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Timber quality and volume growth in naturally regenerated and planted Scots pine stands in S.W. Sweden

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Abstract

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Timber quality in Scots pine (*Pinus sylvestris* L.) stands in Sweden has deteriorated during the 20th century. A possible cause of this is the increasing proportion of timber that originates in planted stands. Two naturally regenerated and two planted pine stands, of the same genetic origin, were compared. The planted stands were established as spacing experiments (1.25 × 1.25–2.5 × 2.5 m) at Tönnersjöheden Experimental Forest (lat. 56°42'N, long.13°06'E, alt. 60 m). Volume growth and timber quality, *i.e.* taper, crookedness, number of branches, branch thickness, branch angle, crown size, occurrence of spike knots and damage were compared. The quality of dominant and co-dominant trees was higher in the naturally regenerated stands than in the planted stands. Of the planted trees, only 25% were straight, compared with 86% of naturally regenerated trees. In the planted stands, the mean diameter of the thickest branch below 2 m was 23 mm, compared to 15 mm in the naturally regenerated stands. Timber quality and planting density were also positively correlated, quality being very poor at the widest spacings. Volume growth at initial spacings of 1.75 × 1.75 m and denser was estimated to be 5–10% higher than that in the naturally regenerated stands.

Keywords: natural regeneration, *Pinus sylvestris*, spacing, planting, timber quality, volume growth.

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Introduction

Although planting has for some time been a standard method of establishing Scots pine (*Pinus sylvestris* L.) stands in Sweden, interest in natural regeneration has recently increased. This can be explained to some extent by the poor timber quality from planted stands, by environmental concerns and by the increasing cost of planting.

During the past 20–30 years, Scots pine stands in Sweden have been planted at wide spacings, *i.e.* 2 × 2 m or more. Experience has shown that the timber quality of such stands is inferior to that of naturally regenerated stands. Differences are most pronounced on fertile sites. Timber quality is defined here in terms of the classification system used in Sweden for several decades (Anon, 1982).

Results from Swedish spacing experiments with Scots pine indicate that initial stand density and timber quality are strongly related (Persson, 1976, 1977; Persson, Persson, Ståhl & Karlmats, 1995). They confirm that the wide initial spacings used in practical plantations will result in poor timber quality. However, Björklund & Hörnfeldt (1996) argued that quality need not be as poor as is indicated by Persson (1976, 1977). They maintain that an appropriate selection of trees at the first thinning may help to improve timber quality.

Arvidsson (1987) noted a drastic deterioration in the quality of sawtimber with time in the period 1925–1975, in sawmills in central and northern Sweden. Some of this may be explained by the relaxation of restrictions on the dimensions of sawlogs. In Finland, Uusvaara (1985) predicted a lower future quality of pine timber, mainly because an increasing proportion will in future come from planted stands, with low stand density. In Norway, too, the quality of timber from planted Scots pine stands has been questioned (Strand, Sines & Dietrichsson, 1997).

In a comparison of naturally regenerated and planted Scots pine stands growing on fertile sites, Ekö & Agestam (1994) found a higher quality of timber from naturally regenerated stands. They also concluded that the increase in quality had a high price, *i.e.* a reduction in volume growth by *ca.* 20%. However, in the case in point, the shelter trees were allowed to remain in the stand far longer than is normal. Strand *et al.* (1997) found only small differences in quality between planted and naturally regenerated trees, if variation in stand density was taken into account.

Where the aim is to achieve acceptable timber quality in relation to that in naturally regenerated stands, recommendations concerning planting density for Scots pine seedlings have been made by authors from different regions of Europe (Dittmar, 1975; Flöhr, 1975; Thomasius, 1975; Mráček, 1983; Huuri & Lähde, 1985). Suggested seedling densities vary widely from region to region, from *ca.* 5 000 to 25 000 ha^{-1}. In Sweden, Persson (1976, 1977) argued that it is not economically feasible to establish stands at the dense spacings required to produce timber equal in quality to that produced in successful, naturally regenerated stands.

In many respects, a naturally regenerated stand is far more heterogeneous than a planted stand. Seedlings may originate from different seed generations, and the shelter trees locally exert strong competition. These conditions often lead to a clustered spatial distribution of young trees. They also tend to increase variation in height between groups of trees and between individuals within groups, as compared to the more uniform planted stands. Therefore, many trees in naturally regenerated stands will develop under conditions that favour the formation of good timber quality. A high-quality stand can then be achieved by treating these individuals as the future crop trees at the early thinnings.

In plantations, in contrast to natural regeneration, genetically improved plant material can be used to improve timber quality. Differences have been found between Scots pine provenances regarding stem straightness and the occurrence of spike knots (Prescher & Ståhl, 1986). The heritability of some traits, *e.g.* branch angle, appears to be high, whereas other traits, such as branch thickness, appear to be influenced far more by growth rate than by genetics (Velling, 1985). In their studies of Scots pine provenances, Remröd (1976) and Persson (1977) found that differences in branch thickness were influenced to a greater extent by stand density than by genetic origin. Hitherto, Swedish breeding programmes have mainly focussed on volume production. Therefore, the use of improved plant material does not seem to be a realistic means of substantially improving timber quality in the near future.

The aim of this study was to compare timber quality in naturally regenerated and planted stands of Scots pine in southern Sweden. The traits studied were taper, crookedness, number of branches, branch thickness, branch angle, crown size, occurrence of spike knots and damage. These traits can be observed non-destructively and are assumed to be well correlated with important timber and wood properties.

Material and methods

Two planted and two naturally regenerated Scots pine stands were studied in southwestern Sweden, at Tönnersjöheden Experimental Forest (lat. 56°42′N, long. 13°06′E, alt. 60 m). The stands were situated within a radius of 1 km. Stand size varied between 1.7 and 2.9 ha. Site conditions were uniform at all four sites. The bedrock was gneiss, the soil texture was gravel, the soil moisture class was dry and the soil type was a podsol. The stands were all of local provenances. Seedlings used for planting were grown from seed collected within or close to the naturally regenerated stands. The young stands were treated according to general practice. Stand age varied between 33 and 42 years when data on timber quality were collected.

The planted stands

In 1962 and 1963, the two planted stands were established as spacing experiments on clearfelled areas. Three- to four-year-old seedlings were planted at spacings varying between 1.25 × 1.25 and 2.5 × 2.5 m. Naturally regenerated broadleaved trees, mainly birch, were removed 11 years after planting.

The thinning programme was designed to result in the gradual equalisation of stand density on the different plots. At each thinning, the basal area was reduced to 19–23 m^2 ha^{-1}. On the plot with the highest initial density, the first thinning was performed at age 20 years. Each plot has so far been subjected to 2–4 thinnings.

The naturally regenerated stands

The stands were established after scarification in 1949 and 1950. Thinnings were made among shelter trees on two occasions. Final fellings were carried out when the new generation was nine years old in the one stand and 12 years old in the other. Broadleaved trees were removed over the entire area on several occasions. Later, one half of each stand was precommercially thinned when mean height was *ca.* 1.5 m, corresponding to an age of eight or nine years. About 4 500 stems ha^{-1} were left. The other half of the stand was left untreated.

The naturally regenerated stands have so far been thinned four times. The first thinning was made at an age of 31 years.

Data collection

Data on volume growth were collected at each thinning, according to standard routines for permanent plots in Sweden (Karlsson, 1994). Plot size varied between 0.04 and 0.1 ha. Diameter at breast height (dbh) and damage were recorded for all trees. Tree height, height to the first living branch and bark thickness were measured on a sample of trees. Stand characteristics at the time of the second thinning were calculated on the basis of these data (Table 1).

Data on timber quality were collected five to six years after the second thinning. Two categories of sample tree were randomly selected. One sample was taken exclusively from dominant and co-dominant trees (DC-trees). The other sample represented potential crop trees (PC-trees), and was chosen among the 400 to 500 trees ha^{-1} with the best timber quality. For the most part, this sample also consisted of dominant and co-dominant trees.

In total, 180 DC-trees on the plots were measured (Table 2). The following data were recorded:

- Dbh and diameter at 5 m height;
- Tree height and height to the first living branch;
- Diameter and angle of the thickest branch below 2 m height and between 2 and 4 m height;
- Number of whorls between 1 and 3 m height;
- Number of spike knots;
- Stem crookedness.

PC-trees were selected only in the buffer zones surrounding the plots, *i.e.* the zones receiving the same treatment as the plot, but not normally used for measurements. The 42 trees were felled before they were measured (Table 2). The fol-

Table 1. *Stand and site data at the time of the second thinning*

Stand No.	Treatment	Age,* years	Top height m	No. stems ha^{-1}	Basal area $m^2\ ha^{-1}$	Mean diam. cm	Volume $m^3\ ha^{-1}$	Mean annual increment $m^3\ ha^{-1}$	Site** index m
	Planted								
1	1.5 × 1.5	26	11.7	1543	20.2	12.9	113	6.5	28.2
1	2.0 × 2.0	26	11.6	1479	20.4	13.3	110	5.5	28.6
1	2.5 × 2.5	26	9.8	1622	18.5	12.1	89	3.5	25.8
2	1.25 × 1.25	26	12.1	1903	21.0	11.9	121	7.8	29.4
2	1.5 × 1.5	26	11.8	1820	20.7	12.0	115	6.3	28.9
2	1.75 × 1.75	26	11.8	1515	20.6	13.2	117	6.6	28.9
2	2.0 × 2.0	26	12.3	1495	21.1	13.4	120	5.8	29.6
	Naturally regenerated								
3		36	14.4	1391	20.8	13.8	133	6.7	26.8
3	Precomm. thinned	36	15.5	1095	20.7	15.5	141	7.3	28.1
4		36	14.0	1341	19.3	13.5	126	6.9	26.3
4		36	15.1	1215	19.4	14.3	127	6.7	27.6
4	Precomm. thinned	36	13.7	1904	21.1	11.9	130	7.7	25.9
4	Precomm. thinned	36	15.7	1319	19.4	13.7	133	8.0	28.3

*In naturally regenerated stands, seed germinated in 1950 was considered as the main cohort.
**Top height at 100 years, average of the 100 largest diameter trees per ha, estimated by height curves (Hägglund, 1974).

Table 2. *Number of sample trees in the quality data collection*

Stand No.	Treatment	No. of DC-trees	No. of PC-trees
	Planted		
1	1.5 × 1.50	10	4
1	2.0 × 2.0	10	3
1	2.5 × 2.5	10	3
2	1.25 × 1.25	15	6
2	1.5 × 1.5	15	4
2	1.75 × 1.75	15	4
2	2.0 × 2.0	15	4
	Naturally regenerated		
3		15	4
3	Precom. thinned	15	4
4		15	3
4		15	0
4	Precom. thinned	15	3
4	Precom. thinned	15	0

lowing measurements or classifications were made:

- Diameter at stump height and diameter at 10%, 20%, ... 90% of tree height;
- Tree height, height to the first living branch and height to every whorl;
- Diameter, angle and length of the thickest branch in each whorl below the live crown and in each second whorl within the live crown;
- Classification of each branch as living, deteriorating, dead and ramified, snag or scar;
- Number of spike knots;
- Stem crookedness.

Branch diameter perpendicular to the branch axis was callipered under bark, 3 cm from the stem surface, to avoid the branch collar (Persson, 1977). Stem crookedness was recorded as the greatest perpendicular distance from the pith to an imaginary line between the pith at the terminal points of the crook. The distance was recorded in relation to the stem radius at the current height.

Analyses

Naturally regenerated trees were compared with trees planted at different spacings. The various traits of the trees were studied both individually and together. Regression analysis and analysis of variance (ANOVA) were used in the case of univariate studies. For clarity, the regression models are shown together with the parameter estimates. In the ANOVA, every stand was treated as an observation in a completely randomised design. For the multivariate case, both principal component analysis (PCA) and subjective classification of data were utilised.

Stand growth for the remainder of the rotation, after the latest inventory, was estimated by means of a growth simulator (Ekö, 1985).

Results

Stem taper

The relationship between taper and diameter at breast height was studied on DC-trees. Regression lines were estimated according to the model:

$$y_i = b_0 + b_1 \cdot L_i + b_2 \cdot dbh_i + b_3 \cdot dbh_i \cdot L_i + \varepsilon_i \quad (1)$$

where

y_i	taper between 1.3 and 5 m tree height;
L_i	an indicator variable for regeneration method;
dbh_i	diameter at breast height;
i	the tree index;
$b_0 ... b_3$	coefficients estimated by OLS (ordinary least squares) procedures;
ε_i	normally distributed random deviations with expectation zero and common variance.

The slopes of the two regression lines differed significantly ($p = 0.0052$). However, absolute differences in taper between planted and naturally regenerated trees were small (Table 3, Fig. 1).

In addition, the relationship between taper and diameter was determined exclusively for planted DC-trees. For this analysis, a regression model based on Eq. 1 was used to compare the closest and widest spacings. Although the slopes of the regression lines did not differ significantly ($p = 0.89$), their intercepts differed by 3 mm/m ($p = 0.043$), the difference being significant.

Table 3. *Estimated relationship between dbh and taper for Dominant and Co-Dominant (DC) trees. Taper was measured between 1.3 and 5 m height*

Dependant variable: Taper (mm m^{-1})

Variable		Parameter estimate	*t*-value	*p*-value
	b_0	−0.2606	−0.3	0.76
Indicator of naturally regenerated trees (*L*)	b_1	0.07645	11.6	<0.0001
dbh (mm)	b_2	0.2958	2.0	0.047
L dbh*	b_3	−0.01947	−2.3	0.023

Multiple *R*: 0.60

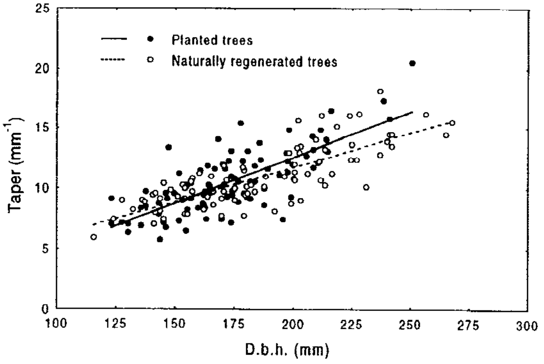

Fig. 1. Stem taper between 1.3 and 5 m, Dominant and Co-dominant (DC) trees.

For PC-trees, taper curves were estimated using a segmented polynomial equation conditioned to join smoothly (Max & Burkhart, 1976):

$$\begin{aligned} y_{ij} = {} & b_1(rh_{ij} - 1) + b_2(rh_{ij}^2 - 1) \\ & + b_3(a_1 - rh_{ij})^2\, S_{ij} \\ & + b_4(a_2 - rh_{ij})^2\, T_{ij} + \varepsilon_{ij} \end{aligned} \quad (2)$$

where

y_{ij}	relative quadratic diameter, d^2_{ij}/dbh^2_j;
rh_{ij}	relative height, h_{ij}/H_j;
a_1, a_2	junction point parameters;
S_{ij}	$=1$ if $a_1 - rh_{ij} > 0$; otherwise $= 0$;
T_{ij}	$=1$ if $a_2 - rh_{ij} > 0$; otherwise $= 0$;
j	tree index;
i	index for measuring height;
$b_1 ... b_4$	parameters estimated by OLS;
ε_{ij}	normally distributed random deviations with expectation zero and common variance.

Values for parameters a_1 and a_2 were chosen on the basis of residual studies and from the magnitude of the residual standard deviation. According to the model used, no difference in relative taper was found between planted and naturally regenerated trees (Table 4, Fig. 2).

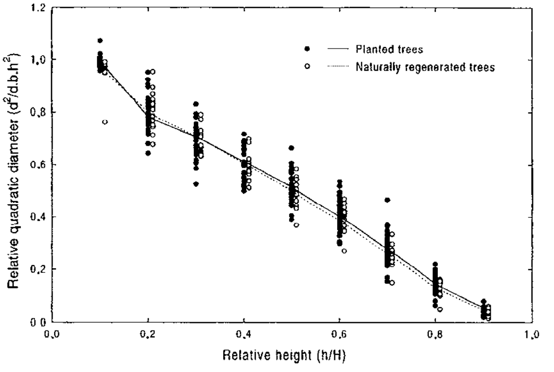

Fig. 2. Estimated curves of stem taper, Potential Crop (PC) trees. (The open circles representing naturally regenerated trees were moved slightly to the right.)

Table 4. *Estimated taper curves for Potential Crop (PC) trees*

Dependant variable: relative quadratic diameter (d^2/dbh^2)		Parameter estimate	
Variable		Planted trees	Naturally regenerated trees
$rh-1$	b_1	0.4674	0.2429
rh^2-1	b_2	−0.5316	−0.3665
$S^*(a1-rh)^2$, where $S=1$ if $a1-rh>0$; else $S=0$	b_3	7.2048	4.4009
$T^*(a2-rh)^2$, where $T=1$ if $a2-rh>0$; else $T=0$	b_4	0.9923	0.9858
	$a1$	0.12	0.12
	$a2$	0.85	0.85
Standard deviation about the function		0.055	0.030

rh: relative height; h/H, where H is tree height

Stem straightness

The percentage of straight trees (crookedness class 0) was higher among naturally regenerated trees than among planted trees ($p=0.043$, Table 5). With one exception, severe crooks (classes 2–4) occurred only among planted trees. The relative frequency of trees in different crookedness classes did not depend on tree size.

Table 5. *Relative distribution of trees by crookedness classes (%). Crookedness was measured as the greatest perpendicular distance from the pith to an imaginary line between the pith at the terminal points of the crook. The distance was recorded in relation to the stem radius at the current height. Class 0: 0–1 radius, class 1: 1–2 radii, etc.*

	Crookedness class				
	0	1	2	3	4
Naturally regenerated trees	*86*	*13*	*1*	*0*	*0*
DC	91	7	1		
PC	50	50			
Planted trees	*25*	*46*	*25*	*2*	*2*
DC	26	44	26	2	2
PC	25	50	25		

Branch thickness

The mean diameter of the thickest branches below 2 m and between 2 and 4 m was greater on planted than on naturally regenerated trees ($p=0.11$ and $p=0.10$, respectively, Table 6). Differences were greater for DC-trees than for PC-trees. All measurements were made on dead branches, since the height to the live crown for all trees exceeded 4 m.

The relationship between *dbh* and the diameter of the thickest branch below 2 m was estimated by means of the model:

$$y_i = b_0 + b_1 \cdot dbh_i + b_2 \cdot L + b_3 \cdot L\ dbh_i + \sum_{j=1}^{4} b_{ij+3} \cdot U_j + \varepsilon_i \quad (3)$$

Table 6. *Average diameters of the thickest branches below 2 m and between 2–4 m*

		Diameter of thickest branch, mm			
		Height 0–2 m		Height 2–4 m	
Stand No.	Treatment	DC-trees	PC-trees	DC-trees	PC-trees
	Planted	*23*	*22*	*26*	*25*
1	1.5 × 1.5	20	26	24	29
1	2.0 × 2.0	26	22	28	27
1	2.5 × 2.5	25	33	28	31
2	1.25 × 1.25	20	20	21	21
2	1.5 × 1.5	20	18	24	24
2	1.75 × 1.75	25	18	27	22
2	2.0 × 2.0	25	24	28	25
	Naturally regenerated	*15*	*19*	*19*	*23*
3		13	22	17	23
3	Precom. thinned	17	20	19	21
4		14	13	17	23
4		13		18	
4	Precom. thinned	15		20	
4	Precom. thinned	17	19	21	25

where

y_i	diameter of the thickest branch below 2 m;
dbh_i	diameter at breast height;
L	an indicator variable for regeneration method;
U_j	an indicator variable for initial spacing;
i	the tree index;
$b_0...b_7$	coefficients estimated by OLS;
ε_i	normally distributed random deviations with expectation zero and common variance.

Branch diameter increased with increasing *dbh*, but the slope of the regression line was less steep for naturally regenerated than for planted trees (Table 7, Fig. 3).

A test was also made to determine whether initial spacing influenced branch thickness. In this test, data from 1.25 and 1.5 m spacings were merged into one group and compared with data from 2 and 2.5 m spacings. Regression lines were estimated separately for the two groups, with a model based on Eq. 3. Although the intercepts differed significantly ($p=0.010$), the slopes did not.

The relationship between branch diameter and height above ground was also studied for PC-trees. Only whorls below the live crown were considered. Regression lines were estimated separately for planted and naturally regenerated trees, by means of a second-degree polynomial (Fig. 4). The difference in branch thickness between planted and naturally regenerated trees did not depend on height.

Distribution of branches along the stem

The number of branches per whorl, as well as internode length, were generally higher for planted than for naturally regenerated trees ($p=0.013$ and $p=0.0038$, respectively, Table 8). Naturally regenerated trees had more branches

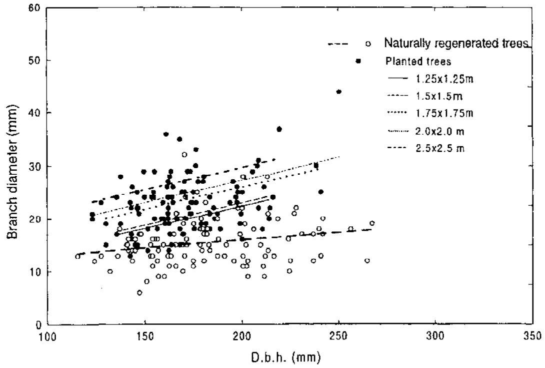

Fig. 3. Relationship between dbh and diameter of the thickest branch below 2 m height, Potential Crop (PC) and Dominant and Co-dominant (DC) trees.

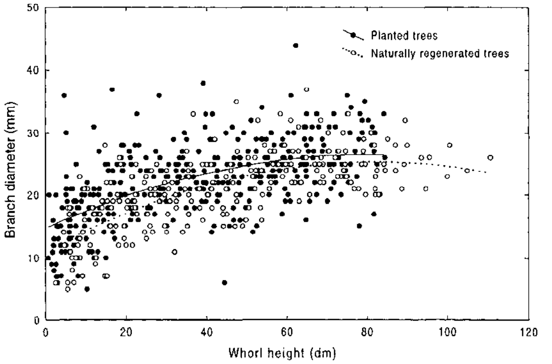

Fig. 4. Relationship between height and diameter of the thickest branch for whorls below the live crown, Potential Crop (PC) trees.

Table 7. *Estimated relationship between dbh and thickest branch below 2 m, Dominant and Co-Dominant (DC) and Potential Crop (PC) trees*

Dependant variable: Diameter of thickest branch (mm)

Variable		Parameter estimate	*t*-value	*p*-value
	b_0	10.09	4.24	<0.0001
Dbh (mm)	b_1	0.02894	2.26	0.02
Indicator of planting (L)	b_2	−4.689	−1.26	0.21
$L*dbh$	b_3	0.05573	2.72	0.01
Indicator of spacing 1.5 m ($U_{1.5}$)	b_4	0.6472	0.54	0.59
$U_{1.75}$	b_5	3.645	2.70	0.01
U_2	b_6	4.917	4.11	<0.0001
$U_{2.5}$	b_7	7.351	4.89	<0.0001

Multiple R: 0.73

per unit stem length than planted trees ($p = 0.031$). The number of branches per unit stem length was also higher on DC-trees than on PC-trees ($p = 0.015$). However, in both cases the differences were small. The correlation between internode length and number of branches per whorl was positive for both planted and naturally regenerated trees, but the frequency of short internodes was higher for naturally regenerated trees (Fig. 5).

Branch angles and spike knots

For PC-trees, the mean branch angle per tree was calculated using the thickest branch in each whorl between 1 m height and the bottom of the live crown. The mean angle did not differ significantly between naturally regenerated and planted trees. However, the frequency of narrow angles was greater for planted trees (Table 9).

The frequency of spike knots was lower for naturally regenerated than for planted trees ($p = 0.056$). Only a few spike knots were found on PC-trees for both types of regeneration method (Table 10).

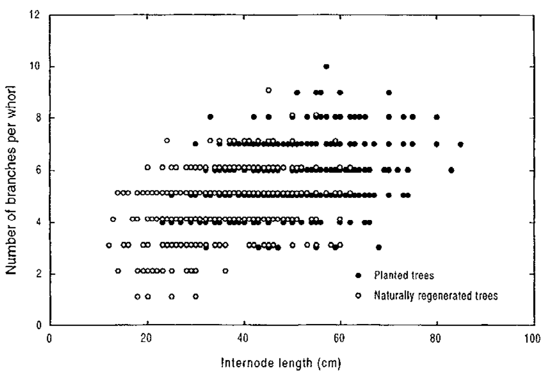

Fig. 5. Relationship between internode length and number of branches per whorl, Potential Crop (PC) and Dominant and Co-dominant (DC) trees. Measurements made between 1 and 3 m height.

Table 9. *Average branch angle per tree, calculated for the thickest branch in every whorl between 1 m and height to first living branch. Relative frequency (%), Potential Crop (PC) trees. If the branch is pointing upwards and the branch axis is parallel to the stem axis the angle is 0°. If the branch axis is perpendicular to the stem axis it is 90°*

Branch angle	Planted trees	Naturally regenerated trees
40°–44°	11	0
45°–49°	14	7
50°–54°	29	29
55°–59°	29	21
60°–64°	7	29
65°–69°	4	14
70°–74°	7	0

Table 10. *Frequency of trees with spike knots (%)*

		DC-trees		PC-trees	
Stand No.	Treatment	No. of spike knots *1*	2+	No. of spike knots 1	2+
	Planted	*27*	*13*	*4*	*4*
1	1.5 × 1.5	20	40	33	0
1	2.0 × 2.0	30	10	0	50
1	2.5 × 2.5	10	20	0	0
2	1.25 × 1.25	40	7	0	0
2	1.5 × 1.5	27	13	0	0
2	1.75 × 1.75	20	7	0	0
2	2.0 × 2.0	33	7	0	0
	Naturally regenerated	*12*	*8*	*8*	*0*
3		20	0	33	0
3	Precom. thinned	13	13	0	0
4		7	7	0	0
4		7	0		
4	Precom. thinned	7	13		
4	Precom. thinned	13	0	0	0

Relative crown length

The height to the first living branch was, on average, 1 m higher for naturally regenerated

Table 8. *Number of branches per whorl, internode length and number of branches per metre of stem. Observations made between 1 and 3 m height*

	Planted trees				Naturally regenerated trees			
	DC-trees Mean	Std. dev.	PC-trees Mean	Std. dev.	DC-trees Mean	Std. dev.	PC-trees Mean	Std. dev.
Number of branches per whorl	6.0	1.0	5.5	1.3	4.8	1.1	4.0	1.1
Internode length, m	0.51	0.11	0.53	0.12	0.36	0.1	0.38	0.11
Number of branches per m of stem	12.2	3.0	10.5	2.9	14.1	4.8	11.1	4.4

than for planted trees. However, it should be noted that the naturally regenerated trees were older and taller.

Mean relative crown length was 40% for naturally regenerated trees and 38% for planted trees. On average, relative crown length was 3–4 percentage units higher for PC-trees than for DC-trees. In the planting experiments there were no consistent differences in mean relative crown length between different initial spacings (data not shown).

The live crown

In the lowest part of the crown, no differences in branch diameter or branch length were found between planted and naturally regenerated trees (Fig. 6). On the whole, it was difficult to make a meaningful comparison of the properties of the live crown, since naturally regenerated and planted trees were at different development stages.

Stand characteristics and volume growth

The mean diameter of the remaining stand at an age of 36–38 years was considerably higher for the planted than for the naturally regenerated stands (Table 11). Top (dominant) height (the mean height of the 100 trees of largest diameter ha^{-1}), was generally higher in planted stands, indicating more rapid height growth. Consequently, site indices were also significantly higher. No clear differences in top height or site index were found between stands planted at different initial spacings.

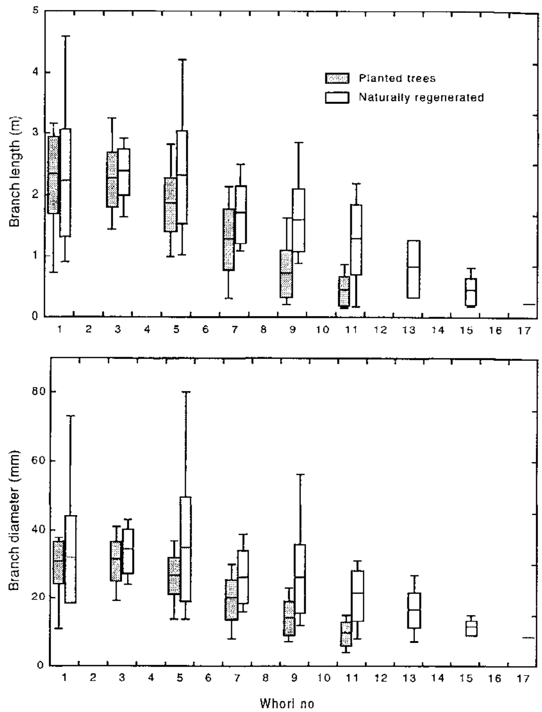

Fig. 6. Diameter and length of the thickest branch in every second whorl in the live crown, Potential Crop (PC) trees. (Whorls were numbered from the crown base upwards.) Mean; box Mean ± SD; whisker max-min.

Compared to the increment in the naturally regenerated stands that had not been precom-

Table 11. *Stand characteristics, volume growth and site index in the remaining stand at an age of 36–38 years. Standard deviation in italics. m^3f—forest m^3*

Treatment	No. of plots	Stand age, years	Mean diameter, cm	Top height, dm	No. of stems ha^{-1}	Basal area m^2 ha^{-1}	Mean annual volume increment, m^3f ha^{-1}	Current volume increment m^3f ha^{-1}	Site index, m*
Planted									
1.25 × 1.25	1	37	19.1	168	777	22.1	9.7	13.8	29.1
1.5 × 1.5	6	37–38	19	164	805	22.6	8.5	12.9	28.6
			0.9	*7*	*78*	*0.2*	*0.5*	*0.9*	*0.7*
1.75 × 1.75	2	37	19.2	183	761	22	8.4	12.5	30.9
			0.6	*10*	*45*	*0.1*	*0.0*	*0.2*	*1.1*
2.0 × 2.0	6	37–38	19.7	166	737	22.3	7.4	12	28.5
			1.1	*7*	*93*	*0.4*	*0.6*	*1*	*1*
Naturally regenerated	4	38	19.8	156	725	22.2	6.8	11.9	27.2
			0.9	*8*	*45*	*1*	*0.9*	*1.4*	*0.9*
	6	36	13	146	1509	19.7	7.3	11	26.8
			1.1	*9*	*278*	*0.8*	*0.5*	*0.8*	*0.7*
Precom. thinned	6	36	14.6	143	1219	20.2	6.9	10.8	27.4
			0.6	*14*	*105*	*0.5*	*0.3*	*0.9*	*0.5*

*Top height at 100 years, average of the 100 largest diameter trees ha^{-1}, estimated from height curves (Hägglund, 1974).

mercially thinned, the mean annual volume increment in the planted stands with an initial spacing of 1.5, 2.0 and 2.5 m was 116, 101 and 93%, respectively (Table 11). In a comparison with naturally regenerated stands that had been precommercially thinned, the corresponding figures were 123, 107 and 99%. The current annual volume increments were slightly higher in the planted stands, but differences were not significant. Both the mean and current annual volume increments were positively correlated with higher planting density.

Prior to the first thinning, the frequency distribution of diameter classes in the stands was affected both by establishment method and by initial spacing (Fig. 7). In the planted stands, the proportion of large-diameter trees was higher in stands with wider initial spacings. Consequently, the mean diameter and the diameter of the 100 largest trees ha^{-1} increased with initial spacing. In the naturally regenerated stands, precommercial thinning resulted in an increased proportion of large-diameter trees.

Discussion

Taper

In several studies, taper has been found to vary with stand density (Larson, 1963; Varmola, 1980; Valinger, 1992) and crown class (Larson, 1963). High density promotes good stem form, *i.e.* small taper. Taper also decreases with decreasing crown class. In the present study taper was, on average, 10 mm m^{-1} of stem in the lower part of the trunk (Fig. 1). No important differences were found between planted and naturally regenerated trees. This seems reasonable, since stem form develops continuously, and the thinning programme was designed to equalise stand density gradually. It should be borne in mind that only dominant and co-dominant trees were compared.

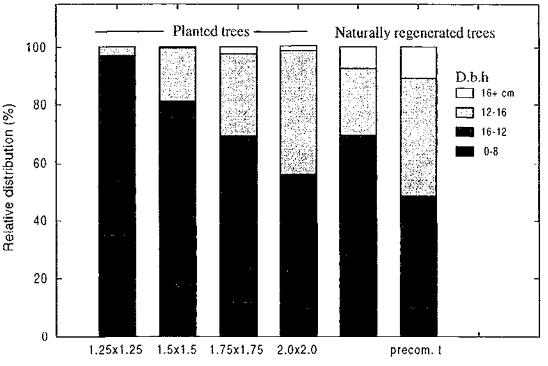

Fig. 7. Relative distribution of trees in diameter classes for planted trees (spacing 1.25 to 2.0 m) and for naturally regenerated stands (cleaned or not).

The significant difference in taper between trees planted at the densest initial spacing and those planted at the widest spacings, was probably caused by differences in stand density existing up to the first thinning.

The yield of sawn timber will, of course, increase with decreasing taper. However, irrespective of the regeneration method and initial spacing, crop trees will grow at about the same density for a long period, up to the final felling. It could therefore be argued that the taper observed in the early part of the rotation should receive less attention than other quality-determining factors. It must, however, be recognised that at any given point in time, stem form will influence the susceptibility to damage caused by snow and wind. A low height:diameter ratio is desirable in high-risk areas. The $h:d$ ratio has been found to increase with increasing stand density (Huuri & Lähde, 1985). In the present study, the $h:d$ ratio was 0.85 (m/cm) for naturally regenerated trees and 0.77 for planted trees. Considering that the planted trees were smaller at the time of inventory, we judge this difference to be of minor importance.

Stem straightness

The frequency of crooked trees differed greatly between planted and naturally regenerated stands. Only 25% of the planted trees were judged to be straight, whereas the proportion for naturally regenerated trees was 86% (Table 5). Also Strand *et al.* (1997) report a higher frequency of basal crooks among planted compared with naturally regenerated trees. In the present study, severe crooks were found almost exclusively among planted trees. In stands with the widest initial spacing, severe crooks were frequent (69%). This agrees well with results reported by Huuri & Lähde (1985), who found that the butt curvature increased with increasing planting density. Kärkkäinen & Uusvaara (1982) found that a basal sweep was more common in planted than in naturally regenerated stands. Prescher & Ståhl (1986) also found a positive correlation between increasing planting density and stem straightness.

The high frequency of crooks among planted trees may have several reasons. One contributing factor may have been the planting method *per se*. It is likely that basal sweep will develop among seedlings with a one-sided root system, seedlings that are leaning or seedlings planted on spots subjected to erosion or mouldering (Huuri, 1976). Another reason may have been rapid seedling growth aboveground, with no corresponding degree of root growth (Hultén, 1982). A third reason may have been that the relatively small number of individuals provides limited opportunities for selection in the early thinnings.

Crooks will directly influence the yield of sawn timber and may also induce the formation of compression wood. The high frequency of crooked stems among planted trees will have a strong adverse influence on future timber quality, especially since the frequency was also high among PC-trees (Table 5).

Crookedness was measured in relation to stem diameter. In general, a crook of a certain relative size is more serious on thicker trees. The difference found between planted and naturally regenerated trees may, therefore, have been slightly overestimated, since the planted trees had a lower mean diameter than the naturally regenerated trees at the time of inventory.

Branch thickness

Branch thickness is strongly correlated with timber quality (Persson, 1976). Thick branches reduce the strength of wood and make it difficult to work. Visual quality is also affected. Thick branches in the lower part of the trunk are indicative of rapid growth at a young age, which tends to result in low wood density (Ericsson, 1966; Persson, 1975, 1977; Kärkkäinen & Uusvaara, 1982). The rate of natural pruning will decrease with increasing branch diameter, as will the rate of occlusion of scars once the branches have fallen off. Thus, thick branches will also reduce the amount of knot-free wood. In this study, large differences in mean branch diameter were observed between planted and naturally regenerated trees, as well as between trees planted at different spacings. In other studies of both Scots pine and other tree species, a positive linear relationship has been found between branch diameter and initial spacing (Johansson, 1992; Huuri, Lähde & Huuri, 1987; Kellomäki & Tuimala, 1981; Persson, 1976, 1977; Skovsgaard, 1988).

The relationship between *dbh* and branch diameter was stronger in the planted than in the naturally regenerated stands (Fig. 3). Although thinning from above could have reduced mean branch diameter in the planted stands, branch diameter would still be considerably higher than that in the naturally regenerated stands.

Number of branches, branch angles and spike knots

Only small differences between regeneration methods were found in the number of branches per unit stem length. Persson (1976) reported similar results, while a slightly increasing number of branches per unit stem with increasing spacing was found by Kellomäki & Tuimala (1981) and by Jokinen & Kellomäki (1982). However, there were differences in internode length and in the number of branches per whorl (Table 8). On average, the whorls of planted trees contained a larger number of branches. This difference in distribution may influence the strength of the timber, especially since the branch diameter of the planted trees was also greater.

Naturally regenerated trees were also superior to planted trees as regards the frequency of trees with narrow branch angles and fewer spike knots. Kellomäki & Tuimala (1981), who studied branch angles in the live crown of young Scots pine stands, found a narrower branch angle with increasing initial number of stems per hectare.

Timber quality

To this point, the different properties have been regarded individually. However, their combined effect determines the overall quality of timber. One possible way of assessing timber quality is to apply the grading system used in practice, and let an experienced scaler make the judgements. This method was not used in the present study, since the trees had not yet reached timber dimensions. Also, such judgements are subjective to some extent, and consequently may vary between scalers. Furthermore, the concept of quality will vary, depending on market preferences.

Principal component analysis (PCA) is one method of making a simultaneous, objective assessment of quality-determining factors. The PCA was based on data from DC-trees concerning variables for which significant differences had been found between planted and naturally regenerated stands, *i.e.* stem straightness, branch diameter, occurrence of spike knots and number of branches m^{-1} of stem. The first two principal components explained 79% of the total variation. The plot of scores showed that there were pronounced differences between planted and naturally regenerated trees (Fig. 8). However, it is difficult to interpret the meaning of the components. We could have worked with weights and uncentred data, but this method is subjective and appeared to have no advantages over direct classification of quality, based on collected data.

The trees were grouped into ten quality classes according to the model shown in Table 12. The distribution of naturally regenerated trees across the classes was quite different from that of planted trees, especially regarding the DC-trees (Fig. 9). There were also great differences between trees planted at different initial spacings, trees grown at the widest spacing being of exceptionally poor quality (Fig. 10). Although the results depend on the classification

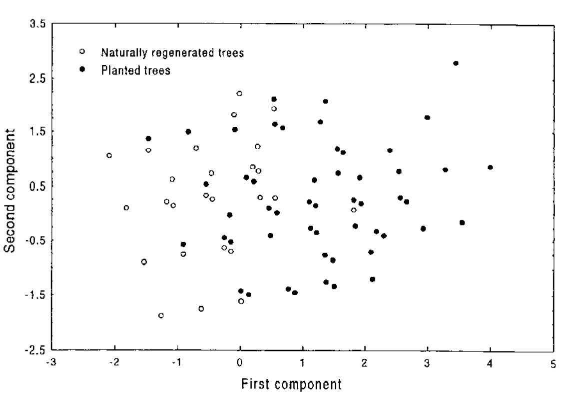

Fig. 8. PCA-analysis performed on data collected to characterise the quality of Dominant and Co-dominant (DC) trees. Stem straightness, diameter of thickest branch below 2 m, number of spike knots and number of branches m^{-1} of stem were considered. (The symbols representing naturally regenerated trees have been slightly shifted to avoid overlap.)

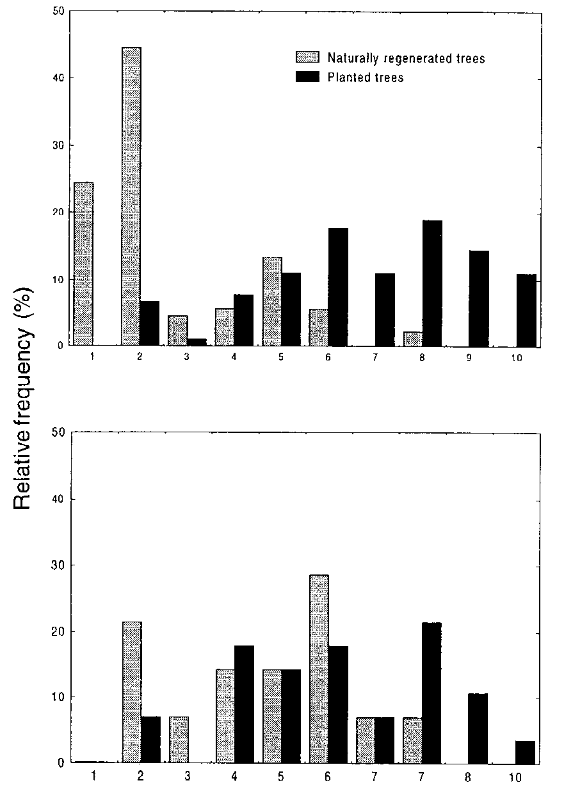

Fig. 9. Distribution of planted and naturally regenerated trees in quality classes. (Quality classes according to Table 12.) Above DC-trees. Below: PC-trees.

model used, we consider that they agree well with our visual impression of the stands.

It was possible only to analyse quality in the bottom logs and second logs, since the stands were still quite young. Since the thinning programme will maintain stand density at the same level, no great differences between planted and naturally regenerated trees are to be expected farther up the stem. This assumption is also supported by the results in Fig. 6.

It was beyond the scope of this study to consider other traits, *e.g.* wood density, fibre length, grain angle or amount of juvenile wood. Nevertheless, there is good reason to believe that such wood properties would be affected by differences in growth rate (Persson *et al.*, 1995).

Stand characteristics and volume growth

At the age of comparison (36–38 years), the naturally regenerated stands had been thinned twice, whereas the planted stands had been thinned twice to four times. As mentioned above, initial differences in stem number and

Table 12. *Classification into timber quality classes 1–10, where 1 represents the best quality. Crookedness: Straight, relative deviation <1; Slightly crooked 1–2; Crooked 2–3; Very crooked >3. Branch thickness: Very thin <12 mm; Thin 12–18 mm; Thick 18–24 mm; Very thick >24 mm*

Croookedness	No. of spike knots	Branch thickness	Quality class	Croookedness	No. of spike knots	Branch thickness	Quality class
Straight	None	Very thin	1	Crooked	None	Very thin	6
Straight	None	Thin	2	Crooked	None	Thin	6
Straight	None	Thick	5	Crooked	None	Thick	7
Straight	None	Very thick	7	Crooked	None	Very thick	9
Straight	One	Very thin	3	Crooked	One	Very thin	7
Straight	One	Thin	3	Crooked	One	Thin	7
Straight	One	Thick	6	Crooked	One	Thick	9
Straight	One	Very thick	8	Crooked	One	Very thick	10
Straight	Two or more	Very thin	5	Crooked	Two or more	Very thin	8
Straight	Two or more	Thin	5	Crooked	Two or more	Thin	8
Straight	Two or more	Thick	8	Crooked	Two or more	Thick	10
Straight	Two or more	Very thick	9	Crooked	Two or more	Very thick	10
Slightly crooked	None	Very thin	4	Very crooked	None	Very thin	9
Slightly crooked	None	Thin	4	Very crooked	None	Thin	10
Slightly crooked	None	Thick	6	Very crooked	None	Thick	10
Slightly crooked	None	Very thick	8	Very crooked	None	Very thick	10
Slightly crooked	One	Very thin	6	Very crooked	One	Very thin	10
Slightly crooked	One	Thin	6	Very crooked	One	Thin	10
Slightly crooked	One	Thick	7	Very crooked	One	Thick	10
Slightly crooked	One	Very thick	8	Very crooked	One	Very thick	10
Slightly crooked	Two or more	Very thin	7	Very crooked	Two or more	Very thin	10
Slightly crooked	Two or more	Thin	7	Very crooked	Two or more	Thin	10
Slightly crooked	Two or more	Thick	8	Very crooked	Two or more	Thick	10
Slightly crooked	Two or more	Very thick	9	Very crooked	Two or more	Very thick	10

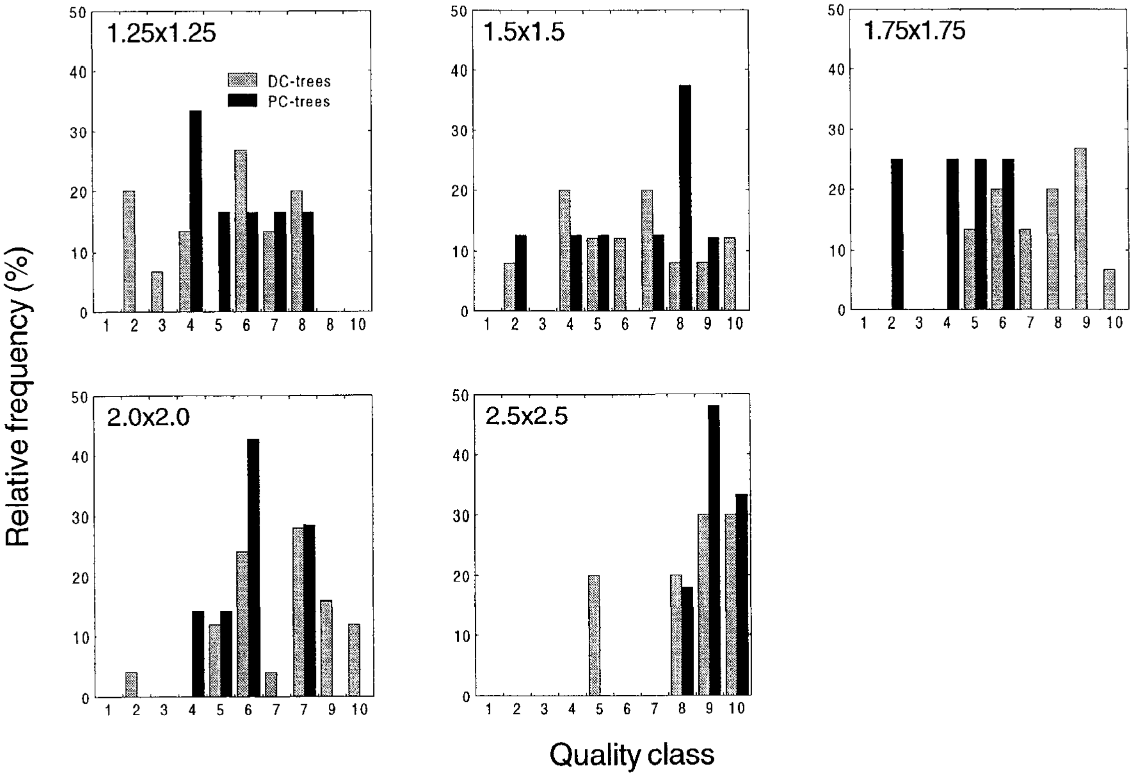

Fig. 10. Distribution of trees planted at different initial spacings in quality classes. (Quality classes according to Table 12.)

basal area between the plots were gradually equalised by fellings (Table 1). Variation in the density of broadleaved trees before cleaning was judged not to have significantly affected the comparison of volume growth or quality.

In the planted stands, volume increment was higher for close than for wide initial spacings (Table 11). This agrees well with results from other spacing experiments (*e.g.* Huuri *et al.*, 1987; Pettersson, 1992).

Volume increment was higher in planted stands with initial spacings of 2.0 m or less, than in naturally regenerated stands, although the initial number of seedlings in the latter was very high. Height growth was also generally faster in the planted stands. Similar results have been reported in other studies (Kardell, 1986; Ackzell, 1993). The stands did not differ with respect to genetic origin or site conditions. The differences in volume increment were therefore probably due to the regeneration method *per se*. One reason for the slower growth in the naturally regenerated stands may have been that young seedlings were subjected to competition from shelter trees and other vegetation. In addition, the nutritional status of the seedlings may have been better in the planted stands, which should have resulted in faster establishment and more rapid early growth.

When comparing volume growth in the planted and naturally regenerated stands, one should also consider the growth of shelter trees, the age of planted seedlings and growth during the remainder of the rotation. An attempt was made to take these circumstances into account. Seedling age at the time of planting was set to two years, and the rotation age was set to 80 years. A growth simulator was used to estimate growth after the observation period (Ekö, 1985). On average, growth during the whole rotation for stands planted at spacings of 1.25, 1.5, 1.75, 2.0 and 2.5 m was estimated at 112, 106, 104, 99 and 96% of that in the naturally regenerated stands. These estimates agree well with the calculations made by Elfving (1981).

Conclusions

- On moderate to fertile sites in southern Sweden, the quality of Scots pine timber in naturally regenerated stands will be higher than that in stands planted at normal densities (*ca.* 2 500–4 000 seedlings ha^{-1}).
- Planting density has a great effect on future timber quality.
- The most significant differences in timber quality between planted and naturally regenerated stands were found for stem straightness and branch diameter.
- Timber quality can be improved through selection. However, in widely planted stands the quality will remain very poor.
- The volume growth of stands planted at high densities ($>$2 500 ha^{-1}) is expected to be 5–10% higher compared with that of naturally regenerated stands.

When drawing conclusions from this study, it should be borne in mind that the outcome, especially after natural regeneration, is highly dependent on site conditions, seed production, method of scarification, weather, length of shelter period, *etc.* Breeding and the genetic traits of the plant material may also affect the conclusions. Site fertility should also be considered, since branch diameter is correlated with growth rate.

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Erratum: Fig. 10—all x-axis scales from 1–10.