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Graded quality of 30-year-old Norway spruce grown on agricultural and forest land

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Studia Forestalia Suecica
No. 203 • 1997

ISSN 0039-3150
ISBN 91-576-5553-7

Abstract

Norén, A. & Persson, A. 1997. Graded quality of 30-year-old Norway spruce grown on agricultural and forest land. *Studia Forestalia Suecica 203*. 19 pp. ISSN 0039-3150. ISBN 91-576-5553-7.

Six 30-year-old, fast-grown Norway spruce (*Picea abies* (L.) Karst.) stands in Sweden, comprising a total of 700 stems, were examined. Four had been planted on agricultural land and two on very fertile forest land. The characteristics studied were branch properties, defects and basic density as well as the graded quality of timber, assessed by Swedish export grading, and the modulus of elasticity, assessed by machine strength grading (E_M). Our aim was to determine how the wood properties of Norway spruce grown on agricultural land differ from those of spruce grown on fertile forest land. The only differences found between the two sites concerned defects, especially spike knots. These were more common in the agricultural stands, where the frequency of logs with at least one spike knot was 33.7%, whereas the corresponding figure in the forest stands was 6.9%. The graded quality was low for boards from all stands according to both export and strength gradings. Only 7.1% of the boards were considered to be of highest export grade, u/s. Eighty-two per cent were approved for structural use, i.e., strength grade T18 or better. Basic density and annual ring width were the only characters that explained significant amounts of variation in E_M. A model for predicting the E_M of boards from a stand is presented. Wood properties could be improved silviculturally by thinning regimes and technically by cross-cutting and using the butt part of the tree for purposes other than sawing.

Key words: Fertile land; silviculture; modulus of elasticity; branch properties; basic density; defects; strength grading; export grading.

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MS. received December 1996
Revised MS. accepted December 1997

Abbreviations and definitions

E_M	Modulus of elasticity, calculated from machine strength grading measured on the flat surface of timber running through the machine.
E_T	True modulus of elasticity, measured statically on the edgeface.
K-grading	The export grading of boards, based only on knot properties, classes as above.
KD-grading	The export grading of boards, based on both knot properties and defects, classes in order of decreasing quality: u/s, V, VI and reject.
MOR	Modulus of rupture (bending strength).
p	Significance level.

Stands

F1	Forest stand, Källslätten
A1	Agricultural stand, Siljansfors
A2	Agricultural stand, Högsten
A3	Agricultural stand, Kullsjö
A4	Agricultural stand, Åsakullarna
F4	Forest stand, Kohagen

Quality characters assessed

Assessments performed before felling

Branch characters within the stem section 1 to 2 m above ground for branches ⩾10 mm, excluding spike knots:

BR	Number of branches
TBD	Diameter of thickest branch, perpendicular to the branch's long axis over bark (mm)

On the lower 4 m of the stem any damage is described, with its position

At breast height (1.3 m above ground):

DBH	Diameter, calipered in one convenient direction over bark (mm)

Assessments made after sample tree was felled:

Heights from the stump to the stem top (m)

HLB	First living branch (m)

At breast height (1.3 m above ground):

RW	Mean annual ring width (mm)
W5	The width of 5 annual rings, 2 cm from the pith and outwards (mm)
BD	Basic density (kg m^{-3})

Introduction

The current grain surplus in northern Europe has caused the rate of afforestation of agricultural land to increase in recent years. Such land has mainly been planted with Norway spruce (*Picea abies* (L.) Karst.).

There are basic differences between Norway spruce grown on agricultural land and that grown on forest land. Agricultural land is highly fertile, and normally is situated on level, sedimentary soil. Such soils contain a plough pan 0.3–0.4 m thick, and have a variable content of organic matter. Spruce stands on agricultural land usually are planted. The homogeneous soil makes it possible to create extremely regular initial spacings, giving high stocking levels.

Over an 80-year rotation, the total yield of Norway spruce is generally 50 to 100 m^3 ha^{-1} higher on agricultural land than on forest land with an equivalent site index (dominant height at age 100 years; Hägglund, 1981; Johansson & Karlsson, 1988). The higher stocking on agricultural land is one reason for the higher yield.

Due to its high growth rate, Norway spruce grown on agricultural land may be expected to have poorer branch properties and a higher proportion of juvenile wood, than Norway spruce grown on forest land. Juvenile wood is formed close to the pith and is characterised by gradual changes in wood properties with distance from the pith (Zobel, Webb & Henson, 1959; Bendtsen, 1978).

Silvicultural methods that reduce the growth rate of young trees, and lengthen the rotation, reduce the amount of juvenile wood produced (Danborg, 1994*a*). Fast-grown Norway spruce with a high juvenile wood content generally has poor strength properties (Schaible & Gawn, 1989; Shivnaraine & Smith, 1990; Kliger, Perstorper, Johansson & Pellicane, 1995).

Other important factors that affect quality grading include severe defects associated with

Norway spruce grown on agricultural land, such as root and butt rot (Vollbrecht & Agestam, 1995), warp (Danborg, 1994*b*; Perstorper, Pellicane, Kliger & Johansson, 1995) and stem cracks (Persson, 1994). In addition, frost damage can result in deformities such as crooks, spike knots and double stems (Ilstedt & Eriksson, 1986). The frequency and severity of such defects can be reduced by silvicultural means, e.g. by dense initial spacing (Persson, 1994), choice of provenance (Persson & Persson, 1992) and thinning regime (Vollbrecht & Agestam, 1995).

Wood properties of Norway spruce on agricultural land have been studied by Handler & Jakobsson (1986), Persson, Ganered & Ståhl (1987), Handler (1988), Johansson, Nylén & Yngvesson (1992*b*) and Kucera (1992), among others. A trial with an extremely wide spacing, situated on agricultural land, was studied by Persson *et al.* (1987). The quality of wood obtained from the stand was very poor: both basic density and strength were considerably lower compared with wood produced on forest land. Furthermore, of the boards subjected to strength grading, only 22% were approved as construction wood (T18 or better).

The initial spacing is one of the most efficient ways of influencing branch properties. On stems from stands with a dense initial spacing, the branches are thinner and the height to the first living branch is greater, compared with stems from stands with a wide initial spacing (Handler & Jakobsson, 1986; Handler, 1988; Johansson, 1992).

Export grading

Branch properties and wood defects are the most important factors considered in Swedish export grading (Anon., 1982). To improve substantially the quality of Norway spruce timber, evaluated according to Swedish export grading rules, the initial spacing on fertile sites in southern Sweden should be less than 1.5 m (Johansson, 1992). A precommercial thinning experiment with Norway spruce seedlings planted on agricultural land, revealed no differences in the wood quality, as determined by export grading, between regimes in which density after thinning ranged from 1 800 to 93 000 stems ha^{-1} (Johansson *et al.*, 1992*b*).

Strength grading

Strength properties are very important quality factors, especially for structural timber. Strength is influenced by factors such as basic density, knot properties and defects. Two important strength properties are modulus of rupture (MOR) and modulus of elasticity (E_T). In Norway spruce, E_T is the factor with the highest correlation with MOR (Foslie & Moen, 1972; Brundin, 1981). Other factors with good correlations with MOR include annual ring width, specific gravity and knot properties (Foslie & Moen, 1972; Harvald, 1988). The E_T of Norway spruce shows a high positive correlation with basic density (Foslie & Moen, 1972; Lundberg & Thunnell, 1978; Brundin, 1981; Harvald, 1988; Høibø, 1991) and negative correlations with branch number and size (Lundberg & Thunnell, 1978; Harvald, 1988).

The relationship between true modulus of elasticity (E_T) and MOR is affected by a number of factors. For instance, the E_T/MOR ratio was found to be lower for u/s than for VII timber grades (Brundin, 1981). Furthermore, the relationship between E_T, and the modulus of elasticity calculated from machine strength-grading (E_M), differed somewhat between spruce timber from southern and that from northern Sweden (Brundin, 1981). In a Danish study, the relationship between MOR and E_T did not differ between sites (Harvald, 1989*b*). However, a study of small, clear specimens indicated that the strength properties of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) did differ between sites (Sunley & Lavers, 1961). Høibø (1991) suggested that the correlation between bending strength and basic density is stronger on fertile sites. It might be expected that strength values in timber from extreme sites, such as that produced in very fast-growing stands, e.g. Norway spruce from agricultural land, would diverge from average values.

Machine strength-grading is a non-destructive and objective method of predicting the strength of timber. The method, developed in the early 1960s (Hoyle, 1961; Senft, Suddarth & Angleton, 1962), has been used by the forest products industry in Sweden since 1974. The principle of machine strength grading is to calculate the modulus of elasticity (E_M) from measurements made on the flat surface of timber passing through the strength-grading machine. The basic principles have been described by Brundin (1981), Johansson & Claesson (1989) and Johansson & Johansson (1987), among others. E_M gives a good prediction of the true modulus of elasticity (E_T), assessed by static bending on the edgeface (e.g. Hilbrand & Miller, 1966; Brundin, 1981; Johansson, Brundin & Gruber, 1992*a*); accordingly, it also predicts MOR (e.g. Foslie & Moen, 1972; Brundin, 1981; Boström, 1994).

The strength properties of timber originating from fast-grown Norway spruce stands, in which the stems had wide rings and a low basic density, were inferior to those of timber originating from slow-grown stands (Kärkkäinen & Hakala, 1983). Some silvicultural methods affect strength properties. For example, the amount of strength-graded Norway spruce timber approved for structural purposes increased with decreasing initial spacing (Høibø, 1991; Johansson, 1992). Significant variation in MOR and E_T was also found among provenances of Sitka spruce (Ishengoma, 1986; Ishengoma & Nagoda, 1986). Heavy thinning regimes tend to produce Norway spruce timber with low values of MOR and E_T (Moltesen & Madsen, 1979; Harvald, 1989*a*).

No comparisons have hitherto been made between the strength properties of Norway spruce grown on agricultural land and those of spruce grown on forest land. Nor has the relationship between the quality characteristics of standing trees and the strength properties of corresponding timber previously been studied. If these relationships can be elucidated, it should be possible to identify before felling those trees or stands which have superior strength properties.

The aim of this study was to determine to what extent the wood properties of Norway spruce grown on agricultural land differ from those of spruce grown on fertile forest land. The effects of certain silvicultural methods were also evaluated. The characteristics studied were branch properties, damage, basic density and the graded quality of timber, as assessed by Swedish export-grading and machine strength-grading.

Materials and methods

Stand description

Six Norway spruce stands in southern and central Sweden were studied; four on agricultural land, designated 'the agricultural stands', and two on very fertile forest land, designated 'the forest stands'. The forest stands were chosen for their similarity with their paired agricultural stand (A1-F1 and A4-F4) in terms of site index, diameter, spacing and plant material. From their field- and ground-layer vegetation, all sites can be classified as a moss-rich type with low herbs. Characteristics of the stands at the time of sampling are described in Table 1. Stands were sampled at the first thinning, except stand A3,

Table 1. *Characteristics of the stands at the time of sampling. Overall mean and stand mean values. (The stands are described in detail in Appendix 1.)*

	Stand and denotation						
	All stands	Källslätten F1	Siljansfors A1	Högsten A2	Kullsjö A3	Åsakullarna A4	Kohage F4
Latitude		60°38′N	60°53′N	59°13′N	58°30′N	58°55′N	58°55′N
Longitude		15°28′E	14°20′E	16°48′E	13°35′E	12°25′E	12°25′E
Altitude, m		235	248	50	120	70	100
Past management		Forest	Agricult	Agricult	Agricult	Agricult	Forest
Site quality class, m[a]	33	27	29	35	38	34	35
Total age, years	30	28	29	28	34	28	30
Initial spacing, m	1.9	2.3	2.1	1.5	1.5	2.0	2.0
Stems/ha	2153	2077	1917	3088	–	1825	1860
DBH, basal area weighted, mm	172	156	140	164	209	185	180
Height, arithm., m	12.3	10.0	9.0	12.5	15.3	14.7	12.2
No. of sample trees	700	77	90	90	141	152	150
No. of logs sawn	451	26	60	44	141	110	70

[a] Site quality class is the dominant height at 100 years of age (Hägglund, 1981).

Table 2. *Limits (DBH, mm) of the dimension class quantiles*

Dimension class	Stand					
	F1	A1	A2	A3	A4	F4
1	<161	<160	<161	<181	<156	<170
2	162–170	161–169	162–165	182–191	157–173	171–181
3	171–187	170–178	166–172	192–205	174–189	182–192
4	188–205	179–187	173–184	206–223	190–202	193–215
5	>206	>188	>185	>224	>203	216

which was sampled at the second thinning. In total, 700 stems were randomly sampled.

Field assessments

The site quality of the stands was determined according to Hägglund (1981). All stems in the stands were calipered on one diameter at breast height (DBH, 1.3 m). From each stand a random sample of 60–150 trees was taken.

Before the sample trees were felled, quality assessments were made as described above (p. 3). At breast height, two horizontal increment cores, with a diameter of 5.0 mm, were taken to the pith on the south- and west-facing sides of trees.

Butt logs of 4 m length were cut. Those with a top diameter greater than 140 mm were classed as sawtimber. Double stems and stems with cracks or with root and butt rot were avoided when choosing logs intended for sawtimber.

To assess how different thinning regimes would affect the wood properties and grading results, the stems were divided into diameter quantiles according to their DBH. Since the DBH distribution differed among the stands, the quantiles were defined for each stand (Table 2).

Export grading

The logs were sawn on the experimental circular saw at the Swedish University of Agricultural Sciences, Garpenberg. From each log, two central yields were sawn into boards, as large as possible, of either 38 × 75, 50 × 100 or 50 × 150 mm dimensions.

Wood quality was assessed by the same scaler before and after sawing. Assessments were made using Swedish export rules (Anon, 1982), which deal mainly with defects and with the number, size and position of knots. The quality of logs was estimated from the surface, by judging the future quality of the central yields. In order of decreasing quality, the classes are u/s (unsorted mixture of classes I-IV), V, VI and reject. Wane and other technical defects were not considered. The grading was carried out in two ways: in K-grading, only the knot properties were considered, while in KD-grading, both knot properties and defects were considered.

Strength grading

After air-drying, the boards were planed to one of the following dimensions: 34 × 70, 45 × 95 and 45 × 145 mm. Before the boards were machine strength-graded, their moisture content was measured using a Timbermaster (Model 71T, Protimeter Ltd., Marlow, Bucks., England). The moisture content was 12–16%.

Strength grading was carried out with a Cook-Bolinder SG-AF machine (Cook Bolinders Ltd., England; Anon., 1978; Brundin, 1981). The machine measures the reaction that develops when timber is bent until it reaches a predefined deflection. The predefined deflection is varied, depending on the dimensions of the timber used. The measurements were performed on the flat surface of boards passing through the strength-grading machine at 94 m min^{-1}. To compensate for any crooks, the boards were bent twice; i.e. each board was bent in the two opposite directions perpendicular to the flat surface. For each board, the force required to bend it to a given deflection was measured at intervals of 0.1 m on each face, except the last 0.6 m at each end. The average value for the two faces was calculated for every 0.1 m.

E_M for each board was calculated from equation 1 (Brundin, 1981) based on the minimum average force of reaction:

$$E_M = \frac{F * s^3}{48 * \delta * I} \qquad \text{[Eq. 1]}$$

where $I = w*t^3/12$

E_M = Modulus of elasticity, MPa
F = Force of reaction acting on the timber in the grading machine, kN
s = Span, the distance between the support rollers; 900 mm
δ = Deflection of board, mm
I = Moment of inertia
w = Width of board, mm
t = Thickness of board, mm

The timber was sorted into four classes in order of decreasing stiffness, viz. T30, T24, T18 and Reject, where T18 is the lowest class approved for structural use. The strength classes were calculated according to PFS 1980:1 (Anon., 1980). The number following the 'T' in the class name indicates that the characteristic MOR of at least 95% of the sorted timber is 30, 24 and 18 MPa, respectively (Brundin, 1981).

Assessments on cores

The total width of five annual growth rings, measured outwards beginning 2 cm from the pith, was measured by micrometer.

The increment cores were cut into sections, each section consisting of three annual rings. The length of each section was measured by micrometer, and the basic density of the sections was subsequently determined by mercury displacement (stands A2, A3, A4; Ericson, 1966) or water displacement (stands A1, F1, F4; Olesen, 1971).

The basic density of each core was transformed, so as to be completely representative of the whole cross-section of the tree at the sampling height. Basic density was calculated by weighting the basic densities of each core section, the weight being proportional to the cross-sectional area that each segment represented. A single mean value per tree was calculated from the assessments made on two cores per tree.

A t-test was used to evaluate differences between values obtained by the two methods. On a sample of 113 sections of cores, the volume of each section was determined once by water displacement and once by mercury displacement. Since the values obtained by the two methods differed significantly ($p \leqslant 0.001$), due to the different surface tensions of the two liquids, volumes measured by mercury displacement were converted using equation 2.

$$H_2O\text{-vol} = -0.0041 + 0.979 * \text{Hg-vol} \quad r^2 = 0.99 \qquad [\text{Eq. } 2]$$

where

Hg-vol = Volume measured by mercury displacement, mm^3
H_2O-vol = Volume measured by water displacement, mm^3

Statistical analysis

Where overall means for the whole material are reported, they were calculated from the means for each stand.

Two-way analyses of variance (Scheffe's grouping) were used to evaluate differences in E_M among stands and export grading classes, and between boards with defects and boards free of defects. All E_M values were transformed by taking the natural logarithm, to meet the requirements of the test. No linear relationship was found between the stands and the diameter quantiles or the dimensions, while one-way analysis of variance (Scheffe's grouping) could be used to evaluate differences between these classes.

Since other data did not meet the requirements of the test, even when transformed, chi-square approximations (Kruskal-Wallis) were used to evaluate differences between classes. Where overall differences were significant, paired chi-square tests were performed to determine which classes differed significantly. To keep the conceptual unit for significance on an experimental level, the Type-I error probability of 0.05 was divided by the number of comparisons into equal portions (Dunn's procedure; Dunn, 1961).

Eqs. 3 and 4 were calculated by stepwise multiple regression analysis. The Pearson correlation coefficients and partial correlation coefficients are reported.

Statistical analyses were performed using the SAS statistical program package for personal computers (SAS, 1987).

Results

Quality characters

Mean values for quality characters, (a) calculated for all sample trees and (b) only for the trees that were sawn, are shown in Table 3*a*

Table 3. *Quality characteristics. Overall mean with SD, and stand mean values with SD, for all sample trees (3a) and for trees that were sawn (3b). The first n in each column refers to measurements of* DBH, HLB, BR *and* TBD; *the second n refers to measurements of* RW, W5 *and* BD. *In Table 3b, means with the same letter within rows are not significantly different at 0.05 mass significance level (Kruskal-Wallis test)*

Table 3a

	Stand						
	All stands $n=5; 6$	F1 $n=77; 67$	A1 $n=90; 60$	A2 $n=90; 77$	A3 $n=141; 113$	A4 $n=152; 141$	F4 $n=150; 150$
DBH, arithm., cm	16.2 (2.3)	14.0 (4.3)	15.6 (3.5)	14.4 (4.0)	20.3 (2.4)	16.5 (4.1)	16.1 (4.1)
HLB, m	2.8 (2.1)	0.7 (0.5)	2.1 (1.2)	4.3 (1.4)	–	5.8 (1.9)	1.2 (0.8)
BR	13.8 (0.9)	13.4 (5.1)	15.1 (4.9)	12.8 (4.4)	–	13.7 (5.1)	14.0 (4.7)
TBD, mm	18.5 (0.9)	18.7 (5.8)	17.3 (3.7)	17.7 (4.0)	–	19.2 (5.4)	19.5 (5.1)
RW, mm	3.9 (0.4)	3.6 (1.0)	3.9 (0.7)	3.6 (0.8)	4.7 (0.8)	3.6 (0.8)	4.1 (0.8)
W5, mm	22.4 (2.5)	18.7 (5.8)	22.2 (4.6)	21.3 (5.4)	26.0 (6.6)	24.0 (5.7)	22.3 (4.9)
BD, kg/m^3	349 (20)	363 (34)	318 (24)	357 (43)	341 (35)	347 (30)	348 (26)

Table 3b

	Stand						
	All stands $n=5; 6$	F1 3 $n=24; 14$	A1 9 $n=58; 29$	A2 4 $n=40; 31$	A3 8 $n=125; 99$	A4 5 $n=108; 100$	F4 6 $n=63; 63$
DBH, arithm., cm	18.7 (1.1)	18.8 b	17.6 a	17.6 ab	20.4 c	18.5 b	19.4 b
HLB, m	2.9 (2.2)	0.6 a	2.4 c	4.6 d	–	5.8 e	1.2 b
BR	15.1 (0.4)	15.8 bc	16.0 bc	14.1 a	–	14.6 ab	15.3 bc
TBD, mm	20.7 (1.0)	24.0 de	17.6 a	19.0 ab	–	20.7 bc	22.4 d
RW, mm	4.4 (0.3)	4.4 cd	4.3 bc	4.2 b	4.9 e	3.9 a	4.7 de
W5, mm	25.4 (1.1)	23.8 a	24.9 a	27.1 bc	25.3 a	26.2 ab	25.0 a
BD, kg/m^3	335 (13)	346 b	309 a	339 b	342 b	341 b	335 b

and *b*. The branch properties differed little among stands, with the exception of height to the first living branch, which ranged from 0.6 (F1) to 5.8 m (A4) for the sawn trees. Chi-square tests showed significant differences ($p \leqslant 0.001$) among all stands for height to the first living branch. The mean diameter of the thickest branch was 20.7 mm for all sawn trees.

Chi-square tests showed that the quality characters differed significantly ($p \leqslant 0.05$) between diameter quantile classes. The low quantile classes had a smaller ring width and branch diameter and a higher basic density and height to the first living branch, than did the high quantile classes.

Defects

Logs from the two forest stands had a lower frequency of spike knots (6.9%) compared with logs from the agricultural stands (33.7%; Table 4). According to the chi-square tests, the frequency of root and butt rots and stem cracks did not differ significantly between forest stands and agricultural stands. Boards from stand A1 had a higher frequency of root and butt rots than boards from the other stands. The relatively high frequency of 'other defects' in the A2 boards was mainly due to the presence of compression wood.

Export grading

Two per cent of all boards were classified as u/s. Since the frequency of u/s and VII grades was low, the frequencies are shown in groups of u/s-V and VI–VII (Fig. 1). The u/s proportion ranged from 0–27%, depending on the stand of origin and on the dimensions of the KD-graded boards. The corresponding range for K-graded boards was 0–36%. Paired chi-square tests on data for 45 × 95 mm boards showed that K-grades for stand F4 were significantly

Table 4. *Frequencies (%) of stems in the stand (S), logs (L) and baords (B) with at least one defect. More than one defect may occur per stem/log/board. Technical defects and wane are ignored*

		Stand					
		F1	A1	A2	A3	A4	F4
Spike knot	S	13.0	23.3	30.9	–	38.2	13.4
	L	3.8	35.0	19.5	42.6	37.6	10.0
	B	10.2	13.4	12.5	25.0	19.0	6.4
Root and butt rot	S	0	0	5.6	–	1.4	8.7
	L	3.8	0	0	3.5	0.9	2.9
	B	8.2	17.6	3.8	3.6	3.8	7.1
Stem crack	S	0	0	0	–	1.4	0.7
	L	0	3.3	0	1.4	1.8	1.4
	B	2.0	3.4	0	0.7	0	8.6
Stem fracture	L	0	1.7	0	0	0	0
	B	2.0	7.6	1.7	8.9	4.3	2.1
Other defects	L	0	0	0	0.7	5.5	0
	B	4.0	1	12.5	1.4	3.3	2.8
No. defects	S	87.0	76.7	50.9	–	61.2	79.3
	L	84.6	66.7	75.6	54.6	55.0	52.9
	B	73.5	54.6	71.3	63.6	70.1	67.9

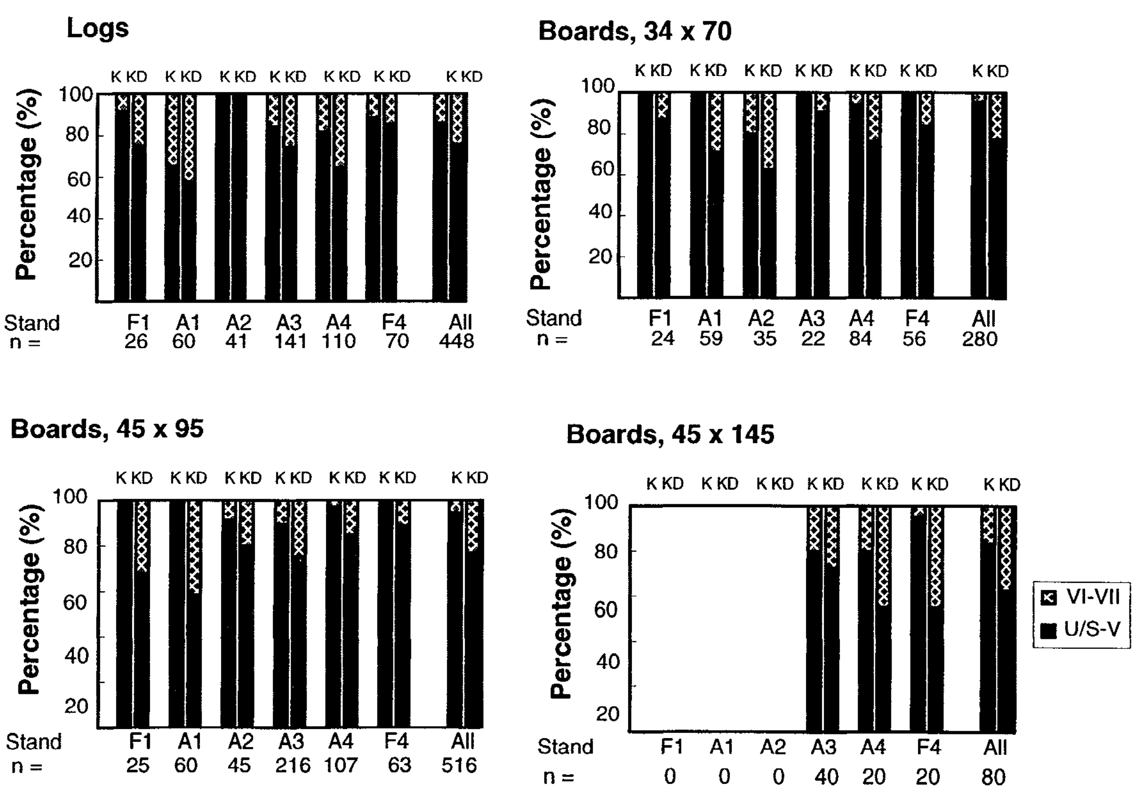

Fig. 1. Frequencies of export-graded K- and KD logs and boards, by stand and dimension. (KD-graded boards were export-graded on the basis of both knot properties and defects. K-graded boards were export-graded on the basis of knot properties alone).

Table 5. *Mean frequencies of samples scored as u/s-V grade and mean E_M for the butt- and top-halves of the boards, overall mean and stand mean values*

	Stand						
	All stands	F1	A1	A2	A3	A4	F4
Frequency u/s-V (%):							
Butt half of the boards	78.6	84.8	64.3	73.6	76.4	86.8	83.8
Top half of the boards	84.9	91.3	70.4	87.4	87.2	88.2	83.8
E_M distribution (MPa):							
Butt half of the boards	6688	6551	6445	6003	6997	6520	6973
Top half of the boards	7510	8049	6459	6367	8070	7778	7387

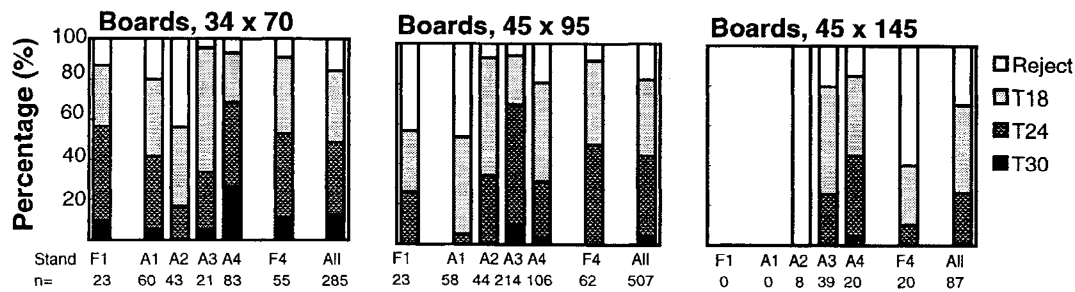

Fig. 2. Frequencies of reject, T18, T24 and T30 boards by stand and dimension.

higher than those for A3 ($p \leq 0.003$), and that KD-grades were significantly higher for F4 and A4 than those for A1 ($p \leq 0.003$).

The u/s-V distributions along the boards are shown in Table 5.

Strength grading

The percentage of boards approved for structural use (strength grade of T18 or better) was 82% for all boards. Depending on the stand of origin and on dimensions, the percentage ranged from 0–94% (Fig. 2).

E_M values are shown in Fig. 3 by stands. A two-way analysis of variance (Scheffe's grouping) showed that boards from stand A3 had a significantly higher E_M than those from stands A1, A2 and F1 ($p \leq 0.05$), when the dimensions were used as a block factor. Boards from stand A2 had a significantly lower E_M than boards from all other stands except A1. There was no significant difference in E_M between boards from the forest stands and those from the corresponding agricultural stands.

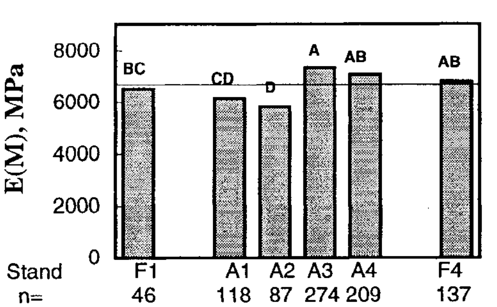

Fig. 3. Mean modulus of elasticity (E_M) for boards originating from the five studied stands. The overall mean for the stands is indicated by a horizontal line. Means with the same letter are not significantly different at a mass significance level of 0.05 (Scheffe's grouping).

A two-way analysis of variance showed that for both K- and KD-graded boards, the E_M of u/s and V class material was significantly higher than that of VI and VII graded boards (Fig. 4), when the stands were used as a block factor. However, variation was large, some boards in the u/s class being classified as Reject, and some boards in the VI class being classified as T30.

From all stands, boards with defects had significantly lower E_M values ($p \leq 0.05$; 6292 MPa) compared with defect-free boards (6850 MPa). Among boards from the forest stands, the two-way analysis of variance showed no significant difference in the E_M between boards with defects and defect-free boards, when the stands were used as a block factor. There was no significant difference between boards from stems with noticeable defects and boards from apparently

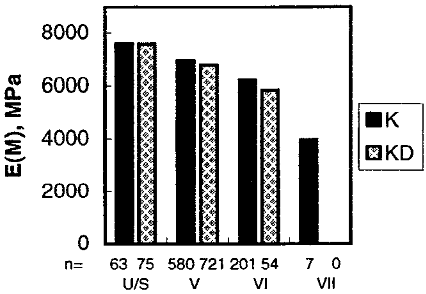

Fig. 4. E_M for boards in each of the export-grade classes (K- and KD-grading) for all stands. Means with the same letter are not significantly different at a mass significance level of 0.05 (Scheffe's grouping).

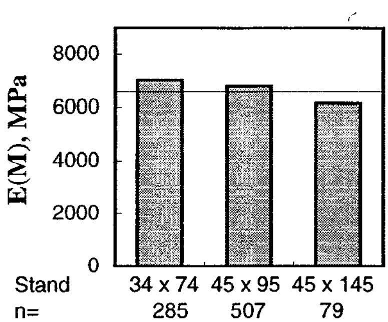

Fig. 5. E_M for boards in each of the three studied dimension classes. Means with the same letter are not significantly different at a mass significance level of 0.05 (Scheffe's grouping).

defect-free stems. The top half of the boards had a significantly higher E_M than the bottom half ($p \leq 0.05$; Table 5).

Boards of small dimensions, and boards originating from small-diameter stems, had higher E_M values than boards of large dimensions and boards originating from large-diameter stems (Fig. 5, 6). One-way analyses of variance (Scheffe's grouping) showed that, for all stands except A2, the difference in E_M was significant ($p \leq 0.003$). Nor did boards from stand A2 exhibit differences in E_M between diameter quantile classes. For the other five stands, E_M was significantly lower for quantile class 5 and significantly higher for quantile class 1, compared with other classes. For four of the stands, even quantile class 2 had a significantly higher E_M value than the other classes.

Of the quality characters studied, basic density had the highest correlation with E_M (0.42; Table 6). The same relationships are shown for each stand separately (Appendix A2).

Stepwise multiple linear regression, in which individual tree values for all stands were included, accounted for 32% of the variance in E_M, while basic density alone accounted for 24% (Table 7). In Appendix 3, regression models are shown for each stand separately. The model based on all characters presented in Table 7 is:

$$E_M = 2799 + 18.8*BD - 272.5*RW - 25.8*TBD - 50.0*BR$$

$$n = 456,\ R^2 = 0.32 \qquad [\text{Eq. } 3]$$

The model based only on quality characters measurable on the outside of the stem is (Table 7):

$$E_M = 9672 + 7.0*HLB - 139.9*DBH - 51.3*BR$$

$$n = 567,\ R^2 = 0.16 \qquad [\text{Eq. } 4]$$

Discussion

Organisation of the study: some reflexions

In our study, each agricultural and forest stand was treated as a replicate unit within a population of agricultural and forest stands, respectively, despite differences in geographical location, plant material and site. The results

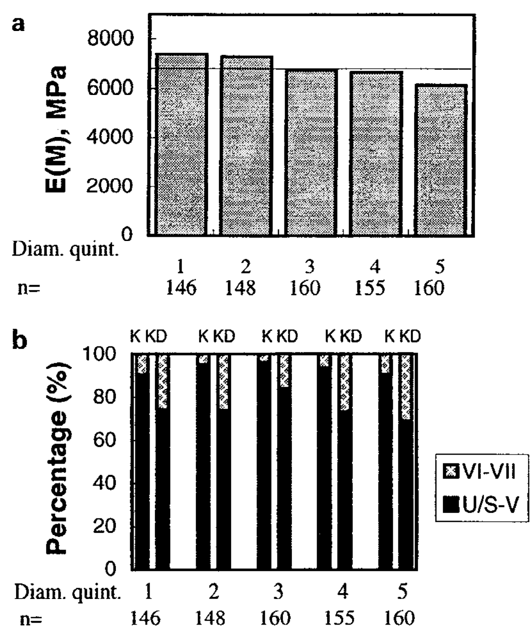

Fig. 6. (*a*) E_M and (*b*) frequencies of export grades (K- and KD-grading) for boards in each of the five diameter-quantile classes. Means with the same letter are not significantly different at a mass significance level of 0.05 (Scheffe's grouping).

Table 6. *Pearson correlation coefficients for quality characters for all stands ($n=456$ for measurements of* DBH, HLB, BR *and* TBD; *$n=567$ for measurements of* RW, W5 *and* BD*). Significance levels are marked (ns = not significant; * = $p \leq 0.05$; ** = $p \leq 0.01$ *** = $p \leq 0.001$)*

	Variables						
	E_M	*BD*	*RW*	*W5*	*DBH*	*HLB*	*BR*
BD	0.42 ***						
RW	−0.27 ***	−0.42 ***					
W5	−0.29 ***	−0.37 ***	0.46 ***				
DBH	−0.21 ***	−0.32 ***	0.69 ***	0.47 ***			
HLB	0.22 ***	0.18 ***	−0.51 ***	0.11 *	−0.19 ***		
BR	−0.25 ***	−0.04 ns	0.22 ***	0.14 **	0.23 ***	−0.23 ***	
TBD	−0.26 ***	−0.18 ***	0.48 ***	0.25 ***	0.53 ***	−0.38 ***	0.28 ***

Table 7. *Partial coefficients calculated by stepwise multiple linear regression analysis for all stands together, based on values for individual trees, using Eq. 3 and Eq. 4. The symbol ' – ' indicates that the variable was not used in the model. All variables in the model are significant at the 0.15 level*

	Material	
	Eq. 3 $n=456$	Eq. 4 $n=567$
BD	0.236	–
RW	0.028	–
W5	ns	–
DBH	ns	0.117
HLB	ns	0.014
BR	0.053	0.036
TBD	0.008	ns
Model	0.324	0.165

should therefore be interpreted as an example of how wood produced on agricultural land can differ in quality from wood produced on fertile forest land.

The provenances in four of the stands are recorded in the stand descriptions as being of local origin. This information may be unreliable, especially for the two stands in southern Sweden where, at the time of planting, provenances from continental Europe were most frequently used. Since the accuracy of this information is uncertain, the effects of provenance on wood properties are not further discussed in our study though this is an important factor. Persson & Dahllöf (1994) reported, for the same locality and initial spacing, that there were differences of about 10% in both export and machine-measured strength grades between boards from Swedish, and those from eastern European, provenances.

The export-grading classification used is subjective, the results depending entirely on the scaler's judgement. An objective classification system was not available. Subjective grading was employed to ensure that the results would have some practical value.

Because of changes in the funding available to the project, and differences in the frequency distribution of dimension classes between stands, the number of logs sampled differed between stands.

Had sawing had been carried out in such a way as to produce logs all of the same dimensions, comparison of the export- and strength-grading results would have been easier. The results of our study varied in some respects with respect to the dimensions of the logs tested. The logs were cut into boards of three different dimensions to allow grading to be carried out under conditions as similar as possible to those used in practice. Logs 4 m long were used to permit comparison between our results and earlier findings.

General trends

Branch properties

Height to the first living branch was generally low in our study (Table 3). Branch properties were analysed in two 30-year-old spacing experiments, one in Denmark on agricultural land (Handler, 1988) and one in southern Sweden on very fertile forest land (Johansson, 1992). Compared with the mean values obtained in our study, height to the first living branch in these studies was greater, i.e. 1.5–1.0 m (initial spacing 1.2–2.4 m) in Denmark, and 4.0–3.0 m (initial spacing 1.5–2.5 m) in southern Sweden. The thickest branch in our study (18 mm) was large compared with those in the southern Swedish trial, where the thickest branch (measured as in our study) ranged from 13 mm at the densest initial spacing to 19 mm at the widest spacing.

Defects

Defects such as stem cracks and root and butt rots are difficult to detect in standing trees. Thus, despite their low frequency and despite attempts to exclude trees with these defects, such defects appeared on logs and boards. Compared with fast-grown Norway spruce stands on agricultural land, reported earlier (Persson, 1994), the stands in our study had a lower frequency of stem cracks (0–9%; Table 4). However, none of the stands had an extremely wide initial spacing. The frequency of root and butt rot in our study (Table 4) agreed with the predictions of Vollbrecht & Agestam (1995), i.e. 5% at the first thinning in both forest and agricultural stands. With the exception of stand A3, which had been thinned twice, the stands had only been thinned once. The frequency of root and butt rots will probably increase after each of the coming thinnings (Vollbrecht & Agestam, 1995).

Spike knots were the most frequent defects in the logs and boards in our study (Table 4). It is difficult to predict how a spike knot in a standing tree or log will affect the quality of the resulting boards. The frequency of spike knots, noted before sawing, differed from that observed after sawing. A defect noted as a spike knot in a standing tree might be classified as a stem fracture in a board. Spike knots that have occluded are not detectable in standing trees. The frequency observed in the present study is similar to that reported in a Swedish provenance trial, where the provenances best suited to the site had a spike knot frequency of 23–49% in standing trees (Persson & Persson, 1992).

Export grading

In general, the percentage of high-grade boards was low for all plots, especially when KD-grading was used. Of the boards evaluated, only 2% were given a KD-grade of u/s. The generally low grades were expected, in consequence of the high growth rate, the high frequency of defects and the young age of the stands. Timber removed later will probably yield higher-grade boards. By comparison, 59–72% of the volume of sawn logs of Norway spruce measured by the Wood Measurement Society in southern and central Sweden during 1987–92, was classified as u/s (Anon., 1993). The proportions are not fully comparable, however, since logs of very poor quality will not be sold for sawing but for pulping.

In the southern Swedish trial mentioned above, 2–25% of the KD-graded boards of 4 m length were u/s grade, and 0–8% were VI grade, depending on initial spacing and dimensions, while the rest of the boards were given a grade of V (Johansson, 1992). Comparison of the grading results from the southern Swedish trial with the KD-grading results in our study (at the same initial spacing and dimensions; both materials graded by the same scaler) shows that the yield of u/s-grade timber was about the same in the two trials. However, by comparison with the southern Swedish trial, the frequency of boards graded VI–VII in our study (5–45%), was higher for all stands and dimensions (Fig. 1).

Although all grading was done by the same scaler, logs were frequently not given the same grade as boards sawn from them. This confirms the earlier finding that it is difficult to predict board quality by inspecting the exterior of the logs, while there are interior defects which are not visible on the surface (Becker, Groß & Metzler, 1988; Johansson, 1992). Some of the difference may be due to regional variation in wood, which was not taken into account by the scaling system. Since 1994, a new Nordic scaling system has been available, which is intended to be better adapted to the needs of the user (Anon., 1994). The Nordic scaling system had not yet been approved for use when our assessments were made.

Strength grading

In general, E_M was low on all plots (Fig. 3). The generally low grades were expected, in consequence of the high growth rate, the high frequency of defects and the young age of the stands, which cause a large proportion of juvenile wood. The results of our study can be compared with the responses to a questionnaire sent to six Swedish producers of wood strength-graded by machine. The mean relative distribution of grades for the six producers can be considered to be representative for wood strength-graded by machine in Sweden (Solli, 1995). The grade distribution of the approved timber was as follows: 41% of the boards were of grade T30, 36% were T24 and 23% were T18. The relative distribution of grades in our study, for the same dimensions, was similar to that reported from the southern Swedish trial referred to above (Johansson, 1992). Taken together, the two studies indicate that the strength of wood from young, fast-grown Norway spruce stands is generally low.

Basic density at breast height gave the best prediction of E_M for all boards (Table 6). This relationship may vary with respect to stand-related differences. The coefficients reported in Appendix 2 also show that the relation between E_M and the quality characters differed between stands. However, basic density was the character that showed the highest, and always significant, correlation with E_M in all of the stands.

The quality characters measured on standing trees accounted for approximately one-third of the total variation in E_M ($R^2=0.32$, Eq. 3; Table 7). External stem characters accounted for 16% of the variance of E_M ($R^2=0.16$, Eq. 4; Table 7). Thus basic density and growth characters explained more of the variation than did the branch properties. These findings agree with those of Foslie & Moen (1972), who found a good relationship between E_T and specific gravity, but a poor relationship with knot properties. These relationships show that for predicting E_M in the stand, the number of branches 1–2 m above ground, basic density and ring width at breast height will give a better prediction than branch properties alone.

Comparison between the agricultural and forest stands

Branch properties

Height to the first living branch was lower in the forest stands than in the agricultural stands, stand A4 having the highest mean value of the investigated stands (Table 3). The low height to the first living branch in the forest stands may be explained by the high frequency of gaps in these stands, i.e. the degree of crown closure was lower. Other branch properties did not differ between stand types.

Defects

Soil characteristics, such as pH (Evers, 1973) and moisture content (Nielsen, 1983), are known to affect the frequency of root and butt rot, which was much higher in stand A1 than in the other stands. Since other factors which influence the frequency of root and butt rot, such as age and thinning regime (Vollbrecht & Agestam, 1995), did not differ between stands, the higher incidence of root and butt rot in stand A1 may result from its soil properties (Table 4).

Boards from the two forest stands had a lower frequency of spike knots than those from the agricultural stands (Table 4). This may be due to a higher frequency of frost damage in the latter. Indeed, 41% of the spike knots were in the lower half of the log, which is where spike knots caused by frost or browsing damage would be expected to occur.

Export grading

Frequencies of u/s grade among boards from the two forest stands (F1 and F4) and their paired agricultural stands (A1 and A4) were similar, but of boards of the same dimensions, those from the agricultural stands had a higher frequency of VI–VII grades (Fig. 1). Where grades of VI–VII were assigned, the most common reason was that the boards contained defects. The outcome of K-gradings was similar for each of the two forest stands and their paired agricultural stand. These findings, together with the results concerning branch properties (Table 3) and defects (Table 4), indicate that Norway spruce grown on agricultural land, and that grown on highly fertile forest land, appear to produce wood of similar quality when evaluated by export grading based on knot properties only. However, when defects are also taken into account, boards from Norway spruce grown on agricultural land are inferior, owing to their markedly higher frequency of defects.

Strength grading

Although significant differences in E_M were found between stands, it was not possible to ascertain whether any of the quality characters contributed to determining the level of E_M in each stand. The multiple regression analysis also shows that the degree to which each of the quality characters explains E_M, differs between stands (Appendix 3). Basic density and ring width were the only quality characters significantly correlated with E_M in all six stands

(Appendix 2). It should be noted, however, that the stand with the lowest E_M (A2, Fig. 3) had the highest frequency of compression wood (Table 4). In conclusion, the agricultural stands could not be distinguished from the forest stands on the basis of E_M.

Comparison between the diameter quantiles and dimensions

The yield of K- and KD-grading from the diameter quantiles varied (Fig. 6*b*). Even though branch properties tended to be superior for the lower quantiles, the grades obtained for these classes were no higher than those obtained for higher quantiles in the K- and KD-gradings. This discrepancy may be due to the fact that logs in small diameter-classes are generally sawn into boards of small dimensions (mainly 34 × 70 mm), and grading rules stipulate that for a given knot size, small-dimension boards will be downgraded more severely than boards of larger dimensions (Anon., 1982). There was a tendency for the yield of boards of export quality to be lower for diameter quantiles 1 and 5 than for diameter quantiles 2, 3 and 4.

Stems from the lower quantiles had a significantly higher E_M compared with those from the higher quantiles. This difference can be explained by the fact that most of the quality characters of thin stems were significantly superior to those of thicker stems. Thus, compared with thick stems, thin stems tended to have a higher basic density and height to the first living branch, while their ring width and branch number and the diameter of their thickest branch, tended to be lower. Earlier studies have also revealed similar relations between these quality characters and DBH (i.e. Handler & Jakobsson, 1986; Johansson, 1992; 1993).

These relationships between export grades and strength grades, on the one hand, and diameter quantiles, on the other, can be used in thinning. The choice of stems culled from different diameter quantiles affects wood properties in the remaining stand.

The significantly higher E_M of boards of small dimensions (34 × 70 and 45 × 95 mm), compared with that of larger-dimension boards (45 × 134 mm; Fig. 5), can be explained by the fact that the former usually originated from stems with a small DBH. Foslie & Moen (1968) also found that small-dimension boards had a significantly higher E_T than boards of large dimensions.

One reason for the high values of the smallest dimension (34 × 70 mm), when classified according to T-values, is that the limits used in this study (PFS 1980:1; Anon., 1980) for the smallest dimension (34 × 70 mm) result in overestimation of the strength of this dimension (Lars Boström, personal communication, 1995). We chose to use this universal standard to be able to compare the results with strength gradings carried out by the industry today. A European standard has recently been developed (CEN 338; Anon. 1995), which will eventually become the universal standard.

Comparison between E_M and export grading classes

A correlation was found between the export grades of boards and their corresponding strength grades (Fig. 4). To some extent, the rules for export grading correspond to those for strength grading. The fact that no differences were found for E_M between K- and KD-grading within export grade classes, indicates that the rules for export grading of branch properties have a greater influence on the strength grades assigned to the boards, than do the rules for grading defects. However, the large variation of E_M within export grade classes shows that export grading is not a reliable method for judging the strength of structural wood derived from fast-grown Norway spruce.

Comparison between the butt- and top-half of boards

The frequency of samples given higher grades (u/s-V) was greater at the top end of the boards (Table 5), due to the fact that defects which result in grades of VI–VII, are more frequent at the butt-end of boards. The strength grades were also significantly higher for the top-half of the boards than for the butt-half (Table 5). This coincides well with the findings of Persson & Dahllöf (1994) whereby, independently of provenance, boards from the second log (4–8 m above ground) had a higher quality than those from the butt log (0–4 m above ground). The relationship was similar, irrespective of whether export grading or strength grading was used. One reason for those differences might be that there is often more compression wood in the butt end of stems (Timell, 1986). In view of the relationship between quality and the butt- and top-half of the boards, the practice of cross-cutting the butt logs as long as possible should be discouraged.

Conclusions and implications

Young, fast-grown Norway spruce yields low-quality wood according to both export and strength grading.

Our study indicates that defects are more frequent in agricultural than in forest stands. Agricultural stands appeared to have the greatest height to the first living branch, probably because they had a higher degree of crown closure than forest stands. Other properties of wood from fast-grown, young Norway spruce on fertile forest land appear to be similar to those of wood from fast-grown, young Norway spruce produced on agricultural land.

Quality characters measured in the stand account for approximately one-third of the variation in the modulus of elasticity (E_M). Together, basic density and ring width at breast height, number of branches (thicker than 10 mm) and thickest branch 1–2 m above ground, account for 32% of the variation in E_M. On the basis only of diameter at breast height, number of whorls and branches, and height to the first living branch (i.e. no core is taken) the modulus of elasticity can be predicted with an accuracy of 16%.

Our study has shown that at the first thinning it is possible to improve the wood properties of the remaining Norway spruce, grown on agricultural land, by the following methods:

- Culling stems with defects. The wood properties of the residual stand will be approximately equal to those of wood from fast-grown Norway spruce on forest land.
- Culling stems of small and large diameters, leaving stems of medium diameter. This will increase the yield of export-grade timber.
- Culling stems of large diameter, leaving those of small to medium diameter. This will improve branch properties, basic density and the modulus of elasticity.
- Cross-cutting a short butt log, e.g. a length of 2 m, for use as pulp- or firewood. The yield of both export-and strength-grade timber from the second log will consequently increase.

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Acknowledgements

Financial support was provided by the Swedish Council for Forestry and Agricultural Research, the Swedish Pulp and Paper Research Foundation, the Östad Foundation and the H. & S. Wingquist Foundation.

Appendix 1

Description of the six stands

Siljansfors

Experimental Forest (A1), section no. 356, Mora, SUAS, Stora Skog AB. The soil type is a cultivated podzol of sandy loamy till. The trial was planted with 2/2 seedlings of a local provenance.

Källslätten

Stand (F1), section no. 66–55, Falun, Stora Skog AB, is an ordinary Norway spruce stand on forest land. The stand was chosen owing to its similarity in terms of age, spacing, diameter, plant material, etc., with the stand at Siljansfors. The soil type is an iron podzol of sandy till.

Högsten

Stand (A2), trial no. S 1080, Malmköping, formerly owned by Holmens Bruks & Fabriks AB, is one of 73 sample plots in a nation-wide trial run by the Department of Reforestation at the

Swedish University of Agricultural Sciences (Bärring, 1967; Johansson & Karlsson, 1988). The soil type is a cultivated podzol of medium sand and medium clay. The stand was planted with 2/2 seedlings of a provenance transferred northward from Kronoberg County.

Kullsjö
Stand (A3), trial no. Eh 57, Remningstorp Experimental Forest, Skara, is a progeny trial established by the Department of Forest Genetics, Swedish University of Agricultural Sciences. Four different provenances are represented: the local provenance, Holminge, Manglidsberget and Schwarzwald. The soil type is a cultivated podzol of sandy silty till. The stand was planted with 2/2 seedlings.

Åsakullarna
Stand (A4), section no. 761, Östad Experimental Forest, Alingsås. The aim of the trial at Åsakullarna was originally to evaluate different types of planting method. The soil type is a cultivated podzol of sandy silty till. The stand was planted with 2/2 seedlings of a local provenance.

Kohagen
Stand (F4), section no. 1226, Östad Experimental Forest, Alingsås. Kohagen is an ordinary Norway spruce stand on forest land. The stand was chosen owing to its similarity in terms of age, spacing, diameter, plant material, etc., with the stand at Åsakullarna. The soil type is fine sand.

Appendix 2

Pearson correlation coeffficients for E_M and quality characteristics for each stand. Significance levels are marked (ns = not significant; *** = $p<0.001$; ** = $p<0.01$; * = <0.05; abbr. see Table 2)

	Stand					
	F1 $n=27; 44$	A1 $n=57; 114$	A2 $n=68; 87$	A3 $n=188; 238$	A4 $n=191; 204$	F4 $n=121; 121$
BD	0.64 ***	0.69 ***	0.31 *	0.29 ***	0.46 ***	0.56 ***
RW	−0.55 **	−0.45 ***	−0.27 *	−0.22 **	−0.40 ***	−0.58 ***
W5	−0.72 ***	−0.39 **	−0.04 ns	−0.17 *	−0.35 ***	−0.46 ***
DBH	−0.37 *	−0.34 ***	−0.03 ns	−0.30 ***	−0.50 ***	−0.55 ***
HLB	0.03 ns	0.21 *	0.52 ***	–	0.25***	0.06 ns
BR	−0.39 **	−0.09 ns	−0.23 *	–	−0.40 ***	−0.09 ns
TBD	−0.53 ***	−0.41 ***	−0.31 **	–	−0.47 ***	−0.17 ns

Appendix 3

Partial correlation coefficients from stepwise multiple regression analysis, from each stand separately. All variables in the model are significant at the 0.05 level

Stand											
F1 $n=27$		A1 $n=57$		A2 $n=60$		A3 $n=184$		A4 $n=191$		F4 $n=121$	
W5	0.52	*BD*	0.48	*HLB*	0.23	*BD*	0.09	*DBH*	0.24	*RW*	0.33
		BR	0.03	*BD*	0.08	*DBH*	0.03	*BR*	0.06	*BD*	0.09
								BD	0.05	*DBH*	0.03
								TBD	0.01	*BR*	0.02