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Modelling the conversion from even-aged to uneven-aged stands of Norway spruce (Picea abies L. Karst.) with a distance-dependent growth simulator

Marc Hanewinkel[a,*], Hans Pretzsch[b]

[a]*Institute of Forestry Economics, University of Freiburg, Tennenbacherstr. 4, 79106 Freiburg, Germany*
[b]*Chair of Forest Yield Science, University of Munich, Am Hochanger 13, 85354 Freising, Germany*

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Abstract

The paper provides a conversion regime from even-aged to uneven-aged stands of Norway spruce (Picea abies L. Karst.). The conversion regime was tested by the distance-dependent single-tree simulator SILVA 2.1. The initial data for the simulation and the assumed site productivity were deduced using inventory data of the north Black Forest. The conversion regime was compared to a typical future-tree oriented age–class treatment system. Thereby four variants of the conversion regime, differing in the number and diameter of the 'regeneration-funnels' (gaps in the canopy of the stand) which were created during the 'graded-regeneration-phase', were compared to a basal-area oriented future-tree age–class treatment. A simulation-run of 110 years — divided into 22 periods of five years — was conducted. The analysis of the simulation-run showed that the possibilities to achieve uneven-aged structures in single-layered, even-aged stands through 'structuring measures' during thinning or target–diameter harvesting were very limited. The success of the conversion depended mainly on the success of the regeneration during the conversion. The early creation of 'regeneration-funnels' was linked to severe losses in increment and standing volume. As well as influences on different stand-parameters (e.g. stem-distribution) changes in structure-parameters caused by the conversion could be assessed. In particular, the modified Shannon-index did react distinctly to the implementation of the natural regeneration in the regeneration-funnels. Indeed, a steady state was only temporarily reached with the variant with the largest gaps. Finally, the results of the conversion experiment were subject to a critical review. Thus, the limits of the model in its current version and further research needs were discussed.

Keywords: Picea abies L. Karst.; Growth simulator; Conversion; Uneven-aged forest

1. Introduction

The forests of the south-west of Germany are largely dominated by pure even-aged stands, with the coniferous forests mainly composed of Norway spruce (Picea abies L. Karst.). The management of these forests has proven to be difficult in many aspects, the small timber issued from thinnings of the young stands is hardly merchantable and the management of the older stands is highly risk-influenced. As the result of windfall in 1990, in some areas of South Germany more than 200% of the usual annual cut was blown down, of which 80% was Norway spruce. Especially in the montane areas (between 600 and 1000 m a.s.l.)

* Corresponding author. Tel.: +49-761-203-3686;
fax +49-761-203-3690.
E-mail address: hanewink@uni-freiburg.de (M. Hanewinkel)

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of the Black Forest region, a long tradition of single tree selective cutting shows that the management of uneven-aged, highly structured forests can be economically as well as ecologically successful (Hanewinkel, 1998b).

As a reaction to the unsatisfactory economic and ecological situation of even-aged forest management, the State Forest Service has introduced close to nature forestry which provides species enrichment and other ecological benefits through the conversion of even-aged into multi-layered uneven-aged forest stands. Consequently, the percentage of public forests managed outside the age–class system (permanent forests and forests in the state of conversion into permanent forests) has risen in the last decade from 0.6% to 3.2 % (Forest Management Statistics, 1990/1995). However, only little is known about the long term economic consequences of such a conversion on large areas. Also the conversion regime has not been elaborated or tested on a scientific basis.

The present investigation provides a first approach to converting even-aged stands of Norway spruce into uneven-aged stands. The concept was tested with the single tree-, distance-dependent growth simulator SILVA 2.1 (Pretzsch, 1992; Pretzsch and Kahn, 1996). The purpose of the present investigation is to give an impression of how a conversion-cycle could look and which different phases are passed during the process. The important factors for the success of the conversion ('structuring measures' during thinning, regeneration) and parameters to control the conversion (standing volume, stem-distribution, structural parameters) will be identified and discussed. It will be shown how a conversion regime can be programmed for the simulator. The limits and restrictions of the growth model for simulating conversion processes will be stated and analysed.

Four variants of the conversion regime, differing in the size and the number of regeneration gaps established during the conversion, are implemented into the simulator in order to analyse them in comparison to a typical age–class management system. Differences between the conversion and the age–class treatment will be elaborated. It will be determined whether a steady state status for a permanent forest can be reached with one of the conversion variants.

2. Methods

2.1. The conversion regime

The conversion regime used in this investigation is divided into three phases (Hanewinkel, 1996). These phases and their silvicultural meaning are briefly described here:

1. Phase of stabilization and selective thinning.
2. Phase of quality improvement cut and graded regeneration.
3. Phase of variable target diameter harvest.

- *Stabilization and selective thinning.*
  Starting at a dominant height (h_{100}) of 13 m, 150 future crop trees are selected and strongly favoured. The selective thinning ends at a h_{100} between 20 and 25 m depending on the quality of the site. After that, there is no more selective thinning, leading to a complete regular coverage of the stand area with equally dimensioned future trees.
- *Quality improvement cut and graded regeneration.*
  In this phase a quality improvement cut (the cutting of few dominant or co-dominant trees of bad timber quality) and graded regeneration in already existing gaps for natural regeneration, or advanced planting takes place. Graded means that a maximum of 1 or 2 spatially separated 'regeneration-funnels' (gaps) or advanced plantation groups per decade are created. Ideally, the installation of the regeneration funnels takes place by cutting 2 or 3 neighbouring dominant or co-dominant trees with visible damage or low timber quality.
- *Variable target diameter harvest.*
  In order to guarantee a long phase of single tree harvesting and thereby a vertical differentiation within the stand, the third phase of the conversion takes place as a variable target diameter harvest, in which the target diameter is smaller at the beginning and rises with the duration of the conversion period. The diameter of the harvested trees may be 50 cm at the beginning — depending on the site index; at the end of the conversion it may be 65, 70 cm or even more.

2.2. Initial state of the conversion

Fig. 1 shows the stem distribution of a fictional pure stand of Norway spruce (Picea abies L. Karst.)

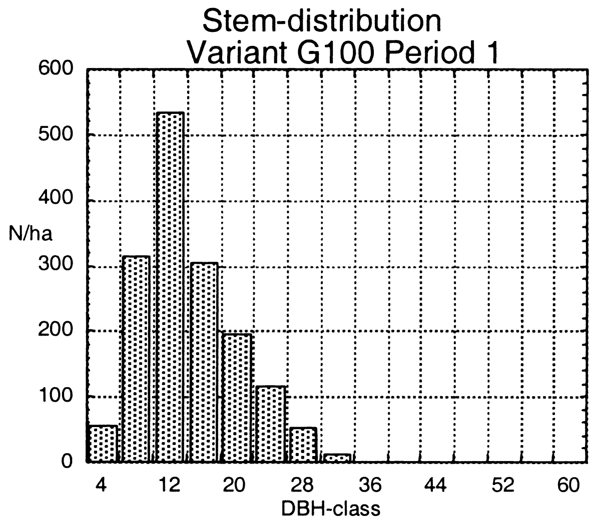

Fig. 1. Stem-distribution (N/ha for DBH-classes). Initial stand (identical for all variants).

representing the initial state for the conversion. This typical spruce stand has been constructed using the results of permanent inventory plots in the Black Forest area (Baden-Württemberg, South-West Germany). These permanent plots are taken during regular forest management in larger forest enterprises of the public forest of the Black Forest area. The stem distribution has a clear tail to the right and shows a wide diameter range resulting from the age class between 20 and 40 years with a mean age of 30 years. The number of stems is 1568/ha with a basal area of 29 m^2/ha and a standing volume of 200 m^3/ha. At the end of the first simulation period of five years, the mean diameter (d_m) is 16.4 cm and the mean height is 14.4 m. The average h/d — ratio is 88. The h/d value of the dominant (100 biggest) trees is 61 ($d_{100} = 27.1$ cm; $h_{100} = 16.4$ m).

As the individual positions of the single trees could not be completely determined from the inventory data, the positions of the trees were generated with the structure generator STRUGEN (Pretzsch, 1993) implemented in the growth simulator SILVA 2.1. After analysing the aggregation index of Clark and Evans (1954) for different distribution patterns (regular, random, clustered) and comparison with trial and inventory plots, the initial state was fixed for a regular to random distribution pattern at a Clark and Evans index value of 1.15.

2.3. Comparison scale — age–class forestry

The question of whether a certain strategy is useful from a sylvicultural or economic point of view can never be answered absolutely, so other action alternatives need to be considered. Modern age–class treatments for Norway spruce stands usually start with a future-tree orientated *selective thinning* (Abetz, 1975; Klädtke, 1992), where between 250 and 300 future trees are selected and released. In the classical treatment-cycle, a *low thinning* follows, where every tree that is not selected to form the final stand is removed. In the following phase, where no interventions are executed, the standing volume — and the financial capital — is accumulated until the trees have reached the desired target diameter. These trees are then harvested through final cutting in a more or less extended regeneration period which can, but need not necessarily, include a clearcut.

Fig. 2 shows how a typical age–class treatment looks compared to the above-mentioned conversion regime.

2.4. The growth model

2.4.1. Description of the simulation model and restrictions for the investigation

There is only one growth simulator that can be used to model such complex processes as conversions in South-West Germany: the distance dependent single tree growth model SILVA, developed by Pretzsch et al. (Pretzsch, 1992; Pretzsch and Kahn, 1995; Kahn and Pretzsch, 1997). The model version 2.1, used in this investigation, was parametrized and calibrated for pure and mixed stands of Norway spruce and beech (Fagus sylvatica) based on 139 lots of 31 long term trial plots in Bavaria (South Germany) with more than 37,000 measurements for Norway spruce (Kahn and Pretzsch, 1997, p. 115).

The position-dependent individual tree model SILVA 2.* can be used for pure and mixed stands of all age combinations. Primarily, it is designed to assist in the decision making processes in forest management. Based on scenario calculations, SILVA 2.* is able to predict the effects of site conditions, silvicultural treatment, and stand structure on stand development, and therefore also serves as a research instrument. To explain the incorporation of a program

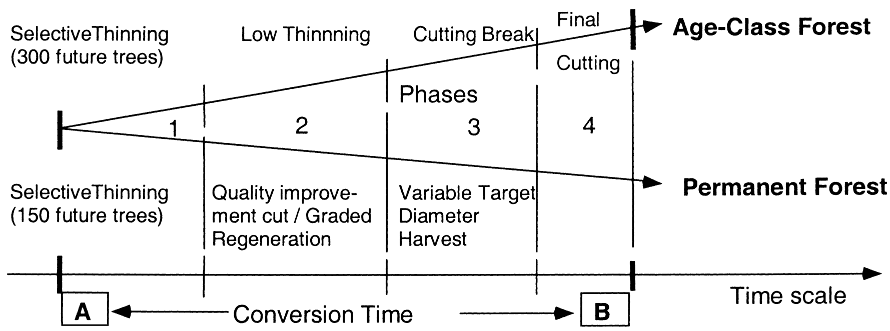

Fig. 2. Scheme of the conversion from even-aged to uneven-aged forests and a possible alternative (age–class forestry). Phases 1–4 = phases of the conversion (resp. Age–class treatment). A = beginning, B = end of the conversion.

routine which permits structural analyses, a representation of the essential elements of SILVA 2.* is provided in Fig. 3. For details on the model see Pretzsch (1992), Kahn and Pretzsch (1997) and Kahn (1995).

The first model element reflects the relationship between site conditions and growth potential and aims

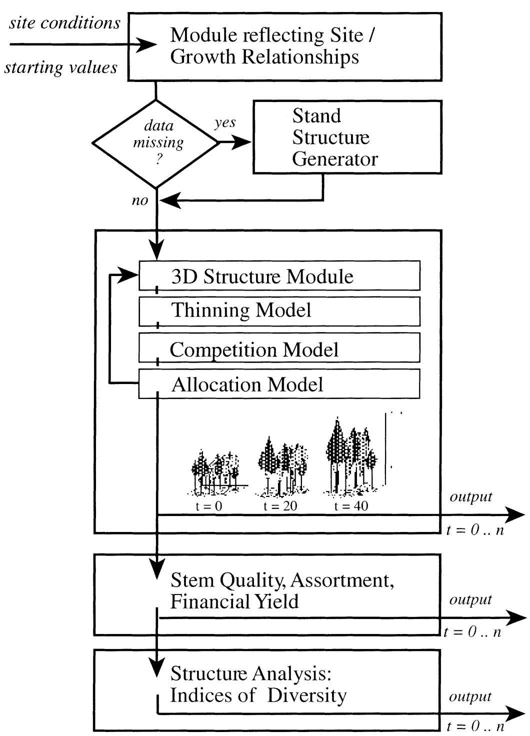

Fig. 3. The stand growth model SILVA 2.* with the program module for structural analysis.

at adapting the increment functions in the model to actual, observed site conditions. With the aid of nine site factors reflecting nutritional, water, and temperature conditions, the parameters of the growth functions are determined in a two-stage process (Kahn, 1994). Thereby, the growth functions can be individually adjusted to the specific site conditions. For the present investigation, a widespread site type (sandy-loamy plain sites) of the North West Black Forest with medium soil humidity was chosen. The growth potential of the model was adjusted and refined using 3300 height measurements on dominant trees of Norway spruce from the above-mentioned inventory plots to characterize the height growth potential.

The stand structure generator STRUGEN facilitates the large-scale use of position-dependent individual tree growth models. The generator converts verbal characterizations commonly used in forestry practice (e.g. mixture in small clusters, single tree mixture, row mixture) into a concrete initial stand structure with which the growth model can subsequently commence its forecasting run (Pretzsch, 1997).The three-dimensional structure model uses tree attributes such as stem position, tree height, diameter, crown length, crown diameter, and species-related crown form models to construct a three-dimensional stand structure model. The generated three-dimensional model of the observed stand supplies the basis for the derivation of structural indices. The thinning model is also individual tree based and can model a wide spectrum of treatment programs. The core of the thinning model is a fuzzy logic controller (Kahn, 1995). In the simulation studies described below the thinning model simulates various thinning methods (thinning from below and selective thinning) and intensities (slight, moderate, and heavy). The competition model employs the light–cone method (Kahn and Pretzsch, 1997) and calculates a competition index for every tree on the basis of the three-dimensional stand model. The allocation model controls the development of individual stand elements. Tree diameter at 1.30 m, tree height, crown diameter, height of crown base, crown shape, and survival status are controlled at five year intervals, in relation to site conditions, interspecific, and intraspecific competition. Finally, classical yield information on the stand and single tree level for the prognosis period are compiled in listings and graphs. Additional information on stem quality, yield, and financial return is produced.

At every stage of the simulation, a program routine for structural analysis calculates a vector of structural indices which serve as indicators for habitat and species diversity. Based on the three-dimensional structural model, structural indices, i.e. the horizontal tree distribution pattern index (*R*; Clark and Evans, 1954), the vertical species profile index (*A*; modified Shannon-index — see Section 3.2.2) and the intermingling index (*S*; Pielou, 1977), which form a link with the ecological assessment of forest stands, can be calculated. The different steps of the algorithmic sequence for predicting forest development with Silva 2.* are described in Fig. 3.

The growth model cannot represent the installation and growth of natural regeneration (distribution of seeds, germination, growth under canopy). Thus, a pragmatic approach to simulate a regeneration process was chosen. A long term natural regeneration process leading to an uneven-aged stand, cannot be simulated with the model version used in this investigation.

2.4.2. Programming the conversion regime for the simulator

Table 1 shows how the different phases of the conversion were realized in the simulator. The first phase was modelled as a future tree orientated selective thinning (referred to as 'selective thinning') with 150 future trees per ha. The selective thinning was an '*A*-value orientated thinning' using the *A*-value after Johann (1982) as a steering parameter. The *A*-value defines the intensity of competition of a central tree due to a defined neighbour by means of measured data (distance of the trees, height, and diameter). The factor *A* is a proportionality factor fixing the intensity of thinning (formula 1, Hasenauer et al., 1996, p.169):

$$E_{i,j} \leq \frac{H_j}{A} \cdot \frac{d_i}{D_j}, \qquad (1)$$

Table 1
Programming the conversion regime for the growth simulator Silva 2.1

Procedure	Action	Control-parameter	Units
Selective thinning	$h_0 < 20$ m: 150 future crop trees favoured using the *A*-value	*A*-Value	4
		N future crop trees	150/ha
Quality improvement cut	$h_0 > 20$ m: a number of dominant trees eliminated using the *A*-value	*A*-value	6
		N selected trees	300/ha
Graded regeneration			
(a) Installing gaps	$h_0 > 22$ m: every ten years a gap is installed and positioned	Diameter of gaps	30–44 m
		N of gaps	3–5/ha
(b) Establishing regeneration	Ten years after the installation of the gap 2000 Norway spruce per ha with $h_m = 3$ m and $d_m = 3.5$ cm are 'planted'	Height/diameter (d_m) of regeneration	3 (3.5)
		Number of plants	2000/ha
Variable target diameter harvest	$h_0 > 30$ m: a defined percentage of trees that has reached the fixed target diameter is cut	Target diameter	45–50 cm
		Maximum cutting rate	20–30%

where $E_{i,j}$ is the distance of tree i to j; H_j and D_j the height and diameter of central tree j; and d_i is the diameter of neighbour tree i.

The smaller the value of A, the more intensive the thinning and more space to grow will be given to the selected future trees. The A-value for the phase of stabilization and selective thinning was fixed at 4, representing an intensive thinning. The *phase of quality improvement cut* was modelled in a similar way with a lower intensity of thinning (A-value = 6) and a higher number of future trees (300 ha^{-1}). The prescriptions for the *graded regeneration phase* are stated in detail in Table 1. The gaps were positioned at a maximum distance from each other without being at the borders of the simulation area. The 'plantation' of Norway spruce regeneration took place ten years after the installation of the gap. It was assumed that the spruce would have reached a mean height of 3 m (which implies an annual height increment of 30 cm) and a mean *dbh* of 3.5 cm within these first ten years. The regeneration activity was preliminary restricted to the area of gaps. Hence, after 18 simulation periods the complete area of the simulation plot of 1 ha was 'planted' with 2000 Norway spruce per ha, simulating a regeneration 'wave' (see Table 2). The *variable target diameter harvest* was based on the diameter of the hundred dominant trees (d_{100}). The target diameter was raised from 45 to 50 cm and the maximum cutting rate of the trees having achieved the target diameter was raised from 20% to 30% after 4 periods of simulation. The trees were randomly selected. Following the principle pattern described here, four variants of conversion, differing in number and size of regeneration gaps, were modelled.

2.5. The conversion variants and the age class model

Table 2 shows the different variants of the conversion process with the respective measures in the

Table 2
The different treatment variants of the conversion regime and the age–class model

Period (Age)	h_{100}	Conversion Variants				Age-class Model
	(ca.)	L30	L35	L44	ZDE	G100
1 (30)	16,4	Selective Thinning				Selective Thinning Basal Area orientated
2						
3	20,3					
4 (45)	22	Quality improvement cut /Graded Regeneration				Low Thinning
		Gap 1 Ø = 30 m ↓	Ø = 35 m ↓	Ø = 44 m ↓		
5						Basal Area orientated
6 (55)		Gap 2				
7						
8 (60)		Gap 3				Cutting break
9 (70)	30					
10 (75)	31	Target Diameter Harvest (TDH) 45 cm (20%)				
		Gap 4				
11						
12		Gap 5				
13						TDH 52cm
14 (95)	35	Target Diameter Harvest (TDH) 50 cm (30%)				
↓	↓					
18 (115)		Complete Regeneration N = 2000 /ha				
22 (135)	38,8					Final Cutting
23 (140)		End of Simulation				

different periods of the simulation compared to the age–class treatment program.

A time period of 110 years, divided into 22 periods of five years, was simulated. The four conversion variants differed in the intensity of admitted light during the phase of graded regeneration. The size of the established light funnels varied from 30 m diameter (700 m^2 — variant "L30") to 35 m (960 m^2 — variant "L35") and 44 m (1500 m^2 — variant "L44"). With the variant "LZDE" (only target diameter harvest), no regeneration gap was established. The variant L30 provided five light funnels in simulation periods 4, 6, 8, 10 and 12; the variants L35 and L44 had only 3. The preliminary area cut for regeneration funnels was 3500 m^2 for the variant L35, 3000 m^2 for L35 and 4500 m^2 for the variant L44. The number of spruce 'planted' ten years after establishing the regeneration gaps varied from 140 (L30) to 300 (L44) per gap.

The age class model (G100) provided a classical treatment cycle as described in Section 2.3. The treatment program was formulated and modelled following guidelines for basal areas (the development of the stand follows a curve, giving a basal area which is dependent on the dominant height) suggested for practical management of Norway spruce stands in South West Germany (Forest Management Guidelines, Baden-Wüerttemberg; Hilfstabellen, 1993). Selective thinning (until 20 m h_0) and low thinning (until $h_0 = 26$ m) followed these basal area prescriptions. After a cutting break (26–34 m h_0) the harvesting began with target diameter harvest at 52 cm *dbh*, thus providing a long regeneration cycle. Final cutting (clearcut) in this modified age class regime took place at 38.8 m h_0.

3. Results

3.1. The progression of the conversion with variant "L35"

The initial hypothesis in developing the conversion regime was that the success of the conversion — the approach to a steady state status for a selection forest — depends on the effect of 'structuring' in phase 1 and 2 of the conversion and on the ability of the regeneration to survive under different light conditions. In the following, the success of the conversion in different phases is examined with the example of the conversion variant "L35". Fig. 4 shows the stem distribution of variant L35 at the age of 60 after six simulation periods (30 years).

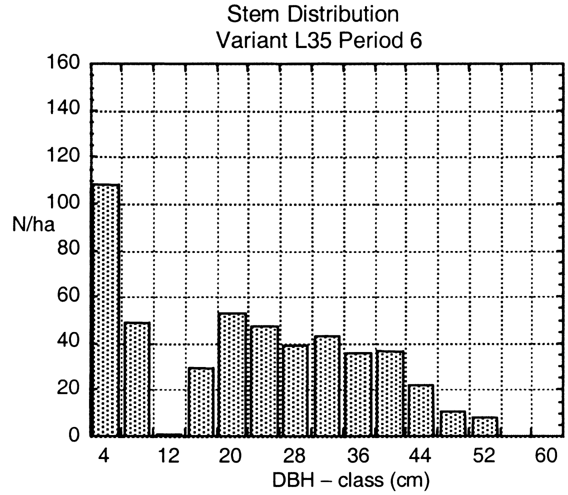

Fig. 4. Stem-distribution (N/ha), variant L35, period 6.

The stem distribution is divided into two parts: the two isolated columns on the left are the new regeneration (around 160 trees per ha). The stem distribution of the initial stand is widely spread, more than 80 stems of the initial stand with a diameter of 20 cm and less have survived the first six simulation periods. The effect of the conversion measures to preserve smaller trees (avoidance of low thinning, ongoing selective thinning) is visible.

Already at this point, the development of the regeneration is decisive for the formation of a selection forest stem-distribution. Here, too few stems are below 20 cm to replace, in the long run, the stems eliminated by mortality or exploitation. A steady state can only be reached if the stem distribution is completed in the smaller diameter classes by newly recruited stems. The success of the conversion directly depends on the survival of the regeneration and sufficient ingrowth. From Fig. 5 it seems, that this process of ingrowth of smaller stems into larger diameter classes does not run continuously.

Fig. 5 shows the stand in a vertical view after 50 years of simulation at the age of 80. Three regeneration funnels are established, and regeneration

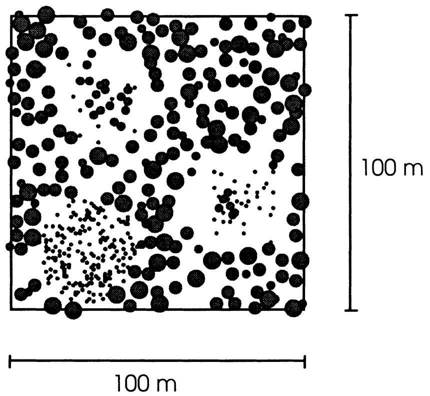

Fig. 5. Vertical view of the stand, variant L35, period 10.

is occurring. In the first gap the major part of the regeneration has already disappeared. The competition conditions for the young spruce plants are obviously so unfavourable that there is hardly a chance to survive, especially at the borders of the gaps. Only in the center of the regeneration funnel were some spruce able to grow into larger dimensions. This process is more obvious in newer gaps.

In the 12th period, at an age of 90 years this development can be distinctly seen in the stem distribution (Fig. 6). Mortality has removed the biggest part of the spruce regeneration in the last established regeneration funnel. At a standing volume of 360 m^3/ha an ingrowth of at least 80 stems per period would be necessary to compensate the loss due to mortality in the smallest diameter classes (4–12 cm) and to generate a steady state condition. As the ingrowth is lacking, the number of stems decreases from the 12th to the 17th simulation period from 300 to 150 ha^{-1}. The complete regeneration in the 18th period can only temporarily change this status. Consequently, conversion with the variant L35 of the concept fails due to a lack of ingrowth. The stem distributions of the other conversion variants will be examined in Sections 3.2.3 and 3.3.

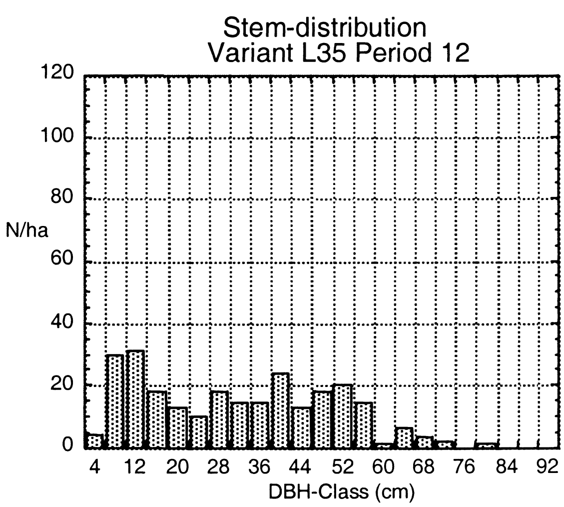

Fig. 6. Stem-distribution (N/ha), variant L35, period 12.

3.2. The different conversion variants compared to the age class treatment

3.2.1. Development of standing volume and volume increment

Fig. 7 shows the development of the standing volume of the different conversion variants during the simulation run. After the first intervention in the first period all variants start at a very low standing volume of 130 m^3/ha. The development of the standing volume is identical until the 3rd simulation period. From the 4th simulation period the gaps in variants

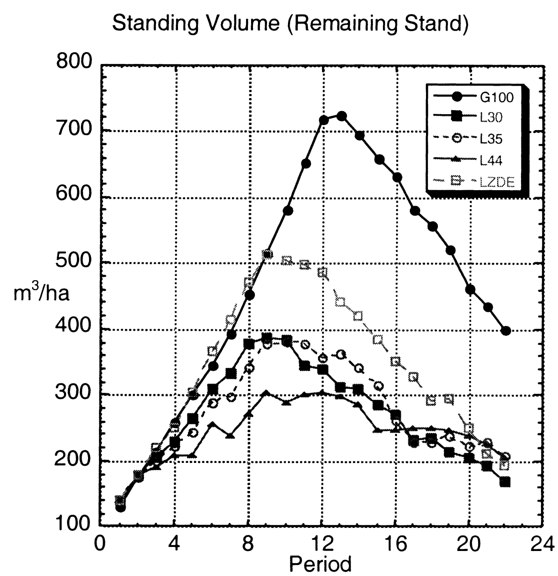

Fig. 7. Development of the standing volume (remaining stand) for the conversion variants L35-LZDE and the age class model (G100).

L30 to L44 are taking effect. The standing volume of these variants is decreasing from that time compared to the age–class treatment and the variant LZDE (pure target diameter harvest). The maximum standing volume of the age–class treatment (variant G100) is reached with 725 m^3/ha in the 13th simulation period. After that a further accumulation of standing volume is interrupted by a target diameter harvest. In the LZDE variant the decrease in the standing volume starts with the 10th period. The maximum here is around 500 m^3/ha. The conversion strategies L30 and L35 reach their maximum standing volume of 400 m^3/ha in the 9th period, while the standing volume of the extreme variant L44 never exceeds 300 m^3/ha. Here, the level of the standing volume is kept stable for a longer period (between the 9th and 14th simulation period).

Fig. 8 shows the progression of the mean total volume increment (in m^3 per ha per year). The volume increment of the age–class treatment G100 culminates after 15 simulation periods at the age of 100 years at 12.4 m^3/ha/yr. The culmination of the LZDE variant is earlier (13th period) and slightly lower (12.2 m^3/ha/yr). Due to the early target diameter harvest, the total volume increment of the LZDE variant is higher than the G100 variant until the 12th period, but then drops distinctly below it. Variants L30 and L35 reach a maximum of 11 m^3/ha/yr. The lowest total volume increment is found in the L44 variant with constantly less than 10 m^3/ha/yr — which again has a long phase of stability with only small fluctuations between the 7th and 15th period.

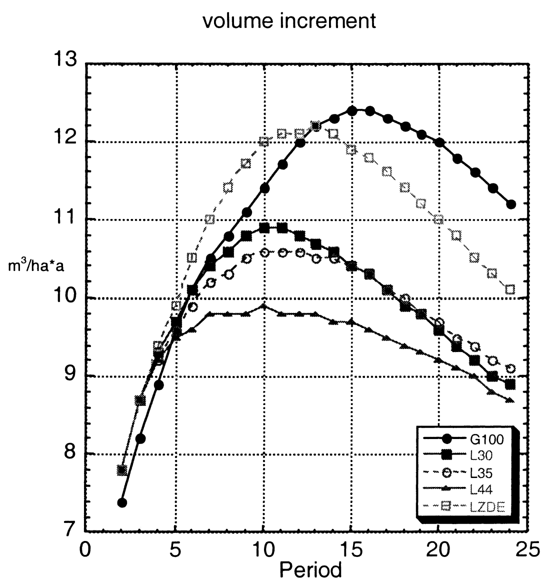

Fig. 8. Development of the mean total volume increment for the conversion variants compared to the age class model (G100).

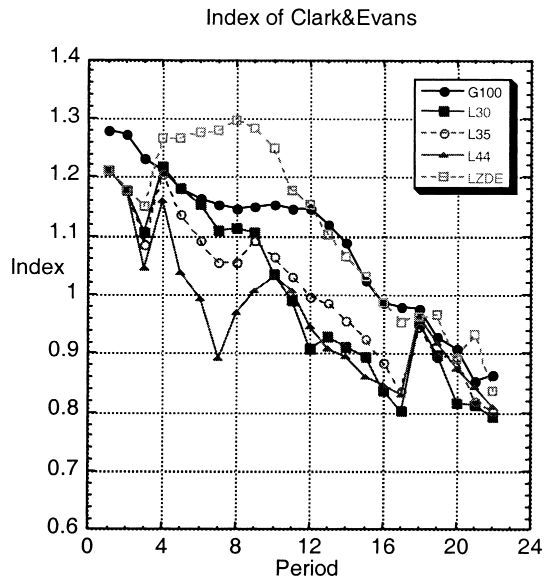

Fig. 9. Development of the index R — Clark and Evans — for the conversion variants compared to the age–class model.

3.2.2. Development of the structure parameters

Interesting structure parameters provided by the growth model Silva 2.1 are the horizontal tree distribution pattern index R (aggregation index after Clark and Evans, 1954, Fig. 9) and the modified Shannon-index A for the vertical species profile (Fig. 10). The starting conditions for the index R are identical for all variants. Until the 4th period the conversion scenarios are very similar. The index R shows, with a value of 1.2, a tendency towards a regular distribution as fixed for the starting values. This tendency is enforced in the variants LZDE and G100, while the installation of regeneration funnels at the variants L30 to L44 leads to a distinct decrease of the R values towards a random distribution (values around 1.0) and in the further progression of the simulation towards a clustered distribution (values below 0.9). For the variant L44, the R index oscillates

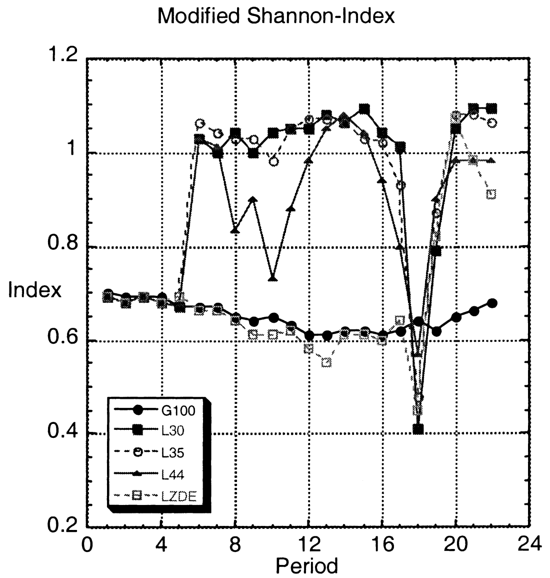

Fig. 10. Development of the modified Shannon-index for the conversion variants compared to the age–class model (G100).

around 0.9 and 1.0 between the 7th and 11th simulation period, a value that can be found in uneven-aged forests (Pretzsch, 1996, p. 214).

A more distinct influence of the different treatment variants shows the development of the modified Shannon-index. The modified Shannon-index for the vertical species distribution used in this study considers species portions separately for three height zones ranging from 0% to 50%, 50–80% and 80–100% of maximum stand height:

$$A = -\sum_{i=1}^{S}\sum_{j=1}^{Z} p_{ij} \cdot \ln p_{ij}, \tag{2}$$

where S is the number of species, Z the number of height zones (three in this case), p_{ij} the species proportions in the zones ($p_{ij} = n_{ij}/N$), n_{ij} the frequency of species i in zone j, and N is the total number of individuals.

Index A summarizes and quantifies species diversity and the vertical distribution of species in the stand. While the index is lowest in one-storied pure stands, it rises for pure stands with two or more layers. A mixture of several species effectively raises the index and peak values are reached in mixed stands with heterogenous structures. Every deviation from the one-storied pure stand is reflected in a distinct rise in species profile index A.

Fig. 10 shows the development of the index for the different conversion variants and the age–class treatment. All treatment variants start with the same — single layered — initial status, characterized by a rather low index value of 0.7. The segregation index (intermingling index S) of Pielou (1977) is constant at 1.0 for the whole simulation run with every variant. The modified Shannon-index for the vertical species profile barely changes in the phase of stabilization/selective thinning. The left skewed stem-distribution at the end of simulation period 3 (see Fig. 11) has not lead to a vertical differentiation. This changes in the conversion variants with the installation of the regeneration

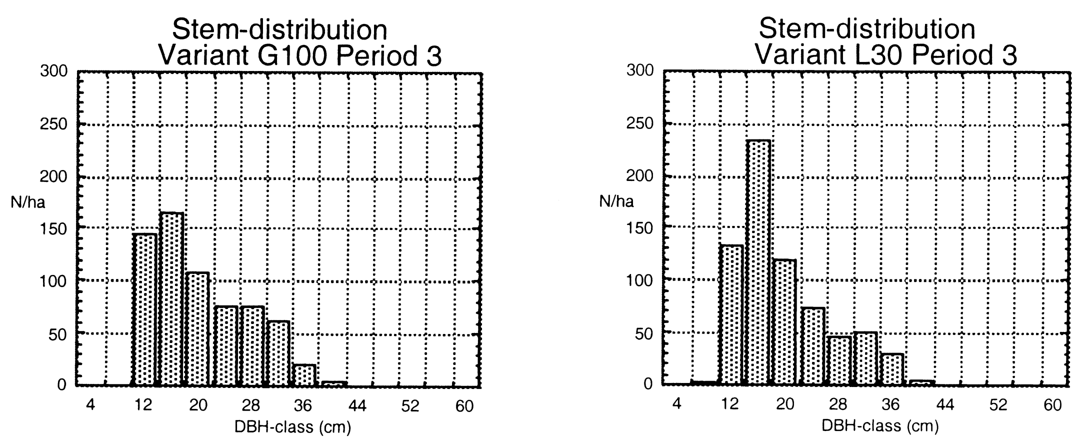

Fig. 11. Stem-distribution (N/ha) variant G100/L30, period 3.

gaps. While the index stays almost constant in the age–class variant G100 and the LZDE variant, it rises distinctly at the variants L30 to L44 and reaches values of more than 1.0 compared to 0.6 or 0.7 for the single layered variants. It is remarkable that the big gaps at the variant L44 are recognized as a homogeneous understory, which leads to a decline of the index between the 8th and 14th simulation period. This appears to be very obvious by the regeneration 'wave' in the 18th period. The modified Shannon-index sinks to a level below the age–class treatment. This obviously unrealistic disturbance is repaired with the beginning of mortality. However, the index for the LZDE variant stays on a distinctly higher level than before due to surviving trees from the regeneration in the understory.

3.2.3. Stem distribution development

The development of the stem distribution for the different treatment variants was analysed in a comparison of the variants L30, L44, LZDE and G100.

Fig. 11 shows the stem distribution of the age–class treatment G100 (Fig. 11 left) and of variant L30 (Fig. 11 right) after the 3rd simulation period (phase of selective thinning). The stem distributions of the conversion variants L35, L44 and LZDE are more or less identical to L30 until this period due to the identical treatment program. Variant L30 shows clearly a left skewed distribution with 150 dominant trees in the large diameter classes and a high number of stems in the 16 cm diameter class. It is clear that many more small trees in the diameter classes 12–20 cm (around 480) have survived due to the intensive thinning concentrated on fewer future trees in the conversion variants than in the age class treatment with 300 future trees (around 400 trees in the diameter classes 12–20 cm). Nevertheless, both stem distributions in Fig. 11 are rather similar.

The stem distributions of the variants L30 and L44 differ distinctly from those of the variants LZDE and G100 between the 4th and the 14th simulation period. They are characterized by the regeneration in the different regeneration gaps. A large part of this regeneration disappears immediately after the installation in variant L30. The size of the gap is decisive for the survival of the regeneration. Most of the young trees survive in variant L44, where e.g. around 40 trees have grown into the 12 cm diameter class in the 8th simulation period (while less than 10 in variant L30). The 'gap' in the stem-distribution between the initial stand and the new ingrowth (see Fig. 4) is not as big as with the variants L30 and L35. Both variants LZDE and G100 show a typical stem-distribution of age class forests. A two-peak stem distribution is visible in the variant LZDE.

In period 14 (target diameter harvest — Fig. 12) 100 young trees occur in the last regeneration gap in variant L30 (Fig. 12 down left) which disappear rather quickly due to the small size of the gap. Almost none of these trees reach the 12 cm class. In variant L44 (Fig. 13 down right) the lack of regeneration is shown in the small number of stems in the 4 and 8 cm diameter class. However, 36 trees in the 12 cm diameter class and 44 stems in the 16 cm diameter class have survived, giving the curve an inverse J-shape. It can be proposed that, with sufficient ingrowth, an uneven aged status could be reached with that conversion variant (see Fig. 13). Variants LZDE and G100 (Fig. 12 top left and right) have very similar stem distributions except for the distinct peak in the 44 cm diameter class of the variant G 100.

3.3. Approach to a steady state status in the variant L44

Fig. 13 shows how variant L44 approaches a possible steady state curve in the simulation run after the 9th period. The curve corresponds to a steady state condition for uneven-aged stands of Norway spruce, which could be reached in the long run (Prodan, 1944). With 400 stems per ha and a standing volume of 300 m^3/ha a steady state condition is reached with an ingrowth of at least ten stems per year into the 8 cm diameter class. In the simulation run this ingrowth disappears after the 13th period due to the lack of a regeneration module in the growth model. The ingrowth could be possible with constant natural regeneration. It is striking how the 'gap' in the stem distribution between 12 and 20 cm, still visible in the 9th period, is filled by the 11th period.

4. Discussion

4.1. The result of the model experiment

From the size of the regeneration gaps in variant L44 (44 m diameter), it is obvious that, at the end of

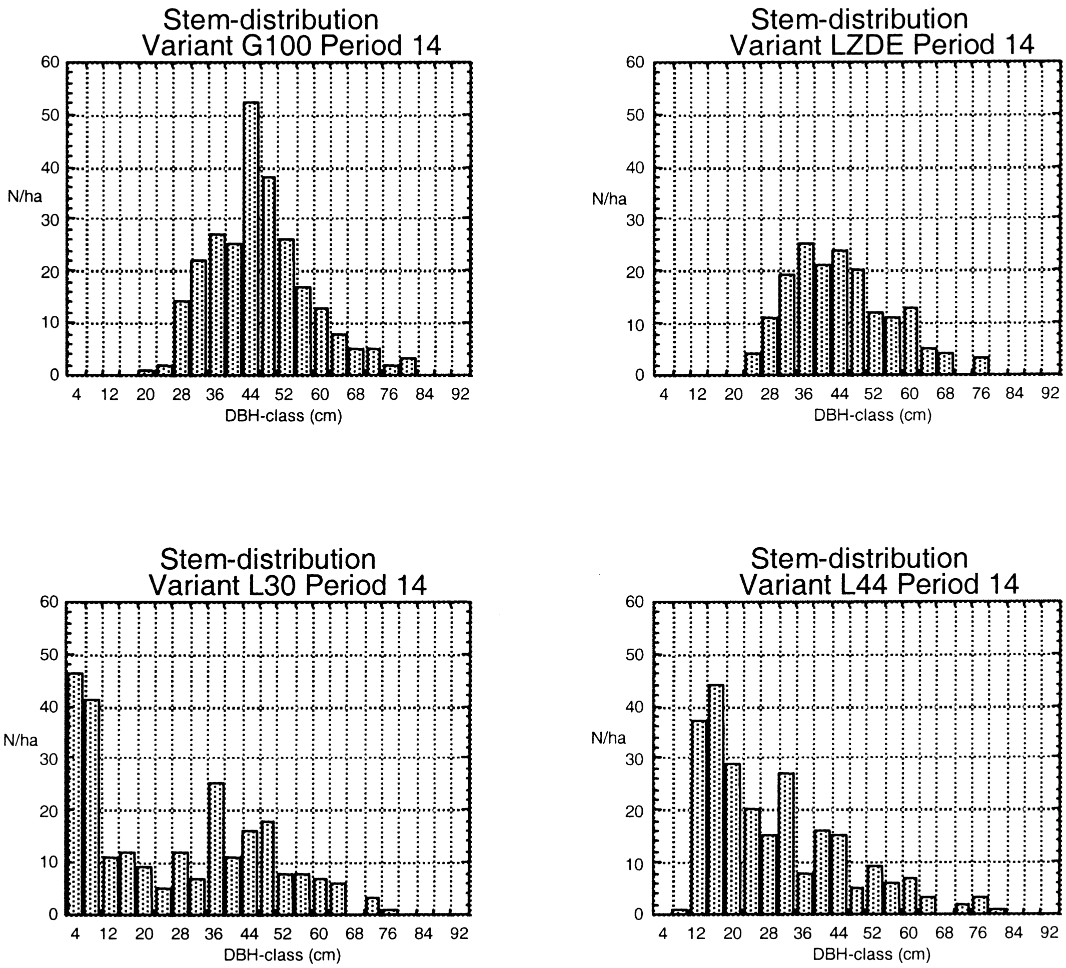

Fig. 12. Stem-distribution (N/ha) variant G100/LZDE/L30/L44, period 14.

the simulation run, this variant does not represent a single-tree-wise but rather a groupwise uneven-aged stand. The differentiation into this uneven-aged status has been reached by massive early interventions as shown by the analysis of the modified Shannon-index. Clearly we are dealing with the result of a theoretical model experiment, an artifact that is not yet ready to serve as a guideline for practitioners.

The question of whether the status represents a stable uneven-aged stand can not finally be answered. However, the progression of the conversion gives us the opportunity to critically analyse the conversion approach and the model in order to improve further research activities in this field.

4.2. Critical analysis of the methods used

4.2.1. Duration and repetition of the simulation

Within the present study, four different conversion variants and one age class treatment are compared on the basis of only one simulation run. Using a complex single tree simulator like SILVA 2.1 such an approach can be problematic. Every simulation run can, despite identical starting conditions and treatment programs, produce different results due to the partly stochastic character of the model. Furthermore, it is unrealistic to presume that no change in sites or climatic conditions will occur in a survey period of 110 years as chosen in the present investigation. The simulation of a

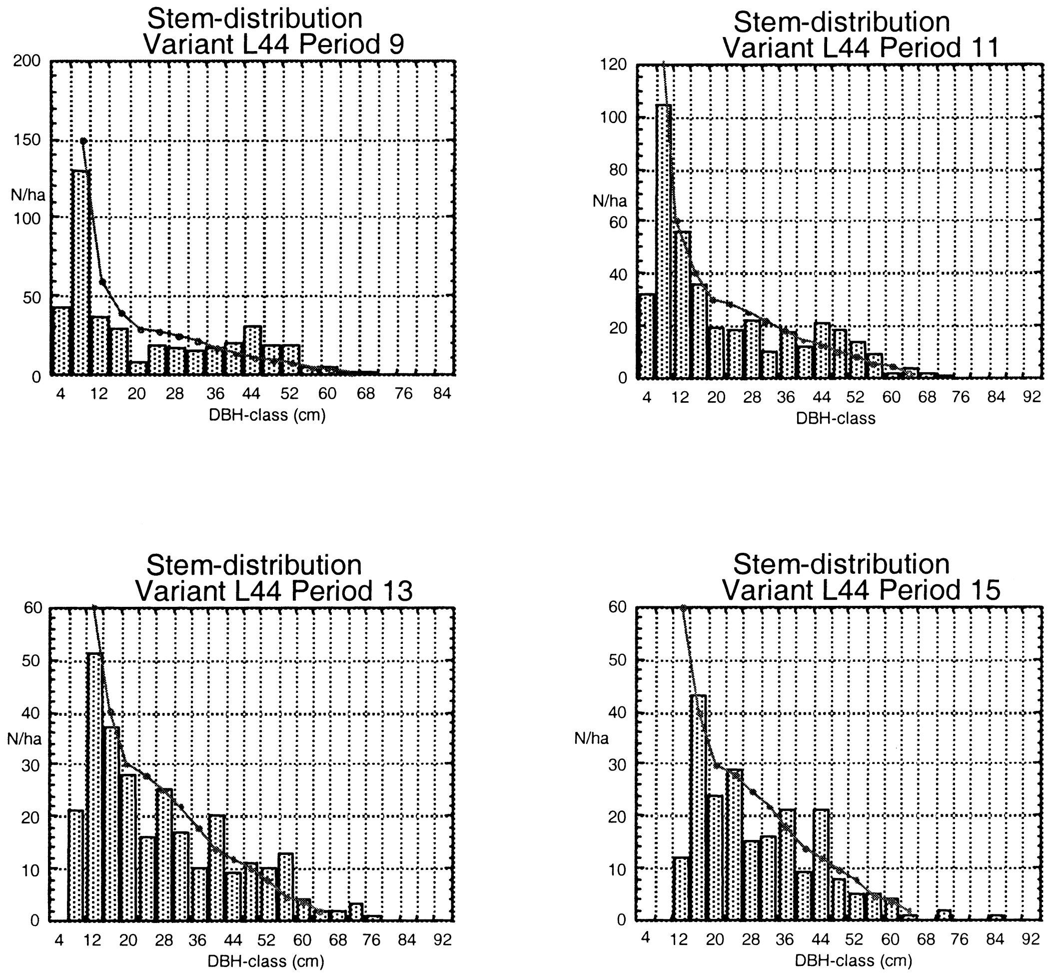

Fig. 13. Stem-distribution (N/ha) variant L44, period 9/11/13/15.

site-condition drift is in principle possible with the used growth model by changing the height- or diameter-growth potential over time. For this simulation run, where the central goal was the comparison of distinctly different treatment strategies, it was assumed that a repetition of simulation runs to analyse the results on the basis of means and standard deviations was not necessary and no change in the climatic- or site-conditions was presumed. This assumption is based on the specific design and goals of this model experiment and does not mean that replicate runs are unnecessary any time distinctly different treatments are being tested.

4.2.2. *The simulation of the regeneration process*

Due to the lack of a regeneration module, the simulation of the regeneration process was modelled using a very simple approach. Distribution of seedlings, germination percentages and survival probabilities for Norway spruce were not reproduced, neither was the influence of competing vegetation. A differentiation of the presumed annual height growth of 30 cm of the 'planted' spruce within the first ten years dependent on the size of the installed gaps was not provided.

A multitude of work has treated the development of naturally regenerated (or planted) Norway spruce in

Europe under different light conditions (Assmann, 1965; Johann, 1970; Pollanschütz and Nather, 1970; Grosse, 1983; Mosandl, 1984; Weise, 1994). The results of these different investigations are not consistent for the evaluation of the presumed regeneration scenarios. Looking at the results of Johann (1970), Assmann (1965) and Pollanschütz and Nather (1970) an annual height growth of 30 cm seems to be realistic. The difficulty in transferring these results to the simulation is to assess the light conditions in the regeneration funnels of different size compared to the conditions in the cited investigations, mainly dealing with various shelter situations. This is also valid for the investigations of Grosse (1983), Mosandl (1984) and Weise (1994) which indicated a distinctly lower height growth than presumed for the regeneration in the simulation run.

4.3. The effects of competition and mortality

The competition model of the simulator is described in detail by Pretzsch (Pretzsch, 1995, pp. 191 ff.) and the mortality model is specified by Durský (1997). Mortality is estimated using a logistic regression model. The extraordinarily high mortality of the newly implemented spruce regeneration during the conversion is conspicuous. Mortality rises with the height of the remaining stand surrounding the regeneration gaps. The new plants in the first gaps have the highest chance of survival.

At the moment it is difficult to clarify finally whether side-light effects, noticeable in long term regeneration development of Norway spruce under canopy (Cescatti, 1996), or long term compression times ascertained by Schütz (1969) on some Norway spruce in the understory of selection forests, are correctly reproduced by the growth model. Many of the newly regenerated spruce are, due to their small height, in the extrapolation range of the mortality model, possibly resulting in greater estimated mortality than appropriate. The model has not been especially parametrized for the simulation of the growth of uneven-aged, multi-layered stands. It is possible that with the present simulation runs a limit of the growth model regarding the regeneration and mortality processes has been reached or even passed.

4.4. The success of the conversion activities

Similar to conversion regimes developed by practical foresters in central Europe (Reininger, 1987; von der Goltz, 1991), the tested conversion regime aims to convert an even-aged stand by means of 'structuring' measures. These measures can be divided into (a) the differentiation of the initial stand and (b) the vertical differentiation by newly regenerated layers through the opening of the canopy. The practical conversion approaches (Reininger, von der Goltz) try to reach this second kind of structuring (b) exclusively by long term target diameter harvest. It is thereby assumed that a steady state for a permanent forest will automatically emerge as an effect of a long term regeneration process while target diameter harvesting (see Reininger, 1987).

This assumption cannot be supported by the present study. Variant LZDE, originally looked upon as a conversion variant, is rather modified variant of age–class treatment with preliminary target diameter harvest. The extremely small gaps in this variant do not lead to a significant vertical differentiation during the phase of selective thinning and quality improvement cut. Despite a rather low basal area in the 18th period, the regeneration 'wave' has only little effect. The number of stems declines to 60 ha^{-1} at the end of the simulation run, regularily distributed over the area of the stand. A complete regeneration taking place at this time would not lead to a multi-layered stand.

The success of the conversion of variants L30 to L44 depends directly on the size of the regeneration gaps. The conversion fails in the variants L30 and L35 due a lack of sufficient ingrowth. Compared to the results of a model experiment by Pukkala and Kolström (1988), the present investigation is nevertheless close to an uneven-aged status. The limits of matrix models for the simulation of conversion processes are shown by Buongiorno et al. (1995). Pure matrix models are certainly very efficient for modelling already uneven-aged stands (Buongiorno and Michie, 1980; Schulte and Buongiorno, 1998) but might have limits in the simulation of the conversion from an even-aged to an uneven-aged status. These limits are also visible in the version of the single tree simulator, used in this investigation. They are mainly the result of a lack of an adequate data base from long term trial plots in uneven-aged stands and the lack of a regeneration module. However, the structure of the model is prepared for modelling even-aged and uneven-aged stand structures and enables the modeller to simulate any conversion strategy. It thus allows, in principle, the modelling of conversion processes.

5. Conclusion

The results of the present study show that the possibilities to convert even aged into uneven aged stands only by 'structuring measures' (thinning, target diameter harvest) are very limited. The success of regeneration is of crucial importance for the conversion. The losses in volume increment and standing volume due to preliminary cutting in order to create regeneration gaps can be important. The modified Shannon-index has proven to be a useful parameter to control the change of a stand from a single-layered to multi-layered structure. Further research could show whether this is also valid for mixed and more irregular stands.

These results are highly influenced by the limits of the model used for this investigation. An elaborated regeneration module is a precondition for successful applications of the model in this scope. The parametrization of the model on a broad database in South Germany and Switzerland for mixed, uneven-aged stands with shade tolerant species beech (*Fagus sylvatica* L.) or silver fir (Abies alba, Mill.) is also necessary for further modelling experiments of conversion processes. The application of the conversion regime on mixed stands with more shade tolerant species appears to be more promising than in pure stands of Norway spruce species (Hanewinkel, 1998a, p.190).

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References

Abetz, P., 1975. Eine Entscheidungshilfe für die Durchforstung von Fichtenbeständen. Allgemeine Forstzeitschrift, Munich 30, 666–667.

Assmann, E., 1965. Der Zuwachs im Verjüngungsstadium. Cbl. Ges. Forstwes. 82, 193–217.

Buongiorno, J., Michie, B.R., 1980. A matrix model of uneven-aged forest management. For. Sci. 26, 609–625.

Buongiorno, J., Peyron, J.L., Houllier, F., Bruciamacchie, M., 1995. Growth and management of mixed-species, uneven-aged forests in the French Jura: implications for economic returns and tree diversity. For. Sci. 41, 397–429.

Cescatti, A., 1996. Selective cutting, radiative regime and natural regeneration in a mixed coniferous forest: a model analysis. In: Skovsgaard, J.P., Johannsen, P. (Eds.), Modelling regeneration success and early growth of forest stands. Proceedings of the IUFRO Conference, Copenhague. Danish Forest and Landscape Research Institute, Horsholm, pp. 474–483.

Clark, J., Evans, F.C., 1954. Distance to nearest neighbour as a measure of spatial relationships in populations. Ecology 35, 445–453.

Durský, J., 1997. Modellierung der Absterbeprozesse in Rein- und Mischbeständen aus Fichte und Buche. Allgemeine Forst- und Jagdzeitschrift, Frankfurt 168, 131–133.

Goltz, H. von der, 1991. Strukturdurchforstung der Fichte. Allgemeine Forstzeitschrift, Munich 46, 677–679.

Grosse, H.-U., 1983. Untersuchungen zur künstlichen Verjüngung des Bergmischwaldes. Schr. Forstwiss. Fak., vol. 55. Universität München, 206 pp.

Hanewinkel, M., 1996. Überführung von Fichtenreinbeständen in Bestände mit Dauerwaldstruktur. Allgemeine Forstzeitschrift, Munich 51, 1440–1446.

Hanewinkel, M., 1998a. Plenterwald und Plenterwaldüberführung — Modellstudien zu planungstechnischen, waldbaulichen und ökonomischen Aspekten am Fallbeispiel des Wuchsgebietes Schwarzwald, vol. 9. Dissertation. Universität Freiburg. Schriften aus dem Institut für Forstökonomie, 252 pp. (English abstract).

Hanewinkel, M., 1998b. Sucessful examples of multiple forest use — the model of selection forests. In: Proceedings of the Forum Biodiversity: Treasures in the World's Forests, Schneverdingen, workshop II, session III.

Hasenauer, H., Leitgeb, E., Sterba, H., 1996. Der A-Wert nach Johann als Konkurrenzindex für die Abschätzung von Durchforstungseffekten. Allgemeine Forst- und Jagdzeitschrift, Frankfurt 167, 169–174.

Hilfstabellen, 1993. Hilfstabellen für die Forsteinrichtung. Selbstverlag der Landesforstverwaltung Baden-Württemberg, Stuttgart, 188 pp.

Johann, K., 1970. Ergebnisse strukturanalytischer Untersuchungen in natürlich verjüngten Fichtenbeständen. FWCBL 89, 228–251.

Johann, K., 1982. Der A-Wert, ein objektiver Parameter zur Bestimmung der Freistellungsstärke von Zentralbäumen. Deutscher Verband der Forstlichen Versuchsanstalten, Sektion Ertragskunde, Weibersbrunn, pp. 146–158.

Kahn, M., 1994. Modellierung der Höhenentwicklung ausgewählter Baumarten in Abhängigkeit vom Standort. Dissertation. Universität München, 204 pp.

Kahn, M., 1995. Rule based modelling of thinning regimes for a distance dependent single tree growth simulator by implementing a fuzzy logic controller. In: Skovsgaard, J.P., Burkhart, H. (Eds.), Recent Advances in Forest Mensuration and Growth and Yield. Proceedings from Third Sessions of Subject Group S4.01 at the World Congress of IUFRO, Tampere. Danish Forest and Landscape Research Institute, pp. 29–44.

Kahn, M., Pretzsch, H., 1997. Das Wuchsmodell SILVA — Parametrisierung der Version 2.1 für Rein- und Mischbestände aus Fichte- und Buche. Allgemeine Forst- und Jagdzeitschrift, Frankfurt 168, 115–123.

Klädtke, J., 1992. Konstruktion einer Z-Baum — Ertragstafel am Beispiel der Fichte. Dissertation. Universität Freiburg, 111 pp.

Mosandl, R., 1984. Löcherhiebe im Bergmischwald: Ein waldbauökologischer Beitrag zur Femelschlagverjüngung in den Chiemgauer Alpen. Forstliche Forschungsberichte München, Nr. 61. Forstwis Fak. der. Universität München, 298 pp.

Pielou, E.C., 1977. Mathematical Ecology. Wiley, New York, 385 pp.

Pollanschütz, J., Nather, J., 1970. Ertragskundliche und lichtökologische Untersuchungen im Raume Litschau. In: Naturverjüngung im Mischwald, Bestandesumbau sekundärer Kiefernwälder. Mitteilungen der Forstlichen Bundes-Versuchsanstalt Wien 90, pp. 71–126.

Pretzsch, H., 1992. Konzeption und Konstruktion von Wuchsmodellen für Rein- und Mischbestände, vol. 115. Forstliche Forschungsberichte, München, 332 pp.

Pretzsch, H., 1993. Analyse und Reproduktion räumlicher Bestandesstrukturen. Versuche mit dem Strukturgenerator STRUGEN, Schriften aus der Forstlichen Fakultät Göttingen und derNiedersächsischen Forstlichen Versuchsanstalt, Band 14. J.D. Sauerländer Verlag, 87 pp.

Pretzsch, H., 1995. Zum Einfluß des Baumverteilungsmusters auf den Bestandeszuwachs. Allgemeine Forst- und Jagdzeitschrift, Frankfurt 166, 190–201.

Pretzsch, H., 1996. Strukturvielfalt als Ergebnis waldbaulichen Handelns. Allgemeine Forst- und Jagdzeitschrift, Frankfurt 167, 213–221.

Pretzsch, H., 1997. Analysis and modeling of spatial stand structures. Methodological considerations based on mixed beech–larch stands in lower Saxony. For. Ecol. Mgmt. 97, 237–253.

Pretzsch, H., Kahn, M., 1995. Modelling growth of Bavarian mixed stands in a changing environment. In: Korpilathi, E., Mikkelä, H., Salonen, T. (Eds.), Caring for the Forest: Research in a Changing World. Congress Report, vol. II, IUFRO XX World Congress, Tampere, pp. 234–248.

Pretzsch, H., Kahn, M., 1996. Wuchsmodelle für die Unterstützung der Wirtschaftsplanung im Forstbetrieb. Allgemeine Forstzeitschrift, Munich/Der Wald 51, 1414–1419.

Prodan, M., 1944. Zuwachs und Ertragsuntersuchungen im Plenterwald — Ein Beitrag zur Methodik der Ertragsuntersuchungen im Plenterwald dargestellt anhand der Ergebnisse der badischen Plenterwaldversuchsflächen. Dissertation. Universität Freiburg, 135 pp.

Pukkala, T., Kolström, T., 1988. Simulation of the development of Norway spruce stands using a transition matrix. For. Ecol. Mgmt. 25, 255–267.

Reininger, H., 1987. Zielstärken-Nutzung oder die Plenterung des Altersklassenwaldes, Österreichischer Agrarverlag, Wien, 163 pp.

Schütz, J.-P., 1969. Analyses préliminaires de hauters et accroissements en diamètre, en foret jardinée, en fonction de la position sociologique et de la durée de compression. Schweizerische Zeitschrift für Forstwesen, Zürich 115, 295–304.

Schulte, B., Buongiorno, J., 1998. Effects of uneven-aged silviculture on the stand structure, species composition, and economic returns of loblolly pine stands. For. Ecol. Mgmt. 111, 83–101.

Weise, U., 1994. Höhenwachstum natürlich verjüngter Tannen und Fichten im Nordschwarzwald. Allgemeine Forstzeitschrift, Munich/Der Wald 49, 194–198.