

# Spatial Growth Model for Scots Pine on Drained Peatland

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A spatial growth model is presented for Scots pine on a dwarf-shrub pine mire drained 14 years ago. The growth model accounts for the variation in tree diameter growth owing to the competition between trees, the distance between tree and ditch and the time passed since drainage. The model was used to study the effect of tree arrangement on the post-drainage growth of a pine stand. Clustering of trees decreased the volume growth by 9–20 % as compared to a regular spatial distribution. Stand volume growth, for a given number of stems, was at its maximum and variation in diameter growth at its minimum when the stand density on the ditch border was 1.5–5 higher than midway between two adjacent ditches.

**Keywords** *Pinus sylvestris*, growth models, linear models.

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## 1 Introduction

Drainage of peatlands for growing trees has been an important aspect of forestry in Finland. About four and a half million hectares have been drained for forestry (Aarne 1993). According to the results of the 7th National Forest Inventory, the annual growth of peatland forests amounts to 22 % of the total annual growth on forest land and scrub land (Paavilainen and Tiihonen 1988).

In Finland, many studies have been done to establish the growth response of Scots pine to drainage. The revival of diameter and height

increment after drainage is greater the more fertile the site is, and the smaller and younger the tree is at the time of ditching (e.g. Multamäki 1923, Lukkala 1929, Heikurainen and Kuusela 1962, Seppälä 1969, 1976). However, tree revival depends more on size than age.

The diameter growth of pine responds immediately to the changes caused by ditching whereas spruce takes a few years to respond to ditching (Seppälä 1969). The length of the revival period (i.e. the time from ditching to the maximum radial growth) depends on site fertility and tree age. The time required for revival lengths

with declining fertility and increasing age (Heikurainen and Kuusela 1962, Seppälä 1969). In the study by Seppälä (1969), the revival period of pine varied between 5 and 20 years.

Trees revive quicker the more efficient the drainage is (Lukkala 1929, 1937, Huikari and Paarlahti 1967). The revival of tree growth also depends on the distance between the tree and the nearest ditch: trees revive quicker the nearer they are to ditches (Lukkala 1929). This is partly due to the enhanced aeration of the substrate, more rapid decomposition of organic matter (Lähde 1966, Lieffers 1988), and the greater growing space available to trees near ditches.

Despite the special post-drainage growth pattern of peatland forests, it is usually assumed in forest management that yield studies conducted on mineral soils apply to drained peatlands as well. This is due to the fact that there are no growth models for peatland forests for evaluating the consequences of silvicultural treatments. The most suitable tool for predicting the post-drainage growth of trees on drained peatland is a spatial single-tree growth model. The need for a spatial model is evident because of the inhomogeneous spatial structure created by the ditches.

The predictors of a spatial growth model for drained peatlands should include the distance between the tree and the nearest ditch and the time passed since drainage, as well as standard tree and stand variables (diameter, age, stand basal area, etc.) and competition indices (Miina et al. 1991). Such a growth model can be used to examine, for example, the effect of the spatial pattern of tree locations and thinning methods on stand growth. Especially important is to compare different thinning schedules in peatland stands since more than 75 % of peatland stands are at the stage of the first commercial thinning or are about to reach this stage soon (Keltikan-gas et al. 1986).

The study is aimed at analyzing the growth of Scots pine (*Pinus sylvestris* L.) on drained peatland. First, a single-tree growth model was prepared for the annual diameter growth after drainage. Second, the growth model was used to examine the effect of spatial distribution of trees on the volume and diameter growth of a Scots pine stand.

## 2 Material and Methods

### 2.1 Material

The data consisted of nine rectangular plots located on a drainage area in North Karelia, Finland (63°N, 31°E, 180 m asl). The area was drained in the winter of 1976–1977. The site type had originally been a dwarf-shrub pine mire. On the plots, the ditch spacing varied between 31 and 36 m, the average ditch depth was 71 cm, and the peat depth was over 1 m. The area of the plots varied between 0.084 and 0.184 ha. The plots were placed so that two opposite sides of each plot were parallel to two adjacent ditches and extended 5 m beyond these ditches.

The total number of trees on the plots was 1277. The plots were almost pure pine stands, only five spruces and six birches were included. All trees were measured for their coordinates, height, double bark thickness and diameter at breast height (Tables 1 and 2). The annual radial growth during the past 30 years was measured from increment cores bored at breast height. Tree age was determined from the core. Trees with underbark diameter of at least 3 cm at the beginning of the growing season were included in computations. Only those 816 pines that were located at least 3 metres from the nearest plot edge were treated as sample trees. All the trees on the plot were used for computing the predictors for the growth model. Because the data included several post-drainage increments from the same tree, the number of observations (for annual diameter growth) was 9535.

The climatic growth variation between years must be taken into consideration when studying growth response to drainage. The diameter growth was corrected by annual growth indices to a level corresponding to normal or average climatic conditions. The growth indices were based on 35 pine trees growing on virgin peatlands near the study area.

The drainage area had been naturally regenerated after a regeneration cutting in 1946. The seed trees had been removed in 1969. No thinning or only light thinning was done at the time of clearing the ditch lines. The trees improved their diameter growth after the removal of the seed trees, but the growth does not vary in ac-

**Table 1.** Stand characteristics of the study plots in 1991. N = number of trees per hectare, V = stand volume,  $i_v$  = mean volume growth after drainage, G = stand basal area, Tg = mean age at breast height, Dg = mean diameter, Hg = mean height. Parameters C and H are the grouping indices of Clark and Evans (1954), and Hopkins (1954), respectively. g = weighted by tree basal area.

Plot	N	V	$i_v$	G	Tg	Dg	Hg	C	H
	[ha <sup>-1</sup> ]	[m <sup>3</sup> ha <sup>-1</sup> ]	[m <sup>3</sup> ha <sup>-1</sup> a <sup>-1</sup> ]	[m <sup>2</sup> ha <sup>-1</sup> ]	[a]	[cm]	[m]		
1	1262	36.9	2.3	8.5	40.1	12.0	7.9	0.87	1.41
2	1064	41.3	2.3	8.6	39.9	13.5	8.9	0.89	1.79
3	967	68.5	2.1	12.4	75.8	16.5	10.6	1.12	0.82
4	1409	23.5	1.3	6.1	40.9	9.2	6.6	0.94	1.42
5	862	35.8	1.9	7.5	40.7	11.7	8.7	1.18	1.03
6	858	59.3	2.5	10.8	56.9	14.3	10.5	1.17	0.87
7	1103	42.6	2.4	9.1	44.7	12.2	8.5	1.06	0.78
8	1572	34.5	1.8	8.1	45.9	10.4	7.5	0.92	2.09
9	761	11.8	0.8	3.4	44.3	9.7	5.7	0.92	1.28

**Table 2.** Mean, standard deviation and range of the predicted variable and some of the predictors in the study material at the beginning of years 1977 and 1990. See Model 1 for the explanation of the symbols.

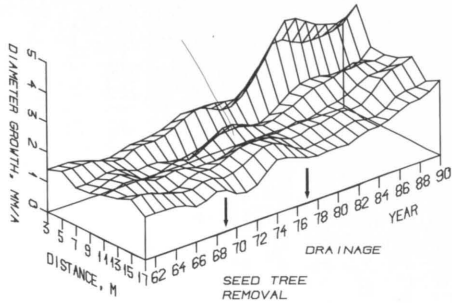
Variable	Year 1977				Year 1990			
	Mean	Sd	Min	Max	Mean	Sd	Min	Max
id, [cm a <sup>-1</sup> ]	0.179	0.095	0.026	0.877	0.329	0.172	0.018	0.982
d, [cm]	6.3	2.6	3.0	18.3	8.1	3.6	3.0	20.4
g, [cm <sup>2</sup> ]	36.3	33.2	7.1	262.2	61.5	53.0	7.1	327.0
age, [a]	34.4	14.9	6.0	118.0	39.8	18.0	7.0	131.0
dis, [dm]	100.2	46.1	10.0	180.0	93.7	47.0	10.0	180.0
ci, [cm m <sup>-1</sup> ]	10.2	7.9	0.0	39.7	16.7	12.1	0.0	80.0
d/D<3, [-]	0.89	0.24	0.24	1.40	0.86	0.27	0.22	1.41
G, [m <sup>2</sup> ha <sup>-1</sup> ]	2.4	1.1	0.6	4.5	5.2	1.6	2.1	7.2

cordance with the distance away from the ditch (Fig. 1). Trees located 4–6 m away from the ditches displayed the most rapid and greatest increase in diameter growth after drainage. Trees further away from the ditch took longer to respond. Despite the free growing space and lowering of the groundwater table, trees nearer than 4 m to ditches had not increased their diameter growth as much as trees located 4–6 m from ditches. This may be due to the injured roots of trees growing near ditches.

### 2.2 Methods

The predicted variable in the growth model was annual diameter growth under bark. Because the data included several increments from the same tree and trees were grouped into plots, a mixed linear model was estimated using the maximum likelihood procedure of the BMDP-program 5V (Jennrich and Schluchter 1986, Schluchter 1990).

The predictors of the fixed part of the growth model were chosen from among many transfor-



**Fig. 1.** Development of mean annual diameter growth (excl. bark) of trees at different distances from ditches in 1961–1990. Growth is the weighted moving average of three years, corrected by growth indices.

mations of tree age, diameter, basal area, competition indices, distance from the nearest ditch, time passed since drainage, stand basal area, mean age, and interaction term of distance from ditch and time since drainage. The interaction term was used as a predictor because trees revive quicker the nearer they are to ditches (Fig. 1). The aim was that all the predictors had to be significant and no systematic errors were observed in residuals. Residual variation was divided into between-plot, between-tree and within-tree components. The within-tree error terms were assumed to arise from a first-order autoregressive process (Henttonen 1990, Miina 1993). The mixed linear model was as follows:

$$\ln(id_{kjt}) = \beta_0 + \beta_1 / g_{kjt}^2 + \beta_2 \ln(g_{kjt}) + \beta_3 age_{kjt} + \beta_4 ci_{kjt} + \beta_5 d_{kjt} / D < 3_{kjt} + \beta_6 1 / dis_{kj} + \beta_7 \ln(dis_{kj}) + \beta_8 \sqrt{(t / (dis_{kj} + 100))} + \beta_9 t + \beta_{10} t^2 + \beta_{11} \ln(G_{kt}) + u_k + u_{kj} + v_{kjt} \quad (1)$$

where

- $id_{kjt}$  = diameter increment (excl. bark) of tree j on plot k in year t [cm],
- $g_{kjt}$  = basal area (excl. bark) of tree j on plot k at beginning of year t [cm<sup>2</sup>],
- $age_{kjt}$  = breast height age of tree j on plot k at beginning of year t [a],
- $ci_{kjt} = \sum_{l=1}^n d_l / s_l$  is competition index of tree j on

- plot k at beginning of year t [cm m<sup>-1</sup>], where  $d_l$  is diameter (excl. bark) and  $s_l$  is distance of neighbour l, and n is number of neighbours nearer than 3 metres,
- $d_{kjt}$  = breast height diameter (excl. bark) of tree j on plot k at beginning of year t [cm],
- $D < 3_{kjt}$  = mean diameter (weighted by tree basal area) of trees within 3 m of tree j on plot k at beginning of year t [cm],
- $dis_{kj}$  = distance of tree j on plot k to the nearest ditch [dm],
- t = number of years since drainage (1–14),
- $G_{kt}$  = stand basal area (excl. bark) on plot k at beginning of year t [m<sup>2</sup>ha<sup>-1</sup>],
- $u_k$  = random plot effect  $u_k \sim Nid(0, \sigma_{plot}^2)$
- $u_{kj}$  = random tree effect  $u_{kj} \sim Nid(0, \sigma_{tree}^2)$
- $v_{kjt} = \rho v_{kjt-1} + e_{kjt}$  is autocorrelated error term of tree j on plot k in year t,  $e_{kjt} \sim Nid(0, \sigma_e^2)$ ,  $\sigma_v^2 = \sigma_e^2 / (1 - \rho^2)$ , and  $\beta_0, \dots, \beta_{11}$  = fixed parameters.

The competition indices with competition distance of 3 m appeared to be more appropriate predictors than indices with shorter or longer competition distances. The mean diameter of trees within 3 m from subject tree was weighted by tree basal area in order to give bigger trees more significance as competitors than smaller ones. The distance from ditch ( $dis_{kj}$ ) was enlarged by 100 in order that the relationship between the dependent variable and the interaction term was linear.

Model 1 does not consider the between-year differences in the annual variation of diameter growth (cf. Henttonen 1990), because annual (climatic) variation in diameter growth was assumed to have been deleted by the annual growth indices.

The between-plot effects were estimated as if they were fixed by determining a dummy-variable for each plot. The between-plot variance can be estimated from the parameter estimates, estimation variances and covariances of the dummy-variables (Lappi 1991, Eqn. A14). The parameter estimate  $\hat{\beta}_0$  is the sample mean of the parameter estimates of the dummy-variables.

### 3 Results

The value of the autocorrelation coefficient  $\rho$  in Model 1 was determined separately of the other parameters by comparing the maximum log likelihoods with different values of  $\rho$ . The coefficient  $\rho$  was chosen to be 0.75.

The estimates of the fixed parameters and variance components are given in Table 3. Most of the random variation was due to within-tree variation. The between-plot and between-tree variance components accounted for 33 % and 15 % of the total residual variance, respectively.

The bias of the fixed part of the model was examined by plotting the residuals as a function of the predictors of the growth model. One has to be careful when examining the residuals because they were correlated. Even though the mean residuals of trees were calculated, they still correlated on the same plot. No systematic errors were observed in residuals and, in addition, the residuals had a constant variance over time (Fig. 2). The residuals indicate, however, that the growth model slightly underestimates the diameter growth of trees at distances of 3–6 m from ditches and 6–7 years after drainage.

### 4 Simulation Experiments

#### 4.1 Simulation of Model Stands

The growth model was used to study the effect of spatial distribution of trees on the post-drainage stand growth by computing growth estimates for simulated model stands. In addition to this, the logic of predictions of the growth model was tested, and the temporal and spatial variation in the diameter growth of trees on drained peatland was illustrated.

The use of model stands purports that tree and stand characteristics must correspond to those observed in the study material. Calculation of growth estimates requires that the following characteristics are known at the time of drainage for each tree: location, underbark diameter and age at breast height.

First, the number of trees per hectare and basal area were defined and the tree coordinates were

**Table 3.** Estimates of the fixed parameters and variance components of the diameter growth model (Model 1).

Parameter	Estimate	Asymptotic standard error	Estimate/Asymptotic standard error
$\hat{\beta}_0$	-0.28715	0.37099	-1.29
$\hat{\beta}_1$	10.78577	2.44633	4.41
$\hat{\beta}_2$	0.23118	0.02886	8.01
$\hat{\beta}_3$	-0.00821	0.00102	-8.01
$\hat{\beta}_4$	-0.01628	0.00120	-13.59
$\hat{\beta}_5$	0.23517	0.06639	3.54
$\hat{\beta}_6$	-8.99460	2.04590	-4.40
$\hat{\beta}_7$	-0.38373	0.05919	-6.48
$\hat{\beta}_8$	-2.22937	0.68052	-3.28
$\hat{\beta}_9$	0.17899	0.01827	9.80
$\hat{\beta}_{10}$	-0.00412	0.00054	-7.56
$\hat{\beta}_{11}$	-0.48263	0.08330	-5.79
$\hat{\sigma}_{plot}^2$	0.09788		
$\hat{\sigma}_{tree}^2$	0.04552		
$\hat{\sigma}_v^2$	0.15344		

generated as a realization of a suitable spatial process. Then, the overbark diameters of the trees were calculated by the method presented by Pukkala (1989b, Eqn. 10). The method predicts tree diameter from stand characteristics and the locations of neighbour trees.

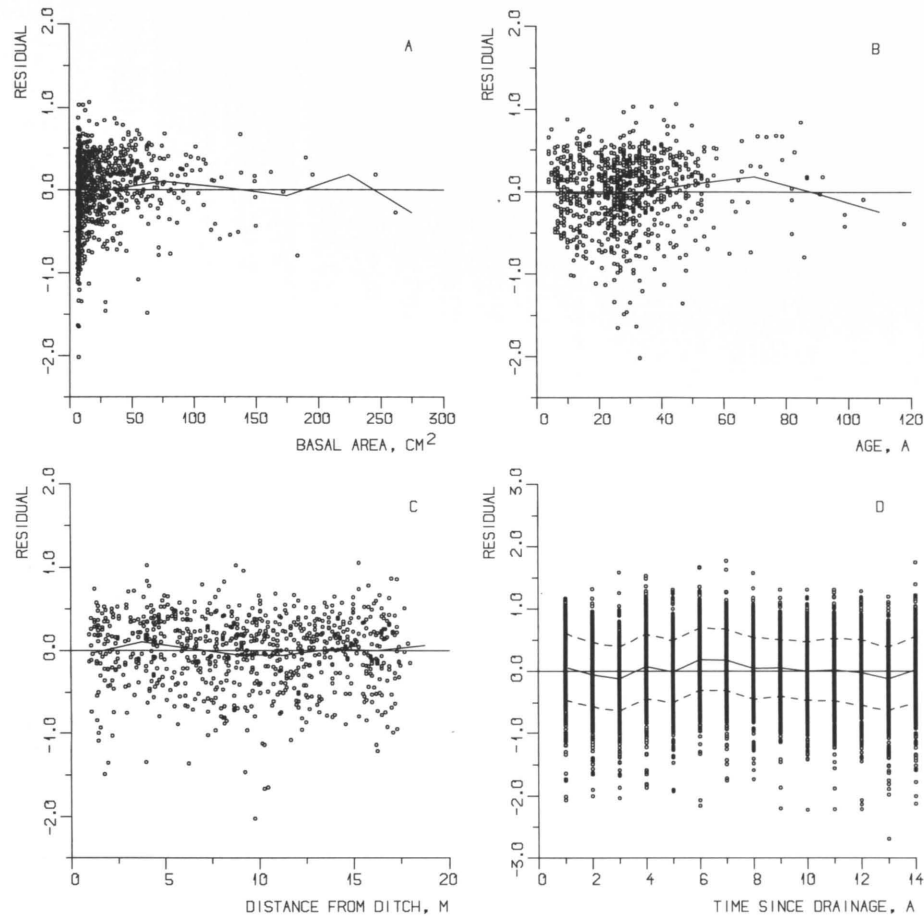
The following linear regression model was calculated for double bark thickness to compute the underbark diameter of trees:

$$2b = -1.0109 + 0.9342 d \quad (2)$$

in which 2b is double bark thickness at breast height [mm], and d is overbark diameter at breast height [cm]. The model was based on 1257 pine trees with underbark diameter of at least 3 cm. The degree of determination and the residual standard deviation of the model were 0.73 and 2.42 mm, respectively.

To calculate the age of each tree at the time of draining, a mixed linear model was estimated using the present study material:

$$\ln(age_{ki}) = 4.0638 - 11.8706 / (d_{ki} + 5) + 0.0075 ci_{ki} + 0.3616 G_k - 0.6234 \ln(G_k) + b_k + e_{ki} \quad (3)$$



**Fig. 2.** Mean residuals of trees as a function of tree basal area at the time of draining (A), tree age at the time of draining (B), distance from ditch (C), and residuals of trees as a function of time passed since drainage (D). Mean of residuals (—), standard deviation of residuals (- - -).

in which  $age_{kj}$ ,  $d_{kj}$ ,  $ci_{kj}$  and  $G_k$  are the same as in Model 1 at the time of draining,  $b_k$  is random plot effect, and  $e_{kj}$  is random tree effect. The estimates of the between-plot ( $\sigma_b^2$ ) and within-plot ( $\sigma_e^2$ ) components of the total residual variance were 0.0118 and 0.0820, respectively.

The age model was used in a stochastic manner: a stochastic component corresponding to within-stand residual variation ( $e_{kj}$ ) was added to

the logarithmic age prediction. Besides,  $\hat{\sigma}_b^2 / 2$  was added to the prediction owing to the logarithmic transformation.

The annual post-drainage volume growth of the model stands was calculated for a period of 14 years. When calculating the competition indices for trees nearer than 3 m of the plot edge, toroidal edge correction was applied, i.e. the plot was surrounded by similar plots on all sides

(Ripley 1981). At the end of the growing period of 14 years, underbark diameters were converted to overbark diameters by assuming that the proportion of bark in the total diameter had not changed.

The overbark stem volumes of trees at the time of draining and 14 years later were estimated by Equation 61.2 presented by Laasasenaho (1982). The equation predicts stem volume from tree diameter. The estimate of the volume increment was the difference in stand volume at two points in time.

#### 4.2 Effect of Clustering of Trees on Stand Growth

Three model stands with different spatial patterns of tree location were simulated to study the effect of clustering of trees on stand growth (Table 4). The stands were 45 m wide in the direction of the ditches and 102 m wide in the direction perpendicular to the ditches.

The spatial processes for generating tree coordinates for model stands 1, 2 and 3 were as follows (e.g. Diggle 1983):

- (1) Regular process. Grid of squares for 33 % more points than needed. A normally distributed random number was added to the x and y coordinates. The standard deviation of the random number was 10 % of the distance between trees in

the x direction. The excessive points were removed randomly.

- (2) Poisson process with a hard core of 0.3 m (minimum distance between trees).
- (3) Clustered process. Cluster midpoints were Poisson distributed. The distance of a point from the cluster midpoint was distributed uniformly between 0 and 8 m and the direction uniformly between 0 and 360°. The average number of points per cluster was 16.

Process (1) corresponds to a planting with mortality, whereas Poisson and clustered processes apply to naturally generated stands. In Poisson process, a hard core of 0.3 m was used to avoid generating the same coordinates for trees. Stand 3 has the clustered tree arrangement frequently occurring in peatland forest stands (Hökkä and Laine 1988).

After producing the coordinates and dimensions of the trees, all the trees were removed from 4 m wide ditch lines, 34 m apart. Thus, model stands 1–3 correspond to untreated stands where the spatial distribution of trees has affected tree growth for a long time, but the ditch lines are of recent origin.

The post-drainage growth of the stands was simulated for 14 years. Stochastic components corresponding to between-tree residual variation ( $u_{kj}$ ) and autocorrelated error term ( $v_{kjt}$ ) were added to the growth prediction. In addition,  $\hat{\sigma}_{plot}^2 / 2$  was added to the logarithmic growth prediction.

**Table 4.** Stand characteristics of model stands 1–3, and model stand sets A, B and C. g = weighted by tree basal area.

Variable	Model stand			Model stand set		
	1	2	3	A	B	C
Number of stems, [ha <sup>-1</sup> ]	874	876	887	857	1445	743
Basal area, [m <sup>2</sup> ha <sup>-1</sup> ]	4.8	4.9	4.8	3.6	2.3	6.6
Stand volume, [m <sup>3</sup> ha <sup>-1</sup> ]	20.3	20.5	20.6	12.8	6.4	29.4
Mean diameter (g), [cm]	9.8	9.9	10.1	7.4	4.6	10.7
Minimum diameter, [cm]	3.4	3.5	3.6	6.3	3.5	9.7
Maximum diameter, [cm]	15.0	15.5	16.2	8.3	5.4	11.6
Mean age (g), [a]	48	50	52	36	24	73
Grouping index C	1.89	0.87	0.59	–	–	–
Grouping index H	0.45	0.86	3.35	–	–	–

The results are based on ten independent simulations.

The mean 14-year growth predictions for model stands 1, 2 and 3 were 28.4, 25.9 and 22.8  $\text{m}^3\text{ha}^{-1}$ , respectively. The standard deviation of the 14-year volume growth was under  $1 \text{ m}^3\text{ha}^{-1}$  for each of the three stands. Irregular spatial distribution of trees decreased volume growth by 9 % in the Poisson stand, and by 20 % in the clustered stand as compared to the regular stand.

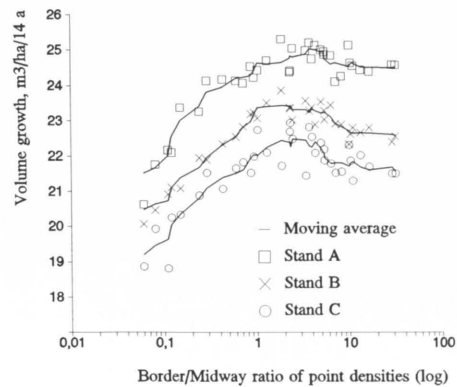
#### 4.3 Effect of Inhomogeneous Spatial Distribution of Trees on Stand Growth

The effect of inhomogeneous spatial distribution of trees on stand growth was studied in the model stands which had the same diameter distribution, but the intensity (stand density) was a function of distance away from the ditch.

First, three different model stands, A, B and C, were simulated (Table 4). Stands A and B were younger than stand C. In stand B the number of stems was higher, but the stand basal area was lower than in stands A and C. Each stand was 40 m wide in the direction of the ditches and 68 m wide in the direction perpendicular to the ditches. After generating the tree coordinates as a realization of a Poisson process (hard core 0.3 m) and calculating tree diameters, trees were removed from 4 m wide ditch lines located 34 m apart.

Then, three sets of 35 model stands were produced from stand A, B and C by generating the new coordinates (locations) for trees. For each stand, the spatial distribution of trees was generated as a realization of separate inhomogeneous Poisson processes (e.g. Diggle 1983). However, the distance between any two trees had to be at least 0.3 m. Tree diameters and ages were not recalculated but they remained the same as in stands A, B and C. Because the diameters and ages of trees are inconsistent with the inhomogeneous spatial distributions of trees, the spatial patterns of trees are considered to be created by thinning dense stands.

The effect of inhomogeneous spatial distribution of trees on stand growth is likely expressed more clearly, if the growth model is used in a deterministic way. Again,

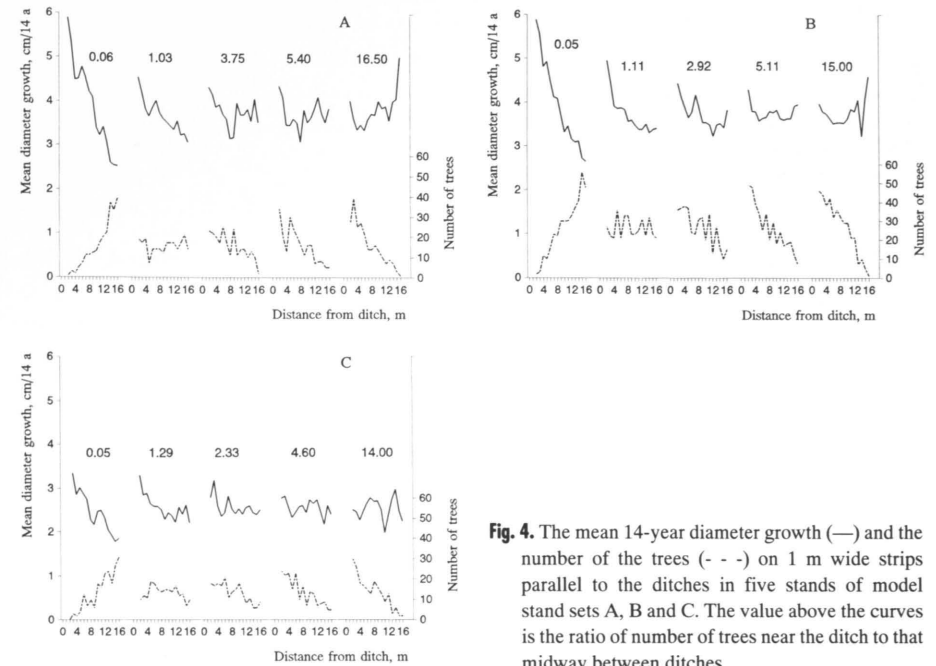


**Fig. 3.** Post-drainage volume growth of stands in model stand sets A, B and C as a function of the ratio of number of trees near the ditch to that midway between ditches.

$s_f^2 / 2 (s_f^2 = \hat{\sigma}_{\text{plot}}^2 + \hat{\sigma}_{\text{tree}}^2 + \hat{\sigma}_v^2$  in Model 1) was added to the logarithmic growth prediction owing to the logarithmic transformation.

The volume growth predictions for model stands of the set A, B and C had a similar pattern, even though they were of the different magnitude owing to stand characteristics (Fig. 3). The volume growth was at its maximum in stands where the Border/Midway ratio of the point densities was 1.5–5. A ratio of 1.5 meant that the number of trees on the 2 m wide strips beside the ditch lines was 1.5-fold as compared to the number midway between ditches. Growth was distinctly at its minimum in stands where the Border/Midway ratio was close to zero; i.e. only a few trees were growing near the ditches and many trees midway between ditches.

Besides the low volume growth, diameter growth varied most of all in accordance with the distance away from the ditch when the Border/Midway ratio of the stand was close to zero (Figs. 4 and 5). In such stands, diameter growth near the ditch-side was more than two times higher as compared to trees growing midway between ditches. Variation in diameter growth was at its minimum in stands where the Border/Midway ratio was about 2–5.



**Fig. 4.** The mean 14-year diameter growth (—) and the number of the trees (---) on 1 m wide strips parallel to the ditches in five stands of model stand sets A, B and C. The value above the curves is the ratio of number of trees near the ditch to that midway between ditches.

## 5 Discussion

The study presented a single-tree growth model for a Scots pine stand on a peatland site drained 14 years ago. Even though some predictors, for example  $1/g_{kji}^2$  and  $\ln(g_{kji})$ , are correlated, the model acts in a logical way. According to the growth model, diameter growth shows a positive correlation with tree diameter. The younger of two trees having the same diameter grows better. The coefficients of the competition indices suggest that the more neighbour trees there are growing near the subject trees, and the bigger they are, the poorer the subject trees' growth. Also, increasing stand basal area reduces tree growth.

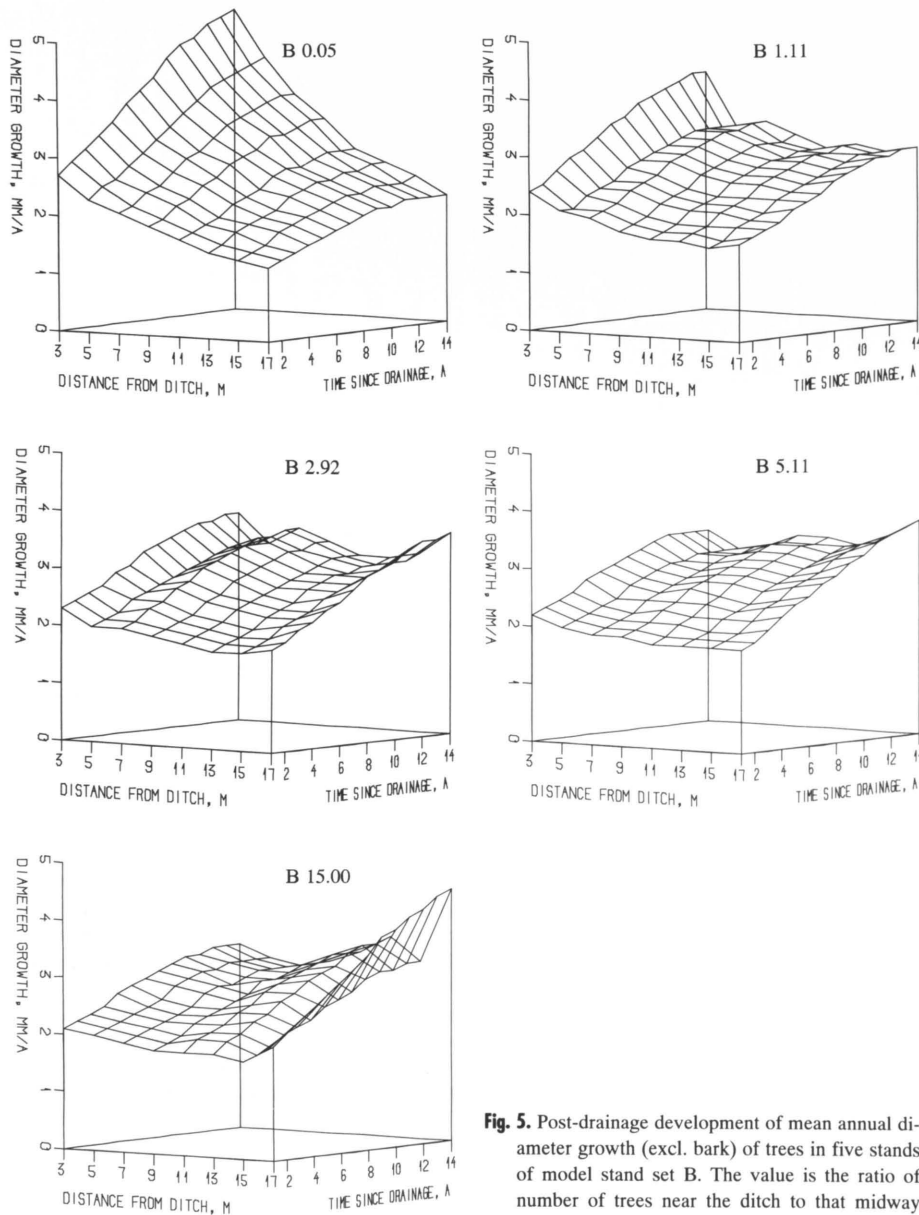
The effect of distance away from the ditch and the time passed since drainage on diameter growth is similar to that presented in earlier studies (e.g. Lukkala 1929, Seppälä 1969). The growth model allocates about 1.5 times higher

diameter growths to trees growing near ditches in comparison to those 16–17 m away from ditches when trees are evenly distributed between ditches (Fig. 4). In the study by Lukkala (1929), the 5-year diameter growth of trees closer than 5 m to ditches was 9.6 mm, while that of trees 6–20 m away was 6.2 mm in sites classified as dwarf-shrub pine mires.

Diameter growth seems to reach its maximum about 13–14 years after drainage (Fig. 5). According to Seppälä (1969), it takes 10–15 years for pine in dwarf-shrub pine mires to reach maximum diameter growth if the age of trees has been 31–50 years at the time of drainage.

The post-drainage development of mean diameter growth of trees in model stand B 1.11 (Fig. 5) and in the study material (Fig. 1) are quite similar excluding trees growing nearer than 6 m from the ditch. In the study material, the growth of trees near ditches responded slightly





**Fig. 5.** Post-drainage development of mean annual diameter growth (excl. bark) of trees in five stands of model stand set B. The value is the ratio of number of trees near the ditch to that midway between ditches.

quicker and more strongly to drainage than was predicted by the model. Because the tree stand near the ditches had been thinned when clearing the ditch lines, trees on the ditch-side, if not injured by ditching, can be more vigorous than other trees in the study material. Stand density at a distance of 2–8 m from ditch was about 25 % lower than elsewhere between the ditches. However, no systematic diameter or age variation with distance from the ditch was observed in the study material.

The aim of this study was not to construct a growth model for practical application, but to estimate the temporal and spatial effects of drainage on tree growth in the study material. Therefore, no independent material was used to test the growth model. Despite the fact that the growth model slightly fails in predicting the growth of trees located 4–6 m away from ditches, the examination of the residual variation of the growth model showed no serious bias with respect to any of the predictors. Thus the model gives, on the average, correct results for the study material.

The mean annual volume increments of model stands 1–3 and model stands A, B and C, where the trees were evenly distributed between ditches, were 1.6–2.0 m<sup>3</sup>ha<sup>-1</sup>. These values correspond to the figures presented for young pine stands on drained dwarf-shrub pine mire (Heikurainen 1959, Seppälä 1969, Keltikangas et al. 1986). Also, this is an indication of good model validity.

Because the growth model is a spatial one and accounts for the growth variation owing to the distance between trees and ditches and the time passed since drainage, it can be used to study the effects of different spatial distributions of trees on stand growth. However, some limitations should be borne in mind when using the model. The study material was collected in a drainage area, in stands representing poor site fertility (dwarf-shrub pine mire). Other growing sites cannot be studied using the present model. Also, ditch spacing should not be more than 36 m and time passed since drainage not more than 14 years.

The diameters of the trees forming the model stands were predicted by models based on plots located on mineral soils (Pukkala 1989b). The use of these models presupposes that the rela-

tionship between spatial distribution and diameter distribution is similar on mineral soils and peatlands.

Not only the diameter, but also the shape of the stem depends on stand density in the vicinity of the tree (Nilsson and Gemmel 1993). Thus, tree height calculated by a spatial height model can be used to get more accurate estimates for the stem volume of trees in model stands. In the present study, stem volume was calculated using an equation based on tree diameter only, because there were no height models available for pine on drained peatlands.

The simulations showed that irregular spatial distribution of trees reduced volume increment by 9–20 % in a Scots pine stand growing on a site of poor fertility. On mineral soils, a heavy clustering of trees has been found to cause similar losses (Pukkala 1988, 1989a). In the study by Miina et al. (1991), it was found that irregularities reduce volume growth by 5–13 % as compared to regular spatial distributions.

It is advisable to leave more trees near the ditches than elsewhere. The post-drainage growth of the stand, with a given total number of stems, is maximized and the variation in diameter growth is minimized when stand density is 1.5–5-fold on the ditch border as compared to midway between ditches. According to Miina et al. (1991), a three-fold difference in stand density results in the best stand development.

In order that longer post-drainage periods might be studied, additional data should be collected in older drainage areas. In long-term simulations, height growth models are needed besides diameter growth models. Owing to the short period of time passed since drainage and the young age of stands in the study material, it was not possible to study the effect of intermediate thinnings on stand productivity. Moreover, thinned stands were not included in the study material.

Future studies should endeavour to determine the optimum management program for Scots pine stands on drained peatland sites over the whole rotation period. In old drainage areas, ditches have often deteriorated and collapsed to such an extent that ditch network maintenance is needed to maintain tree growth. Thus, the effect of ditch maintenance on tree growth should also be included in future studies.

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