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Analysis and modeling of spatial stand structures. Methodological considerations based on mixed beech–larch stands in Lower Saxony

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Abstract

The first part of this paper highlights spatial stand structure as the central stand characteristic and introduces methods of pattern identification. This involves two nearest-neighbour methods for the identification of stand structures, i.e., the aggregation index R by Clark and Evans [Clark, Ph.J. and Evans, F.C., 1954. Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology 35 (4) 445–453.] for univariate patterns and the segregation index S by Pielou [Pielou, E.C., 1977. Mathematical Ecology. Wiley.] for bivariate patterns. Both were used to describe the structure of 53 experimental plots of mixed beech–larch stands in Lower Saxony which provided the data base for this investigation. The second part of the study deals with the development of the STRUGEN stand structure generator, designed for the modeling and reproduction of spatial stand structures. To generate stand structures, a two-dimensional homogeneous Poisson process is used as well as a set of two-dimensional distribution functions which determine mixture type and intermingling intensity of main and associated tree species. Moreover, a distance function secures minimum distances between competing neighbouring trees. Consequently, the produced pattern is the result of a combination of an inhomogeneous Poisson process (for generating mixture units) and a hard-core process (for securing minimum distances between neighbours). The STRUGEN generator was designed and successfully used for the investigation of 53 mixed beech–larch stands. It provides initial values and stand structures for distance-dependent single-tree models from estimated qualitative stand characteristics. STRUGEN is a useful tool and allows initial, pragmatic steps towards fully utilising available qualitative and quantitative information to diagnose the state of a forest and to predict its growth. © 1997 Elsevier Science B.V.

Keywords: Mixed beech–larch stand; Spatial pattern; Nearest-neighbour method; Aggregation index; Segregation index; Stand structure generator

1. Introduction: Spatial structure as dynamics- and stability-determining stand characteristic

Conventional descriptions of forest stands based on yield-related averages or summations tend to neglect three-dimensional stand structures, probably the most important of all stand characteristics. The spatial structure of a forest stand at any given time has a decisive impact on future stand development. Basically, this goes for any type of forest structure and for the projected forests of tomorrow in particular, i.e., for highly structured mixed stands with complicated inter- and intraspecific competition pro-

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Table 1
Stand data and distribution indices *R* (Clark and Evans, 1954) and *S* (Pielou, 1977) for 53 mixed beech–larch stands in the mountainous region of southern Lower Saxony and the Weser Mountains

Plot	Area (ha)	Age (yr)	Stems/ha			Basal area/ha			*R*			*S*
			Total	Beech	Larch	Total	Beech	Larch	Total	Beech	Larch	
Uslar												
101	0.09	59	1200	944	256	38.1	21.7	16.4	1.08	0.99	0.75[d]	0.12
102	0.09	63	1066	844	222	38.1	20.3	17.8	1.09	1.00	0.58[e]	0.24
103	0.09	63	1555	1222	333	43.0	19.1	23.9	0.96	0.89[d]	0.67[e]	−0.18
104	0.25	90	380	340	40	31.5	25.1	6.4	1.29[c]	1.25[c]	0.54[d]	−0.03
105	0.16	73	643	512	131	27.6	12.9	14.7	0.98	0.92	0.86	−0.24
106	0.25	89	324	272	52	28.2	21.6	6.6	1.29[c]	1.21[b]	0.50[e]	−0.06
107	0.16	126	394	350	44	35.8	22.6	13.2	1.20[b]	1.15	0.41[e]	−0.09
108	0.16	143	250	169	81	29.6	19.5	10.1	1.11	1.10	0.68[d]	−0.05
109	0.36	138	289	214	75	35.9	24.4	11.5	1.25[c]	1.12	0.79	−0.23
110	0.20	143	187	118	69	37.5	22.6	14.9	1.25[b]	1.05	0.81	0.07
111	0.20	143	247	163	84	40.5	23.3	17.2	1.23[b]	1.08	0.92	−0.23
112	0.49	148	123	96	27	27.3	20.3	7.0	1.29[c]	1.23[b]	0.65[d]	−0.22
Bovenden												
201	0.16	49	1043	881	162	31.4	18.8	12.6	1.02	0.90[d]	0.75[d]	−0.05
202	0.16	67	1006	900	106	38.7	24.8	13.9	1.08	1.03	0.58[e]	−0.09
203	0.16	69	737	625	112	34.3	22.6	11.7	1.19[c]	1.12[a]	0.55[e]	−0.08
204	0.16	92	306	244	62	32.4	23.1	9.3	1.21[a]	1.11	0.58[d]	−0.20
205	0.16	72	669	532	137	38.9	21.7	17.2	1.13[a]	1.10	0.64[e]	−0.21
206	0.16	65	925	819	106	32.1	22.1	10.0	1.06	1.02	0.53[f]	−0.14
207	0.16	58	819	725	94	31.1	22.0	9.1	1.09	1.03	0.59[e]	−0.05
208	0.16	78	644	550	94	40.2	23.6	16.6	1.11[a]	1.02	0.61[d]	−0.14
209	0.16	78	643	531	112	42.7	21.2	21.5	1.11[a]	0.97	0.82	0.09
210	0.16	126	382	338	44	38.2	24.0	14.2	1.09	1.11	0.51[d]	−0.19
Fürstenberg												
301	0.09	51	1272	1128	144	34.4	22.6	11.8	1.08	1.00	0.62[d]	−0.13
302	0.09	67	833	644	189	34.1	20.4	13.7	1.03	0.85[d]	0.78	0.05
303	0.09	67	823	667	156	35.6	21.3	14.3	1.05	0.87	0.71	0.02
304	0.16	82	400	319	81	29.3	17.0	12.3	1.11	1.00	0.67[d]	0.19
305	0.16	84	449	362	87	36.4	23.1	13.3	1.20[b]	1.04	0.66[d]	0.25
306	0.16	97	456	387	69	34.7	24.0	10.7	1.20[b]	1.19[b]	0.58[d]	−0.20
307	0.16	106	281	237	44	36.3	24.9	11.4	1.23[b]	1.20[a]	0.52[d]	−0.26
308	0.16	106	293	231	62	33.6	21.5	12.1	1.22[b]	1.21[a]	0.63[d]	−0.07
309	0.16	106	287	218	69	34.3	21.4	12.9	1.25[b]	1.22[a]	0.61[d]	−0.28
310	0.25	106	360	320	40	38.3	29.1	9.2	1.19[b]	1.18[b]	0.45[e]	−0.15
311	0.36	95	295	214	81	47.7	25.6	22.1	1.21[c]	1.17[b]	0.75[d]	−0.25[g]
Katlenburg												
401	0.09	63	811	711	100	28.2	17.8	10.4	1.01	0.91	0.63	0.35[h]
402	0.16	79	443	362	81	30.6	19.1	11.5	1.07	1.05	0.59	0.12
403	0.09	70	622	444	178	32.3	11.0	21.3	0.95	0.76[e]	0.85	−0.01
404	0.16	76	925	781	144	38.0	22.9	15.1	1.03	1.01	0.56[f]	−0.21[g]
405	0.16	84	450	350	100	36.4	22.4	14.0	1.23[c]	1.13	0.75	0.11
406	0.36	120	148	117	31	28.6	20.4	8.2	1.14	1.12	0.67	0.35
407	0.25	129	136	100	36	32.5	19.6	12.9	1.31[b]	1.24[a]	0.59[d]	0.05
408	0.49	138	104	88	16	29.1	22.8	6.3	1.28[b]	1.19[a]	0.69	−0.20
409	0.49	138	119	90	29	32.3	23.8	8.5	1.31[c]	1.27[b]	0.68[d]	−0.29
Stadtoldendorf												
501	0.09	61	844	611	233	37.3	20.3	17.0	1.24[c]	1.15	0.75[d]	−0.15
502	0.16	81	456	331	125	35.6	15.9	19.7	1.16[a]	1.03	0.80	−0.14
503	0.16	91	381	300	81	33.2	21.7	11.5	1.28[c]	1.18[a]	0.64[d]	−0.02

Table 1 (continued)

Plot	Area (ha)	Age (yr)	Stems/ha			Basal area/ha			R			S
			Total	Beech	Larch	Total	Beech	Larch	Total	Beech	Larch	
504	0.16	92	400	300	100	35.9	21.8	14.1	1.26[c]	1.08	0.73	0.03
505	0.16	113	331	275	56	31.6	24.7	6.9	1.34[c]	1.25[b]	0.63	−0.28
506	0.36	106	178	147	31	29.6	23.7	5.9	1.29[c]	1.18[a]	0.71	−0.03
507	0.16	114	249	187	62	33.8	24.1	9.7	1.30[c]	1.07	0.84	−0.25
508	0.25	140	136	108	28	29.0	24.6	4.4	1.22[a]	1.18	0.54[d]	0.18
509	0.25	146	228	148	80	31.9	19.1	12.8	1.33[c]	1.21[a]	0.84	0.04
510	0.25	146	176	144	32	30.2	23.4	6.8	1.31[c]	1.16	0.76	0.25
511	0.25	149	128	88	40	27.9	21.3	6.6	1.36[c]	1.24	0.81	−0.58[g]

[a]Regular distribution with an error probability of 5%.
[b]Regular distribution with an error probability of 1%.
[c]Regular distribution with an error probability of 0.1%.
[d]Clustered distribution with an error probability of 5%.
[e]Clustered distribution with an error probability of 1%.
[f]Clustered distribution with an error probability of 0.1%.
[g]Segregation with an error probability of 5%.
[h]Independent distribution with an error probability of 5%.

cesses (Assmann, 1954, von Gadow, 1993, Pretzsch, 1995).

Mixed beech–larch stands may develop in fundamentally different ways in single tree or row mixtures as against group, cluster or strip mixtures, despite same mean values, sums and frequency distributions of tree dimensions. The superior growth characteristics of larch when young and beech at more advanced age may considerably slow down the development of whichever tree species is inferior to the other at any given time when planted predominantly in single tree or row mixes. Group or cluster mixtures result in the more uniform growth of either tree species, as intraspecific competition takes place within a confined space and hence, tends to create less stress (Dippel, 1988; Kramer, 1987).

Apart from forest growth processes in the above sense, spatial stand structure determines, above all, habitat and species diversity within the stand and defines its ecological stability. To date, there are still very many gaps in our understanding of the relationships between stand structure, biodiversity and ecological stability (Altenkirch, 1982; Arbeitskreis Forstliche Landespflege, 1984; Blab, 1986; Ellenberg et al., 1985). It is generally agreed however, that a more pronounced structuring of forests is concomitant, as a rule, with a greater variety in animal and plant species and with greater interspecific relationships, which have a stabilising effect on forest ecosystems (Haber, 1982).

The considerations outlined in this study on the analysis, representation and reproduction of the spatial structure of mixed stands are therefore not only related to yield, but also to an essential aspect of ecological stability.

To determine and identify stand structures, we rely on a sophisticated repertoire of quadrant count and distance methods (as compiled by Pielou, 1975, 1977; Ripley, 1977, 1981; Upton and Fingleton, 1985, 1989). However, all these methods are based on very complex tree distribution maps and distance measurements between trees. This requires detailed data on stand structure which may sometimes be available for a few test plots, but hardly ever in common forestry practice. The stand structure generator described in Sections 4 and 5 was developed for a better interpretation of stand structure information as provided by the poorly defined qualitative descriptions of mixed stands used in forestry practice. Qualitative descriptions of mixed stands are used here to produce stand structures with structural characteristics corresponding to those of the actual stands which serve as basic values for predictions in distance-dependent, single-tree growth models.

2. Materials

The study is based on 53 experimental plots of mixed stands of beech and European larch established by Dippel, 1988 on soil derived from old red sandstone covered by a thin loess layer in the mountainous region of southern Lower Saxony and the Weser Mountains. Test plots are 0.09 to 0.49 ha in size and were originally designed as age series covering ages 49 to 149 for beech and ages 36 to 149 for larch (Table 1). Beeches have a maximum head start over larch of 25 years, so that the mixed stands are more or less even-aged and their vertical stand structure does not reflect the uneven age structure so much as the different growth rhythms inherent in the two associated species. For all experimental plots, yield-related inventories were available, including stem distribution data and canopy maps. The available data were therefore suitable for subsequent structural investigation. The 53 study plots represent a wide range of stand ages, with a basal area-related, intermingled larch portion of up to 40%. When establishing the plots, Dippel (1988) chose stand sections and plot sizes covering the typical mixture patterns that are formed when larch cohorts are mixed into incomplete natural regenerations of beech. Larch was intermingled with beech singly, in groups, in large and small clusters and in strips (for a definition of these mixture types see Niedersächsisches Ministerium Für Ernährung, Landwirtschaft und Forsten, 1987).

3. Measuring aggregation and segregation

The wide range of beech–larch mixtures on these plots is reflected by considerable variation in the aggregation index R by Clark and Evans (1954), as well as in the segregation index S by Pielou (1977). Both indices measure the tree distribution pattern (* * *).

3.1. Aggregation index by Clark and Evans

The aggregation index by Clark and Evans (1954) describes the ratio between the observed average distance $\bar{r}_{obs}$ of a tree to its nearest neighbour and the expected average distance $\bar{r}_{exp}$ for random tree distribution.

$$R = \frac{\bar{r}_{obs}}{\bar{r}_{exp}} \quad (1)$$

Theoretically, R lies between 0 (maximum clustering) and 2.1491 (strictly regular hexagonal pattern) and reveals whether trees in a stand are distributed regularly, randomly or in clusters. Aggregation values below 1 are indicative of a tendency towards clustering, while values around 1 indicate random distribution and those above 1 show a tendency towards regular distribution. R is derived from the nearest-neighbour method, by calculating the distances $r_{i,\ i=1 \ldots N}$ to their nearest neighbours for each of N trees on a test area of size A, using these distances to obtain the average distance to the nearest neighbour by

$$\bar{r}_{obs} = \frac{\sum_{i=1}^{N} r_i}{N} \quad (2)$$

The actual, observed distance to the nearest neighbour is related to the expected average distance $\bar{r}_{exp}$ for random tree distribution

$$\bar{r}_{exp} = \frac{1}{2\sqrt{\rho}} \quad (3)$$

with ρ denoting the number of trees per unit area ($\frac{N}{A}$). The aggregation index R thus measures the extent the observed distribution pattern diverges from a Poisson distribution. In accordance with Clark and Evans (1954), divergence from the Poisson distribution, either in favour of regularity or clustering, was subjected to a significance test (* * *). Edge effects were eliminated using an edge correction formula for compact unit areas by Donnelly (1978).

Fig. 1 shows the relation between spatial patterns and aggregation index R: on study plot 404, aged 76 yr (age of beech), which still retained a relatively large number of trees, the total population and the beech population, considered separately, appear to be randomly distributed ($R_{total} = 1.03$ and $R_{beech} = 1.01$). Larch, considered by itself, occurs in clusters ($R_{larch} = 0.56$). By contrast, the total population and beech on the 92-year-old, better differentiated study plot 204 already exhibited regular distribution ($R_{total} = 1.21$ and $R_{beech} = 1.11$). Here, larch occurs in

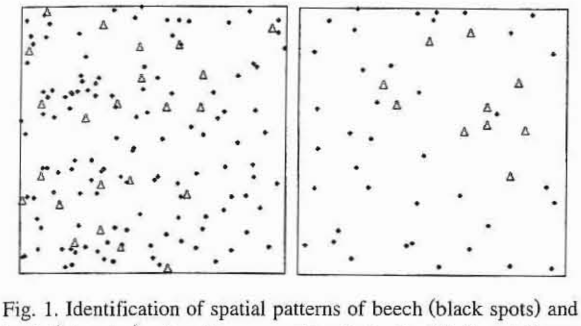


Fig. 1. Identification of spatial patterns of beech (black spots) and larch (triangles) using the aggregation index by Clark and Evans (1954); left plot 404 (40 m×40 m), $R_{total} = 1.03$, $R_{beech} = 1.01$, $R_{larch} = 0.56^{***}$; right plot 204 (40 m×40 m), $R_{total} = 1.21$ $R_{beech} = 1.11$, $R_{larch} = 0.58$.

groups and appears to be significantly clustered ($R_{larch} = 0.58$).

For the 53 mixed beech–larch stands, distribution indices for total population vary between $R_{total} =$ 0.95 and 1.36, i.e., tree distribution is random to regular (Fig. 2, top). There is an increase in regularity with progressive stand development, here expressed in terms of decreasing stem numbers. The aggregation value for larch only lies between R_{larch} = 0.41 and 0.92 and an average value of 0.667 for the entire age range indicates that this tree species occurs in clusters. Even with increasing stand age there is no change, i.e., large and small clusters and groups are being maintained (Fig. 2, centre). With values between $R_{beech} = 0.76$ and 1.27, beech initially tends to cluster and with increasing age, tends to favour random to regular distribution (Fig. 2, below).

3.2. Segregation measure S by Pielou

The segregation measure S by Pielou (1977) describes the combination or intermingling of two tree species, again according to the nearest-neighbour method (* * *). For its derivation, the species of the nearest neighbour of all N trees of a test plot are determined in a search run, giving the total number of trees of species 1 and 2 (m,n), as well as the number of trees with neighbours of their own species (a,d) or of the other species (c,b). The segregation measure S is then derived from

$$S = 1 - \frac{\text{observed number of mixed pairs}}{\text{expected number of mixed pairs}} \qquad (4)$$

and lies between -1 and $+1$. It is then calculated from the basic values as follows:

$$S = 1 - \frac{N(b+c)}{(vn+wm)}. \qquad (5)$$

To test the segregation indices for significant divergence from an independent distribution of the two mixed stand species, the χ^2 test recommended by Upton and Fingleton (1985) was used. If the observed number of mixed pairs is higher than expected, the result will be $S < 0$ and indicates a thorough mingling or association between species. Conversely, if the observed number of mixed pairs is

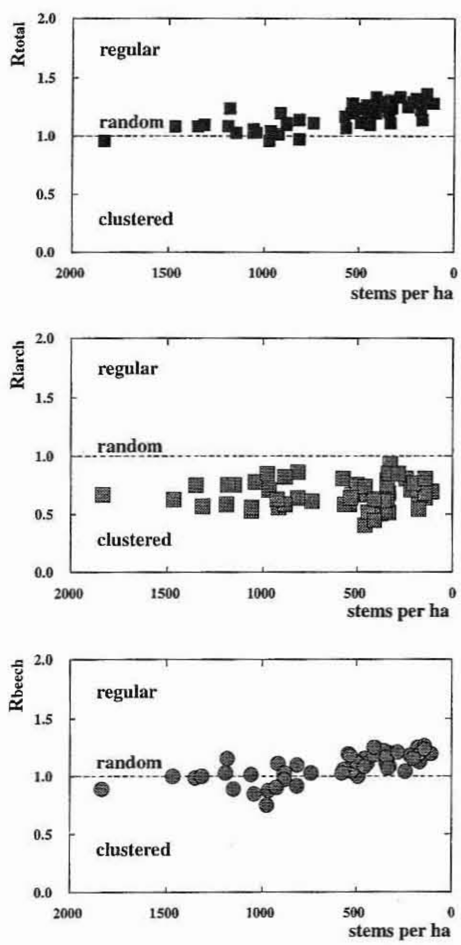


Fig. 2. Variations in aggregation indices R_{total} for the entire stand (top), R_{larch} for larch (centre) and R_{beech} for beech (below) in relation to decreasing stem numbers. The reference line ($R = 1$) represents random distribution, higher and lower values indicate a trend to regular and clustered distribution respectively.

less than expected, this leads to $S > 0$ and is indicative of segregation, i.e., the spatial separation of species. Where $S = 0$, the number of observed mixed pairs corresponds to that of the expected mixed pairs, i.e., the two species are distributed independently of one another.

Fig. 3 (from top to bottom) shows three test plots with increasing segregation of species. The intense intermingling of larch and beech on test plot 311 is reflected in the segregation index of $S = -0.25$. An almost independent distribution of beech and larch was recorded on test plot 403 with an index of $S = -0.01$, while test plot 401 shows pronounced segregation of beech and larch, with $S = 0.35$.

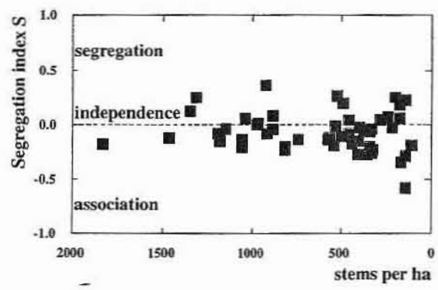


Fig. 4. Variations in the segregation index S with decreasing number of stems. The reference line ($S = 0$) represents the independent distribution of species; higher and lower indices indicate segregation and association of species, respectively.

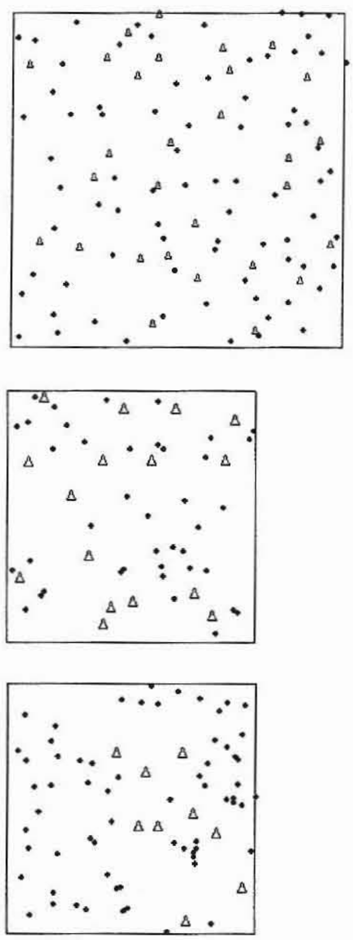


Fig. 3. Identification of the intermingling intensity of beech (black spots) and larch (triangles) on test plots 311 (above, 60 m×60 m, $S = -0.25$), 403 (centre, 30 m×30 m, $S = -0.01$) and 401 (below, 30 m×30 m, $S = 0.35$) using the segregation index S by Pielou (1977).

39 out of 53 test plots showed negative segregation indices (* * *), indicating a tendency towards association, which is rather rare in plant communities (Pielou, 1977). This may be attributed to the fact that larch trees, even when they grow in mixtures of small or large clusters, groups or strips are usually closely surrounded by beech trees and may thus be in closer contact with beech as their nearest neighbours than with their own species. This close association of beech and larch remains unchanged even with further stand growth, in other words no segregation will develop with progressive stand development (Fig. 4).

4. Modeling of spatial stand structures

In forestry practice, comprehensive data on stand structure such as what is available for the 53 test plots of this study are the exception. As a rule, we have to rely on qualitative descriptions of stand mixtures (e.g., large cluster mixture, group mixture) or on a combination of qualitative and numerical attributes (e.g., strip mixture with 15 m strip width). A structure generator was developed to optimize the access and exploitation of the structural information contained in these qualitative descriptions.

4.1. Functional principle of structure generator STRUGEN

The aim was to design a structure generator which, based on the descriptions of tree mixtures used in forestry practice, would generate stands whose dynamics-determined structural characteristics correspond to those of actual stands. In terms of the investigated mixed beech–larch stands, this means that a given number of beech and larch trees with known stem diameters and height distributions is to be arranged on a certain stand in such a manner that the greatest possible conformity be achieved between actual and generated structure. Conformity in this case does not mean that the location of a certain tree has to be identical for both actual and generated stand; rather, the dynamics-generated characteristics of actual and generated stand have to be comparable as far as intermingling intensity, contact frequencies as well as aggregation and segregation of tree species are concerned.

The STRUGEN structure generator was initially developed for mixed beech and larch stands, but is applicable, without great modification, to other pure and mixed stands. A description of merely the most important features of its functional principle will be given here. Assuming that the stem-diameter distribution of a two-species mixture of larch and beech as represented in Fig. 5 is to be arranged on a test plot by means of the STRUGEN generator. Then the first step will be to give all larch trees random,

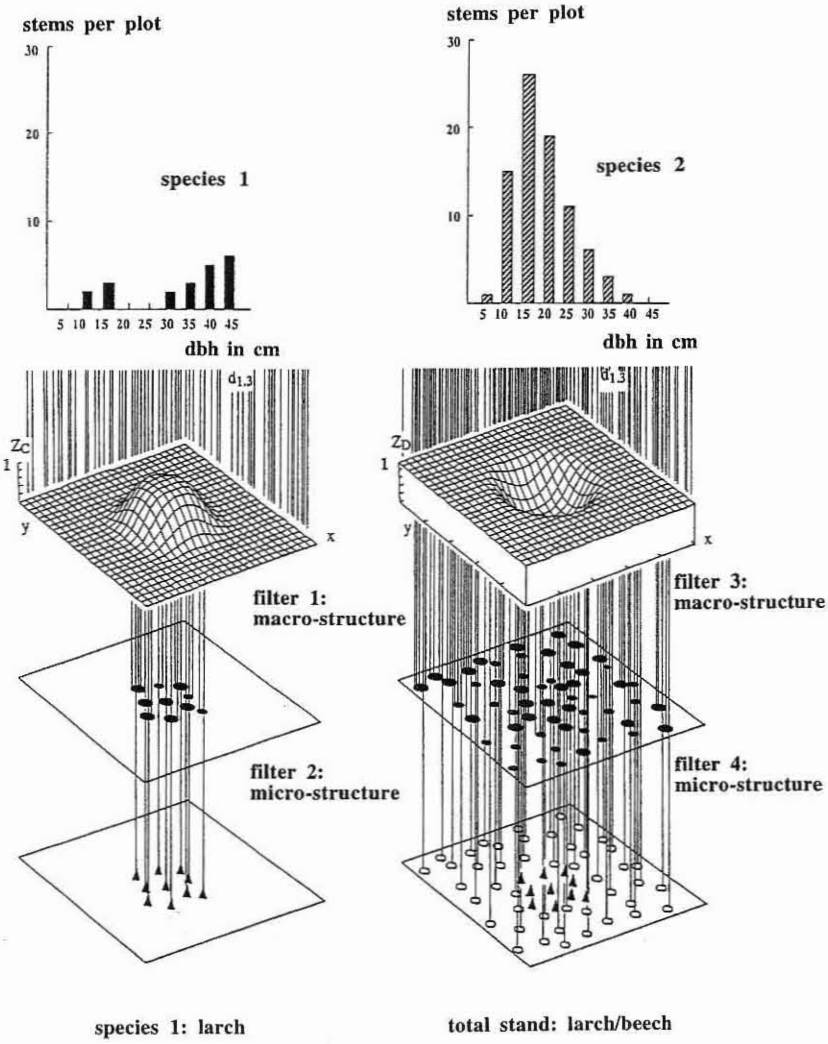


Fig. 5. Functional principle of the stand structure generator STRUGEN.

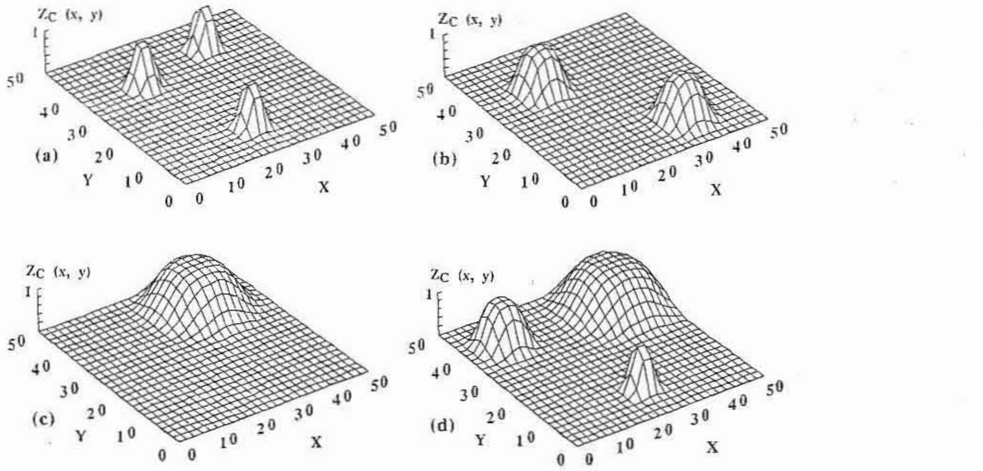


Fig. 6. Function $Z_C(x,y)$ for the generation of different mixture combinations on a 50 m × 50 m test plot. (a) Small cluster mixture, consisting of three clusters with $E = 10$, (b) Group mixture, consisting of 2 clusters with $E = 30$, (c) Large cluster mixture, consisting of one cluster with $E = 100$, (d) Combination of various mixture forms, consisting of circular clusters with $E = 10$, $E = 30$ and $E = 100$.

uniformly distributed x and y coordinates which fall in a 'shower of points' onto the plot (Fig. 5, left hand side). Hence, the starting point for the generator is a homogeneous Poisson process. To generate the macrostructure of the stand, the points are accepted with varying probability, controlled via the functions $Z_C(x,y)$ or $Z_S(x,y)$. In more descriptive terms, the points must pass filter 1 which regulates the mixture type by allowing random points with various position-dependent probabilities to pass through. From the points that have passed this filter, only those which have defined minimum distances to already established neighbours will be accepted, i.e., before points are finally accepted they have to pass a filter 2 which provides species-related distances between individuals, hence, determines the microstructure between the trees. This dissemination process is repeated until the entire stem-diameter distribution of larch has been taken care of. Finally, a second point process is started, introducing beech as the main tree species (Fig. 5, right hand side). Filter 3, which is the function $Z_D(x,y)$, controls the intermingling of beech and larch and a filter 4 secures minimum distances between neighbouring trees.

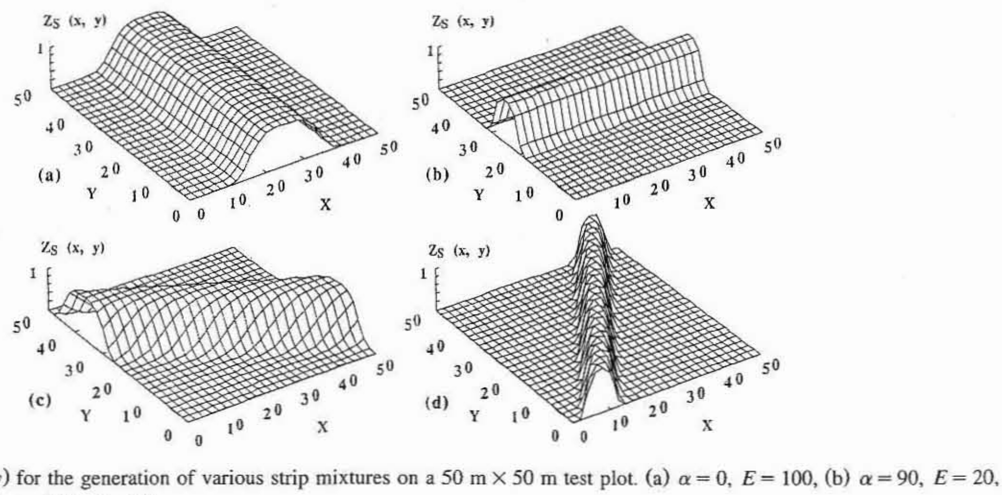


Fig. 7. Function $Z_S(x,y)$ for the generation of various strip mixtures on a 50 m × 50 m test plot. (a) $\alpha = 0$, $E = 100$, (b) $\alpha = 90$, $E = 20$, (c) $\alpha = 65$, $E = 50$, (d) $\alpha = 145$, $E = 10$.

4.2. Probability functions for the generation of circular clusters and strips

To generate mixtures in the form and size of small clusters, groups and large clusters (Fig. 5, filter 1) the following modification of a function developed by Lepš and Kindlmann (1987) is used which, for every point (x, y) on the test plot, indicates the probability between 0 and 1 for the occurrence of one of the associated tree species in this location:

$$Z_C(x,y) = \min\left(1, \sum_{i=1}^{q} e\left[\frac{-\left((x-X_i)^2+(y-Y_i)^2\right)^2}{E_i^2}\right]\right) \quad (6)$$

The randomly generated stem coordinates would provide a random or Poisson distribution; however, they are only being accepted with a position-dependent probability of $Z_C = f(x, y)$. This is achieved by accepting a point and establishing it as a stem coordinate on the test plot only if a uniformly distributed random number u ($u \in [0,1]$ is less than the value for $Z_C(x, y)$. In Eq. (6), q stands for the number of clusters to be established on the plot. X_i, Y_i, $i = 1 \dots q$ give the coordinates for the centre points of q clusters, while E_i, $i = 1 \dots q$ controls the diameters of q clusters. The closer a point lies to the centre of the cluster, the smaller distances $x - X_i$ and $y - Y_i$ will become, and the greater the probability for the point to be accepted, as the point moves towards 1.

Fig. 6 shows functions $Z_C(x, y)$ for generating small clusters, groups and large clusters of larch or various combinations of these mixtures in a main stand of beech. For every point on the test plot, they provide probability values between 0 and 1 with which the generated random points will be accepted as stems.

In the investigated mixed beech–larch stands in Lower Saxony, strip mixtures which are generated via the function

$$Z_S(x,y) = e\left[\frac{-\left(\cos\alpha(x-X_M)+\sin\alpha(y-Y_M)\right)^4}{E^2}\right] \quad (7)$$

prevail. Analogous to the modeling of round clusters, (Eq. (6)) E again denotes the intensity which determines strip width. The STRUGEN generator represents the strip axis as the transect $\cos\alpha \cdot x + \sin\alpha \cdot y = 0$ through the centre point (X_M, Y_M) of the test plot, unless otherwise specified. The gradient of this transect is used in Eq. (7) via the angle α between the straight line and the y-axis of the test plot. Fig. 7 shows function $Z_S(x, y)$ for different strip angles and strip widths with each strip running through the centre point of the plot. The following relationship exists between the diameter of the mixture unit D (D = opening width in meters with

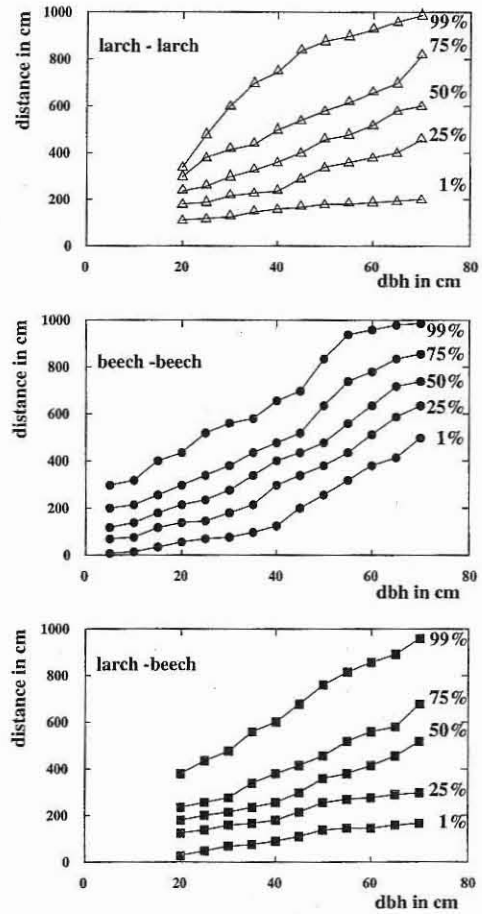


Fig. 8. Distances between larch and nearest larch (above), beech and nearest beech (centre), larch and nearest beech (below) in relation to tree diameter. The 1, 25, 50, 75 and 99 percentiles are shown, calculated for about 5000 trees on 53 experimental mixed beech–larch stands.

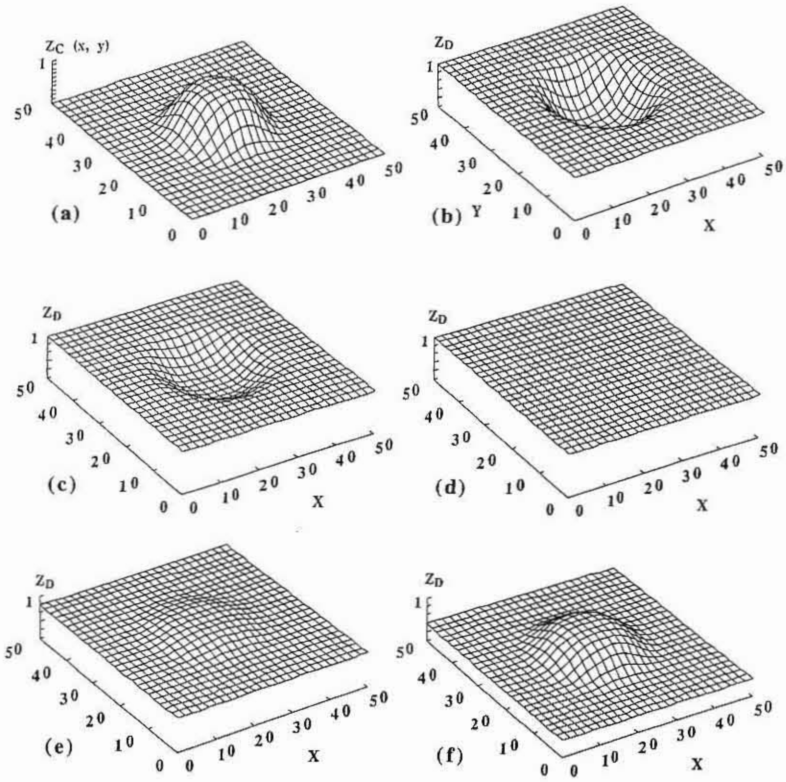


Fig. 9. Function $Z_C(x,y)$ for generating one big larch cluster ($E = 100$) in a main beech stand and function $Z_D(x,y)$ for the control of various intermingling intensities within that cluster. (a) $Z_C(x,y)$ for the establishment of a larch cluster, (b) $Z_D = 1 - Z_C$ generates slight intermingling, (c) $Z_D = 1 - Z_C \cdot 0.5$ generates moderate intermingling, (d) $Z_D = 1$ generates average intermingling, (e) $Z_D = 0.8 + Z_C \cdot 0.2$ generates strong intermingling, (f) $Z_D = 0.4 + Z_C \cdot 0.6$ generates very strong intermingling.

$Z_C(x,y) = 0.05$) and intensity E of the probability function

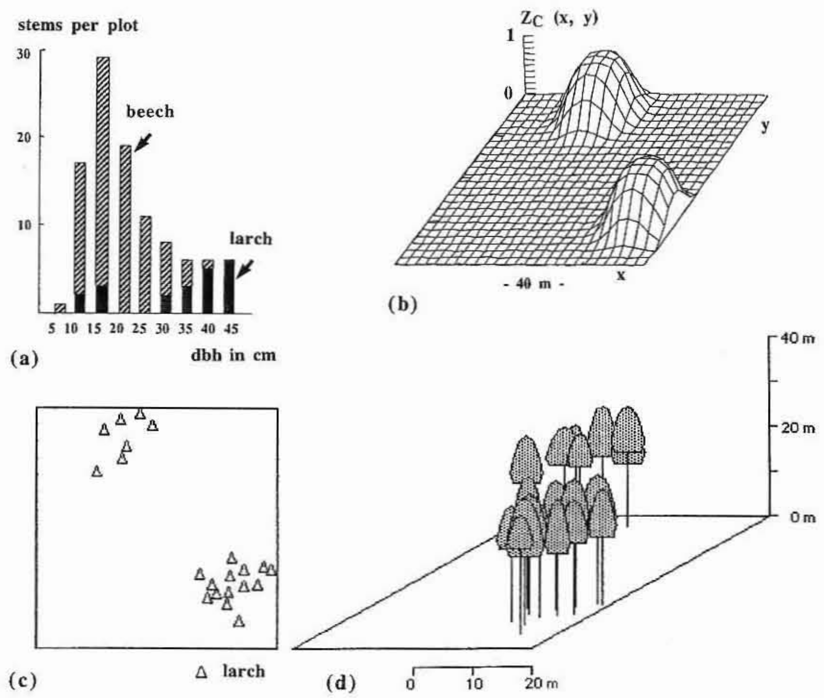
$$E = 0.1444 \cdot D^2 \quad (8)$$

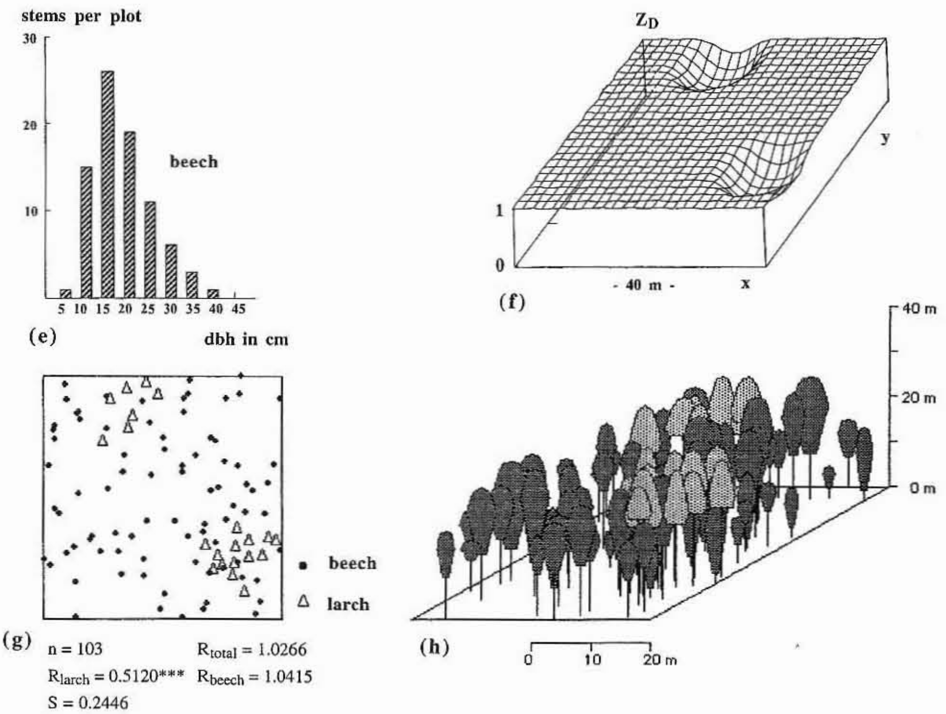
so that for a mixture to be generated, the corresponding intensity E can be derived from D and used to form Eqs. (6) and (7).

4.3. Percentile lines and minimum distances

Generated random points are only accepted if they lie outside the minimum distance, i.e., outside the individual distance range, so to speak, of already established trees. To determine these distances, limits for the 5000 trees of the plot series were deter-

Fig. 10. Generating larch in group mixtures and beech with moderate intermingling of larch. (a) Stem-diameter distribution of test plot 105 to be established in the first step, (b) Function $Z_C(x,y)$ for generating larch in group mixtures ($X_1 = 15$, $Y_1 = 35$, $X_2 = 35$, $Y_2 = 10$, $E_1 = 32.49$ and $E_2 = 32.49$), (c) Stem chart of generated larches, (d) Generated larch groups, lateral view. (e) Stem-diameter distribution of beech to be established in a second step, (f) Function $Z_D(x,y)$ for generating moderate intermingling of larch and beech trees, (g) Stem chart of generated mixed beech–larch stand with indices of aggregation and segregation, (h) Generated mixed beech–larch stand, lateral view.


stems per plot
30
20
10
beech
larch
5 10 15 20 25 30 35 40 45
(a)
dbh in cm
Z_C (x, y)
1
0
y
- 40 m -
x
(b)
40 m
20 m
0 m
(c)
Δ larch
(d)
0 10 20 m


stems per plot
30
20
10
beech
5 10 15 20 25 30 35 40 45
(e)
dbh in cm
Z_D
y
1
0
- 40 m -
x
(f)
40 m
20 m
0 m
• beech
Δ larch
(g)
n = 103
R_{total} = 1.0266
R_{larch} = 0.5120***
R_{beech} = 1.0415
S = 0.2446
(h)
0 10 20 m

mined. Distances were measured for larch to the nearest neighbours of their own species, beech to the nearest beech and larch to the nearest beech and tree diameters were recorded. Based on these data the 1, 25, 50, 75 and 99 percentiles of these distances in relation to diameter are represented in Fig. 8. These percentiles reveal, e.g., that at 99 percentile of the observed cases, larch trees with diameters of 50 cm were located over 180 cm away from the nearest larch, while the distance between beech and the nearest neighbouring beech was 250 cm. The shortest distance was found to be the individual distance between larch and beech with 160 cm. The variations in plotted percentile lines are reflections of the competitive behaviour typical of these species. The following parameterised 1 percentile (minimum distance, M_{dist} and tree diameter at breast height, dbh in cm)

$$M_{dist}\ \text{larch} \rightarrow \text{larch} = e^{3.190} \cdot \text{dbh}^{0.504} \quad (9)$$

$$M_{dist}\ \text{beech} \rightarrow \text{beech} = e^{-0.421} \cdot \text{dbh}^{1.507} \quad (10)$$

$$M_{dist}\ \text{larch} \rightarrow \text{beech} = e^{-0.374} \cdot \text{dbh}^{1.323} \quad (11)$$

are used in the generator to act as filters 2 and 4 (see Fig. 5) which secure tree species-related and diameter-dependent minimum distances.

4.4. Probability functions for modeling intermingling within clusters and strips

Filter 3 controls the intensity with which the main tree species beech was mixed into round clusters and strips of larch. Here, the function Z_D is used which gives the probability of the acceptance of random points for every location on the test plot. Eqs. (6) and (7) are used to establish function Z_D. While the function $Z_C = f(x, y)$ (see Fig. 9a) was used to model larch groups on the test plot, function $Z_D = 1 - Z_C$ shown in Fig. 9b gave merely a weak intermingling of larch groups with beech. This is due to the fact that at the centre of the larch group, where larch is being accepted with a probability of $Z_C = 1$, there are no beech trees because at that point $Z_D = 0$ ($Z_D = 1 - Z_C = 0$). At the periphery of the plot, where larch is being accepted with a probability of $Z_C = 0$, beech manages to establish itself, as here $Z_D = 1 - Z_C = 1$. Hence, there will only be slight intermingling at the periphery of the group, with $0 < Z_D < 1$; while the presence of either tree species more or less precludes the presence of other species at the centre of the cluster. There are five stages of intermingling intensity (Fig. 9, b–f): slight, moderate, average, strong and very strong (Eqs. (12)–(16)).

$$Z_D = 1 - Z_C \quad (12)$$

$$Z_D = 1 - Z_C \cdot 0.5 \quad (13)$$

$$Z_D = 1 \quad (14)$$

$$Z_D = 0.8 + Z_C \cdot 0.2 \quad (15)$$

$$Z_D = 0.4 + Z_C \cdot 0.6 \quad (16)$$

To model the intermingling of strips, Z_S has to take the place of Z_C in Eqs. (12)–(16), so that corresponding values for Z_D, which control the acceptance or rejection for different intermingling intensities in strips, become available. These five functions correspond to the five-stage response scale for intermingling intensities (slight, moderate, average, strong and very strong).

5. Algorithmic sequence of structure generator STRUGEN

To generate the structure of a stand the following algorithmic sequence is adopted: In the first step, the generator is fed with data on the stem-diameter distribution of both main and associated tree species and the dimensions of the test plot to be modeled. In the second step, the stand space requirements for the tree species involved are calculated on the basis of diameter data and a tree species-related fundamental relationship between diameter and crown width (Pretzsch, 1993). The intermingling configuration is specified in the third step: mixture form (strip or cluster), the size of mixture units (strip width or cluster diameter) and intermingling intensity (slight, moderate, average, strong and very strong) are fed into STRUGEN. This specifies the extent to which larch units are to be intermingled with beech. In the fourth step, these mixture attributes and the stand space requirements from step 2 automatically lead to the derivation of filter functions Z_C, Z_S and Z_D described in Sections 4.1, 4.2, 4.3 and 4.4. In the fifth step, according to a process shown in Fig. 5, distributions are being generated based on the diameter distribution data and the specified mixture patterns. This is followed in the sixth step by the calculation of the aggregation and segregation indices *R* and *S*. The generating run ends with the seventh step in which stem distribution plans and three-dimensional stand images are being produced for the generated stand using the fundamental relationships between diameter and height, diameter and crown width and diameter and crown base (Pretzsch, 1993).

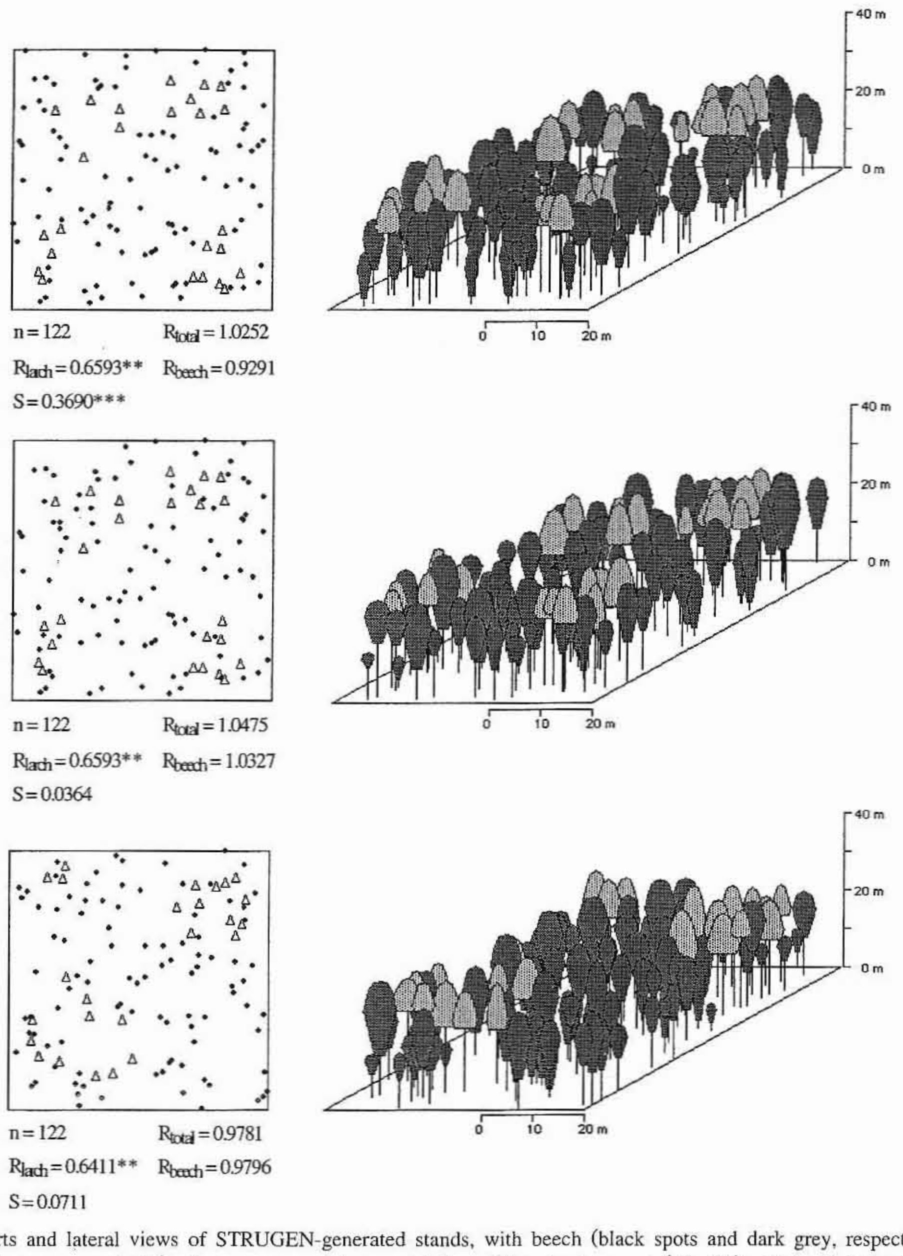


Fig. 11. Stem charts and lateral views of STRUGEN-generated stands, with beech (black spots and dark grey, respectively) and larch (triangles and light grey, respectively). Above, group mixture consisting of four larch groups ($E = 35$) with weak intermingling intensity. Centre, group mixture consisting of four larch groups ($E = 35$) with average intermingling intensity. Below, small to big clusters, consisting of three larch mixture units ($E = 10$, 35 and 90) and average intermingling intensity.

6. Efficiency tests based on mixed beech–larch stands in Lower Saxony

For the following test run data on the stem-diameter distribution of test plot 105 (beech: 82 trees per plot, dbh range = 5–40 cm, mean dbh = 17.9 cm; larch: 21 trees per plot, dbh range = 10–45 cm, mean dbh = 37.7 cm) are fed into STRUGEN (Fig. 10a) which are then to be distributed on a 40 m × 40 m test plot in such a manner that larch will be intermingled with beech in groups (diameter of the group $D = 15$ m) and the larch groups will be moderately intermingled with beech. The generator at first, internally, builds the function $Z_C(x,y)$ (Fig. 10b), which establishes larch trees in group mixtures (Fig. 10c and d). This is followed by the dissemination of beech (Fig. 10e), with the function $Z_D(x,y)$ (Fig. 10f) causing beech to become moderately intermingled with the larch group (Fig. 10g and h). The index by Clark and Evans (1954) (Fig. 10g) indicates that total population ($R_{total} = 1.0266$) and the beech population ($R_{beech} = 1.0415$) are almost randomly distributed and that larch occurs in clusters to a significant extent ($R_{larch} = 0.5120$). The segregation index by Pielou, 1977 ($S = 0.2445$) shows a tendency towards spatial segregation of larch and beech.

The generator produces a wide spectrum of intermingling variants and helps to better understand the relationships between structure and distribution indices. The stands produced by STRUGEN (Fig. 11) were found to be very characteristic of the mixed beech–larch stands investigated in this study. Likewise, beech stands, intermingled with larch trees in rows, were found on a number of plots and can also be generated by means of STRUGEN.

A first validation was carried out for the 53 test plots in which mixture forms (clusters or strips), dimensions of mixing units (width of strips and diameter of clusters in m) and intermingling intensities (slight, moderate, average, strong and very strong) were recorded. Based on this mixture configuration, the STRUGEN program was used to generate stand structures for all 53 test plots and to determine the distribution indices R_{larch}, R_{beech}, R_{total} and S. The comparison between the structure indices of the modeled stands and the real distribution indices was a measure of the performance of the STRUGEN stand structure generator (Fig. 12).

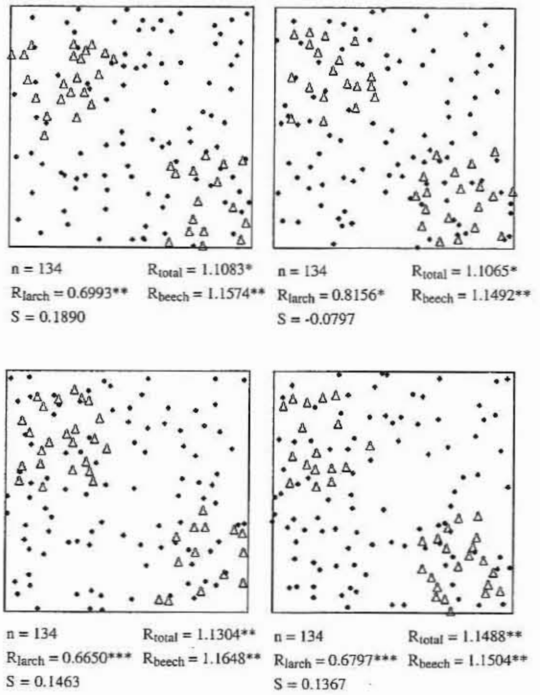


Fig. 13. Stem charts for various random generations of a large cluster mixture consisting of two clusters with $E = 90$ and average intermingling of the larch groups with beech. Beech and larch trees are represented by black spots and triangles, respectively (area dimensions: 50 m×50 m).

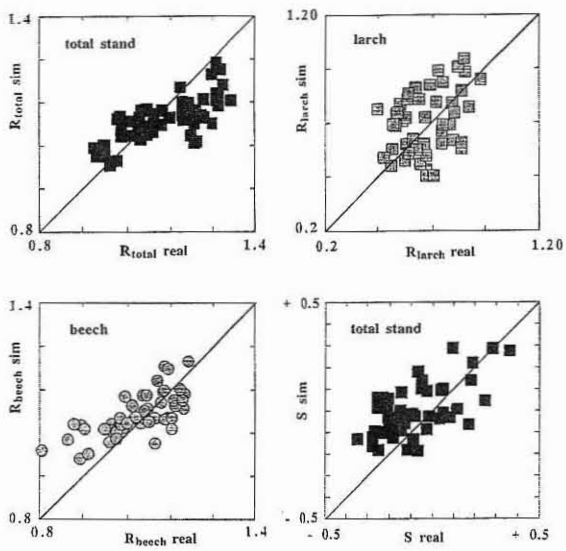


Fig. 12. Comparison between generated and real stand structures, with the simulated structure parameters R_{total}, R_{larch}, R_{beech} and S above the real structure parameters. Generated structural parameters are mean values from 10 simulation runs.

The simulated structure parameters in Fig. 12 are averages from 10 simulation runs. Repetitions of simulation runs are advisable because the generator operates with random numbers and gives slightly different results for each run (Fig. 13). For complete agreement, data pairs R_{total} real/R_{total} simulated, R_{larch} real/R_{larch} simulated, R_{beech} real/R_{beech} simulated and S real/S simulated would have to coincide with the line dissecting the angle. For all distribution indices, the comparison between simulation and reality showed good correlation. The Pearson coefficients for the correlation between the real and the simulated indices shown in Fig. 12 are 0.89, 0.72 and 0.83 for aggregation indices R_{total}, R_{larch}, R_{beech}, respectively and 0.85 for segregation index S. These results are indicative of the relatively realistic predictions by the STRUGEN generator, and of its potential for further improvement.

7. Discussion

The STRUGEN generator was designed to pave the way for the large-scale use of position-dependent single-tree growth models (Pretzsch, 1992). In contrast to position-independent models, which disregard the decisive impact of spatial stand structure on stand development, position-dependent models consider the feedback between structure and growth and are therefore the best possible approach to the modeling of mixed stands. Distance-dependent single-tree growth models break down stands into tree mosaics and model tree interactions as a dynamic space–time system. Based on the initial constellation at time $t = 0$, the dimension development of any tree in a stand is explained in terms of its individual growth constellation. To date, the applicability of position-dependent growth models has been very limited, since the stem coordinates of all single trees need to be recorded as the basic values, which are usually only available for long-term experimental plots or permanent sample plots.

The STRUGEN generator permits initial constellations for a model run to be produced even for stands whose tree distribution is not exactly known and for which only qualitative descriptions exist as is the practice in forest management. The dynamics-determined characteristics of this generated initial constellation are obviously in good agreement with those of the real starting constellation. Qualitative descriptions of the mixture type, e.g., groups, small and large clusters, are converted by the generator into concrete starting images to serve as the basis for forecasting runs by subsequently applied growth models. STRUGEN makes quantitative and qualitative information on stand structure accessible for use in realistic stand predictions. In particular, the potential of qualitative information is not used in position-independent models, whereas the combination of STRUGEN and a position-dependent growth model such as SILVA 2.0 promises a more efficient use of the entire available information (Pretzsch, 1996; Pretzsch and Kahn, 1996).

When the entire structural data material of an inventoried stand is available, including the stem coordinates at time $t = 0$, the model naturally uses the original values. Whenever tree distribution is unknown, however, and only qualitative descriptions of the mixture type exist, STRUGEN will serve as a data generator, i.e., it will produce more or less realistic stand structures which can be used as basic values in growth models. In conjunction with the position-dependent single-tree model SILVA 2.0 which represents stand development as a space–time system, the ability of the generator to produce any required stand structure makes it possible to investigate the effects of stand structure on the yield-related, silvicultural and ecological parameters of stand development (Pretzsch, 1996).

This attempt at bridging the gap between qualitative descriptions of structural characteristics and actual starting values for high-resolution single-tree models is necessarily based on some provisional methods which require further refinement. At this juncture, it was less important to make methodological progress in developing individual steps of the process than to find a pragmatic solution for the overall concept and to develop a program routine in which this gap-bridging enterprise (nominally and ordinally scaled structural attributes → basic values) could be achieved by computerised methods.

8. Conclusions

Once a start had been made towards a feasible solution, various ways and means to improve the process become apparent.

The basic elements for generating spatial patterns are the two tree species and the homogeneous Poisson processes which are converted into inhomogeneous Poisson processes with the aid of filters 1 and 3. No generated points are accepted unless they are at certain species- and diameter-related minimum distances from one another (filters 2 and 4). So called hard-core processes are thus initiated, i.e., accepted points are surrounded by a defined core zone entirely free from other points, while outside this zone point density ρ rises abruptly. A sharp demarcation between a narrow core zone defined by minimum distances, where competition precludes the growth of neighbours, and a wide surrounding zone without competitive influence is used as a first approximation. Perhaps it would be more realistic to assume a smooth transition from a narrow core zone without any competitors whatsoever, (e.g., within the stem radius) to an intermediate zone in which reciprocal growth inhibition of neighbouring trees steadily declines with growing distances between trees and, finally, to a zone where neighbouring influences are no longer to be expected. To model this kind of competition by neighbours and growth inhibition which decreases with growing distances between trees, soft-core processes with paired interaction, e.g., the Gibbs process as applied in statistical physics can be used. Used in conjunction with the STRUGEN process, this could further improve the hard-core principle presently in use.

In its current version, STRUGEN is suitable for more or less monolayer pure stands and for mixed stands involving two species. Moreover, additional filter functions which control the presence of main and associated tree species at different levels of stand height would also permit the use of STRUGEN in multilayer stands. For this, tree species-related functions $Z_V = f(H_{rel})$ proved suitable which describe the probability of the presence of main and associated tree species (Z_V, so that $0 < Z_V < 1$) for relative heights ($H_{rel} = \frac{H}{H_{max}}$) and whose functional parameters are based on qualitative descriptions of the vertical structure, as practised in forest management (Niedersächsisches Ministerium Für Ernährung, Landwirtschaft und Forsten, 1987).

For the generating process, STRUGEN in its present form has to be supplied with data on diameters and species of all the trees growing on the test area to be reproduced. The stem-diameter frequencies for main stands and associated tree species may be based on completely inventoried plots, angle counts and sample circle counts that are frequently, although not as yet consistently, being used. For use in stands whose stem-diameter distributions are not known, a program routine will, in the future, precede STRUGEN which is designed to generate realistic stem-diameter distributions from the minimum information usually available for almost any stand (age, average diameter, average height and number of stems). Fed into STRUGEN, these data will serve as starting values.

The distance-measuring method used in this study involves only the nearest neighbours and analyses the fine-grained texture of a tree's neighbourhood. Characteristic spatial patterns exist at different levels of resolution (e.g., whether a stand consists of large clusters, each composed of small groups with regular patterns as in a chessboard) cannot be revealed with adequate accuracy by the nearest-neighbour method. Galiano (1982) and Ripley (1977) describe improved distance-measuring methods which reach beyond the nearest neighbour and consider trees farther away. These methods identify aggregation and segregation at various hierarchic levels of resolution and may be characterised by corresponding indices.

The essential steps towards adapting the STRUGEN generator to mixed stands of larch and beech were to develop and parameterise the 1 percentile, to develop appropriate rules for generating location and size of mixing units and to determine the intermingling functions. The procedure for estimating the parameters of point processes from available distribution patterns is not as straightforward as it would be e.g., for a regression equation. Methods are still being developed with which the actual realisation of point processes with heterogeneity at different hierarchic levels can be measured without much effort and can be accurately parameterised as well as computer-generated within a reasonable period of time (Penttinen et al., 1992; Ripley, 1981; Stoyan, 1987; Tomppo, 1986). This study shows that the distance-measuring methods used by STRUGEN may well lead to the use of a uniform process to measure and identify spatial patterns, determine distribution parameters for various part processes and to reproduce observed patterns in appropriate models. Recent results that improved elements can replace some of the original pragmatic ones without the need to redesign the entire generator.

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