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Deliverable PD2.5.4
Set of improved models for use in the regional simulators
and in the European simulator

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WP 2.5

Deliverable PD 2.5.4
Set of improved models for use in the regional simulators and in the European simulator

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Abstract

EFORWOOD seeks to develop tools for sustainability impact assessments of the European forestry wood chain. One important part of these tools are the forest models used in the forest simulators, computer tools that, based on a set of forest models, make long term predictions of the status of the forests within a well defined region under a certain scenario of climate, forest policy or management alternatives. Forest simulators usually predict, at each point in time, wood and non-wood products from the forest. It is an objective of EFORWOOD that simulators produce annual estimates of sustainability indicators.

This report lists the forest models that were selected for the forest simulators that will be used under EFORWOOD. These forest models are described in detail in the web-based data base FORMODELS (http://www.iefc.net/) that is structured according to a model proposed under the project. All the models that were selected had been previously developed for other purposes but most of them had to be improved/modified so that they would fulfil the requirements of EFORWOOD. These improvements are described here, with emphasis for the models to be used in the EFISCEN-SPACE European simulator that were fully developed for the EFORWOOD purpose.

It is expected that some more improvements will still be implemented till the end of the project but those will be updated into the FORMODELS data base.

Key words: growth models, regional simulators, EFISCEN, input data, NFI data, improvement, scenarios, indicators' values, volume growth functions.

Executive summary

EFORWOOD seeks to develop tools for sustainability impact assessments of the European forestry wood chain. One important part of these tools are the forest models used in the forest simulators, computer tools that, based on a set of forest models, make long term predictions of the status of the forests within a well defined region under a certain scenario of climate, forest policy or management alternatives. Forest simulators usually predict, at each point in time, wood and non-wood products from the forest. It is an objective of EFORWOOD that simulators produce annual estimates of sustainability indicators.

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It is expected that some more improvements will still be implemented till the end of the project but those will be updated into the FORMODELS data base.

The improvements needed and implemented in the forest models that will be part of the regional simulators include the development of modules for: biomass prediction, through specific models or biomass expansion factors; inclusion of risk (probability of fire and/or probability of attack by pests); initialization functions to model new stands; volume ratio and/or stem taper functions for the prediction of assortments; models for the prediction of wood quality.

The European simulator EFISCEN will be restructured and new models are being developed for this purpose. For this reason a great part of the report is dedicated to the description of the models that will be included in the new EFISCEN-SPACE. This new model will be of high spatial resolution (1 km x 1 km) and will allow the analyzis of 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; the spatial and forest structural aspects of nature conservation.

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1 Introduction and background

EFORWOOD seeks to develop tools for sustainability impact assessments of the European forestry wood chain. One important part of these tools are the forest models used in the forest simulators, computer tools that, based on a set of forest models, make long term predictions of the status of the forests within a well defined region under a certain scenario of climate, forest policy or management alternatives. Forest simulators usually predict, at each point in time, wood and non-wood products from the forest. It is an objective of EFORWOOD that simulators produce annual estimates of sustainability indicators.

This report lists the forest models that were selected for the forest simulators that will be used under EFORWOOD. These forest models are described in detail in the web-based data base FORMODELS (http://www.iefc.net/), implemented in the sequence of D2.5.2 "Framework for the description of forest modelling tools currently available with identification of their ability to estimate sustainability indicators. All the models that were selected had been previously developed for other purposes but most of them had to be improved/modified so that they would fulfil the requirements of EFORWOOD.

The objective of this deliverable is to describe the improvements that have been made into the models that will be implemented in the EFORWOOD regional simulators. In deliverable PD2.5.3 "Report of workshop on methodologies to improve and extend models for forest sustainability analysis" the need for improvements was identified, here we describe how these improvements were achieved. Special emphasis is given to the models to be used in the EFISCEN-SPACE European simulator that were fully developed for the EFORWOOD purpose.

It is expected that some more improvements will still be implemented till the end of the project but those will be updated into the FORMODELS data base.

2 Model improvement for regional simulators

2.1 sIMfLOR, simulator of the Portuguese forest (M. Tomé, S. Barreiro, P. Soares, M. Marto, S. Faias)

- Forest growth models:

  Globulus v3.0 (whole stand model for eucalyptus);

  Glob-tree (individual tree model for eucalyptus);

  Pinaster v1.0 (whole stand model with simulation of diameter distributions for maritime pine);

  Pbravo-tree (individual tree model for maritime pine);

- Improvements on models:

  Initialization module for site index distribution by NUT's III regions for eucalyptus and maritime pine models

  Development of a sub-model to estimate number of sprouts after shoots selection in coppice stands for the eucalyptus models

  The Pinaster v1.0 is a pure even-aged stand model based on the diameter distribution of Modispinaster (Fonseca, 2004) and with some developed sub-modules for:

  - initialization after clear cut and/or in new plantation;

  - biomass prediction (Faias et al, 2005)

  - merchantable volumes with taper equations (Falcão, 1994)

  - thinning and pre-commercial thinning operations

  - Models for the probability of occurrence of attacks of Gonipterus scutellatus and Phoracantha semipunctata and for the prediction of growth reduction due to attacks

  - Model for the probability of occurrence of fire as a function of geographical variables and stand type

- Planned Improvements on models:

  Some improvements will be needed in the individual tree models available.

2.2 Maritime pine in Aquitaine-France (V. Cucchi, C. Meredieu and M. Najar)

- Forest growth models: 4 models for Maritime pine: 1) the whole stand growth model PP1 for south-western of France except the coastal dune area, 2) the whole stand growth model of Lemoine for coastal dunes, 3) the Afocel growth model and 4) the individual tree growth model PP3 for south-western of France except the coastal dune area with the Capsis 4 stand growth simulator. Some additional models exist: biomass

model per compartment, carbon content, windthrow risk model, partly branch, fiber and solid wood models.

- Weaknesses detected on models: Risk concerning insects and fungi are not implemented.
- Improvements on models: Improvement for the INRA growth model will concern mainly prediction accuracy for wood volume production, by improvement of the current stem profile model. To evaluate the wood quality, branch models should be also developed.

2.3 Baden-Württemberg in Germany (J. Zell and P. Duncker)

As described in PD 2.5.3 WEHAM, originally developed to model harvesting-potential, due to its weaknesses detected will no longer be used as regional simulator in the EFORWOOD project. However, it is intended to use WEHAM for cross comparison of regional simulation results.

Instead, W+, as single-tree and stand-level simulator is used, based on NFI-Data. Weise & Kublin (1997, 1998) presented W+ in its original form; the most recent developments are described in detail by Yue et al. (in press).

This most recent version still needed further improvement for serving as simulator in EFORWOOD. Being intended as stand level simulator W+ in its standard version is limited to model forest growth under a single forest management regime over a whole production cycle. This limitation is overcome by adding an automatic processing routine for different predefined treatment regimes on the same plot or to simulate automatically a whole region. In addition, the thinning specification in respect to timing and treatment repetition, thinning type and control of thinning intensity are improved and offer emulating various forest management approaches. Now it is possible by creating lists of input to simulate forest development and timber production for whole regions with W+.

Further, standard output of W+ provides dendrometric data for remaining and cut stand. In order to derive sustainability indicator data regarded in Eforwood additional calculation routines are programmed. While routines for economic indicator are ready to use, further routines for ecological indicators as Carbon-Stocks and nutrient balances are in preparation. It is intended to implement all indicators that are based on forest growth in a automatically programming outside the simulator.

2.4 Västerbotten in Sweden (T. Lind)

- Forest growth models: Models are available for all the species and forest types, both stand models and distance-independent individual tree models
- Weaknesses detected: Risk and effects of forest damages are not implemented in the simulators, i.e models for storm, wind, insects and fungi.
- Improvements on models: Models for recreation suitability and soil carbon are implemented. Models for habitat suitability, climate change and wood quality will be implemented in the new simulator Heureka in the end of 2008.

2.5   Catalonia in Spain (J.J. Gonzalez and M. Palahí)

- Forest growth models: growth and yield models development was based on NFI data, therefore all the forest types are covered. The approach is an individual tree and stand level approach. Additional models exist: fire risk model (occurrence and damage), mushroom yield model, biomass, and scenic beauty.
- Weaknesses detected: habitat suitability, timber quality, water quality…
- Improvements: take into account fires to limit the overestimation of growth; moment method to obtain diameter distribution.

2.6   Scotland (W.L. Mason and S. Pizzirani)

- Forest growth models: Forest Yield - a set of stand level models suitable for even-aged stands and originally produced as 'look-up' tables (see Edwards and Christie, 1981).
- Weaknesses detected: difficulty in modelling mixed species and/or irregular stands
- Improvement on models: The aim is to link this model to other forest management models available within Forest Research (e.g. windthrow- ForestGALES (Suarez et al., 2006): timber properties – CONTIQY (Gardiner pers. comm.): and spatial distribution of habitat – BEETLE (Smith, pers. comm.). This should increase the flexibility of the models to predict the impact of changing management on sustainability criteria.

3 Model improvement for the European simulator (EFISCEN)

3.1 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.

3.2 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 equations used per country or region (??)
- allow option to choose output options from a list

3.3 The spatial dimension: deriving the input maps

3.3.1 Data

3.3.1.1 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 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 3).

3.3.1.2 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 (Figure 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 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 (for a list of basic variables see table 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.
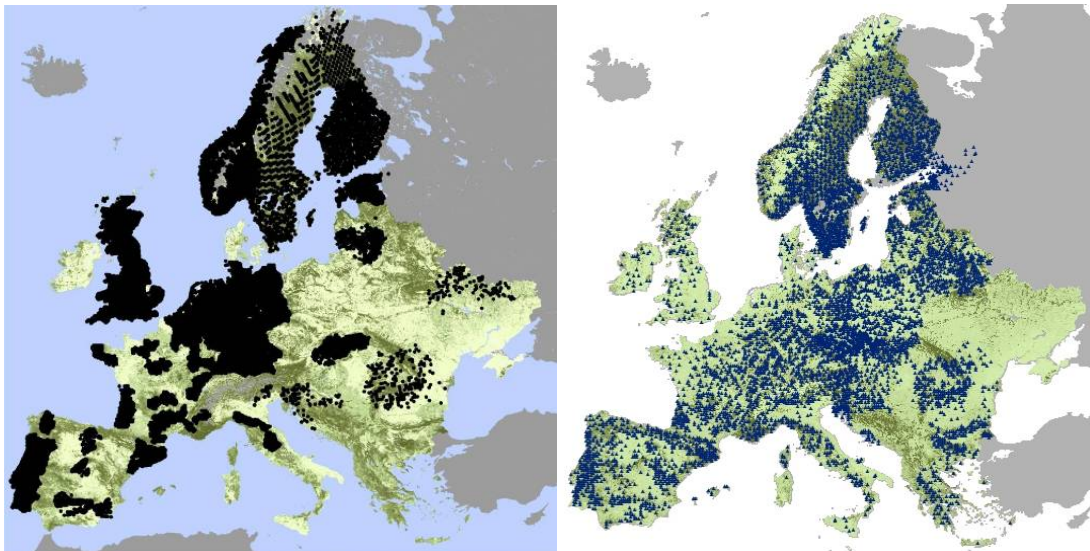

Figure 1: Location of the National Forest Inventory plots (left) and ICP forest plots (right) over Europe

Table 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 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)

Regional level Non-spatial (A)	Regional level Spatial (B)	Grid level (C)	Stand level (D)
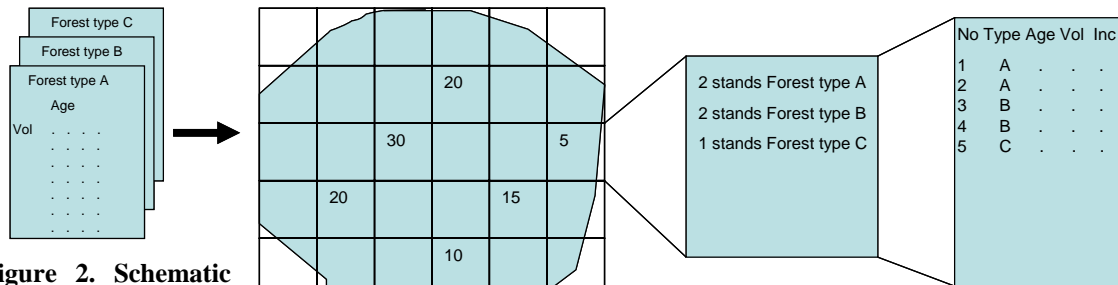
Figure 2. Schematic representation of initialization inventory data are **procedure of EFISCEN-SPACE. Forest converted into matrixes of forest areas within age**

Total area: 100	Total area: 100	Total area: 5	Total area: 5

(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 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.
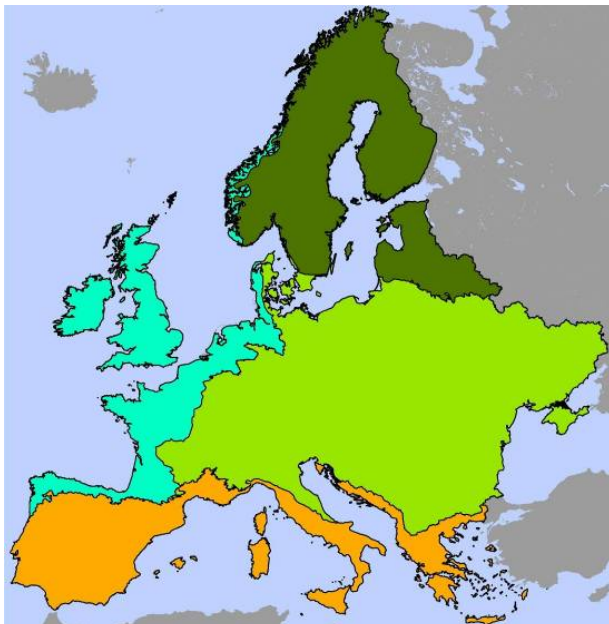

Figure 4. The biogeographical regions as used in EFISCEN Space.

3.3.2 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
- it is still not decided whether **increment** should also be initalised for the simulation, or whether it should only be a calculated variable

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):

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

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

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

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):

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

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.

3.4 The temporal dimension: outline of a dynamic forest model

The model includes the natural processes
- biomass growth,
- mortality and
- 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.

3.4.1 Volume growth

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

3.4.1.1 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,…)

3.4.1.2 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:

$$Ln(\Delta y) = \beta_0 + \beta_1 Ln(y) - \beta_2 y^k$$ (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. An error term was introduced in the equation, which included a random drawing from a distribution fit to the residuals:

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

With

$$\varepsilon_c \in N(0, \sigma_c)$$

$$\sigma_c = \alpha_0 \cdot V_c^{\alpha_1}$$

ε_c	error term for cohort c
σ_c	standard deviation for cohort c
α_0, α_1	species specific constants

Drawing from this distribution led to some very unlikely outliers, while the mean and overall variance seemed well represented. Drawing from the 80% confidence interval of the same distribution gave satisfactory results (Figure 5; Table 3).
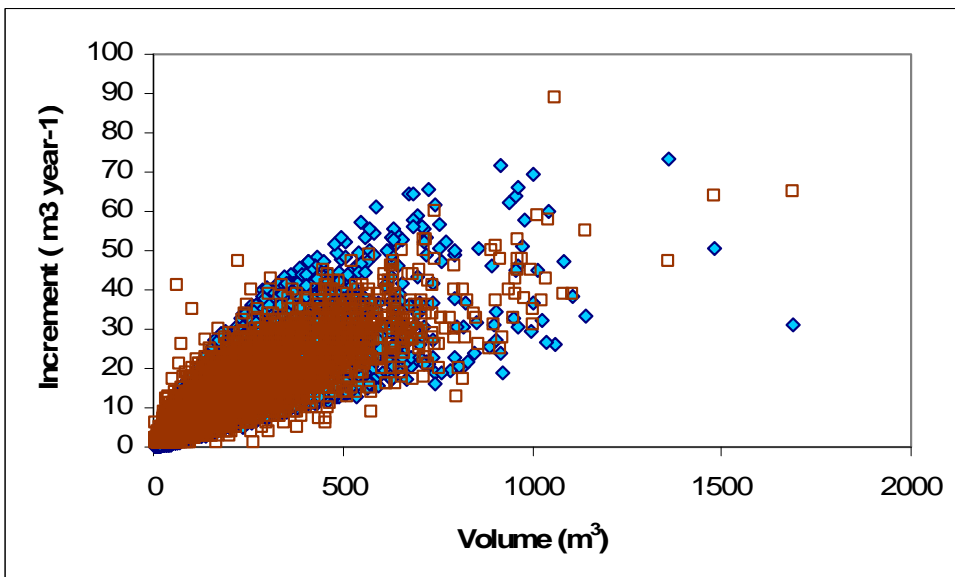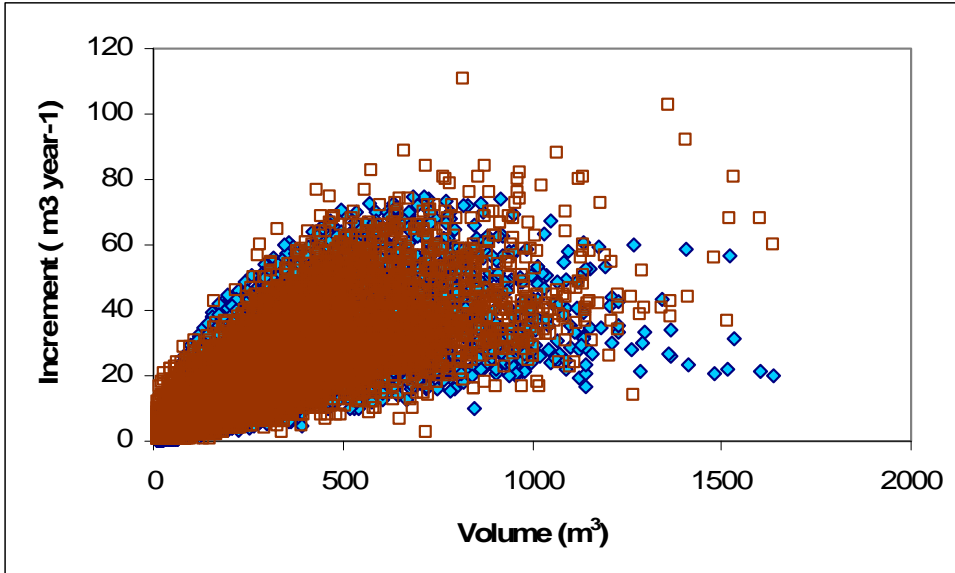
Figure 5: Modelled (blue) and plot data (open brown) increments for Picea (upper) and Fagus sylvatica (lower) in Baden-Wurttemberg

It is not an aim to simulate annual variation with the EFISCEN-Space model. Therefore, the (random value of the error term) is drawn only once for each plot and can be considered as a randomly assigned measure of site quality. Fitting of a conventional site index (based on the relation between height and age) did not give good relations with environmental variables. However, if only part of the variation in the current measure of site quality could be explained by environmental variables, this would further enhance the link between the GIS framework and the model, and will be explored in the near future.

Table 3: Mean and standard deviation for modelled and plot data increments for all species groups for Baden-Wurttemberg (m³ year⁻¹)

	Mean		Stdev	
	Model	Data	Model	Data
Abies spp	12,94	12,80	12,04	11,65
Alnus spp	7,14	7,13	8,93	9,19
Betula spp	3,00	3,00	2,71	3,34
Carpinus betulus	3,74	3,85	3,34	3,49
Castanea sativa	5,43	7,07	5,92	8,06
Fagus sylvatica	11,62	11,26	10,59	9,47
Fraxinus spp	8,07	8,07	8,14	7,89
Larix spp	6,19	6,15	5,68	5,74
other Pinus spp	6,46	6,57	7,68	6,80
other Quercus spp	8,88	8,61	7,95	7,56
Picea spp	20,23	20,29	15,47	15,74
Pinus sylvestris	6,01	6,52	5,28	6,44
Populus spp	8,27	8,49	10,01	10,04
Pseudotsuga menziesii	16,44	15,48	17,54	14,82
Quercus robur + petraea	5,83	5,83	5,47	5,32
Robinia pseudoacacia	10,05	9,44	15,59	13,48

Next steps for the growth model
1) fit the model for more countries
2) fit random basis of error term to abiotic variables

3.4.1.3 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.

3.4.2 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 3.4.6). (Vanclay, 1994).

3.4.2.1 What to model

Only mortality of whole trees is explicitly modelled, and is expressed as a number of trees per ha that dies. These trees are then assigned a certain (mean) diameter and height, based on the plot characteristics and/or the cause of death. From this diameter and height, a volume loss can be calculated. The alternative would be to calculate a certain volume loss, and attribute it to tree numbers, diameters and height. 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,…)

3.4.2.2 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.

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.

3.4.2.3 Derive the total set of variables

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

3.4.3 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.

3.4.3.1 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 = ƒ(state variables)
dDensity = ƒ(state variables)
dVolume = ƒ(dDensity, dDiameter, DHeight,…)
dDiameter = ƒ(dDensity)
dHeight = ƒ(dDiameter, dDensity …)
dBasalArea = ƒ(dDiameter,…)
or
dSpecies = ƒ(state variables)
dDensity = ƒ(state variables)
dVolume = ƒ(dDensity, state variables,…)
dDiameter = ƒ(dDensity, dVolume,..)
dHeight = ƒ(dDiameter, …)
dBasalArea = ƒ(dDiameter,…)

3.4.3.2 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.

3.4.3.3 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.

3.4.4 Management

3.4.4.1 What to model

Management actions aiming at removal of trees.

Impact of thinning on growth in 10 yr period afterwards

User defined management regimes - should be simple to define and implement

3.4.4.2 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) inof (site, location, etc.) and on the wood demand in the region.

Management actions that could 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 stands, with the possibility to manage each of these in a different way. It will therefore be difficult/not be possible to model spatially explicit management regimes, like creating gaps in the forest, or something like the future tree/crop tree system.

The management options will have to boil down into some typical sets of management regimes. These management regimes can then be used for scenario modelling. We will have to find a way to distribute such management regimes.

3.4.5 Regeneration (after clear cut)

Ingrowth may be satisfactory for new trees under continuous forest cover (3.4.3), but after clearcut or – in the future- after afforestation, regeneration is a discontinuous process. Especially which species to initialise is an issue, as well as which variables steer this. Management rules and preferences?

3.4.6 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

3.4.7 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.

3.5 Derived indicators: calculating performance of ecosystem functions from the model output

3.5.1 Above- and below ground biomass & carbon

Copy from EFISCEN

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

Copy from EFISCEN

3.5.3 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

3.5.4 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

3.6 Programming of model code

- Explicit programming of time step!! Time step may be adjusted for mathematical reasons (though output time remains one year)
- Development of user-friendly interface in ACCESS database

4 Conclusions

This report described the improvements that were (or, in some cases are still being) implemented in the forest models that will be used as a basis for the regional and European forest simulators.

The models for the regional simulators are detailed and reasonably detailed models, some of them whole stands models, others individual tree models or, in another cases, a combination of both types of models. These models have all the usual components of a traditional growth model, such as dominant height growth, basal area growth and mortality, to which several other modules have been added in order to be able to achieve the EFORWOOD requirements. These additional modules include: biomass prediction, through specific models or biomass expansion factors; inclusion of risk (probability of fire and/or probability of attack by pests); initialization functions to model new stands; volume ratio and/or stem taper functions for the prediction of assortments; models for the prediction of wood quality.

The new EFISCEN-space is a high spatial resolution European simulator based on forest models fully developed for the purpose. These models are simplifications of forest growth, based on a diameter-class cohort, stand based, with a limited number of stands per each grid cell of 1 km x 1 km. It is planned that EFISCEN-space will include, on its output, a large majority of the EFORWOOD sustainability indicators.

One important achievement of EFORWOOD will be the possibility to validate EFISCEN-space at regional scale by comparing its output with the output provided by a regional simulator, base don more detailed and locally-adapted forest models.

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