Thinning Response and Thinning Bias in a Young Scots Pine Stand

Timo Pukkala, Jari Miina and Marc Palahí

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The study analyses the annual post-thinning response and thinning bias of a young Scots pine stand as a function of tree size, competition faced by the tree, and competition that is removed around the tree in the thinning treatment. The *thinning response* of a tree was defined as the change of tree growth due to a thinning treatment. The *thinning bias* was defined as the difference between the true growth and model prediction. A distance-dependent (spatial) and a distance-independent (non-spatial) growth model were used in the calculations. The empirical data were measured from a thinning experiment consisting of ten plots, each 40 × 30 m in size, which were thinned to different stand densities. The ten-year post-thinning growth of every remaining tree was measured. The results indicated that the highest thinning response is among medium-sized and co-dominant trees. The thinning response is quite small, and even negative for some trees, for two years after thinning but it becomes clearly positive from the third year onwards. The spatial model underestimated the growth of small trees (which usually face high competition) while the non-spatial model overestimated the growth of trees that are small or face much competition. The spatial model used in this study overemphasized the effect of competition while the non-spatial model underestimated this effect. Both growth models overestimated the growth of trees in heavily thinned places, but this bias disappeared in two years. The negative bias was more pronounced with a spatial growth model because the tendency of the non-spatial model to underestimate the growth of trees facing little competition partly compensated for the negative bias.

Keywords growth model, non-spatial model, spatial model, *Pinus sylvestris*
Authors´ addresses Pukkala: University of Joensuu, Faculty of Forestry, P.O. Box 111, FIN-80101 Joensuu, Finland; Miina: Finnish Forest Research Institute, Joensuu Research Centre, P.O. Box 68, FIN-80101 Joensuu, Finland; Palahí: European Forest Institute, Torikatu 34, FIN-80100 Joensuu, Finland
E-mail timo.pukkala@joensuu.fi, jari.miina@metla.fi, marc.palahi@efi.fi
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1 Introduction

The *thinning response* of a tree may be defined as the change of tree growth due to a thinning treatment (Jonsson 1995, Pukkala et al. 1998). It is of great importance in silviculture and forest management planning when aiming at maximising wood production. The thinning response can be assessed through empirical thinning experiments or, more commonly, by using growth models and computer simulation (e.g. Hasenauer et al. 1997, Cescatti and Piutti 1998, Pukkala and Miina 1998, Hanewinkel and Pretzsch 2000, Valkonen and Valsta 2001). Modern forest planning systems use stand-level simulation to predict the consequences of thinnings and other management options. These simulations are then used in a forest level optimisation to find such a treatment for every stand which best satisfies the forest level goals and constraints (e.g. Lundström and Söderberg 1996, Siitonen and Nuutinen 1996).

Since Roise (1986a,b) linked nonlinear programming with individual-tree growth models stand-level management instructions have increasingly been developed with a combined use of stand-level simulation and stand-level optimisation (e.g. Haight and Monserud 1990, Gove and Fairweather 1992, Valsta 1992, Pukkala and Miina 1997, Wikström and Eriksson 2000). The purpose of these optimisations is to find such a combination of cuttings and other treatments which maximises a specified objective function, for instance, soil expectation value or mean annual timber production.

One key question in the use of stand-level simulation in the optimisation of stand management is whether the growth models used in the simulation are able to predict the thinning response correctly. If the predictions are biased, management plans prepared by modern system are also biased, and stand level management instructions based on simulation and optimisation may give erroneous silvicultural recommendations.

Most growth models employ tree diameter, stand basal area and stand age, among others, to predict growth but very few models use the time, type and intensity of thinning. The effect of thinning is indirectly accommodated in the models via its effect on the stand basal area and other predictors. The assumption made here is that a tree in a recently thinned stand will grow exactly as much as a similar tree in otherwise similar conditions but without a recent thinning. However, some studies indicate that this assumption may lead to biased growth predictions in a recently thinned stand (Courbaud 2000). Some researchers have developed growth models which explicitly use thinning parameters as predictors (Saramäki 1992, Hynynen 1995, Jonsson 1995). Others use crown variables (e.g. crown length) as additional predictors with the purpose to improve the model's ability to describe the effects of thinnings (Mielikäinen 1985, Wykoff 1990, Hynynen 1995, Sterba and Monserud 1997, Vettenranta 1999).

When thinning parameters are not used as model predictors it is necessary to analyse the model's performance in thinned stands. An important performance criterion in this analysis is the difference between the true growth of a thinned stand and the model prediction. This difference has earlier been called *thinning reduction* (Pukkala et al. 1998). In this article, the difference between the true growth and model prediction is called *thinning bias*. If a tree experiences stress immediately after a thinning, due to an abrupt change in growing conditions, the thinning bias may be negative, i.e. the tree grows less than the model predicts. A negative bias means that although the total thinning response, which is a sum of positive effects (increased growing space) and negative effects (stress), may be positive the tree grows less than another, similar one (with the same values of model predictors), but which is not growing in a recently thinned stand.

The thinning response and thinning bias in young Scots pine stands have been investigated by e.g. Pukkala et al. (1998). Peltola et al. (2002) studied the thinning response of trees in a young Scots pine stand. Pukkala et al. found that the thinning response of trees correlated positively with the harvested competition and negatively with the retained competition. However, variables describing removal were not useful model predictors in distance-dependent individual-tree growth models; the models based on the retained competition were equally good as models including removal as an additional predictor.

The results of Pukkala et al. (1998) indicate that the thinning bias is zero, i.e. trees of a recently thinned stand grow in the same way as trees in an equally dense unthinned stand. However, there are shortcomings in the study of Pukkala et al. (1998). The first source of problems is the climate-induced growth variation, which must be eliminated from the measured growth before calculating the thinning response. Pukkala et al. (1998) used such a technique to correct for climatic variation, which may remove part of the thinning response from the growth observations. In addition, the model to which the observed growth was compared was estimated from the thinning experiment data. Therefore, the conclusion that there is no significant thinning bias may not be valid for a more general model or for a model which is estimated from independent data. Pukkala et al. investigated the thinning bias of a distance-dependent growth model, although practical forest management relies on distance-independent models. Moreover, Pukkala et al. (1998) analysed only the first 5-year period following the thinning treatment, although the effect of thinning may extend beyond 5 years.

This study aimed at analysing the thinning response and bias in a young Scots pine stand using a modelling approach. The observed growths were compared to a distance-dependent and a distance-independent model estimated from independent materials (Nyyssönen and Mielikäinen 1978, Miina and Pukkala 2000). The thinning response and thinning bias calculated with the models were examined as a function of tree diameter, competition by other trees, and the quantity of competition removed in thinning. The data were measured from the same Scots pine stand as in Pukkala et al. (1998), but by using a longer post-thinning follow-up period. The climatic growth variation was corrected by using a better method than in the previous study.

2 Material and Methods

2.1 Sample Plots and Measurements

The empirical data were measured from a thinning experiment consisting of ten plots, each 40×30 m in size, which were thinned to different stand densities (Table 1). Each plot was surrounded by a 10 m wide buffer zone thinned to the same density as the main plot. The experiment was designed to have a variety of thinning intensities.

The experiment is located in a naturally regenerated stand of Scots pine close to the Mekrijärvi Research Station, in North Karelia, Finland (62º47' N, 30º58' E, 145 m a.s.l.). The site corresponds to a site rather poor in nutrients (*Vaccinium* site type), a typical Scots pine habitat. The mean breast height age of the stand was 22 years at the time of thinning.

The plots were thinned between the growing seasons of 1986 and 1987. The stand basal area at the time of thinning varied between 20 and 25 m^2 ha^{-1}, with the exception that Plot 3 had

Table 1. Stand characteristics of plots after thinning in 1986/87 and in 1997. N = number of stems per ha, G_{before} and G = stand basal area before and after thinning, respectively, D = mean diameter at breast height, H = mean height, T = mean breast height age, and g = weighted by tree basal area.

Plot	After thinning in 1986/87						in 1997		
	N, ha^{-1}	G_{before} m^2ha^{-1}	G, m^2ha^{-1}	D_g, cm	H_g, m	T_g, yrs	G, m^2ha^{-1}	D_g, cm	H_g, m
1	3400	25.1	22.9	10.2	9.8	21.5	32.4	13.2	13.4
2	3683	22.2	22.2	10.7	9.6	20.2	27.8	13.0	13.0
3	575	13.2	5.1	10.9	9.0	21.5	11.3	16.3	11.9
4	1200	20.6	11.3	11.5	9.9	23.0	19.7	15.3	13.0
5	2383	20.2	16.4	10.0	9.2	22.5	25.4	12.8	12.7
6	1492	20.1	12.7	11.0	9.6	23.2	21.2	14.1	12.9
7	850	22.4	8.3	11.5	10.2	21.9	15.7	15.9	13.2
8	1800	21.7	14.5	10.9	9.5	22.4	23.6	14.0	13.4
9	2942	23.2	19.4	10.0	9.6	21.1	28.6	12.7	13.1
10	2083	23.9	17.3	11.0	10.4	22.7	27.0	14.0	14.1

a basal area of only 13.2 m^2 ha^{-1}. The thinning treatments were randomised, but it happened that the plot with the lowest basal area (Plot 3) was also thinned to the lowest retention-stand basal area (5.1 m^2 ha^{-1}). The plots were low-thinned and some dominant trees of poor quality were also removed.

The trees were measured prior to thinning by coordinates and breast height diameter, after which the retained trees were marked and numbered. Every tenth retention tree was measured by height and bored to the pith in order to determine its breast height age. Height and age measurements were used to compute plotwise models for tree height and age using breast height diameter as the only predictor. These models were used to compute tree height and age for the non-sample-trees.

A total of 135 trees of different sizes (dbh from 4.2 cm to 17.5 cm) and in different parts of the experiment were measured for the thickness of their bark. The following mixed linear model was estimated from the sample tree measurements to compute the double bark thickness in later calculations:

$$2b_{kj} = 12.64 + 1.30d_{kj} + u_k + e_{kj} \tag{1}$$

where $2b_{kj}$ is the double bark thickness of tree j on plot k (mm), d_{kj} is the tree diameter at breast height of tree j on plot k (cm), u_k is a random plot effect u_k~Nid(0,σ_{pl}^2), and e_{kj} is a random tree effect e_{kj}~Nid(0,σ_{tr}^2). The variance components σ_{pl}^2 and σ_{tr}^2 are 251.56 and 15.29, respectively. The parameters of the model were estimated using the maximum likelihood procedure of the computer software PROC MIXED in SAS/STAT (SAS Institute Inc. 1992).

An increment core was taken from every retention tree 10 years after thinning. The radial growth for the past 15 growing seasons (1983–1997) was measured from the increment cores with a microscope. The underbark diameters at the beginning of each year from 1983 to 1997 were computed using the overbark diameters measured in 1986/1987, the bark thickness model (Equation 1), and the growth measurements.

The following competition index was computed for every tree (see Fig. 1):

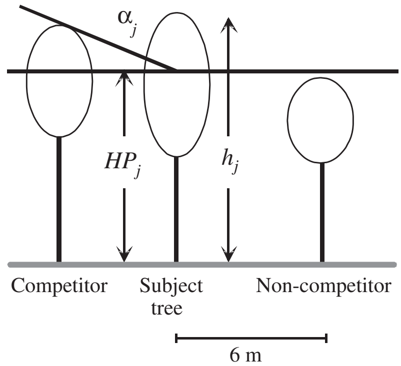

Fig. 1. The principle used for computing the competition index *CI* (Equations 2 and 6) for subject tree j. h_j is tree height, $HP_j = 0.65 + 0.78\ h_j$ is the height of the horizontal plane and *CI* is the sum of vertical angles α_j.

$$CI_j = \sum_{i=1}^{n_j} \alpha(h_j)_{ij} \tag{2}$$

where CI_j is competition index for tree j (rad), n_j is the number of neighbours nearer than 6 m and taller than a given horizontal plane, and α_{ij} is a vertical angle defined by the predicted height of the subject tree j and the competitor i and the distance between the two trees. The height of the horizontal plane HP_j (m) used to define the competitors and to calculate angle α is related to the predicted height of the subject tree h_j (Miina and Pukkala 2000):

$$HP_j = 0.65 + 0.78h_j \tag{3}$$

This is the same competition index which was used in the growth model (*CIp* and *CIs* in Equation 6) to which the observed growths were compared (Miina and Pukkala 2000). The competition index was calculated separately for the retained (CI_R) and harvested competition (CI_H). The retained competition describes the amount of competition that the tree faces immediately after the thinning.

The trees of the experiments varied a lot in their size, post-thinning competition and the amount of competition removed around the tree (Table 2). This is due to the fact that the study material consisted of plots ranging from unthinned stands

Table 2. Range, mean and standard deviation of tree diameter (*dbh*), retained competition (CI_R), harvested competition (CI_H), and the first ($id_{1–5}$) and second ($id_{6–10}$) 5-year post-thinning diameter growth among a total of 1870 retained trees on the thinned plots.

Variable	Minimum	Mean	Maximum	Std.
dbh, cm	4.40	9.66	14.90	2.26
CI_R, rad	0.58	11.27	37.71	6.36
CI_H, rad	0.00	2.63	18.76	2.28
$id_{1–5}$, cm/5 a	0.09	1.14	3.92	0.59
$id_{6–10}$, cm/5 a	0.07	0.94	4.97	0.56

to very heavily thinned plots. The total number of observations (pine trees left to continue growing and alive ten years after thinning) was 2196 of which 326 trees were growing on the unthinned plot and 1870 trees on the thinned plots.

2.2 Correcting for Climatic Variation

The annual growths were corrected to correspond to normal or average climatic conditions. The correction for climatic variation was done using growth indices. Because there were no growth indices for Scots pine valid for the study area and covering the years needed for this study, the growth index series was estimated using the data from the unthinned plot. The data consisted of 4940 growth observations for 330 pine trees during the period 1983–1997.

A mixed linear model (e.g. Searle 1987) was developed to estimate the index series for the annual diameter growth. The method was presented by Henttonen (1990) and applied later by e.g. Ryan et al. (1994), Piutti and Cescatti (1999) and Miina (2000). In the method, the fixed part of the linear model was used to remove the non-climatic growth trend from the data, i.e. the effect of changes in tree (diameter) and stand (basal area) characteristics. Due to hierarchical structure of the data the residual variation was divided into between-year, between-tree and within-tree effects. Furthermore, the within-tree error terms were assumed to arise from the first-order autoregressive process.

The mixed linear model was as follows:

$$\ln(id_{jt}) = 6.0441 + 0.1258d_{jt} - 0.1541G_t + u_t + u_j + v_{jt} \qquad (4)$$

where $\ln(id_{jt})$ is the logarithmic increment in underbark diameter of tree j in year t (1/100 mm), d_{jt} is the breast height diameter (excluding bark) of tree j in year t (cm), G_t is the stand basal area (excluding bark) on the unthinned plot in year t (m^2ha^{-1}), u_t is a random year effect u_t~Nid$(0,\sigma_{yr}^2)$, u_j is a random tree effect u_j~Nid$(0,\sigma_{tr}^2)$, and $v_{jt} = \rho v_{jt-1} + e_{jt}$ is autocorrelated error term of tree j in year t, e_{jt}~Nid$(0,s_e^2)$, $\sigma_v^2 = \sigma_e^2/(1-\rho^2)$. The variance components σ_{yr}^2, σ_{tr}^2 and σ_v^2 were 0.0077, 0.07751 and 0.2647, respectively, and autocorrelation coefficient ρ was 0.67.

Year effects (u_t) for the period 1983–1997 represent the average between-year variation on the unthinned plot. Because the independent variable of the model (4) is logarithmic growth, the predicted year effects are relative deviations from the average of the period 1983–1997. Thus, the growth index series (I_t) with a constant mean (= 100) and homogeneous variance were obtained from year effects (u_t) as follows:

$$I_t = 100u_t + 100, \qquad t = 1983, ..., 1997 \qquad (5)$$

The annual growths were corrected by the estimated growth indices (Fig. 2). Years with the lowest growth indices were 1987 and 1993, and the growing conditions were the most favourable in 1989, 1990 and 1994. Therefore, without correcting the growths to correspond to average climatic conditions, the thinning response and bias would have been underestimated immediately after thinning in 1987 and overestimated in 1989 and 1990.

2.3 Predicting the Diameter Growth

The thinning response and bias were calculated as the difference of the measured and predicted growth. The growth predictions were calculated by using a distance-dependent and a distance-independent diameter growth model which were available and able to predict the diameter growth

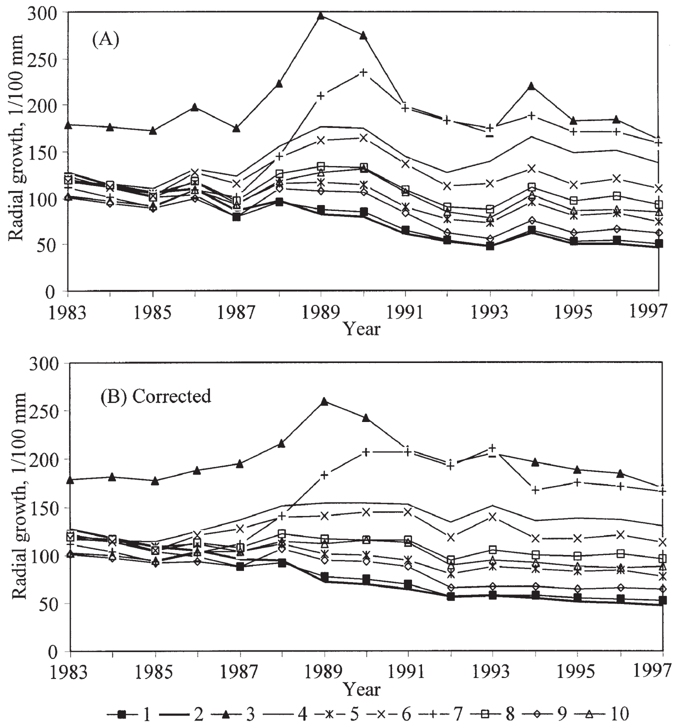

Fig. 2. Mean annual diameter growths of trees on ten sample plots used in the study: (A) uncorrected and (B) corrected with growth indices. Note: Plot 2 is an unthinned plot.

of trees in the study material using the measured tree and stand characteristics.

The distance-dependent growth model was (Miina and Pukkala 2000; Equation 8):

$$(id)^{0.5} = 2.7432 - 3.0645/(d + 5) + 0.3332d/(age + 5) - 0.3115\ln(age) - 0.1160\ln(G) - 0.0411CIp - 0.0358CIs \quad (6)$$

where *id* is the future 5-year increment in over-bark diameter (cm), *d* is the tree diameter (including bark) at breast height (cm), *age* is the tree age at breast height (years), *G* is the stand basal area (including bark) (m^2ha^{-1}), *CIp* and *CIs* are the competition indices computed from pine and spruce competitors, respectively (see Equations 2 and 3). The model was specified to predict the diameter growth of pine growing in the mixture of Scots pine and Norway spruce or in a pure stand located in North Karelia, Finland. In a pure Scots pine stand, *CIs* = 0.

The distance-independent growth model was (Nyyssönen and Mielikäinen 1978; Equation 4):

$$\ln(p_d) = 5.4625 - 0.6675\ln(T) - 0.4758\ln(G) + 0.1773\ln(D) - 0.9442\ln(Hdom) - 0.3631\ln(d) + 0.7762\ln(h) \quad (7)$$

where p_d is the future annual increment in over-bark diameter growth in the next 5-year period, as a compound interest percentage (%), *T* is the stand age (years), *G* is the stand basal area (including bark) (m^2ha^{-1}), *D* is the diameter (including bark) of the median basal area tree (cm), *Hdom* is the dominant height (m), *d* is the tree diameter (including bark) at breast height (cm) and *h* is the tree height (m). The model was prepared to predict the diameter growth in pure Scots pine stands in South Finland.

Both growth models employ tree diameter,

Table 3. The classes of the diameter, retained competition and harvested competition.

Class No.	Range	Number of trees *dbh*	$\ln(CI_R + 1)$	$\ln(CI_H + 1)$
1	$x < \bar{x} - 1.5\,s$	106	148	170
2	$\bar{x} - 1.5\,s \le x < \bar{x} - 0.5\,s$	541	432	440
3	$\bar{x} - 0.5\,s \le x < \bar{x} + 0.5\,s$	632	650	622
4	$\bar{x} + 0.5\,s \le x < \bar{x} + 1.5\,s$	441	540	521
5	$\bar{x} + 1.5\,s \le x$	150	100	117

x is *dbh*, $\ln(CI_R + 1)$ or $\ln(CI_H + 1)$. $\bar{x}$ and s are the mean and standard deviation of x, respectively.

height and age, and stand basal area to predict growth. In the distance-dependent growth model, the local competition between trees is described through the competition index. The effect of thinning is indirectly taken into account in the models via its effect on the stand basal area and the competition index in the distance-dependent model. Thinning variables are not used which means that a tree in a recently thinned stand will grow exactly as much as a similar tree in otherwise similar conditions but without a recent thinning.

2.4 Computing Thinning Response and Thinning Bias

The study examined the dependence of thinning response on tree size, competition, and on the modification of growing space. The absolute thinning response was defined as the difference of the measured (climate-corrected) and predicted growth. The prediction was computed by assuming that the harvested trees were still standing trees, i.e. there was no thinning at all. The 5 year growth predictions of the growth models (6) and (7) were calibrated so that the bias of the growth models for the unthinned plot (Plot 2) was zero, i.e. the average 5-year thinning response of trees on the unthinned plot was zero. The predictions were calibrated separately for the first and second 5-year growth period after thinning.

Both annual and 5-year thinning responses were calculated for the trees. Because the growth model gives a 5-year prediction, it was distributed along five years so that the decreasing diameter growth trend of the unthinned plot was taken into account. The relative mean diameter growths of the trees on the unthinned plot during the first 5-year period after thinning were as follows: 1.00, 0.98, 0.75, 0.73 and 0.66, and during the second 5-year period: 1.00, 1.03, 0.99, 0.91 and 0.90. An example: if the first 5-year diameter growth prediction for a tree is 1.25 cm (average rate 0.25 cm a^{-1}) it is distributed along the different years as follows: 1st year 0.30 cm, 2nd year 0.30 cm, 3rd year 0.23 cm, 4th year 0.22 cm, and 5th year 0.20 cm (total 1.25 cm). These predictions are then subtracted from the measured annual growths to obtain the annual thinning responses.

The thinning bias was the difference between the measured (climate-corrected) and predicted post-thinning growth. In this case, the growth predictions were based on the post-thinning values of competition indices and other predictors, and they were calibrated so that the bias of the growth models for the trees on the thinned plots was zero, i.e. the average 5-year thinning bias of trees on the thinned plots was zero. The calibration was not done plotwise like in the case of unthinned plot. Again, the predictions were calibrated separately for both 5-year growth periods. The 5-year growth prediction was distributed along five years so that the average diameter growth trend of the thinned plots was taken into account. The relative mean diameter growths of the trees on the thinned plots during the first 5-year period after thinning were as follows: 1.00, 1.11, 1.08, 1.09 and 1.04, and during the second 5-year period: 1.00, 1.08, 1.01, 0.99 and 0.99.

The means of the annual thinning responses were computed for five classes of diameter (dbh), retained competition (CI_R), and harvested competition (CI_H) (Table 3). The retained competition was described by $\ln(CI_R + 1)$, and harvested competition by $\ln(CI_H + 1)$.

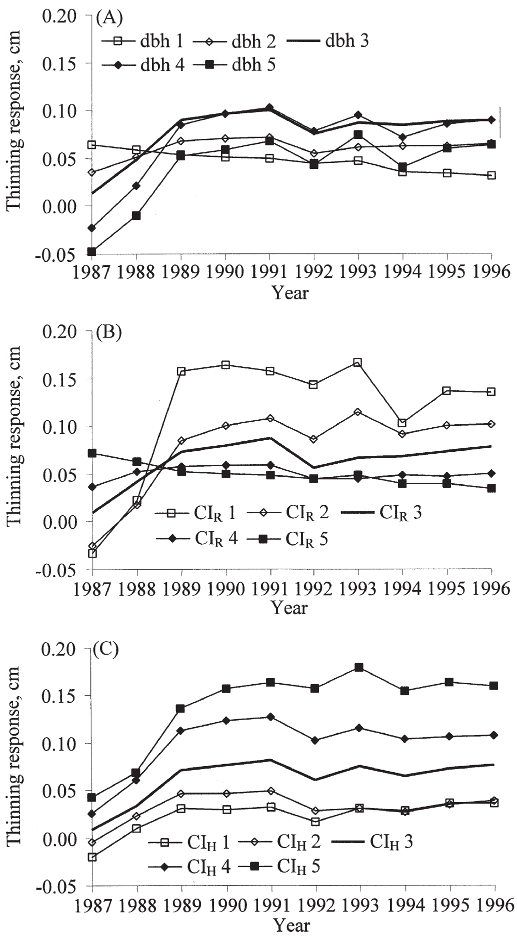

Fig. 3. The annual thinning response in different classes of (A) diameter, (B) retained competition and (C) harvested competition (see Table 3). Diameter growths are predicted with the distance-dependent model.

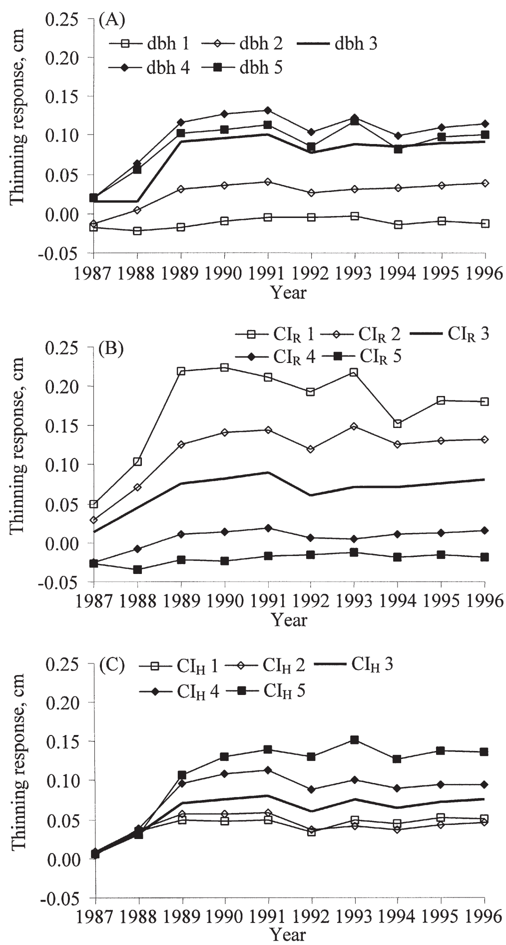

Fig. 4. The annual thinning response in different classes of (A) diameter, (B) retained competition and (C) harvested competition. Diameter growths are predicted with the distance-independent model.

3 Results

3.1 Annual Thinning Response

The thinning responses of the five diameter classes, calculated with the spatial growth model, show different patterns during the five years following the thinning, after which the differences between diameter classes remain unchanged (Fig. 3A). It seems that the thinning response is positive for the whole 10 year observation period in all diameter classes, except in the case of large trees (dbh 4 and 5 in Fig. 3A) for the first two years. Small trees (dbh 1 and 2) have the greatest immediate response but in the subsequent years the response decreases especially in the smallest dbh class. Large trees show an opposite pattern: the response is small during the first two years but much better than in the smallest diameter classes 3–5 years after thinning. The increase in diameter growth is at its highest among medium-sized and co-dominant trees (dbh 3 and 4).

The thinning response is a logical function of the quantity of competition faced by the tree after

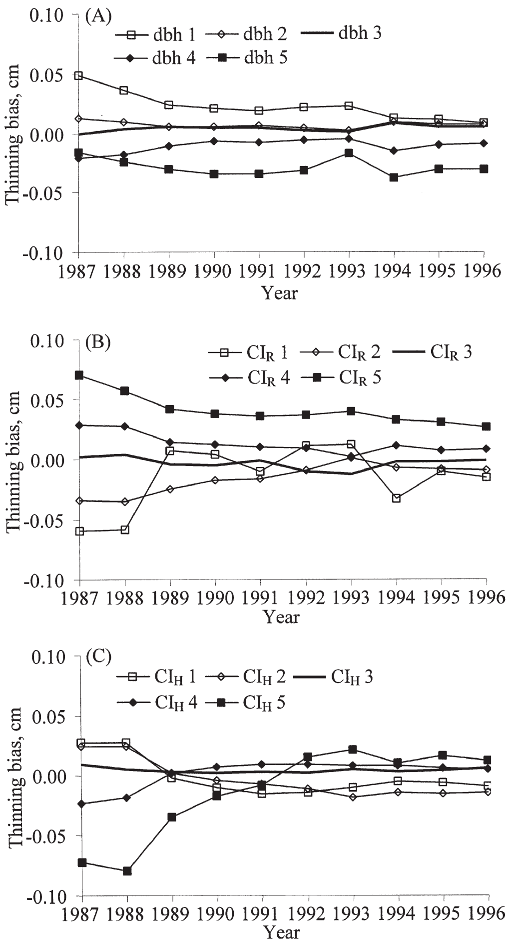

Fig. 5. The annual thinning bias in different classes of (A) diameter, (B) retained competition and (C) harvested competition. Diameter growths are predicted with the distance-dependent model.

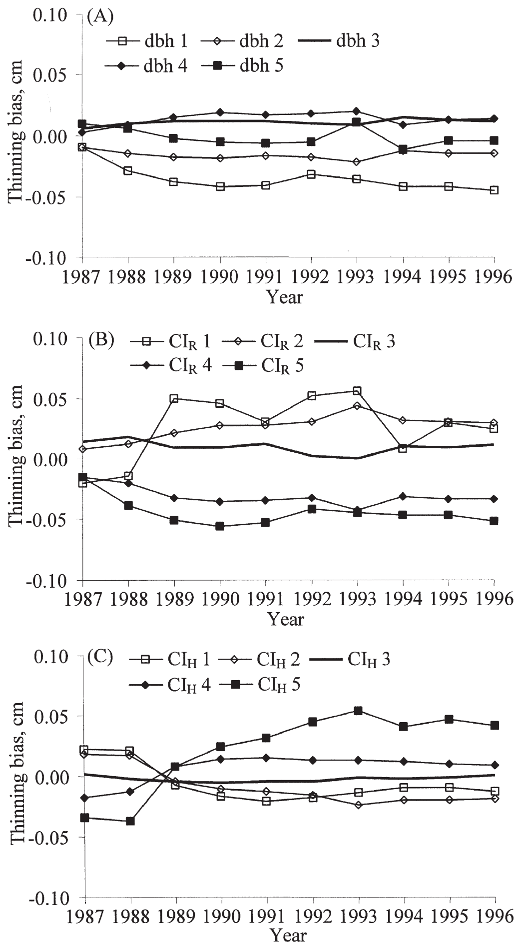

Fig. 6. The annual thinning bias in different classes of (A) diameter, (B) retained competition and (C) harvested competition. Diameter growths are predicted with the distance-independent model.

the thinning (Fig. 3B). The smaller the remaining competition is the better the response. An obvious reason for this is that trees with little competition grow in heavily thinned places. This conclusion is supported by Fig. 3C which shows that trees in most heavily thinned places show the best thinning response.

The thinning response, calculated with the non-spatial model, shows a fairly similar pattern as in Fig. 3, except that dbh-class 4 has the best response, followed by classes 5 and 3 (Fig. 4). When calculated with the non-spatial model, the response of large trees (dbh 4 and 5) is continuously above zero (Fig. 4), whereas the spatial model produces negative responses for 1–2 years after thinning.

3.2 Annual Thinning Bias

The thinning bias of the spatial model, i.e. the difference between measured and predicted post-thinning growth, is quite small in all diameter classes (Fig. 5A). However, it is noteworthy that small trees (dbh 1) show a clearly positive bias and large trees (dbh 4 and 5) a negative bias. This means that the growth model underestimates the growth of very small trees but overestimates the growth of large trees.

When the annual thinning bias is plotted for different classes of remaining or harvested competition, the results reveal that those trees around which many neighbours have been thinned (CI_R 1–2 and CI_H 4–5) show a clear negative bias during the first two years after thinning (Figs. 5B and 5C). The bias is most negative for the highest classes of harvested competition, which indicates that the greater the abrupt change in growing conditions is the more stress the tree experiences. This stress bears a negative impact on growth for 2–5 years. However, the negative bias is over and even partly reversed in the subsequent years.

In the case of the non-spatial model, the dependence of bias on dbh is opposite to the spatial model; the growth of small trees (dbh 1 and 2) is overestimated (negative bias) while the growth of medium-sized and large trees is slightly underestimated (Fig. 6A). The dependence of bias on the remaining and harvested competition is otherwise similar to the spatial model, but the negative bias (overestimate) is smaller during the first two years after thinning for trees with little remaining competition (CI_R 1) or high harvested competition (CI_H 4–5) (Figs. 6B and 6C). Also, while the spatial model underestimated the growth of trees facing high competition (CI_R 5), the non-spatial model overestimates it (Figs. 5B and 6B).

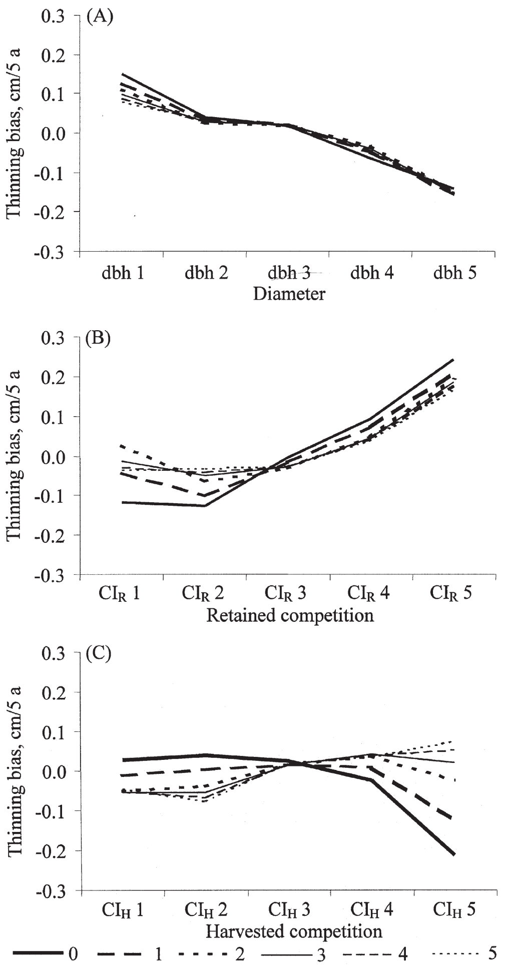

Fig. 7. The 5-year thinning bias in different classes of (A) diameter, (B) retained competition and (C) harvested competition for different years since thinning. Diameter growths are predicted with the distance-dependent model.

3.3 Five-year Thinning Bias

Most growth models predict the 5-year growth instead of annual growth. To study the performance of growth models in thinned stands it is therefore justified to analyse growth in periods of five years. A 10-year follow-up period contains six overlapping 5-year periods, starting 0, 1, 2, 3, 4 and 5 years after the first post-thinning growing season.

With the spatial growth model, the mean five-year thinning bias decreases with tree diameter for all 5-year periods (Fig. 7A). The positive thinning bias (underestimate) of small trees decreases with time but there are no temporal trends for the other diameter classes. Trees with little remaining competition after thinning have a negative 5-year thinning bias (overestimate) at first but the bias approaches zero in subsequent periods (Fig. 7B). The thinning bias is clearly positive (underestimate) for trees which face much competition after thinning, but the bias decreases with time. The more competition has been removed

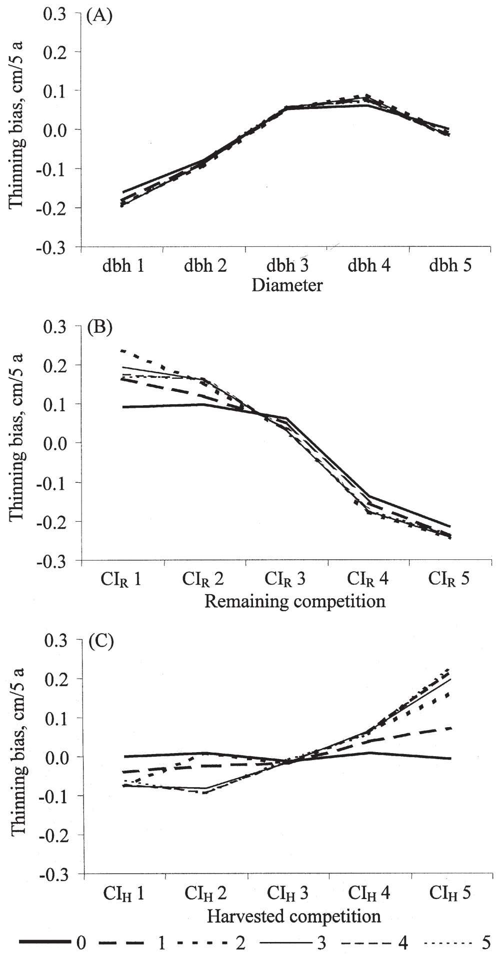

Fig. 8. The 5-year thinning bias in different classes of (A) diameter, (B) retained competition and (C) harvested competition for different years since thinning. Diameter growths are predicted with the distance-independent model.

in the thinning, the greater the overestimate of the first 5-year period is (Fig. 7C). However, this relationship disappears or is even reversed after only two years.

The non-spatial growth model overestimates the growth of small trees similarly in all 5-year periods (Fig. 8A). The model underestimates the effect of remaining competition on growth (Fig. 8B): the growth is underestimated with little competition (CI_R 1) and overestimated with high remaining competition (CI_R 5). This trend in thinning bias becomes more pronounced with time. The growth of trees with in heavily thinned places (CI_H 5) is nearly unbiased at first, but becomes positively biased (underestimated) in later 5-year periods (Fig. 8C). Most probably the non-spatial model has a tendency to underestimate the growth of trees with little remaining competition (and high harvested competition), but the thinning stress partly compensates for this bias during the first few years after thinning.

4 Discussion

This study analysed the thinning response and bias of Scots pine using a distance-dependent and a distance-independent model. For the two models studied, the following conclusions can be drawn from the results:

1) The diameter growth response to low-thinning is highest among medium-sized and co-dominant trees. Nyyssönen (1954) and Niemistö (1994) have obtained similar results, but e.g. Jonsson (1974), Hynynen (1995) and Pape (1999) have suggested the same (relative) thinning response irrespective of tree diameter.
2) The thinning response is quite small, and even negative for some trees, for two years after thinning but becomes clearly positive from the third year onwards. The positive thinning response lasts for more than ten years.
3) The spatial model underestimates the growth of small trees (which usually face much competition), while the non-spatial model overestimates the growth of trees which are small or face much competition. The spatial model used in this study overestimates the effect of competition while the non-spatial model underestimates this effect.
4) Both growth models overestimate the growth of trees around which many neighbours are harvested, but this bias is over in two years. The negative bias is more pronounced with the spatial growth model because the tendency of the non-spatial model to underestimate the growth of trees facing little competition partly compensates for the negative bias.

The overall conclusion is that the thinning bias is rather small with both models if five-year growths are considered. This indicates that there is no need to use special thinning corrections when applying these growth models in simulations. However, this is only true in a rather young Scots pine stand and with the two tested growth models. In older and denser stands and with other tree species the trees' ability to utilise the increased growing space may be poorer, and these trees may find the abrupt change in microclimatic conditions more harmful than young Scots pines.

The results suggest that non-spatial models may overestimate the growth of trees, which are small or face much competition, and underestimate the growth facing little competition. This result is not surprising but the averaging effect should be taken into account when using the model in simulation. Otherwise the simulated size differentiation of trees will be smaller than in reality (Holte and Solberg 1989, Miina 1993). A more surprising result was that the spatial model exaggerated the effect of competition so that the growth of trees facing high competition was underestimated. However, this result most probably pertains only to the model used in this study and the observed trend may not be a common feature of all spatial growth models.

Because the results depend on the models used in the analysis, few general conclusions can be drawn from the study. However, it can be concluded that models that have no thinning parameters as predictors **can** give almost unbiased predictions for thinned stands. If the model is based on a large and variable data set and uses similar predictors as the models analysed in this study, it most probably performs reasonably well in a thinned young Scots pine stand. The models analysed in this study have been used and are currently being used to optimise thinning treatments (e.g. Pukkala and Miina 1997, Pretzsch et al. 2002, Woodward et al. 2002). In addition, the model of Nyyssönen and Mielikäinen (1978) is in use in a forest-level simulation-optimisation system (Pukkala 2001). Therefore, analysing the performance of these particular models in a thinned stand has been a relevant and useful research topic. As is it not possible to analyse all models in a single study, it is recommended that the users of a particular model will carefully test its performance in thinnings, especially if the model is used to support decision-making on thinnings.

The limitation of the data set was a narrow coverage of age classes and tree species. The advantage was that the data covered a wide range of thinning intensities, and both the removed and remaining competition was known exactly for every tree. The coordinates of removed and remaining trees were known. This made it possible to analyse both distance-independent and distance-dependent models, and calculate a tree level thinning response and bias as a function of removed and remaining competition. High between-tree variation in both remaining and removed competition facilitated more general conclusions for the studied stand type than had been possible with data collected from normally managed stands. It is especially important to analyse the model performance in thinnings that a very heavy because the optimisation algorithms suggest and test also exceptionally strong thinning treatments (see e.g. Pukkala and Miina 1997). In this respect the thinning experiment data used in the present study provided far better data for our analyses than a set of normally thinned stands.

The calculation of the annual growth responses and thinning biases involved the distribution of a 5-year growth estimate among the years of the study period. When calculating the thinning response, the predictions were calculated by assuming that the stands were not thinned, and the temporal growth trend on the unthinned plot was used to convert the 5-year growth into five annual growths. When calculating thinning biases the average temporal growth trend of the thinned plots was used in this conversion. Although these choices are justified, it should be noted that the results on the annual thinning response and bias depend on the way of how the 5-year growth is distributed along the individual years. The results for 5-year periods suffer less from this uncertainty, and the first and sixth 5-year periods (0 and 5 years after thinning) involve no subdivisions of the 5-year growth predictions.

Annual growth indices were used to remove the climate-induced variation from the observed growths. The same index series were used for all trees, irrespective of the size and competitive status of the tree. The results would change if trees of different sizes and positions reacted differently to weather conditions. In fact, a part of the irregularity in the growth, thinning response, and thinning bias series shown in Figs. 2B, 3, 4, 5 and 6 may be a consequence of the varying effect of climate on different plots and trees.

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