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Simulation model for natural regeneration of *Pinus sylvestris, Picea abies, Betula pendula* and *Betula pubescens*

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TIIVISTELMÄ: MÄNNYN, KUUSEN JA KOIVUN LUONTAISEN UUDISTAMISEN SIMULOINTIMALLI

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In the model the regeneration process is devided into three subprocesses: birth, growth and mortality of seedlings. The main emphasis is on the birth process where the following phases are simulated: seed crop, quality of seeds, maturing of seeds, predation of seeds and germination. The parameters are based on data published in Finland. Part of the parameters is obtained directly from the investigations and part is proposed by the author. The model can be calibrated by changing parameter values. The simulation is made with the help of random numbers which have the same means as the estimates and the same distributions as the residuals of the equations used in simulation. The time step of the model is one year. The number of emerged seedlings in one year is obtained by multiplying the seed crop with the probabilities that the seed passes different phases of the birth process. Because of stochasticity the regeneration period is simulated several times. From the results it is possible to evaluate the risk and succeeding probability of the regeneration. The main drawbacks of the simulation method are the lack of empirical parameters and the difficulty of validiation. The model could be further developed by including spatiality into the model.

Esitetyssä simulointimallissa uudistumisprosessi on jaettu kolmeen vaiheeseen: taimien synty, kasvu ja kuoleminen. Tarkimmin on simuloitu taimien syntymistä, joka koostuu seuraavista osista: siemensato, siementen laatu ja kypsyminen, itävyys ja siementen predaatio. Mallin parametrit perustuvat Suomessa julkaistuihin tutkimuksiin; osa on saatu suoraan tutkimuksista, ja osa perustuu kirjoittajan subjektiiviseen päättelyyn. Simulointimalli voidaan kalibroida muuttamalla parametrien arvoja. Uudistamisprosessia jäljitellään generoimalla satunnaislukuja, joilla on sama keskiarvo kuin simuloinnissa käytettyjen yhtälöiden estimaateilla ja sama hajonta kuin yhtälöiden residuaaleilla. Simuloinnin aika-askel on yksi vuosi. Itäneiden siementen määrä saadaan kertomalla ko. vuoden siemensato todennäköisyyksillä, että siemen läpäisee syntymisprosessin eri vaiheet. Mallin satunnaisuuden vuoksi uudistumisjakso simuloidaan useita kertoja. Tulosten perusteella voidaan arvioida mm. uudistumisen onnistumistodennäköisyyttä ja siihen liittyvää riskiä. Esitetyn simulointimenetelmän puutteita ovat mm. parametrien puute ja mallin testaamisen vaikeus. Mallia voidaan edelleen kehittää liittämällä siihen siementen leviämismalli ja ottamalla huomioon kasvutekijöiden tilassa esiintyvä vaihtelu.

Keywords: computer model, stochastic simulation, birth model
ODC 231--015+63+236.4

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Definition of symbols and abbreviations for equations

Symbol	Definition
a	Parameter of seed crop distribution
B1, B2, B3, C1 and C2	Correction factors of seed crop due to basal area
BA	Basal area of stand (M^2/ha)
C	Parameter which determines the dependence of PAR3 on basal area
DH	Dominant height of stand (m)
ES	Empty seed percentage
FR	Amount of male flower residuals (g/m^2)
FS	Full seed proportion
GE	Proportion of germinated seeds
HP	Proportion of average heat sum needed for 50 % maturing
HSE	Average heat sum of a particular area (degree days)
HSL	Heat sum in which 50 % of seeds mature
MA	Proportion of mature seeds
MAX	Maximum proportion of germinated seeds
PAR1	Parameter for the rate of decrease of stockable area
PAR2	Parameter which determines the distribution of germination proportion
PAR3	Parameter of mortality model
PAR3(0)	Value of PAR3 when basal area is 0
PC	Pollen catch (grains/mm^2)
PR	Proportion of uneaten seeds
S	Seed crop in units of seed crop distribution (spruce: seeds/m^2, other species: proportion of capacity)
SA(t)´	Proportion of stockable area t years after site preparation
SC	Seed crop generated for one simulation year (seeds/m^2)
SCC	Corrected seed crop of one simulation year (seeds/m^2)
SN	Proportion of emerged seedlings
SU(t)	Proportion of seedlings which survive to year t

1. Introduction

Simulation is becoming an important tool in decision making in forestry. The claims for increasing productivity and the variability of objectives have caused a situation where simple yield tables and silvicultural recommendations do not suffice. A simulation model is another possibility to examine quantitatively the probable outxomes of different treatment alternatives. The model may simulate growth, thinnings and their effects, regeneretation and other processes in the forest.

There are many simulation models for stands which have passed the seedling phase (e.g. Mitchell 1969, Lin 1974, Monserud 1975, aber and Melillo 1983, Kimmins and Scoullar 1983, Siitonen 1983). In most models the regeneration of a stand is simulated with simple techniques or is excluded from the model. Many factors affect the success of forest regeneration. If they are all included in a model made for simulations over long period of time the model may not be operational in studying different regeneration alternatives. One possibility is to make special models for regeneration (e.g. McMurtrie and Wolf 1983, Fox et al. 1984, Parviainen et al. 1984).

In Finland there are lots of data concerning the regeneration of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst.) and birch (*Betula pendula* Roth and *B. pubescens* Ehrh.) (see e.g. Sarvas 1952, 1962, 1968, Koski and Tallqvist 1978). On the other hand, no simulation model for natural regeneration in which this data is in effective use exists.

The aim of this study is to develop a simulation model for natural regeneration based on data published in Finland. The model can be used for simulating the natural regeneration of Scots pine, Norway spruce and birch in Finland.

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2. Modelling technique used

2.1 Subprocesses of natural regeneration

A regeneration model can be deterministic or stochastic. A deterministic model of regeneration always gives the same result in a certain situation. A stochastic model produces a distribution of outcomes similar to that found in nature. With a stochastic model it is possible to examine the whole probability distribution of a phenomenon. With the stochastic model the decision maker can e.g. calculate the probability of obtaining a sufficiently good result.

The natural regeneration of forest stand can be divided into three subprocesses: (1) birth of a plant, (2) growth and (3) mortality. Each of the subprocesses depends on many factors. Usually only a minor part of the variation of a factor can be estimated in the decision making. The unpredictable variation when using, for example, growth equations can be regarded as stochastic. The whole regeneration process can be simulated with random numbers which have the same means as the estimates and the same distributions as the residuals of the models used in simulation.

The birth process of a plant has many subprocesses which vary almost independently. The independence of the subprocesses arises from the fact that the different subprosesses depend on weather conditions of different time periods. The main subprocesses of the birth process are

- seed production (amount and quality of seeds),
- maturing of seeds,
- predation of seeds and
- germination.

The birth process can be regarded as a series of phases which a seed must successfully pass to become an emerged plant. The number of plants is obtained by multiplying the number of seeds (seed crop) with the proportions (probabilities) that the seed passes a phase of the birth process (Fig. 1). So the simulation model is actually a group of random numbers which have the same distributions as these proportions.

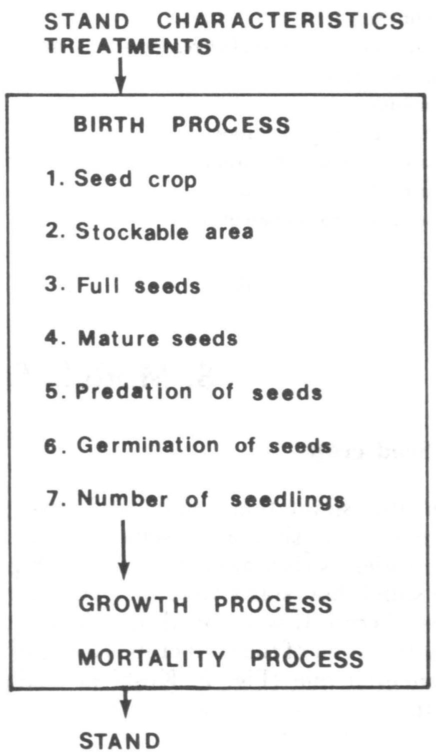

Fig. 1. Processes in the simulation of natural regeneration.

2.2 Model inputs

The input of the model consists of stand characteristics and the schedule of treatments. These define the regeneration situation. The stand characteristics are the predictors of the models used in simulation. All the variables used as predictors are usually known or they are easily measured. The model inputs are

- tree species,
- dominant height of the stand,
- basal area before and after regeneration cutting,
- forest site type,
- heat sum,
- method of site preparation,
- year of regeneration cutting,
- year of site preparation and
- year of removal of parent trees.

The effect of treatment begins a year after the treatment. It is assumed that the treatments are made during the latter half of the year.

Other inputs for the simulation program are the length of the simulation period and the number of simulations. By starting the simulation before regeneration cutting it is possible to take into account those seedlings which appear before regeneration treatments.

Another type of data needed in the simulation are the silvicultural properties of different tree species and sites. This knowledge is hold by the parameters of the simulation model. By changing the parameters values it is bossible to adapt the model to the information which the user may have of the regeneration situation.

3. Models for the subprocesses

3.1 Seed crop

In the simulation model different subprocesses are simulated separately in the same order as they appear in reality (Fig. 1). The simulation starts with the generation of the seed crop. It is assumed that the frequency distribution of the seed crop is a negatively exponential one (Fig. 2; Koski ja Tallqvist 1978):

$$f(S) = a \cdot \exp(-aS), \quad (1)$$

where f(S) = frequency,
a = parameter of the distribution and
S = amount of seed crop.

In pine and birch stands the seed crop is expressed as a proportion of the capacity of the seed crop in a stand. Capacity is the seed crop of the very best seed years (Koski and Tallqvist 1978). In a spruce stand the seed crop equals the number of seeds/m^2.

The parameter of the seed crop distribution depends on the heat sum (degree days, treshold value 5 °C) according to the following equations. The equations are calculated from the data published by Koski and Tallqvist (1978).

Species	Equation	F-value	R^2, %	N
Pinus sylvestris	$a = 4.534 - 0.00163HSE$	24.2	79	7 (2)
Picea abies	$\ln(a) = 11.84 - 2.510\ln(HSE)$	630.0	98	11 (3)
Betula spp.	$a = 13.92 - 0.00850HSE$	10.9	45	13 (4)

HSE is the average heat sum of a particular locality.

When simulating one year's regeneration, the distribution is sampled with the help of a uniform random number and the inverse of the distribution function of the seed crop (Fig. 3). A single seed crop (S) is obtained by formula

$$S = (1/a)\ln(RAN), \quad (5)$$

where a is the parameter of the seed crop distribution and RAN is a uniform random number (0,1). In pine and birch stands the sampled value (S) is the proportion of capacity. It is converted to the number of seeds/m^2 (SC) by formulas of Koski and Tallqvist (1978):

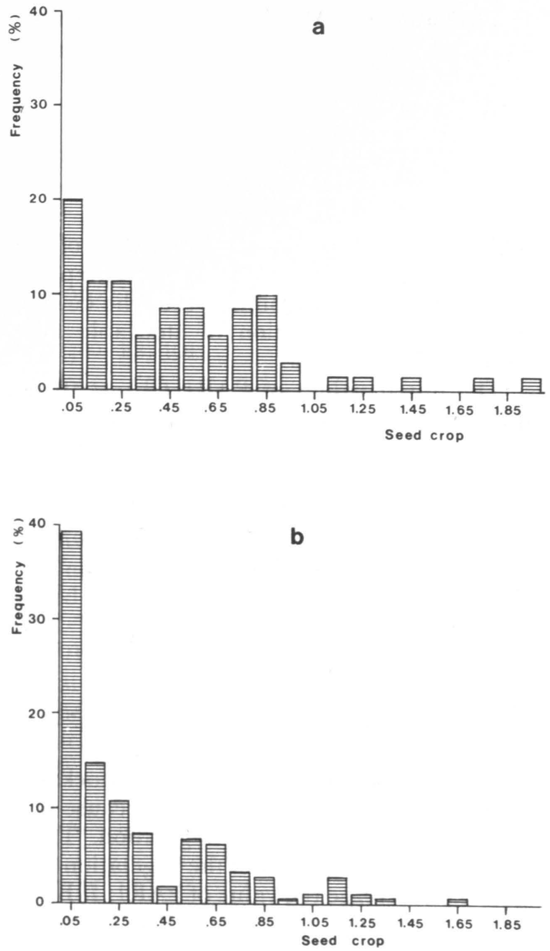

Fig. 2. Frequency distribution of pine seed crop in southern (a) and northern (b) Finland. Seed crop is expressed as proportion of capacity.

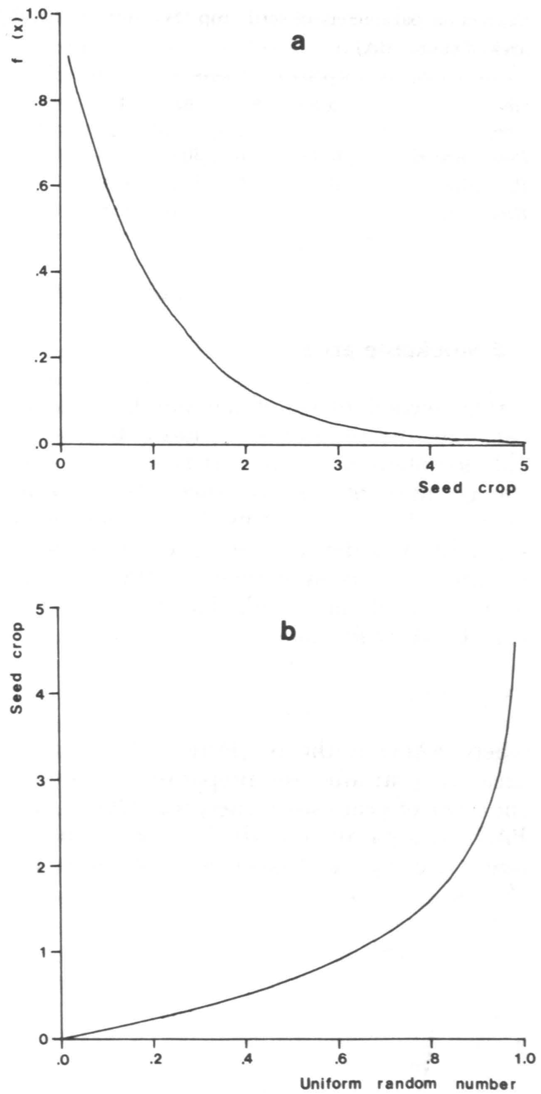

Fig. 3. Density function (a) and the inverse of distribution function (b) of negative exponential distribution. Exponentially distributed seed crops are generated with the help of the inverse of distribution function and a uniformly distributed random number.

Species	Equation	
Pinus sylvestris	$SC = S \cdot \exp(4.0855 + 0.0687 \cdot DH)$	(6)
Betula spp.	$SC = S \cdot \exp(8.7506 + 0.1632 \cdot DH)$	(7)

where DH is the dominant height (m) of the stand. In spruce stand SC = S.

If the basal area of the stand (BA, m^2/ha) is very low or high, the seed crop is corrected to a lower level (SCC). Correction coefficient depends on five parameters (C1, B1, B2, B3, C2) which are defined by tree species (see the setup below). If BA is 0, the coeffiecient is C1. If BA is between B1 and B2, no correction is made. If BA is greater than B3, the coefficient is C2. Between 0 and B1 and between B2 and B3 the correction coefficient is linearly dependent on the basal area.

Correction parameters of seed crop (SC) due the basal area of stand (BA)

Species	C1	B1	B2	B3	C2
Pinus sylvestris	0.05	5.0	30.0	50.0	0.1
Picea abies	0.10	10.0	35.0	50.0	0.1
Betula spp.	0.20	4.0	25.0	50.0	0.1

3.2 Stockable area

The second phase of the simulation is to calculate the proportion of forest floor suitable for plant emergence. It is assumed that the germination can be successful only in areas free from raw humus. The proportion of stockable area depends on (1) forest site type, (2) site preparation method, (3) time and (4) basal area of the stand. The proportion is calculated by formula

$$SA(t) = SA(1) \cdot t^{PAR1}, \quad (8)$$

where SA(1) is the proportion of stockable area one year after site preparation, t is time (number of years since site preparation) and PAR1 is a parameter which depends on the forest site type and basal area of the stand (Fig. 4).

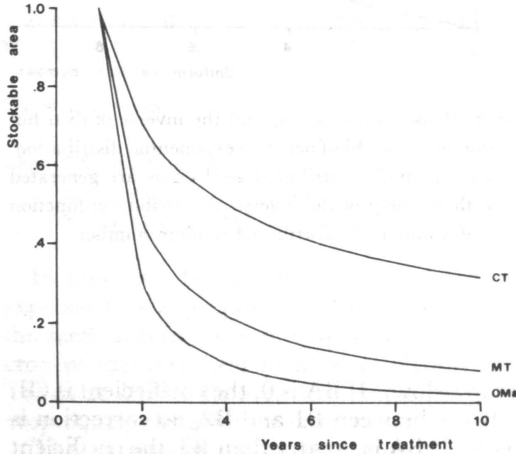

Fig. 4. The decrease of stockable area on different forest site types as a function of the years since treatment. OMaT = very good, MT = medium, CT = poor.

The values of SA(1) for different site preparation methods are:

- No preparation 0.10 %
- Regeneration cutting 0.50 %
- Scalping 3.75 %
- Disk ploughing 13.30 %

which are the calculated proportions of exposed mineral soil in different site preparation methods. It is assumed that the cutting increases the proportion of stockable area from 0.1 % to 0.5 %.

The initial values of PAR1 (BA = 0) on different forest site types are as follows:

Forest site type	Abbreviation		PAR1
Oxalis Maianthemum Type	OMaT	(very good)	−1.7
Oxalis Myrtillus Type	MT	(good)	−1.5
Myrtillus Type	MT	(medium)	−1.1
Vaccinium Type	VT	(rather poor)	−0.6
Calluna Type	CT	(poor)	−0.5
Cladonia Type	ClT	(very poor)	−0.4

The rate of the decrease of the stockable area is highest on the best types because of a rapid recovery of ground vegetation. Trees inhibit the development of the vegetation and thus they increase the value of PAR1: If BA is 50 m^2/ha or more, the value of PAR1 is set to 0. If BA is between 0 and 50, the value of PAR1 is linearly dependent on BA.

If both regeneration cutting and site preparation are made, the value of SA(t) is calculated according to both methods and the maximum value of SA(t) is selected.

3.3 Full seeds

The proportion of full seeds depends on pollination (Sarvas 1962, 1968). If pollen production is abundant, and other factors are favorable as well, the proportion of full seeds is high. Because male and female flowering are positively correlated (Koski ja Tallqvist 1978), the proportion of empty seeds is highest when the seed crop is small.

In the simulation model the empty seed percentage of pine and spruce stands (ES) is calculated with the help of pollen catch (PC, grains/mm^2):

Species	Equation	
Pinus sylvestris	$ES = \exp(3.275-0.1453 \cdot \ln(PC))$	(9)
Picea abies	$ES = 10^{(2.660-0.506 \log(PC))}$	(10)

The proportion of full seeds (FS) is thus

$$FS = (100-ES)/100. \quad (11)$$

The equation (9) is calculated from data published by Sarvas (1962, Table 31). F-value of the equation (9) is 11.3 (d.f. 1 and 26) and degree of determination is 30 %. The equation (10) is published by Sarvas (1968).

A normally distributed random number is added to the estimates of equations (9) and (10). The random number has a zero mean and the same standard deviation as the residual of the equation used.

The pollen catch for equations (9) and (10) is calculated using Sarvas' (1962, 1968) equations:

Species	Equation	
Pinus sylvestris	$PC = 51.2+53.1 \cdot FR$	(12)
Picea abies	$PC = -19.93+39.48 \cdot FR$	(13)

The independent variable of these equations is the amount of male flower residuals (FR, g/m^2). It is calculated by equations

Species	Equation	F-value	R^2, %	N	
Pinus sylvestris	$FR = 2.459+0.01563SC$	64.2	29	155	(14)
Picea abies	$FR = 1.256+0.00369SC$	236.3	61	150	(15)

where SC is the uncorrected seed crop simulated for that year (seeds/m^2). Equations (14) and (15) are based on data published by Koski and Tallqvist (1978).

In a birch stand the above method is not possible because of lack of data. In the simulation model the proportion of full seeds in a birch stand is obtained by adding a normally distributed random number to the average full seed proportion of 0.4 (Sarvas 1952). The mean of the random number is zero and standard deviation 0.2. If the sum (0.4 + random number) is greater than 1, 1 is used, and if it is less than 0, 0 is used.

3.4 Mature seeds

In Northern Finland the main limiting factor in natural regeneration is the maturing of seeds. By the timber line only two or three years in a century are sufficiently warm for seeds to mature (Henttonen et al. 1986). In Southern Finland the seeds mature almost every year.

In a pine stand about 85 % of the average heat sum of a particular region is needed for maturing. This adaptation is not complete; near the northern forest limit the needed heat sum is much more than 100 % of the average heat sum (Koski 1981).

In the simulation model it is assumed that if the heat sum is HP times the average heat sum (HSE), 50 % of the seeds will mature (heat sum limit, HSL). The value of HP is set to 0.85 for all tree species. If the heat sum of the simulation year is less than HSL-50 d.d., no seeds mature. If the heat sum is greater than HSL+50 d.d., all seeds mature. Between these two heat sums the dependence of the mature seed proportion (MA) on the heat sum is a linear one (Fig. 5).

If HSL is less than the minimum value of the tree species, then the minimum value is used instead of HSL. The minimum values of 50 % maturing are:

- *Pinus sylvestris* 900 d.d
- *Picea abies* 950 d.d
- *Betula pendula* 950 d.d
- *Betula pubescens* 850 d.d

The heat sum of one simulation year is obtained by adding a normally distributed random number (N(0,115)) to the average heat sum (HSE) of that region. The standard deviation of the random number is the standard deviation of the heat sum in Finland (115 d.d.; Koski 1981).

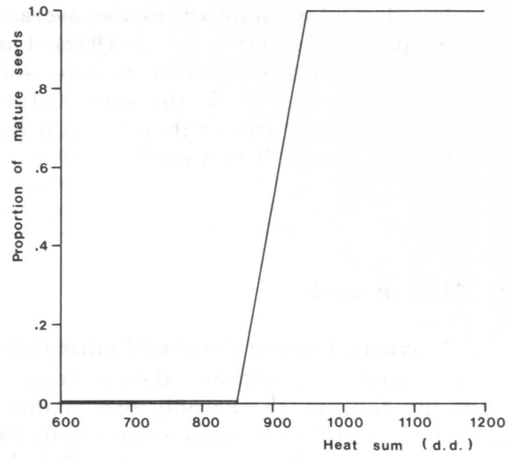

Fig. 5. Effect of heat sum on seed maturing. The position of the line (in abscissa-direction) depends on the mean heat sum of that region. In the figure the average heat sum of the location is 1059 d.d. The heat sum for 50 % maturing is 0.85×1059 d.d. = 900 d.d.

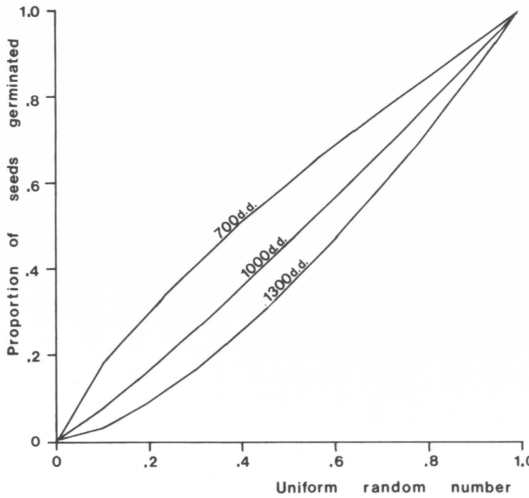

Fig. 6. Simulation of the success of germination in three localities. A uniform random number is generated and the germination rate is calculated by the function presented in the figure.

3.5 Predation of seeds

Insects, birds and mammals eat in general 20 . . . 95 % of the seeds fallen onto the ground (Heikkilä 1977). The proportion of uneaten seeds is simulated with a random number (PR) which is distributed uniformly between 0.05 . . . 0.8.

3.6 Germination

In Northern Finland the climate is more favourable for germination than in Southern Finland because of the greater humidity in the north. The proportion of germinated seeds (GE) is calculated by the formula

$$GE = MAX \cdot RAN^{PAR2}, \quad (16)$$

where MAX is the maximum proportion of successful germinations of the tree species, RAN is a uniform random number (0,1) and PAR2 a parameter which depends on the average heat sum of the locality (also on the distribution of the proportion of germinated seeds, see Fig. 6). PAR2 is calculated by the formula

$$PAR2 = -0.125 + 0.00125 \cdot HSE, \quad (17)$$

where HSE is the average heat sum. The maximum proportions of successful germinations are

- *Pinus sylvestris* 0.80
- *Picea abies* 0.80
- *Betula* spp. 0.05

3.7 Number of seedlings

The final phase in the simulation of the birth process is to calculate the number of emerged seedlings. It is obtained by multiplying the seed crop by all proportions (see Fig. 1).

$$SN = SCC \cdot SA \cdot FS \cdot MA \cdot PR \cdot GE \quad (18)$$

where

SN = number of emerged seedlings,
SCC = corrected seed crop,
SA = proportion of stockable area,
FS = proportion of full seeds,
MA = proportion of mature seeds,
PR = proportion of uneaten seeds,
GE = proportion of germinated seeds.

3.8 Mortality and height growth

In order to simulate a regeneration process over several years it is necessary to simulate also the mortality and height growth of seedlings. In this model the number of seedlings that survive decreases according to an exponential function (see Lehto 1969). The rate of the decrease depends on the tree species and basal area (BA, m²/ha) of the parent trees (Fig. 7).

The mortality model is

$$SU(t+n) = SU(t) \cdot n^{PAR3}, \quad (19)$$

where SU(t+n) is the number of survivals in the year (t+n), SU(t) is the number of survivals in the year (t) and PAR3 is a parameter. The parameter is calculated by formula

$$PAR3 = PAR3(0) - C \cdot BA, \quad (20)$$

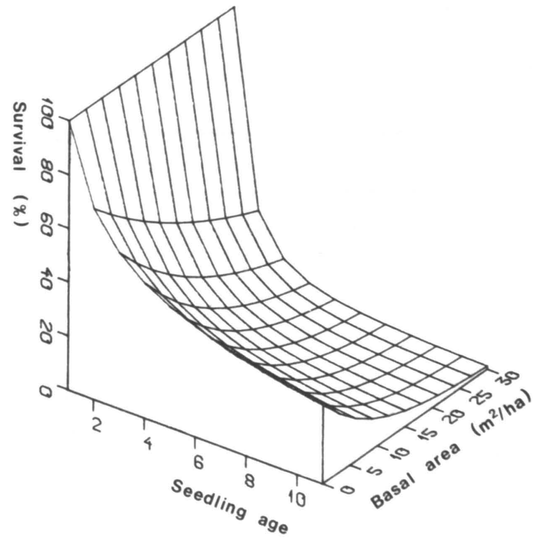

Fig. 7. Dependence of survival of Scots pine seedlings on the basal area and seedling age.

where PAR3(0) is the parameter when BA is 0 and C is a coefficient which determines the effect of BA. The values of PAR3(0) and C are

Tree species	PAR3(0)	C
Pinus sylvestris	−0.50	0.045
Picea abies	−0.45	0.035
Betula pendula	−1.30	0.060
Betula pubescens	−1.30	0.070

The height growth depends on tree species, height of the seedlings and forest site type.

3.9 Output of the simulation

The output of the simulation program consists of tables and figures. Results for a particular year are presented as a table (Table 1). The outputs of one simulation are

- a summary table (Table 2),
- age class distribution in the last simulation year (Fig. 8),
- height class distribution in the last simulation year,
- number of seedlings during the simulation period (Fig. 9),
- number of seedlings in different age classes during simulation period.

If the same regeneration situation is simulated several times the output possibilities are

Table 1. Output of the simulation program concerning results of one year of Scots pine regeneration.

Year: 1990	
Seed crop (seeds/m²)	37.0
Stockable area (%)	2.26
Full seeds (%)	88.67
Mature seeds (%)	100.00
Germination (%)	68.53
Uneaten seeds (%)	78.82
Emerged seedlings (%)	1.082
Seedlings/ha	4006
Survive to last year	2109
Survive to 1.3 m	1642

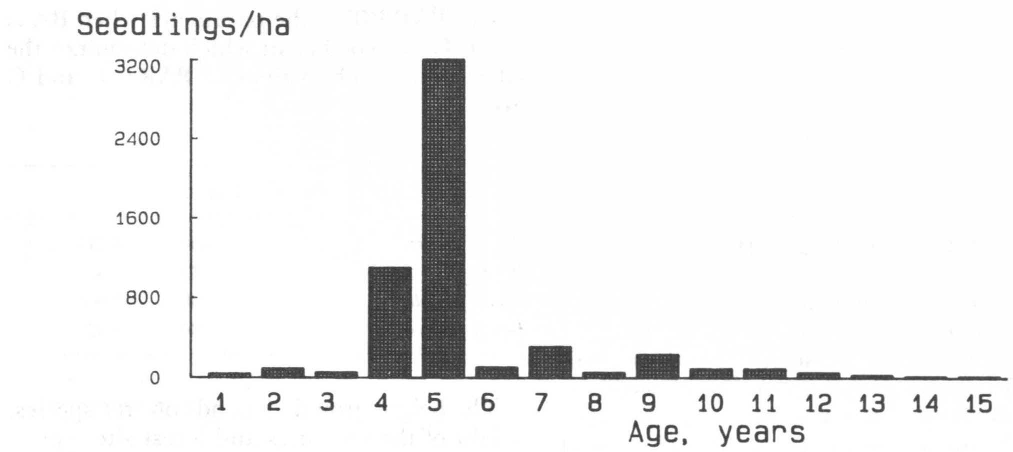

Fig. 8. Age class distribution of Scots pine seedling as yielded by one run of the simulation program.

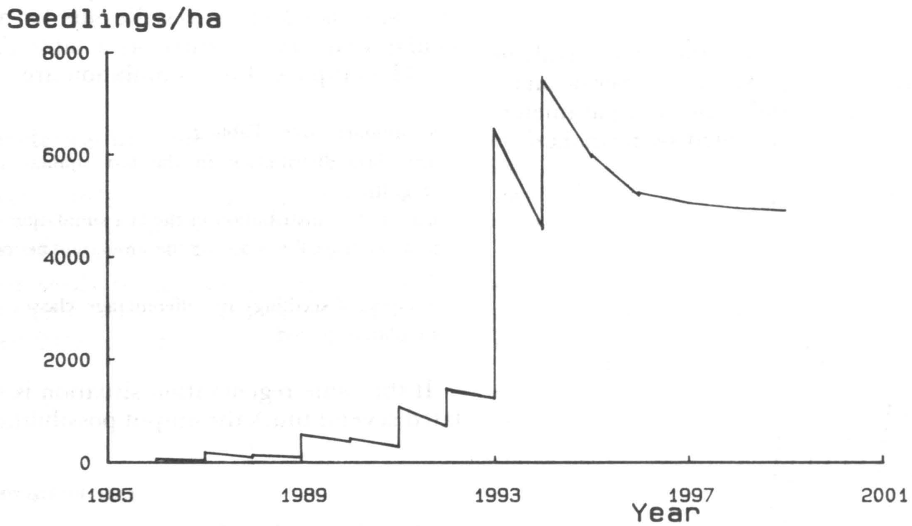

Fig. 9. Change of the number of seedlings during one simulation of Scots pine regeneration.

(1) the probability distribution of the seedling number in the last simulation year and (2) the results of average simulation. The average results are presented in the same manner as the result of one simulation. Probability distributions of several regeneration situations can be presented in one figure (Figs. 10 . . . 15).

The simulation program can be obtained from the author.

Table 2. Output of the simulation program concerning one simulation of Scots pine regeneration.

Year of birth	Age a	Last simulation year Frequency Seedlings/ha	%	Height m	Survive to 1.3 m Frequency Seedlings/ha	%
1986	7	23	0.4	0.95	22	0.6
1987	6	30	0.6	0.78	28	0.7
1988	5	266	4.9	0.61	237	5.9
1989	4	1876	34.8	0.46	1583	39.7
1990	3	2109	39.2	0.32	1642	41.2
1991	2	158	2.9	0.18	107	2.7
1992	1	923	17.1	0.05	366	9.2

Survive to last year: 5385 seedlings/ha
Survive to 1.3 m: 3985 seedlings/ha

4. Examples of the use of the model

4.1 Effect of site type on Scots pine regeneration

In the following examples only the probability distributions of the number of seedlings are presented. Usually this is not sufficient when different alternatives are compared because the age and height class distributions can vary.

The regeneration of Scots pine on different site types (OMT, MT, VT and CT) is examined in a situation where the stand characteristics and the treatments are:

- Dominant height: 20 m
- Basal area before regeneration cutting: 20 m^2/ha
- Basal area after regeneration cutting: 5 m^2/ha
- Average heat sum of the locality: 1200 d.d.
- Site preparation: scalping
- Year of regeneration cutting: 1985
- Year of site preparation: 1986
- Removal of parent trees: 1992

The simulation period is 1984 . . . 1995 (12 years). The number of simulations is 50 on every site type.

The results (Fig. 10) show that poor sites (VT and CT) have about 2000 seedlings more than good ones. The probability of obtaining, for example, 5000 seedlings/ha is about 30 % greater on VT and CT than on OMT and MT. The main reason for this difference is the rapid decrease of the stockable area on the good sites.

4.2. Effect of site preparation on Norway spruce regeneration

The effect of the site preparation method is examined in situation of no preparation, scalping and disk ploughing. The other inputs are:

- Dominant height: 25 m
- Basal area before regeneration cutting: 25 m^2/ha
- Basal area after regeneration cutting: 10 m^2/ha
- Average heat sum of the locality: 1200 d.d.
- Forest site type: OMT
- Year of regeneration cutting: 1985
- Year of site preparation: 1986
- Removal of parent trees: 1992

The effect of site preparation is remarkable: the more intense the preparation the more seedlings will emerge (Fig. 11). In the model the site preparation method affects only via the proportion of stockable area (SA(1)).

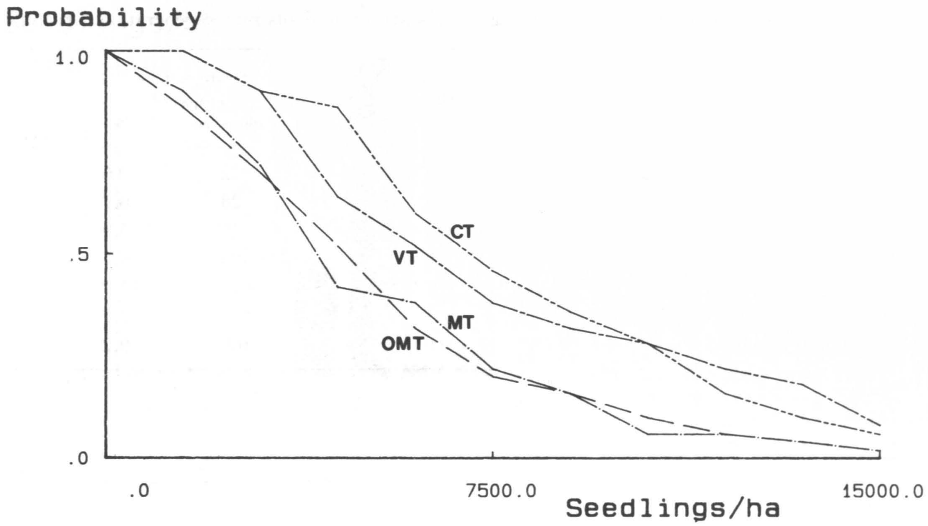

Fig. 10. Simulated results of Scots pine regeneration on different site types OMT = good, MT = medium, VT = rather poor, CT = poor.

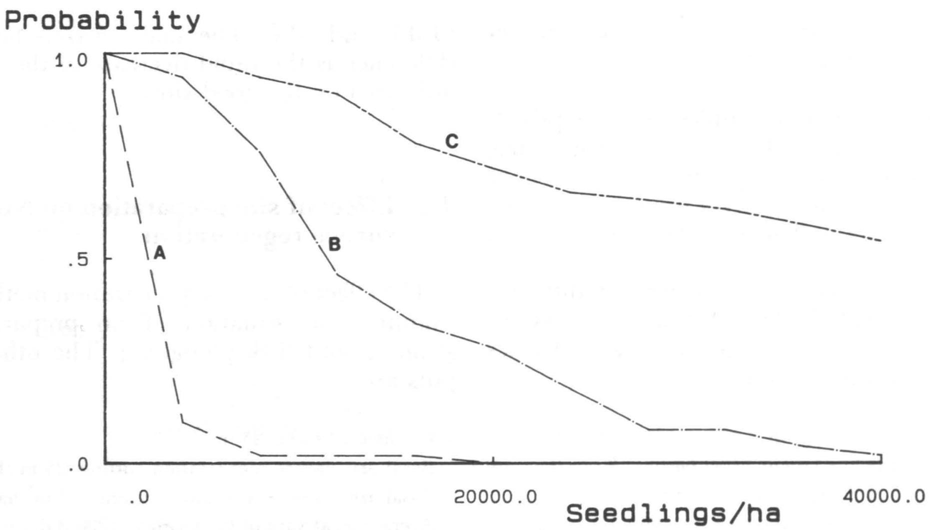

Fig. 11. Simulated effect of site preparation on the regeneration of spruce. A = no preparation, B = scalping, C = disk ploughing.

4.3 Effects of change in parameter values

Two typical examples of the use of the model were given above. The model can also be used for making sensitivity analysis of the parameters. With the sensitivity analysis it is possible to study the most critical factors in regeneration as revealed by the model.

In the following a few examples are given where one parameter at a time is first decreased by 20 % and then increased by 20 %. This means that the difference between parameter values is 40 % of the initial value. With each value 50 simulations are made. It should

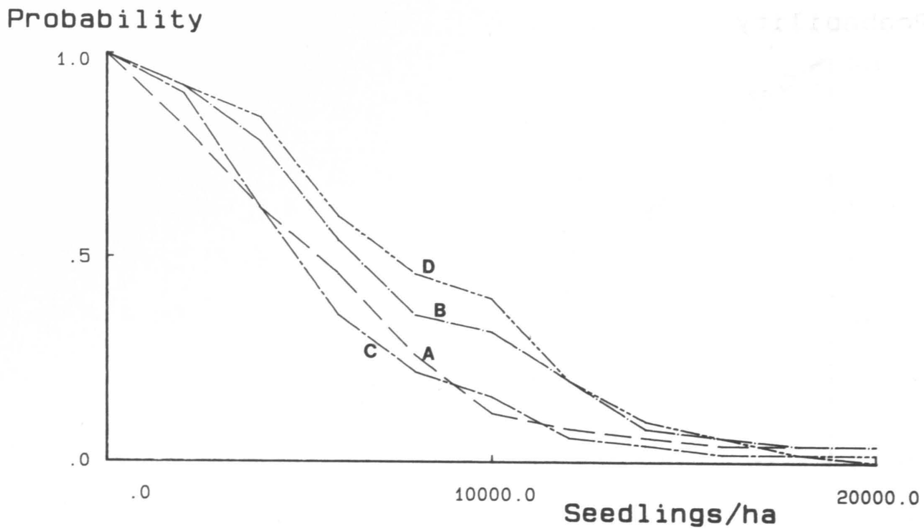

Fig. 12. Effect of change in parameter values affecting stockable area. A = initial value of stockable area (SA(1)) decreased by 20 %, B = SA(1) increased by 20 %, C = rate of recovery of the ground vegetation (PAR1) decreased by 20 %, D = PAR1 increased by 20 %.

be noted that the meaning of the change of 20 % is different if different parameters are concerned. The meaning also varies according to the regeneration situation.

The regeneration situation in these simulations is always the same:

- Tree species: Scots pine
- Dominant height: 22 m
- Basal area before regeneration cutting: 26 m^2/ha
- Basal area after regeneration cutting: 6 m^2/ha
- Average heat sum of the locality: 1200 d.d.
- Forest site type: VT
- Site preparation: scalping
- Year of regeneration cutting: 1985
- Year of site preparation: 1986
- Removal of parent trees: 1992

Change in parameter values which affect the stockable area does not affect the simulation result remarkably (Fig. 12). The probability of obtaining a certain number of seedlings is 5 . . . 20 % greater in situations where the stockable area is larger (B and D in Fig. 12). However, in the natural regeneration the proportion of the stockable area varies greatly, which makes it an important regeneration factor (see Fig. 11).

The model is not sensitive to parameters which affect the mortality of seedlings (Fig. 13). The effect of these parameters greatly depends on the situation studied: if there are only few parent trees, then the parameter which determines the effect of basal area on death rate has only a minor effect. If the timing of treatments is such that almost all seedlings appear during the last simulation year, the initial rate of survival has very little effect.

In Northern Finland parameters which affect seed maturing have a critical effect on the simulation results (Fig. 14). In this respect the model corresponds very well the situation in reality. If the simulations for Fig. 14 were made for Southern Finland, the effects of changes in parameters would not be remarkable.

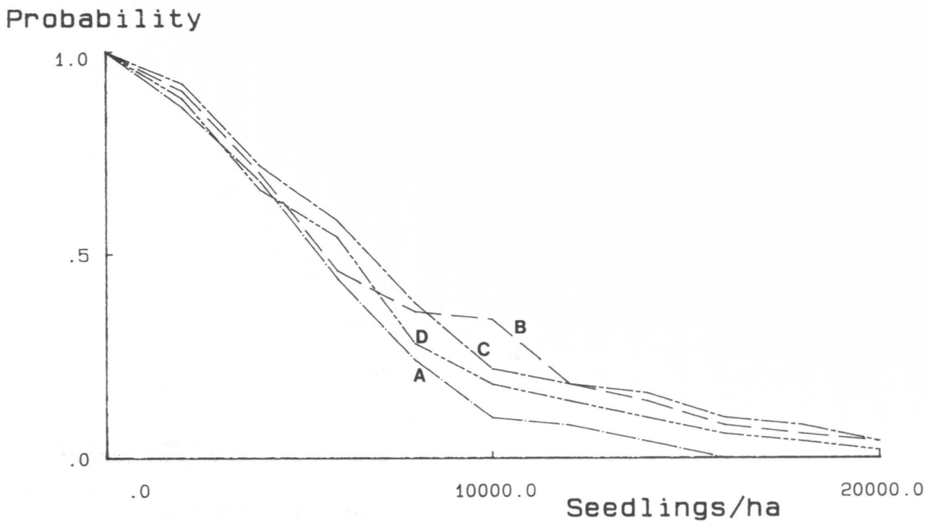

Fig. 13. Effect of change in parameter values affecting mortality. A = rate of survival (PAR3(0)) decreased by 20 %, B = PAR3(0) increased by 20 %, C = effect of basal area on death rate (C) decreased by 20 %, D = parameter C increased by 20 %.

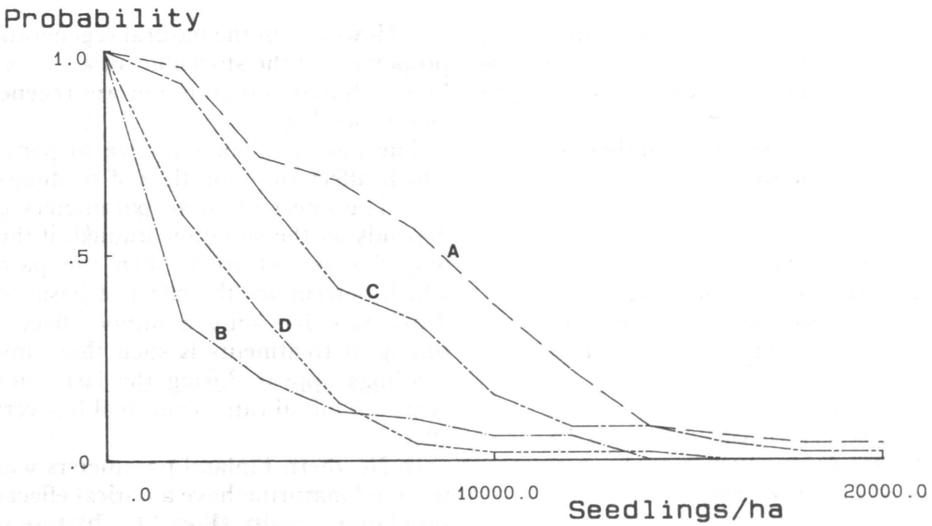

Fig. 14. Effect of change in parameter values affecting seed maturing. A = minimum heat sum value for 50 % maturing decreased by 20 %, B = minimum value increased by 20 %, C = proportion of mean heat sum needed for 50 % maturing decreased by 20 % (from 0.85 to 0.68), D = proportion increased by 20 %.

5. Discussion

The developed simulation model can be used rather flexibly for studying different regeneration alternatives. For example, the effect of three species, site preparation method, forest site type, density of parent trees, locality of stand, and timing of treatments can be evaluated. The output of the model is abundant. It is not possible to find empirical data which covers the whole scope of the model. The consequence is the difficulty to check the validity of the model. An experiment for getting the required data would be very extensive. However, it is not necessary to validiate the whole model at a time. If we have data concerning, for example, regeneration of Scots pine in central Finland, we can calibrate those parameters which affect this part of the scope.

The parameters of the model are partly obtained from previous investigations and partly proposals of the author. Parameters concerning the size of the seed crop and seed quality are based on extensive measurements. These parameters are much more reliable in Scots pine and Norway spruce stands than in birch stands.

The parameters for stockable area, seed maturing, and predation and germination of seeds are not based on statistical analysis of empirical data but are only initial proposals. Parameter values can be changed to calibrate the model or to study the effects of the changes. Use of different parameter values assist to find critical factors of regeneration.

The simulation model is highly stochastic. The stochasticity of the model should correspond to the uncertainty in the situation of decision making. This feature makes it possibly to analyse the risk connected to the natural regeneration. It also raises an important question: how many times the situation should be simulated to obtain a probability distribution which is sufficiently close to the expected distribution of the model. Figure 15 shows the probability distributions of four program runs. The regeneration situation is the same as in examples of Chapter 4.3. In the first two runs the simulation is made 10 times and in the second two runs 50 times.

It can be seen that for the consistency of results more than 50 simulations are needed. When comparing the results simulated for

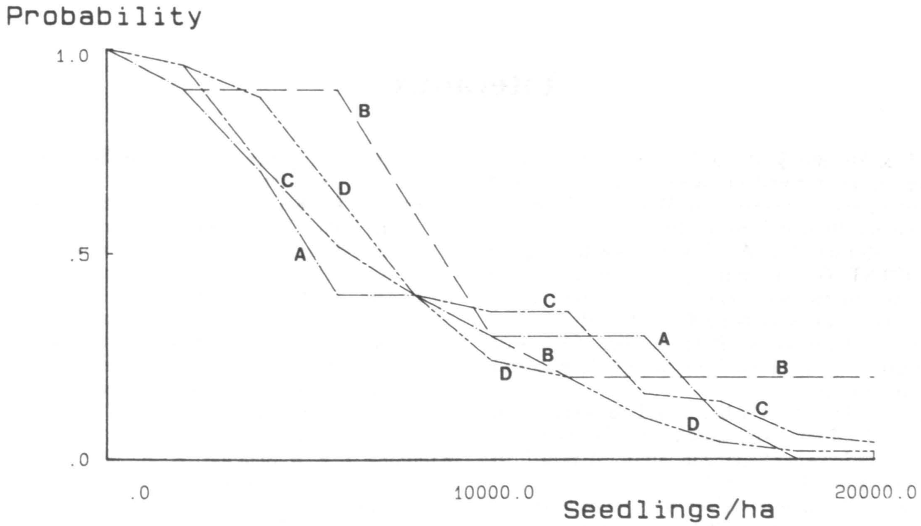

Fig. 15. The constancy of simulation result. A and B: 10 simulations, C and D: 50 simulations.

different treatment schedules on the basis of only few simulations, the probability of making erroneous conclusions is high. It can also be concluded that in the empirical field study of natural regeneration, in order to obtain reliable results, the number of experiments should be high. This is because the unocontrollable variables, especially weather conditions, greatly affect the success of regeneration.

The simulation model presented can be used as a birth model of more comprehensive model (Pukkala 1985). The birth model makes the simulation stochastic. However, the model can be used also in a deterministic way by simulating the situation many times (e.g. 200 times) and then using the average results.

In this study the the birth process of the stand was simulated much more thoroughly than usually done in simulation models (see e.g. Leak 1970, Ek and Monserud 1973, Aber and Melillo 1983, Fow et al. 1984). This causes the shortcoming that very many parameters are needed, part of which are difficult to obtain. However, this kind of simulation makes it possible to study the effects of all the different factors of the birth process. In addition, the preparation of the model clearly reveals those parts of the simulation process which are poorly investigated. These parts are the concept of stockable area, germination and predation of seeds, and growth and mortality of seedlings.

There is no data for checking the correctness of the model, either. This shortcoming would disappear by creating a data base of naturally regenerated stands where all the treatments and inventory results of the seedling stands are recorded.

With increasing amount of data it is possible to further develop the simulation of natural regeneration. In this study the mortality and growth of seedlings were simulated in age classes using very simple models. There were no stochastic variation in growth and mortality. These processes were, however, needed by the program to mimic the development of young stands.

The accuracy of the simulation of mortality and growth processes could be increased by including spatiality into the model. The coordinates of the seedlings could be generated by the method of Kellomäki et al. (1986). Next step is to calculate the spatial variation of growth factors (Pukkala 1986). With spatiality the variation in the availability of growth factors and in the competition between seedlings could be used for increasing the accuracy of the simulation.

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