Description of the modelling approach of the European Forest Information Scenario model (EFISCEN 4.1)

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1 Introduction

European forests are a crucial resource to supply a growing bio-economy, they provide multiple ecosystem services and they can and mitigate the effects of climate change. To assess how European forest can accommodate multiple demands, simulation models are useful tools. The European Forest Information SCENario model (EFISCEN) has been validated (Nabuurs et al. 2000; Thürig and Schelhaas 2006) and used in many studies to provide insight in European forest resource development, woody biomass availability and ecosystem service provisioning. A complete publication overview is available at: http://efiscen.efi.int.

EFISCEN is a large-scale forest model that projects forest resource development on regional to European scale. The model uses national forest inventory data as a main source of input to describe the current structure and composition of European forest resources. The model can project the development of forest resources, based on different scenarios. These scenarios are mainly determined by management actions, but the model can also consider changes in forest area and growth rates. EFISCEN provides data on basic forest inventory data (species, area, stemwood volume, increment, mortality, age-structure), but the model includes multiple indicators related to important forest ecosystem services (carbon sequestration, biodiversity, recreation, wind and fire risk), enabling the assessment of impacts of different policy and management strategies at the national and European level, thus serving forest managers and policy makers at the national and international levels.

The core of the EFISCEN model was developed in the late 1980s for Sweden by Prof. Ola Sallnäs at the Swedish Agricultural University (Sallnäs 1990). The first European application of this model was carried out by the International Institute for Applied Systems Analysis (IIASA) in the early 1990s (Nilsson et al. 1992). With help from the original developers, the model was transferred to EFI in 1996, and given the name EFISCEN. The model was developed further both by EFI and Alterra, resulting in EFISCEN 2.0 (Pussinen et al. 2001). Development of the model continued and the model was then re-programmed into C++ code and a user interface was added. This version was called EFISCEN 3.0. The EFISCEN model has been described in detail by Schelhaas et al. (2007) for EFISCEN version 3.1.3.

To improve transparency and to ensure the tool could be used by the entire research community, EFISCEN was re-implemented from C++ to Java and the source code of the model is now freely available under the GNU General Public License conditions. The process to re-implement and improve EFISCEN was started by EFI in 2011 with participation by the University of Eastern Finland and Alterra. Besides re-implementation, model functionality has been extended as well. Functionality was added to improve the graphical user interface, as well as to make the model more flexible for use in various scenarios. In addition, the whole code was verified and checked, including documentation on model structure and testing.

This document provides a description of the modelling background and assumptions of EFISCEN 4.1. The description is a slightly updated version of the description for EFISCEN 3.1.3 by Schelhaas et al. (2007). A manual describing how to conduct simulations with EFISCEN 4.1 is available from Verkerk et al. (2016).

2 Model description

2.1 General description

EFISCEN is a model that simulates the development of forest resources at scales from provincial to European level. It is a timber assessment model, which means that the user specifies a certain harvest level and the model checks if it is possible to harvest that amount and simulates the forest development under that harvest level. EFISCEN is mostly used as a tool to evaluate and compare different scenarios. Scenarios can be defined in terms of changes in forest area, increment level, management regime and expected wood demand. Output consists of various characteristics or indicators of the forest resource. Examples are tree species distribution, felling/increment ratio, age class distribution, growing stock level and carbon sequestered in biomass and soil.

The forest area under study is divided into forest types. Forest types are defined by region, owner class, site class and/or tree species. The number of forest types can differ per country. The detail level of the input data usually determines how many types can be distinguished. The input data are usually derived from national forest inventories. The following data are required for each forest type and age class:

- Area (ha);
- Average growing stock volume over bark (m^3 ha^{-1});
- Net current annual increment over bark (m^3 ha^{-1} yr^{-1});

EFSICEN is a matrix model, where the state of the forest for each forest type is depicted as an area distribution over age and volume classes. The input data are used to construct the initial matrices (Figure 1). This is done by the P-2009 tool. The real simulator is the core of the model. In this core, transitions between matrix cells are calculated. These transitions represent different processes, such as increment, natural mortality and harvest. The transitions are influenced by the user-defined scenario choices. These choices can be based on expert judgement, or based on outcomes of other simulation models or studies. The core model delivers information on stemwood volume, increment, age class distribution, removals, forest area and natural mortality. With the help of biomass expansion factors, stemwood volume can be converted to whole-tree biomass and subsequently to whole tree carbon stocks. Information on litterfall rates (from turnover), felling residues and natural mortality can be used as input into the soil module, which delivers information on soil carbon stocks.

The matrix approach makes EFISCEN especially suitable for even-aged, managed forests. Results in uneven-aged forests, unmanaged forests and shelterwood systems will therefore be less reliable. Furthermore, the model is currently not suited to simulate fast growing tree species with very short rotations, due to the 5 year time step.

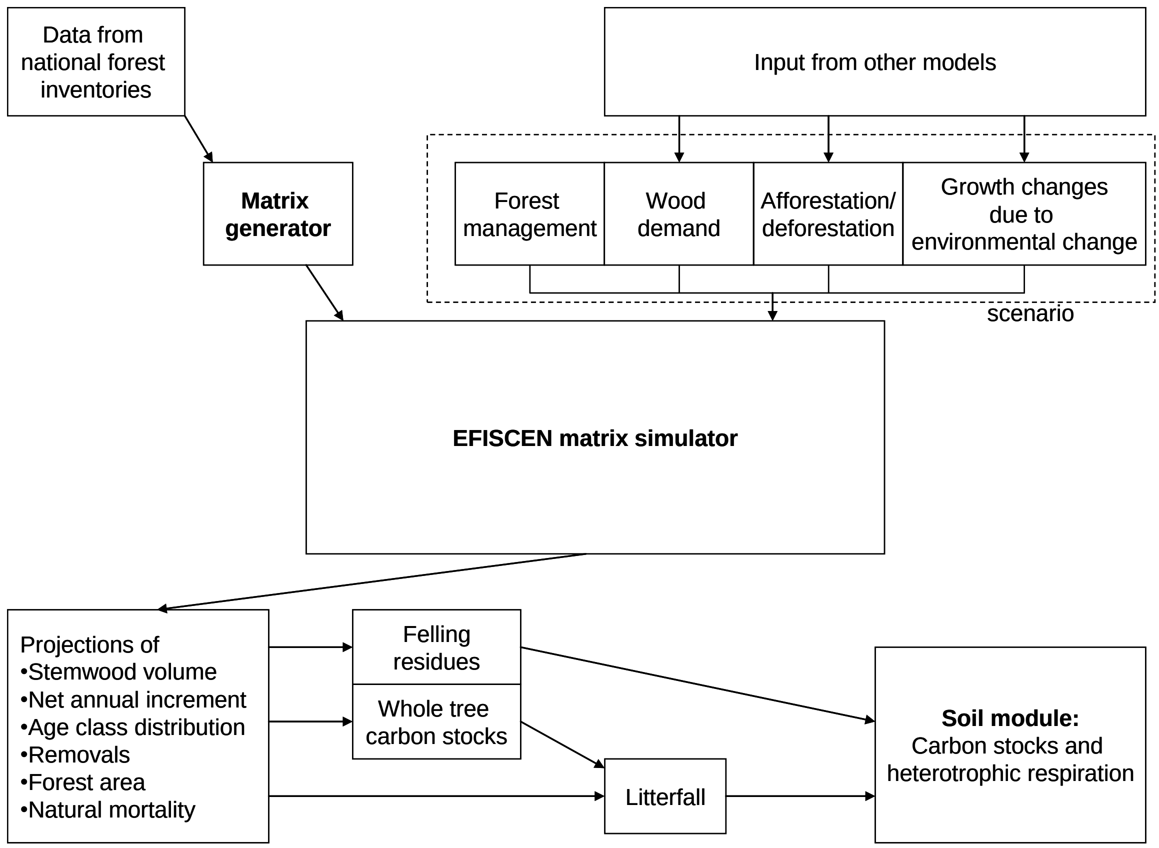

Figure 1: Structure of the EFISCEN model

EFISCEN is usually applied in projects aimed at the exploration of different scenarios and is thus aimed at supporting policy makers. Due to its modest demands on data input, it is the only model at the moment that can evaluate scenarios at the European level.

2.2 Matrix initialisation

The basic input data for each forest type in EFISCEN consist of area, average growing stock volume per hectare and current annual increment per age class. Table 1 shows an example of this input data. In EFSICEN the state of the forest is depicted as an area distribution over age and volume classes. For each forest type that is distinguished, a separate matrix is set up, which consists of 6 to 15 age classes and 10 volume classes (see Figure 2). The amount and width of the age classes is dependent on the input data. The width of the volume classes depends on the maximum volume per hectare that can be reached and the user-defined width of the first volume class. The area per forest type is divided over the cells using the input data. The area within an age class is distributed over the volume classes in such a way that the mean volume as given in the inventory data is reproduced.

Table 1: Example of basic input data.

Age class	Area (ha)	Growing stock (m^3 ha^{-1})	Net annual increment (m^3 ha^{-1} yr^{-1})
0-20	567560	14	1.63
21-40	348815	89	6.88
41-60	165344	158	7.33
61-80	219372	183	6.21
81-100	254784	200	5.32
101-120	142557	199	4.35
121-140	53705	180	3.34
141-160	17692	181	2.76
>160	7663	226	2.55

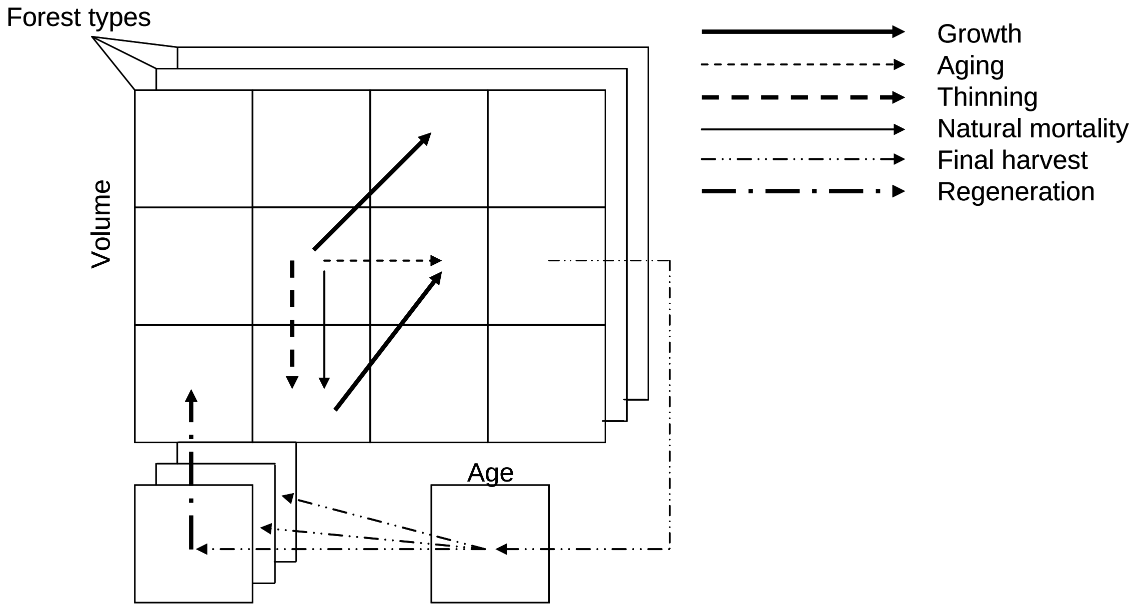

Figure 2: The area matrix approach (modified after Nilsson et al. 1992), with possible movements of area over the matrix, representing different processes.

To keep the required initialization data to a minimum, only the area and the mean growing stock volume per age-class are retained. Therefore, the volume distribution over age-classes (matrix columns) is not based on the initialization data, but is generated by an empirically based function. For the probability density function, EFISCEN uses an Edgeworth approximation series (Abramowitz and Stegun 1965):

$$f(z) = \mathrm{N}(0,1) * \left(1 + \frac{\alpha_1}{6} He_3(z) + \frac{\alpha_2}{24} He_4(z) + \frac{\alpha_1^2}{72} He_6(z) \right) \tag{1}$$

where

$$z = \frac{x - m_i}{s_i} \tag{2}$$

and where x denotes the point of interest where the probability density needs to be calculated (volume per hectare); m_i is the mean volume in age class i (from the inventory data); s_i is the assumed standard deviation in volume per hectare of age class *i*; He_n is the Hermite polynomial of order *n*; α_1 and α_2 are parameters to adjust the shape of the distribution; and N(0,1) denotes a standard normal distribution. By default, their values are set to α_1=1 and α_2=2, but they may be changed to adjust for irregular distributions. In the case where *f(z)* is negative, it is set to zero.

The variance s_i^2 of volume per hectare within an age class *i* is estimated as

$$s_i^2 = k \ln T_i \quad (3)$$

where T_i is the mid point of age class *i*, and *k* is calculated according to

$$k = \frac{\sqrt{(1-r^2)(\overline{V} \times cv)^2}}{\sum_i \ln(T_i) * fArea_i} \quad (4)$$

where $\overline{V}$ is the area-weighted average volume for the forest type; *cv* is the coefficient of variation of the volume per hectare for the forest type; *r* is the correlation between volume per hectare and ln(age) for the forest type; and $fArea_i$ is the fraction of the total area residing in age class *i*. Effectively, the denominator is the weighted average per forest type of ln(age). The parameter *cv* is 0.65 by default for all forest types, whereas *r* ranges from 0.45 to 0.7, depending on tree species, whether the data are separated into site classes, and whether the forests are well stocked (Table 2). The larger the correlation between volume and ln(age), the smaller is the variance of volume per hectare.

Table 2: Recommended values for parameter *r* in different situations (Attebring et al. 1989).

Species	All forests	Separate site classes	Forests well stocked	Separate site classes and forests well stocked
Spruce, beech	0.55	0.6	0.65	0.7
Pine, oak	0.45	0.5	0.55	0.6
Others	0.5	0.55	0.6	0.65

The upper limit of the volume dimension in each matrix is determined by the highest volume per hectare that can be reached for that forest type. This is estimated from the largest volume per hectare from the initialization data plus three times the largest standard deviation:

$$VCL_{10} = Max(V_i) + 3 * Max(s_i^2) \quad (5)$$

where VCL_{10} is the upper limit of the highest volume class; $Max(V_i)$ is the maximum volume per hectare from the inventory for that forest type; and $Max(s_i^2)$ is the largest standard deviation as derived from equation 3. This definition of the upper limit should ensure that the full range of variability in growing stocks is captured in the model. Assuming a normal distribution, this would imply that 99% of the variability is captured. This volume range is then divided in 10 classes. The width of each volume class *j* (VCW) is calculated by:

$$VCW_j = VCW_1 * R_j \quad (6)$$

where *R* is determined such that the cumulative of these 10 volume classes equals VCL_{10}:

$$VCW_1 * (R^n - 1)/(R - 1) = VCL_{10} \tag{7}$$

The left part of this equation is the cumulative of the 10 volume classes. VCW_1 (also known in previous descriptions as *X1*) is set by the user. If the ratio between VCW_1 and VCL_{10} is 10, the volume classes will be of equal width (R=1). In other cases, higher volume classes will be larger (ratio below 10, R>1) or smaller (ratio above 10, R<1). However, due to the way this is implemented in the code, R is restricted to the range between 1 and 2. Therefore, volume classes are either equidistant or of increasing width. Another consequence is that VCL_{10} is overruled in cases where R should have been lower than 1. This means that the maximum volume per hectare that can be reached is increased.

By assigning the average volume of a certain volume class to all area in that class, it is implicitly assumed that the area is uniformly distributed within a class. This will cause a small deviation in the calculated average volume overall volume classes within one age class compared to the average volume in the input data. If the deviation is larger than 1 m^3 ha^{-1}, the distribution is adapted. If the calculated volume is too high, a certain fraction of the highest volume class is moved one class down. If all area of the highest volume class is moved and the difference is still larger than 1 m^3 ha^{-1}, a certain fraction of the area in the next highest volume class will be moved. This procedure is repeated until the difference is less than 1 m^3 ha^{-1}. In case the calculated volume is too low, areas are moved upward in a similar way, starting from the lowest volume class.

2.3 Increment

In EFISCEN, growth dynamics are simulated by shifting proportions of the area in the matrix from one cell to another. Each five-year time step, the area in each cell will move up one age class. Part of the area will also move up one volume class. When area reaches the highest volume class it will remain there until it is harvested, i.e. it cannot grow anymore. Growth dynamics are incorporated as five year net annual increment as a percentage of the growing stock. The growth functions of the model are of the following type:

$$I_{vf}(T) = a_0 + \frac{a_1}{T} + \frac{a_2}{T^2} \tag{8}$$

where I_{vf} is the five-year volume increment as a percentage of the growing stock; T age of the stand in years; and a_0, a_1 and a_2 coefficients. The coefficients for the growth functions are usually estimated from inventory data, or alternatively from yield tables. If this function would be directly applied to the matrix cells, increment would be directly proportional to the average volume in a certain volume class. However, this would give unrealistic increments for both very high and very low volume classes. Therefore a correction factor is introduced:

$$I_{va}(T) = I_{vf}(T) \times \left(\frac{V_{oT}}{V_a}\right)^{Beta} \quad \text{with Beta 1 for } V_a > V_{oT} \quad (9)$$

where I_{va} is the five-year percent volume increment for actual standing volume; I_{vf} is the five-year percent volume increment given by equation 5; V_{oT} is the optimal standing volume at age T; V_a is the actual standing volume (m^3 ha^{-1}); and *Beta* a parameter which describes the relation between the relative standing volume and the relative volume increment (see Nilsson et al. 1992). From studies of this relationship in yield tables and other data, the value of the parameter ranges from 0.25 to 0.45, depending on species, site classification, and the type of data used to construct the yield tables. If the actual standing volume exceeds the optimal standing volume, Beta is assumed to be 1. The consequence is that all stands with higher standing volumes will have the same increment in absolute terms (see Figure 3). The optimal standing volume as a function of age is difficult to define. In practice, the average volume series from the input data are used. In the matrix, increment is expressed as transition fractions between cells.

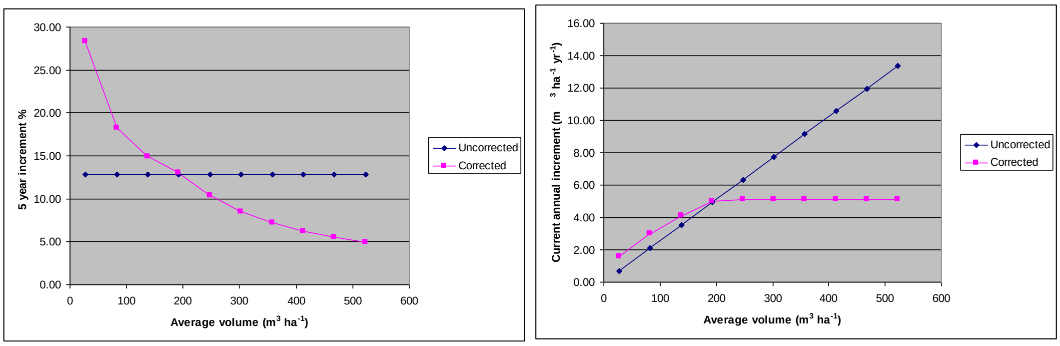

Figure 3: Uncorrected and corrected increment as a function of average volume, expressed as 5 year relative increment (left) and as current annual increment (right). Data for Utopia, age 92.5, optimal standing volume 200 m^3 ha^{-1} with Beta having a value of 0.4.

2.4 Management activities

Management is controlled at two levels in the model. First, for each forest type a basic management of thinning and final felling is incorporated. This is the theoretical management regime, which is applied according to handbooks or expert knowledge for forest management in the region or country to be studied. This theoretical regime must be seen as constraint of what might be felled. Second, total required harvest volumes from thinning and final felling are specified for the region or country as a whole for each time period. Based on the theoretical management regimes, the model searches and might find, depending on the state of the forest, the required volumes. Further the success of a reforestation after clear felling can be incorporated per tree species, as well as a possible tree species change after a clear felling, and a forest area change.

2.4.1 Thinning

Thinning regimes can be defined by forest type and age class, effectively defining over which age range thinnings can be carried out. Thinning is implemented as the move of area to a lower volume class (See Figure 3.1). The volume thinned is calculated as the product of the area that is moved down and the difference in mean volume between the volume classes. In the next period the thinned area grows according to the standard rules. However, because the growing stock of the thinned area is lower than the growing stock of the forest that was not thinned, the increment of the thinned area is somewhat lower than the increment of the latter area. To compensate for this, part of the thinned area will grow one volume class extra during the second time-step, besides the normal increment rate. This is called the growth boost. The growth boost parameter (Gamma) is defined as the fraction of the thinned area that is moved up one extra volume class. This parameter should be set such that the growing stock of the managed stand will approach that of an unmanaged stand (see Figure 4). According to growth and yield tables (Koivisto 1959), 0.4 was assessed as a growth boost parameter for pine forest in Myrtillus site type in Finland. The area of forest that has not received a growth boost yet is not available for thinnings, but might be subjected to final felling. Area will lose its "recently thinned" status only by receiving the growth boost or exceeding the age limit for thinnings.

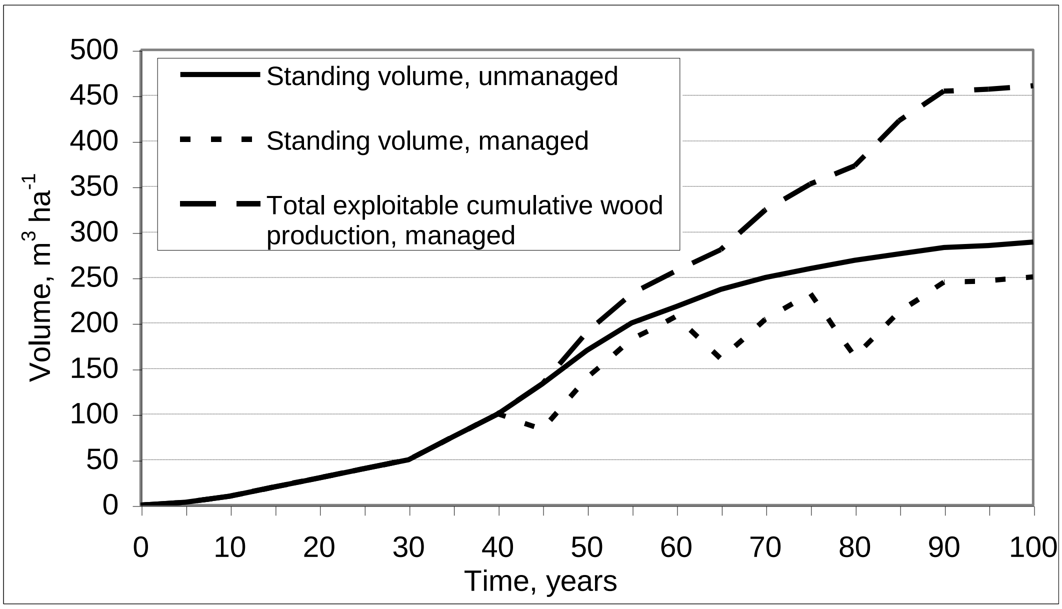

Figure 4: The development of standing volume of a stand in managed and unmanaged forests and the total cumulative exploitable wood production (thinned + standing volume) of a managed stand.

2.4.2 Final felling

As for thinnings, the final felling regime can be defined by forest type and age class. The final felling regime is expressed as the proportion of each cell that can be felled, depending on the stand age. How much of this maximum is actually used depends on the ratio between wood demand for final fellings and the maximum amount that could be felled if all potential final fellings were carried out. The felled area is moved outside the matrix to the bare-forest-land class, from where it can enter the matrix again (see Figure 2). Usually this area will go to the bare land class of the original matrix. However, when a tree species change is defined, (part of) the area will be added to the bare land class of the respective matrix. The final felling regimes can be obtained by handbooks, yield tables or other sources, such as statistical yearbooks.

2.5 Regeneration

Regeneration is regarded as the movement of area from the bare-forest-land class to the first volume and age class (Figure 2). The amount of area that is regenerated is regulated by a parameter that expresses the intensity and success of regeneration, the young forest coefficient. This parameter is the percentage of area in the bare-forest-land class that will move to the first volume and age class during five years. This area will then attain the average volume and age of that class. The amount of area in the bare forest land class depends on the intensity of clear felling, possible changes in tree species after final felling and the height of the young forest coefficient.

2.6 Natural mortality and standing deadwood

EFISCEN can be used to model natural mortality and deadwood (Verkerk et al. 2011). If the forest growth is given as gross annual increment, or if the demand scenario specifies a low roundwood demand and management is thus not very intensive, mortality should be included. When gross annual increment is applied, mortality should include all kind of mortality, such as natural mortality, diseases, insect attacks, fire, windthrow or other physical damage. In EFISCEN mortality is expressed as a fraction of the actual standing volume and is only applied in forests that are not thinned or felled the current time-step and that do not have a recently thinned status (i.e. recently thinned forests that did not receive a growth boost). Mortality can be defined by forest type and age class. EFISCEN performs mortality by transferring area one volume class down to obtain the required reduction in standing volume. Note that this implies a maximum mortality rate of 10%. If all area in the highest volume class is moved down and volume classes are of equal width, the average volume will be decreased by 10%. The volume subject to mortality enters a standing deadwood pool, while branches, foliage and roots are lost in the same time-step and enter their respective litter pools in the soil module. Volume can leave the standing dead wood pool by falling down as complete tree or in smaller pieces, or by removal during management. A deadwood fall rate parameter defines the proportion of standing deadwood that falls down each time step. The fall rate can be defined by forest type. It describes a negative exponential curve and no lag period is assumed. A proportion of deadwood can be removed from the forest during management operations. A dead wood removal parameter can be set for thinning and final felling separately and for each forest type and time-step. Dead wood is only removed in forests that are thinned or final felled. The standing dead wood pool is initialised by calculating the equilibrium between the input of dead wood, the fall down rate and the dead wood removal rate of the first time-step. Fallen dead wood enters the coarse woody litter pool of the soil module, in which fractionation and decomposition of lying dead wood is modelled as a reduction of mass; volume of lying dead wood is not projected by EFISCEN.

2.7 Afforestation and deforestation

It is also possible to take afforestation and deforestation into account. The user can add or remove area per tree species in each time step of the simulations. The area will then be added to the bare-forest-land class of each forest type of that tree species, or the area is removed from the bare-forest-land class. The maximum area for deforestation in one time steps equals the area in the bare-forest-land-class, but in that case also no regeneration will occur.

2.8 Change of increment due to changed environment

The model can simulate the development of the forest for decades. For various reasons, e.g. climate change, increment rates may change during long simulation periods. The model can take into account such changes in increment rate by defining an expected relative change. The basis of the increment calculation is always the increment as calculated by the incorporated growth functions, which are based on the inventory data. The new increment rates are defined relative to the basic growth functions. The expected relative change can be defined per time step, by forest type and age class.

2.9 Biomass and litter production

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 by age classes. 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 5 illustrates the conversion from stemwood volume to estimates of whole tree carbon.

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 litter fall 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.

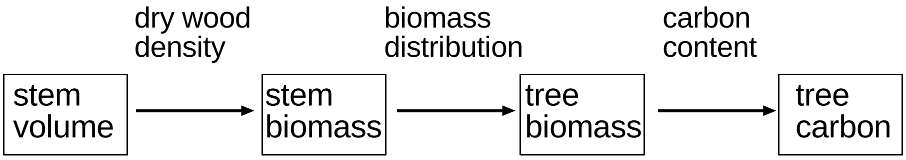

Figure 5: Calculation of biomass and litter

2.10 Soil

The EFISCEN model contains a dynamic soil carbon module (YASSO; Liski et al. 2005) that calculates the amount of carbon in the soil. Carbon input into the soil module consists of felling residues and litter production of trees due to turnover and natural mortality. The soil module consists of three litter compartments and five decomposition compartments (Figure 6). For the soil carbon module, the litter is grouped as non-woody litter (foliage and fine roots), fine woody litter (branches and coarse roots) and coarse woody litter (stems and stumps). Each of the litter compartments has a fractionation rate determining the proportion of its contents released to the decomposition compartments in a time step. For the compartment of non-woody litter, this rate is equal to 1 which means that all of its contents is released in one time step, whereas for the woody litter compartments this rate is smaller than 1. Litter is distributed over the decomposition compartments of extractives, celluloses and lignin-like compounds according to its chemical composition. Each decomposition compartment has a specific decomposition rate, determining the proportional loss of its contents in a time step. Fractions of the losses from the decomposition compartments are transferred into the subsequent decomposition compartments having slower decomposition rates while the rest is removed from the system. The fractionation rates of woody litter and the decomposition rates are controlled by temperature and water availability.

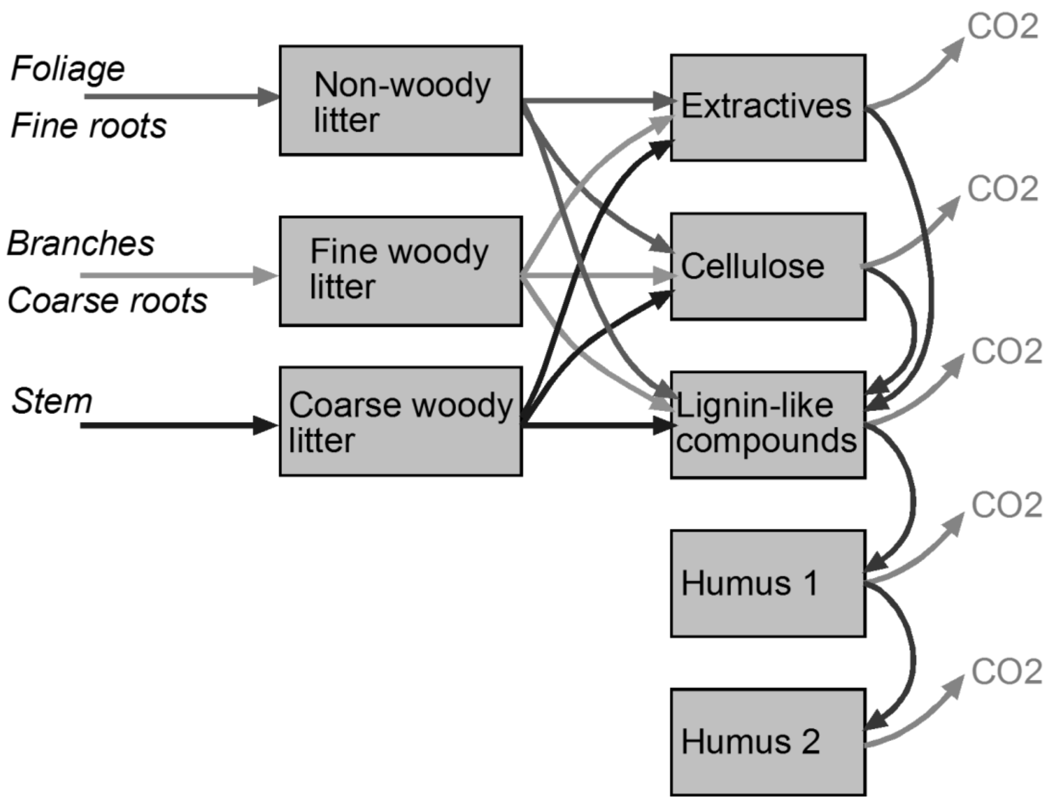

Figure 6: Flow chart of the soil module. The boxes represent carbon compartments, and the arrows represent carbon fluxes.

The dynamics of carbon in the litter (Equation 13 to 15) and the decomposition compartments (Equation 16 to 20) can be described as follows:

$$\frac{dx_{nwl}}{dt} = u_{nwl} - a_{nwl} x_{nfwl} \tag{10}$$

$$\frac{dx_{fwl}}{dt} = u_{fwl} - a_{fwl} x_{fwl}, \tag{11}$$

$$\frac{dx_{cwl}}{dt} = u_{cwl} - a_{cwl} x_{cwl}, \tag{12}$$

$$\frac{dx_{ext}}{dt} = c_{nwl\_ext} a_{nwl} x_{nwl} + c_{fwl\_ext} a_{fwl} x_{fwl} + c_{cwl\_ext} a_{cwl} x_{cwl} - k_{ext} x_{ext}, \tag{13}$$

$$\frac{dx_{cel}}{dt} = c_{nwl\_cel} a_{nwl} x_{nwl} + c_{fwl\_cel} a_{fwl} x_{fwl} + c_{cwl\_cel} a_{cwl} x_{cwl} - k_{cel} x_{cel}, \tag{14}$$

$$\begin{aligned} \frac{dx_{lig}}{dt} &= c_{nwl\_lig} a_{nwl} x_{nwl} + c_{fwl\_lig} a_{fwl} x_{fwl} + c_{cwl\_lig} a_{cwl} x_{cwl} + \\ &+ p_{ext} k_{ext} x_{ext} + p_{cel} k_{cel} x_{cel} - k_{lig} x_{lig} \end{aligned} \tag{15}$$

$$\frac{dx_{hum1}}{dt} = p_{lig}k_{lig}x_{lig} - k_{hum1}x_{hum1}, \text{ and} \tag{16}$$

$$\frac{dx_{hum2}}{dt} = p_{hum1}k_{hum1}x_{hum1} - k_{hum2}x_{hum2}. \tag{17}$$

where:

- $u_i(t)$ the input of litter type i to the system (i = non-woody litter (nwl), fine woody litter (fwl) or coarse woody litter (cwl)),
- $x_i(t)$ the weight of organic carbon in woody litter compartment i at time t (i = fine or coarse woody litter),
- a_i the rate of invasion of litter type i by microbes,
- $x_j(t)$ the weight of organic carbon in each decomposition compartment j at time t (j = extractives (ext), celluloses (cel), lignin-like compounds (lig), simple humus (hum1) or complicated humus (hum2)),
- ci_j the concentration of compound group j in litter type i,
- k_j the decomposition rate of compartment j, and
- p_i the proportion of mass decomposed in compartment i transferred to a subsequent compartment.

The invasion rates of litter by microbes (a_i) and the decomposition rates (k_j) depend on temperature and summer drought as follows:

$$k_i\left(T,D\right)=k_{i0}\left(1+s_i * \alpha_1(T-\mathrm{T_{ref}})+\alpha_2\,(D\text{-}(\mathrm{D_{ref}}))\right) \tag{18}$$

$$a_i\,(T,D)=a_{i0}\,(1+s_i*\alpha_1(T\text{-}\mathrm{T_{ref}})+\alpha_2\,(D\text{-}(\mathrm{D_{ref}}))) \tag{19}$$

where k_{i0} and ai_0 denote microbial invasion and decomposition rates in chosen standard conditions; s_i is a parameter to reduce the temperature sensitivity for certain decomposition compartments; α_1 and α_2 express respectively the temperature and drought sensitivity; T is either the average annual temperature (old version of YASSO) or the effective temperature sum in the growing season (0 °C threshold); T_{ref} is the reference temperature or temperature sum; D is the drought index during the growing season (precipitation minus potential evapotranspiration during the growing season); and D_{ref} the reference drought index. In earlier EFISCEN versions, an older version of YASSO was used. This version used the average annual temperature to express the temperature sensitivity. An improved version of YASSO uses the annual effective temperature sum instead (Liski et al., 2005). EFISCEN 4.1 is able to use both methods, since both actual parameters and the reference values need to be supplied. Table 3.3 shows the parameter values for both approaches. Only the differences in the reference conditions and sensitivity parameters are due to the application of a different method. The differences in the other parameters reflect increased insights. Therefore, the second column reflects a typical parameterization as used in earlier applications (Pussinen et al. 2001), and the third column reflects the most up-to-date parameterization (Liski et al. 2005). For the humus compartments, parameter s_i may have a value lower than one to reduce the temperature sensitivity of humus decomposition (Liski et al. 1999; Giardina and Ryan 2000); for the other decomposition compartments, s_i is equal to one.

At the start of the simulations the initial soil carbon content for each compartment should be known. This can be set by the user, or can be calculated by the model using the litter input of the first year, assuming a steady state. The soil module operates on an annual time step and assumes an equal distribution of litter input over the five-year time step of the forest model.

Table 3: Parameters of the soil carbon module for the reference conditions for the two different methods to determine temperature sensitivity (Liski et al., 2005).

Parameter	Value	Value
Method	Average annual temperature	Temperature sum
Reference conditions		
T_{ref}	4 °C	1903 °C days
D_{ref}	-50 mm	-32 mm
Temperature and drought sensitivity		
α_1	0.0937	0.000387
α_2	0.00229	0.00325
Humus decreased temperature sensitivity		
s_{hum1}	0.6	0.6
s_{hum1}	0.36	0.36
Invasion rates of woody litter by microbes (year)		
a_{nwl}	1	1
a_{fwl}	0.5	0.54
a_{cwl}	0.05	0.053
Litter composition		
c_{nwlsol} for conifers	0.27	0.27
c_{nwlcel} for conifers	0.51	0.51
c_{fwlsol} for conifers	0.03	0.03
c_{fwlcel} for conifers	0.65	0.65
c_{cwlsol} for conifers	0.03	0.03
c_{cwlcel} for conifers	0.69	0.69
c_{nwlsol} for deciduous trees	0.38	0.38
c_{nwlcel} for deciduous trees	0.36	0.36
c_{fwlsol} for deciduous trees	0.03	0.03
c_{fwlcel} for deciduous trees	0.65	0.65
c_{cwlsol} for deciduous trees	0.03	0.03
c_{cwlcel} for deciduous trees	0.75	0.75
Decomposition rates (per year)		
k_{sol} for conifers	0.5	0.48
k_{sol} for deciduous trees	0.8	0.82
k_{cel}	0.3	0.3
k_{lig}	0.15	0.22
k_{hum1}	0.013	0.012
k_{hum2}	0.0012	0.0012
Formation of more complex compounds in decomposition (proportion of decomposed mass)		
p_{sol}	0.15	0.2
p_{cel}	0.15	0.2
p_{lig}	0.18	0.2
p_{hum1}	0.18	0.2

Explanation: nwl – non-woody litter, fwl – fine woody litter, cwl – coarse woody litter, sol – soluble compounds, cel – cellulose, hum1 – first humus compartment, hum2 – second humus compartment

References

Abramowitz M., and Stegun J.A., 1965. Handbook of mathematical functions: with formulas, graphs, and mathematical tables. Applied Mathematical Series 55. Dover Publications, New York

Attebring, Nilsson and Sallnäs, 1989. A model for long-term forecasting of timber yield - a description with special reference to the forest study at SUA-IIASA. Systems Analysis Modelling Simulation 6 (3): 171-180.

Giardina C.P. and Ryan M.G., 2000. Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. Nature 404: 858-861.

Koivisto P., 1959. Kasvu- ja tuottotaulukoita (Growth and yield tables). Communications Instituti Forestales Fenniae. Helsinki, Finland, Finnish Forest Research Institute. 51.

Liski J., Ilvesniemi H., Mäkelä A., Westmann C.J., 1999. CO_2 emissions from soil in response to climatic warming are overestimated - The decomposition of old soil organic matter is tolerant of temperature. Ambio 28: 171-174.

Liski J., Palosuo T., Peltoniemi M., Sievänen R., 2005. Carbon and decomposition model YASSO for forest soils. Ecological Modelling 189(1-2): 168-182.

Nabuurs G.J., Schelhaas M.J., Pussinen A., 2000. Validation of the European forest information scenario model (EFISCEN) and a projection of Finnish forests. Silva Fennica 34, 167-179.

Nilsson S., Sallnäs O., Duinker P., 1992. A report on the IIASA forest study: Future forest resources of Western and Eastern Europe, The Parthenon Publishing Group, UK.

Pussinen A., Schelhaas M.J., Verkaik E., Heikkinen E., Liski J., Karjalainen T., Päivinen R., Nabuurs G.J., 2001. Manual for the European Forest Information Scenario Model (EFISCEN 2.0). European Forest Institute, Joensuu. 49 pp.

Sallnäs O., 1990. A matrix model of the Swedish forest. Studia Forestalia Suecica 183, 23.

Schelhaas M.J., Eggers J., Lindner M., Nabuurs G.J., Päivinen R., Schuck A., Verkerk P.J., Werf, D.C. van der, Zudin S., 2007. Model documentation for the European Forest Information Scenario model (EFISCEN 3.1.3). Alterra report 1559 and EFI technical report 26. Alterra and European Forest Institute, Wageningen and Joensuu. 118 pp.

Thürig E., Schelhaas M.J., 2006. Evaluation of a large-scale forest scenario model in heterogeneous forests: A case study for Switzerland. Canadian Journal of Forest Research 36 (3) p. 671-683.

Verkerk P.J., Lindner M., Zanchi G., Zudin S., 2011. Assessing impacts of intensified biomass removal on deadwood in European forests. Ecological Indicators 11, 27-35.

Verkerk P.J., Schelhaas M.J., Immonen V., Hengeveld G., Kiljunen J., Lindner M., Nabuurs G.J., Suominen T., Zudin S., 2016. Manual for the European Forest Information Scenario model (EFISCEN 4.1). EFI Technical Report 99. European Forest Institute, Joensuu.