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Which Annual Rings to Assess Grain Angles in Breeding of Scots Pine for Improved Shape Stability of Sawn Timber?

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The shape stability properties of sawn timber could be improved by breeding or grading Scots pine (*Pinus sylvestris* L.) for reduced grain angles. Currently, only grain angle assessments performed in single annual rings can be considered feasible in forest breeding programmes. The relevance of such methods in assessing shape stability traits was evaluated by taking grain angle measurements beneath the bark in a 36-year-old Scots pine progeny trial. Several grain angle measurements from stem discs were also taken from a sample of 162 trees. Phenotypic correlations were estimated between grain angle and the bow, crook and twist developed in 316 sawn and dried boards. All single annual ring assessments, including measurements taken directly under the bark, were significantly correlated with twist. The highest correlations (0.60–0.70) were observed in annual rings numbered 8–20 and at distances of 30–70 mm from the pith, indicating those parts of logs where grain angles have the largest impact on twist. These results suggests, that grain angles measured beneath the bark are relevant to the twist of sawn small timber, and that any single annual ring could be chosen for the assessment, provided that the tree diameter is within the 60–140 mm range. No appreciable correlations were observed between grain angles and either crook or bow.

Keywords spiral grain angle / warp / sawn timber / breeding / *Pinus sylvestris*
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1 Introduction

Studs and boards with shape stability problems tend to warp during the drying process or under unstable moisture conditions. This makes them unsuitable for construction. Shape stability is thus a very important property of long lengths or large sheets of sawn timber for use in joinery, veneers, glulam and building construction. The grain angle (i.e. spiral grain) as well as microfibril angle and shrinkage traits, have been shown to influence the shape stability and strength of sawn timber from several softwood species (Harris 1989, Dinwoodie 2000). Warensjö and Rune (2004) have also reported significant positive correlations between grain angle and twist of sawn and dried boards of Scots pine (*Pinus sylvestris* L.).

Significant genetic variation and considerable heritability have been observed for grain angles in Scots pine (Hannrup et al. 2003), and other *Pinus* species (Gapare et al. 2007, Gaspar et al. 2008). Moreover, low estimates of grain angle genotype-by-environment interactions, and small or non-significant genetic correlations with most other important breeding traits (Hannrup et al. 2003), suggest that breeding for reduced grain angles is a promising strategy for the improvement of sawn timber shape stability.

Several previous studies have reported positive correlations between grain angle and the twisting of sawn boards, but the grain angle was measured using methods that are too destructive, laborious, and time consuming in order to be useful for forest tree breeders (e.g. grain angle was measured on debarked logs from trees felled at rotation age). For tree breeding purposes, measurement methods have to be quick and non-destructively applicable to a great number of standing trees, preferably at a young age. The measurement of the grain angle under bark by pushing a small metal wedge through the bark of the standing tree (the wedge naturally orientates itself parallel to the wood fibres of the outermost annual rings) is one method that fulfil these requirements. This method has proven to be very useful in investigations of the genetic variation of grain angle in Scots pine and also in Norway spruce (*Picea abies* L. Karst) (Hannrup et al. 2003).

However, this method only assess the grain angle of a few annual rings. The extent and direction of grain angles also depend on the cambial age of the wood. In most conifers, grain angles in the juvenile core become increasingly left-handed as the annual ring number increases. The development of left-handed grain angles usually peaks after only a few years of radial growth. Further away from the pith, the grain angles tend to decrease with increasing annual ring number; in some species, the grain angle might even become right-handed during the process of maturation (Harris 1989). Because of this variation, the extent to which single annual ring assessments on young trees are relevant for shape stability is uncertain. It is also unclear at what tree age (i.e. which annual ring) measurements under bark should be performed in order to achieve improvements in shape stability most efficiently by breeding. Thus, the relevance of grain angle assessments made under bark and in single annual rings need to be evaluated.

Well designed genetic field trials of Scots pine and Norway spruce old enough to yield sawtimber, are very few. Only recently, sawn timber material from one Scots pine progeny trial became available to study the relationship between grain angle and shape stability in the context of tree breeding. In addition, our knowledge of the radial grain angle pattern and its genetic variation in Scots pine, is very limited in comparison with the extensive investigations made in Norway spruce (e.g. Säll 2002) and Radiata pine (*Pinus radiata* D. Don) (e.g. Cown et al. 1991). Therefore, further studies on the radial variation and genetic variation of grain angle in Scots pine are also needed.

The main aim of this study was to investigate the relationship between the grain angle assessed with methods applicable in tree breeding (i.e. grain angle under bark) and shape stability measurements of sawn small sawtimber. To do this we addressed the following specific questions: Which annual rings yield the most relevant grain angle information with respect to the shape stability of sawn and dried boards? How informative are single annual ring assessments of grain angles with respect to shape stability, in comparison with more complete assessments of the radial grain angle pattern? How large is the response in shape stability traits if a phenotypic selection within the

Table 1. Abbreviations (Abbr.) and descriptions of the traits studied.

Abbr.	Description of the trait
Traits measured in the field on all surviving trees	
Ht16	Tree height at field age 16 years
DBH16	Diameter at breast height at field age 16 years
DBH36	Diameter at breast height at field age 36 years
GABH36	Grain angle under bark at field age 36 at internode closest to breast height
Traits measured on stem discs and in sawn boards from cut trees	
GAS*x*	Grain angle in stem section at annual ring *x* from pith
GAS*x*mm	Grain angle in stem section at *x* mm distance from pith
GASm	Average grain angle in stem section weighted by annual ring widths
Bow	Absolute bow of the top end 2 m of the sawn board
Crook	Absolute crook of the top end 2 m of the sawn board
Twist	Twist angle of the top end 2 m of the sawn board

existing material is performed based on ranking of grain angle values?

2 Materials and Methods

2.1 Field Study Material

The present study utilised a Scots pine progeny trial located at Ramsberg in central Sweden (latitude 59°50’N, longitude 15°18’E, altitude 260 m). The trial comprises progenies from 25 parents structured in 94 full-sib families according to a partial diallel mating design (Kempthorne and Curnow 1961). The parents were plus trees selected for height growth, vigour, and stem form in the geographical range latitude 60°00’–61°24’N, longitude 14°18’–17°18’E and in the altitudinal range 70–215 m. In 1971, plus tree progenies and nine check lots were planted with a spacing of 2.5 m × 2.5 m using 1-year-old plants grown in the paper-pot planting system. The experimental design involved single-tree plots in a randomised complete block design with one replicate per block and a total of 40 blocks.

2.2 Field Study Assessments

In the eight adjacent blocks that exhibited the best survival rate, the height (Ht16) and diameter at breast height (DBH16) were measured after the trees had been 16 years in the field (Table 1). After 36 years in the field, all surviving trees in these eight blocks were further assessed by measuring diameter at breast height (DBH36) and grain angle under bark at breast height (GABH36). GABH36 was measured on the north and the south sides of the stem with a wedge grain angle gauge as described by Hannrup et al. (2003). The mean of these two measurements was recorded thus using the stem axis as a reference. Trees with left-handed grain were given positive values; right-handed grains were given negative values.

2.3 Sawtimber Sampling

For the sawtimber investigation, 26 full-sib families and four check lots within the eight blocks of the field study material were selected for felling. This sampling was based on high survival rates and large tree diameters in order to acquire the greatest number of trees that could be expected to produce sawn timber of a reasonable size from their bottom logs. All 162 trees of the sampled families were marked to record their orientation north–south, felled, and long bottom logs, 3.4 m long, were cut from the felled trees. Sample discs approximately 10 cm thick were excised from the top part of the logs for an assessment of the radial grain angle pattern (Fig. 1) avoiding branch whorls in the discs. Sample discs were stored in a freezer at –20°C.

2.4 Assessment of the Radial Grain Angle Pattern

The frozen sample discs were sawn with a bandsaw in the marked north–south direction into 3 cm wide bark-to-bark stem sections including the pith (Fig. 1). The stem sections were subsequently thawed in plastic bags at 7°C. Ring widths for each annual ring were measured using a scanner combined with the WinDENDRO™ software (Regent Instruments Inc., Canada). The grain angle was measured using the scribe test method in combination with a precision protractor (Säll 2002). The annual rings numbered 2, 4, 6, 8, 10, 12, 16 and 20 from the pith, plus the ring immediately under the bark were assessed. The latewood surface of each annual ring was exposed with a sharp knife and the grain angle of each surface was measured by scribing it three times. The mean of the measurements made at the north and south surfaces (six measurements in total) for each assessed ring was calculated (GAS_x), thus obtaining a grain angle estimate relative to the stem axis and comparable with the GABH36 measurements.

The distance between the position of each grain-angle measurement and the pith was calculated by adding the measured ring widths from the pith to the relevant cambial age (RGS_x). By using GAS_x and RGS_x data in combination, it was possible to evaluate the grain angle at any distance from the pith (GAS$x$mm) within the final growth radius of the sampled trees. This was done by selecting the GAS_x values in each tree that occurred closest to RGS_x = 10, 20, 30, 40, 50, 60 and 70 mm. A ring-width weighted grain angle average (GASm) was also estimated for each stem section:

$$\mathrm{GASm} = \frac{1}{\mathrm{RGS}^2_{x(n)}} \sum_{i=1}^{n} \mathrm{GAS}_{x(i)} \cdot \left(\mathrm{RGS}^2_{x(i)} - \mathrm{RGS}^2_{x(i-1)}\right) \quad (1)$$

where $x(1,2,\ldots,n-1)$ = 2, 4, 6, 8, 10, 12, 16 and 20 annual rings from the pith, $x(n)$ represents the annual rings immediately under the bark. $\mathrm{RGS}_{x(0)}$ is considered to be zero. It was assumed that the annual growth rings were formed in perfectly concentric circles and that each $\mathrm{GAS}_{x(i)}$ measurement was representative of the cross-sectional area of the annual rings $x(i-1)+1$ to $x(i)$. The number of annual rings present in each stem section varied from 16 to 27 with a mean value of approximately 22.

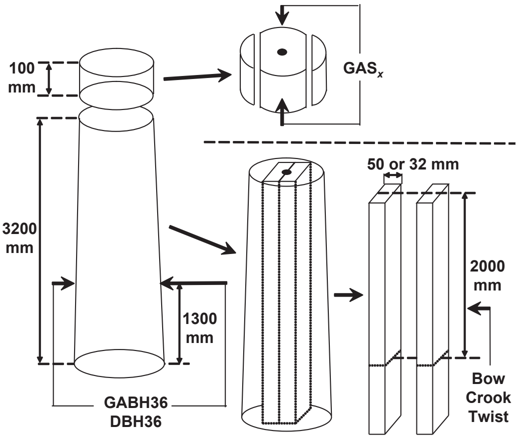

Fig. 1. Sampling strategy and the measurement locations of the different traits. The pith is marked with a black spot.

2.5 Sawing and Drying Boards

After transport to a sawmill (Garpenbergs Såg AB), the logs were sawn with an industrial circular saw (Säter Lindsaw) to give two boards (Fig. 1). Depending on log dimension and straightness, boards of two thicknesses were produced: 182 thin boards (32 mm) and 134 thick boards (50 mm). All boards sawn from the same log were of the same thickness. The boards were piled into two drying stacks, one for each thickness group. Within the stacks, boards originating from the same log were put together in two-board plots. The plots were randomised within the drying stack and the position of each plot was recorded. The stack of thick boards was placed above the stack of thin boards. Without any further load on top, both stacks were simultaneously dried at 55°C–60°C for seven days in a compartment kiln (Nardi MD-5, Italy) and were left standing for some additional weeks within the kiln after it had been switched off. The moisture content of ten thin and ten thick sample boards was measured with a Tramex Wood Encounter confirming the moisture content of both thin and thick boards to be approximately 12%.

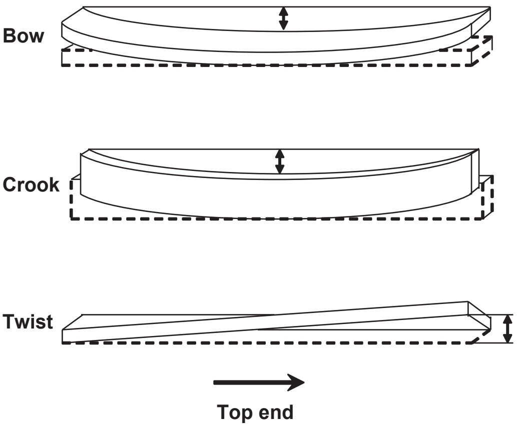

Fig. 2. Definition of the shape stability defects bow, crook and twist (adapted from Johansson et al. 1994). The twist shown is defined as having a positive value.

2.6 Shape Stability Assessments of Dried Boards

The boards were assessed on a 3 m long right-angled aluminium profile used as an inspection table. The width and length of the boards were determined (mean length was 3.2 m). Board widths were more variable than thickness but averaged approximately 80 mm and 110 mm for the thin and thick boards, respectively. Each board was assessed for shape stability traits in the upper 2 m of the board (Fig. 1), because in several cases the bottom part of the board had been shortened by the saw as a result of basal sweep. The basal sweep seems to have been caused by poor root stability induced by the paper-pot planting system. Six boards from four different logs were shorter than 2 m due to cracking or log truncation and were therefore excluded from shape stability assessments. Both bow and crook were assessed directly using a millimetre-graded wedge to localise and measure the maximum deviation (Fig. 2). Twist was assessed by fixing the bottom end of the measured board length to the aluminium profile and measuring the greatest deviation of the top end corners from the profile surface. The twist angle (Twist) was then calculated according to the formula:

$$\text{Twist} = \arcsin\left(\frac{\text{deviation}}{\text{boardwidth}}\right) \tag{2}$$

The direction of the twist was taken into account as shown in Fig. 2.

2.7 Statistical Analysis of the Field Traits

To estimate genetic parameters for the field traits, statistical analyses were undertaken using multivariate mixed linear models excluding the check lot trees from the analysis:

$$\mathbf{y} = \mathbf{X_b b} + \mathbf{Z_p p} + \mathbf{Z_f f} + \mathbf{e} \tag{3}$$

where **y** is the observation vector for the traits; **b**, **p**, **f** and **e** are the vectors of fixed block effects, random parent effects, random family effects and residuals, respectively. The design matrices $\mathbf{X_b}$, $\mathbf{Z_p}$ and $\mathbf{Z_f}$ were used for block effects, parent effects and family effects, respectively. All random effects were assumed to be independently and normally distributed with the expectation of zero and structured as:

$$\text{Var}\begin{bmatrix} \mathbf{p} \\ \mathbf{f} \\ \mathbf{e} \end{bmatrix} = \begin{bmatrix} \mathbf{P}\otimes\mathbf{I_p} & 0 & 0 \\ 0 & \mathbf{F}\otimes\mathbf{I_f} & 0 \\ 0 & 0 & \mathbf{R}\otimes\mathbf{I_e} \end{bmatrix} \tag{4}$$

P, **F** and **R** are variance-covariance matrices for parental, family and residual effects, respectively, while $\mathbf{I_p}$, $\mathbf{I_f}$ and $\mathbf{I_e}$ are identity matrices.

Restricted maximum likelihood estimates of variance and covariance components were performed using ASReml software (Gilmour et al. 2006).

2.8 Shape Stability Traits

In order to estimate measurement repeatability and phenotypic correlations, all shape stability measurements (bow, crook and twist) including those for the check lot trees, were adjusted for different weight loads during drying. Univariate linear regression models were constructed for each trait and board thickness, separately, in order to estimate the trait dependency on height position in the drying stack:

$$y_{ij} = \alpha_0 + \alpha_1 \cdot h_i + l_i + e_{ij} \tag{5}$$

where y_{ij} is the observation of the j-th board of the i-th board pair plot; α_0 and α_1 are the trait intercept and regression coefficients on the height position of the board pair plot in the drying stack (h_i); l_i is the random effect of the board pair plot; and e_{ij} is the residual due to within-log variation and measurement error. For the purpose of estimating α_1, absolute values of twist were used. The data were then adjusted for the estimated effect of height position in the drying stack by the formula:

$$y_{ij,adj} = y_{ij} - \hat{\alpha}_1 \cdot h_i \tag{6}$$

Adjustments were made with the constraints that i) any data point that changed sign when adjusted, was instead assigned a value of 0; and ii) adjusted data points were not allowed to diverge from 0 if $y_{ij} = 0$. After adjustment, the original direction of the twist was again taken into account and the data were then scaled so that the trait means and the total variances ($\hat{\sigma}_l^2 + \hat{\sigma}_e^2$) of thin and thick boards were equal.

To estimate the measurement repeatability of board pairs, the adjusted data of thin and thick boards were used jointly in a multivariate mixed linear model analysis:

$$\mathbf{y} = \mathbf{X_b b} + \mathbf{Z_l l} + \mathbf{e} \tag{7}$$

where $\mathbf{y}$ is the observation vector for bow, crook and twist; $\mathbf{b}$, $\mathbf{l}$ and $\mathbf{e}$ are the vectors of fixed block effects, random board pair plot effects and residuals, respectively. The design matrices $\mathbf{X_b}$ and $\mathbf{Z_l}$ were used for block effects and board pair plot effects respectively. All random effects were assumed to be independently and normally distributed with the expectation of zero and structured as:

$$\mathrm{Var}\begin{bmatrix} \mathbf{l} \\ \mathbf{e} \end{bmatrix} = \begin{bmatrix} \mathbf{L} \otimes \mathbf{I_l} & \mathbf{0} \\ \mathbf{0} & \mathbf{R} \otimes \mathbf{I_e} \end{bmatrix} \tag{8}$$

$\mathbf{L}$ and $\mathbf{R}$ are variance-covariance matrices for board pair plot and residual effects, respectively, while $\mathbf{I_l}$ and $\mathbf{I_e}$ are identity matrices.

2.9 Correlations of Grain Angle with Shape Stability Traits

The data for the shape stability traits and for the grain angle measured in stem sections were too limited to allow the estimation of genetic parameters. Instead, phenotypic correlations were estimated between GABH36, GAS$_x$, GAS$x$mm, GASm and the board pair means of the adjusted shape stability traits. The phenotypic correlations were estimated directly from residual covariances and variances using the model:

$$\mathbf{y} = \mathbf{X_b b} + \mathbf{e} \tag{9}$$

The residuals were assumed to be normally distributed with the expectation of zero and structured as Var($\mathbf{e}$) = $\mathbf{R} \otimes \mathbf{I_e}$.

2.10 Interpretation of Variance Components

Parental $\left(\hat{\sigma}_p^2\right)$, family $\left(\hat{\sigma}_f^2\right)$ and residual $\left(\hat{\sigma}_e^2\right)$ variances were estimated from field trait measurements by Eq. 3 assuming no epistasis. These were subsequently translated to additive genetic variance $\left(\hat{\sigma}_A^2\right)$, phenotypic variance $\left(\hat{\sigma}_P^2\right)$, narrow-sense heritability $\left(\hat{h}^2\right)$ and the coefficient of additive genetic variation $(\hat{CV}_A)$ as:

$$\hat{\sigma}_A^2 = 4\hat{\sigma}_p^2 \qquad \hat{\sigma}_P^2 = 2\hat{\sigma}_p^2 + \hat{\sigma}_f^2 + \hat{\sigma}_e^2$$

$$\hat{h}^2 = \frac{\hat{\sigma}_A^2}{\hat{\sigma}_P^2} \qquad \hat{CV}_A = 100\frac{\hat{\sigma}_A}{\hat{\mu}}$$

Disregarding genetic effects, the variance and the corresponding covariance components of the shape stability traits (Eq. 7); board pair plot $\left(\hat{\sigma}_l^2\right)$ and the residual $\left(\hat{\sigma}_e^2\right)$, were translated to phenotypic $\left(\hat{\sigma}_P^2\right)$ and total variance $\left(\hat{\sigma}_{tot}^2\right)$ as:

$$\hat{\sigma}_P^2 = \hat{\sigma}_l^2 \qquad \hat{\sigma}_{tot}^2 = \hat{\sigma}_l^2 + \hat{\sigma}_e^2$$

Using these variances and covariances, the phenotypic repeatability of board pairs ($\hat{R}_P^2$), phenotypic correlations ($\hat{r}_{P_1P_2}$), and residual correlations ($\hat{r}_{e_1e_2}$) were calculated as:

$$\hat{R}_P^2 = \frac{\hat{\sigma}_P^2}{\hat{\sigma}_{tot}^2} \qquad \hat{r}_{P_1P_2} = \frac{\hat{\sigma}_{P_1P_2}}{\hat{\sigma}_{P_1}\hat{\sigma}_{P_2}} \qquad \hat{r}_{e_1e_2} = \frac{\hat{\sigma}_{e_1e_2}}{\hat{\sigma}_{e_1}\hat{\sigma}_{e_2}}$$

Table 2. Means, additive genetic coefficient of variation ($\hat{CV}_A$) and heritability estimates $\left(\hat{h}^2\right)$ of traits measured in the field.

Trait	Number of observations	Unit	Arithmetic mean	$\hat{CV}_A$ (%)[1]	$\hat{h}^2$
Ht16	603	cm	501 (3)	5 (3)	0.12 (0.06)
DBH16	603	mm	74 (1)	8 (5)	0.12 (0.06)
DBH36	473	mm	160 (1)	12 (5)	0.34 (0.11)
GABH36	458	°	–0.10 (0.07)	*0.78 (0.34)*	0.29 (0.11)

Note: Standard errors are given in parentheses.

[1] For GABH36, the genetic standard deviation $\hat{\sigma}_A$ is given; this is indicated by italics.

The phenotypic correlations between the grain angle and shape stability traits were interpreted as being identical to the residual correlations ($\hat{r}_{e_1e_2}$) which were calculated (as shown above) from the variances and covariances estimated using Eq. 9.

Log-likelihood ratio tests were used to determine whether correlations were significantly different from zero. Standard errors of the variance components and genetic parameters were estimated by ASReml (Gilmour et al. 2006) using the Taylor series expansion.

To illustrate the practical impact of these correlations, test selections for lower grain angles were also performed by ranking the trees phenotypically according to their measured grain angle values (i.e. grading). The indirect selection effect of lower grain angles on non-adjusted shape stability values of these selections was thus evaluated for each board thickness separately.

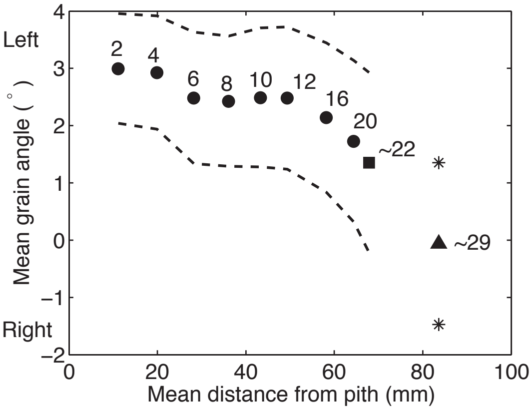

Fig. 3. The average development of grain angle with distance from the pith at a height of 3.4 m in the 162 sample trees (●). The annual ring numbers from the pith are shown in the graph and the mean grain angle under bark of the stem section (■) and the corresponding mean grain angle under bark at breast height (▲) are also presented. Grain angle phenotypic standard deviations added and subtracted from their respective means ($\hat{\mu} \pm \hat{\sigma}_P$) are presented as broken lines and by *.

3 Results

3.1 Trait Means and Variation

At the time of the sawtimber sampling, the mean diameter at breast height (DBH36) of all trees was 160 mm (Table 2), while the mean diameter of the sawtimber sample was somewhat larger (168 mm). The mean grain angles of each annual ring assessed in the stem sections were left-handed but decreased gradually from pith to bark (Fig. 3). The mean of the weighted stem section grain angle average (GASm) was thus 2.2° while the grain angle under bark at breast height (GABH36) was close to zero.

Narrow sense heritability for GABH36 was estimated to be 0.29 and the genetic standard deviation ($\hat{\sigma}_A$) was 0.78° (Table 2). The growth traits exhibited ($\hat{CV}_A$) estimates of 5–12% and heritabilities were in the range 0.12–0.34.

The mean twist for thin and thick boards was 3.3° and 1.9°, respectively, and was therefore very close to the limits of acceptance proposed for wall studs by Johansson et al. (1994) (Table 3). Thus, the rejection percentage was higher for twist than for bow or crook and in total 70% of all rejected boards exhibited excessive twist. Only 3% of the

Table 3. Arithmetic means, medians and total standard deviations ($\hat{\sigma}_{tot}$) of non-adjusted shape stability traits measured in the top 2 m of the boards; the upper acceptability limit for the traits and board thickness in question and the percentage of rejected boards with respect to this limit.

	182 thin boards (32 mm)			134 thick boards (50 mm)		
Trait	Bow	Crook	Twist	Bow	Crook	Twist
Unit	mm	mm	°	mm	mm	°
Mean	5.0	2.4	3.3	4.0	2.0	1.9
Median	5.0	3.0	3.0	4.0	3.0	1.7
$\hat{\sigma}_{tot}$	2.8	2.4	2.3	2.8	2.1	2.0
Acc. limit[1]	6.0	4.0	3.6	6.0	4.0	2.6
Boards rejected[2]	24%	15%	41%	18%	10%	34%

[1] The limits were proposed by Johansson et al. (1994) for structural wall studs.
[2] Boards could exhibit excessive values in several shape stability traits simultaneously.
Therefore, the total rejection percentage cannot be obtained by simply adding together the percentages shown here.

Table 4. Phenotypic repeatability of the shape stability traits ($\hat{R}_P^2$); phenotypic correlations of shape stability traits to grain angle under bark (GABH36) and the weighted stem section grain angle average (GASm); phenotypic (over diagonal) and residual (under diagonal) correlations between shape stability traits.

	Bow	Crook	Twist
$\hat{R}_P^2$	**0.20 (0.08)**	**0.50 (0.06)**	**0.62 (0.05)**
Phenotypic correlations with grain angle			
GABH36	–0.06 (0.08)	0.12 (0.08)	**0.56 (0.05)**
GASm	–0.06 (0.08)	**0.19 (0.08)**	**0.73 (0.04)**
Phenotypic and residual correlations between shape stability traits			
Bow		0.32 (0.20)	–0.10 (0.17)
Crook	–0.11 (0.08)		0.11 (0.12)
Twist	–0.01 (0.08)	**0.17 (0.08)**	

Note: Standard errors are given in parentheses and estimates significantly different from 0 ($p < 0.05$) are highlighted in bold.

boards exhibited negative twist. Bow and crook means were in the range 2.0–5.0 mm.

Statistical analysis of within and between board pair variation (Eq. 7) showed that the phenotypic repeatabilities of crook and twist were considerably higher than the repeatability of bow (Table 4). The coefficients for board pair plot height in the drying stack $\left(\hat{\alpha}_1\right)$ were positive for all shape stability traits but the coefficient magnitudes were small in the case of crook and twist.

3.2 Correlations of Grain Angle and Shape Stability Traits

The phenotypic correlations between grain angle and twist were all significant ($p < 0.001$). The highest correlation was observed with the weighted stem section grain angle average (Table 4). However, the grain angle at the tenth annual ring (GAS_{10}) or 40 mm from the pith (GAS40mm) gave correlations almost as high (0.70) (Fig. 4). Correlations of twist with grain angles measured closer to or further away from the pith, were lower (0.37–0.69) but all annual rings numbered between 8 and 20 and at distances in the range 30–70 mm from the pith, exhibited correlations over 0.60. Phenotypic correlations between grain angles under the bark at breast height and at 3.4 m height were also all significant and positive (e.g. the correlation between GABH36 and $GAS_{x(n)}$ was 0.71).

Positive correlations, although much lower, (0.09–0.24) were observed between grain angle and crook. These were significantly different from zero ($p < 0.05$) in rings numbered 6–20, at dis-

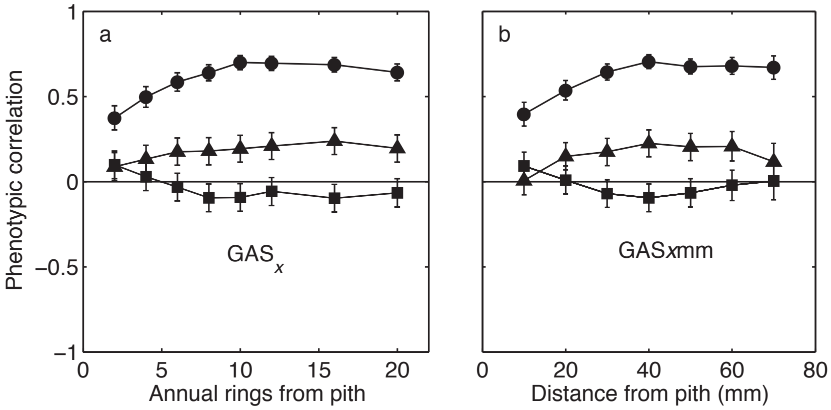

Fig. 4. Phenotypic correlations between shape stability traits and grain angles. Grain angles measured at (a) specific annual rings numbered from the pith (GAS_x) or at (b) specific distances from the pith (GAS*x*mm). Correlations with bow, crook and twist are marked with (■), (▲) and (●), respectively. Standard errors of the correlations are indicated by error bars.

tances 30–60 mm from the pith, and for GASm. All correlations between grain angle and bow were close to zero and non-significant (–0.10 to 0.10). The phenotypic and residual correlations between the shape stability traits were also all near zero (–0.11 to 0.32) and non-significant, with the exception of the residual correlation between crook and twist (Table 4).

3.3 Selection for Lower Grain Angle and Improved Shape Stability

GABH36 was measured non-destructively under bark immediately prior to felling and GAS_{10} exhibited the highest phenotypic correlation with twist among all assessments of single annual rings. Therefore, selections were based on two separate rankings of the phenotypic values of GAS_{10} and GABH36 to illustrate their importance to the twist of the sawn boards. By selecting the 50% of the stems that had the lowest GAS_{10} values, a reduction of the mean twist of approximately 1° for both thin and thick boards was observed (Fig. 5b). The percentage of boards with excessive twist was only 20% and 17% for thin and thick boards respectively in the selected group (Fig. 5c), compared to 41% and 34% in the unselected group (Table 3). A selection of the same intensity for lower GABH36, reduced the mean twist to an extent similar to the selection for lower GAS_{10} (Fig. 5e). The percentage of excessively twisted boards from the 50% of the stems that had the lowest GABH36 values was 26% and 15% for thin and thick boards respectively (Fig. 5f).

4 Discussion

4.1 General Remarks

From the results, it is evident that single annual ring assessments of grain angle, including the non-destructive assessment under bark, were relevant for determining twist propensity in sawn boards of Scots pine. The strong relationship between grain angles and twist has been shown previously in Scots pine and other species (Harris 1989, Warensjö and Rune 2004). However, the present study is unique in the sense that the traits were assessed with methods applicable to forest tree breeding.

The material sampled for sawing in this study was too limited to permit the estimation of genetic parameters. The heterogeneity of the sawn material and the basal sweep induced by the planting system are also important sources of error that

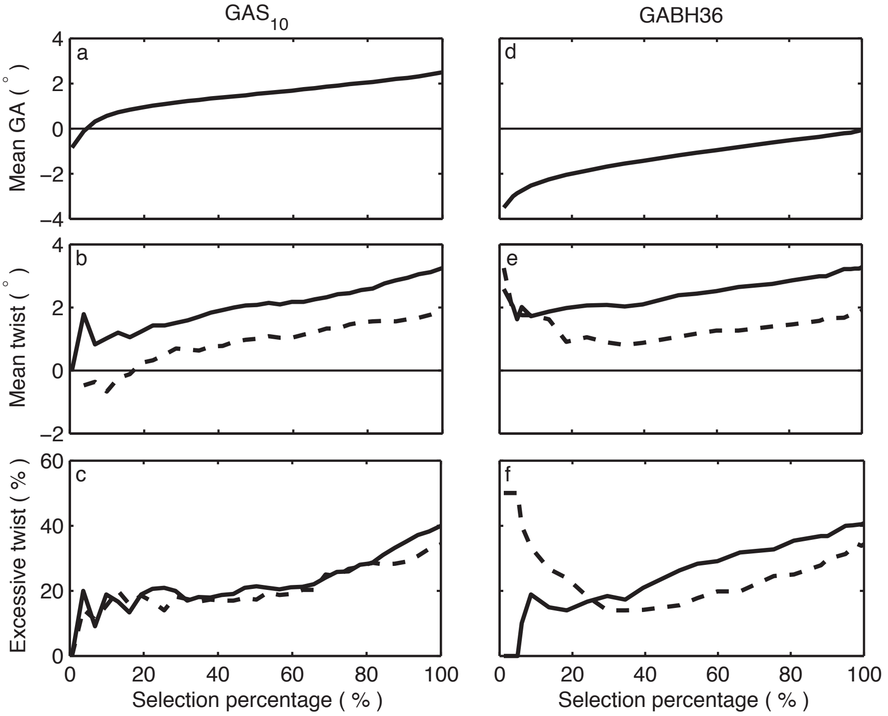

Fig. 5. Effects of phenotypic selection within the existing material of the trees with the lowest grain angle at the 10th annual ring (GAS_{10}), and under bark at age 36 years (GABH36). Effects are shown as (a) mean GAS_{10} and (d) mean GABH36 of the selection, (b,e) mean twist in the sawn boards and (c,f) the percentage ratio of boards with excessive twist. The trends for thin and thick boards are represented by solid and broken lines, respectively.

make genetic analysis difficult. The sawtimber sample was, however, sufficiently large to determine which radial distance from the pith rings should be examined in order to extract the grain angle information most relevant to small sawtimber shape stability. Because the grain angle was measured consistently using the stem axis as the reference, this also indicates the diameter that trees should have reached before relevant grain angle assessments under bark could be performed.

4.2 Means and Variation of the Traits

The grain angle pattern observed in the Scots pine material (Fig. 3) was roughly similar to those of most conifers, with distinct left-handed grain in the juvenile wood, and a subsequent decrease of grain angle as the annual ring number increases from the pith (Harris 1989). Most of the wood volume in the stem sections was juvenile; consequently the positive weighted stem section grain angle average (GASm) was expected.

The heritability and genetic variation of the grain angle under bark (GABH36) was substantial (Table 2), although lower than estimates previously reported in the juvenile wood of two 18-year-old Scots pine progeny trials ($\hat{h}^2 > 0.4$, $\hat{\sigma}_A > 0.9°$, Hannrup et al. 2003). Means, variances, and heritabilities for the growth traits measured in the field were fairly representative of Scots pine in southern and central Sweden (e.g. Eriksson 2008).

The boards investigated in the present study were often heavily distorted (Table 3), especially considering that the limits of acceptance were originally intended to be applied to boards longer than the 2 m lengths assessed here. The poor stem form generally encountered in the progeny trial may have contributed to the observed board distortion, but the boards also consisted mainly of juvenile wood, which is known to be associated with poor shape stability of sawn timber (e.g. Zobel and Sprague 1998). The effect of the height position in the drying stack for crook and twist was small, indicating that the restraint effect exerted by the weight of the stack was minor for these traits. Similar observations have been made by Forsberg and Warensjö (2001) for Norway spruce sawn timber. Furthermore, the substantial board pair repeatability of twist and crook indicated that a large part of the trait variation was determined by characteristics common to the whole log (Table 4), although the magnitude of within-log variation and measurement error must still be regarded as considerable.

4.3 Correlations between Grain Angles and Shape Stability Traits

The grain angle exhibited significant and considerable phenotypic correlations with twist in the sawn and dried boards irrespective of the grain angle measurement method. The correlations were remarkably similar to the correlations estimated by Warensjö and Rune (2004) despite important differences in methods. In that study, boards were dried while hanging from the kiln ceiling without any restraint, and the grain angles were assessed only at breast height on debarked logs.

The high correlation between GABH36 and twist (Table 4) showed that the non-destructive measurement was relevant for genetic improvement and for grading and log sorting in the field. However, the assessed trees were too old to make the result practically applicable in Scots pine breeding. On the other hand, grain angle measurements of all the annual rings numbered in the range 8–20, and at all distances in the range 30–70 mm from the pith exhibited correlations with twist over 0.60. This suggests that assessments of the grain angle under bark performed on younger and smaller trees would exhibit phenotypic correlations with twist as high, or even higher than the correlation observed between GABH36 and twist. Harding et al. (2008) observed similar correlation patterns between twist and grain angle measured in stem sections from hybrid *Pinus elliottii* Engelm. × *Pinus caribaea* Morelet var *hondurensis* clones. The propensity of boards to twist appears to be determined mainly by the grain angle of rings close to the bark faces of the sawn board.

The high correlation (0.71) between grain angles measured under bark at breast height, and at a height of 3.4 m in the stem suggests that the height at which measurements are taken has only a limited influence on the radial grain angle pattern. Other studies of Norway spruce and Sitka spruce (*Picea sitchensis* Bong. Carr.) have reported significant but small interactions between the tree and the measurement height (Danborg 1994, Hansen and Roulund 1998). Given this, it is reasonable to assume that the correlation pattern between grain angles at breast height and twist are roughly similar to the correlation pattern actually observed (Fig. 4) in the stem sections.

In conclusion, grain angle measurements under bark relevant to small sawtimber shape stability, could be performed on trees with diameters in the range 60–140 mm (two times the distance from pith). The choice of annual ring within that diameter range does not appear to be critically important.

The positive but low correlations between grain angle and crook also agree with the observations of Warensjö and Rune (2004). In contrast, Kliger et al. (2003) reported that grain angle does not influence crook in sawn timber of Norway spruce. Furthermore, in the present study the residual correlation between crook and twist was significantly positive, implying an association at the board level, while the phenotypic correlation was very low and non-significant (Table 4). Considering the measurement methods used, the occurrence of extreme twist might have introduced a positive bias in the crook measurements, thus creating an impression that crook is associated with high grain angles. Some authors have suggested that high grain angles are also associated with bow distortion (e.g. Ormarsson 1999), but in the case of bow, a low phenotypic repeatability and a stronger impact of weight restraint was observed. The lack of significant correlations with grain angles was, therefore, not unexpected.

4.4 Single Annual Ring Assessments of Grain Angle

It is notable, that the three traits that had the strongest associations with twist (GASm, GAS40mm and GAS_{10}), exhibited very similar correlation values (0.70–0.73) (Table 4 & Fig. 4). In a breeding context, assessing the whole radial grain angle pattern (e.g. from increment cores), or assessing grain angles at specific distances from the pith, appear to offer very little extra benefit in comparison with the assessment of the best annual ring. This lack of difference should, however, be interpreted cautiously, since strong relationships might have been obscured by the large sources of error and the heterogeneity of materials that was evident in the present study.

The correlations of the grain angles at specific distances from the pith should still be regarded as important because the performance of sawn boards depends on the properties of the wood within the part of the log recovered at sawing. It should also be kept in mind that these results are primarily representative of centrally sawn yields with a high juvenile wood content. Older and larger trees might have provided sawlogs that could have been sawn in alternative patterns, perhaps even to obtain outer yields. The weighted stem section grain angle average or grain angles at specific distances from the pith might have been more relevant to shape stability in such materials.

4.5 Implications for Tree Breeding and Potential Twist Response

Even if the weighted stem section grain angle average and the grain angles evaluated at specific distances from the pith, were the most relevant to sawtimber shape stability in the general sense, the assessment of these traits is unreasonably destructive and cumbersome in a tree breeding perspective. Grain angle measurements under bark relevant to twist development could be performed on trees within the diameter range 60–140 mm which correspond to a tree age span (approximately 15–25 years) more realistic for genetic evaluation in Scots pine breeding. Even though the validity of these results are restricted to centrally sawn small timber, that would nonetheless comprise virtually all the sawtimber from first and second commercial thinnings, and might even be relevant to sawlogs taken further up the stem at final harvest. The sawing pattern, the board thicknesses and the 12% moisture content attained in this study are common in Scandinavian sawmill practice.

The impact of lower grain angles on board twist was demonstrated by selecting that half of the population of trees with the lowest GAS_{10} values. GAS_{10} and twist in boards of both thickness groups were reduced by approximately 1° (Fig. 5a & b) and the percentage of boards with excessive twist was essentially halved from approximately 40% to 20% in comparison with the whole sample (Fig. 5c).

In order to achieve grain angle reductions of a 1° magnitude by breeding, substantial genetic variation and heritability is required. The grain angle under bark (GABH36) exhibited promising genetic variation and heritability (Table 2), but the heritability and genetic variation reported for grain angle in Scots pine by Hannrup et al. (2003) is of greater importance in this respect because the measurements of that study were performed at the 11th annual ring on trees with a diameter of approximately 100 mm (i.e. within the range where the grain angle was found to be most strongly correlated to twist). Assuming an additive grain angle breeding value accuracy (r_{TI}) of 0.80 and a genetic standard deviation (σ_A) of 0.78° (which is reasonable given the available data), the required selection intensity (i) for a genetic grain angle reduction (ΔG) of 1° could be calculated as:

$$i = \frac{\Delta G}{r_{TI}\sigma_A} = \frac{1.0}{0.80 \cdot 0.78} \approx 1.6$$

The selection intensity of 1.6 implies that a selection percentage of about 14% of the parents with the lowest grain angle breeding values would be required to achieve a 1° grain angle reduction. Therefore, a considerable reduction of twist in Scots pine small sawn timber by breeding is likely possible by applying very simple methods.

By selecting the half of the population of trees with the lowest GABH36 values, sawn board twist was reduced to an almost equal extent as the corresponding selection based on GAS_{10} values

(Fig. 5b,c,e,f). Because GABH36 was measured shortly before the trees were felled, this demonstrate the potential of the grain angle measured under bark as a grading criterion for improving the shape stability of sawtimber by sorting trees prior to thinning in the forest. If less than 20% of the trees with the lowest GABH36 were selected, the twist response in the thick boards appeared to be counterproductive. However, the sampling errors of those response estimates are probably very large because the number of observations for such selections was low (less than 30).

In future work, the conclusions of the present study should be further validated by estimating proper genetic parameters for shape stability traits and grain angles simultaneously. In this respect, studies of the grain angle and shape stability traits of Norway spruce are desired because the sawtimber of this species is frequently used in building construction where good shape stability has been shown to be essential (e.g. Woxblom 1999). Furthermore, high shrinkage coefficients, high microfibril angle and large knots have also been shown to impair the shape stability of sawn timber aside from the grain angle (Dinwoodie 2000). To fully determine which traits should be assessed in order to achieve improvements in shape stability most efficiently, knots, shrinkage and microfibril angle should therefore be studied.

4.6 Conclusions

The grain angle measured under bark was found to be phenotypically correlated ($\hat{r}_p = 0.56$) with respect to twist development in centrally sawn boards from Scots pine small timber. However, all single annual ring assessments of grain angle within the range 30–70 mm from the pith were found to be even more relevant for twist ($\hat{r}_p \geq 0.60$). Neither the grain angle measurements made at the best specific distance from pith (40mm), nor the weighted average grain angle of stem sections, showed appreciably higher correlations with twist than did grain angles measured at the best annual ring (GAS_{10}). Phenotypic selection for lower GAS_{10} within the existing material showed that it was possible to achieve substantial twist reductions irrespective of the board thickness. Consequently, breeding for lower grain angles under the bark appears to be effective in reducing twist if the assessed trees have diameters within the 60–140 mm range. Grain angles did not appear to have any substantial association with other shape stability traits like crook or bow, and the radial grain angle development in Scots pine stem sections appears to be similar to that found for Norway spruce and several other conifers.

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