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MODELLING GROWTH OF BAVARIAN MIXED STANDS IN A CHANGING ENVIRONMENT

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ABSTRACT: The tree position-dependent simulator SILVA 2 prognosticates the growth of multi aged pure and mixed stands in Bavaria by reproducing diameter, height, crown length, crown width and mortality of every single tree. As input data SILVA 2 needs variables of tree dimensions, climatic and site conditions as well as information about stand structure and thinning regime. Its initial values, control items and results are closely related to the requested information of forest practice. The simulator is constructed, parameterized and validated mainly on the base of experimental plots with up to 120 years survey. When using SILVA 2 as prognosis and research tool the stand structure generator STRUGEN can be preinstalled as an intermediate unit which generates lacking information about structure and dimension by using the verbal findings concerning stand structure. Climate and site sensitive growth of height and diameter is modelled basing on a system of empirically parameterized response functions that includes climate variables and soil characteristics as well as CO_2 and NO_X-effects and was implemented in the site modul STAOPROD. The core of the in SILVA 2 implemented thinning modul STRUMOD is a rule based fuzzy logic controller. Beside this rule based approach algorithmic thinning instructions are implemented too.

KEY WORDS: Single-tree simulator, space-time model approach, stand structure generator, fuzzy logic controller for thinning regimes, dose-response functions, climate and site conditions

OBJECTIVE AND CONCEPTION OF THE MODEL

The demand for new forest management models has above all three reasons: Firstly forestry has to a growing extent established and taken care about mixed stands for which planning tools are still missing. Secondly, the demands of forest management for information have changed from mean values of the stand and sums per hectare to details on single stem growth under new thinning regimes. Thirdly, numerous recent surveys indicate that we can no longer suppose the conditions of growth to be static and our yield tables have to be replaced by a new more flexible system of prediction. The presented position-dependent simulator SILVA 2 prognosticates the growth of all aged pure and mixed stands in Bavaria by reproducing diameter, height, crown length, crown width and survival status of every single tree (PRETZSCH, 1992). As input data SILVA 2 needs variables of tree dimensions, climatic and site conditions as well as information about stand structure and thinning regime. Its initial values, control items and results are closely related to the requested information of forest practice.

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SITES AND MATERIALS

The construction of SILVA 2, its calibration and validation for pure and mixed stands of spruce (Picea abies L. Karst.) and beech (Fagus sylvatica L.) is based on three growth and yield data sources with different regional and temporal scales and on plots with different survey intensities. The interrelation between environmental conditions and growth reactions in terms of the parameterization of potential height curves in dependence on site conditions is as a first data source based on 72 and 109 resp. long term experimental plots in spruce and beech stands. They represent a broad spectrum of site conditions from Northern Germany to Switzerland.

The construction and calibration of the basic competition dependent growth functions of the simulator SILVA 2 is as a second data source mainly based on the results of five experimental areas of mixed stands with spruce and beech with a total of 22 plots in the forest district of Zwiesel in the Bavarian Forest - under constant observation by the Chair of Forest Yield Science at the University of Munich.

As a third data source serves a series of 6 plots near Freising and 9 plots near Schongau (both Bavaria) representing all age phases in mixed stands of spruce and beech. These two age series were established recently to get additional data about the change of the crown dimensions with increasing age, about the growth and competition in the juvenile and adult growth phase and about the annual incremet reactions after thinning. In addition to standard surveys, stem distribution maps, assessment of the crown radii and the height to crown base as well as increment boring cores, covering the diameter growth in the last 40 years, were analyzed.

QUASI CAUSAL ESTIMATION OF THE POTENTIAL HEIGHT AND DIAMETER GROWTH

Basic Considerations for the model interface STAOPROD

In a changing environment tree and stand growth simulators without climate and site sensitivity are unsatisfactory for many applications in management and science. Nevertheless, including valid site dependent functions into growth models is rather difficult. So the site model of SILVA 2, named STAOPROD, is based on three main conceptual ideas. The first is to establish a site sensitive growth potential for height and diameter development over time. The second conceptual idea is to design a site model that does not only fit the empirical data best but that does also seem to be biological plausibel on a theoretical basis. In respect of modelling a site sensitive height growth potential over time these two concepts lead to the application of the growth function from VON BERTALANFFY (ZEIDE, 1993). The site sensitivity of this function is then expressed by defining the growth function parameters as variables which depend on site factors. In accordance to the second conceptual idea these site sensitive functions should be biological plausibel too. Therefore a system of onedimensional unimodal dose-response-relationships is defined, reflecting the well known fact that there is an optimum supply of a plant with a site factor and that too much and too less of factor supply lead to reduced growth, whilst all other site factors remain constant.

Although many basic relationships between tree growth and environmental factors are well understood, the suitable data collected by growth and yield research could hardly be made accessible for prognosis. This was often neglected in the past. An example is the estimation of nutrient and water supply by verbal description which contains highly aggregated information seldom used for growth prognosis in an adequate manner. As far as we have to rely on those highly abstract data it is defined as a third conceptual idea for the site interface STAOPROD to use the available qualitative data and to make them numerical accessible by transforming ordinal scaled into metrical scaled data.

It can be summarized that the intention was to formulate the models for potential height and diameter growth as a syntheses between an empirical and a theoretical approach. In addition there should be used as much empirical data as available and biological principles where quantitative information is missing. As the core of the growth model SILVA 2 the following potential increment modifier principle is designed:

$$z = z_{pot} * \text{Modifier} + \varepsilon$$

So the estimation of the potential growth z_{pot} seems to be the suitable starting point to implement environmental effects in the model. This begins with the derivation of a formula which tries to explain the potential height increment in dependence on site factors.

Growth function and site variables

Following the first conceptual idea of using a growth function to model potential top height development h_{pot} over time VON BERTALANFFYs growth function is applied as

$$h_{pot} = A * (1-e^{-k*t})^3.$$

Site sensitivity of this function is introduced by defining the parameters A and k as functions of site variables. Because it is rather difficult to give an adequate biological interpretation of the slope parameter k, it is transformed by

$$k = \frac{-\ln(1/3)}{ct}$$

where ct determines the inflexion point of the height curve. Thus the slope parameter k can be interpreted using the biological more satisfying variable of the time, when height increment culminates. The next step is then to find a biological plausibel mathematical definition to express the asymptote A and the culmination time ct as functions of site factors.

The following set of site variables, available on different scale levels, is implemented in the model STAOPROD as growth determining:

- s_1 = nutrients supply of the soil (ordinal)
- s_2 = NO_x-concentration in the air (metric)
- s_3 = CO_2-concentration in the air (metric)
- s_4 = length of the growing season (metric)
- s_5 = difference between temperature of the warmest and coldest month (metric)
- s_6 = mean temperature in the growing season (metric)
- s_7 = index for the draught in the growing season (metric)
- s_8 = precipitation in the growing season (metric)
- s_9 = wetness of the soil (ordinal)

Only the variables nutrients supply and wetness of the soil are on ordinal scale level. These two variables are expressed as linguistic variables applying a fuzzy set theoretic approach (ZIMMERMANN, 1991). Following CHEN and HWANG (1992) standardized lingustic variables are used with normalized abscisses and ordinates, and the verbal descriptions of the soil characterisitcs, for example "the nutrient supply is high", are now defined as fuzzy sets. Again following CHEN and HWANG (1992) these fuzzy sets are numerically approximated to real numbers, an approach which has originally been developed to rank fuzzy described decision alternatives on the real numbers. This defuzzification completes the transformation of the lingustic terms to real numbers out of [0,1] (KAHN, 1994).

Response functions

Now that all site variables $s_{n,\ n = 1 \ldots 9}$, are available on a metrical scale level for each of them unimodal response functions $r_{n,\ n = 1 \ldots 9} = f\ (s_{n,\ n = 1 \ldots 9})$ are formulated, which map the dose (the factor supply) of the site factors on a [0,1]-normalized response space. These functions are parameterized combining empirical data and theoretical considerations. The last aspect means that the response functions are forced to have an unimodal shape (optimum curves) and that for example the response function on precipitation in the growing season for beech must have its maximum on lower precipitations than that for spruce.

Aggregation mechanisms

The resulting [0,1]-normalized site variables $r_{n,\ n = 1..9}$, which express the effect of a given factor supply on height development, are then combined by aggregation to three complex ecological site factors $e_{1..3}$. In accordance to the conceptual idea of enforcing biological plausibility it should be possible with the aggregation mechanism to reflect MITSCHERLICHs mimimum law as well as the phenomenon of compensation between site factors. These only on a first view contradicting demands are fullfilled applying a so called general aggregation operator, the γ-operator developed by ZIMMERMANN and ZYSNO (1980), which is also called "exponential compensatory and":

$$e_j = \left(\prod_{i=1}^{9} r_i\right)^{1-\gamma_{j+2}} * \left(1 - \prod_{i=1}^{9} (1 - r_i)\right)^{\gamma_{j+2}}$$

with , j=1 ... 3 and

e	=	complex ecological factor
r	=	response value of a given site factor supply
γ	=	compensation parameter out of [0,1]

This fuzzy set theoretic aggregation operator can be applied reasonably because the response values r_i of the site factor supplies are available as real numbers out of [0,1], similar to fuzzy sets with normalized membership functions. The compensation parameter γ out of [0,1] expresses high and low resp. compensation between the factors when approaching 1 and 0 resp. Thus we get the three complex ecological site factors $e_{1 \ldots 3}$ as

$$e_1 = f\ (r_{n,\ n = 1 \ldots 3}, \gamma_3)$$
$$e_2 = f\ (r_{n,\ n = 4 \ldots 6}, \gamma_4)$$
$$e_3 = f\ (r_{n,\ n = 7 \ldots 9}, \gamma_5)$$

and e_1 can be interpreted as the nutrient supply of the site, e_2 expresses the temperature situation of the site and e_3 the water supply of the site. In these ecological factors compensation can only take place between factors of similar physiological effects, for example soil wetness and precipitation or mean temperature in and length of the growing season. In the next step of aggregation there will also be possible a compensation between water and nutrient supply and temperatur, so that from a methodical point of view we have an aggregation hierarchy (Fig. 1). In this step the ecological factors are mapped on asymptote of height growth A and culmination time of height increment ct. Applying the powerful γ-operator again, the parameters A and ct of the potential height curve depend only on $e_{1 \ldots 3}$ and the degrees of compensation γ_1 and γ_2:

$$A = f\ (e_{1 \ldots 3}, \gamma_1)$$
$$ct = f\ (e_{1 \ldots 3}, \gamma_2).$$

Potential tree height increment

The parameterization of the SILVA 2 interface STAOPROD is based mainly on data from pure stands of spruce and beech as desribed before as a first data source. The height modelled is the top height. For use in a single tree simulator as SILVA 2 the site dependent top height has to be transformed into a potential height growth of a single tree. Based on the data it was possible to find out that with a probability of 0.99 there was no spruce and no beech resp. that was more than 13.8% and 13.2% resp. higher than top height.

The potential tree height growth does not directly provide a potential tree height increment, given the tree dimensions and site conditions, and which is tree individually reduced by including competitive stress. So assuming first that the environmental conditions have not changed given a tree height h_1 its physiological age can be approximately deduced as

$$t = -\frac{\ln\left(1-\sqrt[3]{\frac{h1}{A}}\right)}{k} .$$

After a time period Δt the height h_2 will be

$$h_2 = A * (1 - e^{-k*(t+\Delta t)})^3$$

and so follows

$$zh_{pot} = h_2 - h_1 .$$

Assuming a change in environmental conditions which leads to a change in height growth, i.e. a change in asymptote A and/or the inflexion point ct and slope paramter k resp., hypothetical tree age is calculated inserting A and k resulting out of the new environmental situation into the inverse growth function and using also these parameter values to determine h_2. Yet if actual tree height is larger than the asymptote after environmental change, the potential height increment ist set to zero. Of course this approximation method only leads to reasonable results if the time steps Δt and the environmental changes per time step are kept small and if it is assumed that the tree is capable of reacting on environmental change without additional complications.

Modelling site dependent diameter growth

The derivation of a site dependent potential or maximum diameter d_{pot} is based on the site dependent calculation of the potential tree height h. With

$$d_{pot} = -\frac{\ln\left(1-\sqrt[p]{\frac{h-1.3}{a}}\right)}{m}$$

the top diameter can for example be estimated with a r^2 of 0.98 for spruce. Obviously this function is the inverse of the CHAPMAN-RICHARDS growth function with the asymptote a and the slope parameters m and p (Fig. 2). This potential top diameter can in a next step be easily transformed (increased) into a potential tree diameter which is necessary for the "potential modifier approach".

An additional site dependent diameter formulation is introduced with a potential modifier function that reduces the potential tree diameter increment zd_{pot} to the actual tree diameter increment zd which is mainly dependent on the trees competitive situation. This can be summarized with

$$zd_{pot} = d_2(h_2,a,m,p) - d_1(h_1,a,m,p)$$

and

$$zd = f(zd_{pot}, \text{tree dimensions, competitive situation, site conditons}).$$

This implies that a tree species specific ability to endure a given competitive stress, i.e. to realize a certain diameter increment zd, is again dependent on site specific conditions ($e_{1 \dots 3}$).

COMPETITION MODEL

Index KKL as indicator for the crown competition

For the calculation of the crown competition index KKL in 60 % of the height of the tree in question j a light cone with the angle of 60° is constructed (Fig. 3). All trees reaching with crowns into the light cone are identified as competitors. In figure 3 for example tree 1 is identified as competitor of tree j. For all competitors the angle $BETA_{ij}$ between the basis of trees j light cone and the connecting line from the basis of the cone to the tip of the adjacent competitor i is calculated. The bigger the angle $BETA_{ij}$ the closer the competitor is positioned near the tree in question or the higher it is and the stronger is its shade casting effect. By registration and addition of $BETA_{ij}$ for all competitors KKL becomes an index for the light supply of tree j and for the shading effects of its competitors resp. Through weighting $BETA_{ij}$ by KQF_i / KQF_j the index KKL takes into accout that apart from the distances from central tree to competitors and their height relations the relationship between their crown dimensions determines the competition effect:

$$KKL_{.j} = \sum_{\substack{i=1 \\ i \neq j}}^{n} BETA_{ij} * \frac{KQF_i}{KQF_j}$$

with the variables

$BETA_{ij}$ =	Angle between the basis of trees j light cone and the connecting line from the basis of the cone to the tip of the adjacent competitors i
KQF_j, KQF_i =	Crown sectional areas of central tree j and its competitors i defined in 60 % of trees j height.

By a repetition of the calculation for the structure of the stand after a thinning process, KKL_{before} and KKL_{after} can be found out and the liberation depending on the thinning can be calculated: $\Delta KKL = KKL_{before} - KKL_{after}$.

In addition there are three more competition indices calculated, which include a variable that indicates symmetric and asymmetric competition effects resp. (NDIST), a variable that takes the directional position of a trees competition centre into account (TALPHA) (Fig. 3) and a variable which focuses on the effects of the species mixture in the trees neighbourhood (PBA).

MODEL CONSTRUCTION

Basic equations

A trees current increase in height is estimated from its potential increase in height zh_{pot}, which could be expected under optimum conditions. As soon as the tree has not got optimum conditions, this value decreases. The individual tree height increment is then a function of the site dependent potential height increment (zh_{pot}), the crown ratio (B) and the trees competitive situation (KKL, TALPHA, NDIST, ΔKKL, PBA):

$$zh = f(zh_{pot}, B, KKL, NALPHA, NDIST, \Delta KKL, PBA)$$

The crown diameter kd is a function of the tree dimension (d, h, B), the competitive situation in the past (KKL, TALPHA, NDIST, ΔKKL, PBA) and site conditions ($e_{1 \ldots 3}$):

$$kd = f(d, h, B, KKL, TALPHA, NDIST, \Delta KKL, PBA, e_{1 \ldots 3})$$

The crown length kl_2 at the end of the n-year increment period is assessed via the following relation:

$$kl_2 = f(kl_1, d, h, KKL, TALPHA, NDIST, \Delta KKL, PBA, e_{1 \ldots 3})$$

For the estimation of the diameter increment the following function is chosen:

$$zd = f(zd_{pot}, M, V, KKL, TALPHA, NDIST, \Delta KKL, PBA, e_1 \ldots e_3)$$

with the additional variables M and V

M = surface of the crown
V = crown volume.

Starting from the competition indices of a tree, its crown surface area, its crown volume, its average annual basal area increment in the preceeding n-year period zg and the site factors $e_{1 \ldots 3}$, the mortality model forecasts whether the tree survives an n-years-period or wether it dies. This "two-group classification" is realized by a LOGIT-model.

$$T = f(zg, V, M, KKL, NALPHA, NDIST, \Delta KKL, PBA, e_{1 \ldots 3})$$

with the variable

T = categorical static variable marked alive or dead

The survival status of a tree depends on the trees vitality and its individual competitive situation. The trees vitality is of course also dependent on the site specific conditions, so that mortality is an important supplement to the site specific definition of the actual tree diameter increment.

Prognosis process

The first step of a simulation run is to read a list of trees with the dimensions of a stand given in the beginning and to generate the stand structure. During the second step, the structure of the stand before a thinning is reproduced in a calculation and depicted by a graph. After the thinning has been specified (step 3), step 4 is made up by the arithmetical reproduction and diagrammatic depiction of the structure of the stand after the thinning process. Step 5 determines the competition indices and their changes caused by the thinning. These results are used in step 6 to regulate the increase in height and lateral crown growth, the shift of the basis of the crown, the basal area increment and the mortality in the growth period of five years to follow. The updated dimensions of the single trees at the end of the first simulation cycle of n years represent the initial values for the second simulation cycle. Steps 2 to 6 are repeated until the whole prognostic period has been passed through in steps of n years each and the prediction run can be finished by presenting the results.

THINNING MODEL STRUMOD

The thinning model STRUMOD consists of moduls, which can be divided under consideration of methodical aspects into the categories of rule based and algorithmic thinning models.

The rule based approach is motivated by the fact that a thinning model should be suitable to represent formally defined thinning regimes as well as human decision making, which seems to be very ill structured in the context of thinning practice especially in uneven aged mixed species stands. In addition the model should be capable of giving a quite exact prognosis of real thinning regimes which have been documented on long term experimental plots. The most central part of the rule based modul is a fuzzy logic controller (ZIMMERMANN, 1991). A formal thinning instruction for heavy thinning from below can for example be expressed as "if the tree is thin and its competitive stress is medium, then its urgency for thinning is medium". The evaluation of the rule base (Fig. 4) is maintained by applying the max-prod-inference, the defuzzification of the resulting thinning decision follows the center of gravity method and can be performed by the center of singleton method too.

In addition the algorithmic thinning models include selective logging for example with fixed distances of thinning around the most valuable trees. Thinning from below and above is with an algorithmic approach available too, because clustering is computational a bit more quick than the rule based approach but not so flexible. For selective thinning the competitive influence of each neighbour on a considered tree can be evaluated. This does not imply much additional computational effort during the simulation run, because the KKL values are summed over the competitors of all trees and the individual competitive contributions on a tree specific KKL are therefore already available.

THE STAND STRUCTURE GENERATOR STRUGEN

When using SILVA 2 as prognosis and research tool the stand structure generator STRUGEN (PRETZSCH, 1993) can be preinstalled as an intermediate unit which generates lacking information about structure and dimension by using the verbal findings concerning stand structure. In practice we have in general only the verbal estimation of the mixture (e. g. mixture by cluster or group) or verbal and numeric information (e. g. strip mixture with stripes of 20 m width). In order to make information about the stand structure, that is enclosed in such inaccurate verbal estimations, accessible to state diagnosis and growth prognosis a stand structure generator is developed. On the basis of the structure characterizations which are usual in practice the generator models stand structures which in their dynamic and stability-determining stand characteristics comply with real stands.

The basis for generating the stem charts is a homogeneous Poisson-process that creates on the test plot uniformly distributed random numbers (the x- and y-co-ordinates) which then according to different rules are accepted or rejected as stem positions for main and associated tree species (Fig. 5). A set of two-dimensional probability functions, for round clusters for example of the type

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

Z_C	=	probability, that a tree will be accepted to establish on a point of the plot with the co-ordinates x and y (Z lies in [0,1])
q	=	number of round clusters that shall be established on the plot
x,y	=	co-ordinates of a tree (or a point) on the plot
X_i, Y_i	=	center of the i-th cluster on the area
E_i	=	determines the diameter of the round cluster

regulates the kind and extend of the mixture of main and associated tree species. The smaller the distance $x-X_i$ and $y-Y_i$ respectively, the higher is the probability that it is a accepted for a tree to establish to a point with the co-ordinates x and y. Moreover secures an empirically fitted distance function the minimum distance between competing neighbouring trees depending on their diameters. Consequently the produced pattern is the result of the combination of an inhomogeneous Poisson-process (which generates the units of the mixture) and a hard-core process (which secures minimum distances between the neighbours). Being able to produce artificial but realistic spatial structures for stands where stem positions are unknown (Abb. 6), STRUGEN opens the way for the use of distance-dependent single-tree growth models on a large scale and allows first pragmatic steps towards the utilization of information on nominal or ordinal scale level for the growth prognosis in forest yield science.

GROWTH DEVELOPMENT IN A CHANGING ENVIRONMENT

After specifying an initial situation, the growth behaviour for different mixture proportions and mixture configuration can be reproduced with the help of the simulator. In addition, different thinning regimes can be simulated. Simulation runs provide yield elements of the stand and detailed dendrometic parametres of all single trees (Fig. 7). The following simulation test-run gives a sketch of the site-specific growth dynamics in respect to environmental change.

Simulating the effects of a changing environment on tree growth it is assumed that mean temperature during the growing season shall increase from 15.5°C to 16.5°C and precipitation during growing season shall decrease from 320 mm down to 250 mm (Fig. 8). Independently on the actual species mixture in a given mixed stand of spruce and beech stand the potential height growth of the species will change only depending on the supply with site factors given. Because of the fact that in this given example the 'factor supply' with mean temperatur has been quite high and the supply with precipitation has been quite low before the assumed climate change occurs the changes in potential height growth are very obvious. This can be explained by the corresponding rapid monotoneous decrease and increase resp. of the response functions of mean temperature and precipitation. But both species react differently on the climate scenario: the simulated decline of height growth of spruce is much more evident than that of beech (Fig. 9). So, as a consequence, the competition between spruce and beech will change.

DISCUSSION

In consequence of the changing environment conditions and forest damages by biotic and abiotic factors forest management intensifies the silvicultural establishment and tending of all aged mixed stands which seem to be ecological more stable than monocultures and which contribute to a risk reduction. The increased need for information about the growth of heterogeneous stands can be met best by position-dependent single stem models - because of their high degree of flexibility. So far, position-dependent growth models - including the model presented - have had a very restricted applicability, because they need the stem co-ordinates of every single tree as initial values; but those are - if at all - only known on experimental plots. The structural generator STRUGEN which functions as a kind of interface, is able to generate initial constellations for model runs also in stands where the tree distribution is not known but only characterized verbally. By generating any stand structures, natural regeneration processes and succession procedures which can be used as start values for simulation runs, STRUGEN opens the way for the use of position-dependent all age single-tree growth models on a large scale.

In respect of including site effects into the model functions of SILVA 2 it has to be remarked that the chosen approach shall be a compromise between highly elaborated mechanistical and mainly trial and error statistical models. As far as we do not have data and knowledge to design mechanistical, ecophysiological models, but as far as we want to include much of what we know about biological growth principles we might be enforced to try the approach presented here. The results that can be achieved with the site model, based on much empirical data, unimodal response functions and compensative aggregation mechanisms, are quite reliable.

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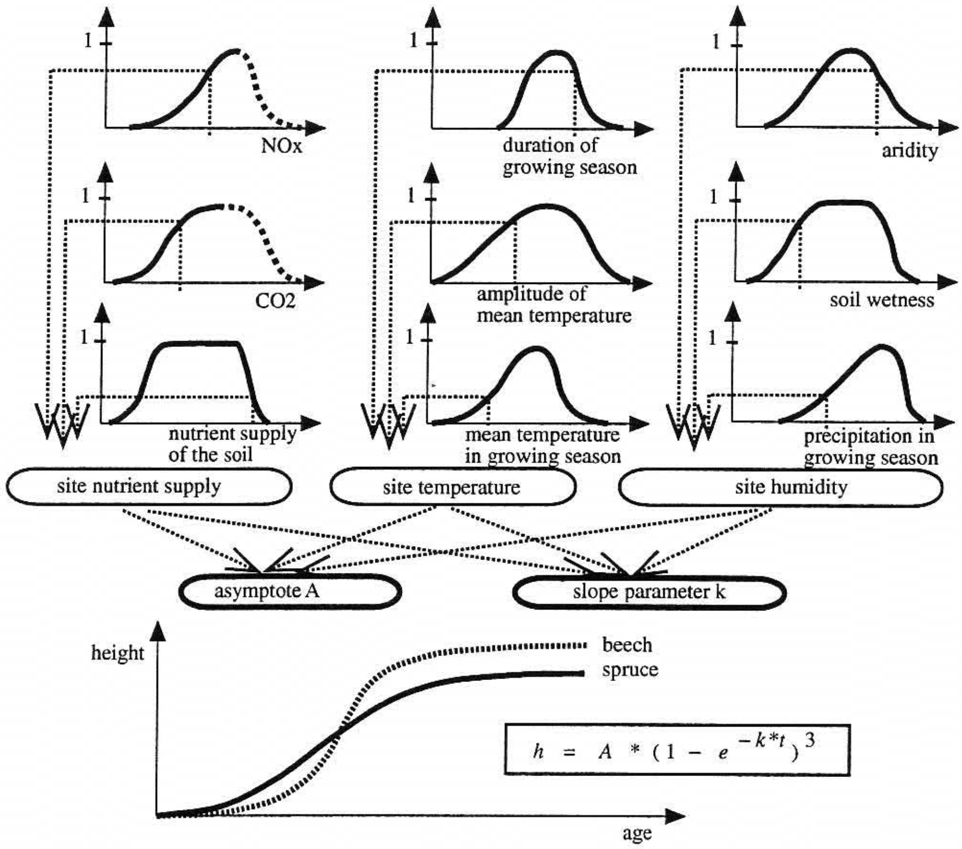


Fig. 1 Structure of the model to predict height growth as a function of site conditions.

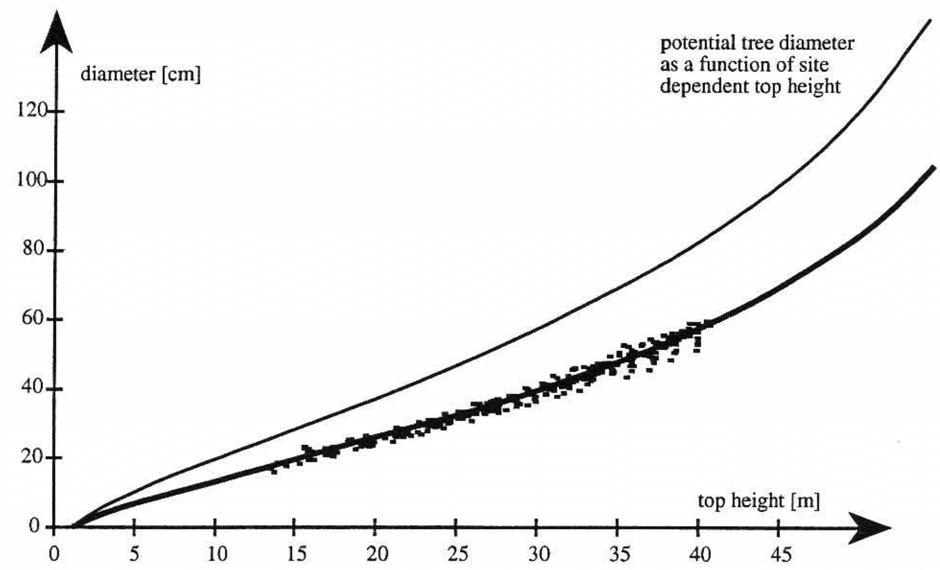
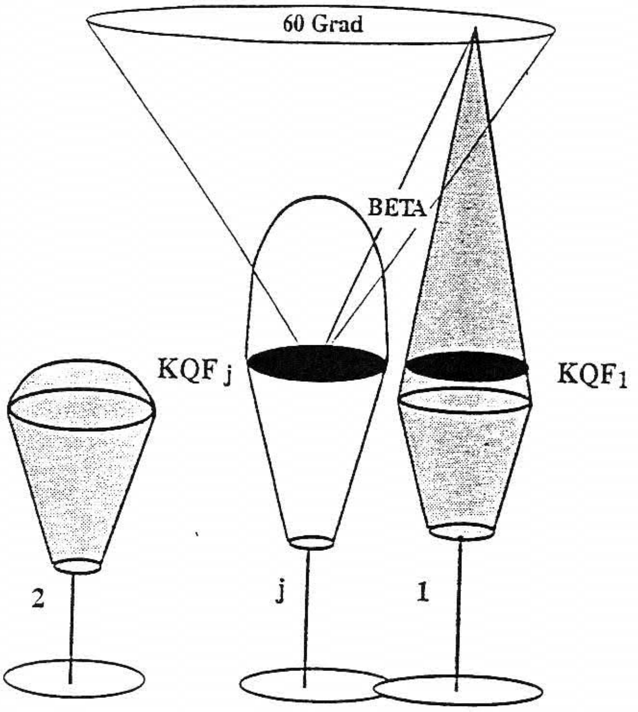


Fig. 2 Potential tree diameter as a function of top height for spruce based on data from Bavarian experimental plots. Top height is site dependent. The data are fitted applying the inverse CHAPMAN-RICHARDS-function. The potential tree diameter is derived from the relationship between top and tree diameters.



$$KKL_{.j} = \sum_{\substack{i=1 \\ i \neq j}}^{n} BETA_{ij} * \frac{KQF_i}{KQF_j}$$

Fig. 3a The crown competition KKL is determined by the light cone method considering the relations of the tree height and the crown size between the central tree j and its neighbours i.

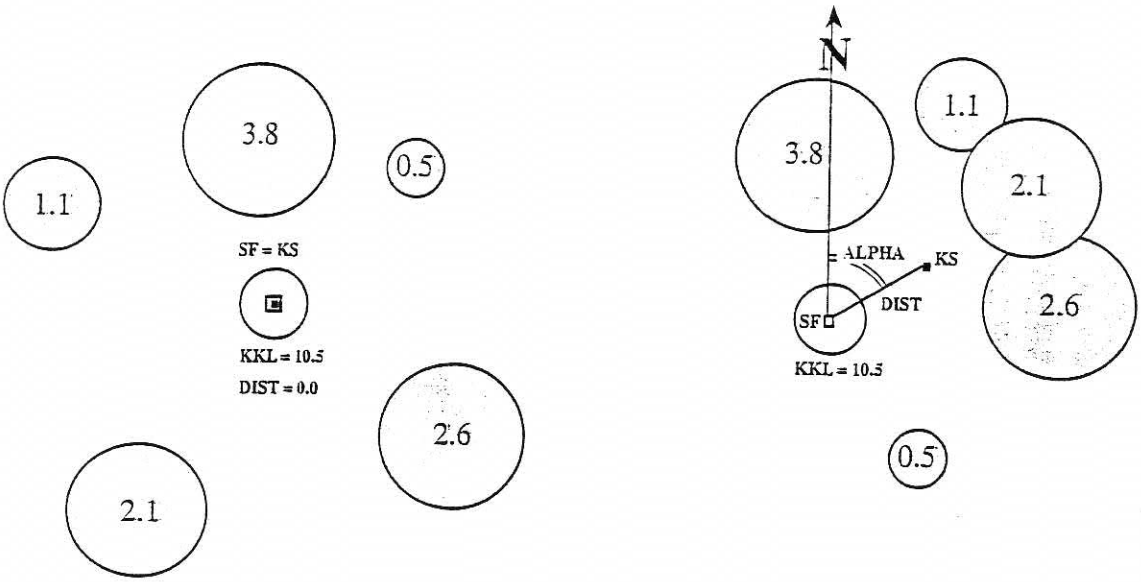
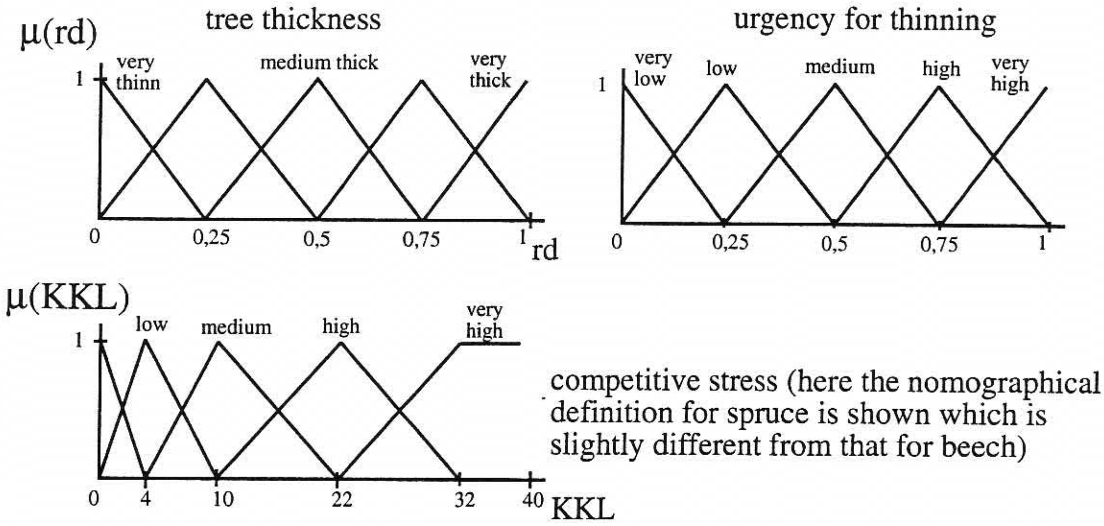


Fig. 3b The central tree (white) whose competitive situation has to be checked, and its competitors (grey) - given a symmetric and an asymmetric competitive situation (left/right). In order to describe asymmetric competitive effects, DIST describes the distance between stem position coordinate SF and the competitive centre KS of the central tree; ALPHA stands for the position of the competitive centre (the angle between the competition centre KS, stem position coordinate SF of the tree and north N).

Linguistic variables:



Scetch of the rule base, inference and defuzzification:

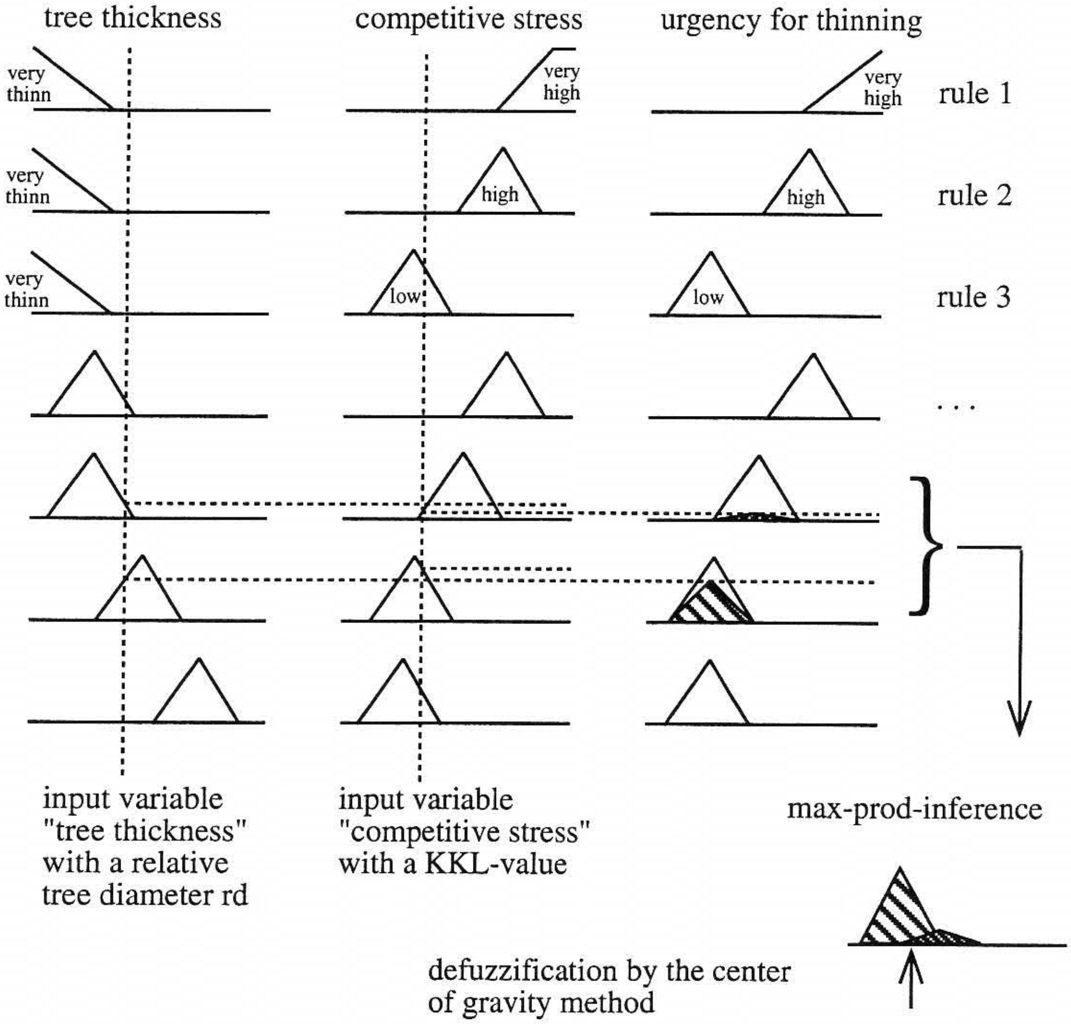


Fig. 4 The linguistic variables tree thickness, competitive stress and urgency for thinning and a scetch of the rule base for a heavy thinning from below. For evaluation of the rule base the max-prod-inference is applied, and the defuzzyfication follows the center of gravity method.

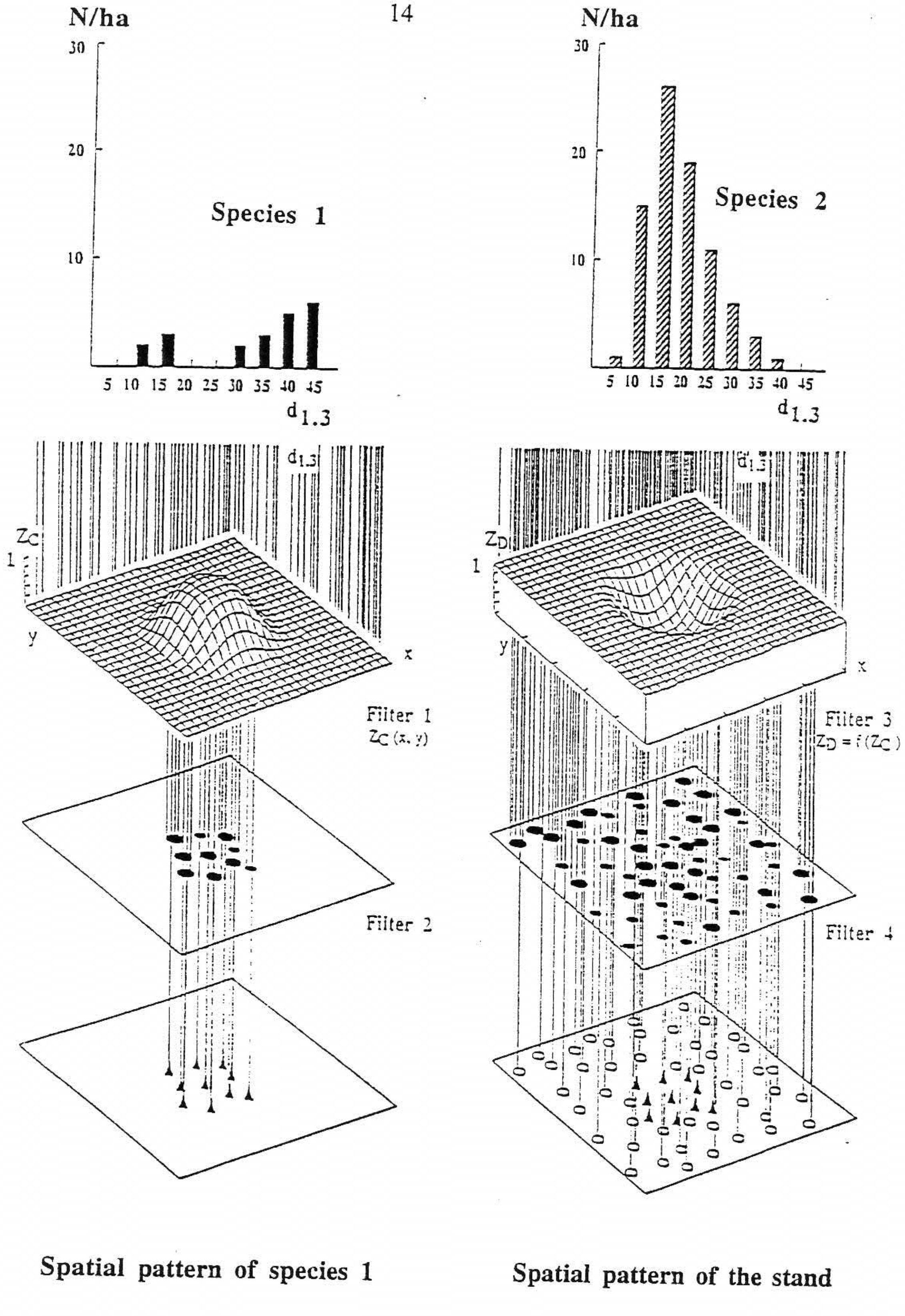


Fig. 5 By combining the inhomogenuous POISSON-process (that generates the mixture clusters) and a hard-core process (that guarantees the minimum distance between neighbour trees), a stand structure generator is created which is able to generate realistic structures of pure and mixed forest stands.

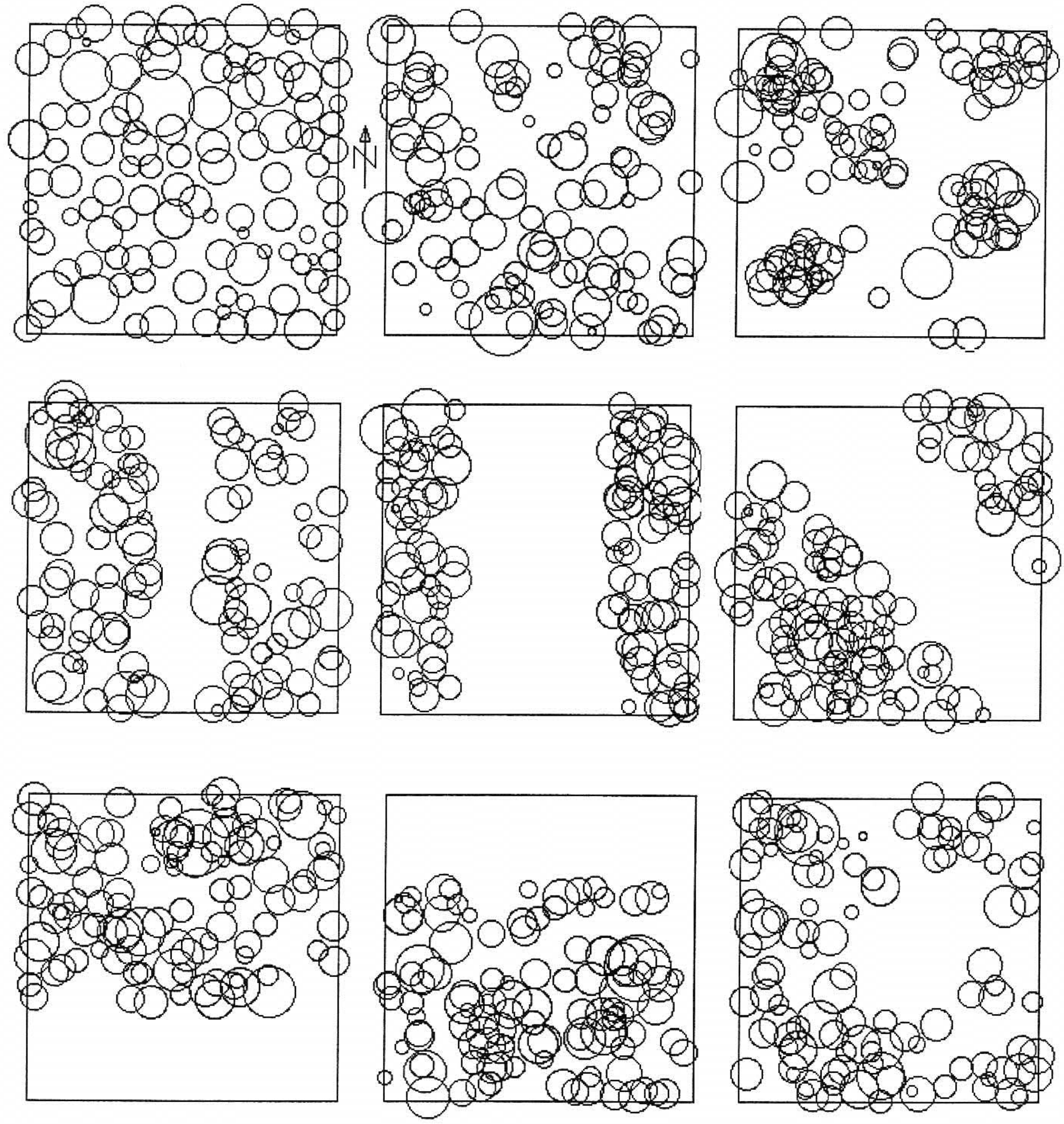


Fig. 6 Spatial patterns generated by the stand structure generator STRUGEN. Regular, random and clustered distribution (above), log trails with different widths and directions (middle), and border and femel structures (below).

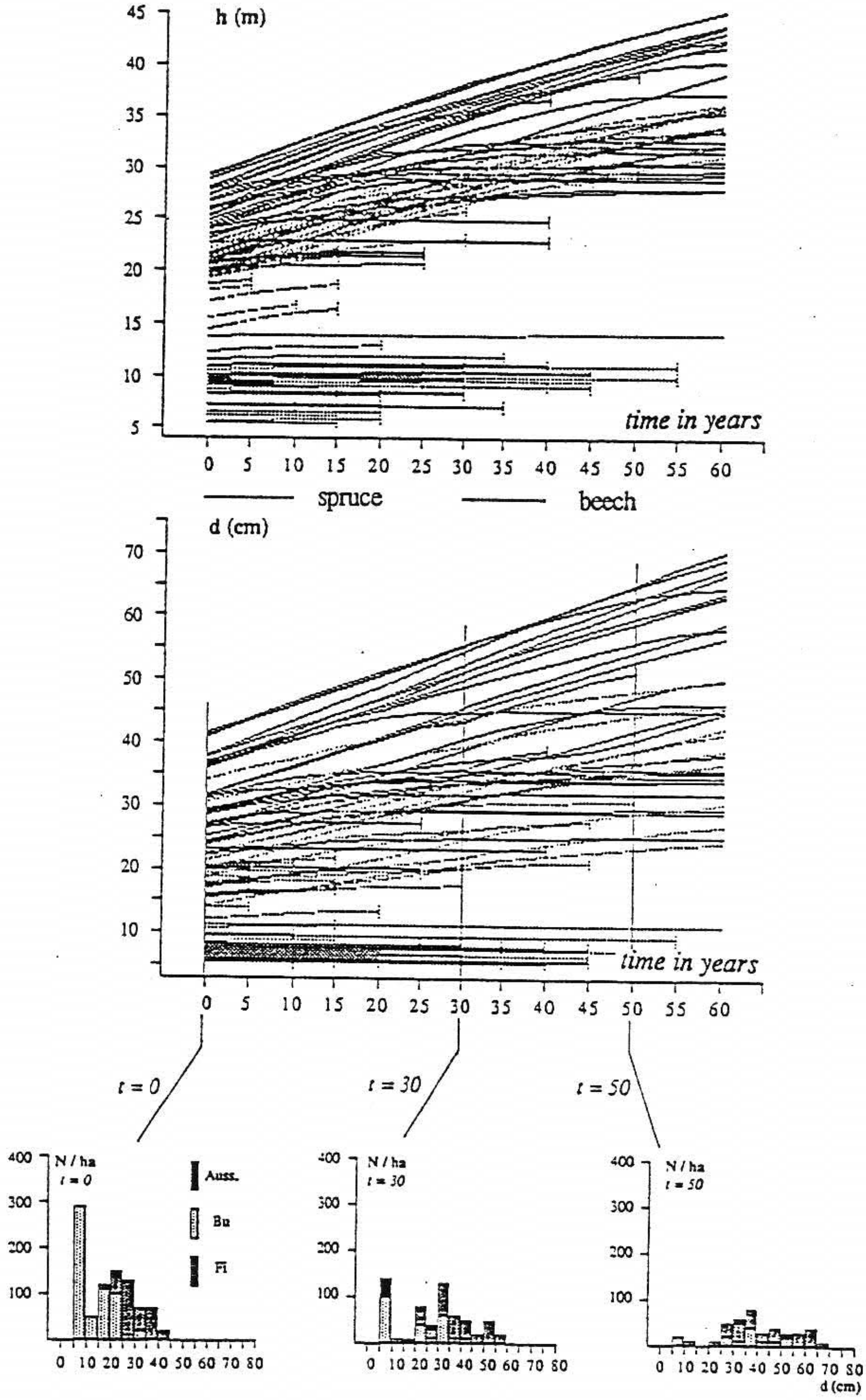


Fig. 7 Developement of the dimension of single stems on an experimental area of 0.125 hectares of a mixed forest stand of spruce and beech (whole lines: spruce and dotted lines: beech) according to the results of a simulation process of 60 years (stem losses are figured by broken lines marked by a cross-line).

above curves of height growth
middle curves of diameter growth
below stem numbers in five centimetre diameter-classes for different points of time t=0, t=30 and t=50