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Effect of spatial distribution of trees on the volume increment of a young Scots pine stand

Timo Pukkala

TIIVISTELMÄ: PUIDEN TILAJÄRJESTYKSEN VAIKUTUS NUOREN MÄNNIKÖN TILAVUUSKASVUUN

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The effect of grouping on 5-year volume increment was studied by a simulation technique using spatial growth models estimated in pine stands in the phase of the first commercial thinning. A total of 24 model stands were generated by applying 12 spatial processes for two different diameter distributions. In addition to model stands, 6 different thinnings were simulated in two real stands. The clustering of trees was described with Fisher's grouping index and by estimating the relative interception of diffuse radiation. In model stands with constant diameter distribution the correlation between the grouping index and volume increment ranged from −0.81 to −0.91. The correlation between volume increment and interception was 0.81 . . . 0.83 with one diameter distribution and 0.70 if both distributions were combined. In one thinned stand the correlation between the growth estimate and grouping index varied between −0.33 and −0.76. The correlation between interception and growth was about 0.30 in one stand and 0.72 if both stands were combined. Small irregularities do not decrease the volume production of a young Scots pine stand, but if the clustering is considerable or there are reasonably wide harvest strips, growth will be reduced by 10 . . . 20 %.

Ryhmittäisyyden vaikutusta nuorehkon männikön 5-vuotiskauden tilavuuskasvuun tutkittiin spatiaalisten kasvumallien avulla, jotka perustuivat ensiharvennusvaiheessa olevissa männiköissä tehtyihin mittauksiin. Tutkimuksessa generoitiin 24 mallimetsikköä soveltamalla 12 erilaista spatiaalista prosessia kahteen läpimittajakaumaan. Toinen osa tutkimuksesta perustuu kahteen todelliseen männikköön joihin kumpaankin simuloitiin 6 erilaista harvennusta. Puuston ryhmittäisyyttä kuvattiin Fisherin ryhmittymisindeksillä sekä laskemalla ennuste hajasäteilyn pidätysosuudelle. Mallimetsiköiden tilavuuskasvuennusteen ja ryhmittymisindeksin välinen korrelaatiokerroin vaihteli välillä −0,81 . . . −0,91, kun läpimittajakauma oli vakio. Interseption ja kasvun välinen korrelaatio oli 0,81 . . . 0,83, jos ainoastaan puiden tilajärjestys vaihteli, ja 0,70, jos myös läpimittajakauma vaihteli. Eri harvennustavoissa kasvuennusteen ja ryhmittymisindeksin välinen korrelaatio vaihteli välillä −0,33 . . . −0,76. Hajasäteilyn pidätysosuuden ja kasvuennusteen välinen korrelaatio oli yhdessä metsikössä n. 0,30, ja 0,72, jos kumpaakin metsikköä tarkasteltiin yhdessä. Simulointien mukaan pieni tilajärjestyksen epäsäännöllisyys ei vaikuta nuoren männikön tilavuuskasvuun, mutta jos ryhmittäisyys on huomattavaa tai metsikössä on leveähköjä ajouria, kasvuennuste on 10 . . . 20 % pienempi kuin säännöllisessä tilajärjestyksessä.

1. Introduction

There is much research on the effect of tree species and diameter distribution on the growth of the stand. Most of this knowledge can be found in yield tables (Koivisto 1954) and growth models (Nyyssönen and Mielikäinen 1978, Vuokila and Väliaho 1980). Those few models in which the spatial pattern of tree locations affects the growth estimate (Vuokila 1965, Mielikäinen 1978, 1980) have not been used in practical forestry. There are, however, many instances where the information about the effect of spatial pattern is essential. In regeneration, for example, it would be useful to know how great irregularities can be allowed in the spatial distribution of seedlings without decreasing the stand productivity too much (Pohtila 1980).

In the thinning of an older stand the forest manager often aims at leaving the best trees to grow on. If poor-quality trees occur in groups, he is confronted with the question of how large gaps may be tolerated after thinning without decreasing the productivity of the stand. The same question arises in systematic thinnings or when planning the width of harvest road strips. Except for purely spatial problems, the knowledge of the effect of spatial pattern could be used to increase the accuracy of growth predictions of ordinary forest management planning.

One way of handling the spatial questions is to develop spatial or distance-dependent growth models (Ek and Monserud 1974). Distance-dependent models usually presuppose that the coordinates of all trees are known. However, this is very seldom the case in practical forestry because the mapping of all trees is expensive and time-consuming. For this reason, ways to evaluate the effect of spatial distribution with one or a few parameters should be developed as well as methods to estimate these parameters quickly. The parameter can be used to generate a spatial pattern corresponding to that in nature, after which distance-dependent models can be utilized. Another approach is to correct the growth estimate of a non-spatial model.

This work is aimed as one step towards the use of spatial information in growth prediction. The objectives of the study are (1) to assess the effect of spatial pattern of trees on the volume production of a young Scots pine stand, (2) to find out stand parameters which could predict the effect of spatial pattern on growth and (3) as an example to estimate how much growth is affected by differences in the thinning practice.

2. Computations

2.1 Outlines of the study

The study is based on model stands with varying size and spatial distribution of trees as well as on real stands in which differences in size and spatial distribution originate from simulated thinnings. For each stand the volume increment was estimated by using empirical growth models. The spatial distribution of trees was assessed by grouping indices and the estimate on radiation interception; these measures of clustering were evaluated by studying their correlation with the growth estimate. Accordingly, the study consists of the following computations (cf. Lundell 1973):

(1) Calculation of spatial growth models.
(2) Creation of different spatial and diameter distributions by generating model stands or by simulating thinnings in real stands.
(3) Estimation of the volume increment of each model stand and thinning method.
(4) Calculation of the grouping index and interception of each model stand and thinning method.
(5) Assessment of different measures of clustering by correlation analysis.

2.2 Growth models

The first phase of the study was to prepare distance-dependent growth models that could depict the effect of neighbouring trees on diameter increment. In the study of Pukkala and Kolström (1987) the horizontal angle sum to the stems of neighbors greater than the object tree and nearer than five metres (Fig. 1) proved to predict differences in radial growth reasonably well in young pine stands, and was therefore used also in this study. The angle sum is a rather simplified description of the competition process. For example, it does not take into account the direction distribution of the competitors. The simplified assumptions increase the residual variation of the growth model. At stand level their effect can be taken into account by generating random variation around the expected value of growth estimate.

Because in the study of Pukkala and Kolström (1978) the past growth was predicted by using actual tree dimensions, the growth models were recalculated for predicting the future growth, using the same material as Pukkala and Kolström. The data consisted of three forest stand plots located in about 40-year-old naturally regenerated Scots pine stands on a rather poor site. The total number of trees on the plots was 1192. The height and diameter of each tree were measured in field. The 5-year radial growth was measured from the increment core bored at breast height of those 764 trees which located inside the 4-meter isolation strip of the plot. The diameter 5 years earlier was obtained by subtracting the doubled radial increment (without bark) from the present diameter. For trees on the buffer zone the diameter 5

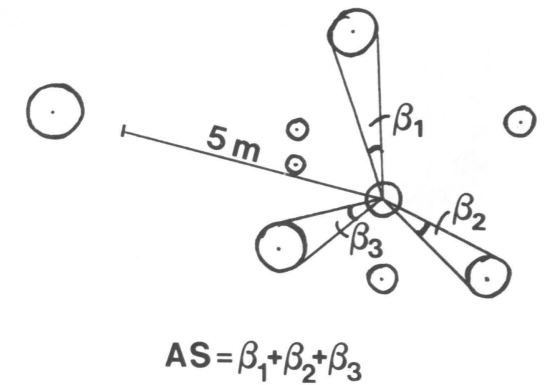$$AS = \beta_1 + \beta_2 + \beta_3$$

Fig. 1. The principle in calculating the angle sum (AS) used for the prediction of diameter increment of the object tree. Neighbors nearer than 5 metres and greater than the object tree are included.

Kuva 1. Läpimitan kasvun ennustamiseen käytetyn kulmasumman (AS) laskemistapa. Korkeintaan viiden metrin etäisyydellä olevat kohdepuuta paksummat naapurit sisällytetään kulmasummaan.

years earlier was estimated by a regression model based on trees inside the buffer zone using the present diameter as a predictor.

For each tree nearer than five metres from the plot edge (636 trees) the angle sum described in Fig. 1 was calculated and used for predicting the diameter increment during the next 5-year period. Two different models were calculated using this data (Fig. 2):

$$i_d = 0.6396 - 0.8075 \ln(AS+0.3) + e_1 \quad (1)$$

$$r_d = 143.1 - 108.9 AS + e_2 \quad (2)$$

where i_d = diameter increment during the next five years (cm),

r_d = relative diameter increment of the next 5-year period (% of the mean diameter increment of the plot),

AS = sum of angles to trees bigger than the tree itself and nearer than 5 m (radian),

e_1, e_2 = error terms.

The residual variation of the growth model was simulated by adding an error term to the expected value of the model. The error term was a normally distributed random number with a zero mean and standard deviation
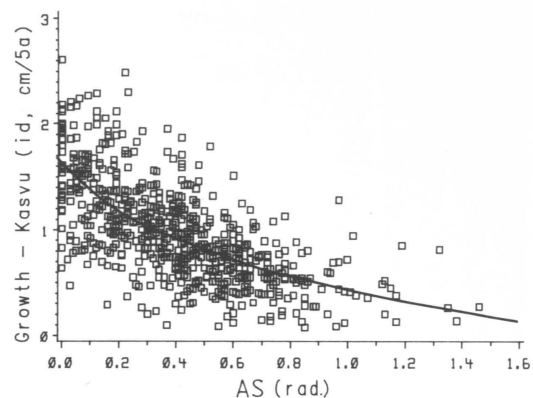
Fig. 2. Dependence of diameter increment on the angle sum (AS) on three Scots pine sample plots according to Eqn (1).

Kuva 2. Läpimitan kasvun riippuvuus kulmasummasta (AS) kolmella männikkökoealalla yhtälön (1) mukaan.

equal to the standard error of the estimate (s_e).

The use of tree diameter, stand age or stand basal area as a predictor did not improve the above models. This was because the diameter was closely correlated with the angle sum ($r=-0.8$) and the stand age and basal area did not vary very much. In addition, the angle sum is highly dependent on the stand basal area in the surroundings of the tree.

The latter equation (Eqn 2) was used in the model stands for which the mean diameter increment was estimated as a mean of the growth estimates of the following distance-independent model (Nyyssönen and Mielikäinen 1978):

$$\ln(p_d) = 5.463 - 0.6675\ln(T) - 0.4758\ln(G) + 0.1773\ln(D) - 0.9442\ln(H_{dom}) - 0.3631\ln(d) + 0.7762\ln(h) + e_3 \quad (3)$$

where p_d = annual diameter increment during the next five years (compound interest percentage),

T = age of the stand (a),

G = stand basal area (m²/ha),

D = basal area median diameter (cm),

H_{dom} = dominant height (m),

d = diameter (cm),

h = height (m),

e_3 = error term.

The main statistical parameters of the growth equations are

Equation	F-value (d.f.)	R^2, %	S_e	Unit	N
1	526 (1, 634)	45.3	0.3483	cm	636
2	406 (1, 634)	39.0	36.53	%	636
3	(not given)	71.9	0.3822	ln(%)	1404

2.3 Simulated model stands

Tree dimensions

Altogether 24 model stands were created for studying the effect of the spatial distribution of trees on the productivity of the stand. Firstly, two different tree populations were generated, and secondly, 12 different spatial processes were applied to both populations to obtain the x- and y-coordinates of trees. The diameter distributions of the two tree populations were defined by using the beta function as a theoretical distribution:

Population 1

$$f(d) = \begin{cases} 0 & \text{if } d<10 \\ (d-10)^{1.38}(12-d)^{1.38} & \text{if } 10 \le d \le 12 \\ 0 & \text{if } d>12 \end{cases} \quad (4)$$

Polulation 2

$$f(d) = \begin{cases} 0 & \text{if } d<9 \\ (d-9)^{1.31}(11-d)^{1.31} & \text{if } 9 \le d \le 11 \\ 0 & \text{if } d>11 \end{cases} \quad (5)$$

where $f(d)$ = relative frequency of diameter d,

d = diameter (cm).

The stand density in population 1 was 1000 trees/ha and 2000 trees/ha in population 2. The stand basal area with diameter distribution (4) and 1000 trees/ha was 10 m²/ha, and with distribution (5) and 2000 trees/ha 16 m²/ha. The corresponding stemwood volumes were 57 and 87 m³/ha, respectively. The stand age was taken as 45 years. With these parameters the model stands had such a diameter distribution that the models derived from the study material could be assumed to apply to them.

Trees for a forest stand plot of 60 m by 60 m were generated by sampling the above

distributions. The height of each tree was calculated by

$$\hat{h} = c_h(1.3 + d^2/(1.933 + 0.09073d)^2) \quad (6)$$

$$N = 278 \quad F=534 \ (1, 276) \quad R^2=65.8 \ \% \quad s_e=0.3102 \ m$$

where $\hat{h}$ = height (m),

c_h = correction factor to obtain a specified height estimate for average tree,

d = diameter (cm).

The correction factor (c_h) was 1.122 for population 1 (1000 trees/ha) and 1.117 for population 2 (2000 trees/ha). The model is based on diameter and height measurements on plots used for growth models (1) and (2) and on sample tree measurements on three other plots in young Scots pine stands.

Spatial distributions

The spatial processes used for producing the tree locations were as follows (Fig. 3):

(1) Grid of squares. The location of the first point is selected randomly. If there are more points than needed, the surplus is removed randomly.

(2) Grid of triangles of equal sides. Otherwise as process (1).

(3) As process (1) but a normally distributed random number is added to x- and y-coordinates. The standard deviation of the random number was 25 % of the average distance between the points in the direction of x- or y-axis.

(4) As process (1) but 33 % more points are produced than the number of trees, after which the surplus is removed randomly.

(5) Poisson process.

(6) Poisson process with the restriction that the distance between any two points must be at least 1 m (so-called hard cord is 1 m).

(7) Clustered process. Process (1) is used for producing the cluster midpoints. The distance of a point from the cluster midpoint is distributed uniformly between 0 and 6 m and the direction from cluster midpoint uniformly between 0 and 360°. The average number of points in a cluster is 10.

(8) Clustered process. Otherwise as process (7) but the maximum distance from the cluster midpoint is 5 m and there are 15 points per cluster on the average.

(9) Clustered process. The cluster midpoints are Pois-

son distributed. The distribution of the distance from the cluster midpoint is negatively exponential with parameter 3 m (average distance also 3 m). The direction from the cluster midpoint is distributed uniformly between 0 and 360°. The average number of trees per cluster is 15.

(10) Poisson process with the restriction that 2-m-wide empty strips must remain at 4-m intervals.

(11) Poisson process with the restriction that 4-m-wide empty strips must remain at 20-m intervals.

(12) Poisson process with the restrictions that 4-m-wide empty strips must remain at 20 m intervals and the distance between any two points must be at least 1 m.

The aim of using different spatial processes was to mimic the different spatial distributions occurring in real stands as well as to get extreme cases. For example, processes (1), (2) and (4) correspond to a very careful planting, process (4) with considerable mortality. Process (3) could be a less careful planting or planting on a difficult terrain. Processes (5) . . . (9) apply to naturally regenerated stands. Process (6) shows the situation after thinning, because of the minimum distance of 1 m between trees. Processes (10) . . . (12) produce spatial patterns corresponding to the situation after thinnings which rely on harvest strips.

Most of the generated spatial patterns have the angle sum distribution (AS of Eqns 1 and 2) within the range of variation of the empirical study material (Appendix 1). Only in very clustered processes part of the trees have the angle sum greater than the maximum value of the study material.

Volume increment

The 5-year diameter increment of the trees of model stands was predicted by using models (1) . . . (3). The height corresponding to the new diameter was estimated by Eqn (6). The present volume and that five years later were estimated by the equation of Laasasenaho (1982, his Eqn 61.3). The estimate of the volume increment was the difference in stand volume at two time points. Although the area of the model stand was 60 m by 60 m, the growth estimates were calculated only for the central part of 50 m by 50 m, because it was
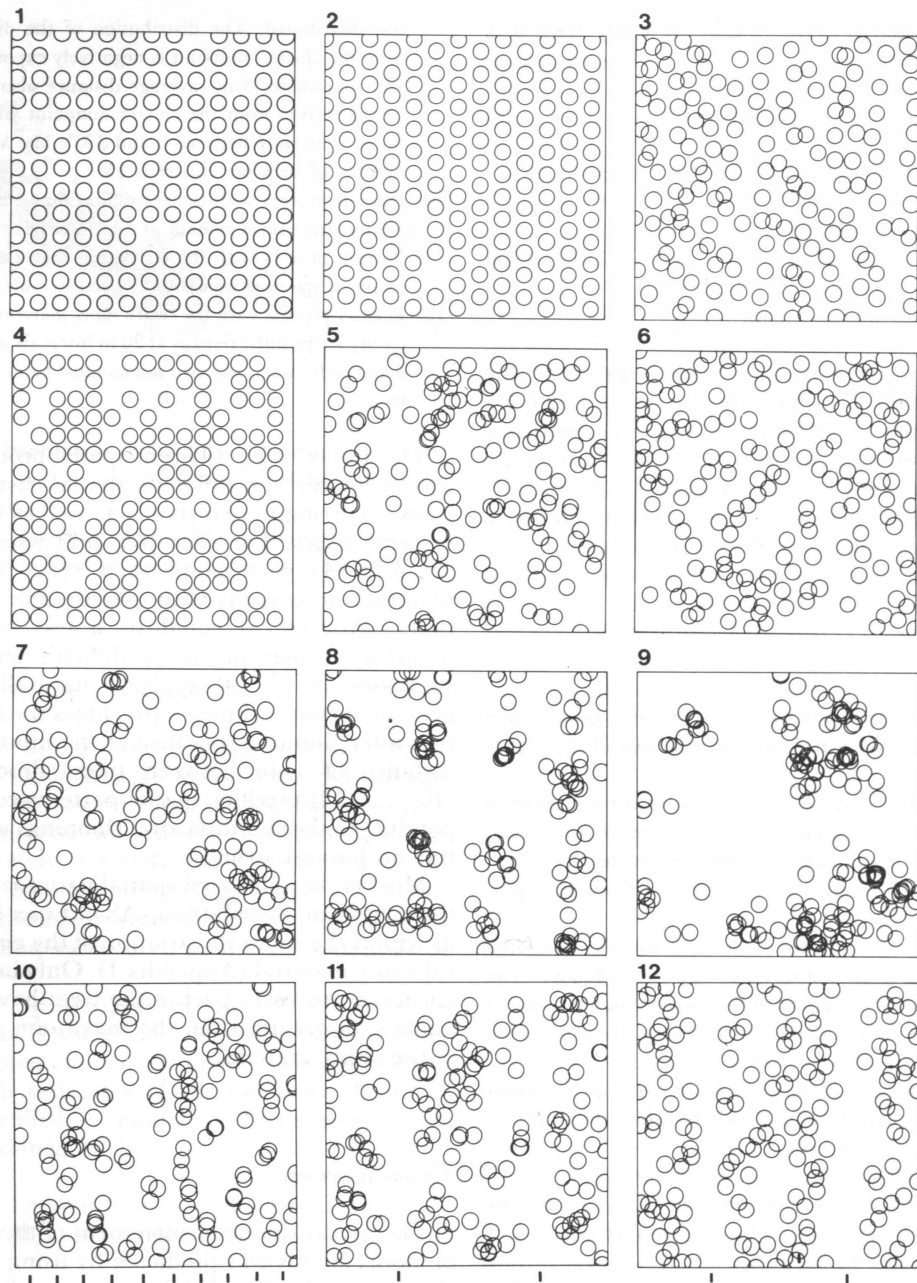
Fig. 3. Maps showing the horizontal crown projections of the 12 different spatial patterns of the model stands. The area of the map is 0.16 ha (in simulations it was 0.36 ha) and the stem number 1000 trees/ha. The diameter of the circle is directly proportional to the stem diameter at breast height. The numbers above the maps refer to the explanation of the spatial process in the text. The vertical bars show the locations of corridors.

Kuva 3. Mallimetsiköissä sovellettujen 12 erilaisen tilajärjestyksen latvuskartat. Kartalla on esitetty 0,16 ha:n kokoinen alue metsikköä, jonka runkoluku on 1000 puuta/ha (simuloinneissa alueen koko oli 0,36 ha). Ympyrän halkaisija on suoraan verrannollinen puun rinnankorkeusläpimittaan. Pienet pystyviivat osoittavat ajourien ym. käytävien sijainnin.

impossible to calculate the angle sum of Eqns (1) and (2) for trees nearer than 5 m from the plot edge.

Because the above spatial processes are mostly highly stochastic, three different realizations of each process were produced to get an idea of the sensitivity of the results to the realization of the spatial process.

One realization of each process was used to estimate the permanence of growth differences between spatial patterns. In these computations, the mean diameter increment was first calculated by using the estimates of Eqn (3), after which the deviation from the mean was estimated by Eqn (2). The estimated diameter increment was added to the present diameter, and the same calculations were repeated two more times. The results are the growth estimates for three successive 5-year periods. Because the growth estimate could not be calculated for trees on a 5 m wide buffer zone, the results for the first 5-year period are based on 50×50 m subarea, and on subareas of 40×40 m and 30×30 m for the two following periods.

2.4 Simulated thinnings

After regeneration the forest manager has very limited possibilities to affect stand productivity via spatial distribution of trees because he cannot very easily change the place of a tree. To study the effects of an individual thinning, two real stands were thinned (in computer memory only) using different rules concerning the location and size of the harvested trees.

The stands to which these rules were applied were two of the three plots of the study material used for growth models (1) and (2) (Fig. 4). In all thinnings about 33 % of the stand basal area was cropped (the exact removal percentage was found by applying the thinning rule (5) below). The remaining basal area was 11.9 m²/ha in stand 1 and 16.2 m²/ha in stand 2.

Six different thinnings were simulated according to the following rules, in addition to the rule of 33 % decrease in basal area (Fig. 5):

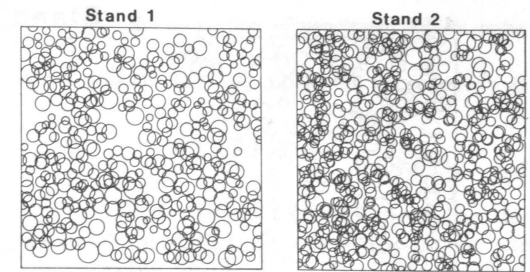(1) Removed trees are selected randomly.

Fig. 4. Crown maps before thinning of two Scots pine plots in which different thinnings were simulated. The plot size in stand 1 is 38 m × 38 m and in stand 2 38 × 40 m.

Kuva 4. Kahden männikköalan latvuskartat ennen simuloituja harvennuksia. Metsikössä 1 koealan koko on 38 m × 38 m ja metsikössä 2 38 × 40 m.

(2) The trees are ordered into ascending order according to diameter and the required basal area is removed starting from the smallest tree.

(3) From any pair of trees with distance less than 1 m the smaller one is removed, after which rule (2) is applied.

(4) Such a minimum distance between the remaining trees is sought that no other rules are needed for the required removal (1.44 m in stand 1 and 1.15 in stand 2).

(5) All trees are removed from parallel harvest strips of 2-m width located at 6-m intervals. This thinning determined the exact remaining basal area in all other thinnings.

(6) All trees are removed from 4 m wide harvest strips 20 m apart. Rule (4) is used between the harvest strips.

From Appendix 1 it is apparent that the spatial growth models derived from the study material apply to the thinned stands.

The thinning reaction depends on the manner in which the size distribution and spatial distribution of trees are affected by the treatment. To evaluate the effect of change in size distribution the growth after treatment was estimated by a non-spatial method using Eqn (3). The result is an estimate for such hypothetical situation that the spatial distribution of trees is affected similarly in all thinnings and only the size distribution is affected differently. Eqn (1) was used to estimate the combined effect of differences in spatial and size distributions.

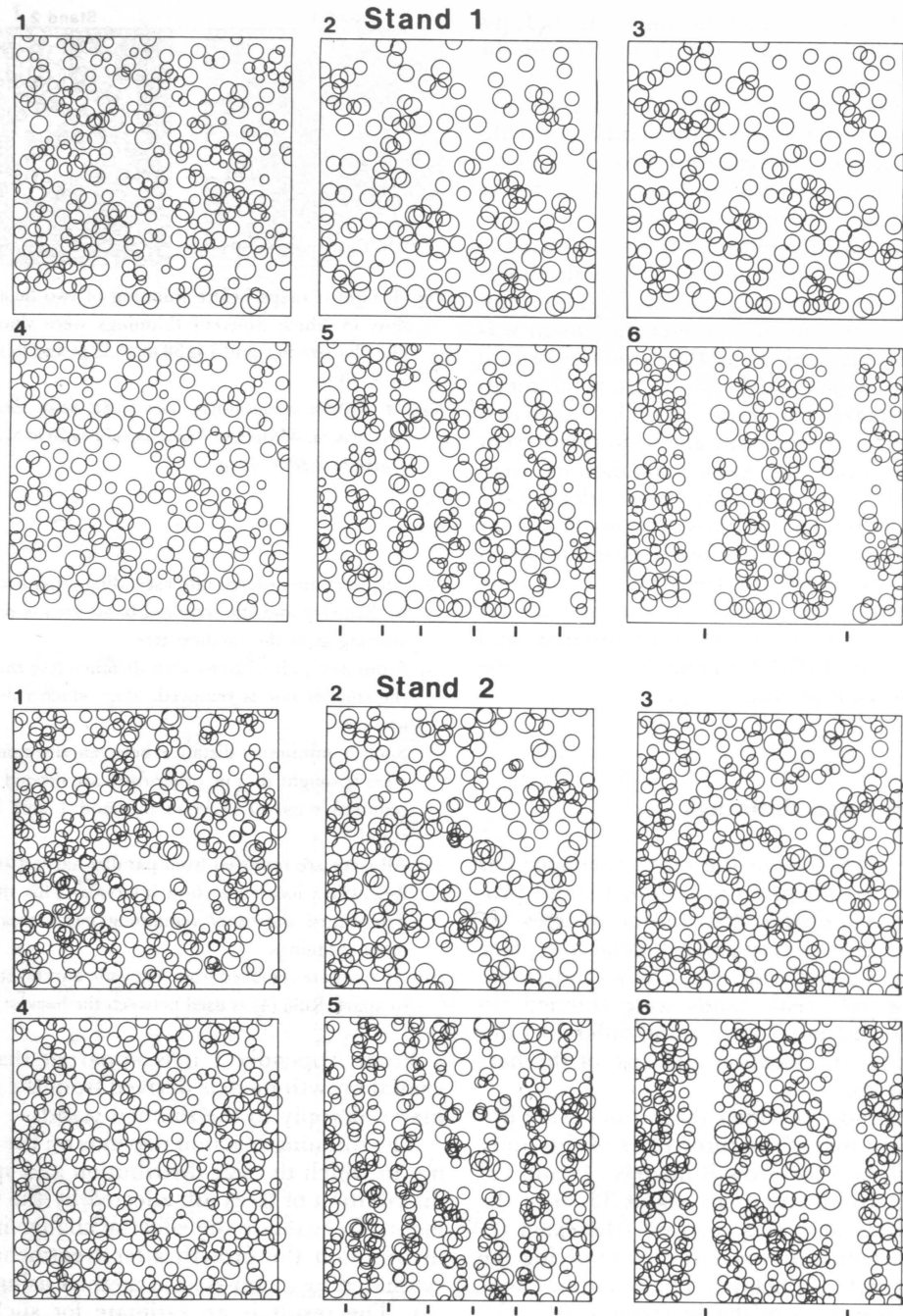The volume increment was estimated in

Fig. 5. Crown maps of the plots presented in Fig. 4 after 6 different simulated thinnings. In each simulation applied to one stand the basal area of the remaining trees is the same. The numbers refer to the explanation of the thinning method in the text. The vertical bars show the locations of corridors.

Kuva 5. Kuvassa 4 esitettyjen metsikkökoealojen latvuskartat kuuden erilaisen simuloidun harvennuksen jälkeen. Samalla koealalla jäävien puiden pohjapinta-ala on aina sama. Pienet pystyviivat osoittavat ajourien ym. käytävien sijainnin.

the same way as in model stands described in the previous Section, except that the height after 5 years was obtained by adding to the present height the difference of height estimates (Eqn (6), $c_h=1$) corresponding to the new and old diameter.

2.5 Measures of clustering

Grouping index

To describe the spatial distribution with one parameter the grouping index (GI) proposed by Fisher et al. (1922) was calculated for each distribution. This grouping index is the ratio between the variance of the stem number in a subarea of a certain size (a) and the average number of stems in that subarea:

$$GI(a) = s^2/\bar{m} \qquad (7)$$

where s^2 = variance of the number of trees,
$\bar{m}$ = average number of trees in the subarea.

For Poisson process the expected value of GI is 1, irrespective of the size of the subarea (Tomppo 1986). In other processes it depends on the size of the subarea (Cox 1971). Processes with GI less than 1 are often labelled as regular or repulsive and processes with GI greater than 1 as aggregated, grouped or clustered (Pohtila 1980, Tomppo 1986, Päivinen 1987).

The grouping index was calculated by using quadrates of two different sizes. In the first case the side of the square was 2.5 m and in the second case 5 m.

Interception

A more biological measure of grouping was obtained by estimating the interception of diffuse radiation for each stand. For this purpose, the model of Nilson (Hari et al. 1985) was used. According to his model, the penetration coefficient of diffuse radiation under standard overcast sky, when calculated at ground level, is

$$p_D = 6/7 \int_0^{1/2\pi} g(\varphi)(1+2\cos\varphi)\cos\varphi\sin\varphi d\varphi \qquad (8)$$

$(P_D=1$ if $g=1)$

where p_D = proportion of penetrated diffuse radiation,
$g(\varphi)$ = proportion of gaps in the canopy in direction φ,
φ = zenith angle.

The expression $(1+2\cos\varphi)$ gives the dependence of the brightness of the sky on the zenith angle (Anderson 1966). The proportion of gaps is

$$g(\varphi) = \exp(-\sum_{i=1}^{n}(s_i\mu V_iC)/\cos\varphi) \qquad (9)$$

where n = number of tree classes (here also number of trees on the plot),
s_i = number density of class i (trees/m²),
μ = extinction coefficient per unit length which the radiation passes inside tree crowns,
V_i = crown volume of a tree in class i (m³),
C = correction factor due to the grouping of trees.

Parameter μ was taken as 0.3 (Koppel and Oja 1984). This may not be quite the correct guess, but it does not affect the relative differences between spatial distributions.

The correction factor (C) is inversely proportional to the number of contacts between crowns, and is given by (Nilson, personal communication)

$$C = \ln(GI)/(GI-1) \qquad (10)$$

where GI is Fisher's grouping index calculated by using the average crown projection area of the tree crown on the horizontal plane at sun elevation 45° as the size of the subarea. When calculating the crown volume (Eqn 9) and average projection area of the crown (Eqn 10), the crown was assumed as a cone determined by tree height, the height of the crown base and maximal width of the crown. The height of the crown base and the crown width were estimated by models of Pukkala and Kolström (1987, their Eqns 2 and 3).

Though the previous method gives only an estimate of the interception of diffuse radiation, it can be supposed to express relative differences in total interception as well, because the interception of direct and diffuse radiation are closely correlated (Pukkala and Kuuluvainen 1986).

3. Results

3.1 Growth effect of spatial pattern of trees

The 5-year growth estimate based on Eqn (1) is about 25 m³/ha for model stands with 1000 trees/ha and 35 m³/ha with 2000 trees/ha (Fig. 6). There is considerable variation between spatial distributions (Fig. 6). Processes (1) . . . (6) have the estimated volume increment near to each other. For Poisson forest (Process 5) and for systematic process with 33 % mortality (process 3) the growth estimate is only a few percent or not at all lower than for strictly regular processes. Poisson process with one meter hard cord (process 6) appears to be as good as the systematic processes.

The clustered processes (7) . . . (9) have clearly lower growth predictions than processes (1) . . . (6), especially the highly aggregated process (9) where there are large areas without any trees (Fig. 3, Fig. 6). The estimated volume increment is about 20 % lower than the highest estimates. The harvest strips in Poisson forest decrease the growth prediction approximately by 10 %. Fig. 6 shows that the decrease in growth is the smaller the more regular the distribution between the corridors. Also it is clear that wide corridors cause greater growth reduction than narrow ones, although the model stands do not reveal it. The results seem to be rather insensitive to the realization of the process: different realizations give almost the same result.

It could be argued that differences between spatial distributions tend to disappear with time, because trees having most growing space will enlarge so that at last the growth resources become fully used in all spatial patterns. According to simulations made for three successive 5-year periods using Eqns (2) and (3), growth differences between spatial distributions seem, however, rather permanent (Fig. 7). Only with 1000 trees/ha there is in some patterns (4, 5, 10, 11, 12) a tendency for the differences to disappear. The constance of the growth estimates may partly be due to the fact that while the growth of some trees of a irregular stand is good, the

competition due to the growth of trees increases most in dense groups, and this compensates for the better growth of some trees.

When comparing the results presented in Figs. 6 and 7, it is apparent that relative differences in volume increment are not sensitive to the manner in which the growth esti-
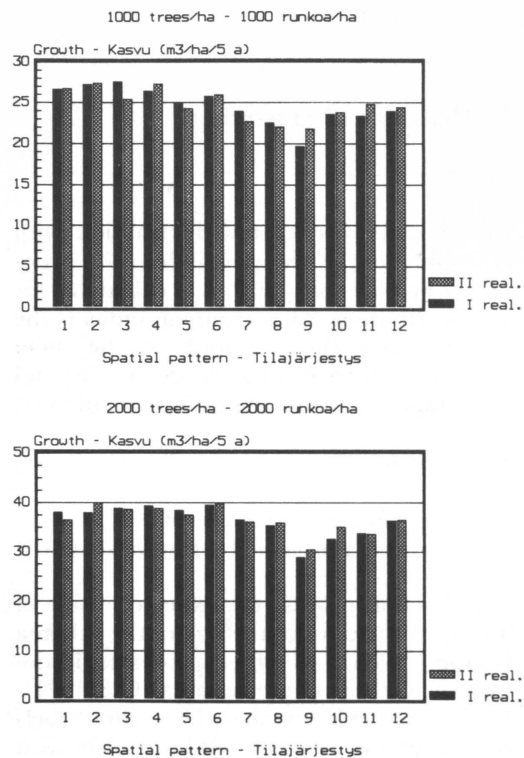

Fig. 6. The predicted volume increment in 24 different model stands. For each stocking and spatial process the results of two realizations of the spatial process are shown (I real. and II real.). The results are based on estimates of diameter increment calculated by Eqn (1).

Kuva 6. Ennustettu tilavuuskasvu 24 erilaisessa mallimetsikössä. Tulokset on esitetty kahdelle eri realisaatiolle jokaisesta spatiaalisesta prosessista (I real. ja II real.). Kasvuennusteet perustuvat yhtälöllä (1) laskettuihin läpimitan kasvun estimaatteihin.
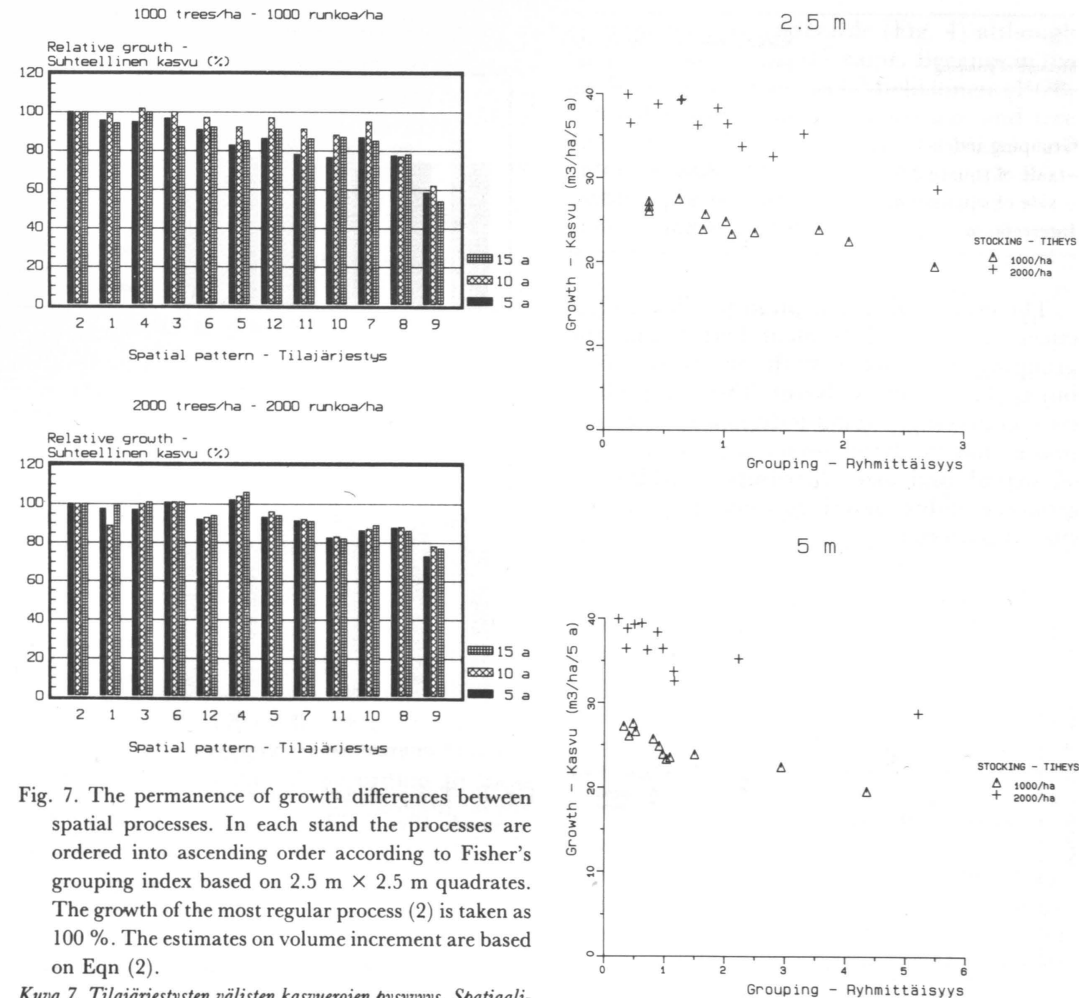

Fig. 7. The permanence of growth differences between spatial processes. In each stand the processes are ordered into ascending order according to Fisher's grouping index based on 2.5 m × 2.5 m quadrates. The growth of the most regular process (2) is taken as 100 %. The estimates on volume increment are based on Eqn (2).

Kuva 7. Tilajärjestysten välisten kasvuerojen pysyvyys. Spatiaaliset prosessit on järjestetty Fisherin ryhmittymisindeksin perusteella nousevaan järjestykseen. Ryhmittymisindeksi perustuu 2,5 × 2,5 m²:n osa-alueisiin. Säännöllisimmän tilajärjestyksen (prosessi 2) kasvua on merkitty luvulla 100. Kasvuennusteet perustuvat yhtälöön (2).

mate is obtained. In both methods (Eqn 1 versus Eqns 2 and 3) the same spatial patterns have the lowest growth prediction. Surprisingly, the effect of spatial distribution is as great for 1000 trees/ha as for 2000 trees/ha. This is because the average competition is higher in denser stands and the dependence of the basal area increment on competition as described by the angle sum is of a convex type. It is clear, however, that if the stocking

Fig. 8. The correlation between the grouping index and volume increment of model stands with two different sizes of the quadrate used for calculating the grouping index (side length 2.5 or 5 m).

Kuva 8. Ryhmittymisindeksin ja kasvun välinen korrelaatio mallimetsiköissä. Ryhmittymisindeksi on laskettu kahta erilaista osa-aluetta käyttäen (neliön sivun pituus 2,5 tai 5 m).

is sufficiently low, growth differences between the spatial processes will disappear.

The growth estimate of Eqn 2 correlates rather well with the grouping index when different stockings are surveyed separately (Fig. 8). There are no clear differences between the two sizes of subareas used in the calculation of competition index:

Measure of grouping	Stocking (trees/ha)		All stands
	1000	2000	combined
	Correlation coefficient		
Grouping index			
– side of square 2.5 m	−0.907	−0.864	−0.434
– side of square 5 m	−0.893	−0.823	−0.328
Interception	0.807	0.826	0.698

The estimated interception predicts differences in volume increment better than the grouping index when both stands are combined (Fig. 9, setup above). The main difference between grouping indices and interception is that the latter predicts the joint effect of spatial and size distribution, while the grouping index describes only the effect of spatial pattern.
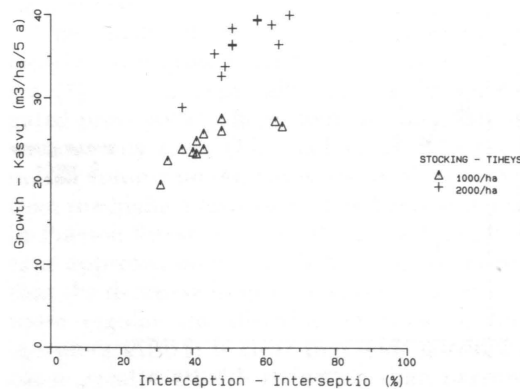
Fig. 9. The correlation between estimated interception and estimated volume increment of model stands.
Kuva 9. Mallimetsiköille ennustetun hajasäteilyn interseption ja kasvun välinen korrelaatio.

3.2 Growth effect of thinning method

The estimates on volume increment calculated by the spatial growth model (Eqn 1) are of the same magnitude for all thinning methods except for the method which uses 4-m-wide harvest strips (Fig. 10). In this spatial pattern of the remaining trees the estimate is 10 . . . 20 % lower than in other patterns.

According to the simulations, a systematic harvest from 2 m wide corridors (method 2) does not decrease the volume production of a young pine stand when compared to selective thinnings, which e.g. method 3 mimics. In a fully-stocked stand, where the diameter of trees is around 10 cm and which grows on a rather poor site, the critical width of the harvest strip appears to be less than 4 m. The effect of harvest strips would obviously be smaller if the stocking were lower or the trees bigger.

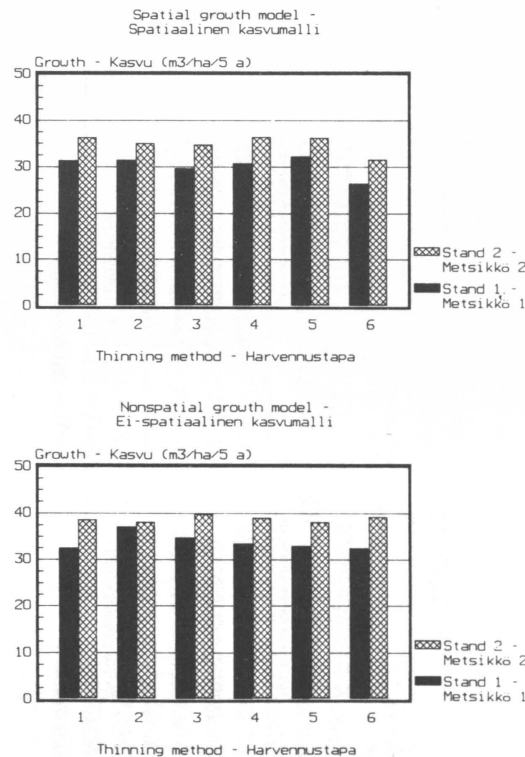The fact that the spatial patterns resulting from thinnings (1) . . . (5) lead to almost

Fig. 10. The predicted volume increment of two forest stands after 6 different simulated thinnings. The results are based on estimates of diameter increment calculated by distance-dependent growth model (above) and distance-independent growth model (below) (Eqns 1 and 3).
Kuva 10. Kahden männikkökoealan ennustettu tilavuuskasvu kuuden erilaisen simuloidun harvennuksen jälkeen. Ennusteet perustuvat spatiaalisella (yläkuva) ja ei-spatiaalisella (alakuva) kasvumallilla laskettuihin läpimitan kasvuihin (yhtälöt 1 ja 3).

equal growth estimates indicates that the only thing that should be avoided in the thinning of a reasonably even young pine stand is big gaps. The cropped trees can be chosen randomly, systematically according to location or diameter, or by putting weight on the distance between trees. This can, of course, be realized only if also the smallest trees are healthy and have good crowns, as was the situation in the study material. Different thinning methods create, however, differences in the proportions of timber assortments, in the quality of trees and in the future differentiation of tree size.

As expected, the effect of harvesting all trees from 4-m-wide corridors cannot be seen in the growth estimates of a distance-independent growth model (Fig. 10). It is noteworthy that in stand 1 the predicted volume increment based on Eqn 3 is clearly the best for the thinning method where the smallest trees were removed irrespective of their location (method 2). In stand 1 the variation
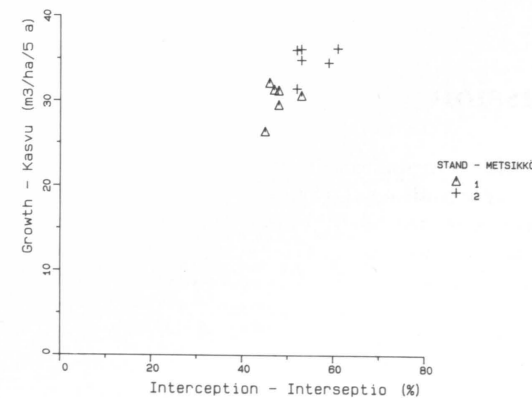
Fig. 11. The correlation between estimated interception and estimated volume increment of two forest stand plots thinned by using 6 different methods.
Kuva 11. Eri tavoin harvennettujen koealojen ennustetun hajasäteilyn interseption ja kasvun välinen korrelaatio.

in diameter is considerable (Fig. 4) although the age of all trees is the same. Because in the model of Nyyssönen and Mielikäinen (1978) the site affects growth only via age and tree dimensions, higher growth estimates are automatically obtained by leaving the best-growing (i.e. biggest) trees on the site.

In stand 1, however, big and small trees tend to occur in separate groups (Fig. 4), which means that the strict thinning from below leads to a more grouped spatial pattern than if also the location of tree affects the selection (the grouping index increases most in method 2, from 0.62 to 0.86). Because the distance-dependent growth model takes the clustering of trees into account, the predicted volume increment based on Eqn 1 is not higher for thinning method 2 than for methods 1, 3, 4, and 5 (Fig. 10).

The correlations between the different measures of grouping and the predicted volume increment are not as good as in the model stands discussed in the previous section:

Measure of grouping	Stand 1	Stand 2	Both stands combined
	Correlation coefficient		
Grouping index			
– side of square 2.5 m	−0.334	−0.470	−0.413
– side of square 5 m	−0.522	−0.763	−0.624
Interception	0.302	0.310	0.718

The grouping index calculated in subareas of 5×5 m predicts the volume increment best. The rather low correlation between the grouping index and growth is due to a small variation in the spatial pattern of trees. The correlation between interception and the growth estimate is far from complete (Fig. 11). The reason may be that the dependence of growth on interception is nonlinear or that the dependence of crown volume on tree size was not estimated correctly.

4. Discussion

The computations showed that small irregularities do not decrease the volume production of a young Scots pine stand. In irregular stands the decrease in production is typically 10 . . . 20 %. About the same loss due to a remarkable clustering of trees have been found in Norway spruce and birch stands (Braathe 1952, Lundell 1973).

Apparently there is some limit which the size of a gap must exceed to make trees unable to utilize all the recources of the site. Presumably there also exists a limit for the size of a dense area before the grouping begins to decrease growth. If there are only a few trees in the group, each of them has a growing space at least on one side. The limit of the size of an effective gap or cluster depends on the size of the trees: the smaller the trees the sooner the gaps begin to decrease growth. The opposite is probably true with clusters: their effect is greatest if the trees are big. It can be concluded that the shortest dimension of a cluster or gap is decisive: a narrow and long shape is less dangerous than circular.

Fisher's grouping index predicted growth differences between the spatial distributions reasonably well. The selection of the size of the quadrate is a problem connected with the use of Fisher's grouping index, because it is obvious that the optimal size of a subarea depends on stand density, diameter distribution, tree species, site fertility, etc. Fisher's grouping index, as most other indices, has the property that the expected value of the index depends on the size of the quadrate. This means that a particular spatial process may appear as regular with one quadrate size and clustered with another size (Cox 1971, Pohtila 1980).

Ficher's grouping index indicates the variation in stand density and in the use of growth resources between quadrates. The index does not take into account the surroundings of the quadrate, although it is clear that there are more unused resources in a quadrate of a given density when it occurs in a sparely stocked region rather than in dense surroundings.

It is apparent that the more there are sparse and dense regions, the more clustering reduces growth. The problem is how to define sparse and dense areas so that the definition reflects the availability of growth resources. Owing to the shortcomings of the grouping index and the probable mechanisms of the effect of spatial distribution on growth, the method of Cox (1978) for finding and mapping the dense and sparse areas of a tree stand seems interesting. The method applies to all stand densities and has the property that a certain subarea alone does not determine whether a point lies in a sparse, average or dense area.

Because the spatial distribution of trees affects stand productivity through the use of growth resources, parameters that predict directly the efficiency of the use of radiation energy, nutrients and water should be good measures of grouping. In addition, they do not, as the methods based on tree coordinates only, omit the size variation of trees. In this study the interception of diffuse solar radiation did not account for the effect of spatial pattern any better than the grouping indices. One reason for this might be error in the model. More inportant, however, could be that the interception does not reflect well enough the efficiency of the use of other resources than radiation energy.

When a good parameter for predicting the effect of clustering on growth has been found, there remains the problem of how to estimate it without mapping the stand. One possibility is to predict it with the help of stand and site characteristics. Another possibility is to use methods based on the distances from random points to the nearest tree, second nearest tree, etc. (Cox 1971, Pohtila 1977, 1980). The relative interception can be measured directly in the field, and be compared with some standard value of the corresponding diameter distribution.

When estimating the growth of a thinned stand it was assumed that the remaining trees can use the additional growing space immediately. In reality the tree improves its growth only gradually, at the beginning the effect of removing a neighbor could be even negative. If it were so, the results would overestimate the effect of thinning on the next five year's growth. However, the results of Erikson (1976) and Mielikäinen (1978) indicate that a young pine reacts rather quickly to thinning; the positive effect of a removed neighbor is equal to the negative effect of a remaining neighbor of same size during the 5-year period following thinning. Also Bucht (1981) found that the competition after thinning predicted the diameter increment well, though variables describing the change in competition were also useful. The height increment was best explained by the competition before thinning.

In this study the effect of systematic thinning with 4-m-wide corridors at 6-m intervals led to 10 . . . 20 % smaller estimates on volume increment for the coming 5-year period than methods where the removed trees were distributed evenly over the area. The reduction due to harvest strips was greater than in Bucht's (1981) investigation where it was 8.4 %, but his calculations covered a period of 9 years. Also in Erikson's (1977) simulations systematic thinning with corridors gave smaller growth estimates than selective thinning if the number of remaining trees was the same, but not if the remaining volume was constant.

The omission of one-sided competition in the study may be one reason for the poor growth estimates for thinnings based on reasonably wide harvest strips. Also the growth of the edge trees of tree groups may have been underestimated. In Bucht's (1981) study the growth response was better if the neighbors were removed from one side of the tree instead of harvesting from all sides. On the other hand, Erikson (1976) found that distance-dependent models which did not take into account one-sided competition gave as good estimates near the harvest strips as elsewhere on the plot.

The growth estimates of this study are based on the central part of the plot which may not always have the same density, diameter distribution and spatial properties as the whole plot. In the results this is reflected as stochastic variation or bias which are greatest in the most irregular spatial processes.

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Total of 25 references

Appendix 1. Grouping index, relative interception and the distribution of angle sum (AS) in the study material and in some simulated stands and thinnings (see text for explanation for spatial pattern and thinning rule).

Liite 1. Ryhmittymisindeksi, hajasäteilyn pidätysosuus ja kulmasumman (AS) jakauma tutkimusaineistossa sekä eräissä simuloiduissa metsiköissä ja harvennustavoissa (simuloitujen metsiköiden tilajärjestys ja harvennusohjeet selostettu tekstissä).

Parameter / Parametri	Study material / Tutkimusaineisto			Simulated stands / Simuloidut metsiköt				Simulated thinnings / Simuloidut hakkuut			
				Trees/ha – Puita/ha				Stand – Metsikkö			
				1000		2000		1		2	
	Stand – Metsikkö			Pattern – Tilajärj.				Rule – Harv. ohje			
	1	2	3	2	9	2	9	4	6	4	6
Measures of grouping – Ryhmittyneisyyden tunnusluvut											
Ficher/2.5	0.62	0.72	1.09	0.38	2.60	0.24	2.74	0.50	0.87	0.48	0.93
Fisher/5	0.58	0.81	1.65	0.34	4.56	0.31	4.98	0.49	0.90	0.45	1.25
Intercept.	0.52	0.60	0.49	0.55	0.20	0.60	0.28	0.45	0.35	0.54	0.43
Agle sum (AS, radian) – Kulmasumma (AS, radiaania)											
Minimum – Minimi	0	0	0	0	0	·0	0	0	0	0	0
Mean – Keskiarvo	0.39	0.54	0.36	0.10	0.48	0.26	0.71	0.21	0.29	0.27	0.34
Maximum – Maksimi	1.09	1.16	1.49	0.21	2.89	0.53	2.99	0.52	0.65	0.60	0.88
Frequency distribution of AS (%) – AS:n frekvenssijakauma (%)											
AS<0.2	24	17	34	97	41	38	22	46	34	36	27
0.2≤AS<0.4	24	18	28	3	15	38	17	50	36	40	35
0.4≤AS<0.6	34	22	16	0	13	24	14	4	28	24	26
0.6≤AS<0.8	15	20	13	0	10	0	11	0	2	0	11
0.8≤AS<1.0	3	16	5	0	8	0	9	0	0	0	1
1.0≤AS<1.2	0	4	3	0	6	0	6	0	0	0	0
AS<1.2	0	3	1	0	7	0	21	0	0	0	0

Fisher/2.5 = Fisher's grouping index with 2.5 m × 2.5 m quadrate size
        Fisherin ryhmittymisindeksi, kun neliön sivu on 2.5 m
Fisher/5 = Fisher's grouping index with 5 m × 5 m quadrate size
        Fisherin ryhmittymisindeksi, kun neliön sivu on 5 m
Intercept. = Relative interception of diffuse radiation
        Hajasäteilyn pidätysosuus