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A spatial model for the diameter of thickest branch of Scots pine

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TIIVISTELMÄ: SPATIAALINEN MALLI MÄNNYN PAKSUIMMAN OKSAN LÄPIMITALLE

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The model predicts the base diameter of the thickest living branch of a tree growing in a planted or naturally regenerated even-aged stand. A mixed model type was used in which the residual variation was divided into within-stand and between-stand components. The study material consisted of 779 trees measured in 12 plots located in 20 to 35 years old Scots pine (*Pinus sylvestris* L.) stands (breast height age 10 to 20 years). Branch diameter was closely connected to the breast height diameter of the stem. In a stand of a certain age, competition by close neighbours slightly decreased branch diameter in a given diameter class. According to the model, the greatest difference is between trees subjected to very little competition and those subjected to normal competition. The model was used in simulated stands with varying age, density, and tree arrangement. The simulations showed that trees with rapid diameter growth at young age had thicker branches at a given breast height diameter than trees with slower diameter growth. However, a very slow growth rate did not produce trees with branches thinner than those possessing a medium growth rate.

Malli ennustaa paksuimman elävän oksan tyviläpimittaa viljellyissä ja luontaisesti syntyneissä männiköissä. Tutkimuksessa käytettiin sekamallitekniikkaa: mallin jäännösvaihtelu jaettiin metsikön sisäiseen ja metsiköiden väliseen osaan. Tutkimusaineisto koostui 779 puusta, jotka mitattiin 12 koealalta metsiköistä, joiden ikä vaihteli välillä 20–35 vuotta (rinnankorkeusikä 10–20 a). Paksuimman oksan läpimitta riippui läheisesti puun rinnankorkeusläpimitasta. Tietyn ikäisessä metsikössä naapuripuiden aiheuttama kilpailu pienensi hiukan oksan läpimittaa tietyssä rinnankorkeusläpimittaluokassa. Mallin mukaan ero on suurin lähes ilman kilpailua kasvavien ja kilpailuasemaltaan keskimääräisten puiden välillä. Mallia sovellettiin iältään, tiheydeltään ja tilajärjestykseltään erilaisiin mallimetsiköihin. Simuloinnit osoittivat mm., että sellaiset puut, joiden läpimitan kasvu oli ollut nuorella iällä nopeaa, kasvattivat paksumpia oksia kuin hitaammin kasvaneet rinnankorkeusläpimitaltaan yhtä paksut puut. Erittäin hidas kasvunopeus ei kuitenkaan tuottanut sen hieno-oksaisempia puita kuin keskinkertainen kasvunopeus.

Keywords: *Pinus sylvestris*, spatial pattern, stand density, simulation, timber quality, branches, competition.
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1 Introduction

The quality of Scots pine logs greatly depends on the amount of branches (e.g. Uusvaara 1985, Kärkkäinen 1986). Many studies have been conducted on the factors that regulate branch diameter. The means to affect branch diameter include tree breeding (Rautiainen 1971, Tigerstedt and Velling 1985), pruning (Heiskanen and Taipale 1963, Vuokila 1982, Hägg 1985, Kellomäki et al. 1992), selection of the growing site (Kellomäki and Väisänen 1986, Turkia and Kellomäki 1987, Lämsä et al. 1990), regulation of stand density (Kellomäki and Tuimala 1981, Jokinen and Kellomäki 1982, Huuri and Lähde 1985, Huuri et al. 1987), and spatial distribution of trees. The most easily controllable silvicultural factors are stand density, spatial distribution of trees, and site selection.

Many studies have been conducted on the effect of site fertility and stand density on branch diameter. The general observations are that an increase in stand density decreases branch diameter, and that the branches on trees are smaller on poorer sites as compared to the situation on fertile sites (e.g. Kellomäki et al. 1992). The relationship between tree arrangement and branch diameter in Scots pine stands has not been studied previously. However, this question is both important and interesting. Increasing aggregation brings trees nearer to each other and increases the between-tree competition. This can be expected to decrease branch diameter. However, in irregular stands with many gaps, the directional distribution of competitors is not uniform. Trees often have free growing space at least on one side, and thick branches may grow in that direction. In addition, aggregation decreases stand productivity through increased competition and through the inefficient use of growth resources. It may also increase variation in between-tree competition and in tree size, and this way affect timber quality.

Several studies on the effect of stand density and site fertility have related branch diameter to the number of trees per hectare and to the forest site type. Both of these are useful variables when giving recommendations for planting density and tending operations, but they are clearly limited as model predictors. Forest site types are subjectively evaluated into rather broad classes. The number of stems per hectare is insufficient for describing the between-tree competition since it omits the size variation among trees and the spatial arrangement of trees. Some of the differences between the results of previous studies may be explained by the shortcomings of the predictors used in them.

Only close neighbours influence the branch diameter of a tree. The effects of neighbouring trees can be accounted for by competition indices that depend on the number, size, proximity, and directional distribution of the neighbours (Pukkala 1989). A spatial model for branch diameter in which competition indices are used as predictors along with the usual tree and stand variables provides the most flexible means of examining the effect of stand structure on branch diameter.

This study presents a spatial single-tree model for the base diameter of the thickest living branch of a tree. The thickest branch was used as the predicted variable because it is a commonly used quality criterion (e.g. Varmola 1980, Kellomäki et al. 1992), it correlates with the overall number of branches, and it is easy to measure. The model was applied to simulated stands in order to examine the effects of spatial distribution of trees and stand density on the diameter of the thickest branch on individual trees.

2 Material and methods

Measurements

The study material consisted of 12 plots of young Scots pines (about 62°N, 30°E, 100 m asl.), the plots differing in density and the spatial distribution of trees (Table 1). The aim was to have wide variation in the between-tree competition and branch diameter (Table 2). The mean breast height age of the stands varied within the range of 9.4–19.4 years, the basal area of the stands was 7–23 m²/ha, the number of trees per hectare varied between 1392 and 5760, and the dominant height was 5.6 to 10 metres. Six plots were naturally regenerated (372 observations), three were plantations (166 observations), and three were established by sowing (241 observations). The site was classified as being of the *Myrtillus* type according to Cajander (1909) (medium fertility) in 2 cases (117 observations), *Vaccinium* type (rather poor) in 8 cases (555 observations), and *Calluna* type (poor) in 2 cases (107 observations). All the stands could be regarded as being even-aged, although there was some age variation in the naturally regenerated stands. The breast height diameter of most trees was between 5 and 15 cm. The trees were in that stage of development that is the most critical for the quality of the lowest logs.

Height, breast height age, and the base diameter of the thickest living branch were measured for trees that were located at least five meters from the nearest plot boundary. The thickest branch was almost always a live branch. Branch diameter was measured immediately beyond the base swelling in a direction perpendicular to the stem and branch. A total of 779 trees were measured to determine their branch diameter. Trees within a 5 metres wide border zone were measured for their breast height diameter and their coordinates were also recorded. They were used to compute the spatial predictors for the branch diameter model.

Table 1. Characteristics of the study plots. No = Plot number, Trees = No. of trees in the plot, Obs = No. of observations (trees that were used to construct the models), N = No. of stems per hectare, G = Stand basal area (m²/ha), V = Stand volume (m³/ha), Tg = Mean age at breast height (a), Hdom = Dominant height (m), Dmin = Minimum diameter (cm), Dg = Mean diameter (cm), Dmax = Maximum diameter (cm), H = Grouping index of Hopkins (1954), C = grouping index of Clark and Evans (1954).

No	Trees	Obs	N	G	V	Tg	Hdom	Dmin	Dg	Dmax	H	C
1	159	56	1767	14	69	19.4	10.0	2.0	11.8	18.0	1.45	0.98
2	360	99	5760	23	103	17.6	9.9	2.0	9.2	16.0	1.21	0.92
3	191	37	2547	14	57	13.1	8.7	2.1	10.4	20.3	0.77	1.07
4	223	73	2973	11	40	12.0	7.3	1.9	8.3	13.0	0.92	1.13
5	245	55	4900	8	26	11.4	6.7	2.0	5.5	9.7	0.60	1.15
6	206	73	2289	16	70	16.4	9.3	2.0	11.3	20.8	0.51	1.22
7	107	52	1427	18	79	11.8	8.1	3.2	13.7	18.8	1.34	1.53
8	174	65	1420	13	48	14.2	7.7	2.0	13.1	20.9	0.57	1.26
9	167	63	1392	16	71	14.8	9.2	3.1	13.5	20.0	0.49	1.25
10	225	105	1837	15	66	15.0	8.6	2.1	12.0	17.9	0.49	1.29
11	183	52	3660	10	33	10.8	6.4	2.0	8.0	15.3	3.66	0.69
12	160	49	2133	7	20	9.4	5.6	2.0	7.5	12.1	0.69	1.38

Table 2. Mean, standard deviation and range of some variables in the study material. Relative diameter is the diameter of the subject tree divided by the mean diameter in a circle with 5-m radius, centred on the subject tree. Basal area of neighbouring trees was computed from trees nearer than 5 metres. Competition index CI1 is defined by Equation 6. Free angle is computed from trees taller than the subject tree.

Variable	Minimum deviation	Mean	Maximum	Standard	Unit
Diameter (dbh)	1.9	8.6	20.9	3.9	cm
Branch diameter	5.0	21.1	48.0	8.8	mm
Competition index (CI1)	0.6	9.8	57.0	9.0	m^{-1}
Free angle	28.0	160.5	360.0	104.5	°
Relative diameter (d/Dg)	0.2	0.8	1.6	0.3	-
Basal area of neighbours	2.4	14.4	31.9	5.5	m²/ha

Modelling

Because observations in the same plot were correlated, a mixed model type was used in which the residual variation was divided into between-plot and within-plot components (Lappi 1986):

$$b_{ij} = f(X1_j, X2_j, \ldots x1_{ij}, x2_{ij}, \ldots CI1_{ij}, CI2_{ij}, \ldots) + p_j + e_{ij} \quad (1)$$

in which b_{ij} is the base diameter of the thickest branch of tree i in plot j, $X1_j$ and $X2_j$ are stand characteristics of plot j, $x1_{ij}$ and $x2_{ij}$ are characteristics of tree i in plot j, $CI1_{ij}$ and $CI2_{ij}$ are competition indices for tree i in plot j, p_j is a random plot factor, and e_{ij} is a random tree factor.

Several different competition indices were tested. They were based on the distances to and diameters of neighbouring trees and on the height differences between the subject tree and neighbouring trees (e.g. Pukkala and Kolström 1987). The widest angle from the subject tree without competitors, with many different definitions for the competitor, was also tested.

Simulations

The effect of stand structure on branch diameter was studied in simulated model stands. The stands were generated from given values for stand age (Tg, a), dominant height (Hdom, m), number of trees per hectare (N, trees/ha), and from a given spatial distribution of trees. The stand basal area (G, m^2/ha) was predicted from Tg, Hdom, N, and the spatial distribution of trees using an empirical model. This model was based on the 12 plots of this study and 54 other Scots pine plots (Pukkala 1989) for which Tg, Hdom, N, G, and the tree coordinates were known. The model for predicting stand basal area was as follows:

$$G = \exp(-2.668 + 0.346\ln(N) + 0.759\ln(Hdom) + 0.00346Tg + 0.760C) \quad (2)$$

where C is the grouping index of Clark and Evans (1954). The model indicates that stand basal area decreases with increasing grouping if N, Tg, and Hdom remain unchanged.

The tree diameters of the model stands were predicted by a spatial model of the same type as Equation (1). This model was computed from the same material as the model for branch diameter. It was assumed that part of variation in tree diameter is related to the variation in stand density. Variation of stand density was described with several competition indices computed from the diameters and distances of close neighbours. Tree coordinates, stand basal area, and number of stems per hectare were used as input variables for the method of producing tree diameters.

A birth-and-death technique was used to get the tree diameters of the model stands. All trees were first given an equal diameter that produced the required total stand basal area. Then, a random tree was selected, and its diameter was predicted using the spatial diameter model. A stochastic component corresponding to the residual variation of the model was added to the prediction. When this process was repeated many times (2 to 3 times the total number of trees), the result was a stand in which variation in tree diameter was related to variation in stand density. If the random tree was nearer than 5 metres to the plot edge, a temporary 5 metres wide buffer zone was generated around the plot to compute the spatial predictors of the diameter model.

The diameter of the thickest branch of each tree was predicted by the model developed in this study. A stochastic component corresponding to the within-stand residual variation was added to the prediction. The plot factor was assumed to be zero. When computing the competition indices, the plot was assumed to be surrounded by similar plots on all sides.

Two grouping indices were utilized to describe the degree of aggregation of the study material and model stands. The index of Clark and Evans (1954) was computed from

$$C = 2v\sqrt{m} \quad (3)$$

in which v is the mean distance between trees (m), and m is the stand density (trees/m^2).

The index of Hopkins (1954) was computed from:

$$H = \sum a_i^2 / \sum b_j^2 \quad (4)$$

in which a_i is the distance from a random point to the nearest tree and b_j is the distance from a random tree to its nearest neighbour. It is assumed here that the number of both distances is the same. C and H are equal to one in purely random (Poisson) tree distribution. C greater than one and H less than one refer to a regular tree distribution, and C less than one and H greater than one refer to an aggregated tree distribution.

3 Results

Model for branch diameter

The model for thickest branch diameter was found out by testing several competition indices with different measures of tree size, stand age, and stand density. The following equation had the smallest residual variation:

$$b_{ij}^{0.5} = 14.55 + 1.187\, d_{ij} - 0.1717\ln(CI1_{ij} + 0.0001) + 0.5231\, Tg_j + 0.62135\ln(G_j) - 8.411\ln(Tg_j) + p_j + e_{ij} \quad (5)$$

in which branch diameter (b) is given in mm, stem diameter at breast height (d) in cm, competition index (CI1) in m^{-1}, stand basal area (G) in m^2/ha, and the mean breast height age of the stand (Tg) in years.

The competition index (CI1) was computed as follows:

$$CI1_i = \sum_{k=1}^{n} s_k^{-1} (d_k / d_i) \quad (6)$$

Table 3. Correlation of branch and tree diameter with some variables.

Variable	Branch diameter	Stem diameter at breast height (dbh)
Stem diameter (dbh)	0.926	1.000
Competition index 1 (CI1)	–0.670	–0.716
Competition index 2 (CI2)	–0.381	–0.390
Competition index 3 (CI3)	–0.467	–0.515
Competition index 4 (CI4)	–0.615	–0.658
Free angle	0.602	0.646
Relative diameter (d/Dg)	0.813	0.767
Basal area of neighbours	0.126	0.162

Formulas for competition indices CI2, CI3 and CI4:

$$CI2 = \sum_{k=1}^{n} d_k / s_k \qquad CI3 = \sum_{k=1}^{n} s_k^{-2} (d_k / d_i)$$

$$CI4 = \sum_{k=1}^{n} s_k^{-1} (d_k / d_i)^2$$

in which n = number of neighbours nearer than 5 m, dk = diameter (cm) of neighbour k (cm), s_k = distance of neighbour k (m), and d_i = diameter of the subject tree (cm).

where d_i is the diameter of the subject tree (cm), d_k is the diameter of competitor k (cm), s_k is the distance (m) of competitor k (m), and n is the number of competitors nearer than 5 metres. The ability of free angles to explain differences in branch diameter was smaller than that of CI1. The number of stems per hectare was not a useful additional predictor if stand basal area, stand age, and competition index were already included in the model.

The degree of explained variance (R^2 adj.) of the model was high, 0.90, because of the very strong correlation with stem diameter and the diameter of the thickest branch (Table 3). Most of the residual variation was among trees in the same plot: the within-stand residual variance was 0.087 and the between-stand variance 0.017. The bias of the model was –0.0002 in the whole study material. The bias for individual plots, which reflects the variation in pj, varied between –0.182 and 0.177. The bias was –0.043 for naturally regenerated stands, –0.037 for planted stands, and 0.069 for sowed stands. For the *Myrtillus* forest site type the bias was –0.084, for *Vaccinium* type 0.012, and for *Calluna* type –0.022. The model was reasonably good in accounting for the differences due to site fertility and the mode of regeneration.

According to the model, competition decreases branch diameter of trees of a given age and stem diameter (Figs. 1 and 2). Most of the decrease occurs at low competition levels (competition index CI1 less than 10). Trees subjected to medium and high competition are almost equal in terms of branch diameter if stem diameter and stand age are the same. Within a given diameter class and a given amount of competition, branch diameter first decreases with stand age, but finally begins to increase again. This type of dependence indicates that branches are thick on the most fertile sites, but not necessarily thinnest on the very poorest sites.

Model stands

The model for computing the tree diameters of the model stands was as follows:

$$d_{ij}^{0.5} = 2.022 + 0.1866\ln(CI5_{ij} + 0.0001) - 0.6202\ln(CI6_{ij} + 0.0001) + 0.47612\ln(G_j) + p_j + e_{ij} \quad (7)$$

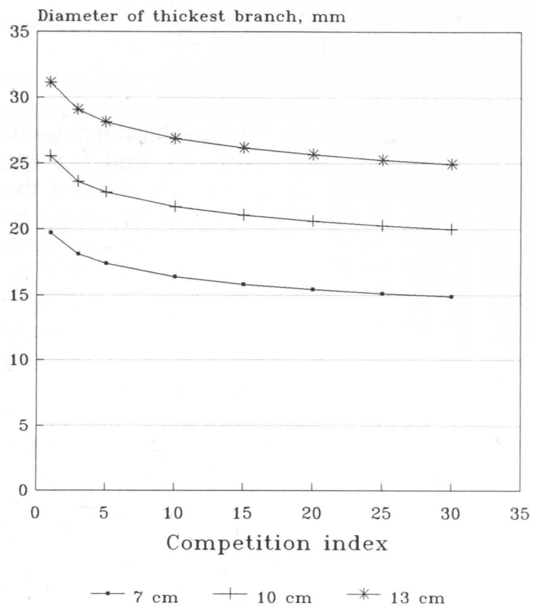

Fig. 1. Effect of breast height diameter and competition on the diameter of the thickest branch. Stand basal area is 15 m²/ha and breast height age 15 years. The mean competition index (CI1) in the study material was 9.8.

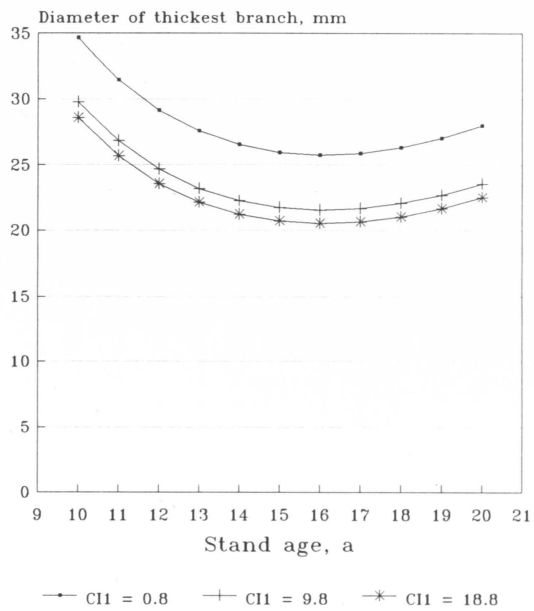

Fig. 2. Effect of breast height age and competition index (CI1) on the diameter of the thickest branch of a tree with dbh 10 cm. CI1=0.8 means very low competition, CI1=9.8 medium competition, and CI1=18.8 high competition. Stand basal area is 15 m²/ha.

Competition indices CI5 and CI6 were defined as follows:

$$CI5 = \sum_{k=1}^{n} d_k / s_k \tag{8}$$

$$CI6 = \sum_{k=1}^{n} s_k^{-1} \tag{9}$$

in which n = number of neighbours nearer than 5 m, d_k = diameter of neighbour k (cm), and s_k = distance of neighbour k (m). The degree of explained variance of the model was quite low, 0.32; this means that only a minor part of the variation in tree diameter was related to the variation in competition. The within-stand residual variance was 0.331 while the between-stand variance was 0.016.

Regular, Poisson-distributed and grouped forest stand plots with 1000, 2000, 3000, and 4000 stems per hectare were simulated to study the

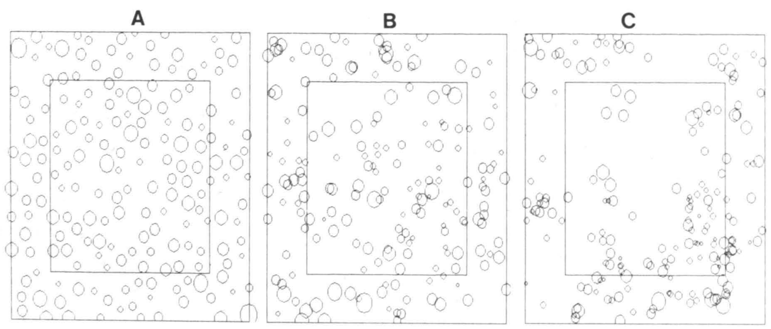

Fig. 3. Tree map of a regular (A), Poisson (B), and grouped (C) model stand (45 m × 45 m plot) with 2000 trees/ha. Stand age is 15 a at breast height.

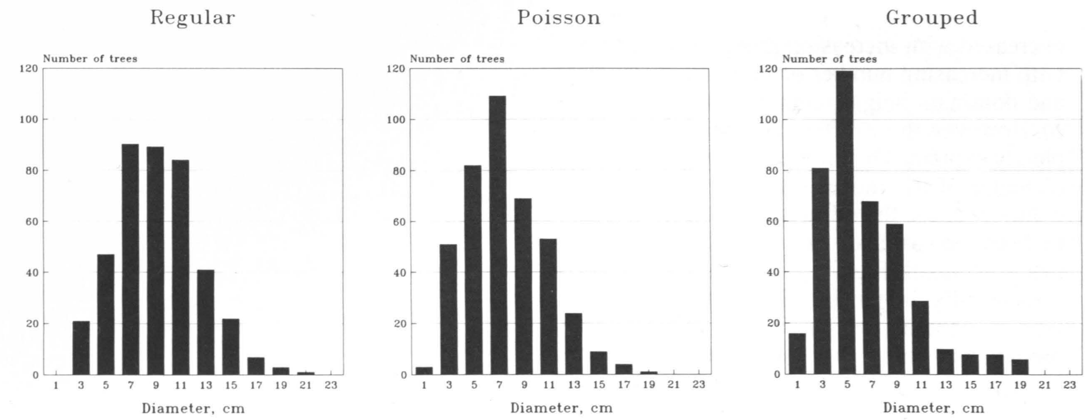

Fig. 4. Diameter distribution of a regular, Poisson, and grouped model stand with 2000 trees/ha (number of trees in a 30 m × 30 m plot). Stand age is 15 a at breast height.

effect of stand density and spatial distribution of trees on branch diameter (Fig. 3). Regular patterns were simulated by sampling x and y coordinates from uniform distribution but the location was rejected if it was closer to another point than a specified limit. Grouped patterns were generated in two steps. First, Poisson-distributed group centers were produced. Second, a specified number of points was generated around each group center.

The stand age in the model stands was set at 15 years (at breast height), and the dominant height at 8.5 m; these parameters corresponded to the typical values in the study material (Table 1). The stand basal area was computed using Equation (2). The size of the plots varied between 0.09 ha (with 4000 trees/ha) and 0.36 ha (with 1000 trees/ha) and the number of trees in the plot varied between 360 and 405.

Grouping index H varied between 0.27 and 0.34 for the regular stands, between 0.87 and 0.93 for the Poisson-distributed stands, and between 2.40 and 4.02 for the grouped stands. The model stands corresponded to the range of variation in the degree of aggregation and stand density manifested by the study material (Table 1). They also covered the most relevant range of variation occurring in nature.

Differences in the basal area and diameter distribution of the model stands described the predicted effect of spatial distribution of trees on diameter growth (Figs. 4 and 5). For a given number of trees per hectare, the stand basal area decreased with increasing grouping (Fig. 5). In the grouped stands, the range of variation in diameter was equally wide or wider than in regular stands, but with more trees belonging to the smaller diameter classes (Fig. 4).

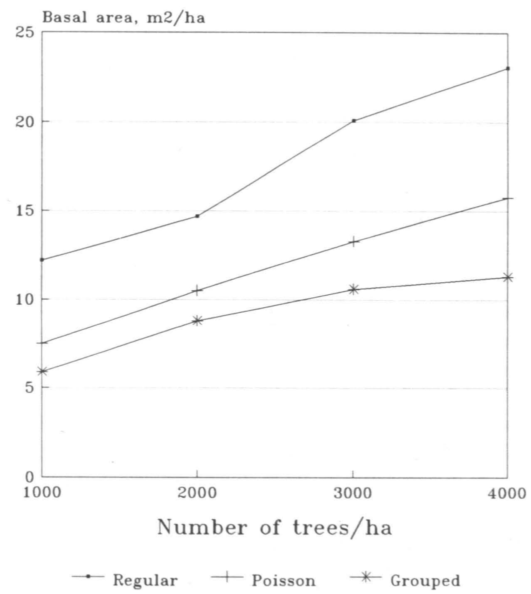

Fig. 5. Effect of spatial distribution of trees and number of trees/ha on the stand basal area in a 15 years old stand (breast height age).

Effect of stand structure on branch diameter

The mean diameter of the thickest branch clearly decreased with increasing grouping of trees and with increasing number of stems/ha if stand age and dominant height remained unchanged (Fig. 6). However, these differences were almost completely explained by differences in the mean stem diameter of the model stands. In a given stem diameter class, the differences in branch diameter between spatial distributions and stand densities were small (Fig. 7).

Especially in the smallest diameter classes, branch diameter decreased with increasing aggregation of trees. For most diameter classes, the increased competition due to grouping reduced the mean diameter of the thickest branch by a few percentage points. The largest trees can, however, have equally thick or even thicker branches in aggregated stands than those in regular stands (Fig. 7). This is not surprising since the largest trees in an irregular stand with small average tree size may be subjected to less competition than trees of the same diameter in a regular stand.

According to the model, competition decreases branch diameter of trees of given stem diameters and ages. Competition may be increased through stand density or grouping of trees. The simulations indicated that with a given tree diameter, branch diameter is not notably affected by stand density (number of trees per hectare) (Fig. 8). The mean diameter of the thickest branch in a given diameter class was almost the same for stands with with 1000, 2000, 3000, and 4000 trees per hectare for all spatial distributions.

Increased stand density slows down the growth rate of individual trees, especially their diameter growth. Closely spaced stands need more time to reach a given mean stem diameter. This leads to the following questions: What happens to the branch diameter if the mean stand diameter and site are the same, but stand age and density vary? What is the result if sparse stands of a given age are compared to somewhat older and denser stands?

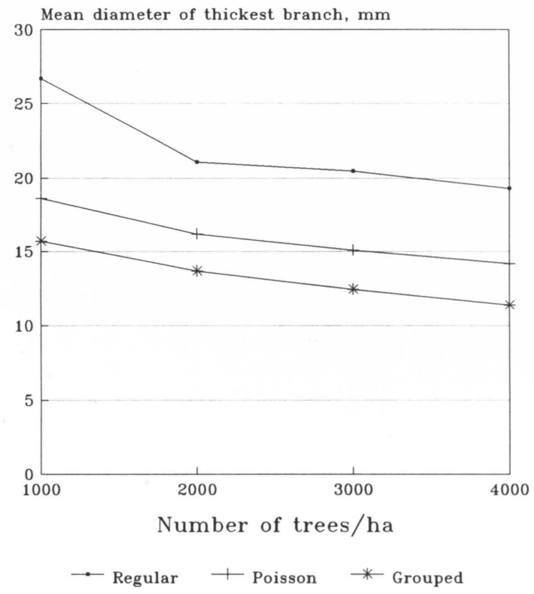

Fig. 6. Effect of spatial distribution of trees and number of trees/ha on the mean diameter of the thickest branch in a 15 years old stand (breast height age).

According to the present models for stem and branch diameter, decreasing growth rate due to increasing stand density reduces branch diameter, particularly in sparesely spaced stands (Fig. 9). If stand density is increased from its normal values, and stands are left to grow on and to reach a certain mean diameter, then the branch diameter of a given diameter class no longer decreases, but eventually begins to increase again. It should be noted, however, that in stands of varying age and density, the trees have different stem forms, and branch diameter alone does not explain quality differences of stems.

4 Discussion

The study presents a spatial model for examining the effect of competition and spatial distribution of trees on the branch diameter of Scots pine. The spatial single-tree model is the most detailed static model to describe variation in branch diameter. The most important factor not fully accounted for by the model is that of the past stand treatment. A branch growth model is required to describe the immediate and long-term effects of tending operations (Oker-Blom et al. 1988). However, it is difficult to reliably estimate the parameters for such a model. In the material of the present study, at least five years had elapsed since the last treatment. This means

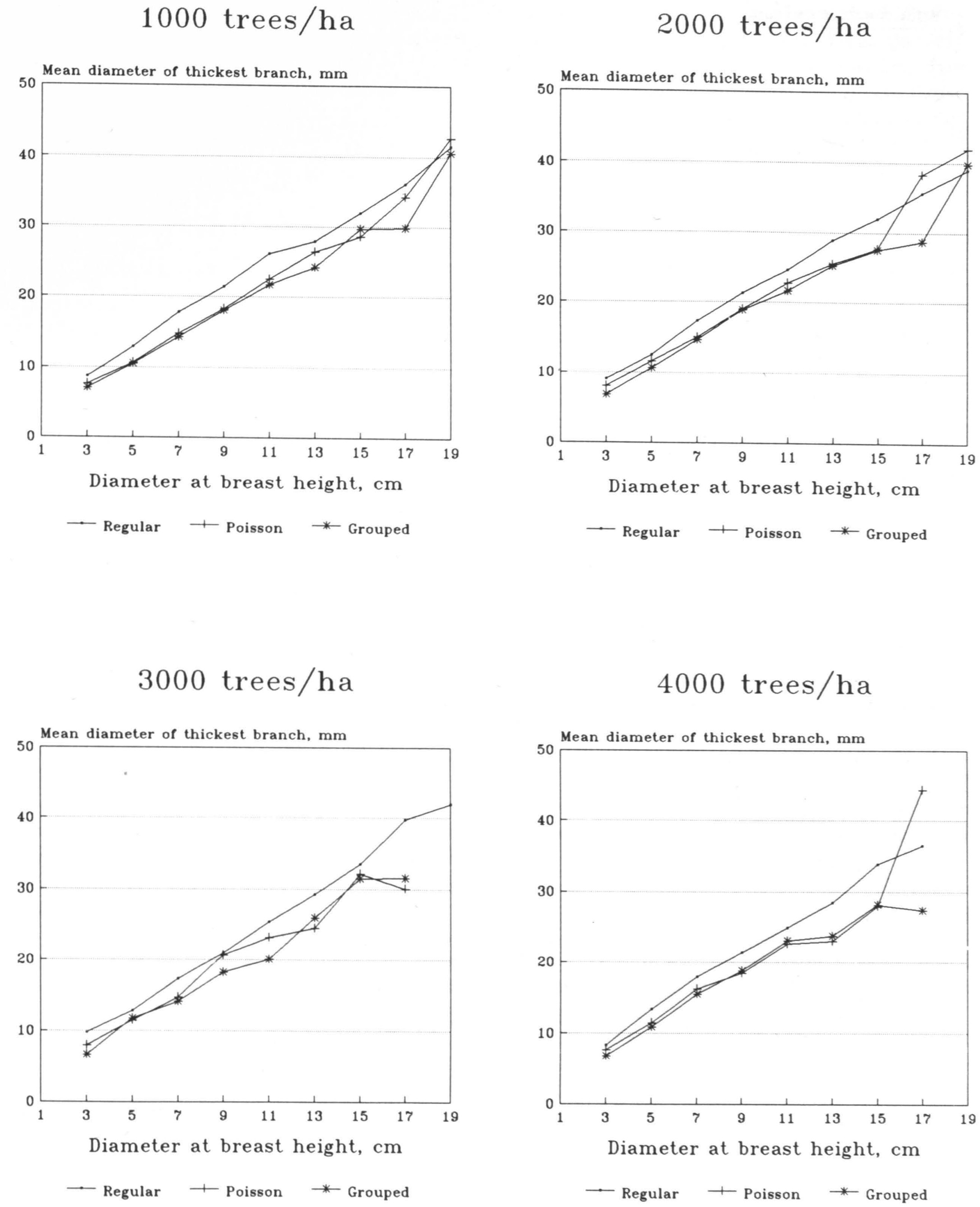

Fig. 7. Effect of spatial distribution of trees and number of trees/ha on the mean diameter of the thickest branch in different diameter classes in a 15 years old stand (breast height age).

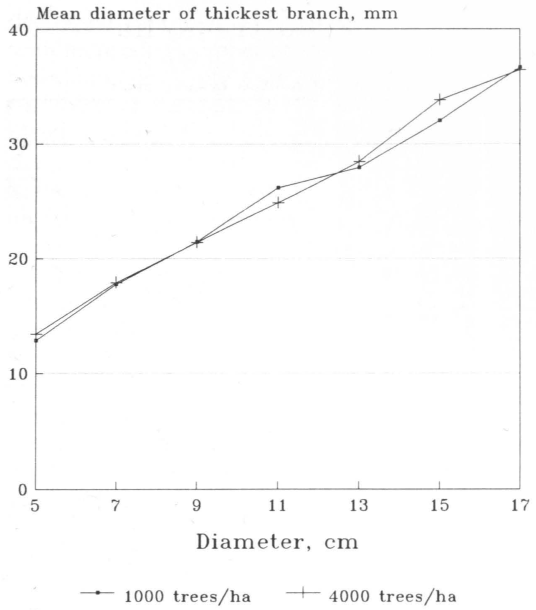

Fig. 8. Mean diameter of the thickest branch of a regular stand in various diameter classes with 1000 and 4000 trees/ha. The breast height age of the stand is 15 a.

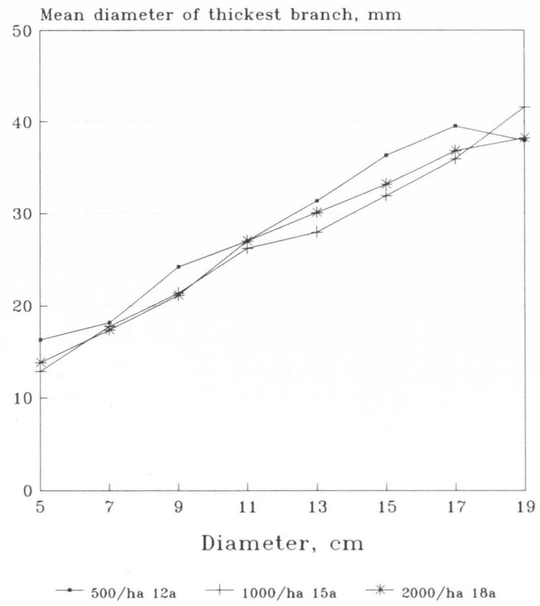

Fig. 9. Mean diameter of the thickest branch of a regular stand in various diameter classes with 500, 1000, and 2000 trees/ha. The mean breast height diameter of all stands is 13.2–13.8 cm (weighted by tree basal area). Stand basal area, tree height and stand age vary according to the number of trees/ha.

that the spatial arrangement of trees had influenced the diameter growth of stems and branches for a reasonable time.

The study material covered stands growing on poor to medium sites. The breast height age of the stands varied between 10 and 20 years, stand basal area between 7 and 23 m^2/ha, and the number of stems per hectare between 1392 and 5760. The competition that individual trees were subjected to varied a lot in terms of the number, proximity, size, and directional distribution of the competitors. The study material consisted of measurements made of 779 trees. The material may be taken to be sufficient for a preliminary study of a new subject. The fit of the model was good; i.e., it accounted for most of the variation in branch diameter.

A simulation approach was used to compare branch diameter in different stands. Compared to direct measurements in different stands, simulation has the advantage that stand properties can be easily controlled. The shortcoming is that simulated results may not correspond to the situation in nature if, for example, the residual variation is simulated incorrectly. Systematic errors are also possible if simulation is extended outside the range of variation in the study material, or if the models are not correctly formulated.

In the simulations for the present study, care was taken in seeing to it that tree size and size variation depended on the spatial variation in stand density. The range of variation of the variables of the simulated stands did not exceed that in the study material. The predicted variable of both stem and branch diameter model (square root of diameter) was selected so that the model residuals were reasonably normally distributed with a constant variance in different size classes.

The site of the simulated stands was defined through stand age and dominant height. The average values of the study material were used, which meant that the simulated results apply to *Vaccinium* sites. The method of stand establishment was not specified because it was thought that the regeneration method as such does not influence branch diameter (Kärkkäinen and Uusvaara 1982). Possible differences are due to other factors connected to different regeneration methods such as stand density and growing site. This conclusion is supported by the fact that the bias of the fixed part of the branch diameter model was not systematically related to the regeneration method.

In the present study material, branch diameter was closely connected to the breast height diameter of the stem. This relationship was slightly modified by competition and stand age. Competition through grouping of trees decreased branch diameter by a few percentage points in the dominant diameter classes of the stand. The biggest differences were observed between trees subjected to very little competition and trees subjected to typical or normal competition. An increase in stand density from its normal values had a very little influence on branch diameter in a given diameter class in a stand of given age.

According to our observations in the study plots, Scots pines often had their thickest branches on the side with the least competition or fewest close neighbours. Therefore, it was surprising to observe that the directional distribution of competitors, as described by the widest free angle, was not as good a predictor as the non-directional index CI1. The reason behind this may be the strong correlation between the diameter of the thickest branch and the stem. If a tree has free growing space on one side, it produces thick branches in that direction, but the stem is also thick.

Branches will be thinner if the growth rate of stem diameter is low (Kärkkäinen and Uusvaara 1982, Uusvaara 1974, 1985). Growth rate can be decreased through site selection or stand density. However, there is a limit beyond which this relationship is no longer valid. Trees on very poor sites do not have thinner branches than trees on poor sites. Similarly, trees in very dense stands do not have thinner branches than stands of normal density if the mean diameter of both stands is the same.

Comparisons between the present results with previous studies are difficult because of differences in the modelling approach and in the way the results are presented and computed. However, it is easily concluded that the relationships are of the same type as observed before. For example, the dependence of the diameter of the thickest branch on tree diameter and the number of trees per hectare is similar to that presented by Kellomäki et al. (1992, p. 42).

The simulations of this study indicate that the possibilities for reducing branch diameter through competition are quite small. Branch diameter decreases both with increased aggregation of trees and with closer overall spacing. Aggregation of trees decreases stand productivity, and often decreases branch diameter only in the dominated size classes, which are usually removed in thinnings. Grouped stands cannot therefore be recommended for practical forestry. To decrease branch diameter, it is more recommendable to use higher growing densities and one should especially avoid very sparse spacings. The main benefit to be gained from a high growing density is that when there are many trees, poor individuals can be removed in thinning, and only good individuals will be left to continue growing.

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