STRUCTURAL DIVERSITY AS A RESULT OF SILVICULTURAL OPERATIONS

ROZMANITOSŤ ŠTRUKTÚRY LESNÉHO PORASTU AKO VÝSLEDOK PESTOVNÝCH OPATRENÍ

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ABSTRACT: The aim of the study is to quantify the effect of silvicultural treatments on the spatial structure of forest stands. The first important basis is indices that are capable of reliably quantifying horizontal tree distribution patterns, vertical stand profile and segregation of species. The second means of modelling the spatial stand dynamics is the single-tree simulator SILVA 2.0. By combining SILVA 2.0 with a program module for structural analysis, we get a flexible tool with the help of which we can examine the influence of different regeneration technics, thinning regimes and site conditions on growth, yield and spatial stand structure. By a series of simulation runs, the influence of the initial structure, thinning method and thinning degree on the spatial structure of mixed stands of spruce and beech is examined. The results underline the fact that especially slight and moderate thinning from the top offer an effective possibility to form the stand structure and support its diversity. Thinning from below has a more homogeneous effect on the spatial stand structure. The desired integration of structural diagnosis into prognosis models that hitherto have been aligned to growth and yield exclusively offers the possibility of considering, quantifying and optimizing production and stability aspects of silvicultural treatment.

diversity; structural parameters and scenarios; growth simulation; stand treatment

ABSTRAKT: Cieľom príspevku je kvantitatívne preskúmanie vplyvu pestovných opatrení na priestorovú heterogenitu a tým aj na druhovú diverzitu lesných porastov. Prvým dôležitým základným nástrojom sú tu indexy, ktoré môžu spoľahlivo kvantifikovať horizontálnu štruktúru rozmiestnenia stromov, vertikálny druhový profil a druhové zmiešanie drevín. Druhým dôležitým nástrojom, ktorý umožňuje reprodukovať priestorovú štruktúru porastu a jej dynamiku, je porastový simulátor SILVA 2.0 Prepojením jednej z programových rutín určenej na analýzu štruktúry porastu s vlastným porastovým simulátorom SILVA 2.0 vznikol flexibilný prognostický a výskumný nástroj, ktorým je možné skúmať vplyv rôznej porastovej výstavby, spôsobov obhospodarovania a stanovištných podmienok nielen na drevnú produkciu, ale aj na štruktúru lesa. V rámci série simulácií sa v príspevku sleduje vplyv východiskovej štruktúry porastu, druhu a sily prebierky na priestorovú štruktúru zmiešaného smreko-bukového porastu. Výsledky, ktoré v podobe indexov charakterizujú horizontálnu štruktúru rozmiestnenia stromov, vertikálny druhový profil a druhové zmiešanie drevín, potvrdzujú, že predovšetkým slabé a mierne úrovňové zásahy ponúkajú možnosť formovania porastovej štruktúry a tým aj podpory diverzity porastu. Podúrovňové prebierky naopak vplývajú na priestorovú porastovú štruktúru homogenizujúco. Uskutočnené spojenie informácií o štruktúre porastu s doteraz výlučne produkčne orientovanými prognostickými modelmi otvára pre pestovanie lesa možnosti optimalizácie medzi produkčnými aspektmi a aspektmi porastovej stability.

diverzita; indexy a scenáre štruktúry; simulácie rastu lesa; obhospodarovanie porastov

INTRODUCTION

In commercial forests spatial stand structure is considered as an important factor in determining habitat and species diversity. Quantitative studies on this subject show that increasing heterogeneity of horizontal and vertical stand structure is concomitant, as a rule, with a higher number of species and with greater ecological stability (Altenkirch, 1982; Ammer et al., 1995; Blab, 1986; Ellenberg et al., 1985; Haber, 1982). Silvicultural operations can modify the stand structure and therefore have an important potential in securing stand diversity and ecological stability.

The objective of the present investigation is to elaborate methodological principles for a systematic analysis of relationships between stand treatment and spatial stand structure. As the first essential basis indices can be used which give a quantitative idea of horizontal tree distribution pattern, vertical species profile and intermingling intensity of tree species and hence serve as valuable indicators of habitat and species diversity. The second important basis is the stand growth simulator SILVA 2.0, which is capable of reproducing spatial stand dynamics for a wide range of site conditions, initial stand structures and treatment variants (Pretzsch, 1992). For the purpose of this investigation SILVA 2.0 was extended to include a program routine for structural analysis and structure diagnosis. A research instrument has thus been developed with which the influence of silvicultural operations on spatial stand structure may be analysed by simulation. In a series of test runs with SILVA 2.0 the long-term effect of slight, moderate and heavy thinning from below and selective thinning as well as the effect of different mixture types on the spatial stand structure were investigated.

MATERIAL AND METHODS

MATERIAL

The data for the study comes from 82 long-term experimental plots in mixed stands of spruce and beech in Bavaria (Tab. I). The single tree simulator SILVA 2.0 was calibrated and validated with the growth and yield data from this network of survey plots. The oldest plots have been under survey since 1928, the youngest were established in 1995. The plots cover a broad range of different ages, proportions and structures of mixture, thinning regimes and site conditions. The model functions are fitted with the whole data set of the network. However the following simulation runs represent the stand structure dynamic on a recently established age series near Freising on fresh sandy loams in the Upper Bavarian tertiary montane area (growth district 12.8 „Oberbayerisches Tertiärhügelland"). Spruce has a productivity index of 40 according to the spruce yield tables by Assmann, Franz (1963), while that for beech is class I according to the beech-yield table by Schober (1975), which implies excellent growth conditions for both tree species. On the modelled test plots of 0.25 hectares beech has 10 years' growth advantage over spruce. At the start of the prognosis runs (age of spruce and beech 30 and 40 years, respectively), the stem number was 2196 trees per ha, with a basal area of 45.2 square metres per ha. Spruce and beech occupy equal portions of the basal area.

METHODS

To determine and identify spatial stand structures we can make use of a repertoire of reliable quadrat count and distance methods, as compiled by Pielou (1975, 1977), Ripley (1977, 1981) and Upton, Fingleton (1985, 1989). The indices *R* by Clark, Evans (1954) and *S* by Pielou (1977) identify the horizontal tree distribution pattern and the intermingling of species, respectively, and thus quantify different aspects of spatial heterogeneity. Index *A* for the vertical species profile, developed in analogy to the index by Shannon (1948) serves to quantify the spatial distribution of tree species.

Aggregation index *R* by Clark, Evans

The aggregation index by Clark, Evans (1954) describes the horizontal tree distribution pattern by re-

I. Data base of the study is 15 long-term experimental plots in mixed stands of spruce and beech in Bavaria (x = data available)

Species	Location	Number of plots	Total area (ha)	Beginning of survey	Number of surveys	Stem chart	Crown dimension	Young growth inventory
sp/be	Zwiesel	8	1.86	1954	6	x	x	
sp/be	Zwiesel	10	3.00	1985	2	x	x	
sp/be	Mitterteich	3	0.76	1928				
sp/be	Freising	6	3.0	1994	1	x	x	x
sp/be	Schongau	8	4.0	1995	1	x	x	x
sp/be	Bodenmais	5	2.5	1995	1	x	x	x
sp/fir/be	Kreuth	22	3.60	1973	2	x	x	x
sp/fir/be	Zwiesel	4	1.93	1987	1	x	x	x
sp/fir/be	Garmisch	5	1.59	1954	5	x	x	
sp/fir/be	Freyung	3	1.50	1980	3	x	x	x
sp/fir/be	Bodenmais	2	1.00	1981	3	x	x	x
sp/fir/be	Ruhpolding	2	0.31	1953	8	x	x	x
sp/fir/be	Ruhpolding	1	0.30	1963	5			
sp/fir/be	Marquartstein	2	0.81	1953	5	x	x	
sp/fir/be	Wolfegg	1	0.31	1952	6	x	x	x

lating the observed average distance to the nearest neighbour to the average distance to be expected when trees are randomly distributed.

$$R = \frac{\bar{r}\ \text{observed}}{\bar{r}\ \text{expected}} \qquad (1)$$

R is obtained by calculating the distances $r_{i, i = 1...N}$ to the nearest neighbour for each of N trees on a test plot of size F, and then proceeding to calculate the average distance

$$\bar{r}\ \text{observed} = \frac{\sum_{i=1}^{N} r_i}{N} \qquad (2)$$

This observed distance to the nearest neighbour is related to the expected average distance for random tree distribution

$$\bar{r}\ \text{expected} = \frac{1}{2\sqrt{\frac{N}{F}}} \qquad (3)$$

where: r_i – distances of $i = 1...N$ trees to their nearest neighbours on the test plot,
N – total number of trees on the test plot,
F – area of test plot in square metres.

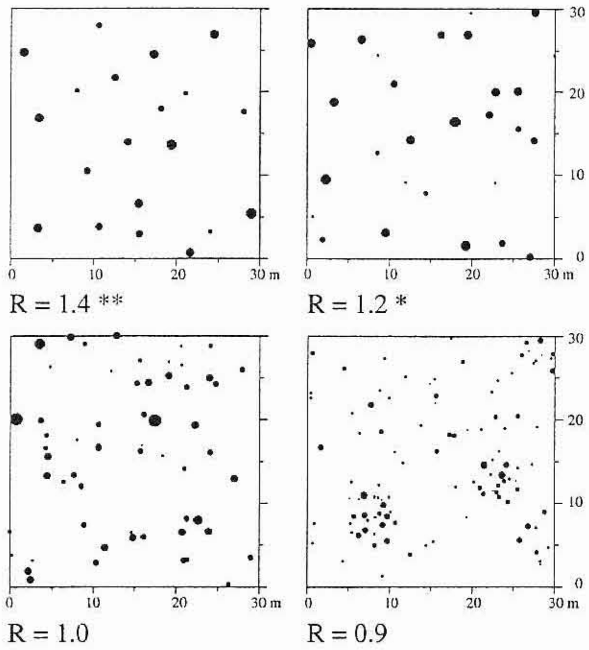
Theoretically, R lies between 0 (greatest clustering) and 2.1491 (regular hexagonal pattern). Aggregation values below 1.0 show a tendency towards cluster formation, while those around 1.0 are indicative of random distribution and those above 1.0 reveal a tendency towards regular distribution. Aggregation index R is hence a measure to what extent the observed spatial pattern diverges from a random or POISSON distribution. It can be used for the overall stand as well as for individual tree species in the stand (Fig. 9).

The calculation of the aggregation index R for the tree distribution patterns shown in Fig. 1 (above) gives values for R which lie between 1.4^{**} and 1.2^{*}, revealing rather more regular distribution patterns as are usually found in age class forests thinned from below. When $R = 1.0$ (Fig. 1, below, left hand side) this is indicative of a random distribution typical of selection forest stands and virgin forests, while an aggregation index of $R = 0.9$ (Fig. 1, below, right hand side) shows a tendency to clustering. The symbols * and ** designate regularity with an error probability of 5 and 1%, respectively.

Index *A* for the vertical species profile

The index A for the species profile is based on the index H by Shannon, Weaver, originally developed in the context of information theory and later applied to the description of species diversity in biological systems (Shannon, 1948).

$$H = -\sum_{i=1}^{S} p_i \cdot \ln p_i \qquad (4)$$



1. Identification of four horizontal tree distribution patterns by the aggregation index of Clark, Evans (1954). The symbol size is proportional to the stem diameter at a height of 1.30 metres. R-values of more than 1.0 indicate a trend to regular distribution, values below 1.0 indicate a trend to clustered distribution. Random distribution is indicated by values of $R = 1.0$

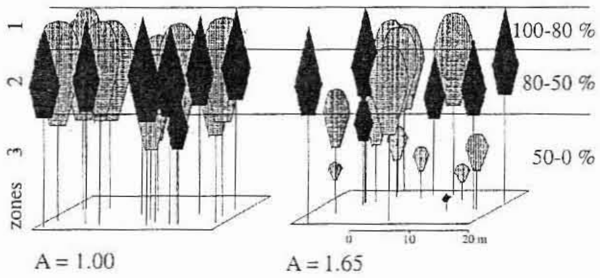
where: S – number of species occurring in the stand,
p_i – portion of species in relation to total population $p_i = \frac{n_i}{N}$
n_i – frequency of species i,
N – total number of individuals.

Index H for species diversity is derived from the product of species portion p_i and logarithmic species portion $\ln p_i$ for the sum of a total of S species occurring in the stand. By introducing the logarithmically transformed species portion as a multiplying factor, the index is disproportionately raised by rare species, while dominant species lead to a disproportionately low increase. The index A for the vertical species profile developed in the course of this study considers species portions separately for three height zones ranging from 0 to 50%, 50 to 80% and 80 to 100% of maximum stand height.

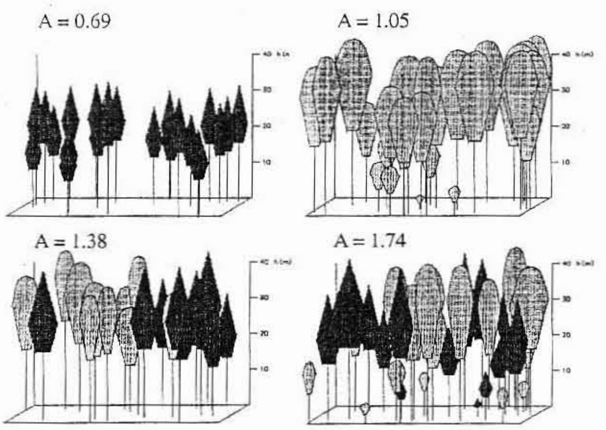
$$A = -\sum_{i=1}^{S} \sum_{j=1}^{Z} p_{ij} \cdot \ln p_{ij} \qquad (5)$$

where: S – number of species in the stand,
Z – number of height zones (three in this case),
p_{ij} – species portions in the zones $p_{ij} = \frac{n_{i,j}}{N}$
n_{ij} – frequency of species i in zone j,
N – total number of individuals.

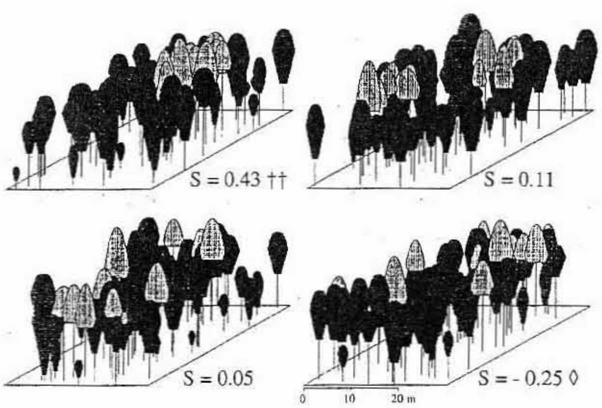
Index A summarizes and quantifies species diversity and distribution of species in the stand. While the index is lowest in stands with one-storied pure stands, it rises for pure stands with two or more layers. A mixture of



2. For the diagnosis of the species profile index A, the stand is subdivided into three height zones. The zones 1 to 3 represent 100–80%, 80–50% and 50–0% of the maximum height of the stand. For the computation of index A, the proportions of the different species are counted out separately according to the different height zones



3. Species profile index A for mono-layered and multi-layered pure and mixed stands of spruce and beech



4. Identification of the mixture type of beech (black) and larch (light grey) by the segregation index of Pielou (1977). S-values of more than 0 indicate a trend to segregation, values below 0 indicate a trend to association. Independent distribution of species is indicated by values near 0

several species effectively raises the index and peak values are reached in mixed stands with heterogeneous structures (Fig. 3). Every deviation from the one-storied pure stand is reflected in a distinct rise in species profile index A.

Segregation index by Pielou for the intermingling of species

The segregation index S by Pielou (1977) determines the intermingling of two tree species according to the nearest neighbour method. For its calculation a search run serves to determine the species of the nearest neighbour for each of N trees on the test plot, giving the number of trees of species 1 and 2 (m, n), the number of trees with neighbours of their own species (a, d) and with neighbours of the other species (c, b). The segregation index is thus derived from

$$S = 1 - \frac{\text{observed number of mixed pairs}}{\text{expected number of mixed pairs}} \qquad (6)$$

and will lie between −1.0 and + 1.0. From the basic values in the 2 x 2 table (Tab. II) it is calculated as follows:

$$S = 1 - \frac{N \,.\, (b + c)}{(v \,.\, n + w \,.\, m)} \qquad (7)$$

If the observed number of mixed pairs is higher than the expected one, this will lead to $S < 0$, indicating

II. Four-field table with the basic variables for the computation of the segregation index S according to formula (7). Explanation of the variables in the text

	Nearest neighbour		
	tree species 1	tree species 2	total
Base tree species 1	a	b	m
Base tree species 2	c	d	n
Total	v	w	N

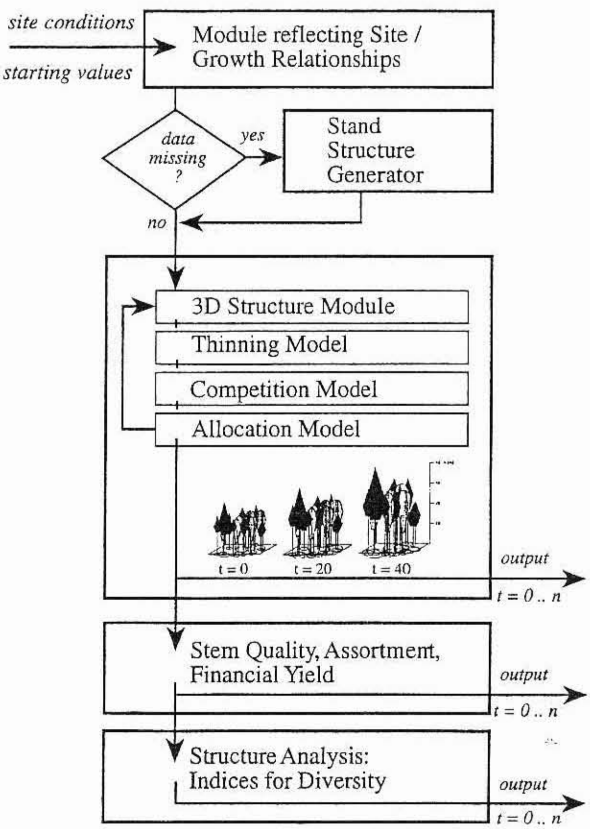
a close coupling or association of species. Conversely, if the observed number of mixed pairs is lower than expected, then $S > 0$ and is evidence of segregation, i.e. the spatial separation of species. Where $S = 0$, i.e. the number of observed and expected mixed pairs is equal, then species are distributed independently of each other.

The mixed stands of beech and larch from the Solling in lower Saxony in Fig. 4 reveal a wide range of intermingling intensities. While big cluster and group mixtures (Fig. 4, above) have segregation indices of $S = 0.43$†† and $S = 0.11$, respectively, small clusters and single tree mixtures (Fig. 4, below) tend to lower them to $S = -0.25x$. High segregation indices are indicative of pronounced intra-species competition, whereas low values imply species association and the dominance of competitive conditions between species. The symbol †† shows significant segregation with 1% error probability, x indicates significant association with 5% error probability.

Stand growth simulator SILVA 2.0 with program routine for structure diagnosis

The position-dependent individual tree model SILVA 2.0 breaks down forest stands into a mosaic of individual trees and reproduces their interactions as a space-time system. It can therefore 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 2.0 is able to predict the effects of site conditions, silvicultural treatments and stand structure on stand development, and therefore also serves as a research instrument. To explain the incorporation of a program routine which permits structural analyses, a representation of the essential elements of SILVA 2.0 is provided in Fig. 5. For details on the model see Pretzsch (1992), Kahn, Pretzsch (1997) and Kahn (1995).

The first model element reflects the relationship between site conditions and growth potential and aims 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). The stand structure generator STRUGEN facilitates the large-scale use for position-dependent individual tree growth models. The generator converts verbal characterizations as 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 from 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 *R*, *A* and *S*. The thinning model is also individual tree based and can model a wide spectrum of treatment programs (Kahn, 1995). The core of the thinning model is a fuzzy logic controller. In the simulation studies described below the thinning model simulates various thinning methods (thinning from below and selective thinning) and thinning intensities (slight, moderate and heavy). The competition model employs the light-cone method (Kahn, 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 height 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 stand and single tree level for the prognosis period are compiled in listings and graphs. Additional information on stem quality, assortment yield and financial aspects completes the growth and yield characteristic.



5. Scheme of the stand growth model SILVA 2.0 with the program module for structural analysis

At every stage of the simulation run 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 the indices described above can be calculated, i.e. the horizontal tree distribution pattern index *R*, the vertical species profile index *A* and the intermingling index *S*, which form a link with the ecological assessment of forest stands.

The algorithmic sequence for predicting forest development comprises the following steps: The first step is the input of data on the initial structure and site conditions of the monitored stand. Secondly, the parameters of the growth functions are adapted to actual site conditions. Once the starting values for the prognostic run are complete monitoring can begin. If there are no initial values, e.g. stem positions are unknown, the missing data can be realistically complemented with the help of the stand structure generator. Once the spatial model has been constructed (step 4) the silvicultural treatment program is specified in the fifth step. The competition index calculated for each tree through the three-dimensional model in step 6 is used in step 7, to control individual tree development. Steps 4 to 7 are repeated until the entire prognostication period has been run through in 5-year steps.

RESULTS

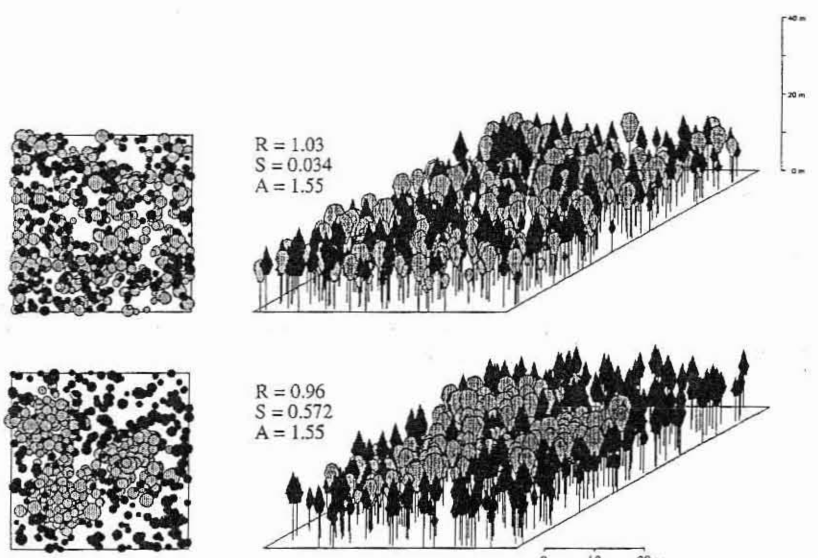
The use of structural analysis in conjunction with a stand growth simulator is explained now on the basis of a series of simulation test runs. Specific examples will serve to demonstrate the effects of different stand establishment structures (single or group mixtures), different thinning methods (thinning from below and selective thinning) and different thinning intensities (slight, moderate and heavy) on the spatial stand.

The input comprises two different variants of mixture structure (Fig. 6). The first is a single tree mixture with a random horizontal distribution pattern of the total stand as well as for spruce and beech separately (R = 1.03, R_{spruce} = 1.01, R_{beech} = 0.99). In this case the segregation index by Pielou shows an independent distribution of the two species (S = 0.034). For the second variant a group mixture of beech with spruce was selected as the initial structure. In this case the horizontal distribution pattern of beech shows significant clustering ($R_{beech} = 0.68^{**}$) and the segregation index by Pielou reveals a highly significant segregation of spruce and beech (S = 0.572†††). Both stands have similar vertical species profiles; A = 1.55 is indicative of great structural diversity in species representation. The thinning regimes simulated in the 100 years lasting prognostication period are characterized in Fig. 7 in terms of the corresponding number of stems and the basal area development of the remaining stand. Thinning from above was carried out in the form of stepwise selective thinning according to the „Schweizer Auslesedurchforstung". When considering two basic structures (single tree and group mixtures), two thinning methods (thinning from below and from above) and three thinning intensities (slight, moderate, heavy) the result is 12 development whose spatial structural diversity is discussed below.

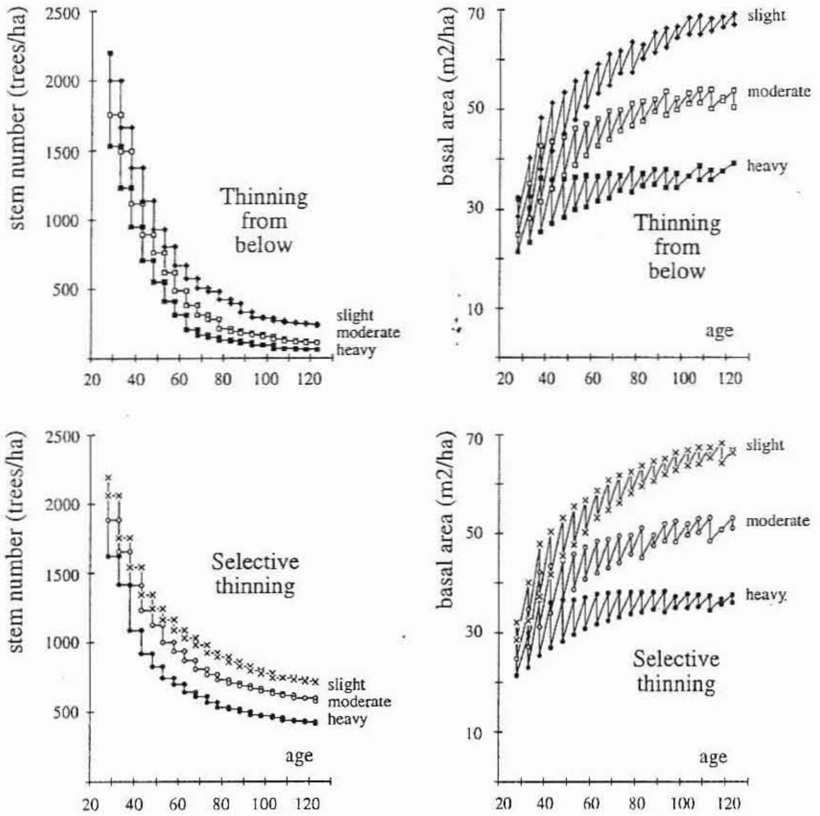
The horizontal tree distribution pattern

The more or less random horizontal tree distribution pattern of the total stand at the beginning of the prognostication period is converted into a rather more regular pattern on account of thinnings from below, especially if these were intense (Fig. 8). This tendency for regular distribution patterns to be caused by thinning from below can be attributed to the systematic removal of understory and intermediate trees, which inevitably leads to qualitatively satisfactory, dominant trees remaining in the stand at rather more regular intervals. This results in stands with a homogeneous spatial structure. Stand structures of this type are more and more replaced by more intensely structured stands which are mainly thinned from above. Selective thinning as observed in this study, especially in its slight and moderate variants, causes random to clustered tree distribution patterns, since vigorous trees occasionally are left to grow in groups while understory and intermediate trees are being maintained. This leads to tree distribution patterns, where parts with denser stocking exist next to those with lesser density. When thinning from below and selective thinning is carried out slightly to moderately they provide greater heterogeneity than heavy thinnings. This is due to the fact that heavy thinning from above supports the ingrowth of understory and intermediate trees into the dominant stand class and heavy thinning from below removes all trees of the lower social classes. Both methods strengthen tendencies towards regular tree distribution patterns.

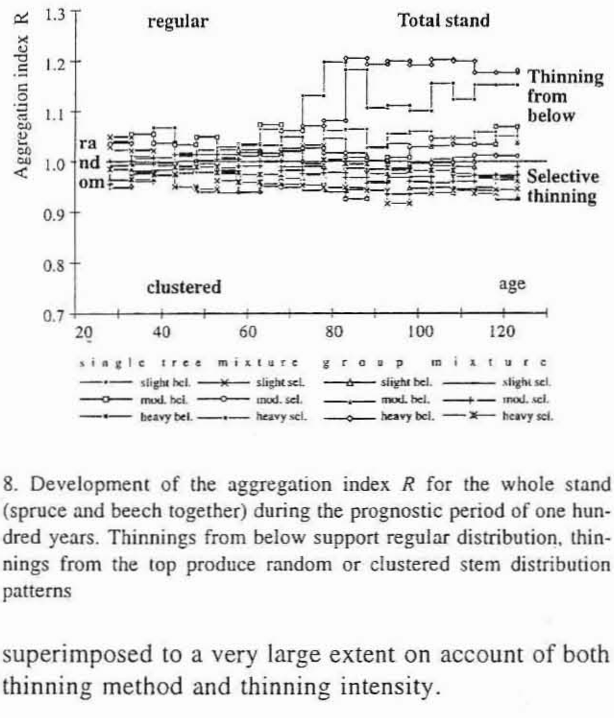
A look at the species-related tree distribution patterns of spruce and beech reveals that spruce tends to maintain its initial distribution pattern. This is again an example of the effect, as evidenced in the overall stand, that slight and moderate thinning from below leads to rather greater spatial homogeneity, while selective thinning is seen to be the cause of rather greater spatial heterogeneity in stand structure. Beech tends to occur in clusters, independent of whether it initially grew in group mixtures or single tree mixtures. This is less pronounced when treatment consisted of thinning from below rather than in selective thinning. In single tree mixtures and large and small cluster mixtures thinning from above very often causes cores with intraspecific competition to remain. Since beech is inferior to spruce at the observed site, its initial distribution pattern is being



6. Initial structures for the simulation study are spruce-beech mixed stands with single-stem mixture of beech (above) and group mixture of beech (below). Indices for single tree mixture: R = 1.03, R_{FI} = 1.01, R_{BU} = 0.99, S = 0.034, A = 1.55 and for group mixture: R = 0.96, R_{FI} = 0.93, R_{BU} = 0.68^{**}, S = 0.572†††, A = 1.55



7. Stem number and basal area curves per hectare (left and right respectively) of the six basic treatment scenarios. Slight, moderate and strong thinning from below (above) and slight, moderate and strong selective thinning from above (below)



8. Development of the aggregation index R for the whole stand (spruce and beech together) during the prognostic period of one hundred years. Thinnings from below support regular distribution, thinnings from the top produce random or clustered stem distribution patterns

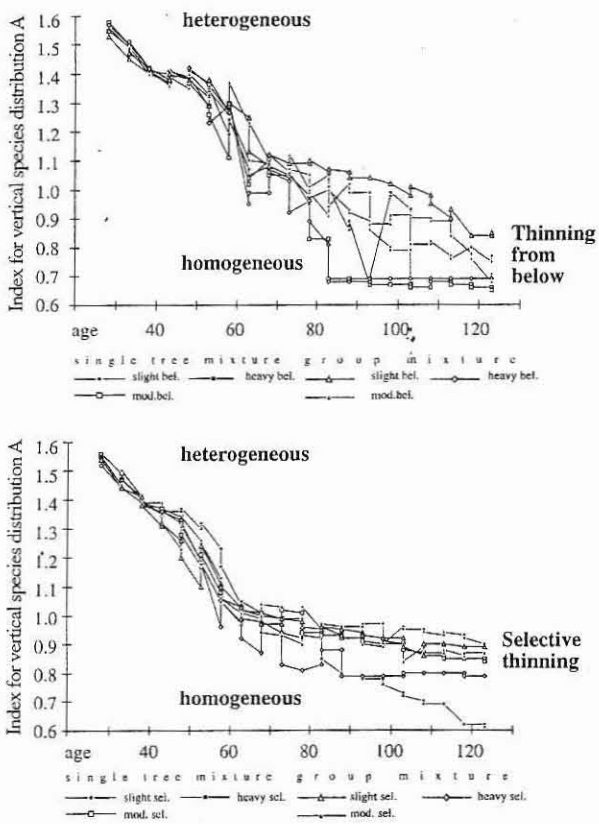
superimposed to a very large extent on account of both thinning method and thinning intensity.

The vertical species profile

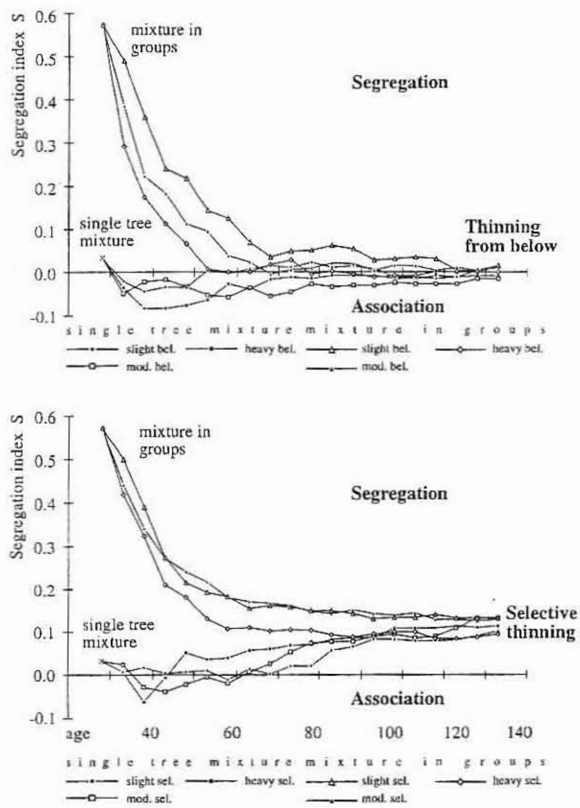
With progressive ageing and differentiation all simulated stands suffer a loss in vertical structure. The particularly severe competition for light in these phases which leads to the decline of structure-contributing but poorly supplied stand elements at lower height levels is evidenced by the severe reduction in index A in pole crops and young timber observed for all thinning programs of this study (Fig. 9). Only when a new stand generation grows in a subsequent regeneration phase does index A seem to recover. While the species profile shows an almost linear decrease in the course of the forecasting period on account of thinning from below (Fig. 9, above), selective thinning, especially if slight to moderate, maintains greater spatial heterogeneity until final felling (Fig. 9, below). With both, thinning from below and above, slight to moderate thinning favours greater structural diversity than does heavy thinning. The higher species profile index A in stands thinned from above is attributable to understory and intermediate stands which can be maintained over the entire production period through slight and moderate thinning of the uppermost layer. There is no statistically significant effect of initial stand structure (i.e. single tree mixtures, large and small cluster mixtures) on the vertical species profile A. Any differences in species profile between single tree and group mixtures which existed at the start of the prognostication period are being totally superimposed by both thinning method and intensity.

The intermingling of species

Similar results, in overall tendency, are obtained when analyzing species intermingling S under varying thinning regimes and intensities (Fig. 10). Differences initially evident in intermingling intensity, with pronounced intermingling for single tree and small cluster mixtures and poor intermingling for large cluster mixtures are increasingly being overlaid by the thinning



9. Effect of thinning from below (above) and selective thinning from the top (below) on the vertical species profile in mixed stands of spruce and beech



10. Effect of initial structure (single tree mixture and group mixture) and thinning regimes (above: thinning from below; below: selective thinning) on the segregation of spruce and beech during the prognostic run of one hundred years

methods in the course of the 100 years lasting forecasting period. Independent of the initial stand structure, thinning from above leads to a rather more segregated occurrence of species, i. e. to cores with stronger intraspecies competition. By contrast, thinning from below led to stand homogenization, also as regards the intermingling of species. The more intense removal of weak trees causes stand parts with intraspecies competition to be increasingly replaced by those whose neighbours belong to the other species. Similar interspecies neighbour relationships at a large scale contrast here with heterogenous stand structures when thinning is done selectively. As in species profile index *A* the segregation index by Pielou shows a particular reactivity, especially in the pole crop and young timber, to subsequent competitive processes and the thinning regimes then employed. In middle and higher stand ages only slight shifts undergo in species intermingling. This supports, quantitatively, the well-known silvicultural rule that growth regulation in forest mixtures is effective in young stands only.

DISCUSSION

The use of a program routine for structural analysis in conjunction with the stand simulator SILVA 2.0 led to the development of a feasible model with which the effects of different stand structures, thinning regimes and intensities on the structural diversity of mixed spruce-beech stands can be studied. The simulation results obtained serve as examples and the small number of samples as yet permits no generalization of the described results. Indices *R*, *A* and *S*, used to quantify horizontal distribution patterns, vertical species profile and intermingling of species, respectively, highlight merely selected aspects of spatial stand structure. The implementation of further indices would lead to an even more accurate description of structural stand formation. In particular, a still better characterization of species intermingling, contact frequencies and border lines between mixture species would be desirable, as this kind of information controls, *inter alia*, faunistic diversity.

First predictive runs give quantitative evidence that stand establishment and stand treatment methods provide effective means of control to improve stand structure and diversity. The comparison between thinning from above and below emphasizes the potential of modern treatment programs to improve stand structure. A vector of structural parameters gives a quantitative idea to what extent silvicultural measures such as mixture regulation, removal and thinning can be used as effective control instruments in securing structural diversity and ecological stability.

Individual tree models, provided they are based on sound parameterisation, offer the best possible link with the analysis of stand structure by reproducing stand dynamics as a time-space system, since, in combination with the spatial model, any amount of structural information is available for every phase of the simulation run. Thus, for a wide range of forest structures, treatment regimes and site conditions and apart from basic natural production indices (e.g. development of stem numbers, basal area, stock, increment), structural parameters are obtainable which can be used as indicators for habitat or species diversity. In this manner production and stability aspects can be coordinated and optimized in the model.

Due to the lack of methodological principles model validation has to date mainly been done using classical yield data and the validity of the simulated spatial structure remained untested. However, the closeness with which the modelled spatial structure is compatible with reality, particularly in distance-dependent individual tree models, is of central significance for its predictive accuracy. As a by-product of this study, the usefulness of structural parameters *R*, *A* and *S* was recognized in the validation of distance-dependent individual tree models. A comparison of modelled spatial structures, with those diagnosed on test plots is possible based on the use of these indices, which permit conclusions to be drawn as to how realistic the structural components of the growth model actually are. The structural indices, primarily introduced to assist in structural diagnosis thus also show new, efficient alternatives to improve model parameterisation and validation.

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ROZMANITOSŤ ŠTRUKTÚRY LESNÉHO PORASTU AKO VÝSLEDOK PESTOVNÝCH OPATRENÍ

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V hospodárskych lesoch je priestorová štruktúra porastu dôležitou veličinou habitatovej (životného priestoru) a druhovej diverzity. Cieľom príspevku je rozpracovať metodické základy pre analýzu vzťahov medzi obhospodarovaním porastu a jeho štruktúrou a prispieť tak k prepojeniu produkčných a ochranárskych aspektov obhospodarovania lesa.

Prvým dôležitým základným nástrojom pre spomínanú analýzu sú indexy, ktoré môžu spoľahlivo kvantifikovať horizontálnu štruktúru rozmiestnenia stromov, vertikálny druhový profil a druhové zmiešanie drevín a byť tak indikátorom habitatovej a druhovej diverzity. Druhým dôležitým nástrojom je porastový simulátor SILVA 2.0, ktorý umožňuje prognózovať dynamiku vývoja porastu pre široké spektrum stanovištných podmienok, východiskových porastových štruktúr a variant obhospodarovania porastu.

Práca sa opiera o základný empirický materiál pochádzajúci z 82 trvalých výskumných plôch (tab. I), ktoré pracovníci Katedry výskumu rastu lesa (Ludwig-Maximilians-Universität München) dlhodobo sledujú v rovnorodých a zmiešaných porastoch v oblasti Bavorska. Na najstaršej z týchto intenzívne sledovaných plôch prebiehajú merania už od r. 1928, na najmladšej od r. 1995. Plochy pokrývajú široké spektrum porastových podmienok z hľadiska veku, foriem zmiešania, intenzity zmiešania a spôsobov obhospodarovania; predstavujú jednu z najlepších možností parametrizácie rastového simulátora SILVA 2.0.

Indexy *R* od Clarka, Evansa (1954) – vzťah 1–3 a *S* od Pielouа (1977) – vzťah 6–7 identifikujú horizontálnu štruktúru rozmiestnenia stromov, resp. druhové zmiešanie v lesných porastoch, a vysvetľujú tým rôzne aspekty horizontálnej heterogenity. Pre kvantifikáciu obsadenia porastového priestoru drevinami bol skonštruovaný index *A* – vzťah 5, ktorého podstata sa opiera o Shannonov index (Shannon, Weaver, 1948). Každý z týchto indexov charakterizuje len určitý, špecifický aspekt priestorovej štruktúry. Široká a podrobná diagnóza štruktúry porastu je možná len súborom (vektorom) indexov štruktúry, ktorý sa v rámci tohto výskumu skladá z indexov *R*, *A* a *S*.

Jednotlivo stromový, pozične závislý, rastový simulátor SILVA 2.0 rozkladá lesný porast na mozaiku jednotlivých stromov, poníma ich ako priestorovo-časový systém a je preto použiteľný nielen pre rovnorodé, ale aj pre rôznoveké a zmiešané porasty (obr. 5). V prvom rade je určený na pomoc pri rozhodovaní sa o spôsobe obhospodarovania porastu. Tým, že umožňuje variantne prognózovať vývoj lesa pri rôznych scenároch obhospodarovania, rôznych porastových štruktúrach a stanovištných podmienkach, je simulátor SILVA 2.0 použiteľný aj ako výskumný nástroj. Spôsob prepojenia programovej rutiny pre analýzu štruktúry porastu na rastový modul bude čitateľovi jasný po získaní prehľadu o základných elementoch a funkčných princípoch rastového simulátora, ktoré sú podrobnejšie popísané v prácach Pretzsch (1992), Kahn, Pretzsch (1997) a Kahn (1995).

Algoritmus prognózy vývoja lesa sa skladá z týchto krokov: na začiatku sa načíta východisková štruktúra a stanovištné podmienky prognózovaných porastov (zoznam s dimenziami jednotlivých stromov a stanovištnými parametrami). Druhým krokom je transformácia parametrov prírastkových funkcií s ohľadom na stanovište. Ak sú štartové veličiny kompletné, začína vlastné prognózovanie. Ak ale východisková štruktúra nie je kompletná, napr. chýbajú koordináty jednotlivých stromov, sú v rámci kroku 3 chýbajúce dáta doplnené pomocou generátora štruktúry porastu. Po vytvorení priestorového porastového modelu (krok 4) sa v piatom kroku stanoví program pestovného obhospodarovania porastu. V šiestom kroku sa pre každý strom stanoví z trojdimenzionálneho porastového modelu konkurenčný index, ktorý slúži v siedmom kroku na odvodenie vývoja jednotlivých stromov. Kroky 5 až 7 sú opakované tak dlho, pokiaľ cez päťročné intervaly neprebehne celý čas prognózy. Paralelne k stanoveniu v užšom slova zmysle produkčných veličín (taktiež v päťročnom cykle) sú vo výstupe výsledkov informácie aj o kvalite stromov, sortimentovej štruktúre a finančnom výnose. Na základe trojdimenzionálneho modelu je možné podľa vzťahov (1), (5) a (7) určiť aj spomínané indexy pre posúdenie horizontálneho rozmiestnenia stromov v poraste – *R*, vertikálneho druhového profilu – *A* a druhového zmiešania – *S*. Indexy tak vytvárajú premostenie na ekologickú taxáciu skúmaných porastov.

Prepojenie analýzy štruktúry porastu s rastovým simulátorom je nové a v príspevku je bližšie predstavené na základe série simulačných priebehov. Pri tom je analyzovaný efekt vplyvu rôznej východiskovej štruktúry porastu (jednotlivo stromové alebo skupinové zmiešanie), rôzneho druhu prebierky (podúrovňová a výberová) a rôznej sily prebierky (slabá, mierna a silná – obr. 7) na porastovú výstavbu pomocou indexov *R*, *A* a *S*.

Práca konkrétne pojednáva o dynamike štruktúry smreko-bukového porastu (obr. 6) na čerstvých piesčito-hlinitých pôdach (stanovištná jednotka 24) z oblasti Hornobavorskej terciérnej hornatiny, kde smrek dosahuje bonitu 40 (podľa rastových tabuliek Assmann, Franz, 1963) a buk I. bonitu podľa Schoberových rastových tabuliek (Schober, 1975), čo možno všeobecne charakterizovať ako veľmi dobré rastové podmienky. Pri štartovej situácii (vek smreka je 40, resp. buka 30 rokov) je počet stromov združeného porastu 2 196 ks.ha^{-1} a kruhová zakladňa 45,2 $m^2.ha^{-1}$. Smrek a buk má pritom približne rovnaký podiel na kruhovej základni.

Porovnanie podúrovňovej a výberovej prebierky zvýrazňuje štruktúru formujúci potenciál moderných výchovných programov. S podporou vektora štrukturálnych parametrov je kvantitatívne dokázané, že pestovné opatrenia ako napr. regulácia zastúpenia, čistky a prebierky predstavujú významnú možnosť zabezpečenia štrukturálnej pestrosti a ekologickej stability lesných porastov.

Na začiatku prognózy viac menej náhodné horizontálne rozmiestnenie stromov celého porastu je vplyvom podúrovňových zásahov (predovšetkým ak sú silné) zmenené na typicky pravidelné. Nami ponímaná výberová prebierka vedie (predovšetkým v slabej a miernej variante) k náhodnej až hlúčikovej štruktúre, pretože nositelia prírastku sú v skupinách a podrast s porastovou výplňou ostáva zachovaný. To vedie k porastovej štruktúre, keď sa vedľa seba v poraste striedajú časti s vysokým zakmenením s časťami medzernatými (obr. 8).

Pokiaľ druhový profil (charakterizovaný indexom *A*) pri podúrovňovej prebierke s časom prognózy skoro lineárne klesá, zachováva výberová prebierka, zvlášť keď je slabá a mierna, až do konca prognózy veľkú priestorovú heterogenitu. Pri podúrovňovej a výberovej prebierke zachovávajú slabé a mierne zásahy všeobecne väčšiu pestrosť štrúktury ako silné zásahy (obr. 9).

Nezávisle od začiatočnej štruktúry vedie úrovňová prebierka k výrazne segregovanému výskytu drevín, t.j. k zosilnenej medzidruhovej konkurencii. Presne naopak vo vzťahu k zmiešaniu drevín pôsobí podúrovňová prebierka, t.j. homogenizujúco. Prostredníctvom odstránenia slabších stromov sa časti s medzidruhovou konkurenciou premieňajú na časti s viac menej druhovo rovnakými susedmi (obr. 10).

Ukazovatele horizontálneho rozmiestnenia, vertikálneho druhového profilu a druhového zmiešania stromov v poraste dokazujú, že predovšetkým slabé a mierne úrovňové prebierky predstavujú významnú možnosť ovplyvňovať formovanie štruktúry porastu a tak aj porastovej diverzity. Uskutočnené spojenie informácií o štruktúre porastu s doteraz výlučne produkčne orientovanými prognostickými modelmi otvára pre pestovanie lesa možnosti optimalizácie medzi produkčnými aspektmi a aspektmi porastovej stability.

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