Forestry Development Scenarios: Timber Production, Carbon Dynamics in Tree Biomass and Forest Values in Germany

Meinrad Rohner and Klaus Böswald

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The dynamics of the age class structure stands at the center of modeling long-run forestry scenarios. This insight has been applied to the construction of the *Forest Development and Carbon Budget Simulation Model* (ForCaBSim), a model which is used for the study of several interrelated questions: the development of timber stocks and the potential level of sustainable harvests, the stocks and fluxes of tree carbon in managed forests, the economy-wide effects of management practices on the value of forest lands and timber stocks. The combined study of these issues allows to assess development scenarios with regard to the productive potential of forestry, the carbon cycle, and forest values. At present, the model is adapted to German data, but it is designed for use with other data sets as well.

This paper provides a description of core mechanisms in ForCaBSim. On this background, the choice and impact of crucial assumptions is examined. Illustrative results are used to demonstrate the use of the model. The paper focuses on the impact of varying rotation ages and the tree species composition. Particular attention is given to the concept of steady states.

Keywords forestry scenario modeling, carbon balance, forest valuation
Authors' addresses *Rohner*, Renewable Resource Modeling, D-63477 Maintal, Germany; *Böswald*, Factor Consulting + Management AG, CH-8045 Zurich, Switzerland
Fax +49 6109 762 035 **E-mail** rohner@rrmodeling.de
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1 Introduction

Understanding the effects of management practices and forest policy on the development of forests and forestry is relevant from various points of views. The contribution of forests and forestry to the stabilization of greenhouse gases in the atmosphere is one of these concerns (Brown et al. 1996). The sustainable timber production potential and the economic foundations of forest management are others. The *Forest Development and Carbon Balance Simulation Model* (ForCaBSiM) was developed in order to study the long-run consequences of management decisions related to these issues by means of computer simulations.

ForCaBSiM is built around the central role of age classes for the structure and dynamics of managed forests. Mathematically, such a structure is best captured by the use of Markov matrices, an approach originally applied to general population dynamics by Leslie (1945). Applying the method to forests means that the area dynamics of age classes and stand types is mapped by means of matrices. Transition matrices of this type capture the patterns of final felling. They must be complemented by stand growth and thinning procedures to arrive at the total stock and periodic fellings. Given the area distribution and the growing stock at some initial date, these model elements allow to propagate timber stocks as well as fellings into the future. (From an economic point of view, the basic structure of ForCaBSiM may be considered as a particular production system with unusually long production periods.) By inferring total biomass from merchantable timber and by considering additionally natural and harvest losses, it is straightforward to calculate the carbon stocks and fluxes implied by these processes.

Complementing the physical production with economic data (prices and production costs) allows to calculate land expectation values as well as the values of nonmature timber stocks. The resulting figures may be interpreted as performance indicators of the scenarios studied. The rules for both valuation procedures have been laid down by Faustmann (1849), and are today generally accepted in forest economics (IUFRO 1999).

The basic model structure and applications are illustrated in Fig. 1. (Note that this text concentrates on the dynamics of the growing stock.)

The model described in this paper is as a revision and extension of CaBProM (Carbon Budget Prognosis Model), a model developed for the study of the present and future carbon balance in Bavarian and German forests (see Böswald 1995–1998). The most notable extension in ForCaBSiM consists in the integration of procedures for forest valuation. However, all modules have been revised thoroughly.

In the classification proposed by Nabuurs and Päivinen (1996), ForCaBSiM is a large-scale forestry scenario model at the national level of Germany. It is based on stand growth projections and solved by iterative calculations. It appears that age class modeling by Markov matrices is quite commonly used in forestry scenario models. However, the steady state characteristics of this approach have seldom, if ever, been exploited in applied studies. Similarly, assessing scenarios by way of their corresponding forest asset values appears to be a new approach.

2 Basic Model Structure

In its present version, ForCaBSiM is adapted to the data provided by the Forest Inventory 1987–90 of the former Federal Republic of Germany (BML 1990) and comparable data about forests in the former German Democratic Republic from 1993 (BML 1994). In view of the time divergence between these sources, 1990 is assumed as base year for data calibration. In accordance with the federal forest inventory, 9 tree species groups and 9 age classes are distinguished. Forests in Germany are considered as a whole without taking into account the regional differentiation.

The tree species groups distinguished are listed in Table 1.

Ash is considered as a typical species for group ‘blr’ and alder for ‘bsr’. Spruce, pine, beech and oak were the dominant species in 1990, with overall area shares of 33, 28, 14, and 7.5 percent, respectively.

The majority of stands observed in reality are mixed by various species and often contain more

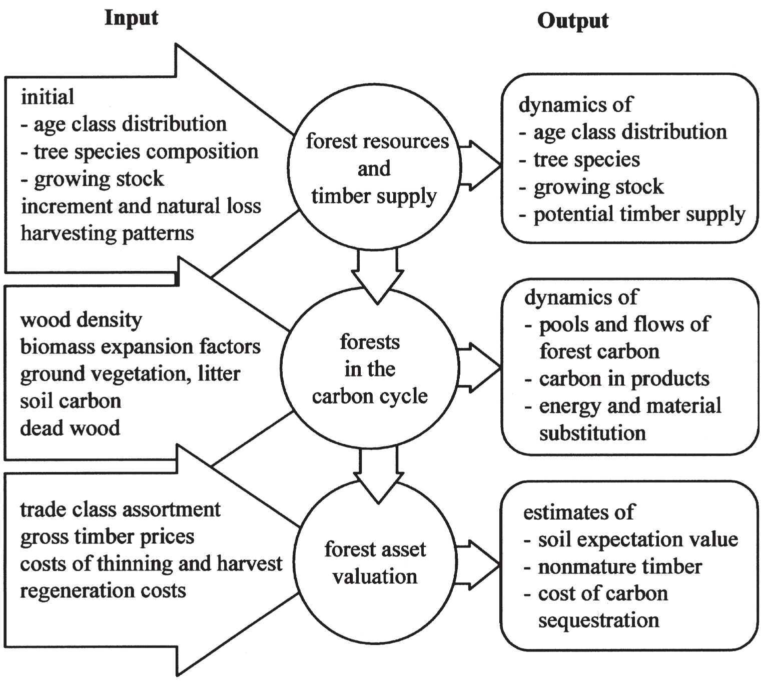

Fig. 1. Fields of model application, with main input parameters and output variables.

Table 1. Tree species groups.

Symbol	Group	Species
spr	Spruce	Norway spruce *(Picea abies)*
fir	Fir	Silver fir *(Abies alba)*
dgl	Douglas fir	Douglas fir (*Pseudotsuga menziesii*)
pin	Pine	Scots pine (*Pinus sylvestris*)
lar	Larch	European larch (*Larix decidua*)
oak	Oak	Common oak (*Quercus robur*), other oak
bee	Beech	European beech *(Fagus sylvatica)*
blr	Other broadleaved with long rotation periods	
bsr	Other broadleaved with short rotation periods	

Tree species groups distinguished in FFI-I (BML 1990-I, 109).

than one growth strata. Only 18% of broadleaved and 39% of coniferous stands were pure stands in 1990. However, the federal forests inventory offers a subdivision of the total forest area into virtually pure stand types according to the nine tree species groups. The model is based on this classification.

The temporal structure of ForCaBSim builds on 20 year intervals. Areas and growing stocks are defined with regard to the beginning of the years 1990, 2010, 2030 etc. The time index $t=0, 20, 40, \ldots, T$ represents these *sample dates*, with the time horizon T suitably chosen in view of the particular simulation experiment under scru-

Table 2. Time structure and age classes in ForCaBSim.

Sample dates	1990	2010	...	$1990 + T$
Index t	0	20	...	T
Periods $\tau = t..t + 20$	0..20	20..40	...	$T - 20..T$
Age class n	1	2	...	$N = 9$
Stand ages in age class n	1–20	21–40	...	161–180
Mean age of age class n	10	30	...	170
Age class transition period n^*	0^*	1^*	...	$N^* = 9^*$
Mean age in transition period n^*	0–10	11–30	...	151–170

Note: The use of the arithmetic mean age assumes an even distribution within age class; values are rounded to integers.

tiny. The largest possible time horizon is 200 years. Time *periods* last from January 1st 1990 to January 1st 2010, and so on. Thus, periods begin at time t and last until $t+20$. The shorthand $\tau=t..t+20$ is introduced to denote *time periods*.

Age classes are 20 years wide and are indicated by the index $n=1,2,\ldots N$, where in the actual implementation N equals 9, and 180 is the oldest possible stand age. The first age class comprises stands with ages between one and 20 years, age class 2 those between 21 and 40 years, etc. Age class n refers to a collection of stands at a specific date (and not a period). It is assumed that the mean ages of these classes are 10, 30, 50, and so on. This implies an even distribution of different aged stands within a specific age class. Notation with regard to time and age classes is summarized in Table 2.

It should be noted that there exist two distinct possibilities to speak of periods in such a modeling context. The first one simply refers to the time passed by when time proceeds from one point of time to the next. Material or financial flows refer to such periods. In Table 2, such periods are symbolized by $\tau=t..t+20$. The second possibility to speak of periods refers to the time required for the *transition from one age class to the next*. Periods which refer to age class transitions also have a length of 20 years, and are denoted by an asterisk on the right-hand side of the age class index n: $n^*=0^*,1^*,\ldots,N^*$. The symbol * on the right-hand side of n should be understood as a visual hint to the fact that one period is required for an age class to come into being. There is no age class 0 but there is a period in which the first age class comes into being, that is $n^*=0^*$.

3 Evolution of Age Class Structure

The methods employed to extrapolate the age class distribution into the future can best be explained by the use of matrix notation. The application of such matrices to forestry has been studied by Suzuki (1983) since the 50s. More recent applications can be found, e.g., in Möhring (1986) or Kohlmaier et al. (1995).

The area distribution of tree species and age classes at time t is defined in matrix $\mathbf{A}(t)$, with $t=0,20,\ldots,T$.

$$\mathbf{A}(t) = \begin{bmatrix} a(1,1,t) & a(1,2,t) & \ldots & a(1,N,t) \\ a(2,1,t) & a(2,2,t) & \ldots & a(2,N,t) \\ \vdots & \vdots & & \vdots \\ a(S,1,t) & a(S,2,t) & \ldots & a(S,N,t) \end{bmatrix} \quad \text{for } t = 0,20,\ldots,T \qquad (1)$$

The first column of matrix $\mathbf{A}(t)$ in Equation 1 denotes the areas of the different tree species in the first age class, measured in hectares. Accordingly, matrix element $a(s,n,t)$ is the area covered by tree species s ($s=1,\ldots,S$) of age class n ($n=1,\ldots,N$) at time t ($t=0,20,\ldots,T$). $\mathbf{A}(t)$ is a quadratic matrix in the present context because, in the particular data set used here, S and N have each 9 elements. In general, this needs not to be the case, and $\mathbf{A}(t)$ may be a rectangular matrix.

The area distribution in matrix $\mathbf{A}(t)$ changes in accordance with patterns of final cuts. A stand which is clear cut moves into the newly established first age class during the period. Thus, it is assumed that any finally harvested stand will be regenerated in the following year. All areas not felled and not damaged by natural hazards move into subsequent age classes.

To determine the life span of each type of stand, a discrete probability distribution about the rotation age is assumed. This distribution expresses the fact that in reality rotation ages vary for several reasons: site-specific yields and silvicultural practices, fluctuating demand, premature cuts forced by natural calamities. Given such a probability distribution, $p(s,n)$ is defined as the probability that a stand of species s planted at time zero is harvested and regenerated at the age of class n. A continuous normal distribution is used to approximate the discrete probabilities $p(s,n)$. The associated mean and the standard deviation define the expected rotation age and the fluctuation around it. Other density functions are conceivable (e.g., exponential, Weibull, Erlang), and could easily be implemented. Any of these distributions have to be truncated because rotation ages are nonnegative and limited by maximum age (180 years in the present implementation).

In order to model the age class dynamics we need to know the conditional *transition* probability that a stand of species s is clear cut at its age n given that it has reached this age class. These transition probabilities are denoted by $h(s,n)$, and fill the elementary components of the species-specific $N \times N$ matrix $\mathbf{H}(s)$ in Equation 2.

$$\mathbf{H}(s) = \begin{bmatrix} h(s,1) & 1-h(s,1) & 0 & \dots & 0 \\ h(s,2) & 0 & 1-h(s,2) & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ h(s,N-1) & 0 & 0 & \dots & 1-h(s,N-1) \\ h(s,N) & 0 & 0 & \dots & 0 \end{bmatrix} \quad \text{for } s = 1,\dots,S \tag{2}$$

Such matrices $\mathbf{H}(s)$ allow to compute successive changes of the age class structure of species s from one period to the next. The components $h(s,n)$ of the first column in $\mathbf{H}(s)$ specify the area shares harvested of each age class. This area shares are transformed into the newly established first age class. Each of the other columns are composed of zeros but one positive element, the complement of the harvesting share. The complement $1-h(s,n)$ is the fraction of age class n which is not harvested and which thus survives and grows into its successor age class $n+1$. $h(s,N)$ is equal to unity by definition. This means that all remaining stands of age N (number 9 in ForCaBSim) are cut during the period. The new age class 1 is composed of area fractions from all other age classes (compare the notation in Table 2). Note that all elements of matrix $\mathbf{H}(s)$ are nonnegative, and components of each row sum to unity.

Assuming the stochastic independence of $p(s,n|(1-h(n-1,s))$ and $h(s,n)$ for n>1, the following relations must be valid:

$$\begin{aligned} p(s,1) &= h(s,1), \\ p(s,2) &= (1-h(s,1)) \cdot h(s,2), \\ &\vdots \\ p(s,N) &= \prod_{n=1}^{N-1} (1-h(s,n)) \cdot h(s,N) \end{aligned} \tag{3}$$

Take for example the second row in Equation 3, $p(s,2)=(1-h(s,1)) \cdot h(s,2)$. It says that the probability that a specific stand s is harvested in the transition period from age class 2 to age class 3 is equal to the probability that this stand has survived its first age period, denoted by $1-h(s,1)$, multiplied with the probability that it is harvested in the following transition period, denoted by $h(s,2)$. Transition probabilities $h(s,n)$ can then be computed from given rotation probabilities $p(s,n)$ in the following way:

$$\begin{aligned} h(s,1) &= p(s,1), \\ h(s,2) &= p(s,2)/(1-h(s,1)), \\ &\vdots \\ h(s,N) &= p(s,N)/\prod_{n=1}^{N-1} (1-h(s,n)) \end{aligned} \tag{4}$$

Based on these operations, it is straightforward to propagate the age class structure into the future. Let us denote the age class vector of an individual tree species s at time t by the symbol $\mathbf{a}(s,t)$. It is a $1 \times N$ row vector extracted from matrix $\mathbf{A}(t)$. Given the final cutting patterns specified in matrix $\mathbf{H}(s)$, the age class distribution in the succeeding period $t+20$ is the product of multiplying vector $\mathbf{a}(s,t)$ from left by $\mathbf{H}(s)$:

$$\mathbf{a}(s,t+20) = \mathbf{a}(s,t) \cdot \mathbf{H}(s), \quad \text{for } s = 1,\ldots,S;\ t = 0,20,\ldots,T-20 \tag{5}$$

Note that in this scheme, $\mathbf{H}(s)$ is assumed to be time-invariant: harvesting, and thus reforestation patterns, do not change in the course of time.

In the simulation model, the process of age class propagation is initialized by choosing suitable parameters for density functions about the rotation age. The value of the mean reflects the expectation value of the rotation age. In an economic view, the rotation period would be chosen such that the land expectation value is maximized (see, e.g., Samuelson 1976). In case economic principles are refuted, physical objectives such as the maximum sustained yield or desired stem sizes could be applied. In practice, the age of 'maturity' varies for various reasons. Accordingly, three sets of rotation ages have been defined in order to compare different development patterns (Table 3).

The set of rotation ages called 'common' is meant to express the most commonly observed rotation ages in German forestry planning (Polley et al. 1996). The set of 'prolonged' rotations

Table 3. Three sets of rotation ages.

Species group	Scenario			
	Common	Prolonged (years)	Short	std (years)
Spruce	100	115	80	25
Fir	110	120	100	25
Douglas fir	100	110	80	25
Pine	120	140	100	30
Larch	110	120	80	25
Beech	140	150	130	30
Oak	160	180	140	30
Broadleaved, long rotations	120	125	100	30
Broadleaved, short rotations	80	100	90	25

Three sets of rotation ages used to analyze the effect of varying harvesting cycles. std = standard deviation.

Table 4. Target proportions of tree species in three scenarios (%).

	Scenario and target year		
	Continuation of present 1990	Moderate ecological 2030	Radical ecological 2050
Spruce	32.4	27.0	20.0
Fir	1.3	1.5	1.5
Douglas fir	1.3	2.0	1.5
Pine	28.1	24.0	20.0
Larch	3.0	3.0	5.0
Beech	13.9	18.0	25.0
Oak	8.7	10.0	14.0
Broadleaved, long rotation	3.8	6.5	6.0
Broadleaved, short rotation	7.4	8.0	7.0
Broadleaved-%	33.8	42.5	52

could, for example, reflect a structural lack of timber demand. Such rotation periods would probably still be acceptable from a silvicultural viewpoint, albeit risks increase with higher stand ages, particularly for coniferous stands. 'Short' rotation ages are in the vicinity of economically optimal rotations, given discount rates which are higher than 4%.

Rotation ages determine the future area distribution of age classes. The choice of species on the area to be regenerated determines the evolution of the overall area distribution of the tree species. Trends to increase the share of broadleaved species provide the background for defining the scenarios in Table 4. The 'moderate ecological' variant will increase the overall share of broadleaved stands to 42.5% until 2030, while the 'radical' variant increases the share of broadleaved stands to 52% by 2050. Continuation of the present species composition is not a realistic scenario, but rather a state of reference. In this sense it is included in Table 4.

The transition to a higher overall share of broadleaved stands requires time since it is restricted, in each period, by that fraction of the regenerated area which is suited for the plantation of broadleaves. Thus, the 'moderate ecological' change of the species composition could be accomplished until 2030, while the more 'radical' variant requires 20 more years of time. Table 4 only shows the target proportions while the transitional steps to this new overall composition are not documented here.

The formal operations on the element of matrix $\mathbf{A}(t)$, required to implement the target species distributions are not explicated here.

4 Steady States

Matrix $\mathbf{H}(s)$, defined in Equation 2, is a semipositive matrix whose components are all either positive or zero, and at least one element is positive. The elements in each row of $\mathbf{H}(s)$ add up to one. Such matrices are called *Markov* or transition matrices (Gantmacher 1986). Their role for the evolving area pattern was defined in Equation 5. This section discusses the steady state properties of the corresponding dynamic system.

For semipositive matrices of this type, a series of theorems named *Perron-Frobenius Theorems* exist which have found wide-spread applications in stochastics and in the theory of linear economic systems (Pasinetti 1977).

Without providing proofs or further explanations in this paper, the mathematical properties of harvesting matrices may be listed as follows:

1) $\mathbf{H}(s)$ is a quadratic and nondecomposable matrix of order N.
2) $\mathbf{H}(s)$ is associated with an eigenvalue λ_m (= λ_1) whose absolute value is greater than the absolute value of any other eigenvalue, that is $|\lambda_m| > |\lambda_i|$, for $i = 2,3,\ldots,N$. λ_m is real and its multiplicity is one.
3) The maximum eigenvalue λ_m is equal to one, i.e. $\lambda_m = 1$.
4) The (left-hand side) eigenvector $\mathbf{x}$ corresponding to the maximal eigenvalue $\lambda_m = 1$ is strictly positive. In the following, this vector is denoted by $\mathbf{x}_1$.
5) The vector $\mathbf{x}^e = c_1 \cdot \mathbf{x}_1$ is the equilibrium solution towards which the difference equation system $\mathbf{x}(t+1) = \mathbf{x}(t) \cdot \mathbf{H}(s)$ converges.
6) The parameter c_1 can be definitized by setting it equal to the inverse of the sum over the components of $\mathbf{x}_1$. Then, $\mathbf{x}^e$ can be interpreted as the vector containing the list of relative frequencies or probabilities of the age class vector in the limit.

Equation 5 can be understood as a homogeneous system of first order difference equations of the following form:

$$\mathbf{x}(t+1) = \mathbf{x}(t)\mathbf{H}(s) \tag{6}$$

Since $\mathbf{H}(s)$ is diagonalizable, the general solution of system 6 is (Tu 1994, 116):

$$\mathbf{x}(t) = c_1\mathbf{v}_1\lambda_1^t + c_2\mathbf{v}_2\lambda_2^t + \ldots + c_N\mathbf{v}_N\lambda_N^t \tag{7}$$

where $\lambda_1, \lambda_2, \ldots, \lambda_N$ are eigenvalues of $\mathbf{H}(s)$, $\mathbf{v}_1$, $\mathbf{v}_2, \ldots, \mathbf{v}_N$ are the associated eigenvectors, and c_1, $c_2, \ldots, c_N$ are constants to be determined either with reference to starting values or by the method described below.

According to property (3) above, we may assume that $\lambda_1 = \lambda_m = 1$. Accordingly, Equation 7 simplifies to:

$$\mathbf{x}(t) = c_1\mathbf{v}_1 + c_2\mathbf{v}_2\lambda_2^t + \ldots + c_N\mathbf{v}_N\lambda_N^t \tag{8}$$

The first term of Equation 8, $c_1\mathbf{v}_1$, represents the steady state or equilibrium solution of Equation 6. When $t \rightarrow \infty$, all terms $c_n\mathbf{v}_n\lambda_n$ with $n>1$ vanish because $|\lambda_n|<1$. In case of complex roots, which are to be expected, the time path of $\mathbf{x}(t)$ converges in a fluctuating movement towards the equilibrium vector.

Vector $\mathbf{v}_1 = [v_1(n)]$ is determined up to a multiplicative constant. It can be normalized by dividing it through the sum of its components:

$$\mathbf{v}_1^e = c_1\mathbf{v}_1, \text{ with } \frac{1}{c_1} = \sum_{i=1}^{N} \upsilon_{1i} \tag{9}$$

Vector $\mathbf{v}_1^e$ in Equation 9 is the age class distribution in the limit, expressed in relative frequencies or probabilities, irrespective of the initial age class distribution. To compute the limit of the age class distribution of species s in terms of areas measured in hectares, $\mathbf{v}_1^e$ must be multiplied with the total area of the initial age class vector.

Following Suzuki (1983), the steady state age class distribution of species s may be interpreted as a variant of a *normal forest*. The traditional concept of a normal forest was developed by Hundeshagen (1826) as foundation of sustainable forest management. Ideally, a normal forest implies an equal distribution of all age classes, and thus allows a constant volume of timber to be harvested each year while the total stock remains unchanged. A 'normal' forest in this sense implies a transition matrix of the following form:

$$\mathbf{H}(s) = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ 1 & 0 & 0 & \dots & 0 \end{bmatrix} \tag{10}$$

Accordingly, if T_s is the rotation age, the share of each class would be $1/T_s$. In contrast, age classes in the steady state computed in ForCaBSiM are not evenly distributed because the values in matrix $\mathbf{H}(s)$ are based on a normal distribution about the mean rotation period. This implies that some stands are cut before and some after the central harvesting time. Hence, age class area proportions decrease monotonously after the first age stage.

It is of course justified to ask how many iterations are required for a system to approach its steady state. The answer to this question depends crucially on the initial age class structure and the rotation length of the tree species considered. The percent deviation of vector $\mathbf{a}(s,t)$ from the equilibrium vector $\mathbf{a}^e(s)$ after time t may be measured by the *root-mean deviation* rmdev(s,t), a measure adapted for the present purpose from Pindyck and Rubinfeld (1991, 338). It is given in Equation 11.

$$\text{rmdev}(s,t) = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{a(s,n,t) - a^e(s,n)}{a^e(s,n)}\right)^2} \cdot 100 \tag{11}$$

5 Growing Stock and Timber Removal

The total growing stock evolves as the result of two factors: (1) the changing area distribution of the age classes and tree species as described in section 3, and (2) the dynamics of the growing stock on a unit basis as explained in this section.

The growing stock per area unit changes in correlation to annual gross increment, natural loss and thinning. Stock variable gs(s,n,t) is defined as the average merchantable timber on each hectare of tree species s $(s=1,..,S)$ and age class n $(n=1,\dots,N)$ at time t $(t=0,20,\dots,T)$. It is measured in m^3 (cubic meters) of merchantable timber over bark. The data set required for the initial year is available from the federal forest inventory (BML 1990). The stock of age class n refers to its mean age as explained in section 2. Equation 12 shows how the growing stock gs(s,n,t) changes from one age class to the next. A stock at $n=0$ does not exist, thus gs$(s,0,t)=0$ by definition. On transition periods n^* compare Table 2.

$$\begin{aligned} \text{gs}(s,n,t+20) &= \text{gs}(s,n-1,t) \\ &\quad +20 \cdot \left[\text{cai}(s,(n-1)^*) - \text{nl}(s,(n-1)^*,\tau)\right] \\ &\quad -\text{th}(s,(n-1)^*) \end{aligned} \tag{12}$$
$$\text{for } s = 1,\dots,S;\ n = 1,\dots,N;\ n^* = 0^*,1^*,\dots,N^*; \quad t = 0,20,\dots,T-20, \text{ and } \tau = t..t+20)$$

The symbol cai(s,n^*) in Equation 12 denotes the *current annual increment* of species s in the period which establishes age class n. Growth is assumed to be constant within the period, thus annual increment $\mathrm{cai}(s,n^*)$ is multiplied by 20, the length of the period. Increment in the oldest age class is disregarded. *Average natural loss per year* is denoted by $\mathrm{nl}(s,n^*,\tau)$.

The symbol $\mathrm{th}(s,n^*)$ denotes *thinning* volume on a stand of species s and age n. By definition, there is no thinning before age class 1 is established. Thus, $\mathrm{th}(s,0^*)=0$. In the present model version only natural losses are time-variant, in contrast to increment and thinnings which have fixed values for each class age. A simulation experiment in which annual increments are time-variant in as far as they react to climate change is reported in Böswald et al. (1998).

The volume of the standing stock $\mathrm{GS}(s,n,t)$ of species s in age class n at time t is a scalar, and is computed by multiplying area $a(s,n,t)$ with the associated per hectare stock $\mathrm{gs}(s,n,t)$, for all s, n, and t, that is

$$\mathrm{GS}(s,n,t) = a(s,n,t)\cdot \mathrm{gs}(s,n,t) \qquad (13)$$
$$\text{for } s = 1,\dots,S;\ n = 1,\dots,N;\ t = 0,20,\dots,T$$

while the *total volume of standing stock* $\mathrm{GS}(t)$ at time t is arrived at by taking the sums over the species and age classes:

$$\mathrm{GS}(t) = \sum_{s=1}^{S}\sum_{n=1}^{N} a(s,n,t)\cdot \mathrm{gs}(s,n,t) \qquad (14)$$
$$\text{for } t = 0,20,\dots,T$$

Growth patterns contained in the $S\times N$ parameters $\mathrm{cai}(s,n^*)$ are basically derived from the most widely used yield tables for Germany (LFV-BW 1993). In this collection, yield (i.e. productivity) classes are ordered in terms of the mean annual increment at the age of 100, abbreviated as mai_{100}.

In recent decades, relatively higher growth on many stand types has been observed in Germany (Pretzsch 1992). Similar observations have been made in other countries (Spiecker et al. 1996). Possible explanations may be found in changed forest management and land use, nitrogen deposition, climate change and CO_2 fertilization. The relative weight of these factors is still largely uncertain (Houghton et al. 1998). Higher growth is, however, not evenly distributed among different age classes. On the contrary, it has been found in German studies that growth in younger age classes has increased relatively more than in older age classes (Foerster and Böswald 1994).

Table 5. Average yield classes in Germany.

Species	Mean annual increment at age 100 in m^3
Spruce	13
Fir	14
Douglas fir	12
Pine	8
Larch	8
Beech	7
Oak	5
Blr (ash)	5
Bsr (alder)	6

Average yield classes (= productivity classes) estimated on the basis of BML (1990).

The deviation of the observed increments at different ages from the growth predictions in the yield tables is ignored in the model in order to retain the internal consistency of the yield tables. However, the relatively higher growth level is taken account of by calibrating yield classes. Since the federal forest inventory does not provide a classification of its survey data into yield classes, average productivity classes are estimated on the basis of available data from the forest inventory. The estimates are documented in Table 5. This table provides only integer values in order not to pretend a higher accuracy of the estimation. The current annual increment in the age classes is then derived from the corresponding yield table. Fig. 2 illustrates the increment curves for the major tree species.

At present, there exist only incomplete and regionally focused surveys of actual growth trends. Reliable estimates of mean annual increments in German forests as a whole may only be expected when the results of the second federal forest inventory planned for 2002 will be available. In ForCaBSiM, the average current increment on all stands amounts to 8.9 m^3/ha per year in the first simulation period. This value is below the average growth rate of 10 m^3/ha estimated by Foerster and Böswald (1996) for Bavaria, and the value of 10.1 m^3/ha assumed in the study

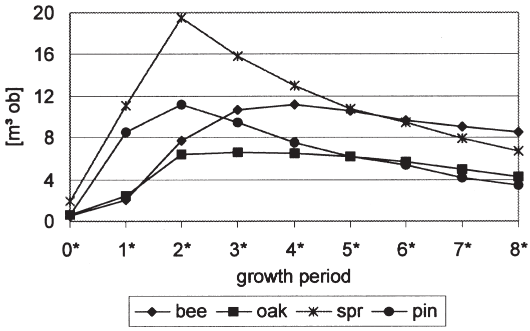

Fig. 2. Current annual increment in growth period n* for the major tree species; adapted from LFV-BW 1993.

of Polley et al. (1996) for Germany as a whole. Coniferous stands grow with an average rate of 9.6 m^3/ha, while the average rate of increment of broadleaved stands is estimated at 6.5 m^3/ha.

Annual increment and thinning practices are of course interrelated. The growth predictions in the yield tables used for this study (LFV-BW 1993) imply moderate low thinning. Corresponding estimates are implemented in the array of parameters th(s,n^*). The concept of low thinning aims to give individuals of the dominant crown class room to grow, and fosters one-layered stands. In its moderate form, it concentrates on the removal of dying, suppressed or inefficiently growing individuals.

Natural losses are the third element determining the dynamics of the growing stock, symbolized by nl(s,n^*,τ) in Equation 12. Such losses are understood as the volume of merchantable timber which cannot be recovered when trees are damaged by calamities like snow break, wind throw, fire or insect infestation, and have to be felled and removed. This definition reflects the fact that timber of damaged trees is often not lost completely. Accordingly, the volume of natural losses is assumed to be left in the forest. Natural losses are implemented as species and age class specific percentages of the growing stock. That is, higher growing stocks imply higher natural losses, and vice versa.

Unfortunately, there exists no reliable information about the actual extent of natural losses. Thus, parameters are estimated on plausibility grounds. Percentages are calibrated such that the fraction of the growing stock lost by calamities amounts to about 4% of gross annual increment in the first simulation period. A compilation in Kuusela (1994) shows that this percentage lies at about the mean value of losses observed in other European regions.

As can be seen in Equation 14, growing stock in forests as a whole at time t is the result of two processes: (1) the evolution of the area structure, reflected in the $a(s,n,t)$, and (2) the dynamics on an area unit basis, represented by gs(s,n,t). Both processes imply volumes of *fellings*, the first from final cutting, the second from thinning. These felling volumes represent the potential timber supply of German forests, given the harvesting patterns expressed in the final cut parameters $h(s,n)$ (Equation 2) and the thinning parameters th(s,n^*) (compare Equation 12).

The average annual volume felled in period τ by final cuts and thinnings on stands of species s and age n, denoted by fel(s,n^*,τ), is computed according to Equation 15. Felling is measured in m^3 of merchantable timber over bark.

$$\begin{aligned} &\mathrm{fel}(s,n^*,r) \\ &=\left[a(s,n,t)\cdot h(s,n)\cdot \mathrm{gs}(s,n,t)+\mathrm{th}(s,n^*)\right]/\,20 \\ &\quad \text{for } s=1,\ldots,S;\ n=1,\ldots,N;\ n^*=1^*,\ldots,N^*; \\ &\qquad t=0,20,\ldots,T-20;\ \tau=t..t+20 \end{aligned} \tag{15}$$

It is assumed that the annual amount of harvest within the period is constant. Annual quantities harvested by final cuts are thus equal to a twentieth of the total volume removed in the period.

A fraction of the felled volume is lost in the process of logging. It consists of bark and logging slash. Annual *removal* in the period following t, expressed by rem(s,n,τ) and measured in m^3 ub (under bark), is equal to the harvest quantity after bark and logging residues have been deducted. It is assumed that bark and other logging residues are left in the forest, and that removal is equal to the quantity of timber which leaves the forest for intermediate or final use. Logging residues are taken into account by species-specific factors logres(s), which vary between 15 and 21 percent. Equation 16 shows the corresponding operation.

$$\mathrm{rem}(s,n^*,\tau)=\mathrm{fel}(s,n^*,\tau)\cdot(1-\mathrm{logres}(s)) \qquad (16)$$
$$\text{for } s=1,\ldots,S;\ n^*=1^*,\ldots,N^*;$$
$$t=0,20,\ldots,T-20;\ \tau=t..t+20$$

Annual removal represents an aggregated quantity which reveals nothing about the size and the quality of harvested wood. Thus, harvested volumes are assorted according to the trade classes distinguished in Schöpfer and Dauber (1989). The tables published by these authors are regarded as representative for Germany. They distinguish ten size classes of stemwood and four categories of small timber. This trade class assortment requires mean stand diameter as entry value, provided by the yield tables in LFV-BW (1993).

In formal language, trade classes can be viewed as additional specification of the variables representing removal quantities. The species and age specific *trade class* parameter trcl(s,n,i), with $s=1,\ldots,S$, $n^*=1^*,\ldots,N^*$, and $i=1,\ldots,I$, generates the subdivision of the removed quantities into timber classes in period τ, denoted by rem(s,n^*,i, τ):

$$\mathrm{rem}(s,n^*,i,\tau)=\mathrm{rem}(s,n^*,\tau)\cdot\mathrm{trcl}(s,n^*,i) \qquad (17)$$
$$\text{for } s=1,\ldots,S;\ n^*=1^*,\ldots,N^*;\ i=1,\ldots,I;$$
$$t=0,20,\ldots,T-20;\ \tau=t..t+20$$

Variable rem(s,n^*,i,τ) is measured in m^3 under bark as well.

6 Carbon Pools and Flows

The components of ForCaBSim thus far described provide the basis for the assessment of the forest resources in terms of timber production. Since the storage of carbon in forests depends to a large degree on the same processes, it is possible, by adding appropriate extensions, to turn the model into an instrument for the assessment of the carbon balance of forestry development scenarios. This is the topic of this section.

While the major part of aboveground carbon in forests is stored in merchantable timber, other tree components store carbon as well. It is thus necessary to estimate the total amount of forest biomass. Additional steps are required to estimate the mass of dry matter, and the carbon fraction therein.

Let us call Cgs(s,n,t) the carbon mass of the growing stock of species s and age class n at time t. This magnitude is calculated as follows:

$$\begin{aligned}&\mathrm{Cgs}(s,n,t)\\&\quad=\mathrm{GS}(s,n,t)\cdot\mathrm{biomf}(s,n)\cdot\mathrm{dens}(s)\cdot\mathrm{Cf}\\&\quad\text{for } s=1,\ldots,S;\ n=1,\ldots,N;\ t=0,20,\ldots,T-20\end{aligned} \qquad (18)$$

GS(s,n,t) is the growing stock of species s and age class n in terms of merchantable timber as computed in Equation 13. The parameter biomf(s,n) represents species and age class specific factors which estimate the ratios between total woody biomass and merchantable timber. Symbol dens(s) denotes the basic wood densities of species s, and Cf is the fraction of carbon in dry wood matter. The latter three parameters are explained in more detail in the following paragraphs.

Merchantable timber is defined as standing timber volume over bark with a minimum diameter of 7 cm. It is wood from stems in the case of coniferous trees, and comprises additionally branches in the case of broadleaved trees. Thus non-merchantable wood includes stems and branches below a diameter of 7 cm. Wood below ground is found in roots. The carbon content of leaves is not considered. Burschel et al. (1993) proposed a series of ratios to expand merchantable timber to total tree volume. These factors are particularly uncertain for the first age class where they are coarsely estimated at 4. For higher age classes, they range between 1.34 and 1.69. These parameters are called *biomass expansion factors*, and denoted by biomf(s,n) in Equation 18.

Basic wood density is defined as kilogram of oven dry wood per cubic meter of original fresh volume. This parameter varies considerably between tree parts, individual trees or species; it may also vary with respect to site, region and season. The values assigned to the parameter dens(s) are average values from the standard reference literature. They amount to 377, 430, 554 and 561 kilogram per cubic meter for the dominant species spruce, pine, beech and oak, respectively.

Average chemical composition of wood underlies variations also, but not as large as basic wood density. Fractions of the basic elements are astonishingly similar in different tree species. Broadleaved trees contain slightly less carbon than coniferous trees. Following international conventions (IPCC 1996), this difference is disregarded, and an average value of 0.5 ton carbon per ton dry matter is assumed for parameter Cf in Equation 18, irrespective of tree species.

Carbon is stored in forests not only in the above- and belowground biomass of trees, but also in other aboveground vegetation, in dead wood, in litter, and the soils. In the present version of ForCaBSim, these carbon stocks are not modeled dynamically, but are assumed to remain constant in the long run.

7 Economic Scenario Evaluation

The output variables of ForCaBSim explained in the preceding sections are measured in terms of physical magnitudes. Economic evaluation of the scenarios is introduced by calculating the net present values associated with the revenues and costs of the forestry activities. The methodology thereby applied is in accordance with the approach founded by Faustmann (1849) in order to calculate the land expectation value and the value of nonmature timber stocks. Faustmann pointed in particular to the necessity to take account of an infinite horizon. The total forest value is equal to the sum of the land value and the value of the nonmature timber. Because it expresses all monetary flows related forestry activities in a single number, it may be used as a performance indicator of the studied scenarios.

The *land expectation value* of species s under the assumption of rotation age T_s and discount rate r is denoted lev(s,r). The value of the *nonmature timber stock* of age n and species s in the base year, under the assumption of rotation age T_s and discount rate r, is denoted by tv(s,n,r). The following equations can only explain basic procedures, without capturing every detail of the actual simulation routines. A comprehensive treatment of the computational steps would require more space than is available in a journal article.

Each timber trade class i ($i = 1,\ldots,I$) of species s is assigned a price, denoted pr(s,i). Prices are equal to the proceeds from timber sales net of harvesting costs and measured in EURO per cubic meter.

Calculations performed in the following Equation 19 determine the value of the compounded revenues rev(s,n,r,t) at time t, for $t = 20,\ldots,T-20$. First, annual revenues in period τ from tree species s, age class n, and trade class i are calculated as the product of the removal quantities rem(s,n,i,τ), derived in Equation 17, and prices pr(s,i). Second, annual revenues are compounded to the end of the period, that is to $t+20$, by interest rate r. This operation is accomplished by using the formula for the future value of a 20-year annuity, $((1+r)^{20}-1)/\mathrm{r}$.

$$\begin{aligned}&\mathrm{rev}(s,n,r,t+20)\\&\quad=\sum_{i=1}^{I}\mathrm{rem}(s,n,i,\tau)\cdot\mathrm{pr}(s,i)\frac{(1+r)^{20}-1}{r}\qquad(19)\\&\qquad\text{for } s=1,\ldots,S;\ n=1,\ldots,N;\\&\qquad\quad t=0,\ldots,T-20;\ \tau=t..t+20\end{aligned}$$

The land expectation value lev(s,r) for each species is computed by taking the sum of the discounted revenues rev(s,r,t) from Equation 19 ($t = 20,\ldots,T$), and subtracting stand *regeneration costs* rcost(s) of the corresponding species. This difference is equal to the present value of the net revenues of one rotation cycle, including any revenues from thinning. It is written into the denominator of Equation 20.

$$\mathrm{lev}(s,r)=\frac{\sum_{t=20}^{T_s}\mathrm{rev}(s,r,t)(1+r)^{-t}-\mathrm{rcost}(s)}{1-(1+r)^{-T_s}}\qquad(20)$$
$$\text{for } s=1,\ldots,S$$

The nominator in Equation 20 introduces the infinite time horizon. Dividing the denominator by $(1-(1+r)^{-T_s})$ computes the present value of the infinite series of rotation cycles. The corresponding quotient is equal to the expectation value of one hectare of forest land lev(s,r). The total value of forest lands in Germany is equal to the sum of the lev(s,r) over species s ($s = 1,\ldots,S$).

To each land expectation value lev(s,r), there corresponds a land rent R which is computed as follows:

$$R = r \cdot \mathrm{lev}(s,r), \quad \text{for } s = 1,\ldots,S \tag{21}$$

Equation 21 reflects the fact that land is considered as a nondestructible resource, bearing an infinite number of annual rent payments.

In order to calculate the value of the nonmature timber stock $\mathrm{tv}(s,n,r)$ of species s and age n, the path of the stand which is in its nth age class in the base year must be tracked. This is done by defining $\mathrm{rem}(s,\overline{n},i,\tau)$ as that removal quantity of species s and trade class i in period τ which was in age class $\overline{n}$ in the base year. Accordingly, revenues from the stands which were at age $\overline{n}$ in the base year are calculated as follows:

$$\begin{aligned}&\mathrm{rev}(s,\overline{n},r,t+20)\\&\quad=\sum_{i=1}^{I}\mathrm{rem}(s,\overline{n},i,\tau)\cdot\mathrm{pr}(s,i)\frac{(1+r)^{20}-1}{r}\\&\qquad\text{for } s=1,\ldots,S;\ \overline{n}=1,\ldots,\overline{N};\\&\qquad\quad t=0,\ldots,T-20;\ \tau=t..t+20\end{aligned} \tag{22}$$

Based on the result in Equation 22, computation of variable $\mathrm{tv}(s,\overline{n},r)$ in Equation 23 is composed of two terms. The first term adds all discounted revenues up to time $t = T_s - \overline{n}\cdot 20$. To see the meaning of this notation, let us say that a stand has reached the second age class in the base year ($\overline{n} = 2$), and that its expected rotation age is $T_s = 120$. Accordingly, final cut will take place at $t = 120 - 4 \cdot 20 = 40$.

The second term in Equation 23 computes the compounded future value of land rent R (from Equation 21) accruing in the periods up to $T_s - \overline{n}\cdot 20$. This term has to be subtracted from the discounted value of the net revenues to take account of the cost of land use in the period up to the age of maturity. The cost of land use was not explicitly visible in the equation of the land expectation value (Equation 20). However, it is implicitly there as well because $\mathrm{lev}(s,r)$ is equal to the capitalized land rent.

$$\begin{aligned}\mathrm{tv}(s,\overline{n},r) = &\sum_{t=20}^{T_s-\overline{n}\cdot 20}\mathrm{rev}(s,\overline{n},t)\cdot(1+r)^{-t}\\&-R\frac{1-(1+r)^{-(T_s-\overline{n}\cdot 20)}}{r}\end{aligned} \tag{23}$$

Gross prices, regeneration and harvesting costs assumed for these computations are taken from the manual for forest valuation of the state North Rhine-Westphalia (LÖBF/LAfAO 1998). Average gross prices in this manual reflect the price development in the years 1995 to 1997. Regeneration costs include site preparation, plants, planting, fertilization, treatment and protection. The present diffusion of natural regeneration which is considerably less costly than plantation has been taken account of by way of a plausible cost mix.

Harvesting and extraction costs are calculated on the basis of labor and machine time requirements estimated in the assortment tables (Schöpfer and Dauber 1989) and the cost tariffs provided by LÖBF/LAfAO (1998).

In the present context, reference for the choice of the discount rate is private profitability because issues of public goods and public planning are not considered explicitly. Nonetheless, the choice of a reasonable discount rate remains difficult. Thus, all values are calculated for a spectrum of plausible discount rates, which may then be interpreted under various perspectives.

8 Simulation Results

This section presents selected simulation results intended to illustrate applications of the model ForCaBSiM.

Steady States

Modeling the dynamics of the age class structure in the way outlined makes possible to compute the long-run equilibrium composition of the age classes of each species s, given the harvesting patterns defined in matrix $\mathbf{H}(s)$. Fig. 3 shows the age class distribution of spruce in 1990 on a total area of 3.23 Mha (Mha $= 10^6$ hectares), and the corresponding area distribution in the steady state. It is obvious that the age class structure in 1990 was heavily influenced by historic events in this century. The second as well as the fourth age class reflect extraordinary large reforestations in the aftermath of overexploitations during and after the two World Wars.

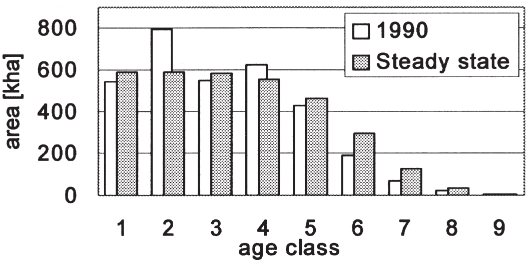

Fig. 3. Age class distribution of spruce in 1990 and in steady state (total area: 3.23 Mha).

Steady states of this kind can only be computed on the basis of a constant forest area and a given species composition. Steady state values for scenarios in which the total forest area or the tree species composition changes for some decades must be computed with regard to the area distribution arrived at when these changes have come to a halt. For the following calculations, it is assumed that the total area of the age class structured high forest, which amounts to 9.96 Mha in 1990, and the species composition on this area remains unchanged. Then, the corresponding total growing stock of merchantable timber in the steady state amounts to 3259 Mm^3 or 327 m^3 per hectare, the stock of carbon in the tree biomass to 1036 Mt or 104 t per hectare, and the total allowable cut (under bark) to 64.9 Mm^3 or 6.1 m^3 per hectare. Comparison with period 1990–2010 in Table 6 shows that steady state values are considerably higher than the values observed in the base period. This means that, at present, forests in Germany are in a phase of build-up.

Average age over all tree species undergoes almost no change in the steady state as compared to 1990 (61 and 63 years), although the average age of individual tree species changes markedly.

Approaching the long-run equilibrium requires time. The length of the convergence process depends primarily on rotation ages, and to a lesser degree on the initial age class distribution. Equation 11 proposes a 'root mean deviation' measure, rmdev(t), which indicates the gap between the actual and the equilibrium distribution at each point in time. Table 7 shows the corresponding results for the dominant species and the total forest area.

As these results demonstrate, it takes at least two rotation periods to bring the actual distribution within a deviation of 5% to the equilibrium distribution. The relatively higher deviation of the total forest area in the base year reflects the

Table 6. Growing stock and allowable cut in the steady state.

	1990	Steady state
Growing stock, Mm^3 ob	2651	3259
per hectare, m^3 ob/ha	266	327
Carbon in tree biomass, Mt C	865	1036
per hectare, t C/ha	86.9	104
	1990–2010	Steady state
Allowable annual cut, Mm^3 ub	52.8	60.8
per hectare, m^3 ub	5.3	6.1

Steady state values compared to values in 1990 and 1990–2010, respectively. M = 10^6, t = ton, ob = over bark, ub = under bark.

Table 7. Root mean deviation of area distribution from steady state.

Species	Rotation age	Years since beginning							
		0	100	200	300	400	500	600	700
		(%)							
Spruce	100	26.5	14.8	4.6	2.5	1.0	0.4	0.2	0.1
Pine	120	41.1	26.3	10.2	6.0	3.0	1.4	0.8	0.3
Beech	140	25.7	22.5	12.9	9.5	5.2	4.1	2.9	1.8
Oak	160	21.8	17.1	14.4	12.0	10.7	8.9	7.1	5.7
Total forest		34.8	23.7	10.1	6.0	3.3	2.1	1.4	0.9

Root mean deviation from the steady state is computed according to Equation 11. Total forest area is calculated as area weighted average of species specific deviations.

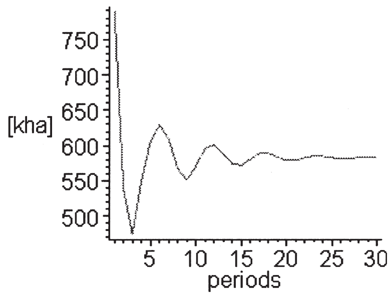

Fig. 4. Example convergence process towards steady state of the third age class area of spruce. 30 periods = 600 years, kha = 10^3 ha.

fact that the minor tree species groups not listed in Table 11 exhibit relatively higher deviations in the beginning. After 200 simulation years the *rmdev* measure for the total forest area has sunk to 10.1%.

It is important to note that the path to equilibrium oscillates around the steady state due to the fact that some eigenvalues are complex. Fig. 4 illustrates this behavior for the third age class area of spruce.

Rotation Ages

Varying rotation ages affects all output variables of ForCaBSiM. For illustrative purposes, we present simulation results for carbon storage and forest values for the three sets of rotation ages listed in Table 3 above. Table 8 compiles the carbon stock in the tree biomass between 1990 and 2150 for the three harvesting scenarios.

The simulation results in Table 8 are based on a most probable development path of forests in Germany. The following assumptions define this path and are valid in all three scenarios:

1) The tree species composition adjusts to the 'moderate ecological scenario' defined in Table 4.
2) The average area annually afforested continues the trend observed in recent decades. Accordingly, the forest area increases by half a million hectares over the next 100 years, amounting to an annual afforestation area of 5000 ha. The tree species composition on this new forest area is equal to the target percentages of the 'moderate ecological' path.

The changing tree species composition (until 2030) and the expanding forest area (until 2090) implies that the age class distribution begins to approach an equilibrium state only after 2090. In this regard, the results of Table 6 and Table 8 cannot be compared. Apart from this caveat, Table 8 shows that prolonging rotation ages increases carbon storage on average, while shortening rotation periods leads to decreasing carbon pool. It should be noted that, with respect to producing a constant stream of timber, all three variants are sustainable. This assessment might change, however, if stand risks or biodiversity are considered. The quantities of harvested timber are highest in the 'short' rotations scenario, and lowest in the scenario based on prolonged rotations (numbers are not shown here).

Alternatively, the dynamics of the carbon stock can be depicted by the dynamics of the annual uptake or release of carbon. These flow values are computed as the change in the carbon stock, that is the change of magnitude GS(s,n,t) in Equation 13 between two time points. Fig. 5 compares these magnitudes for the three harvesting sce-

Table 8. Carbon stored in tree biomass under three harvesting scenarios.

Rotation	Time 1990 (Mt C)	2010	2030	2050	2070	2090	2110	2130	2150
Common	865	998	1045	1039	1030	1046	1097	1152	1164
Long	865	1048	1129	1125	1099	1079	1105	1170	1222
Short	865	895	897	907	937	982	1022	1031	1007

Carbon stored in living tree biomass on the forest area of Germany under a most probable development path (moderate ecological tree species composition, annual afforestation of 5000 ha).

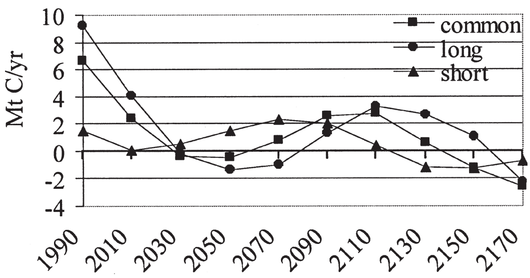

Fig. 5. Annual uptake and release of carbon in tree biomass under changing rotation ages.

narios in Table 8. Because the model is based on 20 year periods and all flow values are averages over these periods, the starting values in 1990 differ. (Only the values for the growing stock are based on a statistical survey in the base year, not any flow values.)

All of the scenario variants in Fig. 5 imply some release of carbon in later decades. The release is postponed into the distant future in the scenario with short rotation ages, while it occurs already after 2030 in the scenarios with common and long rotation periods. Comparing the latter two scenarios, the release is lower in the common scenario. Of course, these paths are far away from their corresponding steady states where there is neither carbon uptake nor release. The divergence of the three rotation scenarios can be explained by the fact that in the case of shorter rotations the share of strongly growing younger age classes increases much faster. Thus, the loss of carbon by harvesting (not considering carbon in wood products here) is compensated by higher annual increments. On the contrary, prolonging the final cuts in the case of long rotation periods implies a higher loss of carbon storage when harvesting becomes inevitable. The loss is then not compensated as easily by regenerated stands. In the long run, however, all paths begin to oscillate around the equilibrium state.

Of equal interest is the cumulated carbon sequestration in a given time period, that is the net carbon uptake in the period. The development of this magnitude in time periods beginning 1990 under the three harvesting scenarios is documented in Table 9. Despite the decreasing carbon stock between 2030 and 2110, the scenario based on prolonged rotation periods, cumulates the highest amount of carbon when compared to the two other alternatives, for any of the considered periods.

The relative economic performance of forestry development in these scenarios is documented in Table 10. It shows land expectations values for Germany as a whole and average values on a per hectare basis. Land expectation values in Table 10 are highest for the scenario with prolonged rotations at discount rates up to two percent. However, relative performance is slightly better for the common rotations at discount rates of three and four percent. This assessment remains valid even if land expectation values are negative for higher discount rates. In the latter cases, relative performance indicates lower losses. If a discount rate ranging between 1 and 2 percent is chosen as proper calculation measure, the prolonged scenario would bring the relatively best performance in terms of carbon sequestration as well as in terms of land value.

The results for individual tree species groups (not documented here) differ considerably from the figures in Table 10. Some coniferous species like spruce and Douglas fir fare much better, while the land expectation values of broadleaved stands are generally lower. It should be noted

Table 9. Cumulated carbon sequestration since 1990.

Scenario	2010	2030	2050	2070	Until 2090 (Mt C)	2110	2130	2150	2170
Common	132	180	174	165	181	232	287	299	274
Long	183	264	260	233	214	240	305	357	379
Short	30	32	42	72	117	157	166	143	117

Cumulated carbon sequestration under the three harvesting scenarios of Table 8. Compare with the annual sequestration rates in Fig. 5.

Table 10. Land expectation values in 1990 at three levels of rotation ages.

Rotation ages	Discount rates			
	1%	2%	3%	4%
Common, million EUR	78621	7381	–9485	–14182
per hectare, EUR	7896	741	–953	–1424
Long, million EUR	92963	8601	–9804	–14381
per hectare, EUR	9336	864	–985	–1444
Short, million EUR	37027	–1503	–11689	–14686
per hectare, EUR	3718	–151	–1174	–1475

Based on the tree species composition and the constant area of 1990; no variation about the rotation age; discount rates are to be interpreted as real rates.

Table 11. Carbon storage in tree biomass and tree species composition.

Rotation	Time (Mt C)								
	1990	2010	2030	2050	2070	2090	2110	2130	Steady state
Continuation	865	969	1023	1035	1017	1004	1018	1047	1023
Moderate	865	967	1007	999	977	980	1027	1080	983
Radical	865	963	1001	983	935	941	1019	1112	937

Results are based on the three scenarios defined in Table 4; steady state values refer to area shares after the new species composition has been realized. In contrast to Table 8, total area is constant.

that these land expectation values reflect economic returns on timber production alone. Forest values arising from non-timber services are not estimated.

Tree Species Composition

Three scenarios in which the composition of the tree species is varied were defined in Table 4. They consist in the 'continuation' of the tree species composition of 1990, in a 'moderate' and in a 'radical' ecological restructuring of the species proportions. Table 11 documents the results of these scenarios with regard to the carbon storage in the tree biomass.

For simulation periods of up to 100 years, it is evident in Table 11 that the higher the share of broadleaved trees the lower the storage of carbon. The 'moderate' and then the 'radical' ecological scenario exhibit higher carbon storage only after more than 100 years. This does not overturn the basic relationship, as can been seen from the steady state values in the last column of Table 11, where the tree species composition with the lowest share of broadleaves clearly dominates the other. This result is explained by the generally lower growth rates of broadleaved trees (compare Table 5 and Fig. 2), which is not compensated by the higher wood density.

From what has been said about the land expectation values of broadleaves, it is to be expected that a higher share of broadleaves implies a lower total land value. These respective results are not documented here.

9 Discussion

The model ForCaBSiM presented in this paper aims primarily at capturing the carbon balance in tree biomass of alternative forestry development scenarios and at evaluating these developments by means of the associated forest asset values. At the same time, it provides an instrument to assess the timber production potential. This section discusses model properties, the assessment of the results presented in the preceding section, and possibilities to improve and develop the model.

Biological Production and Carbon Dynamics

ForCaBSiM is based on the propagation of the age class structure of German forests into the future (section 3). Such a structure is an essential property of managed forests. The age class structure has profound and long-run effects on timber supply and carbon sequestration which is often overlooked in carbon balance studies (Böswald 1998, Maclaren et al. 1996, Price et al. 1996). Regularly harvested and managed forests, as is the case in Germany, which deviate from the associated age class distribution in the steady state may represent large sinks or sources of carbon dioxide. Many decades if not centuries are required to bring the forest area nearer to its equilibrium state. The fluctuations of the carbon storage observed in the data of Table 8 and 11 as well as in Fig. 5 reflect this changing age class structure. The main reason for this phenomenon lies in annual increments which are higher in younger than in older age classes.

Relying on the dynamics of age class forests is a strength in as far as it allows for long-run predictions on the basis of assuming plausible harvesting patterns. The same scheme is weak if mixed and uneven-aged stands or selection forests are to be analyzed. More than half of the stands in German forests are mixed stands. For this reason, the Federal Forest Inventory has introduced virtually pure stands which are also used in ForCaBSiM. It is difficult to assess the error made by this simplification. Selection forests which are not structured in age classes are excluded from the reference area of ForCaBSiM. As selection forests cover only about 2% of the forest territory in Germany, this exclusion does not bear heavily. However, the importance of selection forestry (and mixed stands) is expected to increase in the course of the next decades, so that this limitation will become more pronounced.

In this respect, using yield tables to predict biological growth, as it is done in this study, may be seen as a problem because yield tables assume even-aged and pure stands, while actual stands are often uneven-aged and mixed. Implementing growth mechanisms which react to changes in environmental conditions on the one hand, and which allow for more flexible thinning methods on the other hand, would certainly be desirable. Unfortunately, currently available models applicable to German conditions which model mixed stands, selection forestry and eco-physiological processes are mostly oriented at local sites and at a smaller range of species than studied here (compare, e.g. Pretzsch 1998). More research is necessary to adapt such models to large-scale modeling. Furthermore, one should not easily dismiss the internal consistency of traditional yield tables.

The time steps of 20 years implemented in the present version of ForCaBSiM are clearly too long, even considering the long-run horizon of the simulations. Reducing this intervals to five or even one year would increase the flexibility and usability of the model.

It is of course easy to point to other desirable extensions and improvements as, for example, the implementation of more regional detail and of a stochastic implementation of the major variables. More regional detail would probably not improve carbon accounting for Germany as a whole. Regionalization as well the explicit treatment of stand risks would, however, greatly improve the economic assessment. In this paper, steady state analysis is considered as a very useful complement to the analysis of the dynamic processes. It remains to be examined how this type of computations would be affected by implementing risk analysis into the model.

The biomass expansion factors used in Equation 18 are key parameters for the assessment of the carbon dynamics. They are necessary to expand merchantable timber to total tree volume. As is to be expected for any biological system, the factors used to perform these conversions are in reality bound to vary with site, species, stand age or tree part. Estimates in the literature vary by 50 and more percent. The average value in ForCaBSiM amounts to 1.49. IPCC (1996, vol. 2, 5.6) recommends the use of an average ratio of 1.9 for commercial forests. Kauppi et al. (1992) consider biomass expansion factors for European forests between 1.4 and 2.1. Our choice may thus be considered cautious in nature.

Tree biomass is not the only relevant carbon pool in forests. It would be highly desirable to integrate dynamic models of other pools, in particular soil carbon, into the model.

Forest Valuation

Forest valuation has been introduced into ForCaBSiM as a means to assess the economic performance of various development scenarios. At present, this assessment is confined to the costs and revenues of timber production. Since forests provide many other services than timber, it is of great interest to value these services in monetary terms. The benefits of ecological, recreational, protective or climatic services of forests are, however, difficult to assess because so far no markets exist for such services. Valuation of non-market benefits requires a distinctly different approach than the one applied in this study (Bergen et al. 1993; Hampicke and Schäfer 1997). For this reason, this issue is not pursued at this point. However, the present work provides the basis of estimating the cost of carbon sequestration.

Similar to the shortcomings mentioned with regard to the mapping of biological production into the model, one can find limitations with regard to the present implementation of the economic assessment. For example, prices are fixed and do not react to the volumes of timber brought to the market. No doubt, this is not realistic in a market of primary goods where prices usually fluctuate much more than on markets for industrial goods. That alternative land uses are not considered may also be considered as problematic. This objection is, however, less worrying because in a country as Germany afforestation as well as deforestation are strictly regulated by law. In contrast to markets for timber, which are basically unregulated, this is not the case for forest land markets.

As has been shown in Table 10, land expectation values vary considerably with rotation ages. This begs the question of which is the set of optimal rotation periods given a certain discount rate.

Model Uses and Policy Support

The model presented in this paper serves several purposes, and it may be used to support policy decision processes. Some of these shall be considered here.

ForCaBSiM may support the reporting obligations of the *Parties to the United Nations Framework Convention on Climate Change* agreed upon in the *Kyoto Protocol* in 1997. There, each party is asked to provide data about the emission levels in 1990 and their changes in subsequent years, to establish the level of carbon stocks in biological reservoirs in 1990, and to estimate changes to be expected in carbon reservoirs in subsequent years. Our study underlines the fundamental role of harvesting and silvicultural practices for the development of the national carbon balance. For example, it can be recognized that there exists a not well known trade-off between the ecological objective to increase the share of broadleaved stands and the aim to enhance forest sinks (Table 11).

Forest assets represent a component of the national wealth, and as such they are considered an integral element in the balance sheet of the national economy. In the European System of Accounts - ESA 1995 (EC 1996, 127–144), which has legal status for the member states of the European Union, forest assets are subdivided into land and the stock of standing timber, as it is done in ForCaBSiM. Valuation of nonmature timber stocks in our model complies fully with the rules laid down in ESA 1995. As far as the valuation of bare land is concerned, ESA 1995 states that current market prices should be applied. The procedure followed here deviates from this rule in that the value of forest land is established with regard to the economic results of timber production alone. Observed market prices of forest land deviate to a significant degree from the land expectation values. This fact may be interpreted such that timber production is only one of several factors determining the prices of forest land. Preferences expressing prestige, family tradition, amenities or recreational needs play important roles in the price formation of forest land as well. These factors are not considered in this study. One should though bear in mind that timber production is still the primary financial basis of forest management. The land expectation values calculated here are indicators of this financial resource, and thus of the economic viability of forest management under the present economic and political conditions. They should be taken into account in national balance sheets as well. Thus, apart from climate policy issues, ForCaB-SiM may support the realization and interpretation of the forest component in national balance sheets by stressing the effects of assumptions on harvesting and silvicultural practices on the value of forest assets.

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