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Modelling the inter-tree variation of knot properties for *Pinus sylvestris* in Sweden

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Abstract

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With the help of the Swedish Scots Pine Stem Bank, the variation of internal knot properties was studied between stems and stands in sections in which the vertical variation was small. By means of explanatory site, stand and tree variables, knot property models were developed to describe variation between and within stands. Much of the between-stand variation, and the lesser part of the random tree variation, in knot size, knot length and knots per whorl, was accounted for. However, knot angle was difficult to predict. This probably largely depended both on genetic control of this property, and on the measurement error caused by the low longitudinal resolution of the computer tomography scanning technique employed. Individual tree measurements of variables stable over time, such as growth-ring width close to the pith and stem diameter at the height of the lowest dead branch, were highly significant, and were the most important explanatory variables.

Key words: knot angle, knot diameter, knot frequency, knot length, models, wood quality attributes, CT-scanning.

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Introduction

In recent years, it has become common to design multi-purpose projects which involve the establishment of databases for integrated study of the entire forestry–wood chain, from silviculture to end-products, such as the Canadian Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) task force (Kellogg, 1989), a European Norway spruce (*Picea abies* (L.) Karst.) timber quality project (Nepveu, 1997), and New Zealand Radiata pine (*Pinus radiata* D. Don) research (Kininmonth, 1991). Such integrated projects commonly attempt to cover a wide range of issues related to the recovery of wood products from a forest resource. Examples of such issues are: *(i)* How to predict the interior properties of trees on the basis of site and stand characteristics, and measurements on individual trees (Kellogg, 1989; Houllier, Leban & Colin, 1995; Tian & Cown, 1997); *(ii)* How to design integrated models and conversion simulation tools for linking raw-material properties with end-user requirements (Oker-Blom, Kellomäki, Valtonen & Väisänen, 1988; Kellogg, 1989; Leban, Daquitaine, Houllier & Saint-André, 1997; Mäkelä, Vanninen & Ikonen, 1997); *(iii)* How to evaluate the effects of modified silviculture (Mitchell, 1988; Väisänen, Kellomäki, Oker-Blom & Valtonen, 1989; Maguire, Kershaw & Hann, 1991), and modified conversion processes (Johansson & Liljeblad, 1988; Lönner, 1996; Björklund & Julin, 1998); *(iv)* How to identify the optimum product mix from a given forest resource, or identify suitable raw material for specific products (Björklund, Bengtsson & Lönner, 1997). These examples illustrate how the integrated systems approach can be applied in a number of planning situations, with different requirements as to the input and output of the systems. This approach is supported by Briggs (1992), who also emphasises the need to establish links between growth models and end-product properties, in order to improve the possibilities for market research; many existing modelling efforts tend to be limited to 'low value, undifferentiated, primary commodity products'.

Knot properties are important to the utilisation of many tree species (Zhang, 1997), including Scots pine (*Pinus sylvestris* L.) in Sweden. The number of knots, knot diameter and knot type (sound, loose, black, rotten, *etc.*) is included in visual grading rules for sawn timber in the Nordic countries (Anon., 1994), whereas branch diameter and branch type (green or dead) are the most important quality attributes in grading of logs in Sweden (VMR, 1995). Knot angle may be important from the point of view of utilisation, because it influences both the size of knots as seen on the sawn timber surface, and the knot volume within sawn timber.

Scots pine is a uninodal species, and forms no internodal branches. The internal knot structure is thus composed of knots distinctly grouped into whorls. All knots first have a sound (intergrown) part starting from the pith and, below the live crown, a loose (encased) part (Kollman & Coté, 1968; Panshin & de Zeeuw, 1980). After a period of decay, knots become occluded as new growth rings are formed around the dead branch stub. These knot types are often used to identify three radial-longitudinal knot type zones within stems, *viz.* a sound-knot zone near the pith, a loose-knot zone, and a knot-free zone near the stem surface (Platzer, 1937; Schöpf, 1954; Dietrich, 1973; Kärkkäinen, 1986; Väisänen *et al.*, 1989; Björklund *et al.*, 1997). The distribution of these knot-type zones can form a basis for decisions regarding sawing patterns, *e.g.* in order to keep the centre boards within the sound-knot core (Björklund & Julin, 1998).

To link different components within the integrated approach, tree models must often be developed. This requires statistical models for the relationship between wood properties relevant to end-user requirements, on the one hand, and site, stand and tree variables on the other. Because of the importance of knots as a quality attribute for many solid-wood products, knot models are an important component of tree models. The Swedish Scots Pine Stem Bank (Grönlund, Björklund, Grundberg & Berggren, 1995), upon which the present study was based, is an example of an integrated project for which tree model development is one objective.

The aims of this investigation were: *(i)* To study the variation between stems and stands in terms of internal knot properties (diameter, sound length, loose length, longitudinal angle and number of knots per whorl) of Scots pine in Sweden, on the basis of the Swedish Scots Pine Stem Bank; *(ii)* To study the correlations between various knot properties; *(iii)* To develop knot-property models based on site, stand and tree variables. The vertical variation within stems was not within the scope of this study.

Material and methods

The study was based on the Swedish Scots Pine Stem Bank (Grönlund *et al.*, 1995; Grönlund, Grundberg & Grönlund, 1996), a database jointly developed by the Department of Wood Technology (Luleå University of Technology), the Swedish Institute for Wood Technology Research, the Department of Forest-Industry-Market Studies, and the Department of Forest Yield Research (SLU). The database contains information on 198 Scots pine stems from 33 well-documented research plots (stands) in Sweden (Fig. 1, Table 1). The plots were chosen so as to give a broad range of latitude, site index, regeneration method, and thinning strategy. The stems were divided into three breast-height diameter classes (*DBH-CLASS*) around the stand mean quadratic DBH, with class limits at 0.5 standard deviations (SD) above and below this mean. From each *DBH-CLASS*, two stems with similar DBH were randomly chosen close to the class mean. The mean DBH range within each class was 8, 7 and 12 mm for *DBH-CLASS I, II* and *III*, respectively. For each tree, a number of external characteristics was recorded. Table 2 shows that this stratification resulted in significant differences between *DBH-CLASS*es for DBH, growth-ring width close to the pith, and tree height, whereas height to lowest dead branch and height to lowest live branch were very similar in all three *DBH-CLASS*es.

Growth-ring width was measured at the butt end of the stem along a radius from pith to cambium. Measurements were made on digital images of conditioned discs (9% moisture content) using image-analysis techniques. By means of data from computerised tomography scanning (CT-scanning) in the green condition, growth-ring width was adjusted to the mean distance of 36 directions from pith to cambium, measured at the same height (Table 1).

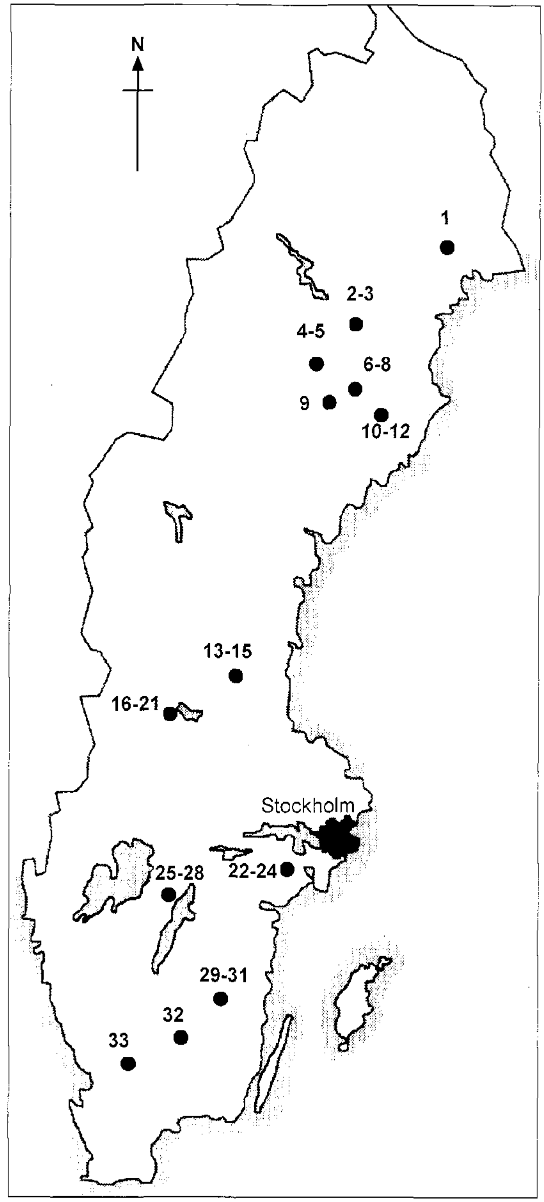

Fig. 1. Map showing the location of the sample plots.

The sawlog section of the stems was subjected to CT-scanning for detection of interior properties. After scanning, the knots (totalling approximately 46 000) were identified and described by means of digital image analysis techniques. Each knot was thus described by a model with ten parameters, giving position, diameter, length (divided into a sound and a loose part), and angles (Grundberg, 1994; Fig. 2). Whorls were defined as groups of knots separated by a specified maximum distance. This distance was

Table 1. *Stand characteristics (listed in order from N to S Sweden). Exact stand location and identification are given in Appendix A*

Stand N°	Dominant Treatment[a]	Temp sum ° days	Site index m H_{100}	Age yrs	Height m	DBH cm	Regeneration method	First thinning[b] Age yrs	Method	Mean ring width MRW_{11-20} mm
1		890	19	145	21.4	27.2	natural	58	low	1.4
2	Low thinning	620	16	139	18.1	24.7	natural	59	low	1.1
3	Crown thinning	620	16	139	17.4	24.4	natural	59	crown	1.0
4	Low thinning	850	20	144	23.3	29.4	natural	53	low	1.0
5	Crown thinning	850	20	144	22.7	28.4	natural	53	crown	1.1
6	1.5 m spacing	810	24	76	19.4	22.4	planted	39	low	2.3
7	2 m spacing	810	23	76	17.9	21.6	planted	39	low	2.4
8	2.5 m spacing	810	23	76	18.7	22.7	planted	39	low	2.6
9		800	24	72	20.0	23.7	sowing	30	low	2.2
10		880	24	77	19.5	21.8	planted	37	low	2.0
11		850	22	82	20.6	24.7	sowing	39	low	2.0
12		820	21	82	19.3	23.1	sowing	40	low	1.8
13	Low thinning	1060	20	146	23.6	37.5	natural	59	low	1.7
14	Crown thinning	1060	20	146	22.6	38.0	natural	59	crown	1.2
15		1040	22	153	24.4	35.0	natural	67	low	2.0
16	Low thinning	1070	16	122	17.7	23.2	natural	51	low	1.3
17	Crown thinning	1070	16	122	17.6	21.1	natural	51	crown	0.9
18		930	24	70	17.7	24.5	plnted	28	low	2.4
19		1000	21	127	20.1	26.0	natural	58	low	1.4
20		1000	21	127	20.0	26.6	natural	58	low	1.3
21		1050	25	85	19.3	25.1	natural	25	low	1.4
22	Low thinning	1350	27	127	27.5	40.3	sowing	37	low	1.8
23	Crown thinning	1350	27	127	24.6	35.7	sowing	37	crown	1.9
24		1340	26	110	22.6	31.9	planted	32	low	1.7
25	0.75 m spacing	1290	28	87	26.2	30.1	planted	21	low	1.5
26	1.25 m spacing	1290	28	87	25.3	34.4	planted	21	low	2.3
27	1.5 m spacing	1290	28	87	25.4	34.1	planted	21	low	2.7
28	3 m spacing	1290	28	87	25.0	38.6	planted	21	low	3.6
29		1320	25	102	23.6	31.7	natural	29	low	1.6
30	Local proven.	1310	25	88	24.7	29.1	sowing	–	low	2.3
31	North proven.	1310	25	88	25.8	29.7	sowing	–	low	2.9
32		1300	22	77	18.6	26.8	sowing	47	low	2.4
33		1380	25	102	24.6	30.2	sowing	25	low	1.8

[a]Treatment refers to silvicultural regime in planned experimental trials.
[b]Unrecorded precommercial thinnings may have preceded the first thinning in some of the older trials.

Table 2. *Sample tree characteristics by DBH-CLASSes (SD = mean standard deviation between stems within DBH-CLASS; Means not significantly different between DBH-CLASSes at $p < 0.05$ are indicated by the same letter)*

DBH-CLASS	Diameter at breast height Mean mm	SD mm	Height to lowest dead branch Mean m	SD m	Height to lowest living branch Mean m	SD m	Tree height Mean m	SD m	MRW_{11-20} Mean mm	SD mm
Small	243a	7	5.3a	1.8	12.2a	1.1	20.5a	1.1	1.64a	0.69
Moderate	286b	6	5.3a	2.0	12.5a	1.7	21.9b	1.3	1.93b	0.73
Large	331c	10	5.4a	1.6	12.4a	1.5	22.7c	0.9	2.14c	0.69

adjusted, depending on site index and height in the stem. Doubtful cases were visually inspected on the CT images.

In the present study, the analysis of knot diameter (*KD*), sound-knot length (KL_S), knot angle (*KA*) and number of knots per whorl

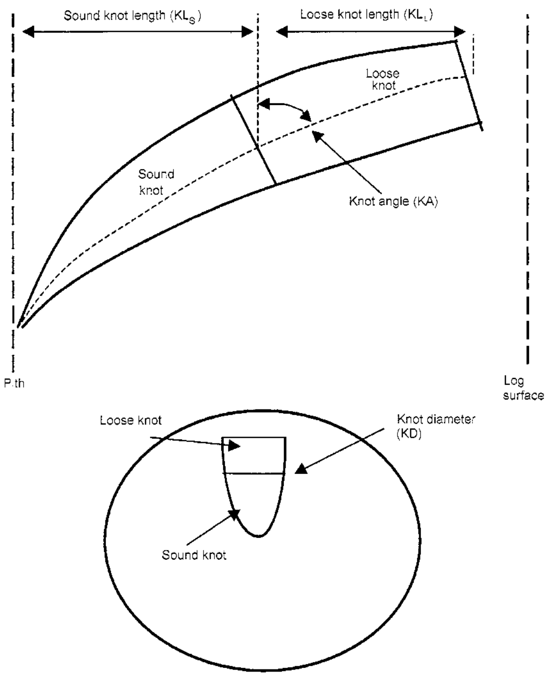

Fig. 2. Knot length, knot angle and knot diameter as recorded in this study.

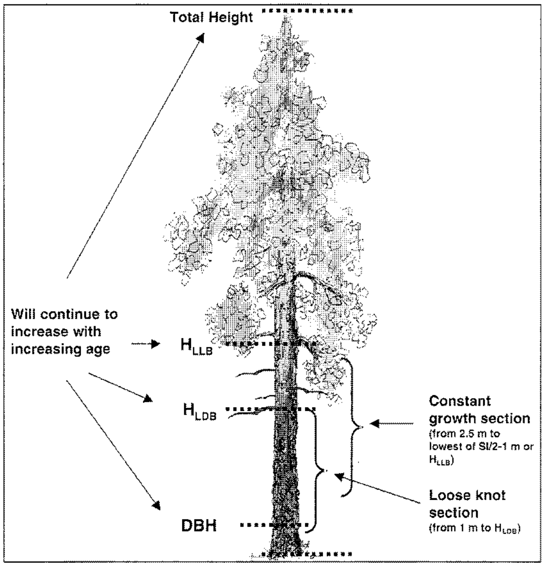

Fig. 3. The constant-growth section and the section used for analysis of loose-knot length.

(KpW) was based on observations within a stem section from 2.5 m to (SI/2–1 m), where SI is site index, the dominant height of the 100 largest trees, or to lowest living branch if this was below (SI/2–1 m). Björklund (1997) found that the diameter of the thickest knot per whorl is relatively constant within that stem section, and named it 'the constant growth section'. Øyen & Høibø (1999) similarly report that the vertical variation of the mean sound-knot length for Norway spruce is small between 10% of stem height and the live crown. Mean values of knot properties within the constant-growth section may therefore be expected to reflect the influence of site, stand and stem characteristics, and thus provide a basis for analyses of variation within and between stands. However, analysis of loose-knot length (KL_L) should be based on occluded knots only, and was therefore restricted to knots below the lowest dead branch. Therefore, a section between 1 m height and the lowest dead branch (Fig. 3) was used to model KL_L. Since large knots affect some product properties (such as stiffness) more than do small knots, knot diameter was described both as the mean of the thickest knot per whorl (KD_{max}) and as the mean for all knots (KD_{mean}). Small knots are difficult to detect with the methods employed (Grönlund, 1995; Oja, 1997); knots of diameter less than 7 mm were therefore excluded from the analyses. This limit corresponds to the smallest knot taken into account in current Nordic grading rules for sawn timber (Anon., 1994).

Variation in knot properties was initially analysed as a mixed model (Eq. 1), with the stand-level effects, the tree-level effect within each stand and *DBH-CLASS*, and the residual within-tree variation defined as random variables. Variance components were calculated for these random effects by the restricted maximum likelihood method (Littell, Milliken, Stroup & Wolfinger, 1996). Since trees were not randomly chosen from within each stand, and since the same principle for classification of trees into size classes was used in each stand, *DBH-CLASS* was treated as a fixed effect.

$$K_{ijk} = \mu + S_i + \beta_j + S_i \times \beta_{ij} + T_k(S\beta)_{ijk} + \varepsilon_{ijk} \quad (1)$$

where
K = knot property;
μ = intercept;
S = stand-level effect (i = 1–33 (see Table 1 for stand descriptions); random);
β = within-stand tree size effect of DBH-CLASS (j = small, moderate, large (see Table 2); fixed);

T = nested tree effect within S and β (k = 1–198; random);
ε = residual error (random).

In accordance with mixed-model theory, the stand values given (Table 5) were Best Linear Unbiased Predictors (BLUPs), whereas the *DBH-CLASS* values (Table 4) were least-square means (Littell *et al.*, 1996). Various preliminary attempts to account for spatial and temporal correlation among within-tree observations did not appreciably change the results or improve the model, which indicates that autocorrelation was not a problem (Littell *et al.*, 1996). Thus, no additional within-tree error structures were included in model (1).

The correlation analysis between knot properties of the constant growth section, and various stem, stand and site variables, started with the screening of a large number of growth-ring variables. These included the widths of the first 10, 20, 30, 40 and 50 growth rings, as well as interval widths from ring 11 to 20, ring 11 to 30, *etc.* The two variables which consistently gave the highest correlations were the width of 50 rings (RW_{1-50}) and the width from ring 11 to 20 (RW_{11-20}). In addition, since DBH and AGE are easily obtainable in a practical implementation, and are correlated with mean ring width at breast height, approximated RW_{mean} was also included in the regression analyses. Mean values from measurements on a number of sample trees within a stand presumably reflect the combined effect of site characteristics and silviculture. Mean values of the six sample trees may therefore be seen as stand-level variables in the correlation analysis (MRW_{11-20}, MRW_{1-50}, MRW_{mean}).

Tree size variables, such as tree height, height to live crown or DBH were not included in any model. The reason for this was that tree size will continue to change until the tree dies, whereas the knot properties of the constant-growth section will not change once they are formed. Therefore, there is a risk that possible correlations with tree-size variables may generate misleading conclusions. Instead, stem diameters at the height to lowest dead branch (D_{LDB}) and at the height to lowest live branch (D_{LLB}), as well as the difference between the two (D_{LDB}–D_{LLB}), were included. Stand sample mean values corresponding to these variables were also tested (MD_{LDB} and MD_{LLB}, respectively). The heights of these measurements will move upwards along the stem as the tree ages, and corresponding stem diameters may thus remain fairly stable over time for depicting the size of the knotty core. The difference variable could in this respect be expected to correlate with KL_L. For similar reasons, live crown length (CL) and its mean stand counterpart (MCL) were included. There is also a need to find readily obtainable variables that can describe within-stand variation. In this perspective, relative DBH (DBH_{rel}, *i.e.* tree DBH divided by stand mean DBH) appears to be a practicable option.

Three alternative sets of explanatory variables were chosen for the development of knot property models:

(A). An ambitious field inventory, in which the aim is to describe the wood properties of the standing resource base. Data collection can include, *e.g.* increment cores from sample trees, crown length and stem diameter measurements. This might be used for tactical planning of future harvesting and wood utilisation strategies, such as the choice of stands for harvesting and the specification of assortments;

(B). Like (A), but assumes that *stand age* is known and that field measurements *do not* include increment cores or stem-diameter measurements except DBH. This might also be used for tactical planning of future harvesting and wood utilisation strategies;

(C). Assumes that stand mean values from previous inventories (type (A)) are available, but that field measurements in direct conjunction with harvesting are restricted to DBH_{rel} (which can be recorded by a harvester when gripping the tree). This type might be used to evaluate the assortment distribution during the harvesting operation.

In summary, the following variables were considered:

Type (A) (2.1),

$K = f(SI,\ T_{sum},\ DBH_{rel},\ RW_{i-j},\ CL,\ D_{LDB},\ D_{LLB},\ D_{LDB}-D_{LLB})$

Type (B) (2.2),

$K = f(SI,\ T_{sum},\ DBH_{rel},\ RW_{Mean})$

Type (C) (2.3),

$K = f(SI,\ T_{sum},\ DBH_{rel},\ MRW_{i-j},\ MD_{LDB},\ MD_{LLB},\ MD_{LDB}-MD_{LLB},\ MCL)$

where

K = knot property;
SI = Site index (dominant height at age 100; m);
T_{sum} = Temperature sum (above a threshold of 5 °C), calculated as a function of altitude and latitude (Morén & Perttu, 1994; °C days);
DBH_{rel} = Relative DBH (DBH/stand sample mean DBH);
RW = Growth-ring width between ring i and j (mm);
CL = Live crown length (m);
D = Stem diameter at a specified crown location (mm).
M before a tree-level variable denotes the stand sample mean value of the variable.

Variables included in the models were selected in an initial model-screening phase, using ordinary least squares based on the following criteria: *(i)* significant at the $p < 0.01$ level; *(ii)* significant contribution to R^2adj (partial R^2adj > 0.02); *(iii)* if R^2adj was very similar, then the combination with lowest $C(p)$-value was chosen (Myers, 1990); *(iv)* at most one growth-ring variable and one stem diameter in each model. In summary, the final models were chosen to include logical variables given an intended implementation, and to give good statistics of fit while avoiding multicollinearity. The final models were fitted using a mixed-modelling approach, thus making it possible to separate the random variation into variance components (Littell *et al.*, 1996).

All statistical analyses were made by means of standard procedures of the Statistical Analysis System (SAS), version 6.12 (SAS Institute, 1989; SAS Institute, 1997).

Results

Apart from the residual variation, the most important source of variation was at stand level (Table 3). In general, the interaction between *STAND* and *DBH-CLASS* was very small, indicating that the within-stand tree size effect was similar among the stands. The random *TREE* variance within *STAND* and *DBH-CLASS* (*i.e.* the variation within tree pairs) was substantially smaller than the *STAND* variance for every knot property except knot angle.

The variation of knot properties between *DBH-CLASS*es is presented in Table 4. Significant differences were found between *DBH-CLASS*es for knot diameter, sound-knot length, and loose-knot length; large trees had larger and longer knots than small trees. The effect of *DBH-CLASS* on knot angle and number of knots per whorl was not as distinct; large trees had slightly larger angles and more knots per whorl.

Mean stand values are listed from north to south in Table 5. There was a large difference in knot size between plots: KD_{max} ranged between 15.6 mm and 36.2 mm; KD_{mean} ranged between 12.9 mm and 25.6 mm. In general, northern localities resulted in smaller knots and in fewer knots per whorl. Similar observations could be made for knot length (KL_S 40.7–80.3 mm; KL_L 29.1–52.3 mm), although the trend with latitude was not as distinct. Knot angle and knots per whorl had, in relative terms, a slightly smaller range (KA 54.0–73.7°; KpW 3.8–6.2) and no clear trend with latitude.

The material includes two initial spacing trials, five thinning trials and one provenance trial. The spacing trial in southern Sweden (stands 25–28) showed a clear tendency to thicker and longer knots with increasing spacing, whereas the spacing trial in northern Sweden (stands 6–8) did not. In most thinning trials, crown thinning resulted in thinner and shorter knots, although the difference in many cases was not significant. The northern provenance (stand 31) had slightly thicker knots, but the provenance effect was small for other properties. Knot angle and the number of knots per whorl were not substantially affected in any of these trials.

Correlations between knot properties and stem, stand and site variables are shown in Table 6. Knot diameter, knot length and number of knots per whorl were all positively correlated with variables associated with high growth rate, whereas knot angle was negatively correlated with most of them. In general, the highest correlations were found with stem variables: knot diameter was best correlated with stem-level growth-ring variables (RW_{11-20} and RW_{1-50}), and with stem diameter at the height to the lowest dead branch (D_{LDB}); knot length (KL_S and KL_L) was best correlated with D_{LDB}; knot angle showed weak correlations with all stem variables. Correlations with stand variables (*i.e.* means of stem variables for the six sample stems) followed the same pattern as correlations with

Table 3. *Variance components (V.C.) of the knot properties*

Source of variation	Diameter[a] KD_{max} V.C.	%	Diameter[a] KD_{mean} V.C.	%	Sound length[a] KL_s V.C.	%	Loose length[b] KL_L V.C.	%	Angle[a] KA V.C.	%	Knots per whorl[a] KpW V.C.	%
STAND	21.4	50	7.8	18	71.9	31	27.5	17	26.4	9	0.49	19
STAND × *DBH-CLASS*	0.8	2	0.5	1	4.4	2					0.09	4
TREE (STAND DBH-CLASS)[c]	5.3	12	2.1	5	24.6	11	21.4	13	34.1	11	0.23	9
Residual	15.7	36	34.0	76	127.7	56	116.6	70	237.2	80	1.73	68
Total	43.2	100	44.4	100	228.6	100	165.5	100	297.7	100	2.54	100

[a]Knots in constant-growth section.
[b]Knots between 1 m and lowest dead branch.
[c]The parentheses denote that *TREE* was nested within *STAND* and *DBH-CLASS*.

Table 4. *Analysis of variation among DBH-CLASS levels. A total of 198 stems divided into 2 stems per DBH-CLASS and 33 stands (means not significantly different between DBH-CLASSes at $p < 0.05$ are followed by the same letter). Number of observations and standard errors are shown in Appendix B and C, respectively*

DBH-CLASS	DBH_{rel}	Diameter[a] KD_{max} mm	Diameter[a] KD_{mean} mm	Sound length[a] KL_s mm	Loose length[b] KL_L mm	Angle[a] KA °	Knots/whorl[a] KpW No./whorl
I Small	0.85	19.7a	15.4a	47.6a	33.2a	61.7a	4.6a
II Moderate	1.00	22.6b	17.2b	55.3b	40.8b	62.8ab	4.9b
III Large	1.16	24.7c	18.5c	62.3c	45.6c	64.5b	5.1b

[a]Knots in constant-growth section.
[b]Knots between 1 m and lowest dead branch.

stem variables. For knot diameter and knot length, these correlations were somewhat lower than corresponding correlations with stem variables. For knot angle and number of knots per whorl, correlations with stand variables were in some cases higher than corresponding correlations with stem variables. Site variables (*SI* and T_{sum}) showed relatively strong positive correlations with knot diameter and number of knots per whorl, but weaker correlations with knot length and knot angle. The correlations between different knot properties were high and positive between knot diameter, knot length and number of knots per whorl, but weak and mainly negative between knot angle and all other knot properties (Table 6).

Knot-property models presented in Table 7 include parameters significant at the $p < 0.01$ level. The highest reduction of variance was attained for knot-diameter models, and very similar reductions of variance were obtained for KD_{max} and KD_{mean}. However, the standard deviation was considerably lower for KD_{mean} than for KD_{max}, indicating that KD_{mean} was predicted with greater precision than KD_{max}. Models for sound-knot length showed slightly higher reduction of variance, but also slightly higher standard deviation, than models for loose-knot length. Models for knot angle showed the smallest reduction of variance of the investigated knot properties.

For all knot properties, the difference between model type (A) (including individual tree measurements) and model type (C) (with tree variables expressed as stand means) was small.

The independent variables of model type (A) in Table 7 were introduced as covariates in Eq. 1. As is evident when Table 8 is compared with Table 3, this resulted in a substantial reduction, primarily in terms of the random *STAND* variance. The *DBH-CLASS* variable was no longer significant, and the random within-stand variation was only slightly reduced. Since no within-tree variables (such as distance from the ground) were considered in this study, the slight change in the residual variation was

Table 5. *Knot properties by stand (values are best linear unbiased predictors, see Littell et al., 1996).* Six sample stems per stand (planned trials are separated by blank lines; means not significantly different at $p < 0.05$ between treatments within trials are followed by the same letter). Number of observations and standard errors are shown in Appendix B and C, respectively

Stand N°	Dominant treatment	Diameter[a] KD_{max} mm	Diameter[a] KD_{mean} mm	Sound length[a] KL_S mm	Loose length[b] KL_L mm	Angle[a] KA °	Knots/whorl[a] KpW N/m
1		18.5	14.8	50.3	42.9	69.5	4.6
2	Low thinning	17.0a	13.6a	50.3a	36.8a	67.9a	4.1a
3	Crown thinning	17.0a	13.3a	49.1a	36.9a	68.6a	4.0a
4	Low thinning	18.7a	15.4a	51.7a	43.4a	61.6a	4.2a
5	Crown thinning	16.4a	13.4b	54.6a	41.3a	63.9a	4.2a
6	1.5 m spacing	21.2a	16.8a	49.3a	41.0	54.0a	4.7a
7	2 m spacing	22.1a	16.9a	48.8a	–	56.6a	5.0a
8	2.5 m spacing	22.0a	17.5a	51.1a	–	57.8a	4.6a
9		19.6	15.6	47.0	–	57.8	4.7
10		17.1	13.7	55.9	41.5	68.6	4.7
11		20.6	15.9	60.3	42.4	61.3	4.8
12		18.7	14.5	62.3	–	63.1	5.0
13	Low thinning	25.3a	19.6a	60.6a	46.2a	68.0a	4.6a
14	Crown thinning	21.0b	16.7b	52.3b	42.6a	73.7a	4.8a
15		23.9	18.4	54.4	44.7	70.1	4.6
16	Low thinning	18.2a	14.8a	45.2a	34.2a	64.2a	3.8a
17	Crown thinning	15.6a	12.9b	40.7a	29.1b	66.0a	3.8a
18		21.5	16.8	52.1	–	55.4	5.1
19		20.0	15.9	47.9	35.9	66.0	3.9
20		19.2	15.3	55.0	33.0	65.0	4.2
21		19.3	15.6	45.9	34.9	59.1	4.4
22	Low thinning	27.3a	19.4a	80.3a	52.3a	66.9a	5.5a
23	Crown thinning	27.1a	19.0a	66.6b	44.8b	62.2a	5.6a
24		24.5	17.6	66.1	42.6	61.3	5.3
25	0.75 m spacing	23.6a	17.6a	54.7a	37.9a	62.8a	5.7a
26	1.25 m spacing	24.9ab	19.3ab	62.9b	41.6a	60.7a	5.7a
27	1.5 m spacing	27.1b	20.4b	64.1bc	42.5a	59.6a	5.6a
28	3 m spacing	36.2c	25.6c	72.0c	–	61.5a	6.2a
29		23.7	18.0	52.7	37.7	61.7	4.7
30	Local proven.	27.1a	19.0a	53.8a	36.5a	60.7a	6.0a
31	North proven.	29.9b	22.2b	58.9a	39.9a	56.8a	6.1a
32		24.8	18.2	48.1	35.4	61.6	5.4
33		27.6	19.2	51.3	38.0	64.9	5.5

[a]Knots in constant growth section.
[b]Knots between 1 m and lowest dead branch.
–Too few observations.

due to missing annual-ring width (RW) values for some trees.

Discussion

Materials and methods

Owing to limited resources and to the fixed number of research plots available to the Swedish Scots Pine Stem Bank project, a strictly random sampling scheme could not be applied at stand level. The plots included in the Stem Bank were chosen primarily to provide substantial variation in terms of site characteristics (site index, latitude and altitude) and silviculture (stand establishment and thinning). Randomisation was chiefly applied to those plots which, by chance, were available for destructive sampling, while also providing the desired variation in site characteristics and silvicultural background. The lack of proper randomisation, the limited number of stands, and the lack of 'modern' forest management practices, implies

Table 6. *Correlation coefficients (r) between knot properties and stem, stand and site variables respectively, and correlations among knot properties at the tree and stand levels (198 stems from 33 stands)*

	Knot properties of constant-growth section (except KL_L)					
	KD_{max}	KD_{mean}	KL_s	KL_L	KA	KpW
	Correlation coefficients (r)					
Stem variables						
RW_{11-20}	0.69	0.71	0.45	0.40	−0.35	0.64
RW_{1-50}	0.75	0.75	0.59	0.42	−0.34	0.75
RW_{tot}	0.65	0.65	0.50	0.35	−0.28	0.70
DBH	0.67	0.65	0.72	0.74	0.30	0.44
DBH_{rel}	0.36	0.36	0.52	0.55	0.19	n.s.
CL	0.34	0.38	0.37	0.38	0.27	n.s.
D_{LLB}	0.44	0.47	0.52	0.60	0.39	n.s.
D_{LDB}	0.73	0.75	0.80	0.79	n.s.,	0.44
$D_{LDB}-D_{LLB}$	0.48	0.46	0.50	0.23	−0.37	0.57
Stand variables						
MRW_{11-20}	0.59	0.60	0.27	0.20	−0.42	0.67
MRW_{1-50}	0.63	0.63	0.39	0.23	−0.41	0.76
MCL	0.30	0.35	0.20	0.25	0.22	n.s.
MD_{LLB}	0.39	0.39	0.35	0.37	0.28	n.s.
MD_{LDB}	0.64	0.64	0.55	0.50	n.s.	0.44
$MD_{LDB}-MD_{LLB}$	0.41	0.38	0.33	n.s.	−0.44	0.65
Site variables						
SI	0.60	0.58	0.43	0.26	−0.34	0.69
T_{sum}	0.63	0.58	0.34	n.s.	n.s.	0.53
Knot properties						
KD_{max}	–	–	–	–	–	–
KD_{mean}	0.96	–	–	–	–	–
KL_s	0.65	0.64	–	–	–	–
KL_L	0.53	0.54	0.75	–	–	–
KA	−0.15	−0.19	n.s.	n.s.	–	–
KpW	0.63	0.55	0.47	0.34	−0.29	–

n.s.–not significant at $p<0.05$.

that the variation of the studied knot properties cannot be assumed to represent the current, entire Swedish forest resource of Scots pine in a strict statistical sense. However, the Stem Bank covers a wide range of pine forest sites and silvicultural methods: *e.g.* the variation in geographical locations shown in Fig. 1; the site index ranges between 16–28 m; the wide (3 m) and narrow (0.75 m) initial spacing on a high site index, by comparison with the naturally regenerated plots with high stand density on a low site index; the thinning trials on high, medium and low site indices. It seems reasonable to conclude that the values in Table 5 correspond to a cross-section of the variation that could be expected among Scots pine stands in Sweden.

The limitation of the Stem Bank to mature stands from older field trials precluded sampling from stands representing modern forest management regimes, and modern statistical methods, such as replication of stand treatments (see Eriksson (1986) for discussion of thinning trials). Valid statistical inference concerning stand-level effects was therefore not possible. However, rather than make use of younger stands, it was judged that the opportunity of studying the long-term effects of branch mortality, encasement of the dead branch, and development of knot-free wood outweighed these disadvantages. This was especially important, since the ultimate aim was to study the variation of knot properties from the point of view of the recovery of solid-wood products, for which trees representing the harvestable resource were required. Moreover, rather than sample from normal, non-research stands, and thus lose the ability to account for silvicultural effects, the detailed documentation maintained for these older trials (*cf.* Anon., 1974) would facilitate integrated, multidisciplinary studies of wood-quality attributes – which was also a goal of the Stem Bank project (*cf.* Grönlund *et al.*, 1995).

Within stands, the stems were separated into three DBH-classes: around the stand mean, and two classes separated by 0.5 SD above and

Table 7. *Modelling knot properties of the constant-growth section of an individual stem, 198 stems from 33 stands. Model type (A) applicable in an inventory situation when growth ring data are collected* $A=f(SI, T_{sum}, SBH_{rel}, RW_{11-20}$ *or* RW_{1-50}, CL *and* $D_{LDB})$, *model type (B) applicable for knot property estimation based on site information and dbh distribution* $B=f(SI, T_{sum}, DBH_{rel}$ *and* $RW_{Mean})$, *model type (C) applicable in a harvesting situation when growth ring data from earlier inventories are available* $C=f(SI, T_{sum}, DBH_{rel}, MRW_{11-20}$ *or* MRW_{1-50}, MCL *and* $MD_{LDB})$

Type	Model (only variables significant at $p=0.01$ are included)	Reduced Variance %[a]	SD[b]
A	$KD_{max}=-4.9+0.0093\ T_{sum}+2.74\ RW_{11-20}+0.049\ D_{LDB}$	82	2.14
B	$KD_{max}=7.01+0.012\ T_{sum}+4.52\ RW_{Mean}+9.40\ DBH_{rel}$	65	3.31
C	$KD_{max}=-21.3+0.009\ T_{sum}+3.24\ MRW_{11-20}+15.7\ DBH_{rel}+0.050\ MD_{LDB}$	79	2.55
A	$KD_{mean}=0.61+0.0049\ T_{sum}+1.79\ RW_{11-20}+0.032\ D_{LDR}$	82	1.47
B	$KD_{mean}=-0.48+0.0065\ T_{sum}+2.85\ RW_{mean}+5.94\ DBH_{rel}$	61	2.16
C	$KD_{mean}=-9.75+0.0044\ T_{sum}+2.11\ MRW_{11-20}+9.75\ DBH_{rel}+0.035\ MD_{LDB}$	78	1.62
A	$KL_S=6.71+4.94\ RW_{1-50}+0.17\ D_{LDB}$	67	6.74
B	$KL_S=-23.80+1.42\ SI+46.5\ DBH_{rel}$	46	8.58
C	$KL_S=-31.7+46.5\ DBH_{rel}+0.27\ MD_{LDB}-0.025\ MCL$	62	7.20
A	$KL_L=7.45-0.0046\ T_{sum}+0.16\ D_{LDB}$	65	5.38
B	$KL_L=1.92+37.8\ DBH_{rel}$	32	7.09
C	$KL_L=-34.1+38.0\ DBH_{rel}+0.15\ MD_{LDB}$	59	5.87
A	$KA=56.7-9.33\ RW_{1-50}+0.093\ D_{LDB}$	31	6.54
B	$KA=51.4-7.07\ RW_{mean}+22.2\ DBH_{rel}$	17	7.14
C	$KA=46.3-10.6\ MRW_{1-50}+11.3\ DBH_{rel}+0.10\ MD_{LDB}$	29	6.62
A	$KF=2.26+0.0012\ T_{sum}+0.95\ RW_{0-50}$	54	0.64
B	$KF=2.00+0.0013\ T_{sum}+1.08\ RW_{mean}$	50	0.67
C	$KF=1.00+1.16\ MRW_{1-50}+0.0010\ T_{sum}+1.13\ DBH_{rel}$	52	0.65

[a]Reduction in stand- and tree-level variance through the models as listed.
[b]Residual stand- and tree-level standard deviation.

Table 8. *Variance components (V.C.) of the knot properties when the independent variables of Model type (A) in Table 7 were introduced as covariates in Equation 1*

Source of variation	Diameter[a] KD_{max} V.C.	%	Diameter[a] KD_{mean} V.C.	%	Sound length[a] KL_s V.C.	%	Loose length[b] KL_L V.C.	%	Angle[a] KA V.C.	%	Knots per whorl[a] KpW V.C.	%
STAND	1.1	5	0.3	1	29	18	7	5	9	3	0.06	2
TREE(STAND)[c]	4.6	22	1.8	5	16	10	19	14	34	12	0.34	14
Residual	15.6	73	33.2	94	120	73	116	82	236	85	2.06	84
Total	21.3	100	35.3	100	165	100	142	100	278	100	2.46	100

[a]Knots in constant-growth section.
[b]Knots between 1 m and lowest dead branch.
[c]The parentheses denote that *TREE* was nested within *STAND*.

below this mean. Each class therefore represents 30–40% of the variation, under the assumption of a normal distribution. Two trees were chosen close to each class mean. Since the trees were not randomly chosen from within the whole class, statistical inference concerning within-stand variation should be restricted to these class means (Tables 2, 3 and 4). A different partition between classes would probably have resulted in corresponding differences in class mean values (Tables 2 and 3). Moreover, had the study trees been selected completely at random from all of the trees within each class (*i.e.* not just close to its mean), the within-stand variation would also be slightly different (the random variation would be larger). On the other hand, the stand means (Table 5) for individual plots might in that case become less representative of the treatments, given the few trees per stand and the lack of stand-level replication.

In the present study, internal knot properties were described by using a non-destructive method: CT-scanning and digital image analysis. Each knot was described by a model with ten parameters. The accuracy of the knot model for diameter and sound-length determination was tested and verified by Grönlund (1995), who found that the model slightly overestimated these properties compared with manual measurements (+5 mm and *ca.* +2.5 mm, respectively). This is to be expected, however, since manual methods have difficulty in locating the maximum diameter. The SD of knot length is 9.7 mm (it is not reported for diameter). The knot-angle estimate of the model has a rather large random error, owing to low longitudinal resolution and to the algorithms used, but should be relatively bias-free (Grundberg pers. com.). The CT-method has also been compared with two destructive methods in a study on Norway spruce (Oja, 1997). The destructive methods were (1) the whorl method, whereby every knot visible on the log surface is split through its centre (*e.g.* Maguire & Hann, 1987), and (2) the flitch method, whereby knots are measured on boards after through-and-through sawing (*e.g.* Samson, 1993). Although measurement of small knots and total knot length is difficult, Oja (1997) concludes that the CT-method is competitive with the destructive methods. Moreover, the whorl method would be difficult to apply on old pine stems, when knots are not visible on the log surface. Therefore, it seems reasonable to conclude that CT-scanning is a viable method for large-scale measurement of the internal knot properties of Scots pine.

Within-stand variation

The stems in the Stem Bank were sampled from intensively managed, relatively small research plots (0.1 to 0.5 ha) with uniform site conditions. Much of the within-stand variation has thus been removed in previous silvicultural treatments. This means that variation within stands might be larger in normally managed, full-size stands, in which within-stand differentiation into crown classes would be expected to occur to a greater extent. Furthermore, such differentiation could potentially be used to a greater extent by more radical thinning methods than the ones employed, with the aim of consistently removing trees with undesirable properties.

The within-stand variation in DBH was a basis for the sampling scheme applied. This resulted in an average relative DBH of 0.85, 1.00 and 1.16, respectively, for the three *DBH-CLASS*es (Table 4). From the average growth ring width close to the pith (RW_{11-20}; Table 2), it can be concluded that these DBH relations were similar on average when the sample trees were young. This is probably a reason why DBH_{rel} was not significant when these ring-width variables were included together with D_{LDB} in the models of type (A) listed in Table 7.

Knot diameter and length

DBH-CLASS was a highly significant variable for knot diameter and length (Table 4). DBH_{rel} was also significant in all models of type (C) presented in Table 7, where all other variables were at stand level. This effect was an expected result of within-stand differentiation, and formed an important part of the sampling strategy. Similar observations have been reported in numerous other studies for knot size, sound-knot length (Vestøl, Høibø, Molteberg & Sundby, 1997; Vestøl & Høibø, 1998*a*; Vestøl & Høibø, 1998*b*; Moberg, 1999*a*; Øyen & Høibø, 1999) and branch size (Elfving, 1975; Persson, 1977; Lämsä, Kellomäki & Väisänen, 1990; Johansson, 1992).

Within-stand differentiation implies that trees with better competitive capacity, through favourable micro-sites or genetic qualities, will increase their crowns at the expense of surrounding trees (Mitchell, 1975; Oliver & Larson, 1990). This will result in less foliage and smaller branches for the latter. Since secondary growth is a relatively low-priority sink for assimilates (Oliver & Larson, 1990), these trees will not be able to attain the same DBH as the more dominant trees. The narrower growth rings also imply that not as much of the knot is occluded within the stem by each ring, resulting in shorter sound-knot lengths in comparison with dominant trees (Table 4 and Høibø, Vestøl, Sundby & Molteberg, 1997; Vestøl *et al.*, 1997; Vestøl & Høibø, 1998*a*; Øyen & Høibø, 1999). Furthermore, the self-pruning time (the time between branch mortality and self-pruning) has been reported to be shorter for lower crown classes (Hägg & Weslien, 1995), leading to the expectation of a shorter loose-knot length for these trees, as was found for small trees in Table 4.

Knot angle

When studying the internal knot angle of Scots pine at a fixed distance from the pith (4 cm), Pietilä (1989) found a large within-stand variation among trees, and presents a model of knot angle as a function of knot size: larger knots have a lower angle (*i.e.* are more vertical). Roeh & Maguire (1997, for Douglas fir) and Eriksson, Ilstedt, Nilsson & Ryttman (1987, for Scots pine) also identify a relationship between branch angle and branch diameter, whereby larger branches have lower, more vertical angles. Since large branches are associated with large trees (see discussion above), it could be expected from these results that tree size would be negatively correlated with knot angle. Indeed, Mäkinen (1996) finds that branch angle is smaller when DBH, a distance-dependent competition index, and the grouping of trees is larger. Gilmore & Seymour (1997) also found a significant effect of crown class on branch angle for Balsam fir (*Abies balsamea* (L.) Miller); branches of dominant trees were more vertical than those of lower crown classes. In the present study, two significant correlations were recorded: (1) lower knot angle for thicker knots (Table 6); (2) larger knot angle for larger trees (Table 4). The latter of these correlations thus contradicted some earlier studies.

Knots per whorl

Maguire, Moeur & Bennett (1994) found a positive effect of relative DBH on the number of branches per whorl for Douglas fir, and attributed this to the increased light conditions experienced by larger trees. Contrary to this result, Lämsä *et al.* (1990) found no significant effect of relative DBH on the number of branches in the uppermost whorl of Scots pine, and Pietilä (1989) found that within-stand variation in the number of knots per whorl was small for Scots pine. Gilmore & Seymour (1997) found only slight differences between crown classes of Balsam fir in the number of branches per whorl, and could not incorporate a tree-size effect in their model. The small, but highly significant effect of *DBH-CLASS* found in this study (Table 4) agrees with the results of Maguire *et al.* (1994). However, this may also be an effect of the size limit of 7 mm, below which knots were excluded from the analyses. Thus the recorded difference need not be a difference in the number of initially formed buds in each whorl, but rather a difference in the number of lateral buds growing to branches thicker than 7 mm.

It is likely that much of the within-stand effect in regression models is accounted for by tree variables such as ring-width or DBH (*e.g.* Lämsä *et al.*, 1990; Gilmore & Seymour, 1997), making redundant separate variables (*e.g.* DBH_{rel}) to account for within-stand variation. This was evident in Table 7.

Random within-stand, between-tree variation

The random *TREE* variance was found to be far smaller than the random *STAND* and residual variance for all knot properties except angle (Table 3). Genetic effects, differences in micro-site or non-uniform spatial distribution affect tree size as well as knot properties, so that very little, if any, additional within-stand effect is usually found when tree size is included in a model (Pukkala, Karsikko & Kolström, 1992; Mäkinen, 1996). Although some of the random *TREE* variance (Table 3) might be explained by differences in tree size among trees within *DBH-CLASS*, the difference in DBH between trees within each *DBH-CLASS* was very small (the mean difference was less than 1 cm). When the random within-stand variation in Table 3 and Table 8 is compared, it is evident that the variance was only slightly reduced when variables of model type (A) were introduced, and that some other explanatory tree variables would be needed to reduce this further. Other tree variables, such as height to the lowest live branch, total height or stem form (DBH/H_t) might reduce the random variation, but they were excluded from the models for reasons stated above (Materials and methods).

Stand-level variation

Initial spacing

The two spacing trials included in this study (northern Sweden, stands 6–8, and southern Sweden, stands 25–28), are analysed in a separate investigation (Moberg, 1999*a*). In that study, substantial variation of knot diameter is found at the southern locality (as is also found for the constant growth section; Table 5). This is primarily attributed to prolonged branch longevity, due to delayed crown recession at wider spacings. Similar effects of stand density on branch diameter have previously been reported for the southern spacing trial (Nylinder, 1959; Persson, 1976), and in many other studies (Cromer & Pawsey, 1957; Grah, 1961; Brown, 1966; Merkel, 1967; Godman & Cooley, 1970; Kenk &

Unfried, 1980; Moltesen, Madsen & Olesen, 1985; Høibø, 1991; Ballard & Long, 1988; Johansson, 1992). Increased radial stem growth and branch longevity at wider spacing also result in longer knots within the stems (see Table 5 and Maguire *et al.*, 1991). The lack of differences in knot size between plots at the northern locality is explained by the much smaller spread in initial spacing (1.5–2.5 m as opposed to 0.75–3 m for the southern locality), and the early mortality experienced in the plots, which further limited stand density differences (Moberg, 1999*a*). Very small differences, or no differences, have been reported for spacing effects on branch angle and number of branches per whorl for Scots pine (Nylinder, 1959; Persson, 1977; Mäkinen, 1996), as was also evident for KA and KpW in the present study (Table 5).

Thinning

Through thinning, the growing space is redistributed to the residual trees, retarding crown recession, and allowing their live crowns to expand. This will affect branch longevity and stem radial growth intensity (Merkel, 1967; Larson, 1969; Madsen, Moltesen & Olesen, 1978; Maguire *et al.*, 1991; Pape, 1999; Valinger, Elfving & Mörling, 1999), and an increase in knot size and sound-knot length would be expected in relation to thinning. However, since knot size is affected by within-stand differentiation (as noted above), knot size in the residual trees can also be affected by the thinning method (Maguire *et al.*, 1991), through the removal of dominant trees (high thinning and, to some extent, crown thinning) or removal of trees from the lower crown classes (low thinning).

Five thinning trials from different localities were included in the Stem Bank (Table 1). In general, crown thinning resulted in smaller knot diameter, and shorter sound- and loose-knot lengths (although the difference was significant in a few trials only; see Table 5). Since the thinning intensity (in terms of trees ha^{-1}) was heavier in the low thinning regimes, it is unclear whether this was an effect of thinning intensity or of thinning method. Indeed, the height of the lowest live branch at the time of thinning was not known, which makes it difficult to isolate any thinning response within the stems. Perhaps a larger thinning effect would be obtained if shorter stem sections at an appropriate height were compared. The first thinnings were also carried out quite late (age 37–59 years). Since older trees are not as capable as more vigorous trees of utilising the available free space after release (Oliver & Larson, 1990), it is possible that earlier thinnings would have resulted in larger responses, and greater differences between treatments. Nevertheless, thinning often resulted in the expected effect (*i.e.* crown thinning resulted in smaller diameter and shorter knots), although the magnitude of the differences was small.

Site quality

Site index is a composite variable, correlated with the productive capacity of a site. Numerous studies have shown that branches become thicker on more productive sites (Heiskanen, 1965; Larson, 1969; Uusvaara, 1974; Turkia & Kellomäki, 1987; Pietilä, 1989; Lämsä *et al.*, 1990; Mäkinen & Uusvara, 1992). This is primarily because a larger foliage mass per tree results in higher branch growth rates (Madgwick, Tamm & Fu, 1986; Lämsä *et al.*, 1990). The positive correlation between SI and KD (Table 6) corroborates these results. The number of knots per whorl increased with increasing site index, as is also reported by Madsen *et al.* (1978) and Lämsä *et al.* (1990).

Temperature sum

Climatic factors affect growth in such a way that the potential photosynthetic capacity of a site is modified. For example, Bergh, McMurtrie & Linder (1998) found a reduction in photosynthetic production due to low-temperature effects. Arlinger (1996) reports a negative correlation between temperature sum and crown length, suggesting reduced competition among trees because of a smaller foliage mass at lower temperatures (given the same stand density and site index). This indicates that lower temperatures may increase branch longevity, but that the lower growth rate due to less foliage still results in thinner knots, as shown in Tables 6 and 7. Higher altitude and latitude (used to define T_{sum} in this study) are also associated with longer self-pruning time (the time between branch mortality and self-pruning; Hägg & Weslien, 1995), leading to the expectation of a longer loose-knot length at low T_{sum} levels. The modelling results presented in Table 7 support this expectation.

Genetic effects

Remröd (1976) studied differences between northern Swedish provenances, and found that increasing latitude is associated with slightly smaller branches, larger (more horizontal) angles and fewer knots per whorl. While the result with respect to branch size is attributed to seedling survival, and thus becomes an effect of spacing (as discussed above), the other properties may be explained as an adaptation to greater snow loads. Since latitude is incorporated in T_{sum}, it is likely that part of this genetic effect was explained in the models in Table 7. Similar results are reported by Persson (1977) and Eriksson *et al.* (1987).

The provenance trial (stands 30–31) resulted in small differences (Table 5), which sometimes were not in the expected direction. For example, the northern provenance had larger and more vertical knots. It is possible that the local provenance was well adapted to the site, and that no appreciable differences in survival occurred.

Of the properties studied, knot angle is likely to be under the strongest genetic control, since branch angle is reported to have a higher heritability than other branch properties (Velling & Tigerstedt, 1984). However, the measurement error was large for knot angle in the present study, and it was difficult to distinguish differences between stands (Table 5). By comparison with environmental effects, genetic differences in knot or branch properties are generally small (Mathieu, 1968; Remröd, 1976; Persson, 1994; Mäkinen, 1996, Vestøl & Colin, 1998; Vestøl, Colin & Loubère, 1999), and it is likely that a larger sample size than six trees per treatment would be required to identify possible significant differences.

Random between-stand variation

In the Swedish Scots Pine Stem Bank, the random between-stand variance was larger than the within-stand variance (Table 3). However, much of the between-stand variation could be accounted for when independent variables of model type (A) in Table 7 were introduced (Table 8). The random between-stand variance was thus reduced by about 60–95% for the knot properties. The property with the least relative reduction in between-stand variance was sound-knot length; the highest reduction was for mean knot diameter.

Modelling knot properties

The modelling approach applied in this study aims at predicting internal knot properties of a stem section situated at a relatively low level in the stem at the time of the last thinning or final felling. Independent variables tested included only variables that will remain stable (or almost stable) during a long period before final felling. This means that inventories aimed at predicting knot properties should give similar results, both when carried out well in advance of harvesting or shortly before harvesting. This combination of dependent and independent variables seems to have been little studied hitherto.

The models presented in Table 7 exemplified three planning situations, in which the amount of available data differs. Model types (A) and (B) represent tactical planning, whereby knot-property information forms part of tree models, in order to be able to predict the size and properties of individual type trees at a future harvest. This information could then be used both for silvicultural planning and for choosing stands for harvesting. Model type (C) could be used to evaluate the assortment distribution in a harvesting operation.

The models predicted mean values of a selected stem section, here termed 'the constant-growth section'. This, the lower part of the stem, is characterised by a more homogeneous knot structure as compared to other sections of the stem (Björklund, 1997; Øyen & Høibø, 1999). Since the models in Table 7 were restricted to part of the stem, they would be most applicable to tactical planning. A better longitudinal stem description is needed, so as to be able to determine an optimal cross-cutting pattern for the whole stem. Such models, however, would probably give a smaller reduction of variance than those shown in Table 7.

The variable which stood out as most important in the models presented, and which was included in the models for all properties except number of knots per whorl, was stem diameter at the lowest dead branch (D_{LDB}). D_{LDB} correlates strongly with DBH, a variable excluded from modelling because of the risk of generating misleading conclusions. However, the important difference is that D_{LDB} may remain static when DBH increases. As is shown in Table 6, correlations with D_{LDB} were stronger than corresponding correlations with DBH for knot diameter and knot length. A word of caution may nevertheless be appropriate, until such time as more information is available about the development of D_{LDB} over time. Also, from a practical point of view, the use of D_{LDB} is doubtful. It becomes difficult to measure if it is high up on the stem, but specially designed calipers that can reach a height of *ca.* 6 m do exist. And undoubtedly, D_{LLB} would be even more difficult to measure than D_{LDB}.

The second most important variable, which was included in the models for all properties (except loose-knot length), was growth-ring width close to the pith (RW_{11-20} or RW_{1-50}). This indicates that the early growth rate of the tree determines most knot properties for the constant-growth section. For loose-knot length, a correlation with growth-ring widths formed during the period when dead branch stubs were encased, *e.g.* RW_{51-70}, was expected. This was also tested during the screening procedure (see Materials and methods). The correlation was very low. Instead, the development of the model for loose-knot length resulted in the inclusion of temperature sum, which indicates that climate is more important for natural pruning than is growth rate. Temperature sum was also included in the models for knot diameter and number of knots per whorl, indicating that climate is a significant factor for these properties, too.

Other relevant questions relate to possible improvements of the models presented in Table 7. What did we not record? If inventories were made in younger stands, knot diameter could be measured on sample trees, and that information, if retained until the final felling, would most probably surpass the models developed here. However, measurement of branch diameter on standing trees shortly before final felling is seldom an option in Scots pine, because very few or no branches then remain on the lower part of the stem. Mean branch diameter, *e.g.* at 5–6 m height, can scarcely be estimated with reasonable precision. Knot angle, on the other hand, would probably be more easily estimated at such a distance. If knot angle is considered to be of interest, it could be included in inventory routines. It may in fact be a better option than modelling, considering the very low reductions of variance for the models tested in this study.

Conclusions

The Swedish Scots Pine Stem Bank represents a broad sample of Scots pine from different sites, silvicultural regimes, and within-stand size classes in Sweden. This resulted in substantial variation among stands and trees in terms of knot properties for stem sections in which the vertical variation was small. By means of explanatory site, stand and tree variables, much of the between-stand variation, and a minor part of the random tree variation, of knot size, knot length and knots per whorl, could be accounted for. Individual tree measurements of variables that are stable over time, such as growth-ring width close to the pith and stem diameter at the height of the lowest dead branch, were highly significant, and the most important explanatory variables. Knot angle was difficult to predict, which probably depended to a large extent on genetic control of this property, as well as on the measurement error caused by the low longitudinal resolution of the CT-scanning technique employed. Within-tree variation was large, but was not within the scope of the regression analyses in this study; this level of variation is addressed in a separate investigation (*e.g.* Moberg, 1999*b*).

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Appendix A. *Stand identification and location*

Stand No.	Dominant treatment	Plot ID[a]	Grönlund ID[b]	Place	County	N Lat	E Long	Altitude m asl
1		87:1	33	Boden	Norrbotten	65 45′	21 16′	100
2	Low thinning	628:1	31	Arvidsjaur	Lappland	65 40′	18 47′	420
3	Crown thinning	628:3	32	Arvidsjaur	Lappland	65 40′	18 47′	420
4	Low thinning	3:3	8	Forsholm	Västerbotten	64 46′	19 01′	220
5	Crown thinning	3:4	7	Forsholm	Västerbotten	64 46′	19 01′	220
6	1.5 m spacing	767:5	13	Lycksele	Lappland	64 40′	19 43′	270
7	2 m spacing	767:2	14	Lycksele	Lappland	64 40′	19 43′	270
8	2.5 m spacing	767:3	15	Lycksele	Lappland	64 40′	19 43′	270
9		769	16	Lycksele	Lappland	64 23′	18 36′	280
10		763:1	1	Vindeln	Västerbotten	64 14′	19 46′	200
11		764:1	5	Vindeln	Västerbotten	64 10′	19 46′	240
12		765:1	6	Vindeln	Västerbotten	64 10′	19 46′	270
13	Low thinning	56:2	29	Voxnan	Hälsingland	61 20′	15 33′	200
14	Crown thinning	56:1	28	Voxnan	Hälsingland	61 20′	15 33′	200
15		61:1	30	Voxnan	Hälsingland	61 20′	15 33′	220
16	Low thinning	S9:3	17	Siljansfors	Dalarna	60 52′	14 27′	240
17	Crown thinning	S9:2	18	Siljansfors	Dalarna	60 52′	14 27′	240
18		S22:24	19	Siljansfors	Dalarna	60 54′	14 23′	400
19		S54:1	20	Siljansfors	Dalarna	60 53′	14 26′	320
20		S634:2	21	Siljansfors	Dalarna	60 53′	14 26′	320
21		S404	22	Siljansfors	Dalarna	60 52′	14 23′	260
22	Low thinning	9:2	3	Jönåker	Södermanland	58 49′	16 22′	50
23	Crown thinning	9:1	2	Jönåker	Södermanland	58 49′	16 22′	50
24		297	4	Jönåker	Södermanland	58 49′	16 22′	60
25	0.75 m spacing	196:7	9	Granvik	Västergötland	58 40′	14 35′	120
26	1.25 m spacing	196:9	10	Granvik	Västergötland	58 40′	14 35′	120
27	1.5 m spacing	196:10	11	Granvik	Västergötland	58 40′	14 35′	120
28	3 m spacing	196:12	12	Granvik	Västergötland	58 40′	14 35′	120
29		515	23	Mariannelund	Småland	57 37′	15 35′	160
30	Local proven.	Pr29:6	25	Mariannelund	Småland	57 37′	15 35′	175
31	North proven.	Pr29:4	26	Mariannelund	Småland	57 37′	15 35′	175
32		197–98:3	24	Tagel	Småland	57 03′	14 23′	220
33		306	27	Markaryd	Småland	56 37′	13 43′	160

[a]Refers to identity at the Faculty of Forestry, SLU (see Anon., 1974).
[b]See Grönlund *et al.* (1995).

Appendix B. *No. of observations*

Description		Diameter[a] KD_{max}	Diameter[a] KD_{mean}	Sound length[a] KL_s	Loose length[b] KL_L	Angle[a] KA	Knots per whorl[a] KpW
No. of observations per stand							
1		123	532	532	444	532	123
2	Low thinning	122	468	468	139	468	122
3	Crown thinning	130	485	485	297	485	130
4	Low thinning	153	585	585	501	585	153
5	Crown thinning	153	597	597	625	597	153
6	1.5 m spacing	107	480	480	34	480	107
7	2 m spacing	104	518	518		518	104
8	2.5 m spacing	105	467	467		467	105
9		104	474	474		474	104
10		120	544	544	48	544	120
11		120	558	558	43	558	120
12		115	558	558		558	115
13	Low thinning	129	564	564	613	564	129
14	Crown thinning	131	610	610	692	610	131
15		126	545	545	656	545	126
16	Low thinning	144	503	503	455	503	144
17	Crown thinning	138	469	469	412	469	138
18		107	551	551		551	107
19		194	701	701	365	701	194
20		141	546	546	444	546	141
21		123	523	523	46	523	123
22	Low thinning	130	716	716	459	716	130
23	Crown thinning	145	781	781	680	781	145
24		151	755	755	428	755	151
25	0.75 m spacing	145	804	804	460	804	145
26	1.25 m spacing	128	698	698	143	698	128
27	1.5 m spacing	124	692	692	304	692	124
28	3 m spacing	118	723	723		723	118
29		161	726	726	519	726	161
30	Local proven.	108	660	660	185	660	108
31	North proven.	110	677	677	407	677	110
32		120	627	627	234	627	120
33		161	866	866	508	866	161
Number of observations per DBH-CLASS							
I	Small	1490	6484	6484	3363	6484	1490
II	Moderate	1423	6686	6686	3293	6686	1423
III	Large	1377	6833	6833	3485	6833	1377

[a]Knots in constant-growth section.
[b]Knots between 1 m and lowest dead branch.

Appendix C. *Standard errors corresponding to the mean values given in Tables 4 and 6*

Description	Diameter[a] KD_{max}	Diameter[a] KD_{mean}	Sound length[a] KL_s	Loose length[b] KL_L	Angle[a] KA	Knots per whorl[a] KpW
Per stand						
1	0.98	0.63	2.03	1.86	2.24	0.22
2 Low thinning	0.98	0.64	2.03	2.27	2.25	0.22
3 Crown thinning	0.98	0.64	2.03	1.88	2.24	0.22
4 Low thinning	0.97	0.63	2.02	1.84	2.23	0.22
5 Crown thinning	0.97	0.63	2.02	1.82	2.23	0.21
6 1.5 m spacing	0.99	0.64	2.03	3.10	2.24	0.22
7 2 m spacing	0.99	0.63	2.03		2.24	0.22
8 2.5 m spacing	0.99	0.64	2.04		2.25	0.22
9	0.99	0.64	2.03		2.25	0.22
10	0.98	0.63	2.03	3.03	2.24	0.22
11	0.98	0.63	2.02	3.06	2.23	0.22
12	0.99	0.63	2.02		2.23	0.22
13 Low thinning	0.98	0.63	2.02	1.82	2.23	0.22
14 Crown thinning	0.98	0.63	2.02	1.82	2.23	0.22
15	0.98	0.63	2.03	1.82	2.24	0.22
16 Low thinning	0.98	0.64	2.03	1.84	2.24	0.22
17 Crown thinning	0.98	0.64	2.03	1.84	2.25	0.22
18	0.99	0.64	2.03		2.24	0.22
19	0.96	0.62	2.01	1.87	2.22	0.21
20	0.97	0.63	2.02	1.84	2.24	0.22
21	0.98	0.63	2.03	3.04	2.24	0.22
22 Low thinning	0.98	0.62	2.01	1.84	2.22	0.22
23 Crown thinning	0.97	0.62	2.01	1.82	2.22	0.21
24	0.97	0.62	2.01	1.84	2.22	0.21
25 0.75 m spacing	0.97	0.62	2.01	1.84	2.21	0.21
26 1.25 m spacing	0.98	0.62	2.01	2.27	2.22	0.22
27 1.5 m spacing	0.98	0.62	2.01	1.86	2.22	0.22
28 3 m spacing	0.99	0.62	2.01		2.22	0.22
29	0.97	0.62	2.01	1.83	2.22	0.21
30 Local proven.	0.99	0.62	2.02	2.28	2.22	0.22
31 North proven.	0.99	0.62	2.02	1.85	2.22	0.22
32	0.98	0.63	2.02	2.22	2.23	0.22
33	0.97	0.62	2.01	1.83	2.21	0.21
Per DBH-CLASS						
I Small	0.87	0.54	1.64	1.25	1.16	0.15
II Moderate	0.87	0.54	1.64	1.27	1.16	0.15
III Large	0.87	0.54	1.64	1.24	1.16	0.15

[a]Knots in constant-growth section.
[b]Knots between 1 m and lowest dead branch.