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A STAND GROWTH MODEL AS A TOOL IN STUDYING MANAGEMENT OPTIONS FOR MAB-RAINFOREST ECOSYSTEM PROJECTS AND FOR TEMPERATED FORESTS

by

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1. INTRODUCTION

The development of dynamic growth simulation models and cybernetic sensitivity models is part of the interdisciplinary Amazon ecosystem research project at San Carlos de Rio Negro, Venezuela which is on multinational contribution to the Unesco program "Man and the Biosphere". The development of these models is a first step in the demonstration of the complex interactions within forest ecosystems by using dynamic and cross-linked multivariable biocybernetic sensitivity models. One of the objectives is to quantify the consequences of the divers human impacts on the functional system of forests. Based on these models, silvicultural and agrosilvicultural systems and production schedules could be designed which aim at simultaneously high ecological stability, environmental suitability, technological and economical flexibility and productivity, and generally at optimum benefits to man and the biosphere.

The development of a model hierarchy of models which simulate tree and stand structure, growth and functions and which at higher level involve cybernetic models for sensitivity analysis and prediction in the fields of ecology, economics and sociology is part of a cooperative program of the Department of Forestry, University of Oxford, the Chair of World Forestry, University of Hamburg, the Computing Centre of Hamburg University, the Institute

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for World Forestry, Federal Research Centre for Forestry and Forest Products, Hamburg-Reinbek, the "Planungsgemeinschaft Untermain", Frankfurt and the "Studiengruppe Biologie und Umwelt", Munich. The stand structure and growth modelling is supported by the Association of German Forest Owners Unions and in the tropical ecosystems part of the project by the German Research Foundation (DFG).

The general methodology of forest growth modelling is now quite well developed. It is not intended to review the literature in this report but refer to ADLARD (1977/78), ALDER (1977; 1977/78), FRIES (1974), FRIES et al. (1978) which provide a general introduction to the field and to the papers by GROSSMANN, SCHWARZ, v.HESLER and VESTER elsewhere in this volume. Development of the model described below has progressed to an intermediate stage. Consequently this report is preliminary and modifications will be introduced during further development.

The mathematical principle of the model is applicable to any tree species which grows in pure stands or in mixed stands. The model, however, requires that information on annual growth rates is available. The first model which has been developed in the first phase of the modelling project is referred by the acronym KIM, which stand for Kiefer (German name of pine = Pinus sylvestris L.) and Modell. It is designed to be used as a tool in studying the management options which may be feasible for the large areas of over-stocked P. sylvestris plantations, which are to be found in Northern Germany, and which urgently require ameliorative treatment.

2. THE PROBLEMS

Substantial areas of Pinus sylvestris plantation have been established over the last 50 years in Northern Germany. Yield tables for these stands have been published by SCHOBER (1975), based on work by WIEDEMANN (1948). However, as a result of the economic conditions that have developed in post-war years, especially high labour costs, the frequent light thinnings implied by the yield tables have not been possible in many of these plantations.

This has led to two distinct management problems. The first concerns the ameliorative treatment of the very large areas of forest that are overstocked as a result of lack of thinning. The second relates to the study of alternative, more feasible treatment regimes that can be applied through the use of a systems simulation model of the growth of even-aged, nonspecific stands. This model is an adaption of previously published work which has been extended to include estimates of branch size and wind throw frequency. Both these are relatively critical factors in the silviculture of P. sylvestris in Germany.

3. GENERAL MODEL STRUCTURE

The model, called KIM (Kiefer Modell), is an adaption of the VYTL model described in ALDER (1977). It is, in the terminology of MUNRO (1975), a distance-independent tree model. As with most systems models, its operation can be divided into two main phases: initialization, and dynamic iteration over time.

In the initialization phase starting values are set for the main variables in the model. In the dynamic phase, new values are calculated in each 5-year time period for all the variables based upon the values of certain key 'state' variables at the end of the previous time period.

In KIM, the main features of the dynamic phase are as shown in figure 1. The main independent variables, exogenous to the simulation, are stand age (derived directly from the iteration number), yield class, and the intensity of thinnings. There are two key state variables, which are carried over from one iteration to the next and from which all the other dependent variables are derived. These are stocking (numbers of trees per hectare) and the array of diameter deciles. Other variables are then calculated from these to serve as intermediary components of feedback loops to determine end of period diameter deciles and stocking. These intermediary variables are mean diameter, the array of tree heights corresponding to each diameter decile, crown competition factor, mean height, and mean slenderness ratio. Finally, there are a number of variables important to the manager, such as volume, branch diameter, losses from windfall and suppression, and thinning removals, as well as some not shown on the diagram, such as basal area, mean annual increment, and so on, which are calculated for output from the model but do not themselves effect any other variable.

Figure 1 is intended to illustrate these interactions and highlight the functions involved. Thus for example, it can be seen that mean height is derived from age and yield class via function 3; and that the diameter increment function (7) depends on age, yield class, crown competition factor, and the internal relationships in the array of diameter deciles. The figure is slightly simplified in order to render it presentable; some small discrepancies will be pointed out in the sections describing the model in detail.

The initialization phase of the model is not shown in figure 1.

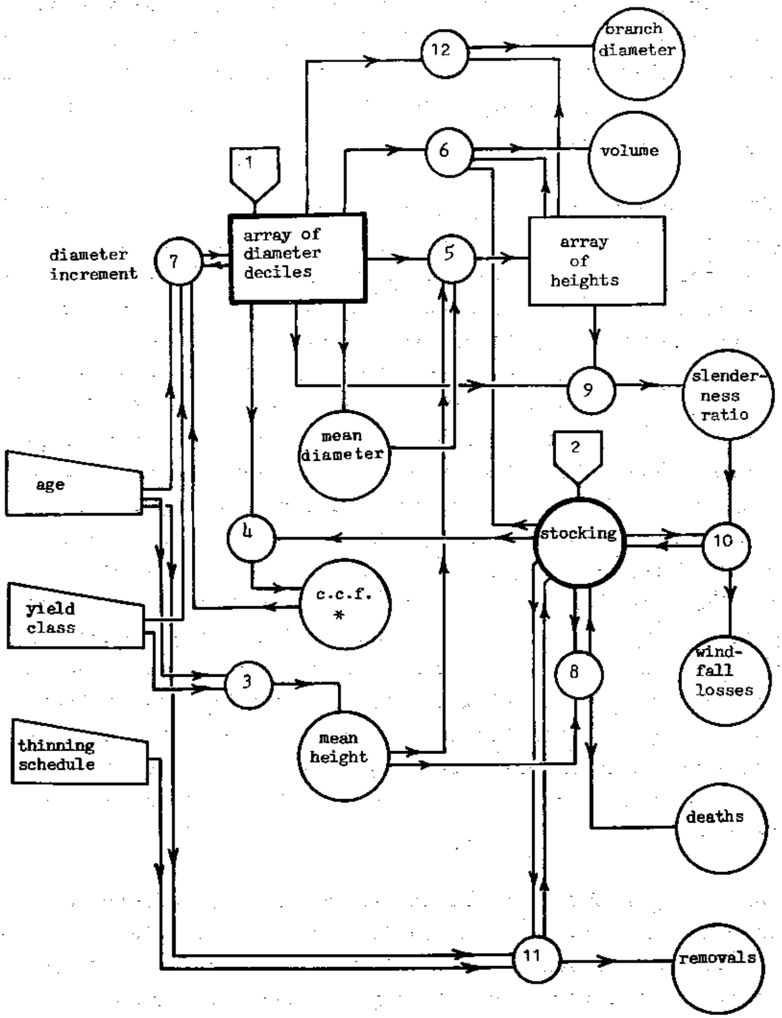


Figure 1: Interrelation of variables in the dynamic phase of the KIM stand model

* crown competition factor

functions used only in initialization

functional relationships

independent or exogenous variables

scalar quantities

vector or array relationships

indicates whether a variable is an input or an output for a particular function

Simulation commences at age 15, when functions 1 and 2, as shown on the diagram, are invoked to set starting values for the array of diameter deciles and for stocking. The full list of all the function numbers on the figure is as follows:

Function	Description
1	Sets the initial diameter distribution as a function of yield class and planted stocking.
2	Sets the initial stocking, as either the planted stocking or a value reduced by early mortality.
3	Gives mean height as determined by age and yield class.
4	Gives crown competition factor as determined by the diameter array and stocking.
5	Sets the array of heights corresponding to diameter deciles.
6	Computes stand volume from individual class diameters, heights, form factor and stocking.
7	Calculates diameter increment. This is a complex function mainly determined by age, yield class, relative tree size, and crown competition factor.
8	Calculates losses from suppression and removes them using the standard thinning simulation routine of the model.
9	Calculates mean slenderness ratio as the average of individual class slendernesses.
10	Determines the likely proportion of the stand windthrown, as a function of mean slenderness

Function	Description
(cont....)	and simulates its removal.
11	Simulates thinning in accordance with management directives supplied to the model by the user.
12	Computes mean branch diameter as a function of class diameters and heights.

The model as a whole has the following main parameters which are controlled by the user:

(1) Windthrow protection factor. This is a subjectively determined factor which has extreme values of zero, for completely protected sites, and one, for an exposed site with shallow rooting soil.

(2) Yield class. These are the relative yield classes given in SCHOBER (1975). The model is calibrated for classes 1 to 4. It has not been tested for the yield classes lower than 4.

(3) Initial stocking after planting.

(4) The age and residual stocking for each thinning treatment. There is no limit on the number of thinnings or their severity or timing, except that they may not take place before age 15.

Given these specifications, the model then produces a yield table for output. An example, for SCHOBER's moderate thinning on yield class 2, is shown in **table 1** . The computer time required is about 1 second.

PLANTED AT 40000. STEMS/HA. - YIELD CLASS 2.0 - WINDTHROW FACTOR 0.00

AGE	STEMS /HA	MEAN HT	DIAMETER LIMITS 5%	D(G)	95%	CROWN HT	BRANCH D@CB	H/D RATIO	DEATHS /HA	WINDT N/HA	VOLUME CUM/HA	BA SQM/HA	- THINNINGS - N/HA	MEAN DIAM	BA	VOLUME	- CUMULATIVE YIELDS BA SQM/HA	MAIV	CAIV
15	11073	3.8	0.9	3.8	6.7	1.4	0.7	1.0	0	0	27.0	12.5	0	0.0	0.0	0.0	13.0	1.8	0.0
20	7224	6.0	1.5	5.2	9.6	2.9	0.6	1.2	3854	0	56.5	15.3	0	0.0	0.0	0.0	17.4	3.4	8.1
25	5476	8.1	1.9	6.5	12.3	4.3	0.6	1.2	1749	0	93.6	18.1	0	0.0	0.0	0.0	21.1	4.6	9.6
30	3465	9.9	2.7	8.4	15.4	5.4	0.7	1.3	976	0	120.5	19.4	1034	4.8	1.9	15.1	24.5	5.6	10.6
35	2580	11.6	3.4	10.2	18.0	6.5	0.8	1.3	0	0	150.1	21.1	885	5.8	2.4	23.1	28.1	6.3	10.5
40	2009	13.1	4.2	12.0	20.4	7.4	0.9	1.2	0	0	177.5	22.7	571	7.1	2.3	24.1	31.6	6.8	10.3
45	1608	14.5	5.0	13.8	22.7	8.3	1.0	1.1	0	0	201.7	24.0	401	8.5	2.3	25.4	34.9	7.2	9.9
50	1338	15.7	5.8	15.5	24.7	9.0	1.1	1.1	0	0	224.6	25.2	270	9.9	2.1	24.1	38.0	7.4	9.4
55	1136	16.8	6.7	17.2	26.6	9.7	1.2	1.0	0	0	245.0	26.3	202	11.3	2.0	24.1	40.9	7.5	8.9
60	978	17.8	7.7	18.8	28.4	10.4	1.3	1.0	0	0	262.4	27.1	153	12.7	2.0	24.3	43.6	7.6	8.4
65	857	18.8	8.7	20.3	30.0	11.0	1.4	1.0	0	0	278.3	27.8	121	14.1	1.9	23.3	46.0	7.6	7.8
70	761	19.6	9.7	21.8	31.5	11.5	1.5	0.9	0	0	292.5	28.3	96	15.5	1.8	22.5	48.3	7.6	7.3
75	683	20.4	10.8	23.2	32.9	12.0	1.5	0.9	0	0	305.1	28.8	78	16.8	1.7	21.8	50.4	7.5	6.9
80	617	21.2	11.8	24.5	34.2	12.5	1.6	0.9	0	0	315.8	29.1	66	18.0	1.7	21.6	52.4	7.5	6.5
85	561	21.9	12.9	25.8	35.4	12.9	1.7	0.9	0	0	324.8	29.2	56	19.3	1.6	21.2	54.2	7.4	6.1
90	513	22.5	14.0	27.0	36.6	13.4	1.7	0.8	0	0	332.5	29.4	48	20.5	1.6	20.7	55.9	7.3	5.7
95	471	23.1	15.1	28.2	37.7	13.8	1.8	0.8	0	0	338.7	29.4	42	21.7	1.5	20.5	57.4	7.2	5.3
100	435	23.7	16.1	29.3	38.8	14.1	1.9	0.8	0	0	344.1	29.3	36	22.8	1.5	19.6	58.9	7.1	5.0
105	401	24.2	17.2	30.4	39.8	14.5	1.9	0.8	0	0	347.1	29.2	34	23.9	1.5	20.6	60.2	7.0	4.7
110	371	24.7	18.3	31.5	40.8	14.8	2.0	0.8	0	0	349.2	28.9	30	25.1	1.5	20.0	61.5	6.9	4.4
115	344	25.2	19.4	32.6	41.7	15.1	2.0	0.8	0	0	350.2	28.6	27	26.2	1.5	19.8	62.7	6.7	4.2
120	319	25.6	20.5	33.6	42.6	15.4	2.1	0.8	0	0	349.9	28.3	25	27.3	1.5	20.0	63.8	6.6	3.9
125	298	26.0	21.6	34.6	43.5	15.7	2.1	0.8	0	0	350.1	28.0	21	28.3	1.3	18.2	64.8	6.5	3.7
130	279	26.4	22.7	35.5	44.3	16.0	2.1	0.8	0	0	349.8	27.7	19	29.3	1.3	17.8	65.8	6.4	3.5
135	261	26.8	23.7	36.5	45.1	16.2	2.2	0.7	0	0	348.1	27.3	18	30.3	1.3	18.1	66.7	6.3	3.3
140	245	27.2	24.7	37.4	45.9	16.5	2.2	0.7	0	0	346.4	26.9	16	31.3	1.2	17.2	67.6	6.2	3.1
145	245	27.5	25.2	37.9	46.5	16.8	2.2	0.7	0	0	361.1	27.7	0	0.0	0.0	0.0	68.4	6.1	2.9
150	245	27.8	25.7	38.5	47.0	17.0	2.3	0.7	0	0	375.3	28.5	0	0.0	0.0	0.0	69.2	5.9	2.9

Table 1: Yield table for P.sylvestris produced by the KIM simulation model, assuming a thinning schedule equivalent to Schober's moderate thinnings and relative yield class II. The windthrow risk is assumed to be zero.

4. CALIBRATION DATA

In order to fit the specific functions listed above, some additional calibration data was required over and above previously published work on Pinus sylvestris. This was obtained by sampling individual tree plots in a number of carefully selected stands in several forest districts in northwestern Germany during the winter 1977-1978. The sampling was stratified to cover a range of competition from solitary trees to the densest stands, and of ages from 5-10 years upto 120-130 years. In each of the denser stands, dominant, co-dominant, sub-dominant and suppressed trees were sampled.

For each single tree plot, the diameter at breast height, total height, and crown radii on two axes were taken from the subject tree and from neighbouring trees judged to be competing with the subject tree. The distance and bearing of each neighbour was also recorded. In cases where it was permitted to fell the subject tree, discs were taken at breast height and at stump height for increment and age analysis. Branches were measured at approximately 2m intervals up the bole for diameter and orientation, and whether alive or dead. Internode diameters were also measured at 2m intervals for estimates of form. In cases where felling was not possible, the height to the base of the live crown was estimated, and increment borings taken to assess growth over the past 5 years.

Approximately 90 subject trees were sampled altogether. The main use of this data in the present study has been to derive relationships between:

- diameter and crown radius for solitary trees;
- diameter and crown length;
- branch size and upper stem diameter;
- dominance and tree form;
- height and diameter for solitary trees.

The analysis of increment is not yet completed and will be the subject of future publications. Instead, the model was calibrated to respond as far as possible in the same way as published yield tables to variations in yield class and stand density.

5. SPECIFIC FUNCTIONS IN THE MODEL

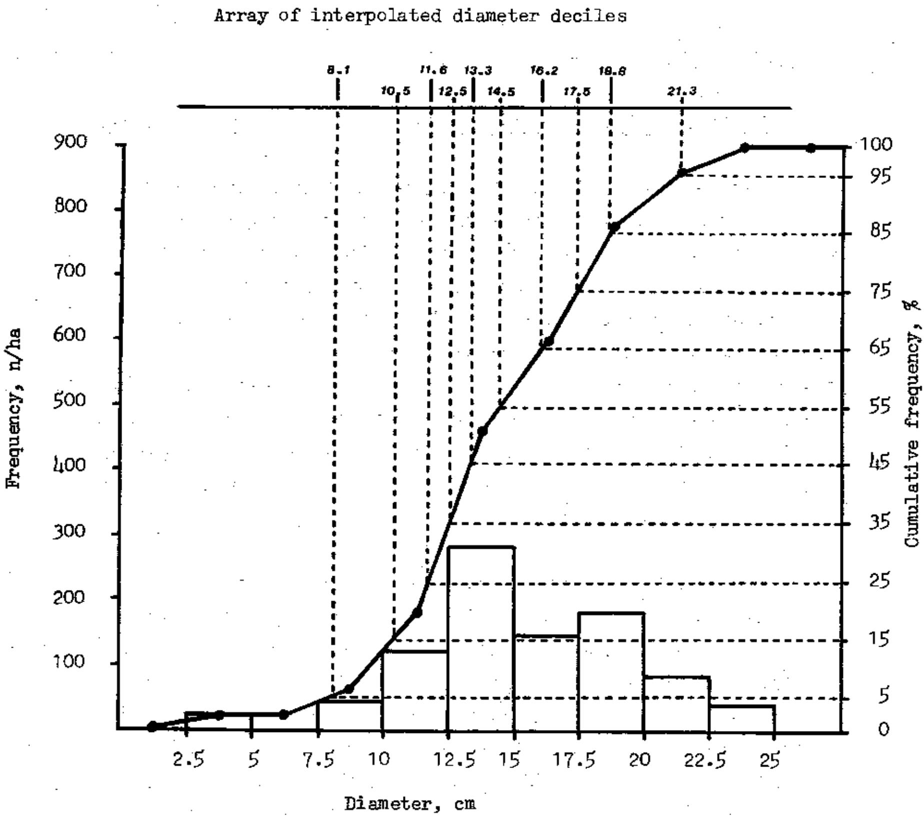
In this section, the various specific functions developed for P. sylvestris and utilized in the model are described in detail.

5.1 Initialization of the diameter deciles and stocking

The conventional representation of diameter distribution in a forest stand is by a stand table, or frequency distribution, which shows the number of trees in different size classes. Any frequency distribution can be converted to a cumulative distribution by summation of the frequencies so that each size class contains its own frequency plus the sum of all frequencies in the smaller classes. The cumulative classes can then be converted to percentage cumulative frequencies by division of each cumulative class by the total stocking. Figure 2 shows this process graphically for an imaginary frequency distribution.

Once the cumulative distribution has been obtained, a new set of diameters may be interpolated which correspond to some convenient percentage points on the cumulative frequency scale. Figure 2 shows the interpolation of the diameters corresponding to the 5%, 15%, 25% and so on at 10% intervals upto the 95% cumulative frequency. This is the array of 10 diameters that is used in the KIM model as a basis for stand description. This approach is not entirely new, and can be traced back to the work of JEDLINSKI in 1932 (c.f. DAGNELIE et al., 1971). The use of the cumulative distribution instead of the frequency distribution results in greater computational efficiency in the model.

Figure 2 Method of representing a stand table by a distribution of cumulative frequency percent, together with interpolation of the array of diameter deciles.



At the commencement of the simulation, initial values of the diameter deciles must be assigned. This initial stand is generated at 15 years of age. The first step is derivation of mean height at this age, as a function of age and yield class. This is done using the equation described in section 5.2 below. From this height is derived a possible upper limit of stocking, using the equation :

(1) $$N_{max} = 39472.H^{-0.946}$$

For definition of symbols, see appendix A. This equation represents the logarithmic 'Reineke line' relationship between height and stocking, and was derived from the assumption that the moderate thinning schedules of the yield tables for different sites would, at their early stages, be just below the limiting stocking line. The parameters of equation (1) may of course be sensitive to site factors, and a more accurate relationship for the dependence of limiting stocking on dominant height can probably be derived for a particular locale by sampling the live stocking of dense stands (i.e. those with visible mortality from suppression) over a range of site and age classes.

When the planted stocking is greater than N_{max}, then the actual stocking is set equal to N_{max}; that is to say, planted stocking is reduced by density dependent mortality.

Another function, derived from the yield tables in a similar way, is used to relate the basal area development of young 'fully stocked' stands to their dominant height. Full stocking in this context is defined by a logarithmic height stocking line of the form:

(2) $$N_{min} = 6000.H^{-0.95}$$

When a stand has a stocking exceeding N_{min}, its basal area at age 15 is assumed to be independent of stocking, and derivable from the relationship:

$$(3) \qquad G^{*} = -152 + 148.H^{0.07787}$$

When the stocking is less than N_{min}, then the predicted basal area at age 15 is reduced in proportion to stocking:

$$(4) \qquad G = G^{*}.\ N/N_{min}$$

From this predicted basal area, mean diameter[1] is derived. The array of diameter deciles is then generated using the Weibull function (c.f. BAILEY et al., 1973) with the origin, or minimum diameter at zero; the scale parameter (approximately the 63rd percentile) set to the mean diameter; and the shape parameter as 2, giving a moderately left-skewed distribution. The equation for predicting the i'th decile of the initial distribution then becomes:

$$(5) \qquad d_i = D.(-\ln(1-p_i)^{\frac{1}{2}})$$

which will be recognised as the inverted form of the Weibull distribution, with the appropriate parameter values substituted.

These equations (1) to (5), used to establish the initial value of the array of diameter deciles have been derived from a consideration of the yield tables, together with some simple assumptions. For greater accuracy in the model, it would be desirable to establish these functions instead from an empirical sampling program; but the effect of the initial values of the diameter deciles on overall model performance is slight. It has proved possible to construct a sufficiently accurate model for the purpose in hand using the above relationships.

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1. Throughout this paper, 'mean diameter' implies the diameter at breast height (1.3 m) of the tree of mean basal area. 'Mean height' is the height of the mean basal area tree.

5.2 Mean height

Mean height is modelled as a simple function of age and yield class, using an equation fitted to the values published in the yield tables. The equation is :

$$H = \exp(4.0893-14.145t^{-0.7}-0.13423Y-1.1742Yt^{-0.7}) \quad (6)$$

where t is the age of the stand in years, and Y is relative yield class. This function is similar to that published in ALDER (1977) in form, although an exponent of -0.7 was added to the age factor to give a better fit than the linear form of this model (which has t^{-1}). The equation gives an almost exact fit of the mean height data published in Schober's yield tables for yield class 1-4.

5.3 Crown competition factor

The treatment of competition is an important component of all tree and stand growth models. Various indices have been used by different authors, including stocking, basal area, and spacing relative to height for stand models; and for tree models, overlap areas of adjacent crowns, and crown space derived from consideration of competing tree dimensions.

In the present case, it was decided to use the crown competition factor (CCF) described by STRUB et al.(1975). This relies upon establishing a relationship between the crown diameter and tree diameter of solitary (i.e. open-grown) trees. From this a 'maximum crown area' is computed from the stand table which is then expressed as a percentage of the ground area. The CCF is not the same as the crown projection area of the actual crowns except in stands which have been established and grown at wide spacings, but it is a better measure of stand density than crown projection area, in as much as the latter is modified by the allometric response of crown dimensions in close competition.

The tree diameter/crown diameter relationship was computed in the present case from the sample tree data collected for the model, using only crown radius data for solitary trees and dominants in open stands. The fitted regression was:

(7) $$r = 0.793 + 0.0773d$$

where d is diameter in centimetres, and r is root mean square crown radius, in metres. There were 22 points in the regression, and a coefficient of multiple determination (R^2) of 0.93 was obtained.

The crown competition factor is then computed from the array of diameter deciles as:

(8) $$K = \pi . 10^{-3} . N . \sum (0.793 + 0.0773\ d_i)^2$$

K is the crown competition factor % . It is an important component in the function for increment estimation, described in section 4.6 .

4.4 Tree heights corresponding to the diameter deciles

In order to estimate volume and branch sizes, it was necessary to predict, not only the stand mean height and the individual diameter deciles, but also the tree heights corresponding to each decile. The following approximation was used:

(9) $$h_i = 1.3 + ((H-1.3)/D) .\ d_i$$

This is a linear function which has the property that height is 1.3 metres when diameter is zero, and mean height corresponds to mean diameter. The latter must be true by definition. In actual stands, the relation is slightly quadratic, but the error involved is small.

5.5 Form factor and volume

Form factor is defined in the usual way as:

$$(10) \qquad f = v / (ad^2h)$$

where v is tree volume and a is the constant 8.754×10^{-5} when diameter is in centimetres, height in metres, and volume in cubic metres. In the sample data, it was found that the relationships between form factor and various stand parameters was weak. The best simple relationship was with slenderness, or height/diameter ratio, with an R^2 of 0.42 :

$$(11) \qquad f_i = 0.40429 + 0.0746\ h_i/d_i$$

The h/d ratios in this case ranged from 0.3 to 1.6, and the form factors from 0.38 to 0.52.

In the model, stand volume is calculated as the sum of the class volumes, computed using the form factor from equation (11) and the transformation of equation (10) in terms of volume.

5.6 Diameter growth

The starting point for diameter growth is the prediction of increment on a solitary tree of the same age and yield class as the simulated stand. This is given in the model by:

$$(12) \qquad \Delta d_o = 2.6 \Delta h_o$$

where Δh_o is the predicted height increment for an open grown tree. Δh_o is derived directly from equation (6) for mean height, except that the yield class is raised to the power 0.75 .

This in effect suggests that diameter increment in solitary trees is somewhat less adversely effected by site than height increment. The coefficient of 2.6 in equation (12) is the slope of the linear relationship between diameter and height for solitary trees, as determined from the calibration data. Hence it represents the diameter increment per metre of height increment for a solitary tree.

Δd_o is then reduced by a series of multipliers which account for the various factors acting on trees that are or have been growing in closed stands.

The first of these multipliers, m_1, concerns the effect of the crown competition factor K, as previously defined, on increment. This is :

(13) $$m_1 = \sqrt{80/K}$$

provided that m_1 is less than 1; that is, that K is greater than 80 %. Otherwise the competition multiplier is taken to be 1. This may be taken to imply that crown competition factors over 80% will begin to reduce the growth below the level of solitary trees of the same height.

The second multiplier, m_2, concerns the effect of growth retardation arising from past competition, and is defined in terms of the ratio of the trees present diameter to the diameter of a solitary tree of the same height :

(14) $$m_2 = d_i / (2.6(h_i - 1.3))$$

The factor $(2.6(h_i - 1.3))$ is the relationship between height and diameter for solitary trees, as determined from the calibration data.

The third multiplier, m_3, introduces the effect of the dominance class upon diameter increment. This multiplier is defined as the simple ratio of the class diameter decile to the largest decile diameter in the distribution, raised to the power of a factor from the crown competition factor, via the multiplier m_1. The actual expression is :

(15) $$m_3 = (d_i/d_{10})^{(1/m_1-1)}$$

This expression has the effect that when m_1 is 1 (i.e. a stand of such low density that inter-tree competition is negligible) then the power $(1/m_1 - 1)$ will be zero, and the multiplier m_3 will always be 1 regardless of relative tree size. This is as it should be, since in an open stand, assuming homogeneous spacing, there are no suppressed or subdominant trees. At the other extreme, a very dense stand with CCF of 320%, then m_1 will be 0.5, and the growth reduction associated with dominance class will be linearly proportional to the ratio d_i/d_{10}. A more normal case, with CCF of 140% (approximately the value for <u>P. sylvestris</u> "moderately thinned" stands 40-60 years old) will give a power of 0.32 for the ratio d_i/d_{10}.

These three multipliers are then combined in their effect in the equation to predict diameter increment for the i'th decile :

(16) $$\Delta d_i = \Delta d_o \cdot m_1 \cdot m_2 \cdot m_3$$

The various powers and terms in the above expressions have been adjusted on the basis of a theoretical consideration of the behaviour of increment and published empirical information for <u>P. Sylvestris</u>. Adjustment was made using repeated trials of the model until the outputs gave good conformance with Schober's yield tables for the range of sites and stand densities incorporated.

These tables mainly cover stands at 'normal' stockings, corresponding in practice to fairly high competitive intensities not far below the level at which density dependent mortality occurs. A feature of the increment model is that for open stands, the multipliers m_1, m_2, m_3 will all be unity, and diameter increment will be as determined for the calibration data for solitary trees. Thus the model is responding accurately at the two extremes of stand density (open stands and high stocking levels). It may be concluded with some confidence that intermediate values of stand density will inconsequence also be modelled accurately. This feature is an important aspect of the model's design.

5.7 Losses from suppression and mortality

The maximum number of stems that a stand of given mean height can maintain as viable, living trees is given in equation (1), section 5.1 . When the stocking is found to exceed this limit, as will be the case through normal growth with lightly or unthinned stands, then the excess stocking is removed by the model, and the array of diameter deciles are adjusted on the basis of the assumption that this mortality will be very largely, but not entirely, concentrated in the smallest size classes.

The actual mechanics and assumptions of this adjustment process are identical to those used in the thinning algorithm (see section 5.9). Mortality is assumed to correspond in its effect to a very light low thinning.

5.8 Losses from windthrow

The sensitivity of the stand to windthrow is affected by many factors, including soil type and depth, tree slenderness, and aerodynamic roughness of the canopy. It is also a function of the frequency distribution of severe windstorms in a given locale, and the protection given by local topography. Of these factors, two are internal features of the stand dynamics, and subject to incorporation in the model. These are slenderness (height/diameter ratio) and aerodynamic roughness. The other factors (soil type and depth, local protection, and storm frequency) are external factors of the site.

No information on the sensitivity of stands of P. sylvestris in North Germany to windfall was available at the time of preparing this model, beyond the general opinion that trees with a slenderness[1] greater than 0.9 are subject to high risk

1. Slenderness is defined as height in metres divided by diameter in centimetres.

of windthrow in severe storms. Whilst it appears highly probable that aerodynamic roughness is also a factor, its contribution to risk is likely to be of much smaller magnitude than slenderness, and it has been excluded from the model for the present time. In the future, with the acquisition of some empirical data on windthrow, aerodynamic roughness will probably be included if it proves to be a significant variable.

The present windthrow model is based on the mean slenderness of the stand, but with an additional risk factor included based on height. This allows for the fact that the turning moment of the wind, and the pressure upon the crown will both be greater on taller trees than on shorter ones. Mean slenderness for the stand, S, is defined as :

(17) $$S = (\sum h_i/d_i)/10$$

The windthrow risk factor for the stand, W, is computed from S, and stand mean height H via three multipliers, w_1, w_2, and w_3 :

(18) $$W = w_1 . w_2 . w_3$$

The multiplier for the slenderness effect is w_1. A hypothetical graphical relationship between w_1 and slenderness was constructed as shown in figure 3(a). This was then expressed mathematically by the function :

(19) $$w_1 = 1 - \exp(-((S-0.65)/0.35)^4)$$

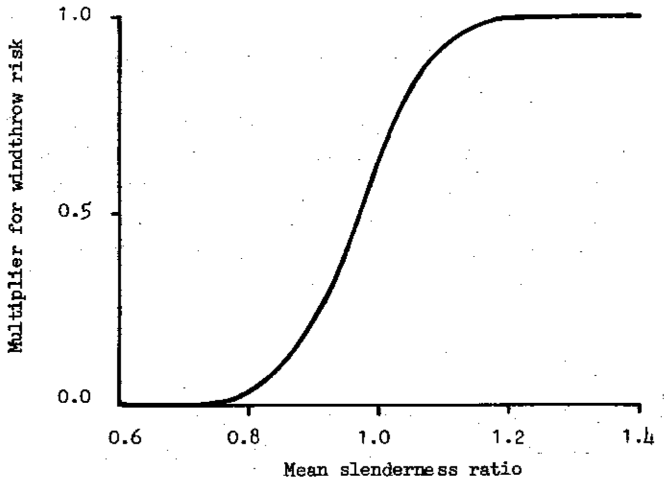
The multiplier for the effect of height on windthrow risk is w_2. This was again drawn graphically as a hypothetical relationship, and then approximated with a simple equation, in the form :

(20) $$w_2 = \exp(0.4901 - 20.27.H^{-1.05})$$

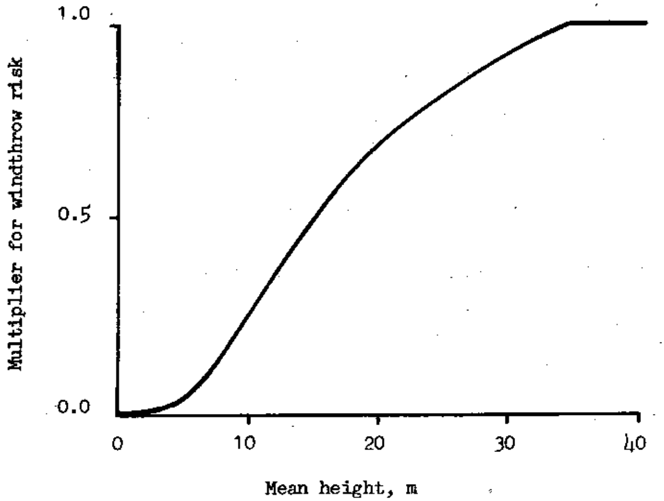
where w_2 is subject to the constraint that it may not take

Figure 3 Postulated graphical relationships between windthrow risk multipliers and stand mean slenderness and height.

(a) The effect of slenderness on windthrow risk.



(b) The effect of height on windthrow risk.



values greater than 1.

The third multiplier in equation (18) is designed to take account of the differences in windthrow risk between sites. It is supplied to the computer model by the user, and appears on the printout as 'windthrow factor' (see table 1). It should take values between 0 and 1, where zero represents either a completely protected site, or an idealized stand with no windthrow, and one represents a high risk situation such as an exposed convex slope on shallow rooting soil. This windthrow factor can be varied by the user in order to test the effect of varying degrees of windthrow risk on particular silvicultural regimes.

KIM is a deterministic model, whereas it is apparent that windthrow is a highly stochastic process. This duality is resolved by treating the risk, or probability, that any one tree will experience windfall in a given five year time period, W, as the frequency of windfall over a large area, and hence the frequency per hectare for a mean stand. Thus in the model, windthrow risk W is interpreted directly as a multiplier for stocking reduction :

(21) $$\Delta N = -N.W$$

Windthrow risk in this sense is assumed to be equally distributed through the size classes of the stand, and in consequence the array of diameter deciles is unaltered by a windthrow event. Only the total stocking changes.

This model of windthrow effects is almost entirely assumed, and is certainly capable of improvement with further empirical study. Nonetheless, it does provide a means for examining the interaction between silviculture, windthrow, and subsequent yield. In this sense, the model provides a much more realistic tool for studying management of the P.sylvestris stands in North Germany, which are prone to this problem, than the idealizations of conventional yield tables, which usually succeed only in ignoring the problem altogether.

5.9 Thinning

The model incorporates a single type of low thinning, using an algorithm which has been described in some depth in other work (ALDER 1977, 1979). For this reason it will be presented here only in general terms.

Low thinning, or thinning from below, is the most usual and ecologically satisfactory form of thinning in plantation crops of shade intolerant tree species. It is usually considered to involve removal of the smallest trees in the stand, whilst leaving the dominant stratum, and most codominants to continue their development. In terms of its effect upon the diameter distribution, low thinning will remove the smallest trees, but with a certain spread, caused by a variety of factors, into the larger sizes. The most important factor governing the distribution of diameter classes in a low thinning, relative to the main crop, is the intensity of the thinning. As a greater proportion of the total stocking is removed, so will the distribution of thinned stems tend to approach that of the main crop.

The thinning algorithm used in the model produces these effects, and hence results in a realistic pattern of changes in diameter distribution in response to thinning. The low thinning is specified by two parameters only, which are the age at which it is to take place, and the residual stocking, in terms of stem numbers, to be left after thinning. When the age specified for a thinning in the model is reached, the total stocking and the array of diameter deciles are modified to account for the effects of thinning. At the same time, an array of diameters and frequencies of thinned stems is produced, from which the mean diameter of thinned stems is calculated. The volume of thinnings is calculated in KIM as the difference between the before and after treatment standing volumes.

5.10 Branch diameter

The estimation of branch diameter is very important in relation to silvicultural treatments involving wide spacings or heavy thinnings. The economic evaluation of such treatments requires either that the wood quality due to large sized knots be taken into account, or that pruning is necessary, with the frequency and cost of pruning appearing as variables dependent on branch size.

In the present model, it is assumed that the key parameter is mean branch size at the base of the green crown. This will, together with information on the height of the crown base, provide a complete profile of dead branch diameters up the bole as the stand develops over a period of time. In the output table, as shown in figure 2, the height of the crown base and the branch diameter estimated at that point are shown as means for the whole stand. Working down the table provides a complete profile for a mean tree.

To predict branch diameter at the crown base, it was necessary to provide three subsidiary equations :

(1) Prediction of the height of the crown base in a given stand.

(2) Prediction of the bole diameter at the crown base, knowing its height, and the height and diameter of the tree.

(3) Prediction of mean live branch diameter as a function of bole diameter and the tree's dominance class.

The model for the height of crown base was determined by examining in turn a number of correlations among variables and ratios in the set of sample data. The best and most reasonable relationship was between breast height diameter and crown length. This was a slightly curviliear function, and was fitted with the quadratic equation :

$$(22) \qquad L = 0.9293 + 0.3833\, d - 0.003385\, d^2$$

where crown length L is in metres, and tree diameter d in centimetres. This equation had an R^2 of 0.807 with 52 sample trees. It is important to remember the very broad base of growing conditions represented in the sample, from dense stands to solitary trees, and from 5 to 100 years old. The equation predicts a maximum crown length for P. sylvestris of 11 metres with trees of 56 cm. diameter. Equation (22) then suggests that crown length will decrease with a further increase in diameter. However, this is an artefact of the quadratic equation used, and in practice, the 11 m. crown length should be regarded as an asymptotic maximum for all trees over 56 cm. diameter.

The next step is to determine bole diameter at the crown base. This is performed with the commonly used taper equation :

$$(23) \qquad d_k/d = (h - h_k)/(h - 1.3)$$

This equation gives a good approximation to stem form over the middle part of the bole, although it underestimates diameter on the lower part of the bole, and overestimates it near the tip. Since the crown base falls in this middle region, it provides a satisfactory approximation for the present purpose.

We may note that the upper stem height, h_k, at the crown base, is tree height h less the crown length L. Defining diameter at the crown base as d_c, we then have, from (23) :

$$(24) \qquad d_c = d.L/(h - 1.3)$$

The final step in predicting branch size is to derive a relationship between mean branch diameter and the corresponding diameter on the bole. For this, a number of regression models were studied relating the ratio of live branch diameter b with corresponding bole diameter d_k to various tree and stand parameters. The best relationship was with dominance class, as defined in section 4.6. In the sample data, dominance class was considered to be the ratio of the subject tree diameter to the diameter of the largest tree on the plot, including the subject tree itself. The fitted regression equation between branch diameter/ bole diameter to dominance was:

$$(25) \qquad b/d_k = 0.31554 - 0.74773(d_i/d_{max})^2 + 0.59056(d_i/d_{max})^3$$

This equation had an R^2 of 0.38 . In practice, this equation has relatively little effect, and it would be almost as satisfactory to assume a constant ratio of b/d_k of approximately 0.15 to 0.20 . However, at the time of writing, equation (25) provides the final link in the model to estimate branch diameter at the crown base.

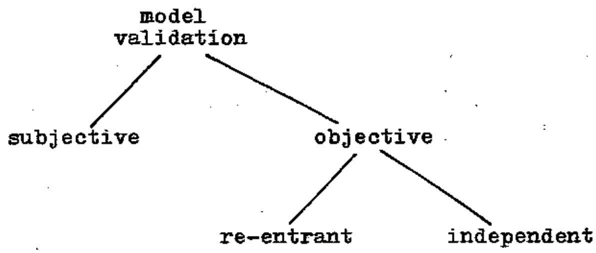
6. VALIDATION

Validation is an important phase in the development of any systems model. It involves, quite simply, the evaluation of the performance of the total system by comparison with selected independent data in order to ensure that the model is accurate within the required limits over the range of performance.

In practice, it is not so easy to achieve a fully satisfactory validation of a model. In some cases,for example, of simulation from purely theoretical considerations, one may have little objective data about system performance. In such cases, the validation consists of ensuring that the model behaves in a fashion that is considered 'reasonable' by specialists in the relevant field. This type of validation is essentially subjective.

In other cases, where the model has been constructed from empirical data concerning elements of a system, validation may be possible by comparison of the behaviour of the total system with the behaviour of the objective systems from which the discrete empirical components of the model were derived. We may call this 'objective re-entrant' validation, because one is essentially using the same data for validation as that from which the model was constructed.

Finally, one may have assessments of the performance of systems that are completely independent of those from which the relationships in the model were derived. These independent assessments can then be compared with overall system performance for an 'objective independent' validation. One may represent these three cases diagrammatically, as shown below:



For KIM, re-entrant objective validation has been used for the most important aspect of the model, which is the prediction of the main growing crop diameters and heights when subjected to various thinnings and in various yield classes. Subjective determination of reasonable performance has been necessary for branch diameter and windthrow estimates.

The main stand parameters are validated by comparison with SCHOBER (1975). In the examples of validation given here, standing volume predictions are compared for KIM and the yield tables. Standing volume effectively integrates all the many subcomponents of KIM, including diameter increment, diameter distribution, tree height, and stem form, and thus provides a sensitive test of any cumulative errors in the system as a whole.

Figure 4 compares the performance of the model for two yield classes (1 and 3) with the yield tables for the moderate thinning schedule. The results show close agreement. Yield classes 2 and 4 show similar close correlation.

Figure 5 compares model predictions for the two extreme thinnings given in the tables, which are the moderate or normal schedule, and the low stocking regime. The two examples shown are for yield class 2. Again it can be seen that the model shows close agreement with the yield tables.

We may conclude this section by stating that the model in its present form appears to respond in a very similar fashion to published growth data for P. sylvestris, and that accordingly some confidence may be placed in the silvicultural studies which follow.

7. SILVICULTURAL STUDIES BASED ON THE MODEL

In this section, the KIM model is used to examine some questions regarding optimal spacing and thinning regimes with respect to windthrow hazard, and to consider how branch size of unpruned stems grown under such regimes will vary compared with current practice. The problem of ameliorative treatment of existing overstocked stands is also studied.

7.1 Optimal spacing and thinning under windthrow hazard

The effect of windthrow hazard upon the stocking level of stands grown at various spacings, at yield class 2, is shown in figure 6. The thick solid line shows the point at which stands at constant stocking reach a slenderness of 0.9, which may be regarded as the critical stability condition. The fine solid line shows the stocking/age relationship for stands thinned according to the moderate thinning schedule in SCHOBER's yield tables, assuming a site completely protected from windthrow.

The fine broken lines illustrate the course of events in stands

Figure 4 Comparison of standing volume predictions from the KIM model and Schober's yield tables for moderately thinned stands, yield classes I and III.

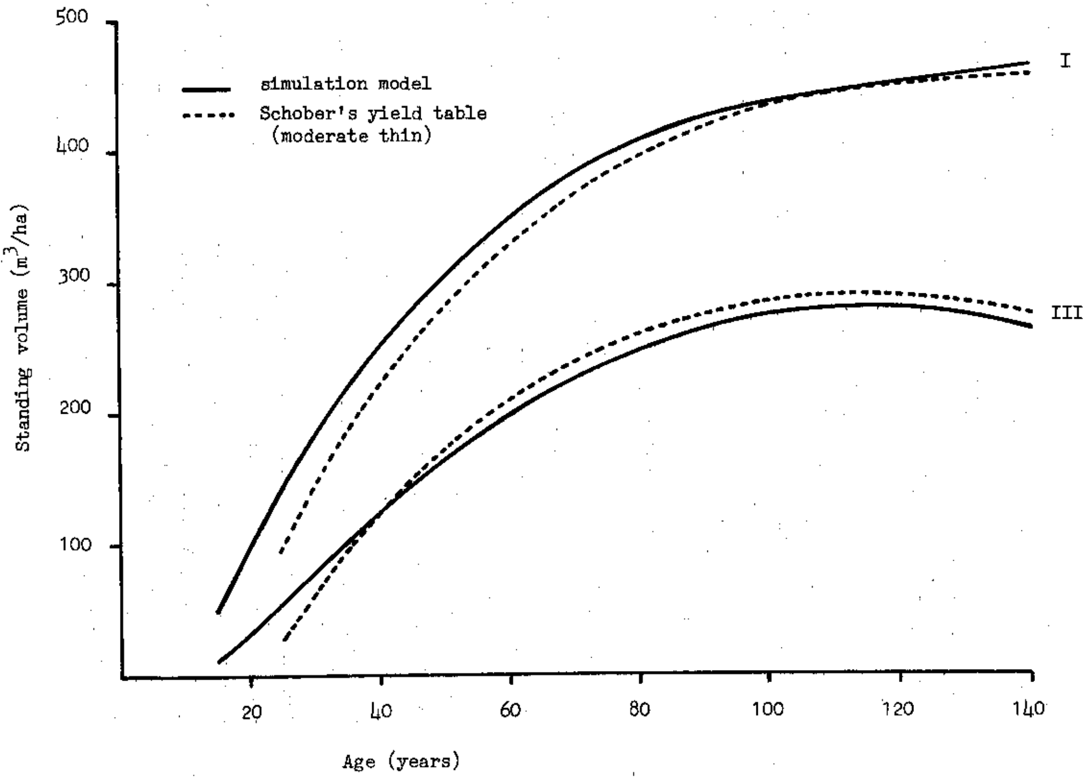
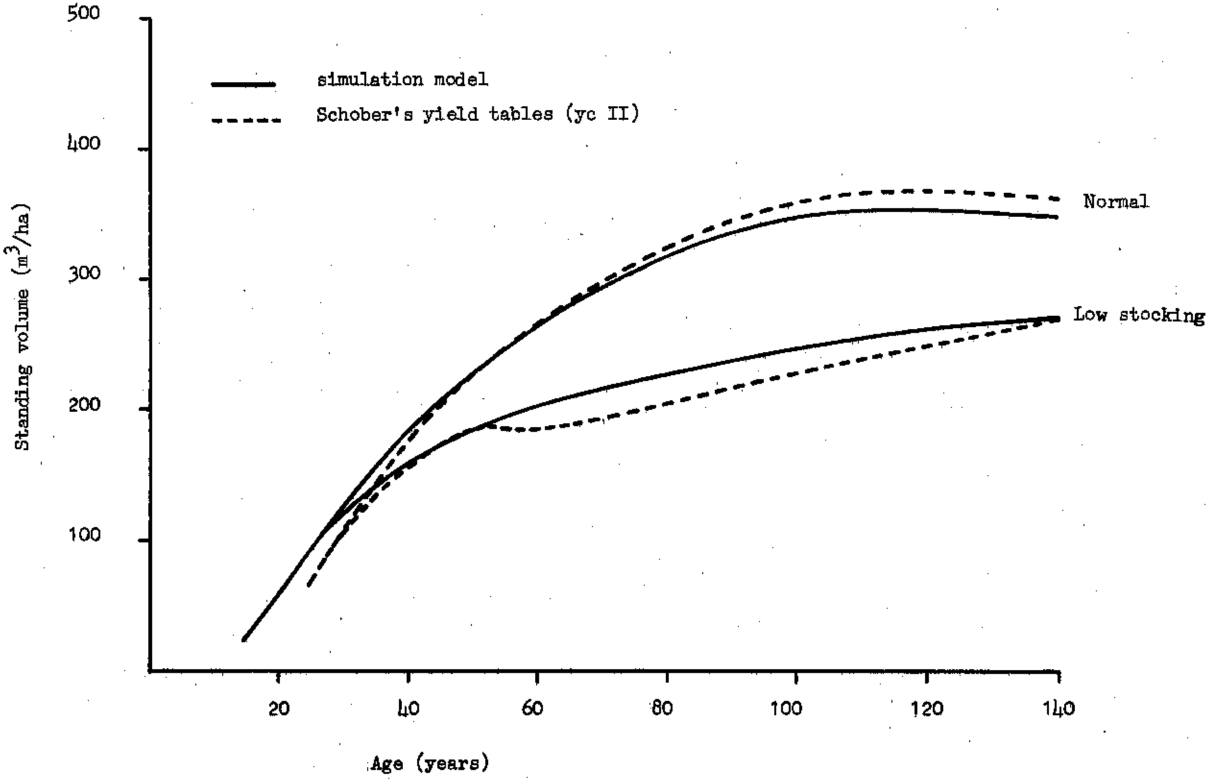


Figure 5 The effect of two different stocking levels on standing volume predictions from the KIM model, compared with Schober's yield tables. Both are yield class 2, and represent the treatments for the normal ("massige durchforstung") and low stocking ("lichtung") yield tables.



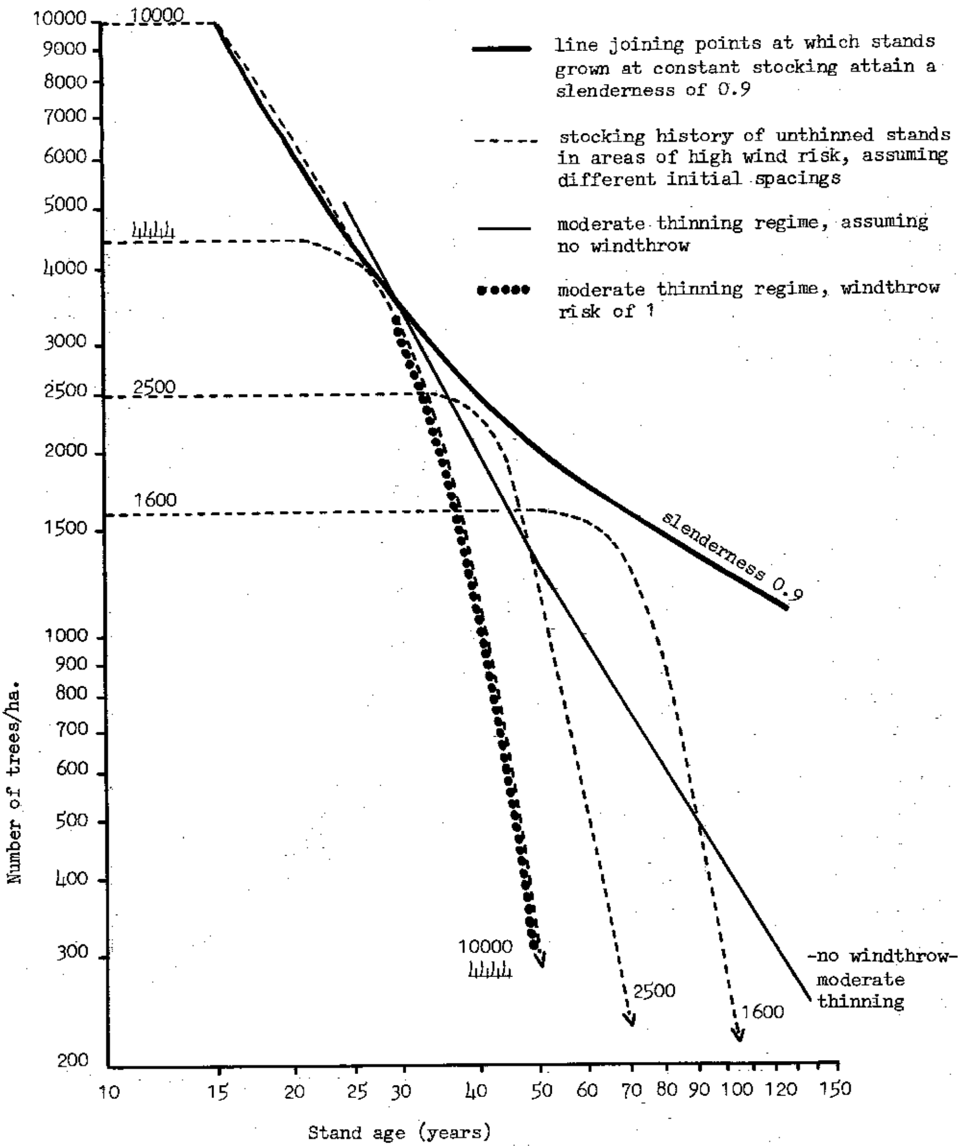


Figure 6 The effects of windthrow on the stocking of stands grown unthinned at different spacings and upon stands grown under the moderate thinning schedule.

at different spacings subject to a high windthrow risk factor. Stands planted at 10,000 stems/ha (1 x 1m) or 4444 stems/ha (1 x 2 m.) show a rapid and catastrophic decline in stocking between ages 30 and 50 years. At lower stockings the windthrow effect is similar but more gradual. The moderate thinning schedule is as sensitive as the high stocking levels (10,000 and 4444 stems/ha.) to wind damage.

In arriving at an alternative treatment regime, it is important to understand what is happening to the slenderness ratio, which is the critical factor, in these stands. At close spacings, the rapid early height growth of the stand is being combined with very restricted diameter increment. The result is that the whole stand, by the age of 30 years at yield class 2, has a slenderness greater than 0.9, and furthermore, rising rapidly to values of 1.2 or more. When part of a stand in this condition is destroyed by wind, then the condition of the growing stock is such that the diameter growth response to increased growing space is unlikely to be sufficient to increase the stability of the trees significantly, which in terms of the model means lowering the slenderness below 0.9.

It is clear that for secure managment of stands growing under conditions of high windthrow risk, the early stocking should be as low as possible, preferably at or below 2500 stems/ha. (2 x 2 m. or 1 x 3 m.). First thinning is an extremely sensitive operation for the future stability of the stand. It should be heavy, in order to ensure an economic yield, and take place no later than age 35 on yield class 2. Subsequent thinnings then cease to be critical to wind stability, and they may be delayed or omitted if economic or social factors so indicate. If a higher stocking than 4444 stems/ha. were to be used, it would be almost certainly impossible to obtain a commercial yield from the first thinning; hence it is likely that thinning of such stands would be delayed until they have entered the critical condition that is characteristic of so many of the existing plantations. Once this has happened, then further treatment, as described below, requires difficult and somewhat draconian measures.

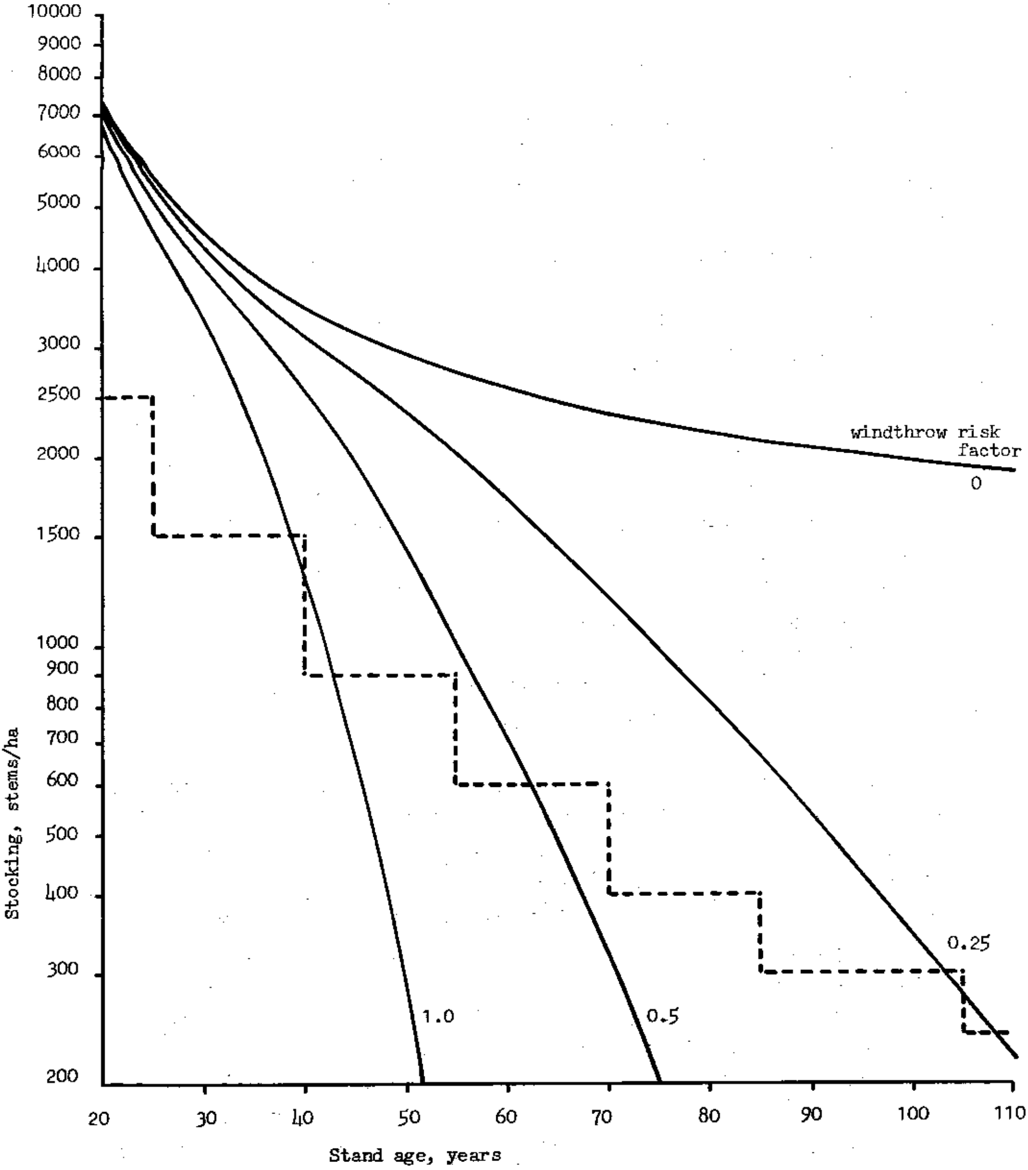


Figure 7 Stocking-age relationships, for yield class II, for untreated stands assuming different levels of windthrow risk. The broken line is the stocking-age relation for the proposed radical treatment schedule.

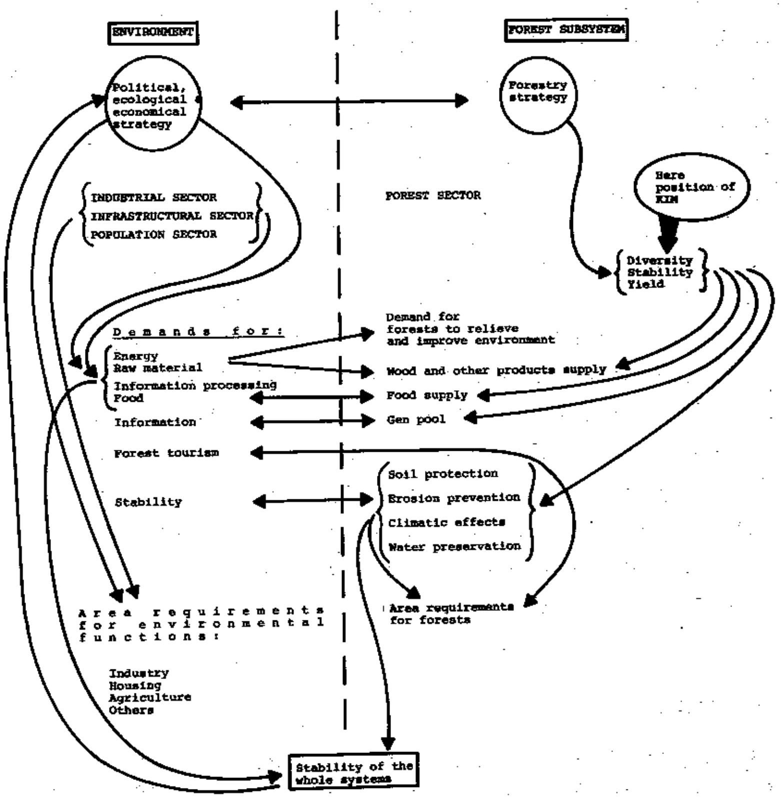


Fig. 8. Model of the interactions between the environment and the subsystem "Forest" with the position of the stand growth model KIM indicated by the thick arrow (Forest Interaction Model from GROSSMANN elsewhere in this volume).

8. CONCLUSIONS AND INTEGRATION WITH OTHER MODELS

The stand growth model provides a very detailed picture of stand structure and it's changes. It is capable of being developed not only to fulfill its primary aims of growth prediction, but it's information on structure and change can be used in studying relationships between growing-space and stand structure, and between forest structure, environmental influences and forest functions.

The growth model and the available structural stand models (see sect. 21 in this report and sect. 53 in the report by BRUNIG, ALDER and SMITH) are sub-models of the "interaction model" (fig. 8) which demonstrates the interactions between the forest and the environment (GROSSMANN, see report elsewhere in this volume). This "interaction-model" in turn is sub-model of the general cybernetic regional simulation model (see reports by SCHWARZ, v.HESLER and VESTER elsewhere in this volume). The hierarchy and interdependencies of these models are described in detail in the reports by GROSSMANN.

9. REFERENCES

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Alder, D. (1977). A growth and management model for coniferous plantations in East Africa. D. Phil thesis, Oxford University.

APPENDIX A

Algebraic symbols used in the text

a	The constant 8.754×10^{-5} .
b	The live branch mean diameter at a particular reference point on the stem.
D	The diameter of the tree of mean basal area, cm.
d	The diameter of a single tree, cm.
d_i	The diameter of the i'th decile of the cumulative frequency distribution.
d_c	The diameter of the bole at the base of the live crown.
d_k	The diameter of the bole at any measurement point k.
d_{max}	The largest diameter on a plot, or d_{10} in the simulated distribution.
Δd_o	The diameter increment of a solitary tree, cm/yr.
f	The form factor of a single tree.
f_i	The form factor of a tree of diameter d_i .
G	The basal area of a stand, m^2/ha.
G^*	The predicted basal area of a young fully stocked stand.
H	The mean height of the stand, equivalent to the height of the tree of mean basal area, metres.
h	The height of a single tree, m.
h_i	The height of a tree of diameter d_i.
Δh_o	The height increment of a solitary tree, m/yr.
h_k	The height of a point k on the bole of a given tree.
K	Crown competition factor for the stand, which is the sum of the crown areas, in are, which the trees in the stand would have if they were open grown stems of the same diameter, are/ha. or %.
L	The length of the live crown of a single tree, in metres.
m_1	Multiplier factor to reduce open grown diameter increment in response to stand density.
m_2	As for m_1, but in response to past competition.
m_3	As for m_1, but in response to current dominance class.
N	The number of trees per hectare.
N_{max}	The limiting stocking that can be supported without compensating mortality.
N_{min}	The minimum stocking on a young stand that can be supported without loss of basal area increment.
ΔN	The change in stocking over a 5-year period.

Algebraic symbols (continued....)

p_i The cumulative frequency of the i'th diameter class. For a diameter d_i in the cumulative distribution, a proportion p_i of the stocking will be smaller than d_i.

r The radius of the crown of a single tree, m.

S The mean slenderness (height in m./diameter in cm.) of a stand.

t The age of a tree or stand, in years from planting.

v The volume of a single tree, m^3.

v_i The volume of a tree of diameter d_i and height h_i, m^3.

W The total frequency of windblown stems over a 5-year period, as a proportion.

w_1 A multiplier for windthrow frequency based on mean slenderness.

w_2 A multiplier for windthrow frequency based on mean height.

w_3 A windthrow frequency multiplier to account for site differences. It is supplied to the model as a value between 0 and 1 by the user.

Y Relative yield class, on the scale 1-4, supplied for a given simulated stand by the user.

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