraxinus spp., Larix spp., other broadleaves, other conifers, other Pinus spp., other Quercus spp., Picea spp., Pinus pinaster, Pinus sylvestris, Populus spp., Pseudotsuga menziesii, Quercus robur/petraea,Robinia pseudoacacia ; [2] DB – dendrobiomass; EAF – even-aged forestry; COF – combined objective forestry; CN – close to nature; NC – nature conservation

2 sIMfLOR: simulator of the Portuguese forests

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Abstract:

sIMfLOR is a forest simulator for eucalyptus, maritime pine and cork oak mainly driven by wood demand. It was designed for long-term simulation of the Portuguese forest development using National forest inventory data as input and taking into account the effect of different drivers such as wood demand, hazards occurrence, percentage of land use changes and changes between different forest management alternatives. This report describes the present status of the simulator and the improvements that are expected in the short term. The use of the simulator is illustrated by two simulation runs for two main scenario lines. In the first one, increasing wood demand rates are combined with a low severity fire scenario, whereas the second one considers an increasing number of high severity wildfires for a given wood demand rate as well as the impacts of different scenarios of use of burnt wood by the industry. These simulations provide some insight on the impact of increasing wood demand combined with an increasing number of severe wildfires. As higher the wood demand rate is the more drastically carbon stocks decrease. The 5% wood demand rate scenario shows a 67% reduction in carbon stock throughout the analyzed period, against a 17% reduction for the 4% rate scenario and a 55.5% increase for the 2% one. The impact of an increasing number of severe wildfires for a wood demand rate of 4% results in carbon stock depletions that can reach a 50% loss for the more severe wildfire scenario. If less burnt wood is used by industry, only allowing burnt stands near the rotation age to be harvested and dropping the percentage of these stands that are used with industrial purposes, the situation can get even worse with carbon stocks shortening in 60% when compared with the beginning of the simulation period. Holding all other variables constant and varying wood demand and wild fires once at a time, despite the impact of the number of wildfires occurrence, wood demand is still the crucial driver with the major impact on changing forest conditions.

Key words: Portugal, forest simulator, eucalyptus, maritime pine, carbon sequestration, carbon stock, wood demand, forest fires.

2.1 INTRODUCTION

The sIMfLOR is a forest simulator for the Portuguese forests designed for large-scale and long term analysis. sIMfLOR is suitable for assessments of the future state of the forest under assumptions of future wood demand, hazards occurrence and land use changes. The model simulates the state of the forest under different conditions defined by the user, although it does not comprise any optimization module. At present it just considers pure stands of eucalyptus, maritime pine and cork oak but it is expected that in a near future it might consider other species and other mixed-forests.

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

The simulator is still 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 and maritime pine in Portugal. Another characteristic that will be added very soon is the possibility to simulate other forest management alternatives than even-aged forestry. In order to illustrate the present abilities of the simulator it is used to analyze the impact of different scenarios of fire and wood demand on carbon sequestered and carbon stock.

2.2 SIMFLOR - THE SIMULATOR CONCEPTION

sIMfLOR has been conceived to simulate all the stands in a region, but it also allows the user to simulate the growth of an individual stand providing an yield table as output as well as a large set of sustainability indicators and an economic analysis. This possibility is highly appreciated by the users as a way to follow the future development of individual stands and, in this way, gain confidence on the simulator. When running the simulator for different scenarios, it starts with forest inventory information to characterize the forest resources in a region (e.g. NUT, country) and 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. For each year of the simulation it computes a set of sustainability indicators that directly relate to forest resources.

2.3 SIMFLOR - THE SIMULATION UNIT

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 a certain species in the country divided by the respective number of NFI plots. The simulator allows the user to divide the stand in as many parts as desired in order to adjust the area to which harvest and forest operations are applied.

2.4 SIMFLOR - THE STRUCTURE

Figure 2.1 illustrates the structure of the regional simulator. The same “philosophy” is applied to each species. The simulator can run more than one species at the same time but the drivers are applied by species. It starts by calling in the growth module for all the stands at year j in order to update the forest resources to year j+1. After growth has been updated the fire module is called in and analyses all the stands in order to decide if they burn. Each stand can either burn or not according to a P_fire probability. On one hand, if the stand burns it is assumed that the whole stand will be harvested. It is up to the user to define the conditions under which it is possible to use the harvested burnt wood. The user can define a minimum age to allow harvesting the burnt stand with industrial purposes (tminfire) as well as the quantity of burnt wood that will have an industrial use (%UseFire). The amount of wood to be used by industry (Vdi_fire Industry Used) is "stored" in a V_harvest variable. After the fire module runs the modules for each one of the pests will be called (not yet implemented). Once a stand is attacked the intensity of the attack will have to be taken into account. Different pests will have different consequences on growth and on the silvicultural operations that will follow. Therefore, if the attack comes from a borer sanitary thinning or clear cut will take place depending on the intensity of the attack. Similarly to what happens when a fire takes place, part of the wood deriving from an attacked stand can be used by the industry (Vdi_pests Industry Used), "stored" in the V_harvest variable. Finally the harvesting module will be called in and according to a user defined probability (P_harv) each stand can be harvested or not. If harvesting takes place the volume will be "stored" in the V_harvest variable.

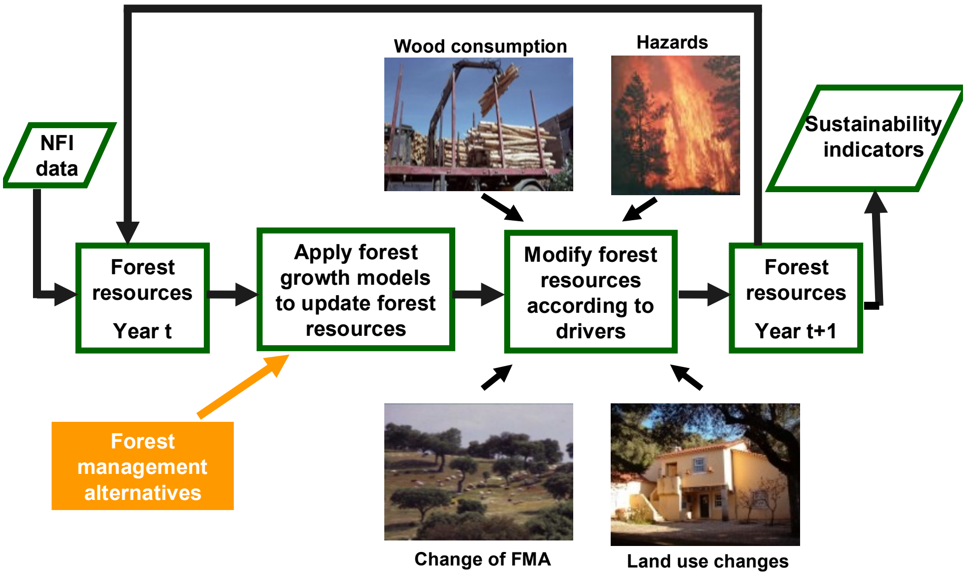

Figure 2.1. Structure of the sIMfLOR regional simulator.

After each stand is analysed in 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 calling in the afforestation module, planting as many new stands as the total amount of afforestation defined by the user for that year. In case the volume harvested is greater than the wood demand (which is usually the case because the unit of simulation is a stand), the exceeding volume is stored to be used in the next year of simulation.

2.5 sIMFLOR - THE DRIVERS

The simulator comprises 4 types of main 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 and per year and the area affected by each of the most important pests per year as well as the intensity of the attack; iii) the changes in management intensity expressed as the percentage of area changing from one forest management alternative (there are 5 FMAs: dendro-biomass, even-aged, combined objective, close to nature and nature conservation) to another and finally iv) the land use changes (LUC) to and from other uses: the afforestated area per year and the deforestated area per year. The changes in the forest management alternatives module is not yet implemented in the simulator and therefore will not be described in this report. The hazards module, as mentioned before, whereas it has been implemented for fire does not yet include pests.

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 total amount of one driver for each year can be given as an area or a proportion of an existing area, whereas the probability of occurrence of the event is estimated according to a probability function (user defined or following some logistic function) and implemented with Monte-Carlo simulation. In case the event occurs the simulator takes a specific action depending on the event.

The simulator can be run simultaneously for more than one species, however the drivers algorithms runs separately for each one of the species considered in sIMfLOR, eucalyptus and maritime pine.

2.5.1 Hazards occurrence

The hazards occurrence is the first driver to be "called in". This driver comprises different types of hazards such as fire, pests and diseases and storms. So far, only the fire algorithm has been implemented in the simulator. The model for prediction of probability and intensity of attack by *Phoracantha semipunctata* in eucalyptus stands is still under development as well as an algorithm to simulate its impact. The other pest that will be considered in eucalyptus is *Gonipterus scutellatus*. It is planned to consider *Thaumetopoea pityocampa* attacks in maritime pine.

At present the amount of area burned every year (Afire) has to be provided by the user in the scenario input file and the selection of stands that are burnt is based on Monte-Carlo simulation assuming an equal probability of being burnt for all the stands (P_fire). Wildfire behaviour is influenced by weather, in the short and the long-term, as well as by topography and fuels. Therefore, forest conditions combined with extreme fire weather conditions can lead to high severity fires (USDA Forest Service, 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, 2008). 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 predicts fire ignition probability using the distance of the stand to the nearer different land uses as well as the azimuth as predictors (Vasconcelos et al.,2001)

The simulator starts with a burnt area equal to zero and selects the stands that are burned by Monte-Carlo simulation. The burnt area is summed up 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.

After a fire it is assumed that the stand is harvested and that part of its wood can be industrially used. Therefore, apart from the total amount of the driver there are other user defined driver options taken into account. One is the minimum age that allows the industrial use of trees after a fire (tminFire) while the other is the percentage of these stands which is actually used by the industry (%UseFire).

2.5.2 Wood demand

As the unit of harvesting is the stand, with a fixed area, the volume harvested at the end of each year of simulation is usually slightly higher than the wood demand. The difference is kept for the following year as a stock (Vstock). Before the wood demand driver is "called" 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 it is up to the user to define the total amount of volume harvested in each year of the simulation (Vharvest) in the scenario input file. Just like for hazards, there is also a user defined age threshold that keeps non-burnt stands under a certain age to be harvested (tminHarv) regardless of fire occurrence. It is also the user's responsibility/choice to define the percentage of harvest in non-industrial stands (%HarvNI).

There are two alternative harvesting algorithms. Both of them give increasing harvesting priority to older stands up to the user defined age limit (tminHarv), a harvesting probability to non-industrial stands (%HarvNI) and keep on harvesting until wood demand is met (Vharvest). The main difference between the two algorithms lies in the way of setting the harvesting priorities. One searches for the older age class harvesting all stands in it before it moves down to the following age class with stands to be harvested, while the other draws a random number for each stand and compares it to the harvesting probability (P_harv) which is pre-defined by the user according to the age class.

2.5.3 Land use changes

The land use changes module includes an algorithm for the new areas planted where land use used to be other than forest. These areas represent the afforestation per year. The other algorithm part of this driver is the one for the abandoned areas per year. The simulator assumes that part of the forest area is abandoned and converted to other land uses, which corresponds to deforestation.

The first step in the afforestation algorithm is to determine the number of stands that correspond to the total amount of new planted area per year of simulation (APlant) that is defined by the user 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) which will be used to estimate each stand site index according to the observed distribution of site indices for the species in that particular climatic region. After this, the new planted stands are ready to be simulated.

In the deforestation algorithm the main input information is the total amount of forest land with each species being converted to a different land use (%LandChange) given as a proportion of the respective area. Thus, the first step is to determine the abandoned area in hectares as well as the number of stands that correspond to that same area. The next step is drawing a random number for each harvested stand and considering that each stand has 50% chance of being abandoned. This is not realistic, because it is more likely that stands located in less productive areas will be abandoned than stands located in highly productive ones. Thus this is a subroutine to be improved.

2.6 sIMFLOR – THE FOREST MODELS

2.6.1 Eucalyptus

2.6.1.1 Globulus 3.0 - eucalyptus whole stand model

The Globulus 3.0 model is a stand level growth and yield model developed for pure even-aged stands. It gathers 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 previous version – Globulus 2.1 - was parameterized for 8 different climate regions (Ribeiro and Tomé, 2000). A set of 7 dummy variables was defined in order to assess the need to parameterize each model component for the different regions which allowed obtaining different growth curve shaps for different soil and climatic conditions. Descriptions of the previous versions of the model can be found in Tomé et al. 1998, Tomé 1999, Tomé et al. 2001a and Tomé et al. 2001b.

Most of the components of the Globulus 3.0 model were already available in the previous version, but some of them were improved and some of the parameters of the model are now expressed as a function of climatic variables: the number of days with rain, the altitude, the total precipitation, the number of days with frost and the temperature. New components were developed for stand parameters before the thinning of the shoots takes place. The new version allows simulating the transition between rotations by simulating growth for coppice stands before the thinning of the shoots usually occurring during the 3rd year after the final harvest. Therefore, the following equations were developed for the first time and introduced into the model:

- a growth function for the number of stools per year
- a prediction function for the number of sprouts before the thinning of the shoots
- a prediction function for the number of sprouts by the age of three years after an operational thinning of the shoots

Another improvement is related to the biomass functions, which were rather incipient in Globulus 2.1. Thus, new biomass functions for total and per plant components were also developed.

The development of the Globulus 3.0 model was based on a large amount of information deriving from various sources: permanent plots, experimental trials and continuous forest inventory plots from the pulp and paper companies was compiled and exhaustively analyzed to build up a database (Soares et al., 2006). The amount of data stored is impressive but the coverage of the data on the control variables still has some weaknesses:

- Even though the number of planted and coppiced stands is pretty close they are not equally distributed all over the country. Coppice stands are mainly located by the Tagus River basin, while the planted stands are spread out over Portugal.
- A small number of stands is found in extreme density classes (below 600 ha-1 and above 1800 ha-1). For density classes between these thresholds the number of planted stands decreases with stand density, while the inverse relation is observed for coppice.
- About 45% of the stands are found in the Site Index (SI) class that goes from 18 up to 22, around 25% fall in the SI class of 14 to 18 while nearly 20% of the stands have a SI class from 22 to 26. The remaining 10% are more or less equally distributed between the classes from 10 to 14 and from 22 to 26.
- The great majority of stands have 8 to 10 years of age. There are barely any stands over 14 and the remaining ones are distributed in the age classes below 6 and between 10 to 14 with the singularity that the proportion of coppices in the younger age class is higher than the one of planted stands, while the opposite is observer for the class of 10 to 14.

2.6.1.2 The Globulus 3.0 model structure

Globulus 3.0 includes two types of variables – state variables and control variables – and three main modules – initialization, projection and prediction.

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 derived variables. On the other hand, the control or external variables control the development of the state variables and can be of three different sub-types: environmental, cultural or intrinsic to the stand. Table 1 lists all variables currently included in the model.

The overall structure of the Globulus 3.0 model is shown in Figure 2.2.

The model includes state variables and control variables. Table 2.1 lists all variables currently included in the model. Globulus 3.0 is composed of three main modules: the initialization module, the projection module and the prediction module.

The initialization module predicts each stand variable as a function of the control variables that characterize the stand.

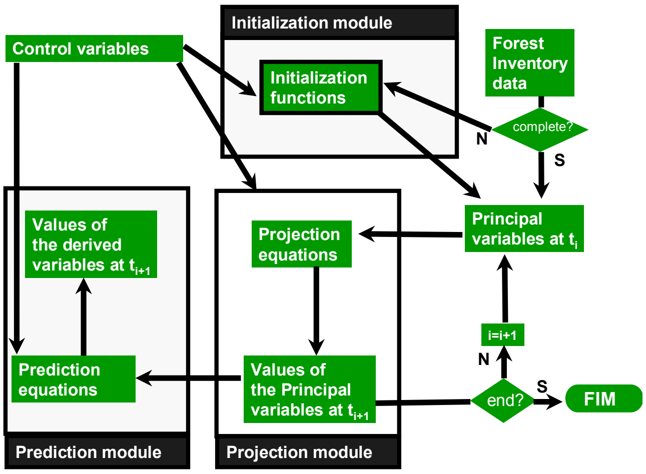

Figure 2.2. Structure of Globulus 3.0 model.

The projection module consists of a system of compatible growth functions for each principal variable as a function of its starting value, control variables and other principal or derived variables. All the sub-models are growth functions formulated as first order non-linear difference equations. On the prediction module, derived variables are predicted as a function of principal variables as well as of control variables.

The initialization module is essential because it allows initializing a new stand either by planting or coppice.

The equations included in the Globulus 3.0 model are shown in tables of **annex I**, as well as the list of symbols used in the equations.

Table 2.1. Variables currently included in the model Globulus 3.0

State variables	**Control variables**
Principal variables	Environmental
Dominant height	Number of days with rain in a year
Stand basal area	Altitude
Number of trees per ha	Number of days with frost in a year
Total volume without bark	Total precipitation
Stump volume	Temperature
Bark volume	Site Index (base age =10)
Derived variables	Cultural
Number of sprouts per ha before the shoots selection	Initial stand density (planted stands)
Number of sprouts per ha after the shoots selection	Number of sprouts per ha after shoots selection (coppice)
Merchantable volume	Rotation age
Aboveground biomass and biomass per tree component and respective C and nutrients	Stand
Roots biomass and respective C and nutrients	Rotation
Total biomass and respective C and nutrients	Age
	% of stools that die in the transition between rotations

Cultura

2.6.2 Maritime Pine

2.6.2.1 Pinaster 1.0 – maritime pine diameter distribution model

Pinaster 1.0 is an whole stand model with diameter distribution simulation. This model is based on the model Modispinaster structure but some additional equations were developed in order to improve or complement the original model. The model structure is presented on Figure 2.3

The main control variable is site index (S) that can be measured or selected according to the distribution of S found in the Portuguese NFI for the region NUT III where the stand is located. Table 2.2 lists the variables included in the model.

Table 2.2. Variables included in the model Pinaster 1.0

Control variables	Principal variables	Derived variables
Site index (S)	Age (t) Dominant height (hdom) Basal area (G) Stand density (N)	Total and merchantable volume (over and under bark) Total biomass and biomass per tree component – wood, bark, branches, leaves, roots – and respective C stock and nutrients

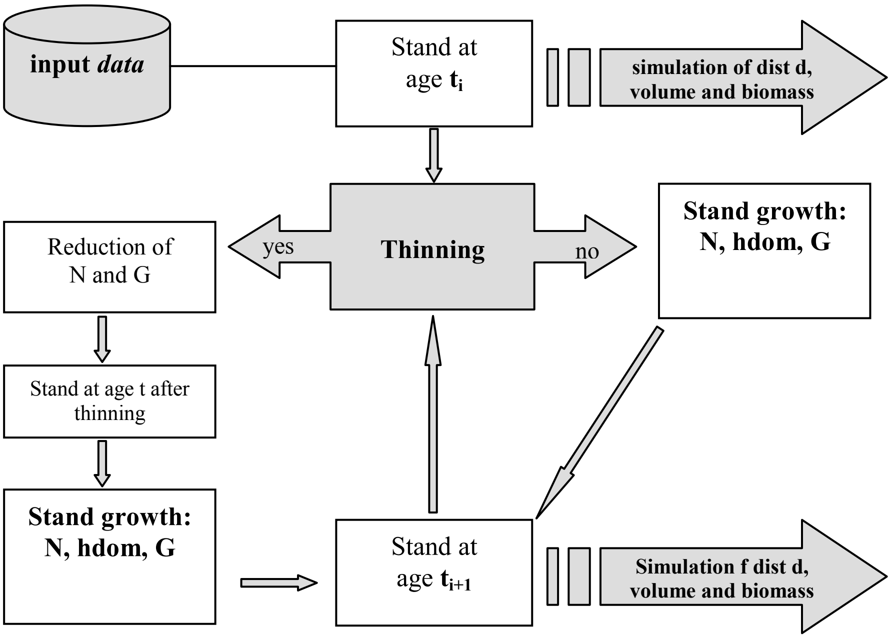

Figure 2.3. Structure of Pinaster 1.0 model.

The model can be initialized in three different ways that are summarized on table 2.3.

Table 2.3. Pinaster 1.0 initialization module

Condition	Variables that are needed as input
Existing stand with information from a forest inventory	age (t_i), dominant height ($hdom_i$), density (N_i), basal area (G_i)
New plantation	number of trees per ha at planting, initial mortality rate for the first 3 years, site index (S)
New stand naturally regenerated	site index (S)

In the new plantation sub-module the initial plantation is introduced and the initial mortality rate is applied in the first 3 years after planting. For the regeneration module the initial number of trees is estimated with the equations for maximum stand density. This density is reduced with a pre-commercial thinning that considers a specific spacing or the percentage of the number of trees removed.

In general, there is a constraint in stand density estimation per year that can not be greater than the maximum stand density estimated by the model equations.

The model has a thinning module that considers 3 different options to define thinning intensity: spacing index (Fw), residual G (G_{res}) and % of G removed (%G).

The model uses the specifications functions for very young stands that are subdivide in two stages:

1. Regenerating, for hdom<2 m:
   The diameter dependent variables (G, dg, ddom, dmed, dmin, dmax, d0.50) are null, just dominant height and stand density are considered
2. Very young stands, for hdom>= 2 m but d>75 mm:
   - The maximum number of trees is estimated with a linear equation of hdom, in older stand maximum stand density is estimated with a function of dg (3/2 power law).
   - Total volume is estimated as function of site index and dominant height
   - Aboveground and total biomass are estimated as function of the volume stand

The diameter distribution starts to be simulated when the stand achieves dg ≥ 75 mm and the volume and biomass components are computed as the sum of those variables estimated by diameter classes. The Johnson-S_B distribution function used in the Modispinaster model (Fonseca, 2004) is used to simulate the diameter distribution.

The equations included in the Pinaster 1.0 model are shown in tables of **annex II**, as well as the list of symbols used in the equations.

2.7 SIMFLOR - THE INPUT FILES

There are different types of input files:

- Base year plot input file - Input file characterizing the forest resources for the first year of simulation.
- Scenario input file - Input file describing the scenario to be simulated.
- FMA input file - Input file describing the different forest management alternatives
- Costs input file - Input file listing costs

The base year plot input file contains the list of forest inventory plots to be simulated. The file structure has to have descriptive information on each plot as well as the stand variable information listed on **Table 2.4** (principal variables).

Table 2.4. 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})

If not available from the forest inventory, all these variables can be predicted in the initialization module based on the site index and forest management alternative specifications. If site index is not available it can be simulated on the basis of the site index distribution of the NUTIII in which the stand is located.

The scenario input files define the scenario by describing the values of the drivers. There is one scenario input file per species. The file has the structure shown in **Table 2.5**.

Table 2.5. Structure of the scenario input files for the sIMfLOR simulator.

Initial year : 1997
Nr of years to project: 15
tminHarv: 8
tminFire: 5
%UseFire: 60
%HarvNI: 10
TopDiameter: 5
%deathRot: 20

Year	VHarvest	AFire	ANewPlant	%LandChange
1997	3524	4817	3800	0.0012
1999	3891	2353	3800	0.0012
2000	3985	7326	3800	0.0012
2001	4222	4837	3800	0.0012
2002	4618	6954	3800	0.0012
2003	5312	30526	3800	0.0012
2004	5593	6054	3800	0.0012
2005	6083	20000	3800	0.0012
2006	5938	7000	3800	0.0012
2007	5938	7000	3800	0.0012
2008	5938	7000	3800	0.0012
2009	5938	7000	3800	0.0012
2010	5938	7000	3800	0.0012
2012	5938	7000	3800	0.0012
2013	5938	7000	3800	0.0012

2.8 sIMFLOR - THE OUTPUT FILES

The simulator has 3 types of outputs: output per plot and year (output_plot.prn), output of area distribution per age class and year (output_clt.prn) and output of different areas and stand variables per year for each species and stand type (output_year.prn). In sIMfLOR a stand type is originated by a FMA.

The main output is given in the file output_year that encloses information regarding what has happened for each year of simulation. 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 in the beginning of each year of simulation with the existing standing volume after all drivers have been called in and the total volume harvested due to fire occurrence. The equivalent information regarding biomass can also be found in this output file. It also holds the information on areas, such as existing forest area before the drivers have been called in, total forest area after calling in the drivers, the area that corresponds to the actual harvested volume and the area that was burnt per year.

On its turn, the output_clt file includes the area distribution per age class contains the existing forest area per year allocated to one 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.

On the other hand, the output_plot file allows tracking the history of a given stand throughout the simulation period by analyzing the values of several stand variables.

2.9 SIMFLOR – A CASE STUDY FOR EUCALYPTUS

2.9.1 Input data

The 1995-1998 NFI provided the eucalyptus input data for the simulator. In the case study presented here just pure even-aged stands were taken into account. Stand evaluation in terms of structure, production and vitality was achieved through field work on 490 pure even aged eucalyptus inventory plots. All trees holding a dbh greater or equal to 5 cm were measured. The area of pure even aged eucalyptus stands is 513 439 ha and holds a standing volume of 52.28 10^6 m^3. Figure 2.4 shows the distribution of the eucalyptus area by age class and stand type.

2.9.2 Scenarios

Two main scenario lines were considered. The first line assumes different wood demand increase rates jointly with an unrealistically soft scenario of fire occurrence, while the other line incorporates increasingly severe fire scenarios. Both lines have the following assumptions in common:

Eucalyptus stands are managed with a planted stand being followed by two coppice stands;

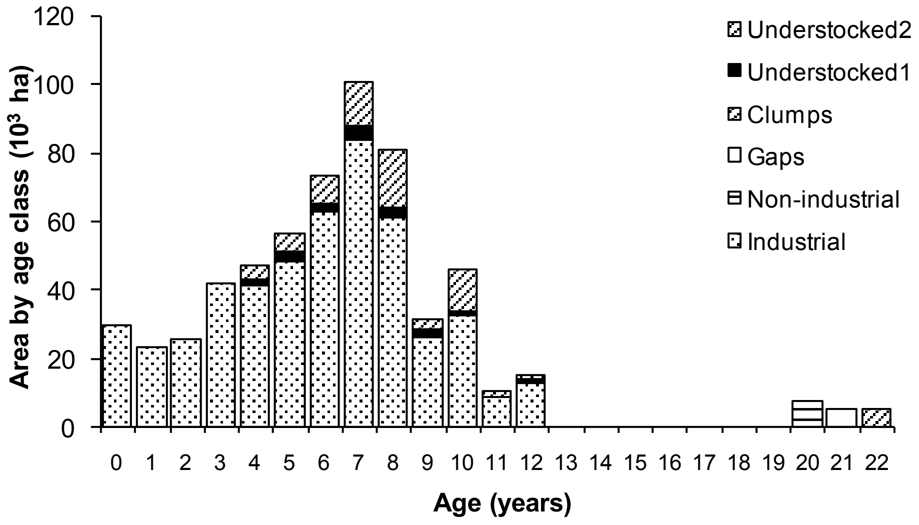

Figure 2.4. Area of pure even-aged eucalyptus stands by age class and type. The area of industrial stands and under-stocked stands is distributed in one year age classes. Two levels of under stock intensities were considered: plots with a number of trees per hectare less than 250 (understock1) and plots between 250 and 650 (understock2). All plots older 12 years of age were classified as non-industrial (indicated in the figure as age class 20). Gaps and clumps were also set aside into two different classes (appointed as age classes 21 and 22, respectively).

- Until 2004 wood consumption by species can be found in the Portuguese statistics (IA, 2006). This information concerns all types of eucalyptus stands while this study only focuses on pure even-aged stands and the official numbers correspond to volume of wood including bark. For the definition of the scenarios the wood demand from the statistics were therefore adjusted using a 17% discount for bark (Tomé et al. 1995) and the ratio between the area of pure even-aged eucalyptus stands and the total area of Eucalyptus to set the proportion of wood demand to be used in the scenarios;
- The minimum age for harvesting (tminHarvest) assumes that stands younger than 8 years cannot be harvested unless they have burnt, situation for which the threshold drops to 5 years (tminfire);
- The probability of a stand being harvested is a function of stand age as was defined as described as follows:

Age (years)	**P_harv (%)**
8	10
9	20
10	30
11	40
12	50
13 and 14	95
15 and 16	99
>=17	100

- A user defined top-diameter of 5 cm was used;
- It was assumed that 20% of trees/stools die in the transition between rotations;
- The percentage of harvested volume coming from non-industrial stands is user defined and was considered to be of 10% (%HarvNI);
- The total amount of new planted areas (Aplant) as well as abandoned ones (P_Aband) were considered to be constant over the simulation period and equal to the values presented on table 2.5.

2.9.2.1 Wood demand driven scenario line

Three scenarios were considered under this scenario line. The total wood demand after year 2004 was assumed to increase at different rates per year: 1, 2 and 4% rates for scenarios S1, S2 and S3, respectively. Despite the fact that the first year of simulation corresponds to year 1997 and that high severity wildfires took place in years 2003 and 2005, the total amount of burnt area was considered much lower. Based on statistical information on the burnt area since 1968 up until 2006 a fire scenario that excludes the two big wildfires of 2003 and 2005 was built (Figure 3b.). For all the scenarios under this line it was assumed that 60% of the wood that had been harvested due to a fire would be used by the industry (%UseFire).

2.9.2.2 Wildfire occurrence driven scenario line

For the fire driven scenarios a 2% wood demand increase rate was assumed combined with 3 different fire scenarios. The total amount of burnt area for the projection length was set based on burnt areas from the past and the difference between scenarios is found in the number of high severity wildfires considered through the projection period. In this way the fourth scenario (S4) takes into account the real burnt area in years 2003 and 2005 (two severe wildfires), while the fifth one (S5) considers a third severe wildfire in 2012 apart from the ones already included in S4. The last scenario run shows a chaotic situation where a reasonable number of high severity fires are happening during the projection period (S6).

A sensitivity analyses was made for all the scenarios under this line varying the percentage of wood harvested due to a fire that is used by the industry (%UseFire) and the minimum age that allows burnt harvested wood to be industrially used (tminFire). Age thresholds were considered to vary from 7 to 10 years and the percentage of use from 30 to 70%.

2.9.3 Results

2.9.3.1 Wood demand driven scenario line

The results of the simulations show that for the first two scenarios S1 and S2, the wood demand is met all along the simulation period. Nevertheless, when a 4% increase in the wood demand per year (S3) is considered, for the last year of the simulation period the forest can no longer cope with the amount of wood required in Figure 2.5a. The depletion of the forest resources under this scenario becomes visible in the middle of the simulation period when the carbon stock starts to decrease (Figure 2.5c.). Even though, the carbon stock decreases during the simulation, there is a clear sign of recovery since the carbon sequestered raises again after a strong decrease in the middle of the period (Figure 2.5d). S2 shows an intermediate situation giving evidence that, on a longer term, it will be possible that the wood demand will not be met.

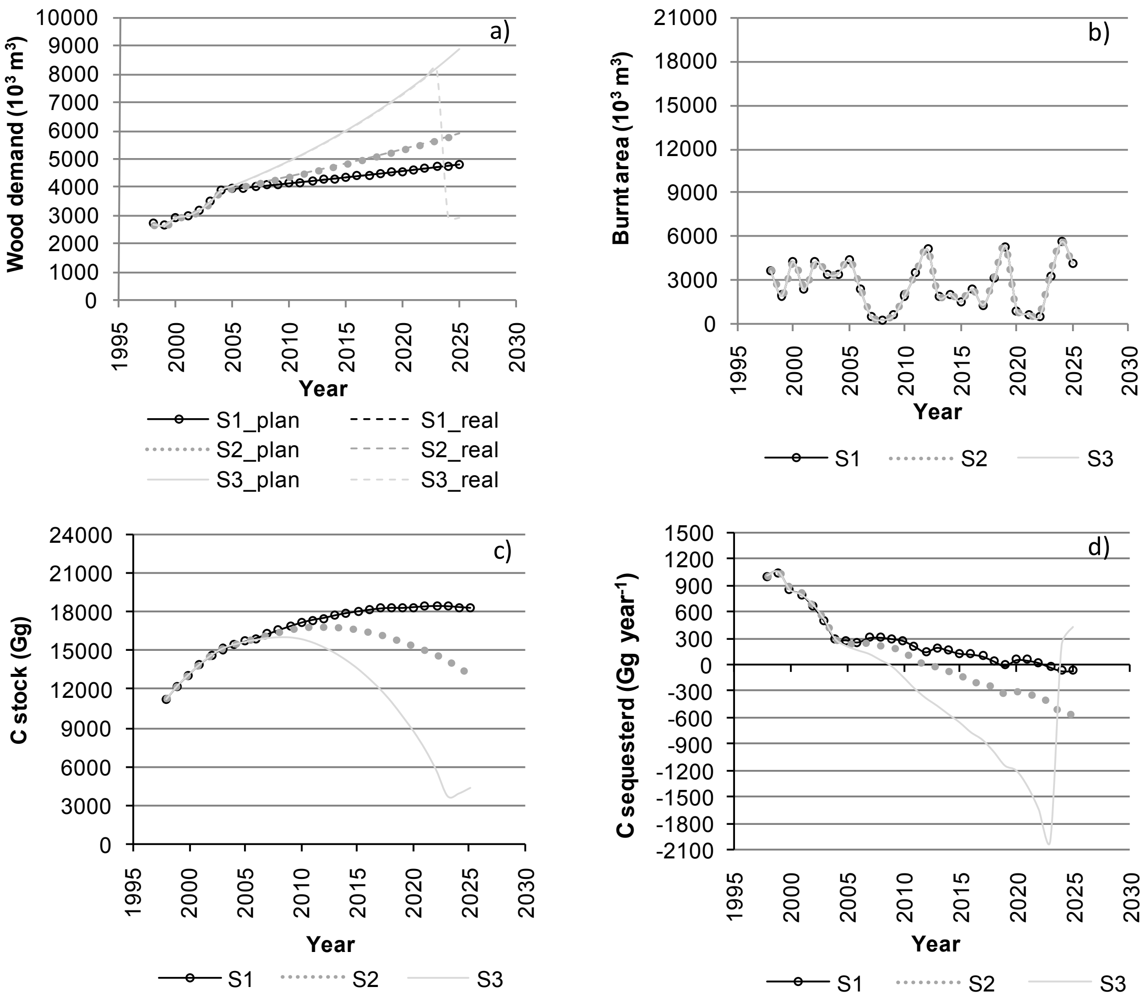

Figure 2.5. Evolution of the main drivers and indicators characterizing the wood demand scenario line: a) evolution of wood demand driver, where S1_plan represents the wood demand defined in scenario S1 and S1_real represents the amount of volume that was available to be harvested under the user defined imposed restrictions; b) evolution of burnt area driver; c) evolution of carbon stock and d) evolution of carbon sequestered.

2.9.3.2 Wildfire occurrence driven scenario line

Figure 2.6 shows the results for this scenario line with a 3% wood demand increase rate and 3 different fire scenarios characterized by a different number of high severity wildfires: 2, 4 and 8, scenarios S4, S5 and S6, respectively.

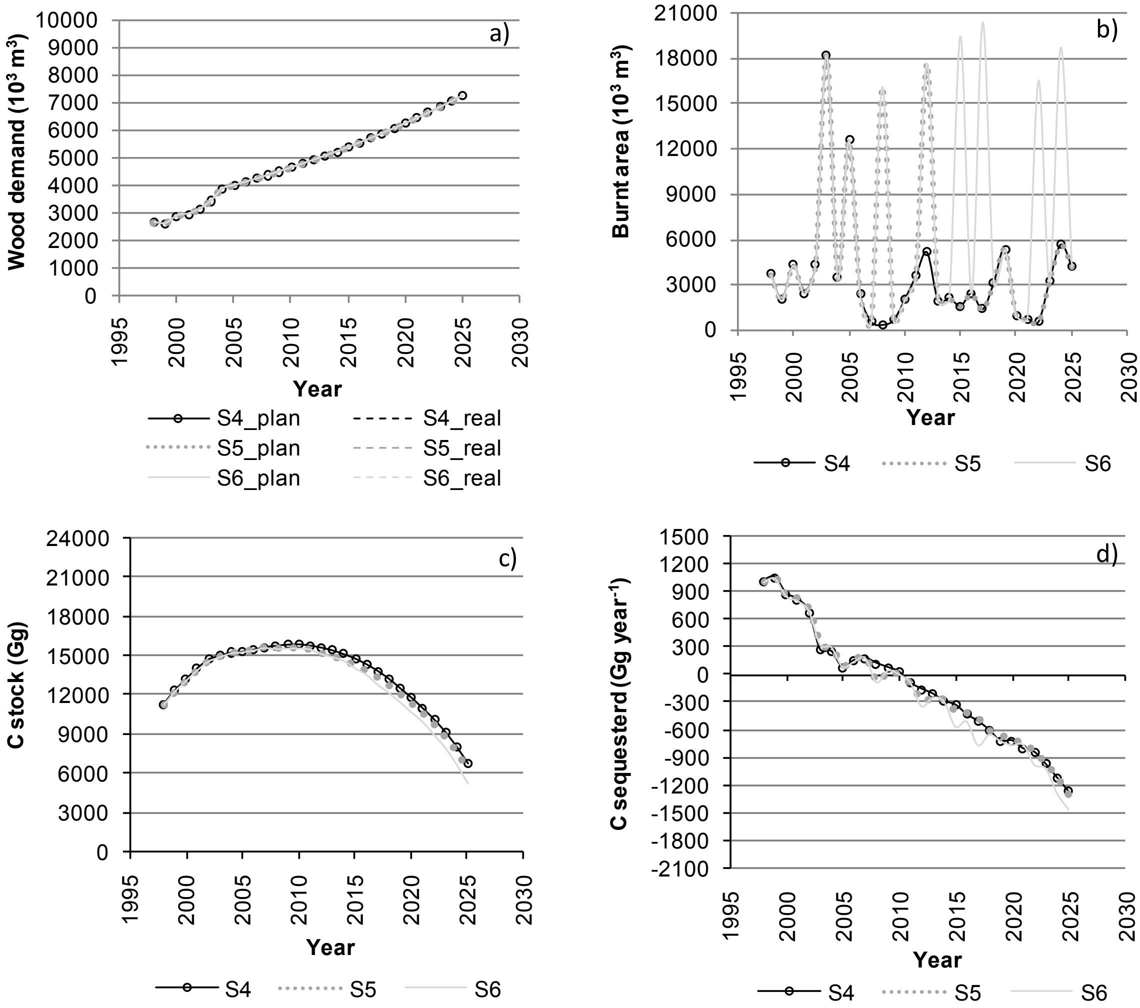

Figure 2.6. Evolution of the main drivers and indicators characterizing the wildfires scenario line: a) evolution of wood demand driver, where S4_plan represents the wood demand defined in scenario S4 and S4_real represents the amount of volume that was available to be harvested under the user defined imposed restrictions; b) evolution of burnt area driver; c) evolution of carbon stock and d) evolution of carbon sequestered.

The sensitivity analyses shows that for soft wildfire scenarios (S4 and S5) for all percentages of burnt wood harvested to be used by the industry considered it is possible to meet the wood demand as long as the minimum age that allows industrial usage remains below 9 years. However if usage percentages go under 50% the wood demand won’t be meet for S7 (Table 2.6).

Table 2.6. Impact of different age thresholds that allow burnt wood to be industrially used (tminFire) combined with different percentages of burnt wood industrially used (%UseFire) for the three scenarios in the wildfire scenario line; where Last x represents that the wood demand cannot be meet for the last x years of the simulation period and √ represents wood demand being meet.

			Age thresholds that allow burnt wood to be industrially used (tminFire)			
			7	8	9	10
industrially used % of burnt wood (%UseFire)	30%	S4	√	√	Last 2	Last 9
		S5	√	√	Last 3	Last 10
		S6	Last 1	Last 1	Last 4	Last 10
	40%	S4	√	√	Last 2	Last 8
		S5	√	√	Last 3	Last 10
		S6	√	√	Last 4	Last 9
	50%	S4	√	√	Last 2	Last 9
		S5	√	√	Last 3	Last 10
		S6	√	√	Last 4	Last 9
	60%	S4	√	√	Last 2	Last 8
		S5	√	√	Last 2	Last 9
		S6	√	√	Last 3	Last 9
	70%	S4	√	√	Last 2	Last 8
		S5	√	√	Last 2	Last 8
		S6	√	√	Last 3	Last 10

In the scenarios where high severity wildfires (S6) take place very often, weakening the forest resources, it gets even more difficult to meet the wood demand

Figure 2.7 shows the evolution of the indicators under some variations of scenario S6 varying percentages of burnt wood industrially used (%UseFire) and minimum age threshold for burnt wood to be used (tuseFire). Three different scenarios that prevent wood demand from being meet were considered: S7, %UseFire=40% and tuseFire=8; S8, %UseFire=50% and tuseFire=9 and S9, %UseFire=60% and tuseFire=10.

2.9.4 Discussion

Even though fires are of extreme importance conditioning forest resources, wood demand variations have a greater impact on carbon stocks and on carbon sequestered by the forest. Not only the number and severity of wildfires considered in the scenario have proven to be relevant, varying percentages of burnt wood harvested to be used by the industry (%UseFire) together with the minimum age that allows this wood to be industrially used (tminFire), have significant impacts on the forest ecosystem. For usage percentages above 40% the age threshold of 9 seems to be of crucial importance. Furthermore, there is a big impact of rising the minimum age for using burnt wood from 9 to 10 years. Changing tuseFire from 9 to 10 years only allows the wood demand to be met during the first 9 years of the projection period. This will result in major fluctuations in carbon sequestration per year. sIMfLOR is the only tool of this kind developed for the Portuguese forest and at this point these results cannot be compared with those of any other forest simulator.

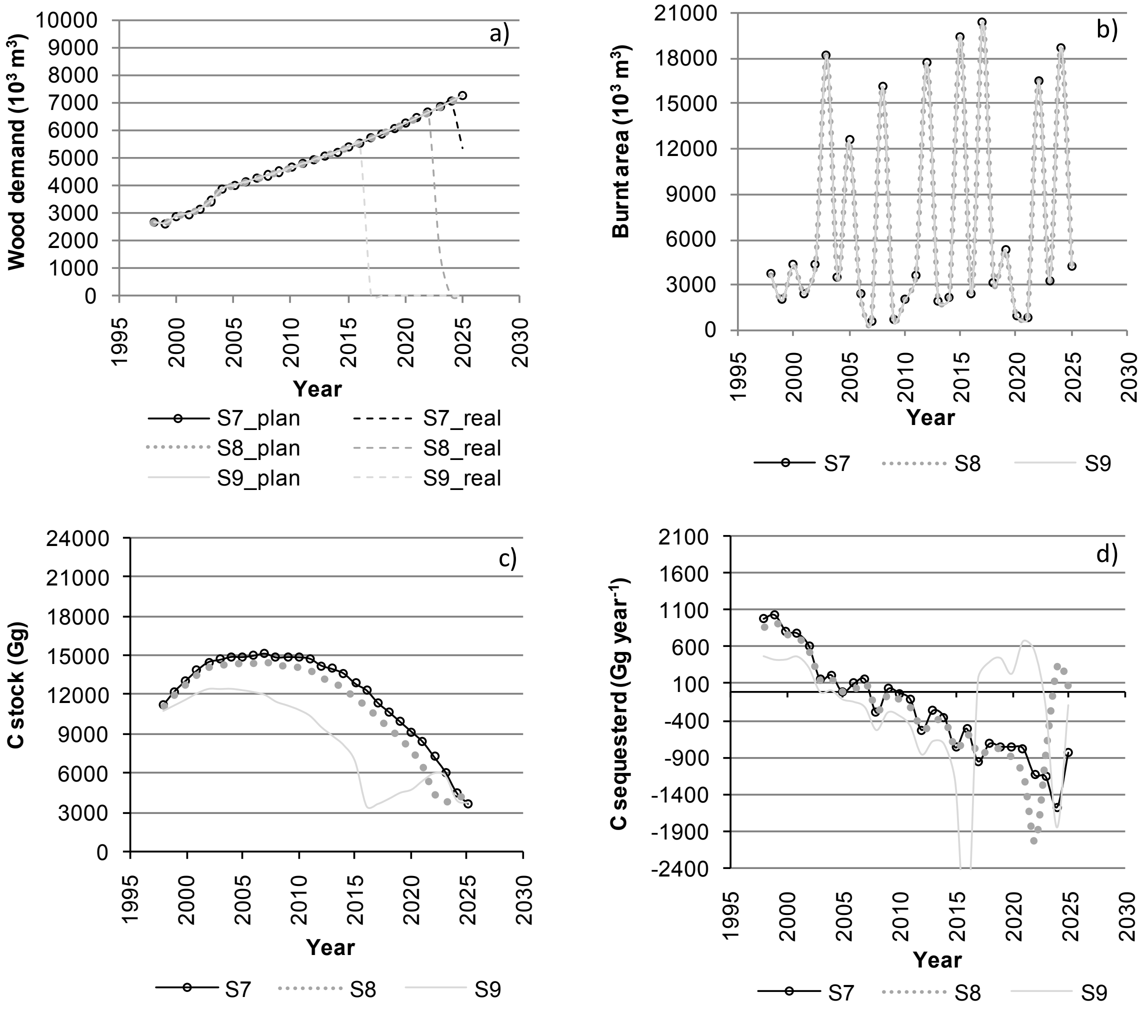

Figure 2.7. Evolution of the main drivers and indicators that characterize the wildest fire scenario S6 under different combinations of %UseFire and tuseFire. a) evolution of wood demand driver, where Sx_plan represents the wood demand defined in scenario and Sx_real represents the amount of volume that was available to be harvested under the user defined imposed restrictions; b) evolution of burnt area driver; c) evolution of carbon stock and d) evolution of carbon sequestered.

2.10 CONCLUSIONS

The analysis of the results shows the capacity of the simulator to respond to changes in wood demand and fire occurrence. As wood demand rates get higher and severe fires occur, in order to be able to respond to the wood demand in the course of the projection period, less restrictive minimum age thresholds will have to be combined with higher usage percentages of burnt wood. Since sIMfLOR integrates reliable growth models as long as quality data is used as input and reasonable assumptions on society needs are made it can be a powerful tool for explorative studies.

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Annex I – Globulus 3.0 Equations

Table I.1. Site Index and dominant height projection functions.

Models

$$(1)\ SI = A\left(\frac{\text{hdom}}{A}\right)^{\left(\frac{t}{t_p}\right)^{n}} \qquad (2)\ \text{hdom}_2 = A\left(\frac{\text{hdom}_1}{A}\right)^{\left(\frac{t_1}{t_2}\right)^{n}} \qquad A = a_0 + a_1\ DR$$

model	a_0	a_1	n
(1) and (2)	29.0669	0.2880	0.4890

Table I.2. Basal area: initialization function (1) and growth projection function (2).

Models

$$(1)\ G = A_G e^{-k_G \left(\frac{1}{t}\right)^{\left(n_{Gp} + n_{GN}\right)}} \qquad (2)\ G_2 = A_G\left(\frac{G_1}{A_G}\right)^{\left(\frac{t_1^{\,n_{GN1}}}{t_2^{\,n_{GN2}}}\right)\left(\frac{t_1}{t_2}\right)^{\left(n_{Gp}\right)}}$$

$$A_G = (a_{G0} + a_{G1} DR) \qquad K_G = k_{G_0} + k_{G_1} SI + k_{G_2}\frac{100}{SI\ \sqrt{Npl}} + k_{G_3} rot$$

$$n_{Gp} = n_{G_0} + \frac{n_{G_1}}{\left(1 - \left(\frac{\cot a}{2000}\right)\right)} + n_{G_2} rot \qquad n_{GNi} = n_{G_3}\frac{N_i}{1000}$$

model	a_{G0}	a_{G1}	k_{G0}	k_{G1}	k_{G2}	k_{G3}	n_{G0}	n_{G1}	n_{G2}	n_{G3}
(1)	80.1683	0.2354	8.8294	-0.1876	3.3759	0.1180	0.4493	-0.0441	-0.0164	0.0655
(2)	80.1683	0.2354	-	-	-	-	0.4493	-0.0441	-0.0164	0.0655

Table I.3. Planted stand's density of trees initialization function (1), planted stand's density of trees growth projection function as weel as for coppices older than 3 years (2), coppice stand's density of living stools prediction function (3), Coppice stand's density of spouts for stands under 3 years of age (4) and Coppice stand's density of spouts for stands at 3 years of age (5).

Models

(1) $N = Npl\ e^{-am\ t}$ (2) $N_2 = N_1\ e^{-am\left(t_2 - t_1\right)}$

(3) $N_{stools} = N_{trees\ at\ harvest}\ e^{-am\left(t_2 - t_1\right)}$ $am = am_0 + am_1 rot + am_2 \frac{Npl}{1000} + am3 \frac{1}{SI}$

(4) $N_{sprouts\ t \le 2} = b_0\ N_{stools} + b_1\ t$

(5) $N_{sprouts\ t=3} = N_{stools} \left(1 - e^{\frac{1}{-\left(am_2 \frac{N_{stools}}{1000} + am_3 \frac{1}{SI} \right)}} \right)$

model	am_0	am_1	am_2	am_3	b_0	b_1	b_2	b_3
(1)	0.0104	-0.0025	0.0023	-	-	-	-	-
(2)	0.0104	-0.0025	0.0023	-	-	-	-	-
(3)	0.0147	-0.0025	-	-	-	-	-	-
(4)	-	-	-	-	4.26831	285.96252	-	-
(5)	-	-	0.4050	13.6400	-	-	-	-

If there is any kind of thinning rule model 5 won't be needed.

Table I.4. Volume initialization function (1) and Volume projection function (2),

Models

$$(1)\quad V_i = Kv\; t^a\; hdom^b\; G^c \qquad kv = kv_0 + kv_1 rot + \left(\frac{kv_2}{1 - \left(\frac{\cot a}{2000} \right)} \right) + kv_3 \frac{100}{SI\sqrt{N_0}}$$

$$(2)\quad V_{i2} = V_{i1} \left(\frac{t_2}{t_1} \right)^a \left(\frac{hdom_2}{hdom_1} \right)^b \left(\frac{G_2}{G_1} \right)^c$$

model	a	b	c	kv0	kv1	kv2	kv3
(1) Vu	-0.0510	0.9982	1.0151	0.3504	0.0011	0.0049	0.0908
(2) Vu	-0.0511	0.9982	1.0151	-	-	-	-
(1) Vb	-0.0548	0.7142	1.0513	0.1502	-	0.0014	0.1336
(2) Vb	-0.0548	0.7142	1.0513	-	-	-	-
(1) Vst	-0.0821	0.3440	0.9914	0.0567	-0.0002	-	0.0104
(2) Vst	-0.0821	0.3440	0.9914	-	-	-	-

Where N0 represents Npl for planted stands and N sprouts by age of 3 years for coppice stands

Table I.5. Mercantile volume above stump without bark up to a predefined top diameter prediction function.

Model

$$Vumdi = (Vu - Vst)\, e^{a\left(\frac{di}{dgdom} \right)^b}$$

$$a = a_0 + a_1 rot + a_2 \left(\frac{Npl}{1000} \right) + a_3 \left(\frac{100}{SI\sqrt{N_0}} \right) + \left(\frac{a_4}{1 - \left(\frac{\cot a}{2000} \right)} \right) \qquad b = b_0 + b_1 rot$$

model	a_0	a_1	a_2	a_3	a_4	b_0	b_1
V umdi	-1.1075	-0.3436	0.0741	1.2604	0.2660	3.1854	0.5513

Where N0 represents Npl for planted stands and N sprouts by age of 3 years for coppice stands

Table I.6. Biomass functions.

Models

$$W_i = a\ G^{b}\, hdom^{c} \qquad b = b_0 + b_1 rot + b_2\left(\frac{N}{1000}\right) + b_3\left(\frac{SI}{1000}\right) + b_4\left(\frac{t}{1000}\right)$$

$$W_a = W_w + W_b + W_l + W_{br} \qquad W_r = a\ W_a \qquad W_t = W_a + W_r$$

model	a	b_0	b_1	b_2	b_3	b_4	c
W_w	0.0967	1.0547	-0.0018	-0.0065	-0.5198	-1.2105	1.1886
W_b	0.03636	1.1691	-0.0083	-0.0459	3.2289	2.0880	0.6710
W_l	1.0440	1.0971	-	-0.0112	-1.2207	-6.2807	-0.3129
W_{br}	0.3972	1.0005	-	-0.0192	3.3170	-1.2747	-0.0160
W_r	0.2487	-	-	-	-	-	-

Table I.7. List of symbols used in the equations.

DR – weight average of the central values of the classes of the number of days with precipitation ≥ 0.1 mm found in each square of the grid (cm);

SI – Site Index, which is the stand's dominant height at the age of 10 years (m);

t – Stand age (years);

t_1 – Stand age at instant 1 (years);

t_2 – Stand age at instant 2 (years);

t_p – Standard age, which for eucalyptus corresponds to 10 years (years);

hdom – Stand sominant height (m);

$hdom_1$ – Stand dominant heigh at instant 1 (m);

$hdom_2$ – Stand dominant heigh at instant t_2 (m);

N – Stand density (ha^{-1});

N_1 – Stand density at instant 1 (ha^{-1});

N_2 – Stand density at instant 2 (ha^{-1});

Npl – Stand density at plantation (ha^{-1});

N_{stools} – Number of stools after the first harvest (ha^{-1});

$N_{sprouts\ t\leq 2}$ – Number of sprouts before sprouts selection (ha^{-1});

$N_{sprouts\ t=3}$ – Number of sprouts after sprouts selection (ha^{-1});

rot – dummy variable with 0 representing planted stands and 1 representing coppice stands;

cota - weight average of the central values of the classes of altitude found in each square of the grid (m);

Rain - weight average of the central values of the classes of total precipitation found in each square of the grid (mm);

Frost - weight average of the central values of the classes of nr of days with frost in a year found in each square of the grid;

Temp - weight average of the central values of the classes of the yearly averages of the daily average temperature found in each square of the grid (ºC);

G – Stand basal area (m^2 ha^{-1});
G_1 – Stand basal area at instant 1 (m^2 ha^{-1});
G_2 – Stand basal area at instant t_2 (m^2 ha^{-1});
V_u – Stand volume under-bark with stump (m^3 ha^{-1});
V_b – Stand volume of bark (with stump?!) (m^3 ha^{-1});
V_{st} – Stand volume of stump (m^3 ha^{-1})
V_{umdi} – Stand mercantile volume without stump and bark up to a top diameter of di (m^3 ha^{-1});
di – top diameter with bark (cm);
dgdom – Stand quadratic mean d.b.h of the dominant trees (cm^2 ha^{-1});
W_i – Stand biomass per component, where i represents: w, b, l, br or r (Mg ha^{-1});
W_w – Stand wood biomass (Mg ha^{-1});
W_b - Stand bark biomass (Mg ha^{-1});
W_l – Stand leaves biomass (Mg ha^{-1});
W_{br} - Stand branches biomass (Mg ha^{-1});
W_r - Stand roots biomass (Mg ha^{-1});
W_a – Stand aboveground biomass (Mg ha^{-1});
W_r - Stand belowground (roots) biomass (Mg ha^{-1});
W_t - Stand total biomass (Mg ha^{-1});

Annex II – Pinaster1.0 Equations

Table II.1. **Site Index and dominant height projection function**

Models

(1) $S = A\left(\frac{hdom}{A}\right)^{\left(\frac{t_i}{50}\right)^{\beta 0}}$ (2) $hdom_{i+1} = A\left(\frac{S}{A}\right)^{\left(\frac{t_i}{t_{i+1}}\right)^{\beta 0}}$

model	**A**	β0	**Reference**
1 and 2	69	0.4582	*Tome et al, 2001*

Table II.2. Diameter equations when hdom ≥ 2m

Models

(1) $ddom = \beta 0 + \beta 1\ hdom - \frac{\beta 2}{t} + \beta 3\ \sqrt{N}$ (2) $dg = 100\sqrt{\left(\frac{4 \times G}{\pi \times N}\right)}$

(3) $dmed = dg\left(1 - \exp\left(\beta 0\ dg^{\beta 1 - \beta 2\ BE}\right)\right)$ (4) $dmediana = \beta 0\ N^{\beta 1}\ e^{\beta 2\ BE} dg$

(5) $dmin = \beta 0\ dg^{\beta 1 + \beta 2\ BE}\ N^{\beta 3\ BE}\ t^{\beta 4\ BE}$ (6) $dmax = \beta 0\ N^{\beta 1 + \beta 2\ BE}\ G^{\beta 3}\ e^{\beta 4\ hdom}$

Variable	**model**	β0	β1	β2	β3	β4	**Reference**
ddom	1	5.6622	1.2185	45.1595	0.0470		*Faias S.P., 2008*
dmed	3	-1.165	0.4078	-0.0926			*Fonseca T. 2004*
dmediana	4	1.1598	-0.0258	-0.0202			*Fonseca T. 2004*
dmin	5	0.1105	1.5456	0.6694	-0.1245	-0.4764	*Fonseca T. 2004*
dmax	6	69.1418	-0.3052	0.01807	0.3334	0.0056	*Fonseca T. 2004*

Table II.3. **Basal area: initialization function (1) and growth projection function (2) when hdom ≥ 2m.**

Models

(1) $G_i = \beta 0 \ hdom_i^{\beta 1} \left(\frac{N_i}{1000} \right)^{\beta 2} e^{\left(\frac{\beta 3}{t_i} \right)}$

(2) $G_{i+1} = \left[G_i^{0.5} + \beta 0 \ e^{\beta 1 \ t_i} \left(1 - e^{\beta 2 \ (t_{i+1} - t_i)} \right) \right]^2 e^{\beta 3 \ \frac{(N_i - N_{i+1})}{N_{i+1}}}$

Variable	model	□̃	□ ı	□ □	□ □	Reference
G_i	1	3.0850	0.9604	0.6814	-13.3722	*Faias S.P., 2008*
G_{i+1}	2	14.5661	-0.0306	-0.0306	-0.7223	*Fonseca T. 2004*

Table II.4. **Stand density Equations**

Models

(1) $N_{i+1} = N_i \ e^{\left(\frac{\beta 0 \ (t_{i+1} - t_i)}{100 \ fw} \right)}$

(2) IF dg$_i$<75 mm ⇔ $N_{max_{i+1}} = \beta 0 - \beta 1 \ hdom_{i+1}$

(3) IF dg$_i$>75 mm ⇔ $N_{max_{i+1}} = e^{(\beta 0 - \beta 1 \ \ln dg_i)}$

Variable	model	□̃	□ ı	Reference
N_{i+1}	1	-0.1508		*Fonseca T., 2004*
$Nmax_{i+1}$	2	19023	1372.9	*Faias S.P., 2008*
$Nmax_{i+1}$	3	12.8687	1.8794	*Faias S.P., 2008*

Table II.5. **Equations for the thinning module**

Spacing index – Wilson factor

(1) IF $fw_i > fw_{\text{desbaste}}$ ⇔ $Fw_i = \frac{100}{\sqrt{N_i} \times hdom_i}$

(2) IF $fw_i < fw_{\text{desbaste}}$ ⇔ $N_{after} = \frac{10000}{(fw \times hdom)^2}$

(3) $G_{after} = G_{before}\left(\frac{N_{after}}{N_{before}}\right)^{\beta 0\ G_{before}^{\beta 1}}$

Variable	model	□̃	□ ı	Reference
G	2	2.0310	-0.3539	*Fonseca T., 2004*

Basal area

(1) Percentage of G removed: $G_{after} = G_{before} - G_{before} \times \%G$

(2) Residual G: IF Gbefore< Gresidual ⇔ Gafter=Gbefore or IF Gbefore> Gresidual ⇔ Gafter=Gresidual

(3) $N_{after} = N_{before}\left[1-\left(1-\frac{G_{after}}{G_{before}}\right)^{\beta 0}\right]^{\beta 1}$

Variable	model	□̃	□ ı	Reference
N	3	0.715054	0.820574	*Pascoa F., 1987*

Table II.6. **Equations used when dg < 7.5 cm**

Volume and Biomass Models

(1) $V = \frac{k}{\exp\left(\frac{\beta 0 + \beta 1\ S}{hdom}\right)}$ $k = V_{dg\approx 7.5} \exp\left(\frac{\beta 0 + \beta 1\ S}{hdom_{dg\approx 7.5}}\right)$

(2) $W_i = \beta 0\ + \beta 1\ V$

Variable	model	□̃	□ ı	Reference
V	1	9.609754	1.080492	*Oliveira, 1985*
Wa	2	0.82753	0.67531	*Faias S.P., 2008*
W	2	2.17274	0.93846	*Faias S.P., 2008*

Table II.7. **Equations used for the estimation of stand volume and biomass with the simulated diameter distribution when dg ≥ 7.5 cm**

Diameter and Height Models

(5) $h = hdom\left(1+\left(\beta 0+\beta 1\frac{N}{1000}\right)e^{\beta 2\ hdom}\right)\left(1-e^{-\beta 3\frac{d}{ddom}}\right)$

Variable	model	□̃	□ 1	□ □	□ □	□ □	Reference
h	5	0.0795	0.0211	0.0254	-1.1658		*Tome et al, 2008*

Volume Models

(1) $v = \beta 0\left(\frac{dl}{100}\right)^{\beta 1} h^{\beta 2}$ (2) $v_{di} = e^{\left(\beta 0\frac{di^{\beta 1}}{d^{\beta 2}}\right)}$

Variable	model	□̃	□ 1	□ □	Reference
V	1	0.7520	2.0706	0.8031	*Tome et al, 2008*
Vu	1	0.4585	2.1373	0.9122	*Tome et al, 2008*
Vd	2	-0.7084	4.5312	4.3164	*Tome et al, 2008*
Vud	2	-1.4130	4.3488	4.3188	*Tome et al, 2008*

Biomass Models

(1) $W_i = \beta 0\ d^{\beta 1} h^{\beta 2}$ (2) $W_i = \beta 0\ d^{\beta 1}\left(\frac{h}{d}\right)^{\beta 2}$

i=s,b,br,l,r $W_a = W_s + W_b + W_l + W_{br}$ $W_t = W_a + W_r$

Variable	model	□̃	□ 1	□ □	Reference
Ws	1	0.01460	1.9468	1.1066	*Tome et al, 2008*
Wb	1	0.01140	1.8728	0.6694	*Tome et al, 2008*
Wbr	2	0.00308	2.7576	-0.3938	*Tome et al, 2008*
Wl	2	0.00998	1.3925	-0.7196	*Tome et al, 2008*
Wr	1	0.455	1.1294		*Tome et al, 2008*
Wc	1	147.7	2.4977		*Tome et al, 2008*

Table II.8. List of symbols used in the equations.

[dmed] mean diameter (cm)
[dmin] minimum diameter (cm)
[dmax] maximum diameter (cm)
[dcentral] central diameter class (cm)
[dtop] top diameter (cm)
[$d_{0.50}$] median diameter (cm)
[ddom] dominant diameter (cm)
[dg] mean quadratic diameter (cm)
[fw] wilson factor (spacing index)
[BE] stand structure (0-regular; 1-irregular)
[G] Basal area (m^2 ha^{-1})
[hmed] mean height (m)
[hdom] dominant height (m)
[N] stand density (number of trees per ha)
[S] site index (m)
[t] stand age (years)
[V] Total volume over bark with stump (m^{3}ha^{-1})
[Vu] Total volume under bark with stump (m^{3}ha^{-1})
[Vm] Merchantable volume over bark with stump (m^{3}ha^{-1})
[Vum] Merchantable volume under bark with stump (m^{3}ha^{-1})
[$V_{classeA}$] Volume over bark to diameter > 20cm (m^{3}ha^{-1})
[$V_{classeB}$] Volume over bark to 12 cm < diameter < 20 cm (m^{3}ha^{-1})
[$V_{classeC}$] Volume over bark to 6 cm < diameter < 12 cm diameter (m^{3}ha^{-1})
[V_{Top}] Volume over bark to top diameter 6 cm (m^{3}ha^{-1})
[W] Total biomass (t ha^{-1})
[Wa] Aboveground biomass (t ha^{-1})
[Ws] Stem biomass (t ha^{-1})
[Wb] Bark biomass (t ha^{-1})
[Wbr] Branches biomass (t ha^{-1})
[Wl] Leaf biomass (t ha^{-1})
[Wr] Roots biomass (t ha^{-1})
[Wc] Pine cones biomass (t ha^{-1})

3 RegWise: Regional simulator for Swedish forests

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Abstract:

RegWise is a new forest simulator designed for long-term simulation of Swedish forest development using mainly National Forest Inventory data as input. The simulator is one of several applications of the Heureka system developed at SLU for multipurpose forestry analysis and planning. RegWise works for all types of forests, pure and mixed-stands as well as even-aged and uneven-aged forests. All species important for wood production in Sweden such as Scots pine, Norway spruce, Birch, Lodge-pole pine, Oak and Beech can be dealt with the simulator. Basically, RegWise rely upon forecasts of the tree-layer development and output of goods and services are a result of treatments and the state of the tree layer for each five-year period. Assumptions on extent and intensity of different treatments (forest management actions) are defined by the user and influenced by drivers such as wood demand, economic development, forest owner behaviour and forest policy impact. Results of simulations are evaluated in terms of outputs of goods and services expressed by a large set of indicators for each period.

Key words: Sweden, forest simulator, Scots pine, Norway spruce, wood demand, biomass, carbon sequestration.

3.1 INTRODUCTION TO REGWISE

RegWise is a regional simulator designed for long-term forecasts of the development of the Swedish forests. It is suitable for assessments of the future state of the forest and goods and services produced for long-time horizons with specified assumptions on future wood demand and forest management. The model simulates the state of the forest witg different management actions and conditions defined by the user. Although using a simulation approach an optimization module is a potential option within the Heureka framework. RegWise considers all type of stands, both pure and mixed stands as well even-aged as uneven aged stands.

The main input data source is National Forest Inventory (NFI) data. The basic output of the simulator is indicators reporting the state of the forest and output of goods and services for five-year periods. Examples of indicators are volumes of growing stock, tree species distribution, harvested areas and volumes, amount of biomass in growing stock and harvested trees, carbon stocks and a wide set of social, economic and environmental indicators.

The simulator is at present under development within the Heureka research programme (http://heureka.slu.se) at the Swedish University of Agriculture Sciences (SLU). It is one of several applications of the Heureka system developed for multipurpose forestry analysis and planning. Other applications concern, e.g., planning on estate level (PlanWise) and individual stand analysis (StandWise).The development of the simulator is not finalised, but a beta version exists with most models implemented. This paper describes the current version and to some extent models that will be implemented in the near future.

3.2 REGWISE – APPROACH AND STRUCTURE

The basic approach adopted in RegWise for evaluating future development on a forest area is to run simulations based on assumptions of different treatments (forest management actions) defined by the user and evaluate the consequences in terms of outputs of goods and services expressed by a set of indicators. Normally, the assumptions of management strategies is based on interpretation of drivers such as wood demand, economic development, forest owner behaviour and forest policy impact.

Basically, RegWise rely upon forecasts of the tree-layer as described in figure 3.1. Simplified, output of goods and services are a result of treatments and the state of the tree layer for each period.

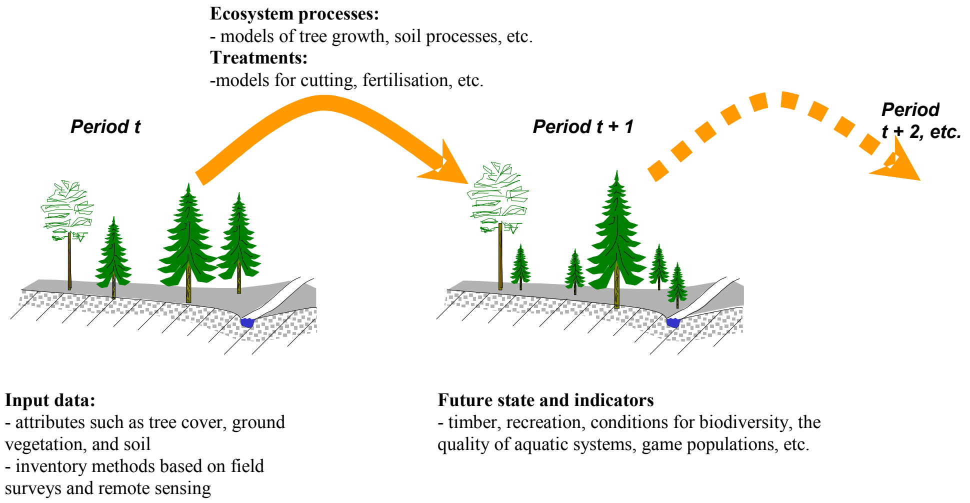


Figure 3.1 Outline of RegWise forecasts of the tree layer.

A forecast with RegWise can be divided in five steps, see figure 3.2.;

1. Select forest inventory information in the analysis area to get a description of the forest resources, see chapter 3.3.
2. Translate important drivers having an influence on the future forest development and parameterise it in models guiding treatments in RegWise. By changing parameters for treatments such as areas regenerated by plantation and volumes cut for forest treatments as cleaning, thinning and clear-cutting the simulator will direct development in a way that corresponds to expected influence of the drivers.
3. Associate forest areas to FMA;s, see chapter 3.5.1. FMA:s brings together sequences of treatments for a rotation period.
4. Choose suitable ecosystem processes models such as single tree growth models, growth models for young forests and mortality models.
5. Choose which indicators to report, see chapter 3.7

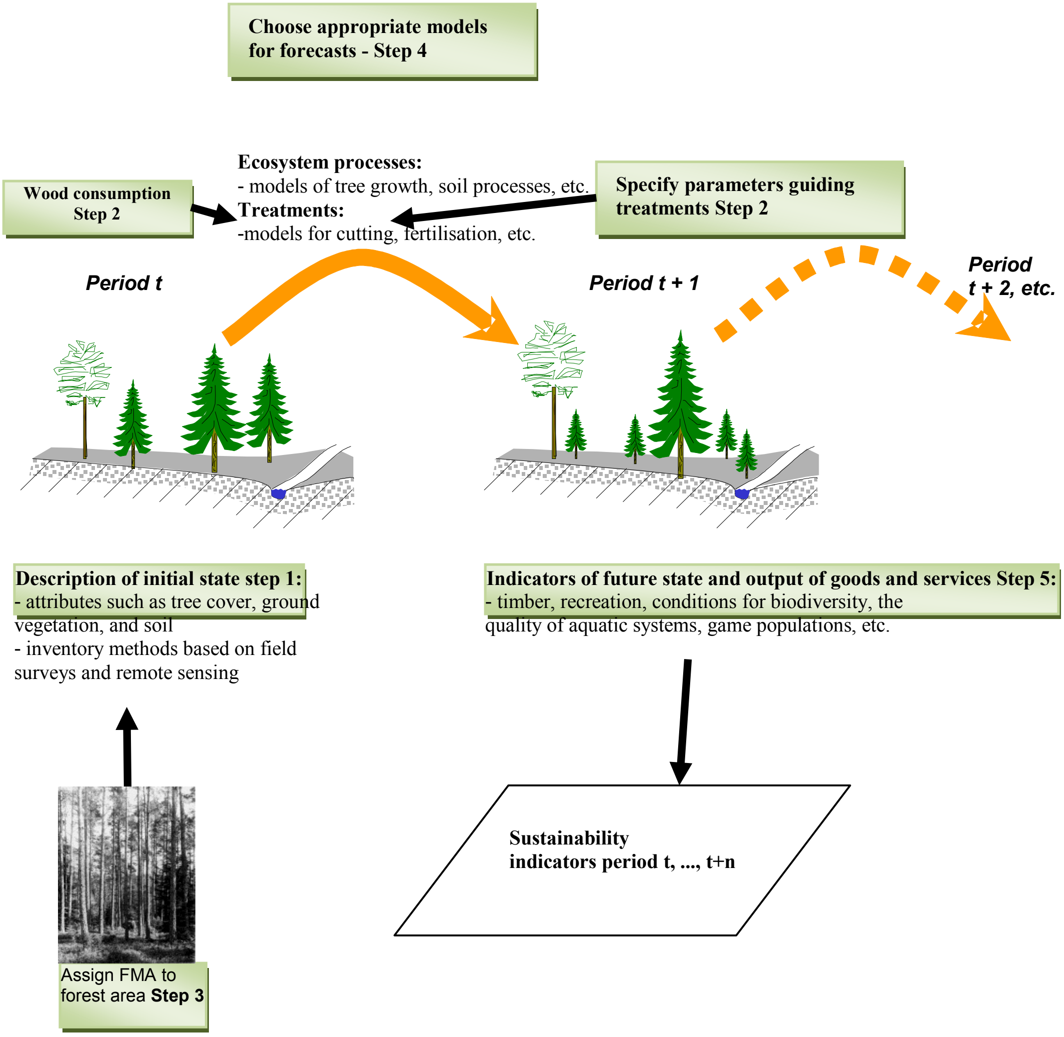
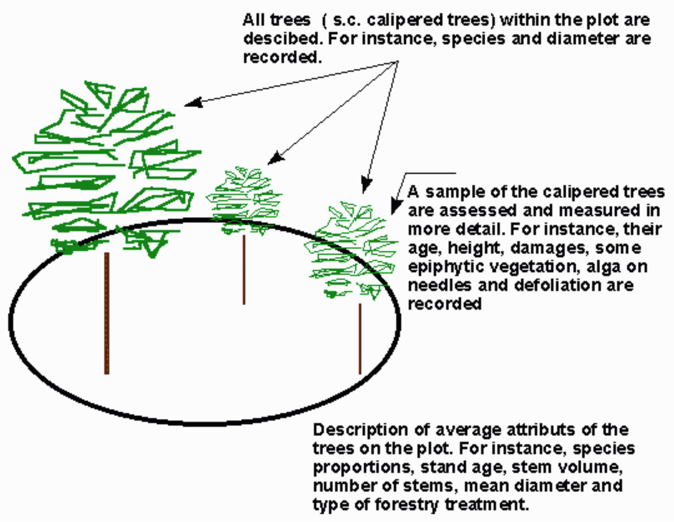


Figure 3.2 Outline of running the regional simulator RegWise.

3.3 INPUT DATA

3.3.1 Description of initial state

To be able to predict future forest development, a good description of the initial state on the forest area being analysed and information about other factors that may influence the evaluations are needed. In case of RegWise, the most important data is acquired from NFI sample plots, see figure 3.3.



All trees (s.c. calipered trees) within the plot are descibed. For instance, species and diameter are recorded.

A sample of the calipered trees are assessed and measured in more detail. For instance, their age, height, damages, some epiphytic vegetation, alga on needles and defoliation are recorded

Description of average attributs of the trees on the plot. For instance, species proportions, stand age, stem volume, number of stems, mean diameter and type of forestry treatment.

<u>Types of collected inventory data</u>

- Tree and shrub layer
- Ground vegetation
- Humus layer and mineral soil
- Site conditions
- Position in landscape

Figure 3.3 Description of NFI sample plots.

Input data are stored in a relational database (SQL server) consisting of data mainly from NFI with data for the years 1983 to 2007. Other external data such as data forming restrictions on forest management on plot or stand level is imported from other sources as digital map data.

The data can be divided into groups as seen in table 3.1.

Table 3.1 Description of database

Type of input data	Example of variables
Tree	Type of tree, species, diameter and height.
Plot	Site index, soil moisture, altitude, latitude, vegetation type, maturity class and dominant species.
Treatment unit	Owner, weight for scaling up, geographical location and restrictions on management.
Treatment history	Data on treatments made up to 25 years back in time.
Young forest database	Database with more than 4700 plots with forest state (number of stems and height distribution) at 3 meters mean height associated to performed treatment after final felling. The plots are used to simulate initial state of new forest on bare land or after final felling.

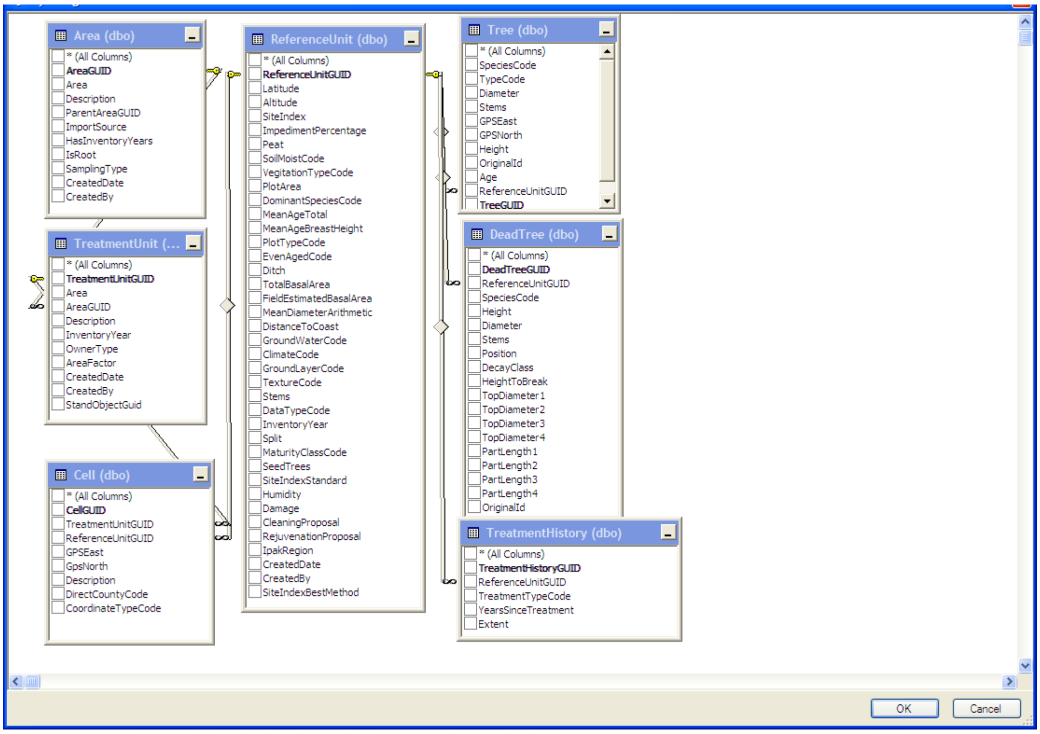


Figure 3.4 Example of tables in input database

3.3.2 Use of data

RegWise is developed to use individual NFI sample plots or combination of sample plots and remote sensing data enabling spatial comprehensive (wall-to-wall) data representing the landscape. Within EFORWOOD the individual sample plot approach is used where single NFI sample plots makes up treatments units, see figure 3.5. Each tree and sample plot has a weight scaling up the trees and plots to represent the analysis area. The size of the weights depends on sample plot size and the number of inventoried plots within the forest area analysed.

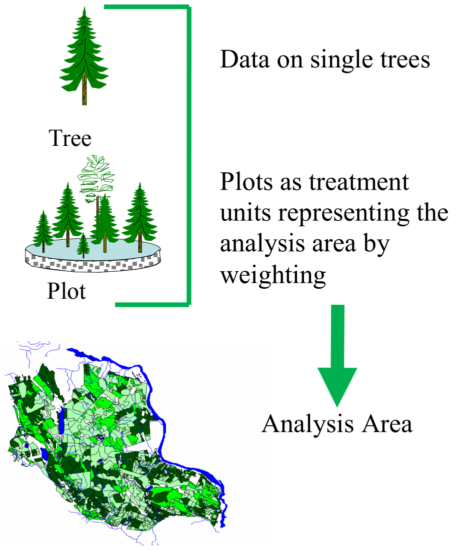


Figure 3.5 Data use in RegWise in individual sample plot approach (typically NFI data).

3.4 REGWISE - THE DRIVERS

Drivers the forest development can be translated in the simulator by two main drivers: i) the wood demand which has implications on the amount of harvest per year; ii) treatments with different intensity assigned to optional forests within analysis area (the four EFORWOOD FMAs; even-aged, combined objective, close to nature and nature conservation, can be defined but the simulator makes arbitrary definitions of FMAs possible, se section 3.5.1).

The influence of a driver for each period can be given in different ways; as a fixed or a proportion. An example is fertilization that can be performed on a fixed area each period or on a proportion of an area suitable for the treatment. The probability of occurrence of the event is estimated according to priority functions (normally parameterised by the user).

3.4.1 Hazards occurrence

Occurrence of hazards as drivers comprises different types of hazards such as fire, pests and diseases and storms. So far, none of these drivers have been implemented specifically in the simulator as catastrophic (large scale) events. However, natural mortality containing some of these hazards indirectly makes up an important part in the simulator and thereby having an effect on the outcomes. Natural mortality models in RegWise simulates probability of natural mortality on plot and single tree level based on plot variables (Fridman, J. & Ståhl, G. 2001).

3.4.2 Wood demand

It is up to the user to define the total amount of volume harvested in five-year periods of the simulation distributed on felling forms (thinning and final felling). This can be done either by specifying fixed values of volumes to be cut per period or relate cutting volumes to current and future growth based on a model, see equation 3.1. The distribution on clear-cut and thinning is automatically calculated based on productivity an age-class distribution. The plots are cut according priority rules (equation 3.2 and 3.3) until cuttings reach the demand of wood set by the user or calculated. The same is valid for treatments guided by defining areas such as cleaning areas.

$$(3.1)\ \boldsymbol{Total_p} = \boldsymbol{T_p} \cdot \left[\frac{\boldsymbol{T_{p-1}}}{\boldsymbol{T_{p-2}}}\right]^{\alpha} \cdot \left[\frac{\boldsymbol{V_p}}{\boldsymbol{V_{goal}}}\right]^{\beta} \cdot \left[\frac{\boldsymbol{A}_{>1.0}}{\boldsymbol{R}_{>1.0}}\right]^{\chi} \cdot \left[\frac{\boldsymbol{A}_{>0.9-1.0}}{\boldsymbol{R}_{>0.9-1.0}}\right]^{\delta} \cdot \left[\frac{\boldsymbol{A}_{>0.7-0.9}}{\boldsymbol{R}_{>0.7-0.9}}\right]^{\varepsilon},$$

where

Total = total cutting volumes period p for all felling forms.
p = period
T = growth
V = Growing Stock
V_{goal} = advisable growing stock calculated by model
A = available area in age-class (> 1.0 means older than lowest allowable clear-cutting age, 0.7 – 0.9 within age 0,7 – 0,9 times lowest age, etc)
R = desirable area in age-class
$\alpha,\beta,\chi,\delta,\varepsilon$ = parameters set by user

Harvest probabilities for clear-cut on a plot are calculated for each sample plot whit a priority function Ps and for thinning with Pg.

$$(3.2)\ Ps = \frac{1}{Pv}$$ *(High number implieshigh priority for clear-cut)*

where

Pv is current growth divided by growing stock.

$$(3.3)\quad Pg = \frac{Gf - Gr}{Gm - Gr} + a \cdot H + b \cdot H100 + c \cdot \text{Deciduous}$$

Pg = Priority number (high number – high priority for thinning)
Deciduous = share of deciduous of growing stock
H = height of dominant trees
Gf = Current basal area on plot
Gr = Recommend basal area
Gm = Highest recommended basal area
H_{100} = Mean height of dominant conifer trees

Gr and Gm are calculated by models dependent on parameters set by the user.

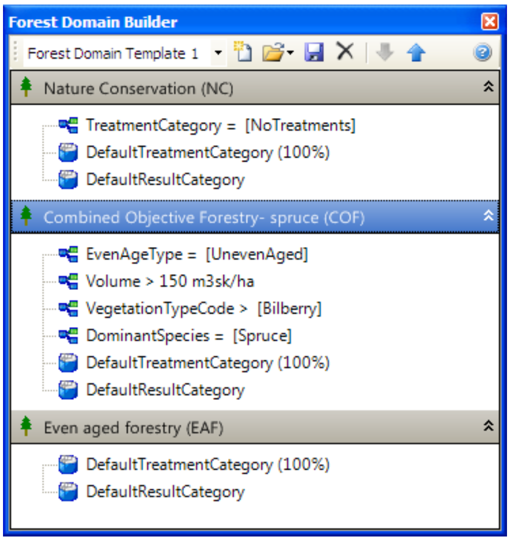
3.4.3 Land use changes

In the current version of RegWise there is no algorithm included for land-use changes. Historically, the land-use changes in Sweden last 50 years have been very small with almost constant area of forest.

3.5 REGWISE - TREATMENTS

3.5.1 Forest management alternatives

The user can associate FMA's to treatment units in a flexible way by specifying site and tree cover criteria to allow a FMA to be applied on a plot. The criteria are based on data available in input data. Figure 3.6 shows an example where criteria for selection has been used to associate FMA's to plots. The different FMA's have different parameter settings, e.g., for extraction of trees in thinning, regeneration and fertilizations.



Nature Conservation (NC)
- TreatmentCategory = [NoTreatments]
- DefaultTreatmentCategory (100%)
- DefaultResultCategory

Combined Objective Forestry- spruce (COF)
- EvenAgeType = [UnevenAged]
- Volume > 150 m3sk/ha
- VegetationTypeCode > [Bilberry]
- DominantSpecies = [Spruce]
- DefaultTreatmentCategory (100%)
- DefaultResultCategory

Even aged forestry (EAF)
- DefaultTreatmentCategory (100%)
- DefaultResultCategory

<u>**FMA**</u>

NC - No forest management on these treatment units

COF - Single tree selection system with recurrent thinning from above.

EAF - Even aged forest management with plantation or seed trees

Figure 3.6 Example of association of forest to FMA's.

3.5.2 Regeneration

When a final felling is applied the plot is regenerated by using data from the young forest database based on assumptions of regeneration treatments specified by the user;

- Method used – share of methods (plantation, seed trees, sowing or doing nothing) are set for moisture classes (dry, fresh and moist) in percentage.
- Soil preparation - share of soil scarification in percentage on regenerated area dependent on method.
- Species to plant – share of species in percentage if planting for moisture classes and site index classes.

Which method applied on (suitable) single plots is stochastically distributed depending on shares.

3.5.3 Cleaning (pre-commercial thinning)

Firstly the user specifies height limits for cleaning in meters and the minimum number of stems allowed to be cleaned per hectare. Secondly, for each period the extent of cleaning is set as a fixed area or a proportion of area allowed for cleaning. Priority functions are used to direct cleaning to certain plots based on site index, mean height and proportion of deciduous trees.

3.5.4 Thinning

Thinning are simulated by specifying parameters deciding thinning form (from below – directing cutting towards smaller trees or from above – directing cutting towards larger trees) and removal distributed between tree-species (within conifers and between conifers and broad-leaved).
Total thinning volumes can be set by the user to a fixed value or estimated automatically as a share of total cuttings, see chapter 3.4.2. Priority of the single plot for thinning is calculated by function 3.3.

3.5.5 Final felling

Final felling volumes can be set to a fixed value per period or automatically estimated as a share of total cuttings, see chapter 3.4.2.

3.5.6 Other felling

Single-tree selection is simulated as repeated thinnings with the same framework as ordinary thinnings but with other parameter settings. Shelter wood forestry will also be implemented in RegWise as repeated thinnings. Special models estimating mortality of the shelter trees will be used.

3.5.7 Nature conservation

The implementation of a framework for simulating nature conservation will be done during the first months of 2009. Different types of nature conservation will be handled. For example plots within set-aside areas will be marked for FMA NC based on external data. Individual trees (“eternity trees”) or groups of trees left after final felling due to nature conservation considerations will be handled as well as plots near objects influencing management. Examples are plots near streams and lakes were forest management actions are restricted.

3.5.8 Cost and revenues

Costs for all treatments are included in the analysis. Some are specified as fixed costs per hectare such as costs for sowing, soil scarification and cleaning. Costs for harvesting and forwarding are estimated by models made by the Forestry Research Institute of Sweden (Skogforsk).

To calculate revenues from harvested volumes, type trees representing different diameter-classes and part of the stem (root, middle or other log) are optimally marked for cross cutting against a user specified pricelist and given a value. Trees cut in the system are then assigned values based on diameter class and part of stem.

Revenues from extracted residues are set to fixed revenue per ton.

3.6 REGWISE – ECOSYSTEM PROCESSES

The basic prediction unit is the single tree and the simulation unit is the plot. Each tree has a weight on plot level and each plot has a weight for the analysis area. RegWise is, however, also prepared for using wall-to-wall data. This by using plot data assigned to stands by using remote sensing data. An example of this approach is the use of satellite image data combined with NFI plots (Reese, H., Nilsson, M. et al. 2003).

3.6.1 Growth models for single trees and sample plots

The user can choose between two approaches for estimating growth and yield. In the first approach single tree models solely are used. In the second approach – which is recommended so far – growth is first estimated using area (plot) based models. Then, growth level from these models calibrates the growth levels estimated by single-tree models. On single-tree level growth are then assigned by calibrated single-tree growth levels. There are growth models for Scots pine, Norway spruce, Birch, Aspen, Beech, Oak and other deciduous species (Söderberg, U. 1986; Elfving, B. 2004).

3.6.2 Natural mortality

A three-step approach is used to estimate natural mortality, which consists of (I) estimating the probability of mortality on a sample plot; (II) quantifying the mortality in terms of proportion of basal area; and (III) distributing the mortality among individual trees. The system predicts the mortality for five years periods (Fridman, J. & Ståhl, G. 2001). This model is combined with a model that estimates the limit for self-thinning (Söderberg, U. 1986). If mortality stays below the limit the three-step approach is used, otherwise the model by Söderberg is used.

3.6.3 Ingrowth

The ingrowth model consists of four parts, describing: (I) Probability for occurrence of saplings (1-39 mm diameter at breast height (DBH)) on plots with r = 5 m. (II) Number of saplings on stocked plots (plots with saplings of target species). (III) Probability for ingrowth of a sapling over 39 mm DBH during a 5-year period. (IV) Diameter of ingrown trees at the end of the 5-year period. The model was based on data from NFI permanent plots. Separate functions were developed for seven species and species groups (Wikberg, P. E. 2004).

3.6.4 Dead wood volumes and decomposition

Initial volumes of dead-wood distributed on decay classes are available in the NFI plot data (dead-wood is defined as dead trees more than 10 cm in diameter). Supply of dead-wood in the forecasts is derived from the mortality models. The user specifies the share of dying trees that are utilised by the forest owner and rate of decomposition of biomass and volume for the dead-wood for different tree species based on literature e.g. (Harmon, M. E.,Krankina, O. N. et al. 2000) or expert guesses.

3.7 REGWISE - THE OUTPUT FILES

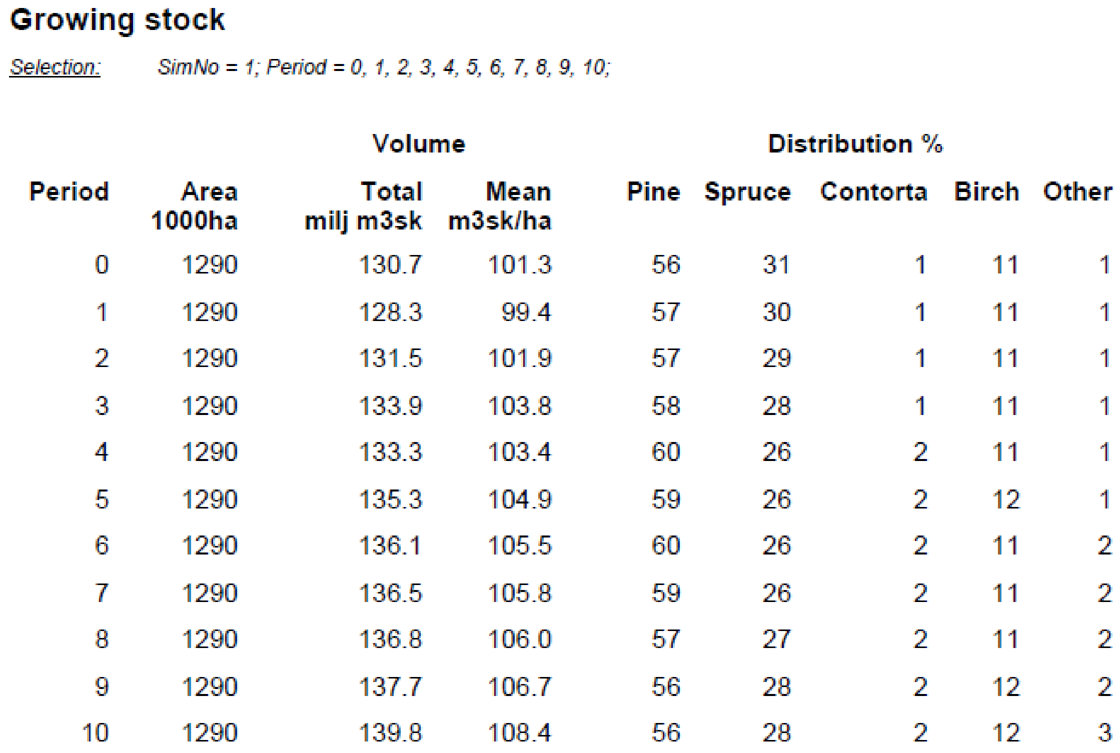
All results from a simulation is stored in a database (SQL server). The results for indicators for tree species and treatment units (plots) are put into tables based on type of indicator, see table 3.2. Parameter settings for the simulation is also stored in the database making it possible to rerun a more or less identical simulation. Data on forest domain areas associated to FMA's is also stored in the database. All this supports a very flexible reporting of results where tables and diagrams are made based by compile indicators.

Indicators reported can be classified in groups as follows:

Table 3.2. Description of output data

Type of output data	**Description of indicators (values on plot level per period)**
Biomass	Amount of biomass (dry weight) for parts of trees parts (stems, branches, needles, bark, roots and stumps) distributed on tree species
Dead-wood	Volumes for dead-wood distributed on tree species and decay classes on plot level. Carbon content distributed on tree species.
Diameter classes	Felled volumes and number of stems distributed on diameter classes.
Forest data	Age, height, volumes/ha, number of stems/ha and basal area/ha on standing forests per period.
Growth data	Net, gross and annual growth distributed on tree species
Mortality	Mortality volumes divided on tree species
Carbon	Carbon content in soil and living biomass above ground distributed on tree species.
Recreation	Recreation index
Species	Age, mean height, volumes/ha, number of stems/ha and basal area/ha on standing forests per period and tree species.
Treatment	Data on cuttings; Stems, volumes and basal area per ha. Average volume per stem, thinning form and intensity. Regeneration measures.
Value	Volumes of cuttings distributed on assortments. Costs for harvesting, forwarding, planting etc. Income from cuttings and net values.

Example of standard report in figure 3.7 and a diagram specified by user in figure 3.8.



Growing stock

Selection: *SimNo = 1; Period = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10;*

		Volume		Distribution %				
Period	Area 1000ha	Total milj m3sk	Mean m3sk/ha	Pine	Spruce	Contorta	Birch	Other
0	1290	130.7	101.3	56	31	1	11	1
1	1290	128.3	99.4	57	30	1	11	1
2	1290	131.5	101.9	57	29	1	11	1
3	1290	133.9	103.8	58	28	1	11	1
4	1290	133.3	103.4	60	26	2	11	1
5	1290	135.3	104.9	59	26	2	12	1
6	1290	136.1	105.5	60	26	2	11	2
7	1290	136.5	105.8	59	26	2	11	2
8	1290	136.8	106.0	57	27	2	11	2
9	1290	137.7	106.7	56	28	2	12	2
10	1290	139.8	108.4	56	28	2	12	3

Figure 3.7. Report summarised from database

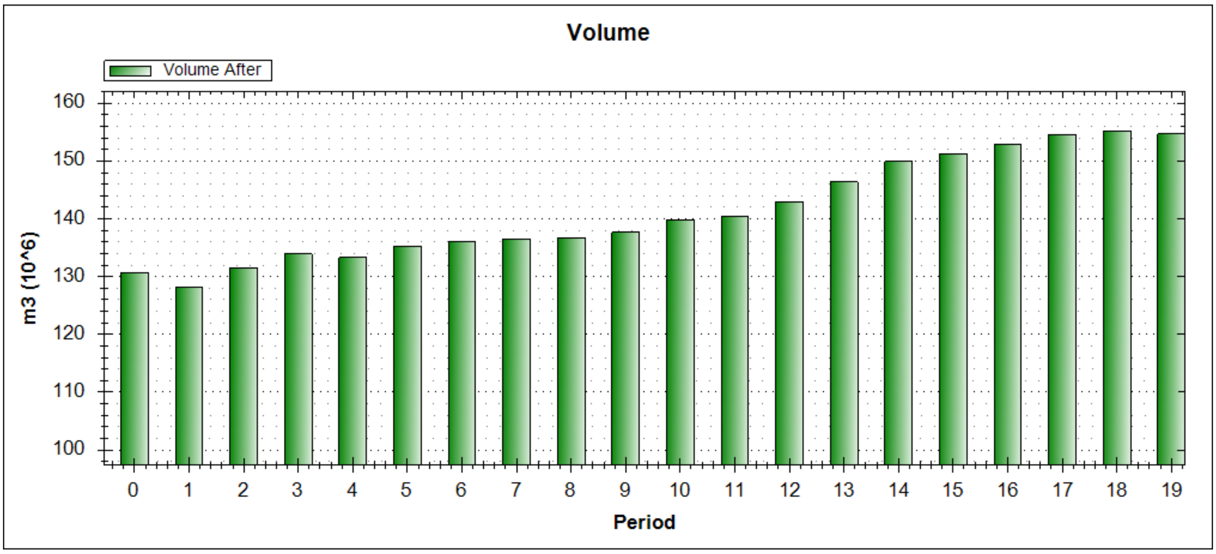


Figure 3.8. Diagram specified by user in RegWise.

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4 ESCEN: simulator of the Catalan forests

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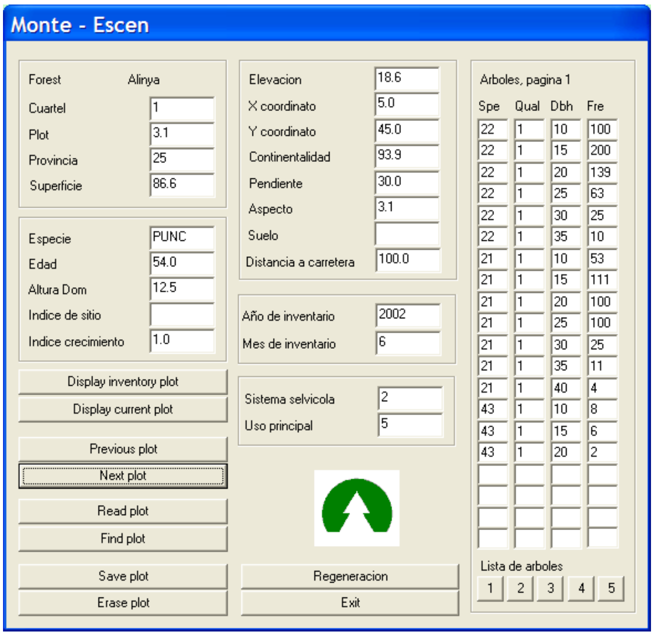
Abstract

ESCEN simulator has been used in the EFORWOOD project for comparative analyses purposes.

ESCEN is a regional forest resource simulator for Catalonia (Spain). The program calculates the present status (inventory results) of a forest region or can respond to *what if* scenario analysis questions for user-specified simulation horizons. The calculation unit can be a plot or a stand.



Forest Alinya
Cuartel 1
Plot 3.1
Provincia 25
Superficie 86.6

Especie PUNC
Edad 54.0
Altura Dom 12.5
Indice de sitio
Indice crecimiento 1.0

Elevacion 18.6
X coordinato 5.0
Y coordinato 45.0
Continentalidad 93.9
Pendiente 30.0
Aspecto 3.1
Suelo
Distancia a carretera 100.0

Año de inventario 2002
Mes de inventario 6

Sistema selvicola 2
Uso principal 5

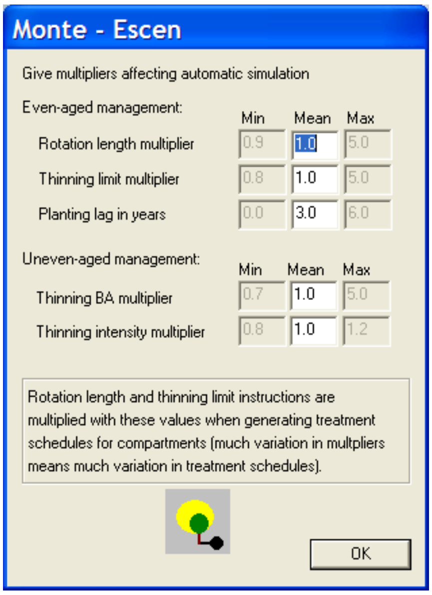
Arboles, pagina 1

Spe	Qual	Dbh	Fre
22	1	10	100
22	1	15	200
22	1	20	139
22	1	25	63
22	1	30	25
22	1	35	10
21	1	10	53
21	1	15	111
21	1	20	100
21	1	25	100
21	1	30	25
21	1	35	11
21	1	40	4
43	1	10	8
43	1	15	6
43	1	20	2

Figure 4.1. Data entry in ESCEN system.

ESCEN is suitable for even-aged and uneven-aged one-species stands or species mixtures. In every plot/stand, one species is the dominant species the simulation of regional scenarios uses: (a) individual tree models, (b) inventory data (National forest inventory plots) and (c) simulated management instructions. In addition, ESCEN integrates a fire occurrence and fire damaged model for Catalan forests, which can be run stochastically to simulate forest fires.

Management instructions can be defined separately for different species, sites and management systems and then they can be scaled. Therefore, different regional scenarios can be produced by changing the simulation instructions or by scaling them.


Monte - Escen

Give multipliers affecting automatic simulation

Even-aged management:

	Min	Mean	Max
Rotation length multiplier	0.9	1.0	5.0
Thinning limit multiplier	0.8	1.0	5.0
Planting lag in years	0.0	3.0	6.0

Uneven-aged management:

	Min	Mean	Max
Thinning BA multiplier	0.7	1.0	5.0
Thinning intensity multiplier	0.8	1.0	1.2

Rotation length and thinning limit instructions are multiplied with these values when generating treatment schedules for compartments (much variation in multpliers means much variation in treatment schedules).

Figure 4.2. Developing management instructions

ESCEN produces different output tables and figures for the different regional scenarios. ESCEN can calculate for a given simulated period the following regional-level variables:

- Volume development
- Biomass development
- Carbon stock
- Harvested volumes
- Areas of treatments

In addition ESCEN calculates plot or stand level information like the:

- Development of each plot
- Removals in each plot
- Virtual reality visualization of each plot

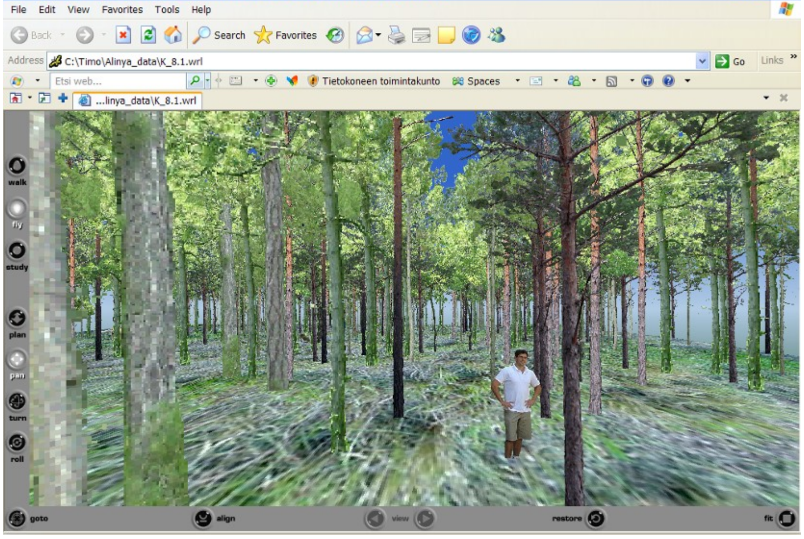


Figure 4.3: Virtual reality plot.

5 Sylvognene: simulator of the Maritime pine forests in Aquitaine (South West France)

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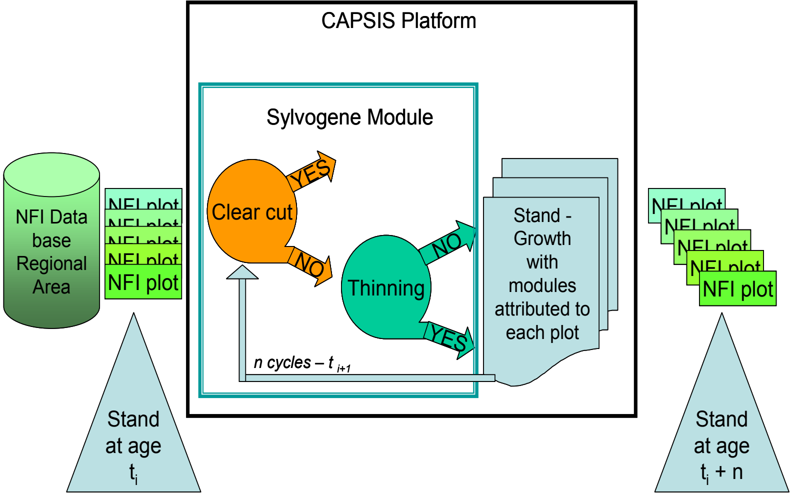
Abstract:

Sylvogene is a regional forest simulator. It was designed for long-term simulation using National Forest Inventory data as input. It was not connected to a GIS. This simulator belongs to the Capsis platform. This program is like a script with user interaction at the beginning only. It runs simulations with one or several Capsis modules dedicated to Maritime pine growth. It interacted with three types of growth modules: distance –independent tree growth model, stand model and diameter/age classe growth model. The two first types were designed for Maritime Pine. At present, it only considers pure stands of Maritime pine of South-West France, but it was designed in order to consider other species and mixed forests depending on different modules interactions.

This abstract describes the present status of the simulator and the improvements that are expected in the short term. At the moment, our work focused on NFI input data and the connection with our different growth models. We defined the control variables that are needed to choose the proper growth model able to manage each NFI plot (even-aged plot, dominant species, age, stand density …) during all the steps of simulation. Then we designed a regional harvesting module: clear cut and thinning scenarios at the regional level. These specifications take into account the general characteristics of the regional level to carry out clear-cuts and thinning. Knowledge of the status of all plots at each time step will determine the clear cut and thinning scenario that will be applied individually before the step of evolution. Then, each plot is processed by the selected growth module.

The next steps will be i) to describe the three main forest management characteristics (DB, EAF, and COF (if possible for the last one) in the harvesting module; then ii) to determine the number of NFI stands that correspond to each FMA at the beginning of the simulation. For example, it is more likely that stands located in highly productive areas will be used for DB FMA than stands located in less productive ones. Finally, we will try to implement one type of main drivers: the changes in management intensity expressed as the percentage of area changing from one forest management alternative to another.



Key words: France, Aquitaine forest simulator, maritime pine, regional scenario.

6 Applications with the Austrian simulators

6.1 PROGNAUS

Authors

Sterba, H. and Hauser B.

Abstract

PROGNAUS is a distance independent individual tree growth simulator, originally based on the concept of the stand prognosis model of Stage (1973). Its parameters were estimated from the permanent plots of the Austrian National Forest Inventory. Thus, it is intended for the use of inventory data, gained from angle count sampling for a broad spectrum of mixed and pure, even- and uneven-aged forests. It therefore intentionally does not use age and site index as input variables. Input variables are tree size, site quality and competition. Site quality enters the model through site descriptors, such as elevation, aspect, slope, soil type, vegetation type, a.s.o., tree size variables are breast height diameter, tree height and crown ratio, and competition is described by the basal area of larger trees per hectare and the crown competition factor. Parameters have been determined for Norway spruce (*Picea abies*), silver fir (*Abies alba*), Scots pine (*Pinus sylvestris*), Austrian black pine (*Pinus nigra*), Stone pine (*Pinus cembra*), Larch (*Larix europaea*), common beech (*Fagus silvestris*), Oaks (*Quercus robur* and *Q. petraea*), and other broadleaved species. The interventions possible in this simulator are selective thinning, thinning from below, precommercial thinning, clear cutting and individual tree harvesting. For this study the simulator as it was developed and described by Ledermann (2006) was modified for long term forecasts by (i) a new height increment model and (ii) an improved mortality model. With these modifications it was used for an alpine spring protection forest area to study the variants: No intervention, managing for maximum timber production (thinning and clear cut), and individual tree harvesting for spring protection reasons.

6.1.1 Introduction

PROGNAUS has been developed for simulating forest growth in forest management districts, based on inventory data with angel count sampling. It follows the concept of FVS-models, the development of which started with Stage's (1973) Stand Prognosis model. The parameters of its sub-models were determined, based on the data of the permanent sample plots of the Austrian National Forest Inventory for the most important tree species in Austria. It has been validated (Sterba and Monserud 1996, 1997, Sterba et al. 2001, Huber and Sterba 2008) and re-parameterised several times, and described by Monserud et al (1997) and Ledermann (2006). Because of its concept and its data base it is applicable for a continuum of pure and mixed species stands, and for even-aged as well as uneven-aged stand. This concept intentionally avoids age and site index as input variables, because these are not available in uneven-aged forests. The Windows version 2.2, as described in Ledermann (2006) has been improved recently by a new height increment model (Nachtmann 2006) and a modified mortality model (Huber and Sterba 2008).

6.1.2 The concept of PrognAus

PROGNAUS consists of several submodels, namely a basal area increment model (Monserud and Sterba 1996), a height increment model (Nachtmann 2006), a crown ratio model (Hasenauer and Monserud 1996), a mortality model (Monserud and Sterba 1999), and an ingrowth model (Ledermann 2002). All these models follow the concept

$\Delta = f(Site, Size, Competition)$,

where Δ is a change in basal area, i.e. basal area increment, a change in tree height, i.e. height increment, mortality as a change of a tree from being alive to dead, and ingrowth, as the occurrence of a tree exceeding the minimum dbh of 5 cm. Site is a vector of site descriptors, e.g. elevation, slope, aspect, soil type, growth district, vegetation type, etc..
Size consists of the variables breast height diameter and crown ration and competition is described by the crown competition factor and the basal area of larger trees.

6.1.3 Data input and management interventions

Input data for the model are, besides the site descriptors, a list of sample trees with their dbh, their height, their crown ratio if available, and their represented stem number. The minimum dbh in the model is 5 cm. Growth, ingrowth and mortality are calculated in five-year steps.
Management interventions can be given in two ways.
The first option is to give percentages of tree numbers by species, stem quality class and dbh- class that should be removed.
The second option is to use predefined thinning actions, such as pre-commercial thinning, selective thinning and thinning from below, and final harvest actions, i.e. clear cut or target diameter harvest.

6.1.4 Example of Application in the case study

For the case study "Alpine Spring Protection Forests" with its 15,300 ha forest area, the simulator PROGNAUS was adjusted, using the two inventories based on permanent angle count samples with a total of 1274 plots. The increments, as they followed from the two measurements were used to adjust the basal area and the height increment equations by determining species specific multipliers for each of the models. With this modified model the simulator was started with the data of the last inventory and run with three strategies:

- 1st no treatment at all;
- 2nd treatment for optimum timber production, i.e. with planting of Norway spruce, then one precommercial thinning, two selective thinnings and then clearcut at age 100; and
- 3rd abandoning the clear cut system, only individual tree harvesting (target diameter harvest) in order keep the forest floor covered, only natural regeneration without any planting.

These treatments were simulated for 40 years. For the results after 40 years note, that the simulation are done for the whole forest district, thus the results cannot be interpreted as stand developments, but rather the summary of the development of all stands in the district.

The total stocking volume after 40 years is – as expected - highest when the stands were not managed at all. It is much lower in the clear cut system and only somewhat higher in the target diameter harvesting system (Fig. 6.1.1). The species proportions do not differ very much between the unmanaged system and the target diameter system, while in the clear cut system the proportion of Norway spruce has clearly been increased at the expense of the broadleaved species (Tab. 6.1.1). Due to the target diameter harvesting system, the distribution of the dbh-classes seems truncated at breast height diameters of about 60 cm.

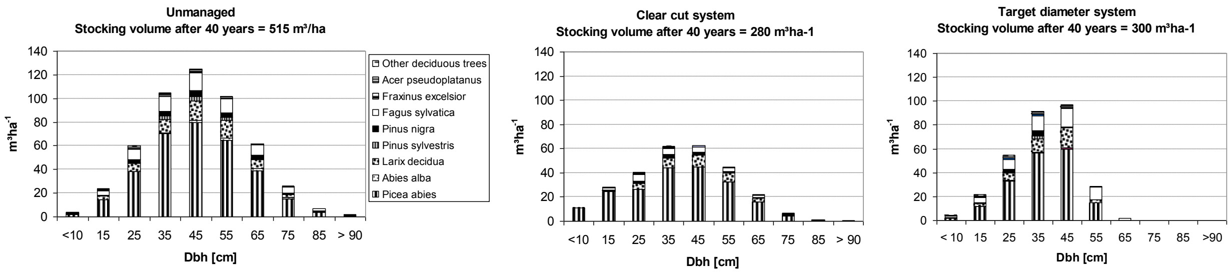


Fig. 6.1.1: The distribution of the remaining volume per hectare after 40 years simulation

The harvests as shown in Figure 6.1.2 highlight the concentration on larger trees, and a smaller proportion of beech, harvested in the target diameter system.

Table 6.1.1: Volume proportions (%) by species after 40 years

	Unmanaged	Clear cut system	Target diameter system
Picea abies	63.6	73.1	59.3
Abies alba	1.6	0.3	1.1
Larix europaea	12.3	12.5	12.8
Pinus sylvestris	2.2	0.8	1.3
Pinus nigra	3.9	2.9	2.5
Fagus silvatica	13.5	7.9	18.2
Fraxinus excelsior	0.9	0.9	1.4
Acer pseudoplatanus	1.4	1.0	2.1
Other deciduous trees	0.6	0.6	1.2

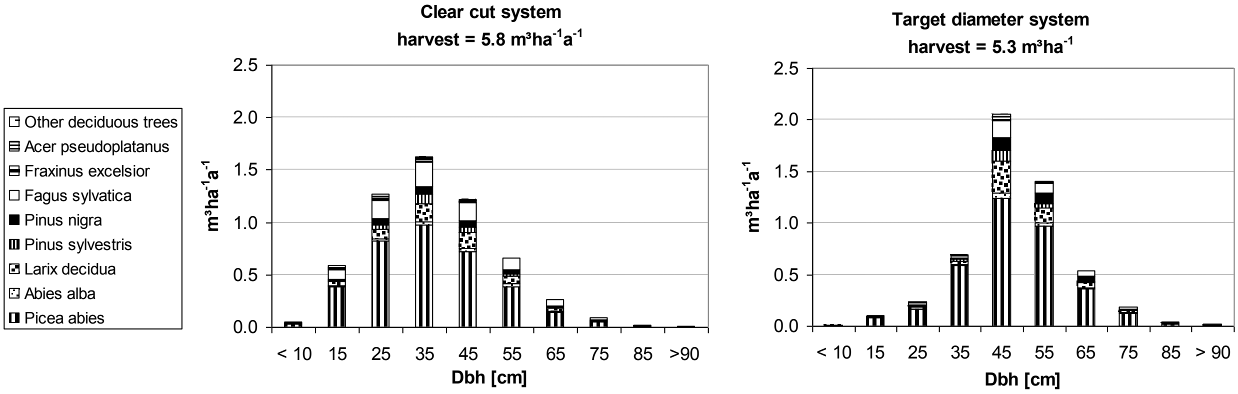


Figure 6.1.2: The harvests within the between 40 years simulation by dbh and tree species

The dbh-distributions after 40 years (Fig. 6.1.3) exhibit the highest average stem number in the clear cut system, a lack of small trees in unmanaged variant and the reverse J-shape stem number distribution in both, the clear cut system and ion the target diameter system. Note again, that this is not a stand, but the whole management district, and thus the dbh-distribution in the clear cut system is not unexpectedly reversed J-shaped and steeper than in the finally uneven-aged management of the Target diameter system. Additionally it can be seen again, that the clear cut system in the long run will lead to higher proportion of Norway spruce.

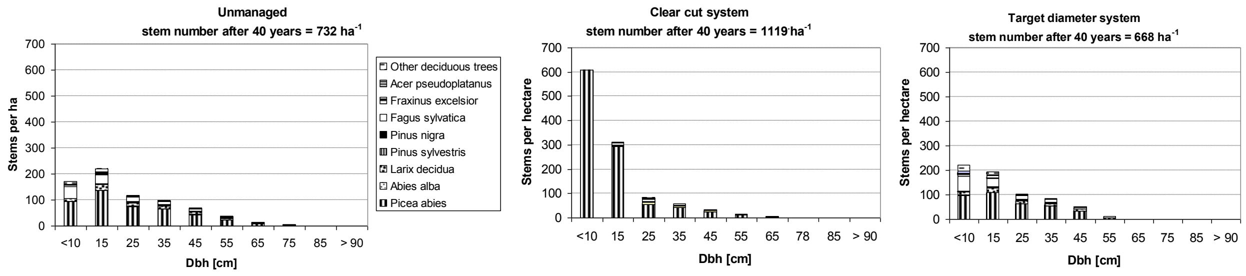


Figure6.1.3: The dbh-distribution of the remaining stands after 40 years

A comparison of the volume increment in the three management variants (Fig. 6.1.4) shows, that the increment is highest in the unmanaged variant and smallest in the clear cut system although the differences are not large. The increment proportion of Norway spruce and of other deciduous trees is highest in the clear cut system, the latter one because of the additional natural regeneration of deciduous trees on the clear cut areas. The increment proportion of beech will be highest in the Target diameter system, due to the shade tolerance of beech.

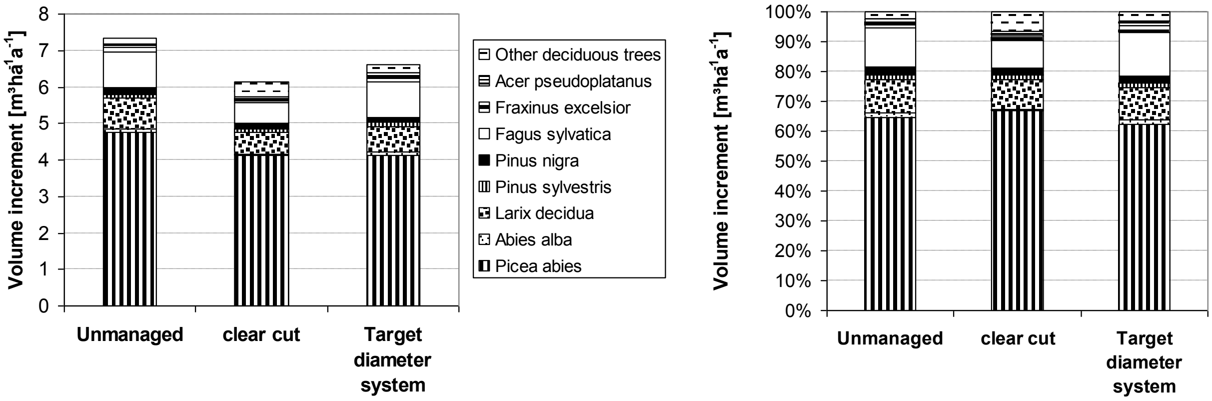


Figure 6.1.4: The net volume increment by species and management system

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6.2 THE TREE GROWTH MODEL MOSES

Authors

Hubert Hasenauer and Mario Klopf

Abstract

MOSES is a distance dependent tree growth model. The model has been developed using permanent research plot data from Austria and Switzerland including more than 78,000 five year growth periods recorded in uneven-aged mixed species forests. The model covers nine tree species. One application has been developed for Quercus frainetto in Greece. In combination with the stand generation tool STANDGEN the model is explicitly designed for forest stand simulations. Two software implementations are available: MOSES 3.0 (Steinmetz 2004) for single stands and MOSESbatch (Kindermann 2004) for batching. For a Project with the Austrian Federal Forests (Hasenauer and Kindermann 2007) a graphical user interface for MOSESbatch was developed (Basch et al. 2006). As management model MOSES is used especially for treatment scenario testing (Hasenauer et al. 1995, Hasenauer et al. 1996, Hallenbarter and Hasenauer 2003, Wohlgemut 2004, Kindermann 2004, Hasenauer and Kindermann 2007, Liu 2007) but for alternative applications like estimation of dead wood development (Klopf 2007) too.

6.2.1 Introduction

MOSES – **MO**deling **S**tand r**ES**ponse (Hasenauer 1994, Hasenauer 2000) – is a distance dependent tree growth simulator that bases on the potential concept. It consists of diameter increment, height increment, dynamic crown and mortality sub models. The simulator is calibrated for all major tree species in Austria and Switzerland: Norway spruce (Picea abies), Fir (Abies alba), Larch (Larix decidua), Scots pine (Pinus sylvestris), Stone pine (Pinus cembra), “other needle trees”, Common beech (Fagus sylvatica), Oak sp. (Quercus sp.), Willow (Salix sp.), “other broadleaves” as well as for Quercus frainetto in Greece (Spyroglou 2004). The data source for calibrating the model came from permanent research and sampling plots across the Alpine Arch. The prediction interval is five years except for Willow (Wohlgemut 2004) which uses a one year prediction interval.

6.2.2 Concept of MOSES

The increment prediction within MOSES follows the potential growth concept (Newnham 1964), which predicts the current annual height (ih_{obs}) and diameter increment (id_{obs}) according to a predefined potential height (ih_{pot}) and potential diameter increment (id_{pot}) for each tree. Species and site specific potentials are reduced by crown ratio (CR), overstocking impacts and crown release. The CR represents past growing conditions, overstocking impacts are expressed by competition index (CI) according to Monserud (1975) and change in competition (ΔCI) represents changes in growing conditions resulting from crown release. Different crown releases or thinnings (measured by ΔCI) can result in either an acceleration or a decline in diameter or height growth for trees which experienced similar past growing conditions. To avoid trivial relationships between observed and potential tree growth, the relative 5 year increment is predicted as

$$\frac{id_{obs}}{id_{pot}}, \frac{ih_{obs}}{id_{pot}} = CR^{b_1}(1-e^{\frac{b_2}{CI(1+b_3\cdot\Delta CI)}})+\varepsilon$$

where id_{pot} is determined from empirical open grown tree dimensions in Austria (Hasenauer 1997), ih_{pot} follows a suggestion by Newnham (1964) and Monserud (1975) and uses the height increment development of dominant trees for a given site. The potential periodical (e.g. 5 years) height increment for a given tree is derived from regional site index functions. This procedure works as follows: After determining the site index the corresponding index function is rearranged to derive the calculatory age a given tree would have had if it had grown as a dominant tree. Adding the length of the prediction interval and calculating the future dominant tree height, the difference between the two heights give the potential periodical height increment. These tree heights are needed and used for deriving the breast height diameters (Hasenauer 1997). The corresponding differences give the potential periodical diameter increment for a given tree.

To update crown ratio a dynamic crown ratio model is used. It predicts the change in the height to the live crown base (ΔHLC) as a function of tree height (h), Crown ratio (CR), competition index (CI), and the diameter at breast height (DBH) using the equation

$$\Delta HLC = b_0 \cdot h^{b_1} \cdot e^{\left(b_2 \cdot CR^{05} + \frac{b_3}{CI} / + b_4 \cdot DBH\right)} + \varepsilon$$

Finally, the probability of individual tree mortality (P) is predicted using the LOGIT-function

$$P = \frac{1}{1 + e^{(d_1 + d_2 \cdot CI + d_3 \cdot CR + d_4 \cdot DBH)}} + \varepsilon$$

where CI is the competition index (Monserud 1975), CR the crown ratio and DBH the breast height diameter. All models include the remaining error component (ε) to address the variance not explained by the model.

MOSES includes an explicit regeneration tool for all trees smaller than 1.4 m (Golser and Hasenauer 1997, Kindermann et al. 2002, Hasenauer and Kindermann 2002, Kindermann 2004). The algorithm predicts the probability of regeneration within a 5-year growth period, the species proportion and the regeneration density of all juveniles. Once the juveniles are established their growth and mortality are developed from overstory competition, the intra and interpecific competition and compensatory adjustments due to edge effect (Golser and Hasenauer 1997) incidence of light. If the juvenile trees have passed the threshold height of 1.4 m they belong to the overstory and can be modeled with the standard growth functions as previously defined.

The model includes form factor functions (Pollenschütz 1974, Schieler 1997) and assortment tables (Sterba 1983, Eckmüllner 1985, Kleine 1986) to assess merchantable timber volume. It also allows for a simple assessment of storm and/or snow damage (Schön 1982) using probability functions based on the height to diameter ratio as an indicator for stability.

6.2.3 Model Calibration, Validity and Software application

The model has been calibrated for all major tree species in Austria and Switzerland using more than 78,000 five year growth periods ranging from even-aged pure forests with no treatment to uneven-aged mixed and heavily released forest stands. Figure 1 shows the distribution of the sampling points over Austria and Switzerland. The data set used for calibration included x and y coordinates, DBH, tree height and height to the live crown measurements for each tree.

In the regression runs only observed tree data were used to avoid a potential bias due to a heuristic transformation of missing tree data for deriving increment data (Hasenauer and Monserud 1997). Generated input data don't have random variation. Thus they lead to artificially high coefficients of determination and even more importantly this procedure may lead to biased or inconsistent coefficient estimates (Hasenauer and Monserud 1997). Equations within a tree growth model can be considered as a system of equations and may not be independent. For example the remaining error components of one equation may affect the calibration results of the other equations within the system (see Hasenauer et al. 1998). To address the simultaneous nature of tree growth models and to ensure unbiased coefficient estimates within MOSES, the system of equations was calibrated using Full Information Maximum Likelihood (FIML) Methods (Hasenauer 2000).

The growth model has also been extensively validated using independent data sets from Switzerland and Austria including more than 55,000 growth periods. For example Hallenbarter et al. (2005) validated MOSES for Swiss conditions, Klopf (2007) for the Kalkalpen Nationalpark. The location of sample points for calibration data is shown in figure 6.2.1.

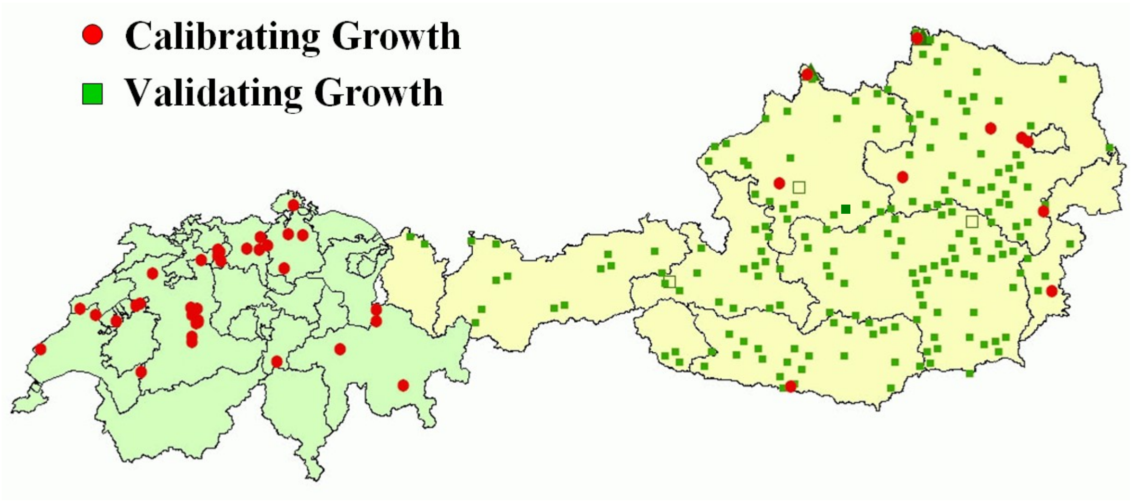

Fig.6.2.1: Investigation sites of Austrian and Swiss calibration and validation data.

6.2.4 Model application

For the application of MOSES two different Versions are available. MOSES 3.0 (Steinmetz 2004) is a stand level simulation program with graphical device for sketching the simulated stand that allows interactive individual tree treatments during a simulation run. This version is useful for demonstration and educational purposes. MOSESbatch (Kindermann 2004) has been developed for batching – processing a large number of stands at once – and offers the option to deactivate equations. This has been proven to be very important for model testing and validation using data from long term field experiments and permanent inventories (Hallenbarter et al. 2005). The simulation of forest stands follows a sequential order and each stand can be assigned to predefined treatments. Possible treatments are thinning from below, thinning from above, random thinning and clearcut. The extension with a graphical user interface (GUI, Basch et al. 2006) allows an easier handling of the program.

For both versions a regional site index function must be specified for each tree species and DBH, height, height to the live crown base and coordinates are required for each single tree. The tree's coordinates may come from measurements or by using stand generation procedures (Kittenberger 2004, Pommerening 2000, Degenhardt 1998, Pretzsch 1993). Within the MOSES simulation system STANDGEN (Kittenberger 2003) is used as stand generation program.

MOSES has been used for a variety of applications of these two will be presented briefly and some others are only mentioned.

In cooperation with the Austrian Federal Forests Hasenauer and Kindermann (2007) did an evaluation of different treatment scenarios for the forest districts Zederhaus (Salzburg) and Lauffen (Upper Austria). In all 1707 stands were surveyed and simulated and 31 were sampled to gain data for adjusting the surveying data and validation purposes. MOSES was initialized with the adjusted surveying data and the following five treatment scenarios were run for the next 40 years:

No:	No interventions
Tax:	Interventions for the next 10 years according to the survey and no treatments afterwards
TaxAuto:	Interventions for the next 10 years according to the survey and automatically generated treatments for the remaining 30 years
d40:	Target diameter harvest at DBH > 40 cm
d50:	Target diameter harvest at DBH > 50 cm

As figure 6.2.2 shows with the TaxAuto scenario in Zederhaus there will be a slight increase of volume from 2005 to 2045 with a decrease in between in the second half of the prediction timeframe. That can be explained by a backlog of the age class 140+. The scenarios d40 and d50 lead to a severe loss of volume. Reasons are the tree dimensions and the harvest immediately after reaching harvesting dimension. Nonetheless volume at d50 recovers again until 2040 and at d40 increases again too. d40 and d50 can't achieve a balance of age structure and would lead to big clear cuts. The over proportional harvest for scenario d40 and d50 at the end of the first period can be seen in figure 6.2.3, where d40 leads to a total harvested volume of approx. 270,000 m³ and d50 to 155,000 m³ and amounts smaller 3,000 m³ as from 2015.

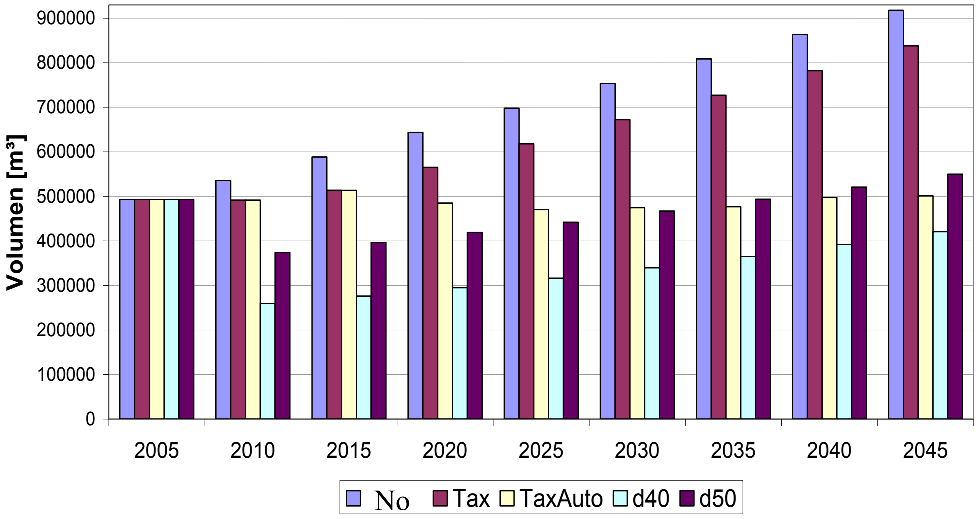

Fig.6.2.2: Zederhaus. Development of stand volume according to different treatment scenarios for the next 40 years.

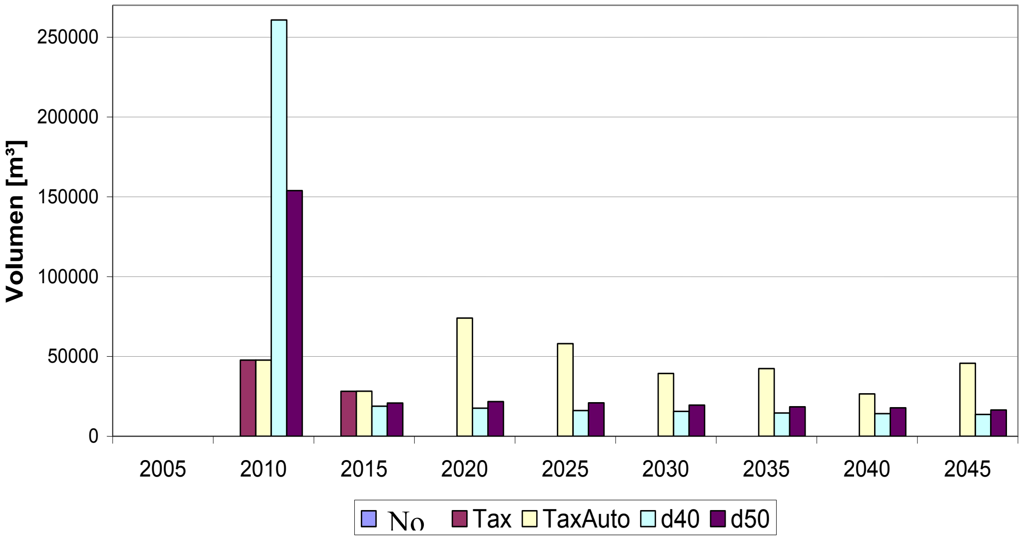

Fig.6.2.3: Zederhaus. Harvested volume according to the different treatment scenarios for the next 40 years.

Other examples like the described one were to assess timber values resulting from differing treatment scenarios (Hasenauer et al. 1995), to develop treatment scenarios for beech forests (Hasenauer et al 1996) and to asses the success of thinning (Hallenbarter and Hasenauer 2003). Wohlgemut (2004) developed treatment strategies for protecting forests along rivers (Wohlgemut 2004), Kindermann (2004) regeneration establishment and juvenile tree growth scenarios according to different silvicultural treatments (Kindermann 2004). Liu (2007) used MOSES for the comparison of productivity of managed versus unmanaged Swiss forests.
A trial to apply MOSES in a not typical scope for management models was done by Klopf (2007). The model was used for estimating the development of dead wood in the Kalkalpen Nationalpark (Upper Austria). Figure 6.2.4 shows the development of predicted volume and mortality (volume of recently died trees) at beech dominated sample points for each simulation period. Out of these mortalities the amount of dead wood at a certain time was calculated by applying a model for the volume loss of dead wood over time (Ranius et al. 2004).

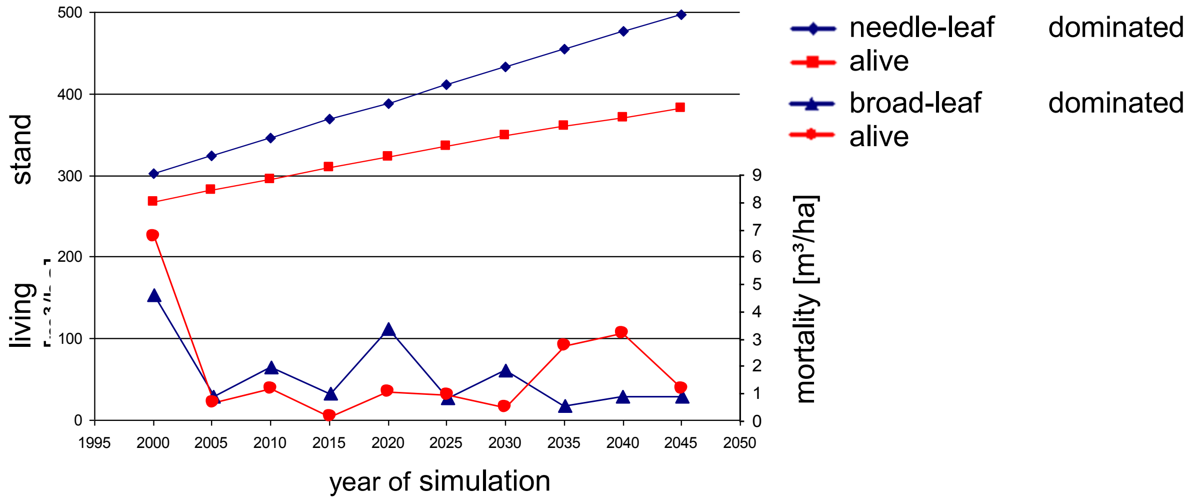

Fig. 6.2.4: Kalkalpen Nationalpark. Volume and mortality of broad-leaf and needle-leaf tree dominanted sample points for the simulated time span.

The results of validation of the height- and DBH-increment model and the test for plausibility of the mortality model allow the application of MOSES for the Nationalpark's region and predicting mortality. Due to a lack of models that are able to describe the volume loss of dead wood and their implementation in the investigation area prediction of the amount of dead wood out of cumulative mortalities is currently not possible.

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6.3 BIOME-BGC

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Abstract

Biome-BGC is a large scale ecosystem model developed at the University of Montana (Thoprnton et al. 2002) and adapted to Central European conditions (Pietsch and Hasenauer 2002, 2006; Pietsch et al. 2003, 2005; Petritsch et al. 2007). In Biome-BGC photosynthesis interacts with other ecosystem processes such as transpiration, evaporation, soil hydrology, assimilate allocation, growth and maintenance respiration, biomass mortality, heterotrophic respiration, decomposition, mineralization, and nutrient leaching and volatilization. These processes are of biological, physicochemical and hydro-geological nature and are summarized under the term biogeochemistry. Input data to run the model include daily weather data (minimum and maximum temperature, precipitation, vapour pressure deficit and short wave radiation) and site information like slope, aspect, elevation, soil depth and soil texture to calculate the cycles of Carbon, Nitrogen, Water and Energy within forest stands of Norway spruce, European larch, Scots pine, Cembran pine, Common beech and sessile and pedunculate oak. In this study we focused on the effect of the forest management system on the growth performance of oak by comparing coppice with standards with high forest management systems. Results indicated that the coppice with standards system exhibits a higher yield than the high forest system and that this higher yield is attributable to a higher nitrogen use efficiency of the coppice with standards management regime.

6.3.1 Introduction

Large scale ecosystem models like Biome-BGC (Thornton et al. 2002) describe the fluxes of carbon, nitrogen, water and energy within ecosystems. Photosynthesis and related processes are central as they transform inorganic carbon into carbohydrates, thus providing the organic backbone for structural and functional molecules of living organisms. In large scale ecosystem models other processes such as allocation of assimilates for growth of shoots and roots, growth and maintenance respiration, phenological biomass turnover, mortality, decomposition, mineralization, denitrification, evapotranspiration, soil water outflow and flooding, surface reflectance or heat transfer must be considered in order to capture the growth and decay following mortality within these ecosystems.

In Austria oak stands cover about 4% of the total forest area, commonly associated with beech and hornbeam (Hochbichler, 1993). Half the area of oak stands is managed by coppice or coppice with standards, and the rest is managed by high forest. Due to economic changes and increasing respect for the ecological interrelations, the management of oak forest in Austria in federal and private forests has been increasing. It emphasized the management systems like increasing planting of oak stands, a more intensive tending and fostering of oaks in the oak-rich high forests and coppice with standards, and an increasing change from coppice systems and/or coppice with standards into over-wood rich coppice with standard (high forest system). The reason behind applying such management intervention is to use the existing capacity of the sites more efficiently and to make more stable oak forest stands. The objective oriented treatment of oak stands, considering the growth potential of the site in the high forests as well as in the coppice with standards forests, has been emphasized to presents the opportunity for forest owners (Hochbichler, 1993).

The main aim of management is to sustain the amount of harvest through controlling the stand structure but the selection of management strategies depend upon tree species in the forest and management objectives as well as those of the owners. Sustaining products and services is very much concerned to the maintenance of productivity of forest resources, and now a day's management focuses on optimal extraction of forest resources. The dealing of larger forest area is really difficult task as the detail information on management history and climatic condition always been lacking. That's why a suitable model has to be used to describe the forest development well. In this situation the BIOME-BGC 4.1.1 adapted by incorporating extensions on hydrology (Pietsch et al., 2003), species specific parameterisation (Pietsch et al., 2005) and self initialization (Pietsch and Hasenauer, 2006) is suitable one to simulate the forest ecosystems in Austria. The Biome-BGC model also has been extended with from unmanaged and fully stocked to managed forests (Petritsch et al. 2007).

The objectives of this study is to model the effects of thinning on the growth response of oak forests under coppice with standards and high forest management regimes. Our hypotheses are

(i) The yield of coppice with standards and high forests does not differ significantly.
(ii) There is no significant difference between the growth efficiency, the nitrogen use efficiency, the water use efficiency and the radiation use efficiency of coppice and high forests.

6.3.2 Material and Methods

6.3.2.1 Site description

The study site located in Hochleithenwald is a flat land with geographic position of 48°23'59'' latitude and 16°34'0'' longitude. The study site lies in lower Austria, the north east direction from Vienna, Austria. The lowest and highest elevation among the selected plots in Hochleithenwald was 233m and 283m above see level respectively. It is situated in the river basin of Danube, Thaya and March. The basin was developed in Miocene period (20 million years ago) and it is still active. The basement of basin is composed of sand stone (greywacke), flysch, limestone and crystalline. The basin is filled with fluvial sediments of ancient Danube developed in the periglacial region through the action of erosion, discharge, relocation and deposits of soil. Wind blown and deposited the loess to the hochleithenwald basin, and ranges between decimetre to few meters. Loess is carbonated, yellowish coloured and exhibits very high silt contents of 65-80%, clay 10-25% and sand 10 -15% (Scheffer 2002. cited in Pietsch et al, 2007).

The meteorological input parameters comprise daily air minimum and maximum temperature, incident short wave solar radiation, vapour pressure deficit and precipitation and day length are not always available directly for the whole area of study. The climatic data is to be interpolated to each required plot from the possible surrounding weather stations. Climate data was provided by the Austrian National Weather Centres. The point version of DAYMET (Petritsch, 2002) validated for Austria (Hasenauer et al., 2003) was applied. The program needs the geographic position, the elevation, slope, aspect and the angle to the horizon in the West and in the East to calculate the climate for a location.. The climate details of the region are given in table 1.

The CO_2 content in the air in the preindustrial CO_2 concentration of 280ppm (IPCC WG I, 1996) was used in the model for the spin-up. When the industrialisation activities started, the CO_2 concentration has been increasing annually since 1765 to the present levels.

In case of atmospheric nitrogen deposition, a preindustrial level of 0.0001 kg m^{-2} yr^{-1} was assumed (Ulirch and Williot, 1993, Cited in Pietsch, et al., 2002) and has been increasing at the same rate as the CO_2 concentration to an actual value of 0.00172 kg m^{-2} yr^{-1} with reference to the year 1995

Table 6.3.1: Meteorological data (averages of maximum and minimum temperature, vapour pressure deficit, solar radiation of study area) calculated by using DAYMET climate model for the year 1960-2005

	Daily Tmax (^{o}C)	Daily Tmin (^{o}C)	Tday (^{o}C)	Annual precipitation (mm.yr^{-1})	Vapor pressure density (Pa)	Solar radiation (W.m^{-2})	Average day length (hours)
Average	12.96	4.71	10.69	536.82	545.88	232.85	11.20
Minimum	-15.09	-23.02	-17.08	343.28	16.78	18.76	7.56
Maximum	35.01	21.16	30.36	745.89	2376.24	487.63	14.84
std. dev.	9.04	6.85	8.32	81.97	416.19	117.05	2.51
Mode	18.09	4.61	16.79	352.84	160.65	174.57	14.84

6.3.2.2 The Model

The study was based on the Biome-BGC Version 4.1.1 model (Thornton et al., 2002), which is used to assess the forest ecosystem dynamics. The integration of the main physical, biogeochemical and physiological processes based on our current understanding of key ecophysiological mechanisms is the basic concept of this model. It gives the mechanistic description of the interactions between the living plants and their surrounding environment (Waring and Running, 1998). Models, which operate and simulate on a daily time basis, are explicitly designed to assess the cycling of energy, water, carbon and nutrients within a given ecosystem.

In this study, the BIOME-BGC 4.1.1 was adapted by incorporating extensions on hydrology (Pietsch et al., 2003), species specific parameterisation (Pietsch et al., 2005) and self initialization (Pietsch and Hasenauer, 2006) to simulate the forest ecosystems in Austria. The ecosystem is defined on the basis of the following variables which describe the cycling of energy, water, carbon and nitrogen in a daily time resolution.

- Daily canopy interception, evaporation and transpiration
- Soil evaporation, outflow, water potential and water content
- Leaf area index (LAI)
- Stomatal conductance and assimilation of sun lit and shaded canopy fractions
- Gross primary production (GPP) and net primary production (NPP)
- Allocation of carbon and nitrogen to the different ecosystem compartments (soil, litter, roots, stem leaves)
- Litter-fall and decomposition
- Mineralisation, denitrification, leaching and volatile nitrogen losses

6.3.3 Simulation Procedure

The simulation procedure is based on the available input information and the type of ecosystem which has to be modelled. Here, as the initial information about the forest ecosystem is not sufficient, the simulation with the particular stand has been done with a spin-up procedure. As the study was further interested in comparing the results of different forest management, the spin-up is followed by site history simulation and finally by the current stand simulation to develop the desired forest ecosystems.

6.3.3.1 Spin-up

The self-initialisation of the model or spin-up run has to be used to obtain the starting values for further simulation, if the initial information is missing. The spin-up starts without soil organic matter (SOM), a very small initial carbon amount in leaves (0.001 kg C m-2) and 50% soil water saturation. Organic matter is accumulated during the ongoing simulation. When the simulation reaches a dynamic equilibrium (i.e. the difference in SOM between two successive climate periods does not exceed the value 0.0005 kgCm-2Y-1) of all ecosystem pools, the spin-up process will be stopped. The achieved equilibrium is dynamic with large inter-annual variability caused by variation in weather condition. So, for the simulations, the available climate records, from the year 1960 to 2005, were used. The records are repeated as necessary to create weather records for the model runs for a longer period. At the end of a simulation process the initial values of the following necessary variables are produced:

- Water stored in soil, snowpack and crown
- Carbon and nitrogen amount in particular plant organs (leaf, stem, coarse and fine roots), in coarse woody debris, in four litter pools, in four soil pools
- Amount of mineral nitrogen in soil
- Nitrogen amount for re-translocation
- Maximum amount of carbon in leaves, stem, fine and coarse roots during the year
- Number of days per year without precipitation

The time period this process needs varies between 3000 and 60000 years under different climatic conditions, at different sites and with different vegetation types (Pietsch and Hasenauer, 2006). The typical spin-up run lasts approximately 20000 years depending on the simulated vegetation types (Thornton et al., 2002). For this study the oak is found as the dominating tree species before and also after human intervention. Here, the self-initialisation took 5400 simulation years.

Moreover, a dynamic mortality model is applied for the self-initialisation, as the linear mortality (commonly set to 0.5%) can lead to an overestimation of the ecosystem carbon content by 400% (Pietsch and Hasenauer, 2006). The dynamic mortality setting (vary between 0.6 to 2% of vegetation biomass per year) was used to reach high carbon biomass values. Furthermore, the elliptic mortality length of 150 to 450 years was used.

6.3.3.2 Historic land use

It is well understood that forest management and humans as well as natural disturbances have been affecting the ecosystem. Thus ignoring management site history within the model, simulation leads to systematic overestimations of the carbon amount in litter and soil when compared to the field observations (Pietsch and Hasenauer, 2002). The steady state of the self-initialisation procedure represents the situation without any human interference, and is considered as the starting point for simulating historic land use.

In central Europe, where the intensive forest management began in some areas approximately 600 years ago (Gude 1960, cited in Merganicova, 2004), an exact description of the site history is lacking. The degradation of forest soil due to forest management is caused by the loss of carbon and nutrition, and finally the reduction of site productivity (Pietsch and Hasenauer, 2002). Therefore, based on the available general information, it is suggested to simulate a certain number of successive rotations, assuming clear cutting and the replanting of the forest stand to account for management impact (Pietsch and Hasenauer 2002).

Apart from the direct human impacts, indirect human impacts to nature have been noticed for 250 years through industrialisation and have resulted in an increasing atmospheric CO_2 concentration and higher rates of nitrogen deposition. The designed model can mimic the temporal changes of atmospheric chemistry into account during the simulations, where the changes in CO_2 concentration follow IPCC scenario (IPCC WGI, 1996) and nitrogen deposition changes from the preindustrial levels to current levels at a particular site following the pattern same as of carbon (Thornton et al., 2002).

With a clear-cut all the above ground biomass is removed and the below ground biomass is transferred to the coarse woody debris compartment. Planting means that each plant adds 10 gram of carbon to the leaf pool and 25 gram to the stem pool. To mimic historic land use two complete rotations with 120 years and the current estimated age of stand were simulated, and it finally provides the current situations of forest ecosystems.

6.3.3.3 Current stand

The current forest stands are the functions of the management practices applied and the amount of input information. As the initial information about oak forest is not available, the simulation of the current stands is done only after the first two procedures, i.e. spin-up and the site history for the managed forests. The assumptions of the fully stocks forest is being replaced to address the management issues in forestry. Recently a sub-model of BIOME-BGC has been developed to address the forest growth response to thinning (Petritsch et al., 2007).

The new routines were implemented to permit specification of thinning. Previously, the acceleration of growth following thinning was implicitly included, and now it was designed on the basis of the intensity of the biomass removal (Petritsch et al., 2007). The changing in distribution patterns of assimilates between above and below ground biomass and between wood and leaf biomass observed after a thinning intervention are addressed by a new dynamic carbon allocation regime. With this model the thinning procedure can be explicitly defined, i.e. it is possible to fix the exact amount/percentage of stem carbon removal, leaf carbon removal, stem carbon that is left in the forest and is transferred to the coarse woody debris carbon compartment, root carbon that also goes to the coarse woody debris carbon pool and leaf and fine root carbon that is added to the litter carbon pool.

As the study is conducted in an oak forest, a broad leaved leaf shading tree species, and the thinning is done after the growth seasons, it is assumed that while thinning the whole bole is removed but the leaves remain in the forest and are therefore added to the litter pool. Values are given as the percentage of the total pool size. The same percentage of fine roots as stem carbon removed will therefore be allocated to the litter pool, and bigger roots are assigned to the coarse woody debris carbon pool.

For the simulations of the current stand the species specific model for oak tree parameterized in Austria was used. With the information received from the forest inventory the age of the stand was calculated, and find out the year of planting. From the literature the trend of the management intervention to different management system were fixed. As the rotation age of the high forest and coppice standards were assumed same as 120 years, and also the multiple integer of the rotation age of coppice, the study only focused on the current stand. This is because both management has the same year of clear cut and planning, and have no differences until the first intervention was made to the coppice with standards forests. With considering the available information, the following intervention scenario (Table 6.3.2) was developed to simulate the forest ecosystem within each management system.

Table 6.3.2: Developed intervention scenario. Note: CP is clear cut & planting, and T is thinning.

Type	Stand before 3 rotations & more	Stand before 2 rotations	Stand before 1 rotation	Age of current stand						
				0	30	50	60	80	90	120
CF	No intervention	CP	CP	CP	T	-	T	-	T	CP
HF	No intervention	CP	CP	CP	-	T	-	T	-	CP

6.3.4 Results and Discussion

The yield production of coppice and high forests, each having different management intervention, was presented in the table 1. The study shows the coppice with standards showed higher amount of harvest and yield production by 49.90 and 2.97 percent respectively, and lower growing stock by 19.69 percent than high forests. Although the extraction of biomass was comparatively high in coppice with standards, the yield was still higher in coppice with standards by 10 cubic meters per hectare in one complete rotation (see table 6.3.3). Table 6.3.4 gives the results of the comparison of growth efficiency (GE), nitrogen use efficiency (NUE) , radiation use efficiency (RUE) and water use efficiency (WUE) of the coppice with standards system and the high forest management system in order to detect the reason for the differences in yield.

Table 6.3.3: Summary of the yield statistics of both forest management practices.

Age	Growing stock ($m^3.ha^{-1}$)		Cumulative harvest ($m^3.ha^{-1}$)		Yield ($m^3.ha^{-1}$)		Difference in percent (CWS-HF)/HF*100		
	CWS	**HF**	**CWS**	**HF**	**CWS**	**HF**	**GS**	**Harvest**	**Yield**
30	91,27	91,27	0,00	0,00	91,27	91,27			
40	85,11	129,72	41,30	0,00	126,40	129,72	-34,40		-2,56
50	121,92	163,94	41,30	0,00	163,22	163,94	-25,63		-0,44
60	155,68	145,98	41,30	46,50	196,98	192,48	6,65	-11,20	2,34
70	121,14	177,69	105,33	46,50	226,46	224,19	-31,83	126,49	1,01
80	155,56	208,88	105,33	46,50	260,89	255,39	-25,53	126,49	2,16
90	188,81	166,42	105,33	116,98	294,13	283,40	13,45	-9,96	3,79
100	150,81	201,33	175,36	116,98	326,17	318,32	-25,09	49,90	2,47
110	190,55	238,56	175,36	116,98	365,91	355,55	-20,13	49,90	2,91
111	194,57	242,28	175,36	116,98	369,93	359,26	-19,69	49,90	2,97

Table 6.3.4: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to growth efficiency of the oldest plot planted in year 1896

	Growth efficiency		Nitrogen use efficiency		Water use efficiency		Radiation use efficiency	
	CWS	**HF**	**CWS**	**HF**	**CWS**	**HF**	**CWS**	**HF**
Mean	1,337	1,330	5,651	4,921	0,312	0,259	1,926	1,923
Median	1,328	1,323	4,726	3,817	0,158	0,147	1,952	1,941
Std deviation	0,114	0,107	2,383	2,458	0,410	0,345	0,198	0,196
Std error	0,011	0,010	0,226	0,233	0,039	0,033	0,019	0,019
95% confidence level	0,022	0,020	0,448	0,462	0,077	0,065	0,037	0,037
99% confidence level	0,028	0,027	0,593	0,612	0,102	0,086	0,049	0,049
Observations number	111	111	111	111	111	111	111	111
Minimum	1,000	1,000	0,990	0,990	0,059	0,038	1,000	1,000
Maximum	1,776	1,776	11,532	11,532	2,227	2,002	2,301	2,259

A statistical analysis revealed that nitrogen use efficiency was the only variable that exhibited significant differences between the two management systems (pair wisse t-test: t = 10.082, P = <0.001, df = 110, and α= 5%) exhibited that the NUE between two management systems differ significantly. Figure 1 shows the effects of thinning on NUE. The relative efficiency increased in the earlier age of stand and reached to the maximum at the age of 18 years. Afterwards, the efficiency gradually falls down. When the first thinning intervention was applied to 30 year old forests which is managed under the coppice with standards system, such intervention not only stops the decreasing rate of efficiency but increased the efficiency to the higher level than it was before thinning. Then, the differences in NUE between two management systems was noticed just a year after the thinning intervention and reached to the maximum after 3 years (Fig. 1). Although the efficiency decreases gradually afterwards it still shows the higher efficiency than the high forests, except the year when the high forest was treated with thinning. When the second thinning was applied in the coppice forests to the stand turned 60 years old, it increased the NUE of the coppice forests, and the differences again continued. Unlike the first thinning, the relative NUE of coppice forests after thinning was increased to higher level in the following year and remains stable for almost 20 years (Fig. 1). The second thinning applied in high forest increases the efficiency level and shows higher efficiency than coppice forests after the 5 years, and it continues for the age when the coppice forest was treated with third thinning. When the third thinning was applied in the coppice forests the NUE increased as like after second thinning, but the increasing intensity is lower than the first and second. The second thinning intervention applied in the high forests increases the NUE and the highest efficiency was seen 15 years after thinning although it was lower than the coppice forests. As the NUE increased in the high forests after 80 years but decreased in the coppice forests after 84 years, the efficiency level of the applied management systems culminate when the stand reached to 87 years old. After 3 years when there was next thinning was applied in coppice forests, it increased and went above the high forests. The difference in the NUE continues up to the rotation age (Fig. 6.3.1). We therefore conclude that NUE is the main driver of differing yield levels evident between coppice with standards and high forest management systems of sessile and pedunculate oak.

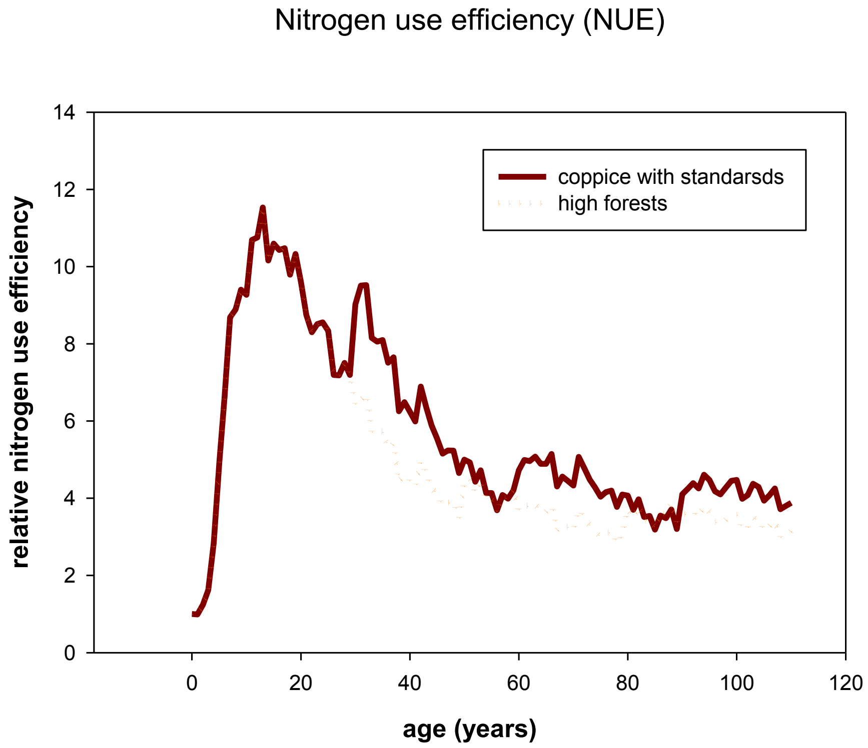

Figure 6.3.1: The temporal development of relative nitrogen use efficiency in coppice and high forests planted in year 1896. The value of planting year was considered as 1 and rest were assigned accordingly.

6.3.5 References

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7 EFISCEN-Space

7.1 INTRODUCTION

Forest resource analyses have been conducted at the pan European scale with the EFISCEN V3 model successfully for a range of applications. However, these scenario projections are most reliable for managed even aged, monospecific forests as were traditionally dominant in large parts of Europe. With European forestry shifting away from a timber production system towards more nature oriented management or short rotation biomass plantations, there is a need to adopt a more flexible approach. Furthermore, the EFISCEN V3 approach had serious shortcomings for the Mediterranean countries, where part of the data are organized by diameter class. And the EFISCEN V3 approach was often only geographically explicit down to the NUTS2 level, or even NUTS1 (country) level. This did not allow the proper use of all sorts of GIS based data. Nor did V3 provide any insight in forest structure or assortments. As the goals of forest management are becoming more diversified and the calculation of scenario projections has grown towards extensive sustainability impact assessments integrated over a whole sector, the robust but simple approach of EFISCEN does not fulfill the current requirements anymore.

Therefore a new high spatial resolution (1 km x 1 km) forest simulator EFISCEN-Space is (being) developed as an improved tool to analyze the development of forest resources on a regional to European scale under scenarios of management, societal demand and environmental circumstances. The model is based on a large set of National Forest Inventory plot level data integrated in a GIS framework including earlier pan-European forest maps and related information. The model will work with 20 tree species groups (table 1) over an extent covering the EU, extended with Norway, Switzerland, the Balkans, Moldavia, Belarus and Ukraine. The use of a GIS framework allows incorporation of spatial information (soil maps, elevation, NATURA2000 sites, ….) in the model. The model is diameter-class cohort stand based, with a limited number of stands per grid cell. This enables dealing with multiple stand types, such as even-aged monocultures, uneven-aged monocultures, mixed-species stands and coppice. In a later stage, the influence of environmental changes might also be included. The model simulates forest dynamics in terms of forest area, species composition, stand structure, standing volume, current annual increment, as well as harvested volumes of timber by thinning and final felling at the km^2. This spatial approach allows addressing questions related to:

- The forecasting of timber yield in a spatial context and by assortments;
- The logistical and economic implications of the location of timber harvest;
- The identification of areas that will act as (future) carbon sinks, including land use changes to and from the agricultural sector;
- Spatial and forest structural aspects of nature conservation.

7.2 REQUIREMENTS FOR EFISCEN-SPACE

The main purpose of EFISCEN-Space is to predict the performance of forest functions over a long period (20-70 years) on a regional to European scale under scenario’s of management regimes, societal demand and environmental circumstances. The model should be data based where possible and make use of algorithms to interpolate/ extrapolate when this is not possible. This requires a flexible approach where plot level data are integrated in a GIS framework to produce European maps with the initial data needed to run a dynamic forest development model. This forest development model should be able to deal with anticipated changes in forest management and the consequential changes in forest structure away from even aged monospecific stands. Without the complexity of a physiological model, it should be able to deal with observed and anticipated changes in growth conditions (see Spiecker et al. 1996, Kahle et al 2008). The output produced should provide information that allows calculation of indicator values to evaluate the performance of ecosystem functions by forests in the simulated region. For the development period, the main focus will be on calculation of wood by assortment.

Translating these more general requirements in specific criteria leads to the following list:

Integration of plot data into a GIS framework

- The model can deal with land use changes (afforestation, reforestation, deforestation)
- Maybe later full land use coupling (to allow dynamic simulation of land use changes)

A dynamic forest development model on regional to European scale which:

- should be applicable to large areas and many grid cells
- is designed to give robust predictions on regional to European scale but outcomes should not be used on local scales
- can be driven with the kind of information collected in National Forest Inventories (NFI's) in combination with available European GIS maps with ancillary data and (inter)national forest statistics
- is able to simulate current developments in European forestry (in the end):
  - → uneven aged forests, i.e. modelling independent of age (also used for even aged)
  - → mixed species stands from 1 to 20 species, with competition effects included
  - → changes in tree species (composition)
  - → forests with a structure deviating from "standard" (i.e. coppice,…)
  - → as a future development: effects of climate change
- is able to simulate in a realistic way the consequences of a wide range of individual "management actions" on forest development
- includes equations that calculate (at least) growth of standing stock, regeneration and natural mortality
- harvesting of wood products is demand driven, i.e. a predefined amount of wood extraction is distributed over the plots
- calculation of quantity and quality of harvested and harvestable wood should allow future coupling to economic modules

Calculate the following indicators to evaluate forest functions

- Production: growing stock & increment
- Production: harvest quantity and quality (volume per diameter class and tree species , damage classes?)
- Carbon sequestration: biomass, carbon in living and dead wood, carbon extracted by management, soil carbon
- Land use information: forest area per type, species, …
- Biodiversity: stand structural diversity, standing and lying dead wood, tree species composition, natural disturbances

User friendliness & flexibility

- allows management regimes to be built up of several individual predefined "management actions"
- allow option to change the parameters used per country or region
- allow option to choose output options from a list

7.3 THE SPATIAL DIMENSION: DERIVING THE INPUT MAPS

7.3.1 Data

7.3.1.1 Tree species distribution

In order to simulate forest development at the 1 km x 1 km resolution, first the distribution of tree species over Europe should be predicted at this resolution. For the 20 species-groups that are considered, distribution maps are modelled based on the available NFI plots and the ICP plots (Figure 7.1) in combination with ancillary maps (biogeographic regions, elevation, FAO soil map, EFI forest cover map, average rainfall, average temperature, average radiation, country, XY-coordinates). In those areas where NFI plot data are available at a high resolution, the occurrence of species is interpolated from the locations of the plots through compositional kriging, while for those areas where NFI plot data were unavailable a multinomial logistic regression was fitted on the ICP plot data and the auxiliary maps. The regression predictions were scaled to fit the regional (NUTS-2) NFI statistics and the whole map was scaled to the European Forest map (EFI). (an extended description will appear in Hengeveld et al. in prep.). The final result is a prediction of the coverage of each tree species for the whole of Europe at the 1 km x 1 km resolution (Figure 7.3).

7.3.1.2 Initialisation of stand characteristics in a grid cell

From this map, the occurrence of the species should be translated into an estimate of the stand characteristics at the scale of the km^2.

To provide an estimate of the stand characteristics for each species group predicted to occur in a km^2, a NFI plot containing the species is assigned to each predicted species group. These plots (including the other species reported in them) are taken as representative of the area predicted to be covered by the species. Species predicted to occur below a threshold of 1 ha are neglected. This will result in a map with for each grid cell a number of forest types completed with initial values for the core variables characterizing a stand in the dynamic forest model (Figure7. 2)

The subset of NFI plots from which plots are chosen, is determined first by the sample region of the NFI-plots; within NFI-sample regions for which plots are available, only those plots taken within this region are used. If the grid cell is within a region for which NFI-plots are unavailable, the subset of NFI-plots is determined by those plots that fall within the biogeographical region (Figure 7.4). As biogeographic region are large and are an important variable to predict species occurrence, it is not likely that any species will be found in a biogeographic region with no corresponding plots to draw data from. If this would occur, however, this species would be drawn from the whole database.

For a large part of the NFI plot dataset, all necessary variables are available. However, a substantial part of the dataset is yet incomplete. “Incomplete” sets vary from NFI regions where only species and age are available, to regions where only one basic variable is missing (for a list of basic variables see table 7.2). If only one or two variables are missing, and these can be estimated from the ones that are available, the stands are drawn from the regional NFI plot database, and established relations between variables (e.g., diameter - height) are used to fill the missing variables. If variance in these relations is important in the simulation, an error term may be added to create it.

If however one or very few variables are available, it is not yet clear how this information can be used. One option would be to use it along with species to narrow down the number of plots from which to draw from the total set available in the biogeographic region.

This way natural stand characteristics are preserved and both the local distribution of mixed-species and monoculture stands and the local combination of species can be maintained.

Correspondence with the NUTS-2 NFI statistics on growing stocks hopefully comes natural with the proposed approach (most likely only in the regions where the NFI-plots are available). If the discrepancy between predicted and reported statistics is to large, stands need to be either grown or reduced in age and volume to scale the prediction to the reported statistics. This scaling will involve the use of the growth model described in chapter 4.

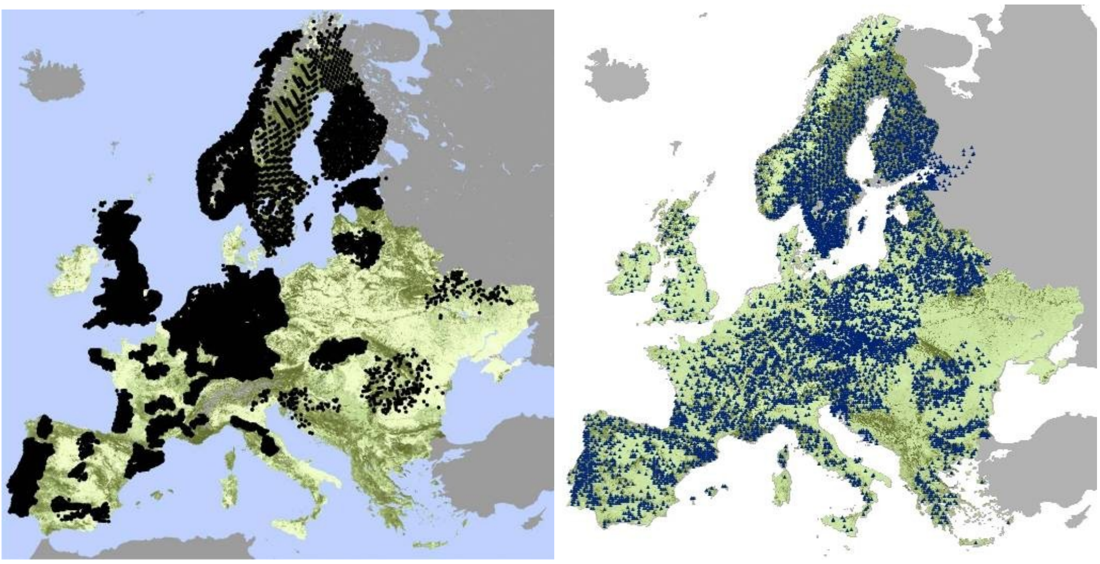

Figure 7.1: Location of the National Forest Inventory plots (left) and ICP forest plots (right) over Europe

Table 7.1: Tree species groups distinguished for the tree species map and the model

Main tree species (groups) in Europe	**Total Surface (kha) (to do)**
Abies spp.	
Alnus spp.	
Betula spp.	
Carpinus betulus	
Castanea sativa	
Eucalyptus spp.	
Fagus sylvatica	
Fraxinus spp.	
Larix spp.	
Other broadleaves	
Other conifers	
Other Pinus spp.	
Other Quercus spp.	
Picea spp.	
Pinus pinaster	
Pinus sylvestris	
Populus spp.	
Pseudotsuga menziesii	
Quercus robur + petraea	
Robinia pseudoacacia	

Table 7.2. The variables asked for in the NFI plot data enquiry: (note that it differs per country what was received)

1. X coordinate
2. Y coordinate
3. Main tree species (scientific name)
4. Age (y)
5. Recording year (y)
6. Mean height (m)
7. Mean diameter at breast height (cm)
8. Minimum diameter at breast height (cm)
9. Maximum diameter at breast height (cm)
10. Stem number (N/ha)
11. Basal area (m2/ha)
12. Growing stock volume (m3/ha overbark)
13. Volume of dead trees (m3/ha overbark)
14. Net annual volume increment (m3/ha.y overbark)
15. Harvesting volume (fellings, overbark, m3/ha.y)

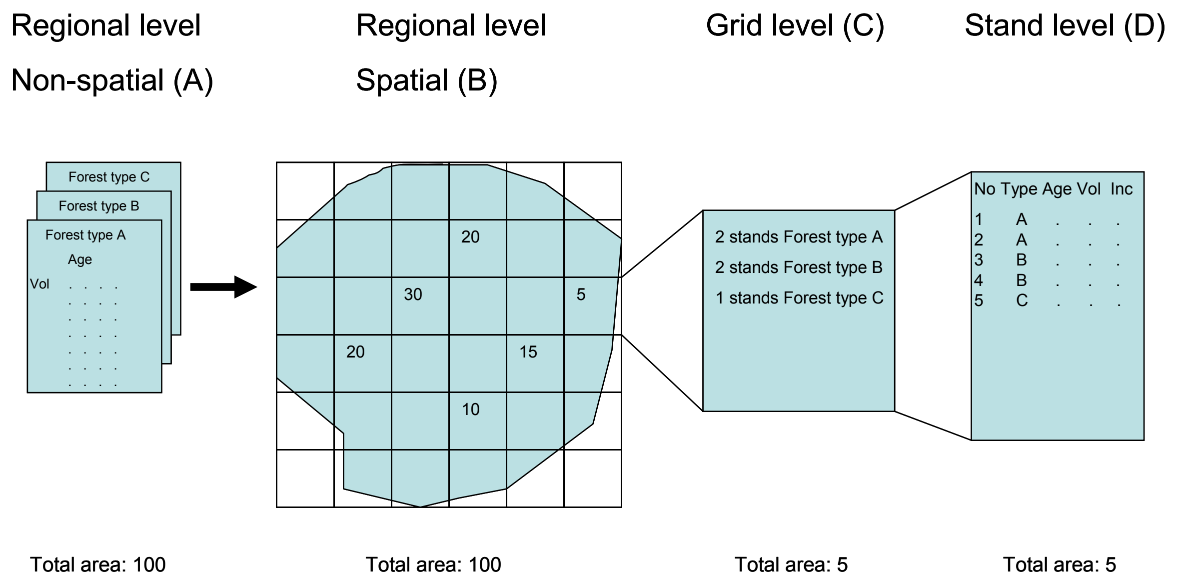

Figure7. 2. Schematic representation of initialization procedure of EFISCEN-SPACE. Forest inventory data are converted into matrixes of forest areas within age (including a category uneven aged) and volume classes at the regional level (A). Matrixes are subsequently converted into spatial maps (at the regional level) with the forest area indicated for each 1km x 1km grid cell (B). At the grid level, the surface for each forest type is recorded using the chance of occurrence of each species and national forest statistics (C). Note that we do not keep track of the location of the forested area within the grid cell. Finally, initial variables of each forest type are recorded, such as species composition, age structure, volume and increment (D).

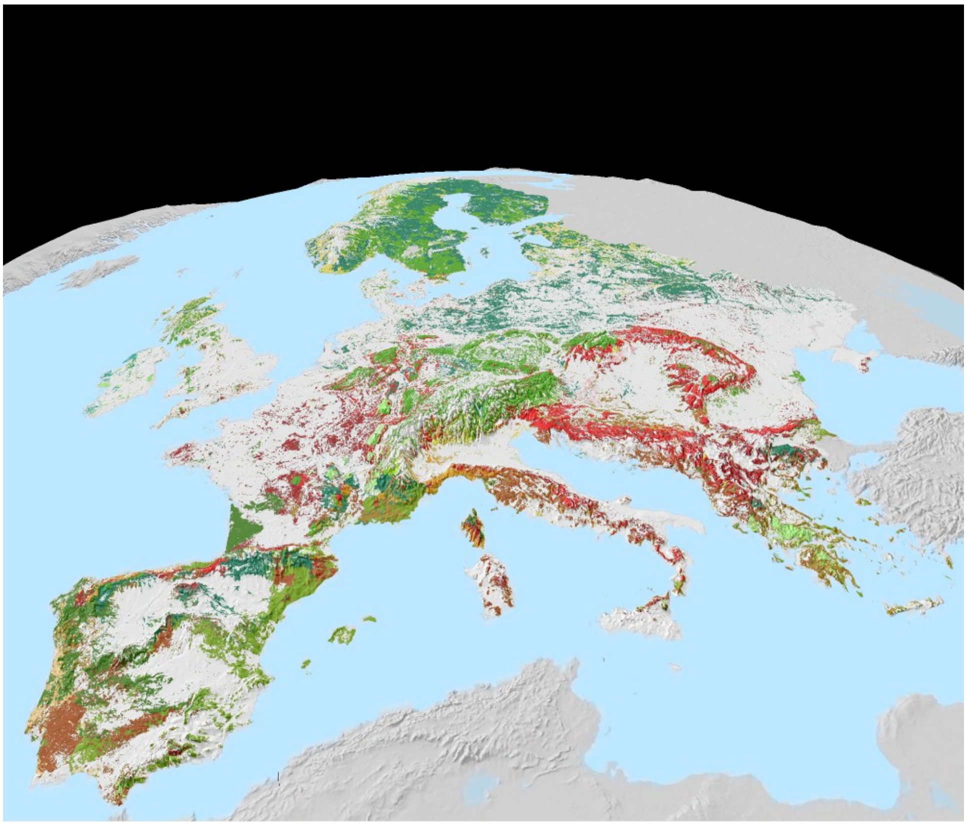

Figure 7.3. Tree species for Europe for 20 tree species. Each gridcell represents the dominant tree species. Only gridcells with a forest cover larger than 25% are shown.

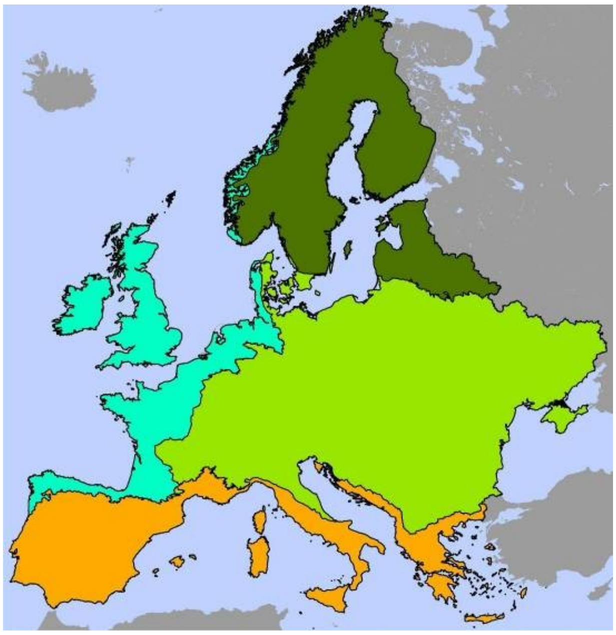

Figure 7.4. The biogeographical regions as used in EFISCEN Space.

7.3.2 Created variables: diameter distribution

Each stand is built up of one to several cohorts, which allows the simulation of mixed stands. During initialisation one cohort is initialised for each species. Each cohort is defined by information on :

- **species**
- **stem density**
- **diameter & height** (mean diameter; mean, maximum and minimum diameter; diameter distribution; diameter – height relation; height distribution; two-dimensional diameter – height distribution)
- **basal area** (may be calculated from stem density and diameter distribution)
- **volume** (may be calculated from basal area and height)
- for initialisation purposes, **age** may also be included

The NFI plot database provides information on mean diameter and height, and for some countries, maximal and minimal diameter for each plot are also given. The aim for EFISCEN-Space is to simulate forest development using diameter distributions.

The three parameter Weibull distribution is used to describe tree diameter size distribution. This distribution combines mathematical simplicity with a high flexibility. It can describe the inverse J shape of natural forests ($c<1$) and the exponential distribution ($c=1$). For $1<c<3.6$ the density function is positively skewed and for $c=3.6$ becomes approximately normal. For $c> 3.6$ it becomes increasingly negatively skewed (Nord-Larsen and Cao, 2006). Its main limitation is that it cannot deal with bi- or multimodal distributions. In EFISCEN-Space this is solved by using multiple cohorts. The parameters for the Weibull distribution are derived from the average (or if applicable median), minimum and maximum diameters in the NFI plot data according to the following set of equations substituting a_D , b_D and c_D (Saucier, 2000):

$$a_D = D_{\min} \qquad \text{(eq 1)}$$

$$D_{mean} = D_{\min} + \beta_D \Gamma\left[(c_D+1)/c_D\right] \Leftrightarrow \beta_D = \frac{D_{mean} - D_{\min}}{\Gamma\left[(c_D+1)/c_D\right]} \qquad \text{(eq 2)}$$

$$1-e^{-\left(\frac{D_{\max}-a_D}{\beta_D}\right)^{c_D}} = 1-\frac{1}{N} \Leftrightarrow \left(\frac{D_{\max}-D_{\min}}{D_{mean}-D_{\min}}\Gamma\left[(c_D+1)/c_D\right]\right)^{c_D} = -\ln\left(\frac{1}{N}\right) \qquad \text{(eq 3)}$$

As the Weibull distribution has no upper limit, the information about maximal diameter is used to delimit a certain percentage of the cumulative distribution. Here this percentage depends on the stem density, with the maximal diameter occurring exactly once. This percentage can also be made dependant on the set-up of the inventory (e.g. if max diameter is mean of 100 largest trees,..)

The resulting diameter distribution can be checked for consistency or further constrained if the basal area is available using (Nord-Larsen and Cao, 2006):

$$G = \pi/40000 \cdot N \cdot \left(a_D^2 + 2a_D\beta_D\Gamma\left((c_D+1)/c_D\right) + \beta_D^2\Gamma\left((c_D+2)/c_D\right)\right) \quad \text{(eq 4)}$$

However, if the mean diameter (used for parameter estimation) is predicted right, equation 4 should not yield much additional information. It is primarily a check against non-fitting. For the development of the model, mean values will be used at first, taking into account that the step to simulating with distributions should be made later.

7.4 THE TEMPORAL DIMENSION: OUTLINE OF A DYNAMIC FOREST MODEL

The model includes the natural processes
- biomass growth
- mortality
- ingrowth.

All of these are impacted by
- management and/or
- disturbances (both natural and anthropogenic)

The processes are formulated as a state-space model, with all equations age-independent.

7.4.1 Volume growth

In this module, the accumulation of standing volume through annual growth of existing trees is calculated.

7.4.1.1 What to model

The growth of biomass can be expressed as an increase in stand volume or in mean diameter and/or height. The only rate variables available from the NFI data are volume increments, thus stand growth is driven by an increase in volume. The other stand variables that are affected by growth (diameter and height, basal area) are consequently updated using assumptions on the distribution of the increment over the trees. The variables on species and density are not affected by biomass growth:
- dSpecies = 0
- dDensity = 0
- **dVolume = *f*(state variables)**
- dDiameter = *f*(dVolume,…)
- dHeight = *f*(dVolume,…)
- dBasalArea = *f*(dDiameter,…)

7.4.1.2 How to model

The equation used for modelling increment should fulfil the following requirements:
- Should enhance the chance of appropriate behaviour of the model outside the range of data on which is was fitted, i.e. a theoretical growth function or an empirical analogue (Tome et al 2006; Vanclay, 2004; Zeide, 1993)
- Should allow fitting (in its most simple form) on NFI data only
- Should allow age independence of predicted increment
- Should allow incorporation of competition between cohorts of different species and between cohorts of the same species

One equation that, in its most simple form, only needs one state variable and does not include age is:

$$Ln(\Delta y) = \beta_0 + \beta_1 Ln(y) - \beta_2 y^k \qquad \text{(Equation 1)}$$

It is typically used for diameter growth with k=1 (Zeide, 1993; Vanclay 1994) or k=2 (Wykoff, 1990; Vanclay 1994) as used in the Prognosis model, adding an environmental (E) and a competition term to describe the growth of individual trees (Wykoff, 1990).

We chose k=1 and y = standing volume and adapted the equation to a multi-cohort stand:

$$Ln(\Delta V_c) = \beta_0 + \beta_1 Ln(V_c) - \beta_2 V_s$$

With

ΔV_c	volume increment in cohort c
V_c	volume in cohort c
V_s	volume in the total stand s (= sum of all cohorts in the stand)
$\beta_0, \beta_1, \beta_2$	species specific coefficients

A pilot for Baden-Wurttemberg showed that the mean growth rate could be reasonably well predicted, but that the variation was greatly reduced, especially towards above average growth.

The next step is to include a measure of site quality. Preliminary analysis showed that fitting a site index based on a relation between height and age showed low correlation with both increment data and environmental variables. Sterba (1987) and Sterba & Monserud (1993) developed the concept of potential density as a measure of site productivity and applied it for unevenaged and mixed stands (Sterba & Monserud, 1995).

The envisaged steps for further work are:

- Select a number of “homogeneous” sets of plots based on environmental variables
- Fit potential density equation parameters for these plots
- Correlate potential density parameters with environmental variables
- Combine the potential density with the growth equation, assuming that density at maximal gross increment can be described in terms of maximal density.

7.4.1.3 Derive the total set of variables

In order to derive new height and diameter from volume (increment) there are two main options:

- Fixed relation between diameter and height, distribute volume increment over diameter and height increment based on this relation
- Fixed height growth curve, distribute volume increment over diameter and height increment with height growth as given

The first option was chosen, however no definite choice has been made yet on the function. The aim is to introduce some variation in this relation, i.e. one free parameter that can be calculated on plot level if both height and diameter are available from the initialisation. If diameter and height are not both available from the database, this parameter may then be drawn randomly from a predefined distribution during initialisation or for species that are introduced in a stand during the simulation.

Both species and tree density are not affected by the biomass growth process.

7.4.2 Mortality

In this module, the “regular” mortality is estimated, i.e. caused principally by ageing, suppression, competition, by chance or “normal” weather circumstances and from normal incidence of pests and diseases. “Catastrophic” mortality is modelled in the module on disturbances (see par 7.4.6). (Vanclay, 1994).

7.4.2.1 What to model

Mortality is expressed as the number of trees per ha that die in a certain stand. The attributes of the dying trees (mean diameter, height) determine what the effect of the death is on the other plot characteristics.

For mortality, no data on rates are available in the NFI plot database (only volume of lying and standing dead for some countries). Therefore, an analytical approach is chosen and data will have to be collected on a more ad hoc basis. Currently, a database with repeated (2x) surveys of forest reserves in The Netherlands is being used for model development.

- **dSpecies = ?**

- **dDensity = *f*(state variables)**
- dVolume = *f*(dDensity, dDiameter, DHeight,…)
- **dDiameter = *f*(state variables)**
- dHeight = *f*(dDiameter,…)
- dBasalArea = *f*(dDiameter,…)

7.4.2.2 How to model

Two different kinds of "regular" mortality are distinguished:

- Density dependent mortality, caused by competition and suppression
- Density independent mortality, caused by all other factors and often described as a random function (Vanclay, 1994)

Density dependent mortality will be based on the theory of self thinning (Reineke, 1933; Yoda et al., 1963). Despite some serious points of critique (e.g. Zeide, 1987), the concept of a fixed relation between maximal density and either maximal mean volume, maximal mean basal area or maximal mean diameter seems currently the only option to use information from the plot data.

Mortality is expressed as the number of trees per ha that die. The number of trees dying is calculated from the idea that at a certain density (the self-thinning line), any increase in diameter results in a decrease in number of plants following the derivative of the relation between diameter and stem number. Further away from the self-thinning line, a modification factor is introduced (Tang et al, 1994). The self thinning line is described using the parameters from the potential density concept (see 4.1.2) and the distance from the self-thinning line is expressed as a function of the ratio between actual and potential basal are for a certain height. As height increases, potential density increases as well and even a fully stocked stand may grow with little mortality.

Density independent mortality can be a fixed percentage of the total number of stems taken randomly from the total stand and thus not influencing the distributions of diameter and height.

7.4.2.3 Derive the total set of variables

How to assign species, mean diameter and height to the dead trees? Under development.

7.4.3 Ingrowth

In this module, the ingrowth of new trees into the stand is estimated, rather than the regeneration. Thus, the process of flowering, seed setting, germination and earliest mortality is not taken into account. Only trees that reach a certain minimal diameter and/or height are introduced into the stand.

7.4.3.1 What to model

Ingrowth of young trees is expressed as number of trees per ha that meet the criteria. Given a minimal diameter cq. height and a defined relation between these two variables, the initial characteristics of ingrowing trees or tree cohorts can be defined. No data of young threes are available from NFI, nor are there any data on regeneration or ingrowth rates. Thus, an analytical approach is chosen, and data are collected on a more ad hoc basis. Currently, a database with repeated (2x) surveys of forest reserves in The Netherlands is being used for model development.

- **dSpecies = *f*(state variables)**
- **dDensity = *f*(state variables)**
- dVolume = *f*(dDensity, dDiameter, DHeight,…)
- dDiameter = *f*(dDensity)
- dHeight = *f*(dDiameter, dDensity …)
- dBasalArea = *f*(dDiameter,…)

or

- **dSpecies = *f*(state variables)**
- **dDensity = *f*(state variables)**
- **dVolume = *f*(dDensity, state variables,…)**
- dDiameter = *f*(dDensity, dVolume,..)
- dHeight = *f*(dDiameter, …)
- dBasalArea = *f*(dDiameter,…)

7.4.3.2 How to model

The concept of a self-thinning line that is used to model density-dependent mortality also determines the amount of "free space" in a stand that is available for young trees. A higher amount of "free space", i.e. a less dense forest, would allow more ingrowth than a more dense forest.

As a pilot a two stage ingrowth model was fitted to data from an excerpt from the forest reserves database in the Netherlands. Information was available for at least two points in time. Data is divided in trees that were alive at both measurement points, trees that disappeared between the measurements, and trees that appeared at the second measurement. Available are number of trees, basal area, average diameter, average height and total volume, both per species and for the total plot. Measurement threshold is 5 cm.

For all species separately and for the plot as a whole, we tested a binary logistic regression to predict if ingrowth would occur or not, and we tried a linear regression model to predict the number of trees that would grow in.

Variables that were taken into account were:

- Total basal area of the plot
- Number of trees of the same species
- Share of the basal area occupied by species that caste heavy shade
- Basal area present at t1, but not present at t_2 (=mortality)

For the lineair regression, the dependent variable was calculated as:

$Y = \ln(\text{number of new trees at time } t_2 / (t_2 - t_1))$

This includes only cases were ingrowth of species i actually occurred. The natural logarithm ensures that no negative ingrowth is predicted, and the shape of the curve better fits expected patterns.

The data were such that only for *Pinus sylvestris*, a species specific model could be constructed that first decides if ingrowth will occur and subsequently how much, with a reasonable explanation of variance ($R^2 = 0.314$). For all species together this was also possible, but with low explanation of variance ($R^2 = 0.135$). For the remaining 14 species, no correlation could be found for 7, while for the other 7 either binary OR lineair regression was possible. This illustrates the expected problem of data availability. Where regressions were made, total basal area of the plot plays the expected role, while basal area removed (through mortality) does not play a role in most regressions. However, these were unmanaged stands.

The experiences from this pilot will be used to further develop the ingrowth module.

7.4.3.3 Derive the total set of variables

With diameter and height of each individual set by the model-specific definition of ingrowth, and the number of individuals per species predicted by the model, the basal area and the volume of the new cohort can be calculated. For some stands, with distinctive generations of trees, the new trees will

remain in a cohort of their own. For other, unevenaged, stands with a more smooth age distribution, the new cohort will be merged with the existing cohort of the same species.
A big issue is how to determine the species of new trees. Especially if a gradual change in species composition is simulated, the management regime is an important impact on the species of ingrowing trees. One management options would e.g. be to focus on a specific species and control all ingrowth of alternative species.

7.4.4 Management

The aim of the model is to simulate at least part of the spectrum of management regimes within a region occurring at the same time. This poses the problem of matching large area targets/scenario's with management regime per cell or stand. For the millions of stands that will be run in EFISCEN Space an automated assignment of management is needed.

7.4.4.1 What to model

The implementation of management in the model in order to simulate the effects of scenarios involves both a bottom up (based on stand specific information) and a top down (mostly based on wood demand, but possibly also on other goals) component.

The top down component involves the translation of a scenario storyline or user defined management regimes (at regional or higher level) into volume demands and management trends (or areal proportions of Forest management Alternatives). National wood demand is scaled down to regional targets based on current statistics (MCPFE, other), GIS information (slope, etc…) and information from the initialization file. Targets for management trends (e.g. surface targets for nature oriented managed forest,…) affect chances of a cell/stand being assigned a certain management regime or Forest Management Alternative (see below).

The bottom up component involves the actual assignment of a management regime or Forest Management Alternative to individual forest stands based on:

1) (Combinations of) Tree species defines broad class of management
2) (National or regional) culture of management and area statistics (e.g. MCPFE statistics on protective forest), possibly combined with scenario targets (top-down)
3) Overlays with GIS slope and soil maps narrows down the type of management regime
4) Overlays with other GIS information, in particular maps with nature protection areas, reserves, etc…

For each of the sets combinations as defined above, management tables are constructed (up to about 100 per country) that describe the parameters used in the application of management actions (final felling chance, thinning per diameter class etc…).

For the first and core version of the model, management actions are limited to different ways of removing a number of trees or a certain amount of wood biomass from the stand. Though adding trees through planting or seeding are also management actions, these are discussed separately in 4.5.

7.4.4.2 How to model

Each management action can be defined as the proportion of trees that are removed in each cohort. Different types of management actions can be simulated by distributing removals differently over cohorts and diameter classes. If a management action will be performed or not will depend on the state of the forest (like growing stock volume, current vs. required tree species distribution, stand density, diameter distribution, time since last harvest?), other (GIS) info (site, location, etc.) and on the wood demand or management targets in the region.

Management actions that can be modeled:

Tending: initiated when stand density is above a certain threshold and most trees are in a certain diameter class. Possibly also when species composition is unfavourable. Possibility to steer in species distribution (preferred removal of certain species), removal randomly from all diameter classes?

Thinning (see also Soderberg et al., 2003): initiated by stand density, time since last thinning, stand composition. Possibility to favour certain species (removal of other species' cohorts), possibility to distribute removals in different ways over diameter classes. Thinning from below: removals concentrated in lowest diameter classes, thinning from above: removals concentrated in highest diameter classes. Or thinnings randomly in all diameter classes.

Final harvest: Clearcut: removal of all trees, probably except lowest diameter class (advanced regeneration). Shelterwood: Leaving a certain number of trees of the highest diameter classes, possibly focusing on certain tree species.

Uneven aged management: Removal of trees in different diameter classes to approach a negative exponential distribution.

All actions are assumed to take place homogeneously in the whole stand. However, it will (most likely) be possible to divide a stand in several cohorts, with the possibility to manage each of these in a different way. It will therefore not be possible to model spatially explicit management regimes, like creating gaps in the forest, or something like the future tree/crop tree system, without additional information from more detailed models.

Impact of thinning on growth, ingrowth and mortality in 10 yr period afterwards should be included in the respective module. However, for the implementation of management regimes, specific tests will be run with the model to check and adapt the responses of various types of stands to the management regimes.

7.4.5 Regeneration (after clear cut)

Ingrowth may be satisfactory for new trees under continuous forest cover (7.4.3), but after clearcut or – in the future- after afforestation, regeneration is a discontinuous process. For the revegetation of "empty" plots an algorithm will be developed similar to the initial assignment of management regimes. Based on top down constraints, i.e. statistics or targets for management regimes or Forest Management Alternatives, and site specific GIS information (slope, soil type,…) a coherent set of species and management regime will be assigned. Site quality of the plot for any new species will be based on environmental variables as done for all plots during the initialisation.

7.4.6 Disturbances

To be developed later, should contain:

- Occurrence of disturbances: storms, fire,…?
- In the future use weather simulations over Europe?
- Damage caused by disturbances
- A relation between stand characteristics (biotic and abiotic) and disturbance risk/damage:

→ stand & soil characteristics & slope to storm damage
→ built up of litter to fire occurrence and damage

7.4.7 Decomposition and soil module

For decomposition of large wood and litter, as well as carbon cycling in the soil, the soil model Yasso (Liski et al., 2005) is implemented. This model has been developed for forest soils and is already in use for European applications in combination with the EFISCEN model. Initialisation will be based on the European Soil Carbon map, with a species specific profile. Modelling the soil dynamics of mixed stands will be difficult and we will probably resort to refrain from any interaction effects between the litter of different species in the same stand.

7.5 DERIVED INDICATORS: CALCULATING PERFORMANCE OF ECOSYSTEM FUNCTIONS FROM THE MODEL OUTPUT

7.5.1 Above- and below ground biomass & carbon

The calculated stemwood volumes are converted to stem biomass by using the basic wood density (dry weight per green volume). Based on the stem biomass, the model calculates the biomass of branches, coarse roots, fine roots and foliage. For this calculation the model requires biomass distribution tables, depending on diameter at breast height. These tables can be based on the results of more detailed models or on literature values, for example from literature on biomass expansion factors (BEFs). The biomass distribution tables are defined by regions and tree species. For the conversion to carbon, the carbon content of biomass is also needed. Figure 3.4 illustrates the conversion from stemwood volume to estimates of whole tree carbon. Many of these expansion factors have been derived for the EFISCEN V3 model and can be used for EFISCEN-Space.

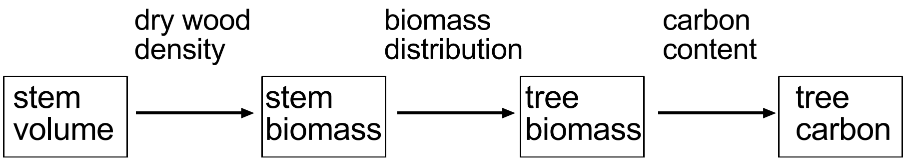

Figure 7.4: Calculation of biomass and litter

7.5.2 Litter production: turnover of above- and below ground biomass

Each year, a proportion of the stems, branches, roots and leaves of the trees die, the so-called turnover. The produced litter is input for the soil module. To calculate litter production, the proportion of annual litterfall of the standing biomass is needed. Also, when a thinning or final felling is carried out, all biomass of the other tree components is added to the litter production and thus litter production depends on the harvest level in the region. Furthermore, part of the felled stem volume will remain in the forest, defined by the ratio between removals and fellings. Usually this is wood that is considered to be non-commercial, e.g. due to too small diameter (topwood) or presence of rot. Another source of litter is due to natural mortality.

7.5.3 Carbon from other than wood

For the soil module, carbon in litter and roots from the undergrowth is vital. However, this will be developed only in a later stage

7.5.4 Effects of climate change

To be developed in a later stage

- Derive method to describe altered volume increment induced by climate change (either based on process-based models or generalized empirical relationships)
- Should now be able to do this better than the transient step-wise way in EFISCEN V3.maybe more directly related to soil and altitude, weather data cross Europe etc

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8 W+ Simulator for the Baden-Württemberg region

Authors

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Abstract

W+ is a simulator based a combined stand level and individual tree level growth model for even-aged forests. Its parameters are estimated from permanent thinning experimental plots of Norway spruce (*Picea abies*), Douglas-fir (*Pseudotsuga menziesii*), and common beech (*Fagus silvestris*) situated in south western Germany. The plots cover a wide range of site types and growth conditions. Further, a wide range of different treatments is included with respect to initial spacing, type of thinning (e.g., low thinning, high thinning, crop tree thinning), and intensity of thinning: from un-thinned high-density plots to very widely-spaced "solitary" plots. The simulator W+ is intended for use as silvicultural decision support system. Since it allows long term forecasts of alternative treatment systems different production programmes can be compared. Input variables are tree size, age and site quality. Site quality enters the model through site index (top height at age 100), requested tree size variables are breast height diameter distribution. Detailed descriptions of W+ and its growth functions are provided by Weise and Kublin (1997 and 1998) as well as by Yue et al (2008). W+ is used in EFORWOOD to study different management approaches for Norway spruce and common beech reference forest types within the Baden-Württemberg region.

8.1.1 Introduction

W+ is specific in its approach to combine growth information generated from tree- and stand-level growth models parameterized from data of permanent plots in Baden-Württemberg. Approaches to combining information generated from different models are recognized for improving forecast quality. The combination approach to forecasting has been introduced by Bates and Granger (1969). However, such an approach has not been developed for forest growth predictions. W+ is the first simulator to combine the different levels models. The tree-level model predicts relative tree diameter growth rates of a cumulative diameter distribution. The stand-level models predict absolute stand basal area growth. The combined prediction system consists of three basic steps: preliminary prediction, combination, and feed-back modification. Preliminary predictions of stand basal area growth are generated annually from both types of growth models. The preliminary predictions are then combined based on variance and covariance method and the combined estimator is used to update the growth models in a feed-back procedure. In the tree-level growth model, the updated stand basal area is subsequently disaggregated to individual trees (Yue et al 2008). The growth potential and height growth dynamic is modelled according to a static site class determination (Assmann 1963).

8.1.2 The concept of W+

Among different submodels W+ consists of a combination of a tree-level relative diameter growth rate model and a stand-level basal area growth model. The tree-level growth rate is modelled in the initial step as a function of the relative cumulative diameter distribution. The growth rate is mediated by stand age, basal area and intrastand competition. The stand level basal area increment model predicts growth as a function of site index, stand age, quadratic mean diameter and basal area. The two models are combined through the variance- and covariance-based combination approach of Bates and granger (1969). Yue et al (2008) are describing the concept in much detail and provide a comprehensive model evaluation.

8.1.3 Data input and management interventions

Input data for the model are, besides the site index and stand age, a list of sample trees with their dbh and height. In case empirical data on sample trees are missing Johnson curves (Elderton and Johnson 1969) are used to generate diameter distribution based on stem number, basal area, age and mean height (site index). Growth and mortality are calculated in annual steps or a multiple of it.
Management interventions can be given in multiple ways. Predefined basal area or crop tree oriented thinnings and final harvest systems are provided that allow individual adjustments, i.e. number of crop trees, thinning intervals, min/max cut volume. Further, real thinnings with individual tree or diameter class removals can be loaded in. In addition, alternative thinning regimes can be predefined, i.e by type of thinning, basal area removed and time of operation, which will be applied to an initial stand in a routine.

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9 Calibrating a dynamic stand growth model for sessile oak (Quercus petraea (Matt.) Liebl.) in Lorraine, France

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Abstract

Based on a recent, unpublished growth model for pedunculate oak in Denmark a dynamic stand-level growth model was calibrated on permanent sample plot data for sessile oak in the Lorraine region of France. Estimated parameters corroborated the expected growth path of stand height and stand basal area as well as the expected mortality. The final model explained more than 98% of the variation in stand top height and stem number and more than 91% of the variation in basal area. The height growth model yielded unbiased estimates but estimates of basal area growth and mortality were slightly biased, resulting in an overestimation of quadratic mean diameter growth. Despite differences in growth patterns for oak in Denmark and France, the dynamic model was successfully calibrated on the French oak data. The apparent versatility of the dynamic model is probably due to the choice of a model that closely reflects fundamental processes of plant growth.

Keywords: growth model, oak, dynamic, EFORWOOD

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9.1 INTRODUCTION

Stand-level growth models provide simplistic representations of the forest stand. Generally they require only basic input variables such as age, stand top height, stand basal area, stem number or quadratic mean diameter to predict forest growth. Often, data to calculate driving variables are collected as part of routine inventories at estate, regional, national or super-national level. The information produced by stand-level models are of great value to forestry practice as necessary information can be easily obtained in the forest to make predictions of expected future yield and revenues and for tactical and operational planning. At the policy level model predictions may be used for scenario simulations and strategic planning. Consequently, in spite of their simple structure and unsophisticated input requirements, stand-level growth models are among the most versatile and reliable tools for decision-making in forest management. The simplest form of stand-level growth models are yield tables that represent expected stand development patterns for a specific management regime. For even-aged, monospecific stands these are commonly tabulated by site class, stand age and management regime. Most yield tables include expected yields as well as other stand-level variable. The first yield tables were published Germany in the late 1700's (Skovsgaard and Vanclay, 2008, c.f.). By 1880, more than 1,200 yield studies had been published for different species in Germany alone and since then thousands of yield tables have been developed for predicting forest growth across the world (Vuokila, 1965). Yield tables are generally static in the sense that they represent only one growth path representative of a specific set of treatment options. When the silvicutural practices differ from that of the equation or table, the model can no longer be expected to provide accurate predictions. Consequently, the yield tables are inadequate for simulating contrasting treatments and their resulting growth paths. In contrast to the static growth models, as for example in yield tables, the concept of dynamic modeling incorporates adaptive model components which are capable of adjusting the model to local site and stand conditions as well as to any deviations in growth pattern which may occur now or in the future. This could include, for example, perturbations in growth conditions due to climate change, or simple changes in forest management practices such as harvesting intensity. In recent attempts to develop growth models for common Danish forest tree species, dynamic stand-level models were developed for oak (Quercus robur L., Johannsen, 1999). As part of the major EU research initiative EFORWOOD, numerous growth models were recently calibrated for different tree species and forest types in various parts of Europe, with the aim to provide a reliable and exible basis for assessing sustainability of the entire European FORestry-WOOD chain (http://87.192.2.59/eforwood/default.aspx). This paper reports the calibration of the Danish model for oak for simulating growth of sessile oak (Quercus petraea (Matt.) Liebl.) in the Lorraine region of France

9.2 DATA

The dynamic stand-level models and additional functions were calibrated using data from permanent sample plots in even-aged and mono-specific spacing and thinning experiments of L'Institut de Recherche Agronomique (INRA). The data included 19 experiments with a total of 35 individual plots. Plot size varied between 0.16 and 2.00 ha, with an average of 0.96 ha. The data were collected from 1903 to 2006, and the stands were observed for 6 to 94 years. The total number of measurement occasions was 366. Stem number, N (ha-1), was calculated as the number of individual trees per hectare taller than 1.3 m. When trees forked below 1.3 m, each stem was measured individually but multiple stems from the same root were counted as one tree. Stand basal area, G (m2 ha-1), of each plot was estimated by summation of individual tree basal areas calculated from measurements of stem circumference at 1.3 m above ground level. Quadratic mean diameter, Dg (cm), was derived from the estimates of N and G. Diameters of individual trees were calculated from the measurements of circumference, assuming a circular cross-sectional area. Based on paired observations of diameter and height, height-diameter regressions were estimated for each plot and measurement combination. Subsequently, the equations were used to estimate the height of trees not measured. Stand top height, defined as the mean height of the 100 thickest trees per hectare (H_{100}), was calculated for each plot and measurement occasion based on measured and predicted tree heights. Table 1 presents a summary of the data.

Table 1: Summary statistics of stand top height (H_{100}), age (T), quadratic mean diameter (D_g), stem number (N) and basal area (G).

Variable	Unit	n	Mean	Minimum	Maximum	Std. Dev.
H_{100}	m	261	25.2	8.9	39.4	5.9
T	years	366	107.7	29.0	305.0	44.1
D_g	cm	366	32.2	4.3	78.2	14.3
N	ha^{-1}	366	704.8	7.0	14,690.0	1,456.0
G	$m^2\ ha^{-1}$	366	25.8	2.0	45.8	5.8

The data included a range of contrasting treatments in terms of initial spacing and subsequent thinning practices, from unthinned control plots to heavily thinned plots. In the thinning experiments, the stand density index according to Reineke (1933) ranged from 0.4 to 1.0.

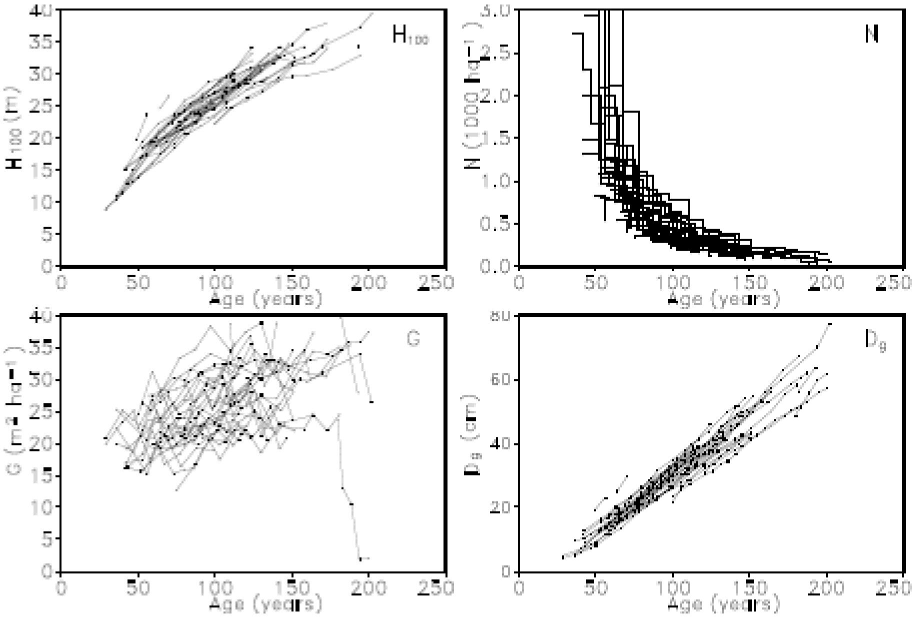


Figure 1: Stand-level values of H_{100}, G, Dg, and N for sessile oak plots in Lorraine.

Stand ages ranged from 29 to 305 years, but the majority of measurement occasions were in stands of 50 to 150 years (Figure 1). Site index ranged from 12.5 to 20.9 m at age 50 years. The majority of stands were quite moderately thinned with residual basal areas of more than 20 m2ha-1 (in contrast to the more heavy thinning practise with residual basal areas of 14-18 m2ha-1 as often practised in northern Europe).

9.3 METHODS

Dynamic stand-level growth models based on the state-space approach have previously been developed for radiata pine (Garcia, 1983), loblolly pine (Zhang and Borders, 2001), Norway spruce (Leary et al., 2008; Skovsgaard et al., 2008; Johannsen et al., 2008), oak (Johannsen, 1999), Douglas fir (Christensen et al., 2004), and European beech (Nord-Larsen and Johannsen, 2007). The hypothesis underlying this approach is that the current state of the system reflects the past causes of the system and constitutes all the information needed to predict its future behavior. Using this approach an even-aged oak stand may be characterized by, for example, the current basal area and stand top height, and predictions of future basal area growth does not depend on the timing and intensity of thinnings leading to the current state of the system.

9.3.1 Estimating dynamic stand-level growth models

In the state-space model it is assumed that the n dimensional state vector at some point in time, x(t), can be predicted by the transition function F of the state variable, x(t0), and a vector of input variables, U at some other point in time (cf. Garcia, 1994):

$$\begin{aligned} \boldsymbol{y}(t) &= \boldsymbol{g}\left[\boldsymbol{x}(t)\right] \\ \boldsymbol{x}(t) &= \boldsymbol{F}\left[\boldsymbol{x}(t_0), \boldsymbol{U}, t - t_0\right] \qquad (1) \end{aligned}$$

where the current output, yt is a function g of the current state. In other words, the state-space approach predicts any future states of the system from the initial state, x(t0), through iteration. For example, an initial observation of the two-dimensional state vector of height and basal area may be used to predict basal area and height after one period. The new estimates of the two state variables are then re-entered into the model to predict the state after one more period, and so forth. Abrupt changes in, for example, basal area due to thinnings are handled by simulating the shifts in the state vectors and are seen as shifts between different growth paths.

9.3.2 Stand-level model

The general model form for all species entails three equations for predicting stand top height growth (ΔH_{100}), basal area growth (ΔG), and mortality (ΔN):

$$\frac{\Delta H_{100,ij}}{\Delta t} = a_j H_{100,ij}^{\alpha_1} e^{\alpha_2 H_{100,ij} + \alpha_3 G_{ij}} + \varepsilon_{H,ij} \qquad (2.1)$$

$$\frac{\Delta G, ij}{\Delta t} = (\beta_{01} + \beta_{02} \cdot a_j) G_{ij}^{\beta_1} e^{\beta_2 G_{ij} + \beta_3 H_{100,ij}^{\beta_4}} + FV[G]_{i+1,j} + \varepsilon_{G,ij} \qquad (2.2)$$

$$\frac{\Delta N_{ij}}{\Delta t} = -\gamma_1 N_{ij}^{\gamma_2} e^{\gamma_3 \sqrt{N_{ij}} H_{100,ij}} + FV[N]_{i+1,j} + \varepsilon_{N,ij} \qquad (2.3)$$

where $H_{100};_{ij}$, Gij and Nij are stand top height, stand basal area and stem number at the *i*th measurement occasion of the *j*'th plot. Parameter *aj* is plot- or site-specific and is estimated locally, and the remaining parameters, $\alpha_1 - \alpha_3$, $\beta_{01} - \beta_4$ and $\gamma_1 - \gamma_3$, are estimated globally. The residuals $\varepsilon_{H,ij} \sim N(0, \sigma_H^2)$ and $\varepsilon_{G,ij} \sim N(0, \sigma_G^2)$ are the error terms of the *i*th measurement occasion on the *j*th plot. The forcing values, FV[G] and FV[N], represent shifts in G and N, respectively and are caused by thinning. For practical application of the stand model, *aj* must be estimated from a series of observations of height and basal area. When the model is applied where sessile oak has not been grown before or when there are no sequential observations of stand variables, the estimation cannot be carried out. A preliminary study showed that *aj* was highly correlated with the more traditional measure of site quality, site index, defined as the stand top height at age 50 years. To allow flexible use of the model, depending on the available data, we also estimated the stand level model where site specific effects were substituted by a linear function of site index (S):

$$\frac{\Delta H_{100,ij}}{\Delta t} = (\alpha_{01} + \alpha_{02} \cdot S_j)\, H_{100,ij}^{\alpha_1} e^{\alpha_2 H_{100,ij} + \alpha_3 G_{ij}} + \varepsilon_{H,ij} \qquad (3.1)$$

$$\frac{\Delta G_{ij}}{\Delta t} = (\beta_{01} + \beta_{02} \cdot S_j) G_{ij}^{\beta_1} e^{\beta_2 G_{ij} + \beta_3 H_{100,ij}^{\beta_4}} + FV[G]_{i+1,j} + \varepsilon_{G,ij} \qquad (3.2)$$

$$\frac{\Delta N_{ij}}{\Delta t} = -\gamma_1 N_{ij}^{\gamma_2} e^{\gamma_3 \sqrt{N_{ij}} H_{100,ij}} + FV\,[N]_{i+1,j} + \varepsilon_{N,ij} \qquad (3.3)$$

The three equations in the stand-level models were estimated following the approach of McDill and Amateis (1993). Using this approach, the estimation problem may be written as a series of annual difference equations that increment stand height, stand basal area or stem number from some initial state to a state at some later point in time, using the number of growth seasons between the two observations as the number of iterations. Considering height, the state at the end of the growth period may be predicted from the state at the beginning of the growth period by a series of predicted annual increments:

$$\widehat{H}_{i+1,j} = H_{i,j} + f(H_{i,j}, G_{i,j}) + \varepsilon_{i+1,j} \qquad (4.1)$$

$$\widehat{H}_{i+2,j} = \widehat{H}_{i+1,j} + f(\widehat{H}_{i+1,j}, \widehat{G}_{i+1,j}) + \varepsilon_{i+2,j} \qquad (4.2)$$

$$\vdots$$

$$\widehat{H}_{i+t,j} = \widehat{H}_{i+t-1,j} + f(\widehat{H}_{i+t-1,j}, \widehat{G}_{i+t-1,j}) + \varepsilon_{i+t,j}, \qquad (4.j)$$

where $f(H_{i,j}, G_{i,j})$ is expressed in equation (2.1) and models annual height increment of the *j*th plot at time i+t (t = 0; 1; 2; : : : ; n). The parameters of the annual difference equation were then estimated using a nonlinear least squares procedure (the Marquardt procedure of PROC MODEL, SAS 8.2) that minimized the squared deviations of $\widehat{H}_{i+t,j}$ from $H_{i+t,j}$. The data used for this study represents a structure of repeated measurements on individual plots. Failure to recognize within-plot correlation in measurements may result in inefficient estimates and underestimated standard errors when correlations are strong. When growth is viewed as an incremental process where only current conditions influence current growth, the problems of serial correlation are usually avoided (Garcia, 1983; Seber and Wild, 1989). However, we explicitly modeled the serial correlation by including a generalized formulation of the first-order autoregressive model that accommodates for the irregular spacing of measurements, i.e.

$$\varepsilon_i = \rho_m^{t_i - t_{i-1}} \varepsilon_{i-1} + u_i \qquad (i = 1, 2, \cdots)\ , \qquad (5)$$

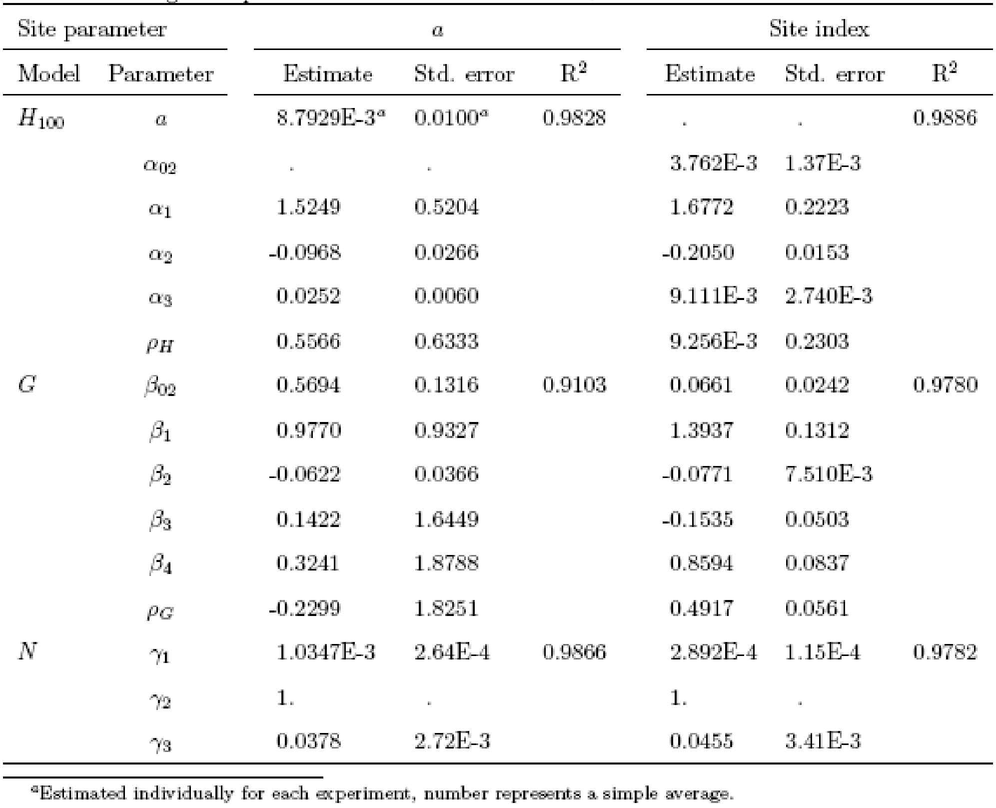
where ε_i is the error at the *i*th measurement, t denotes time, ρ_m is the coefficient of correlation of the *m*th equation, and the u_i's are normally and independently distributed random errors.

9.4 RESULTS

Most parameter estimates of the system of equations (2.1) - (2.3) were statistically significant ($P<0.05$). As the individual parameter determines the shape of the growth path, non-significant parameters were consequently not left out. The correlation coefficients of both the height growth model (ρH) and the basal area growth model (ρG) were not significant, indicating that height and basal area growth in subsequent periods were uncorrelated. The system of models, using the site specific parameter a (equation (2.1) - (2.3)) accounted for about 98% of the observed variation of H_{100} and N and 91% of the variation of G at the end of the growth period (Table 2). Based on periodic annual increment (PAI) the height and basal area models explained 42% and 76% of the total variation in annual growth, respectively, whereas the mortality model explained 37% of the observed annual changes in stem number.

Parameter estimates of the model system using site index as the site specific variable (3.1) - (3.3) were all significant ($P<0.05$) except for α_{01}. The use of site index as the site specific variable resulted in only a slight decrease in precision (Table 2). Residuals of the height growth model for sessile oak were evenly distributed around zero and revealed no apparent irregularities when plotted against predicted height (Figure 2). Residuals of the basal area growth model showed some large deviations from the model, particularly in relation to large prediction intervals. Also, the basal area growth model showed some bias resulting in underestimation of basal area growth when stand basal area is large. Residuals of the mortality model showed some large deviations between predicted and observed values, mainly for some young stands (<40 years) with excessive mortality. The residuals of the mortality model revealed an apparent bias that resulted in an overestimation of mortality in stands with low stem-number.

Table 2: Parameter estimates for sessile oak of the system of equations presented in equations (2.1) { (2.3) and (3.1) { (3.3) along with their standard errors. R_2 was calculated from the deviations between predicted and observed values at the end of each growth period.



Site parameter		a			Site index		
Model	Parameter	Estimate	Std. error	R^2	Estimate	Std. error	R^2
H_{100}	a	8.7929E-3[a]	0.0100[a]	0.9828	.	.	0.9886
	α_{02}	.	.		3.762E-3	1.37E-3	
	α_1	1.5249	0.5204		1.6772	0.2223	
	α_2	-0.0968	0.0266		-0.2050	0.0153	
	α_3	0.0252	0.0060		9.111E-3	2.740E-3	
	ρ_H	0.5566	0.6333		9.256E-3	0.2303	
G	β_{02}	0.5694	0.1316	0.9103	0.0661	0.0242	0.9780
	β_1	0.9770	0.9327		1.3937	0.1312	
	β_2	-0.0622	0.0366		-0.0771	7.510E-3	
	β_3	0.1422	1.6449		-0.1535	0.0503	
	β_4	0.3241	1.8788		0.8594	0.0837	
	ρ_G	-0.2299	1.8251		0.4917	0.0561	
N	γ_1	1.0347E-3	2.64E-4	0.9866	2.892E-4	1.15E-4	0.9782
	γ_2	1.	.		1.	.	
	γ_3	0.0378	2.72E-3		0.0455	3.41E-3	

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[a] Estimated individually for each experiment, number represents a simple average.

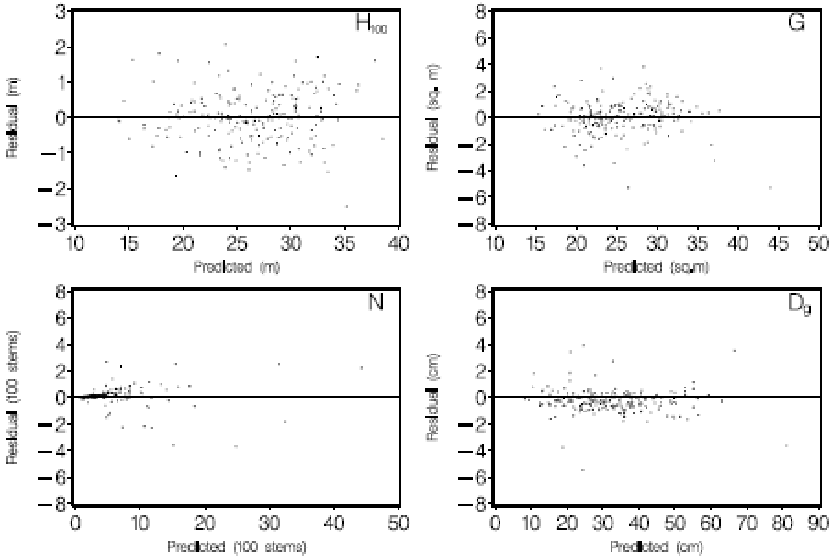

Figure 2: Residuals of the stand-level model for oak. Residuals are calculated as the difference between observed and predicted periodic annual growth (PAI).

9.5 DISCUSSION

The stand-level system of models showed significant bias for the models of basal area and mortality. The bias was caused mainly by influential observations from young stands with excessive mortality. The bias was mitigated entirely by restricting the model to stands older than 40 years, thereby omitting data from younger stands. However, as the permanent sample plot data after removal of these observations lacked data from heavily thinned stands (i.e. stands with a basal area of less than 20 m2ha-1), this caused unreasonable predictions of basal area growth in less dense stands. The signs of the parameter estimates generally corroborated the anticipated growth paths of stand top height, basal area, and mortality (Table 2). The positive $\alpha 2$ and $\beta 2$ indicate an initial multiplicative expansion of growth followed by an exponential dampening as a result of the negative estimates of $\alpha 3$ and $\beta 3$, the resulting growth curve being sigmoid (Figure 3). The parameters of the mortality model show a low probability of death that is increasing with increasing density (Figure 4). The estimate of $\alpha 4$ indicates a positive response of stand top height growth to increasing levels of stand density (Figure 3). This finding contradicts the generally accepted notion that height growth is essentially unaffected by stand density. A similar pattern was also observed by Johannsen (1999) for oak and by Nord-Larsen and Johannsen (2007) for beech using a similar system of models.

Compared to the Danish oak data, the French oak grows taller, basal area growth is larger and thinnings are generally lighter, resulting in larger stand basal area and larger mortality. Despite the differences in growth patterns among the two regions, the transfer of a dynamic model developed for sessile oak in Denmark to the Lorraine region in France was successful. Similarly, models similar to those presented in equations (2.1)-(2.3) have recently been successfully used for developing stand growth models for species with highly different growth patterns such as oak, Norway spruce, Sitka spruce, European silver fir and Douglas fir (Nord-Larsen et al., 2008b,a). The apparent versatility of the dynamic model is probably due to the selection of a model that is closely connected to two opposing processes of plant growth: an intrinsic tendency toward unlimited growth and restraints imposed by environmental factors (competition for limited resources) and aging. The two effects may be synthesized into two basic laws (Medawar and Medawar, 1983):

1. Growth is fundamentally multiplicative.
2. Relative growth is always decreasing.

The resulting cumulative growth curve has a sigmoid form where an initial expansion is followed by a dampening effect. Similar to the models applied in this study (equations (2.1) and (2.2)), the resulting growth pattern may be described by the two opposing factors: initial multiplicative expansion followed by exponential dampening. This model form may be transformed into most of the commonly used equations for describing forest growth (for example the monomolecular, logistic, Gompertz and von Bertalanffy functions (Zeide, 1993; Vanclay, 1994).

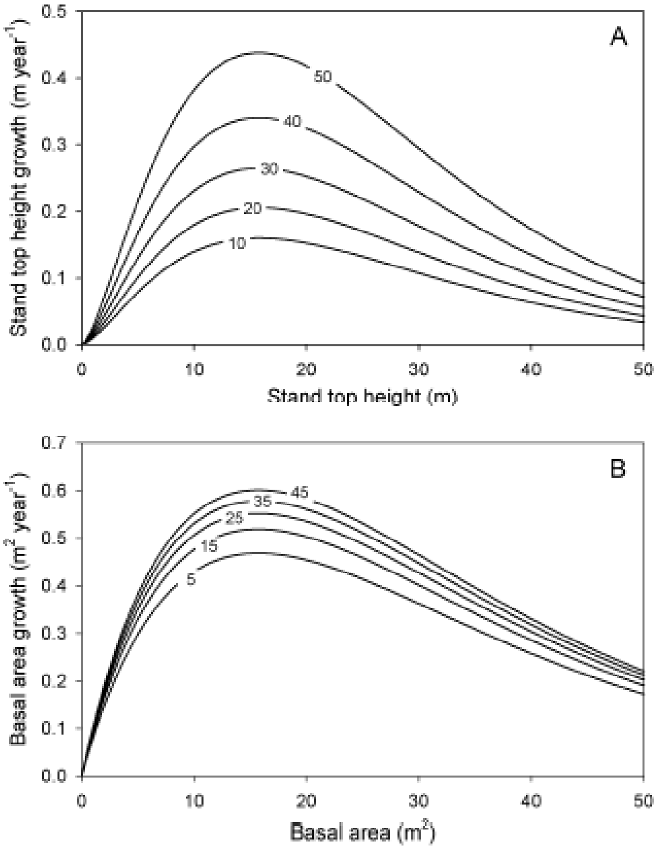

Figure 3: Simulated growth of the stand growth model for oak. (A) shows predicted stand top height growth vs. current height at different levels of basal area (basal area is shown above the individual lines). (B) shows predicted basal area growth vs. current basal area at different levels of stand top height (shown below lines).

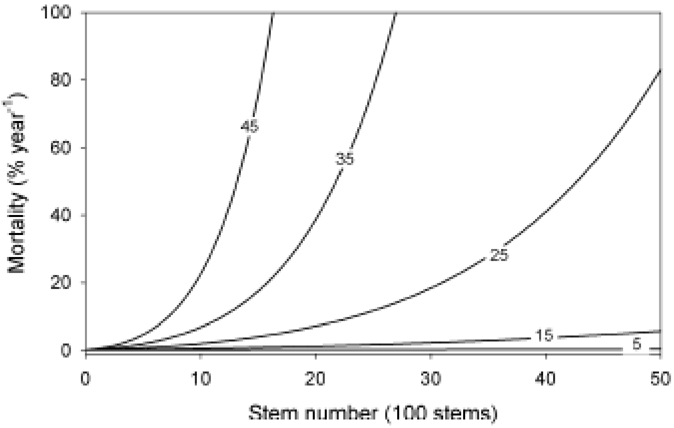

Figure 4: Predicted mortality in percent of the total stem number vs. current stem numbers at different levels of stand top height (shown above individual lines).

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10 FINAL REMARKS

This deliverable presents the on-going work that has the objective to develop tools for the long-term prediction of sustainability indicators of forests manage under alternative forest management alternatives. The presented descriptions show how different type of simulators – stand, regional and European – can be used for this purpose. Some of the simulators presented were developed during the course of EFORWOOD, such as sIMfLOR, RegWise, SYLVOGENE and EFISCEN-SPACE, while other simulators were already available and, with or without adaptation, are used just for application. The first are still under development and the version here described is not the final one.