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Spatial variation in spiral grain: a single stem of *Pinus radiata* D.Don

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Abstract

A single 18-year-old *Pinus radiata* D.Don tree was felled and log sections (2.5 m) removed at intervals up the stem for intensive spiral grain measurements. All logs were assessed externally with a laser dot scanner to quantify grain direction at 16 radial positions circumferentially, and subsequently four discs were removed from each log – two representing internodal sections and two close to branch whorls. Grain angles were measured by scribing at each growth ring boundary along 16 radii corresponding to the external measurements.

The study highlighted the degree of variation in grain angles determined using a disc "scribing method" and the log surface grain angles determined using a laser dot scanner. The former method of "point sampling" does not reveal the small-scale (mm) spatial variation quantified by higher intensity sampling such as is possible with dot laser scanning. Both approaches confirmed an average "generic" pattern of within-stem variation in grain angle (i.e. higher values in juvenile wood and at higher levels in the stem) but also quantified the spatial variation radially, circumferentially and longitudinally in a mid-rotation stem.

Average angles increased rapidly over about the first 5 rings from the pith to an average of 6 to 10 degrees and thereafter decreased outwards to the bark at all levels. Circumferentially, grain angles were highly variable and varied by several degrees within a matter of millimetres. The degree of variation recorded here for radiata pine was much greater than had previously been reported for other species and the results highlight the limitations of studies which only examine single radii or widely spaced disc samples. Even the average values around the stem for individual radii were observed to vary by up to 6 degrees, at least partly due to some tilting of the disc with respect to the stem axis. Within individual growth rings, grain angles did not show a strong consistent longitudinal pattern up the stem, apart from an increase from the lowest log to the upper logs. In the sample discs, grain angles above the lowest log were, on average, 2 degrees greater at equivalent growth rings. In this study, the impact of branches and knots was found to be very localised. When discs from within 50 mm of visible branch whorls were analysed, the effect on grain angle was not obvious.

The disc scribing and log laser dot scanning methods were compared and found to give similar grain angle values – the averages were generally within 2 degrees with no obvious bias. Given the documented spatial variation, and the difficulty of referencing "true" grain angles, it is a moot point as to what can be considered a reasonable level of sampling accuracy for a particular study. In the authors' opinion, 2 degrees is a very acceptable level.

The implications for spiral grain sampling were discussed. For comparative purposes, studies of silvicultural and breeding effects require cost-effective sampling. Assessment of spiral grain angles along single radii (as from breast height cores or discs) is not recommended, unless a minimum of two radii can be averaged to compensate for possible tilt in relation to the stem. The current study showed that there can be real variation in radial median values of up to 4 degrees.

Dot laser scanning is the most practical option for assessing log and timber surface grain angles in processing plants, where deviations around knots and branches and due to log sweep can be screened out to reveal important average trends for timber twist prediction.

Keywords: Spiral grain; within-tree variation.

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Background

Distortion (twist, crook, bow) of wood during drying and in use is a major issue affecting softwoods including *Pinus radiata* D.Don (radiata pine) (Cown et al., 1996; Johansson & Kliger, 1999; McBride, 1967; Säll, 2002). In fact, Kliger, 2001 recommended that the central portion of Norway spruce (*Picea abies* (L.) Karst) should not be considered for structural timber due to instability. Specialised kiln drying schedules for twist-prone radiata pine (i.e. juvenile wood), involving high temperatures and stack weighting, have been adopted as the industry standard in Australasia (Haslett et al. 1991). Distortion is recognised as one of the limiting factors affecting utilisation of plantation softwoods (Fosberg & Warensjö, 2001).

Among the factors leading to distortion, spiral grain has been strongly implicated (Mishiro & Booker, 1988; Harris, 1989; Johansson et al., 2001; Forsberg & Warensjö, 2001). Other contributing factors include growth ring curvature, dimensional shrinkage, distance from the pith, and drying conditions (Booker, 2003; Evedad, 2005; Haslett & McConchie, 1986; Mackay, 1973).

While knowledge of the contribution of spiral grain to distortion has existed for decades (Fielding, 1967; Balodis, 1972; Harris, 1984), the exact mechanism has been the subject of debate (Booker et al., 1992; Johansson et al., 2001; Booker, 2003; Ekevad, 2005). A recent study using Finite Element Modelling (Ormarsson & Cown, 2005) compared the tendency of juvenile wood to distort in radiata pine and Norway spruce, and concluded that radiata pine is worse, mainly due to its higher spiral grain angles and greater longitudinal shrinkage. Due to the importance of spiral grain on wood properties, researchers have sought to improve methods for measuring spiral grain and predicting distortion.

Traditionally, tree stem grain angles in wood quality and tree breeding studies have been measured on standing trees (Harris, 1984; Lausberg, 1995) or from scribing discs removed from stems (Northcott, 1957; Cown et al., 1991; Danborg, 1994; Hannrup et al., 2002; Gjerdrum & Bernabei, 2008). These methods have the advantage that samples at equivalent positions on either side of the pith can be averaged to eliminate bias due to inaccurate positioning of discs with respect to the vertical stem axis (hence giving 'absolute' values referenced to the vertical axis of the stem). The bulk of studies in New Zealand have used these approaches (Cown et al., 1991; Haslett et al., 1991; Tian et al., 1995).

Discs have given the most reliable and repeatable data, particularly when opposite radii are measured to compensate for disc tilt (Brazier, 1965; Northcott, 1957; Harris, 1989; Danborg, 1994). Sampling has been done at fixed heights in the stem, often representing commercial log lengths (e.g. 5 m). The method developed by Brazier (1965) involved splitting the discs through the pith and measuring the deviation of the split surface of each growth ring from the stem axis. A lot of research has also been done using disc-scribing and splitting methods, and most species have been shown to exhibit left-hand (positive) angles near the pith, decreasing or reversing with age (Fielding, 1967; Cown et al., 1991; Danborg, 1994; Hannrup et al., 2002, 2003; Säll, 2002).

Wobst et al. (1994) completed a small study of circumferential variation in discs of *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir). Their conclusion was that there was significant tangential variation around individual rings, thus complicating analyses of the effects of age, growth conditions, genotypes, etc. Measured values around individual growth rings showed deviations of up to 5 degrees.

Most published studies deal with grain angles determined from a rather low level of sampling, which are often averaged over a specified distance or groups of growth rings. More recent detailed studies (Sarén et al., 2006; Nilsson et al., 2007) have indicated that there may be much more variation present within a tree than has been previously reported.

Nyström (2002) developed an automated method for measuring spiral grain on sawlogs and timber, that utilised the light conducting properties of softwood tracheids to measure fibre orientation on the exterior of debarked logs. Its use allowed the possibility of measurement at high resolution intensity over large areas and segregation of material with high surface grain angles.

Other non-destructive methods for measuring spiral grain in stems or logs have been attempted using x-rays and/or microwaves (Buksnowitz et al., 2008; Sepulveda et al., 2003; Sjödén et al., 2005; Nilsson et al., 2007). These techniques require expensive equipment and powerful mathematical modelling capability and are starting to be adopted in commercial board-scanning systems (Nilsson et al., 2007). Sarén et al. (2006) used both x-ray and laser methods to investigate within-tree patterns of spiral grain in Norway spruce at about 0.5 mm intervals. Variations were noted to be large (up to 10 degrees), but not in phase with the growth-ring boundaries. Most significantly, these fluctuations occurred over short distances. The implications of the findings could be dramatic if confirmed in other species, suggesting that the traditional scribing methods based on growth rings may be of less accuracy than desired for some purposes.

The study reported here was designed to provide information on the spatial variation of spiral grain within a single stem of radiata pine, in terms of:

- circumferential variation around individual growth rings;
- longitudinal variation within growth rings up the stem;
- radial variation from pith to bark;
- effects of branch whorls on local grain angle;
- comparison of laser scanning and disc scribing methods; and
- implications for sampling tree stems and sawn products.

By undertaking this detailed examination of a single stem, we aim to improve our understanding of what level of spatial variation can exist within a stem, and how this might influence future sampling.

Materials and Methods

A single radiata pine stem from a 1990 breeding trial at Scion in Rotorua was selected, based on average diameter for the stand and the presence of some visible stem distortion which would allow examination of the effect on the measurement of spiral grain. At the time of felling (2008), the tree was eighteen years old and was considered to be "mid-rotation" (about 400 mm diameter at a breast height of 1.4 m) and hence to have completed the period of juvenile wood in the lower stem (Cown et al., 1991). After felling, a reference line was marked on the stem and four 2.5 m logs removed from near the base and at three other positions up the stem to a top diameter of 175 mm (Figure 1). Table 1 gives the characteristics of each log.


FIGURE 1: Four logs prior to debarking

TABLE 1: Log characteristics

Log number from base	Position in tree (m)	Small end diameter (mm)	Large end diameter (mm)	Length (m)	Comments
1	1.5 - 4.0	340	380	2.51	Pruned with 27 mm sweep
2	6.5 - 9.0	295	330	2.52	62 mm sweep with small branches (30 - 50 mm)
3	11.5 - 14.0	230	285	2.55	Large branches (>50 mm)
4	16.5 - 19.0	175	205	2.53	High visible angle and huge branches (< 75 mm)

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FIGURE 2: All four debarked logs

The logs were carefully debarked by hand (Figure 2) and kept moist before scanning[1]. Log 2 had visible sweep and logs 2 – 4 showed signs of external spiral grain under the bark.

External Grain Angle Variation by Laser Scanning

Each log was mounted on a traveling flatbed (Figure 3) and scanned with a T1 Fiber On-LineTM laser scanner (SP Trätek, Borås, Sweden) which uses the "tracheid effect" to determine grain orientation (Oja et al., 2006). The laser source projected a beam on to the log surface where the fibres conducted light preferentially along the major grain direction (Figure 4). An in-built camera recorded the dimensions of the laser spot continuously along 16 radii around the circumference to generate about 3000 data points/scan for analyses. The data were converted to grain angles (Nyström, 2003).

The circumferential scanning positions were chosen to allow analysis of possible systematic variations on the stem surface, and contributing factors such as stem sweep and branches. The raw data were sorted with an angle criterion to remove idiosyncrasies due to deviations around large knots, loose fibres and bark residues all of which can have a negative impact on the data quality (Figure 5). It can be seen from the figure that branch effects were quite localised. Median values were used to reduce the impact of such points.

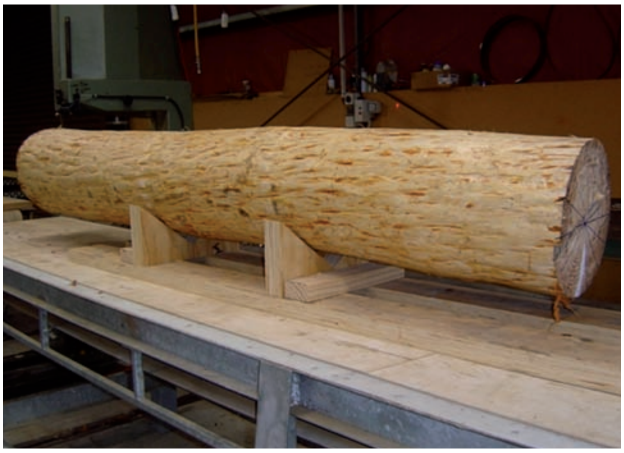

FIGURE 3: Log 1 (pruned) on carriage awaiting scanning

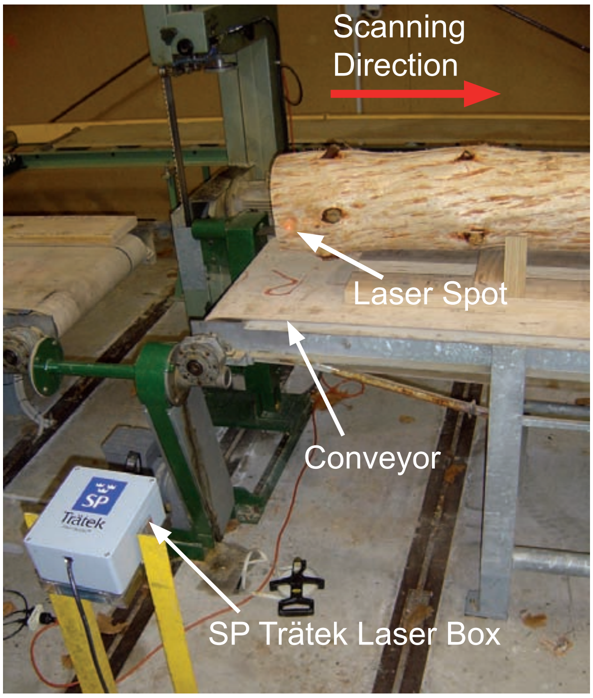

FIGURE 4: Laser Dot Scanning of log on moving carriage

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[1] *Best results for laser dot scanning are obtained from fresh, wet wood.*

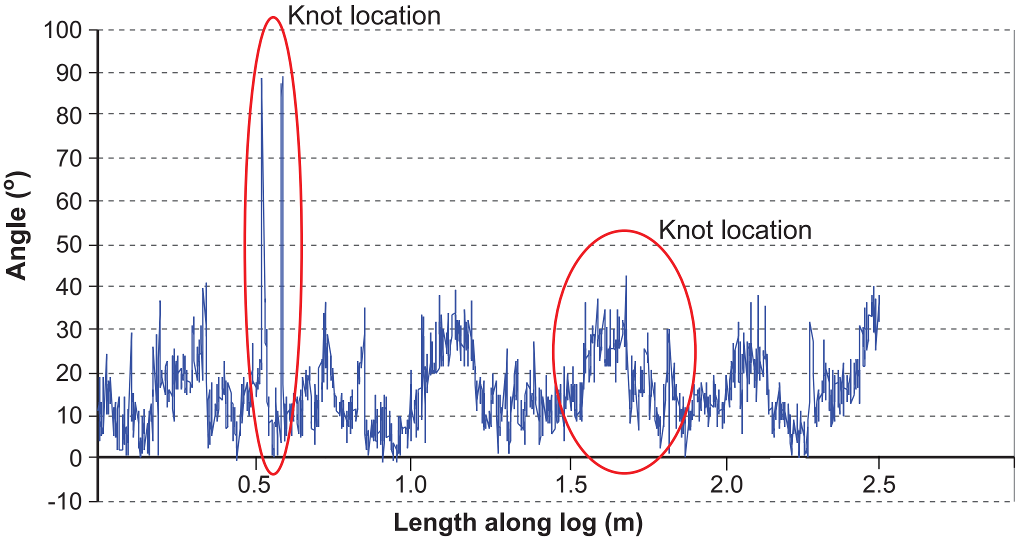

FIGURE 5: Analysis of a single external log scan

Radial Variation by Disc Scribing

After laser scanning of each log, 4 disc samples were collected from each log to represent both clear internodes (2 discs) and positions about 50 mm below the largest and smallest branch cluster (2 discs). Each disc was oven-dried and sanded on one side to provide a stable reference surface and to highlight the annual ring boundaries. Growth rings were traced on the smoothed surface, segments marked on each disc corresponding to the sixteen external scan positions (Figure 6), rings split off from the pith outwards, and the all rings assessed by scribing at the growth ring boundary. Grain angles were thus assessed in reference to the reference surface at 16 positions around each annual ring in a similar manner to the external laser scanning of the logs. The convention used was for grain direction upward to the left (as seen from the bark side – left-handed grain) to be allocated positive angles and values upward to the right to be labelled with negative values, as proposed by Harris (1984).

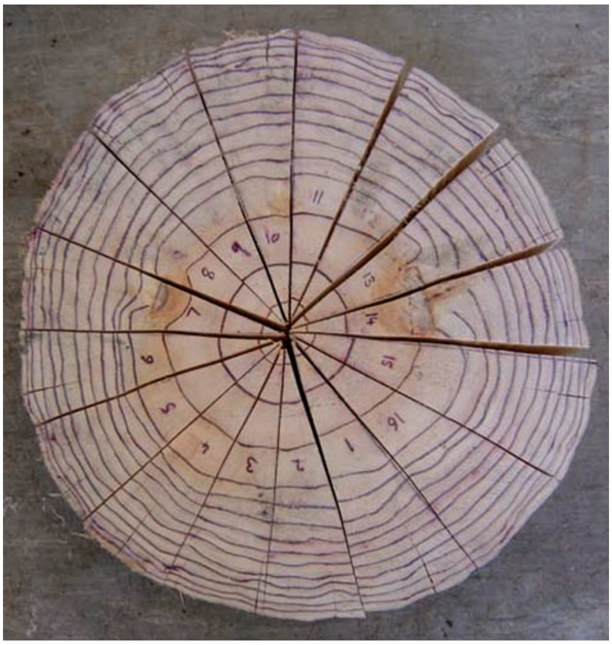

FIGURE 6: Annual rings marked on discs and segments 1-16 prepared for scribing.

Analyses

Log external grain angles measured with a laser scanner were analysed in relation to:

- median circumferential values (16 positions);
- vertical patterns along logs;
- log height in stem;
- log shape (sweep); and
- branch nodes.

Disc radial grain angles measured using the scribe test were examined in relation to:

- growth rings from the pith;
- circumferential position;
- effect of discs not being perfectly orientated at right angles to the predominant stem direction; and
- proximity of knots.

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Results

Laser Scanning – External Grain Angle Variation

After data collection, “maps” were generated to illustrate the variation of the external spiral grain angle across the surfaces of each log (Figure 7).

The summarised data are presented in Table 2 and Figure 8.

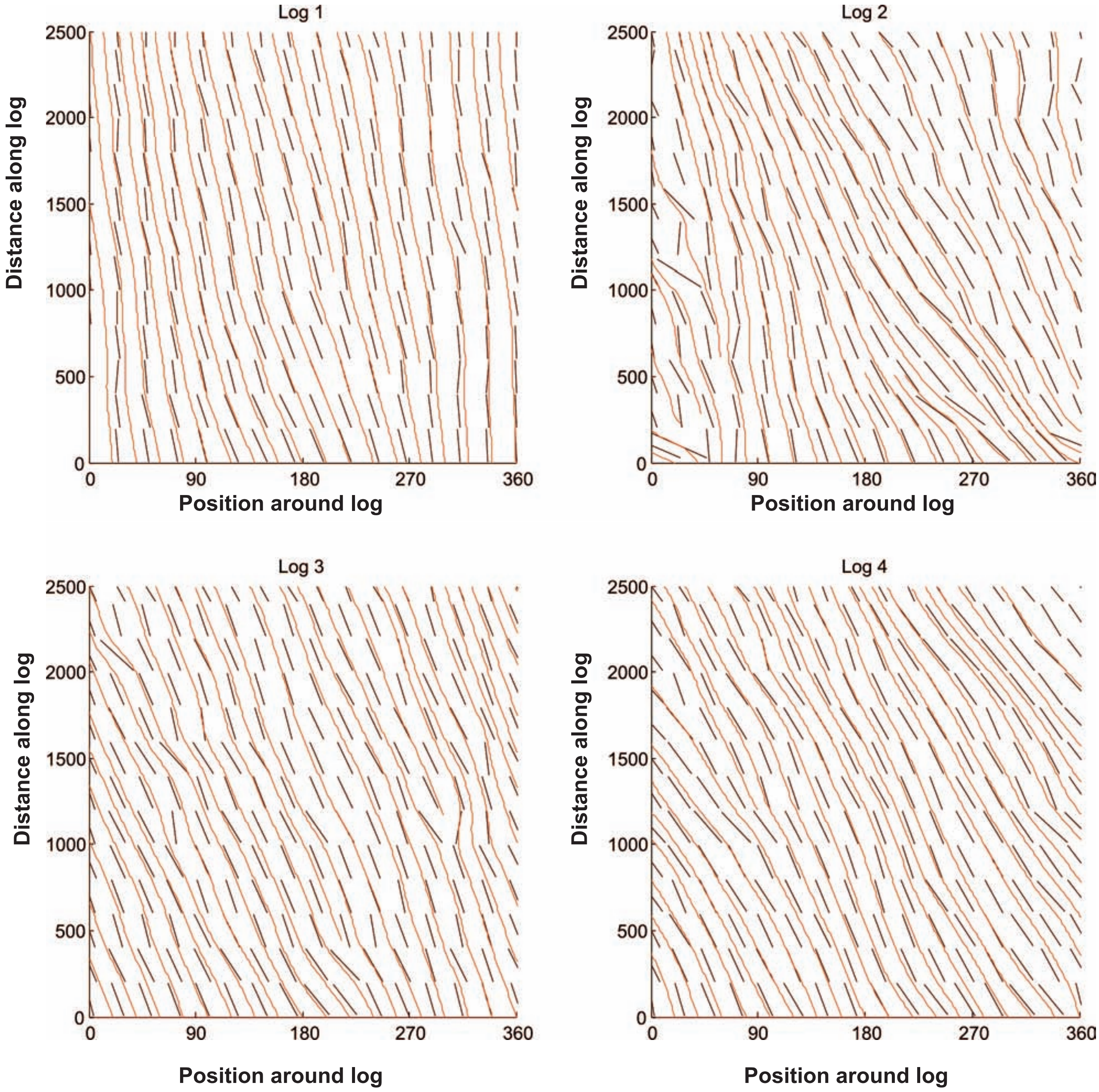

FIGURE 7: External spiral grain angles (median values) across log surfaces (16 scans)

TABLE 2: Median and range of grain angles of 16 peripheral log scans per log

Log number	Median (degrees)	Range of angles (degrees)
1 - Base	4.69	3.34 - 6.33
2	8.61	2.54 - 12.09
3	8.53	7.38 - 9.63
4 - Top	10.85	7.88 - 13.87

Several patterns are apparent:

- all logs show considerable variation in the median values for the 16 circumferential scans. The lowest variation (2.3 degrees) is in Log 3 and the highest (10.2 degrees) in Log 2 – the swept log;
- the sample stem followed the "normal" increase in external spiral grain angle with height of the stem documented in other radiata pine studies (e.g. Cown et al., 1991); and
- a greater range of grain angles is seen in the swept log (Log 2) than in the other three logs. The high range in recorded grain angles in this case (2.5 to 12.9 degrees) seems to be related to the orientation of the sweep which "forces" the external angle (as detected by the laser scanner) to follow the log shape.

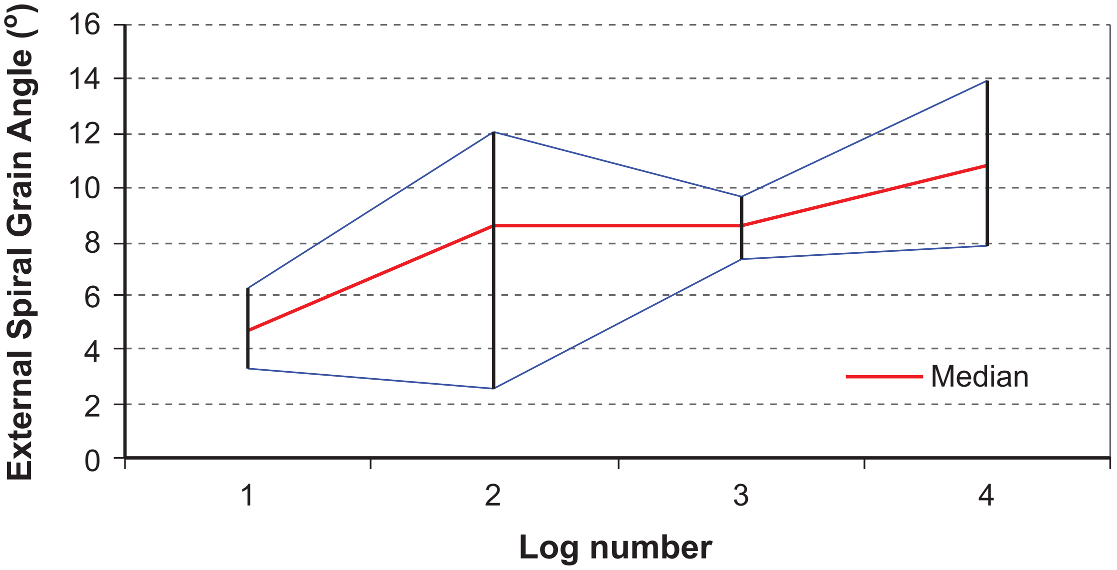

FIGURE 8: Range of external spiral grain angles per log

TABLE 3: Sample Disc Data

Log	Disc	Diameter (mm)	Growth Rings	Comments[1]
1	1	375	16	Pruned
	2	356	16	
	3	360	15	
	4	345	15	
2	1	314	13	6 Branch clusters;
	2	316	13	Average branch
	3	315	12	diam. 31 - 57 mm
	4	310	12	
3	1	248	9	7 Branch clusters;
	2	253	9	Average branch
	3	238	9	diam. 16 - 37 mm
	4	227	8	
4	1	193	7	7 Branch clusters;
	2	195	7	Average branch
	3	185	6	diam. 12 - 42 mm
	4	186	6	

[1] Typically, a 3-m section of stem in radiata pine represents two years of height growth and can contain several internodes.

Disc Assessment - radial and circumferential grain angle variation

The diameter and number of growth rings for each disc are presented in Table 3.

The individual grain angle values for one disc, obtained by scribing, are shown in Figure 9 (Log 1; disc 1) and demonstrate the high level of spatial variation observed, particularly in the 5 rings closest to the pith, where differences of up to 25 degrees were

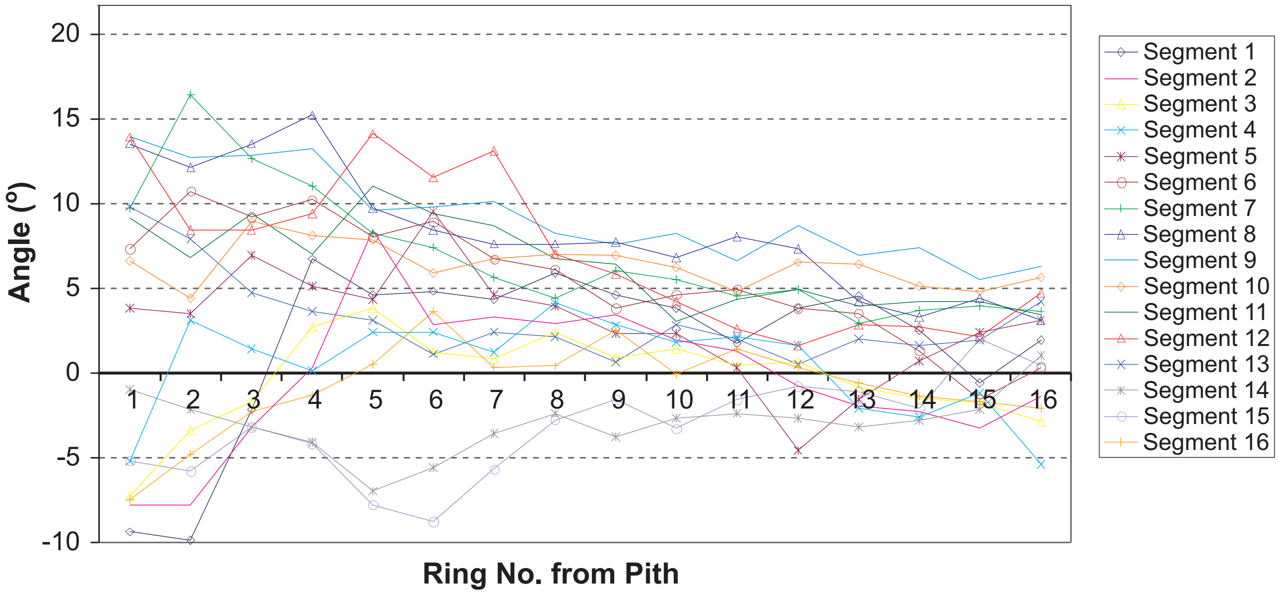

FIGURE 9: Log 1 disc 1 individual ring spiral grain values (16 segments)

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seen. Further out, the differences reduced to around 10 degrees, with many negative values observed (right-hand grain). Some of this variation is inevitably associated with the orientation of the discs in relation to the local log axis, although they were nominally collected perpendicular to the stem.

Summaries of the radial and circumferential grain angle values determined for all rings in all discs are shown in Figure 10a and b respectively. Figure 10a demonstrates that the well-established generic trends apply to this stem, i.e. an increase in grain angle within the first five or so juvenile rings, followed by a steady decrease outwards. Older stems tended to have right-hand angles and an increase in grain angle with height in the stem within annual growth rings (Cown et al., 1991). The large circumferential variation was unexpected (Figure 10b), as most study methods do not attempt to quantify this aspect. In this case, the average ring values along the segments varied by up to 5 degrees *on a log basis*, but even more on a *disc basis*.

The spatial variation in spiral grain is well illustrated by examining both the 2-dimensional and 3-dimensional distributions (Figures 11 & 12, respectively). Figure 12 was generated by linking the maps of external grain angle for each log (Figure 7) with the segment values from the discs (Figure 11), thus providing a 3-dimensional vision of grain angle variation throughout the stem.

Using Figures 11 and 12 and the raw data from each of the 16 radial scans taken around each log, we can observe that the external spiral grain angle variation in this stem tended to be helicoidal along the stem height and circumference. However, the raw data was based on observations on 16 individual radial samples/disc, without any regard to possible disc "tilt".

A separate analysis was performed to compare the use of individual radii versus diametric averages to quantify the effects of possible "disc tilt". Figure 13 confirms that the observed variation was dramatically reduced by averaging opposing sectors (as has been noted in some previous studies, e.g. Harris, 1989). This confirms that some of the high values illustrated in Figures 9 and 11 were at least partly due to disc orientation but that, even by removing the tilt effect by averaging across radii, there can still be several degrees of real variation within logs.

Relationship between external assessments (Laser Scanning and Disc Scribing)

The scribed values derived from the outer exterior surface of each disc (16/disc; 4 discs/log) were averaged and compared to the median values for the 16 laser scans/log (Figure 14).

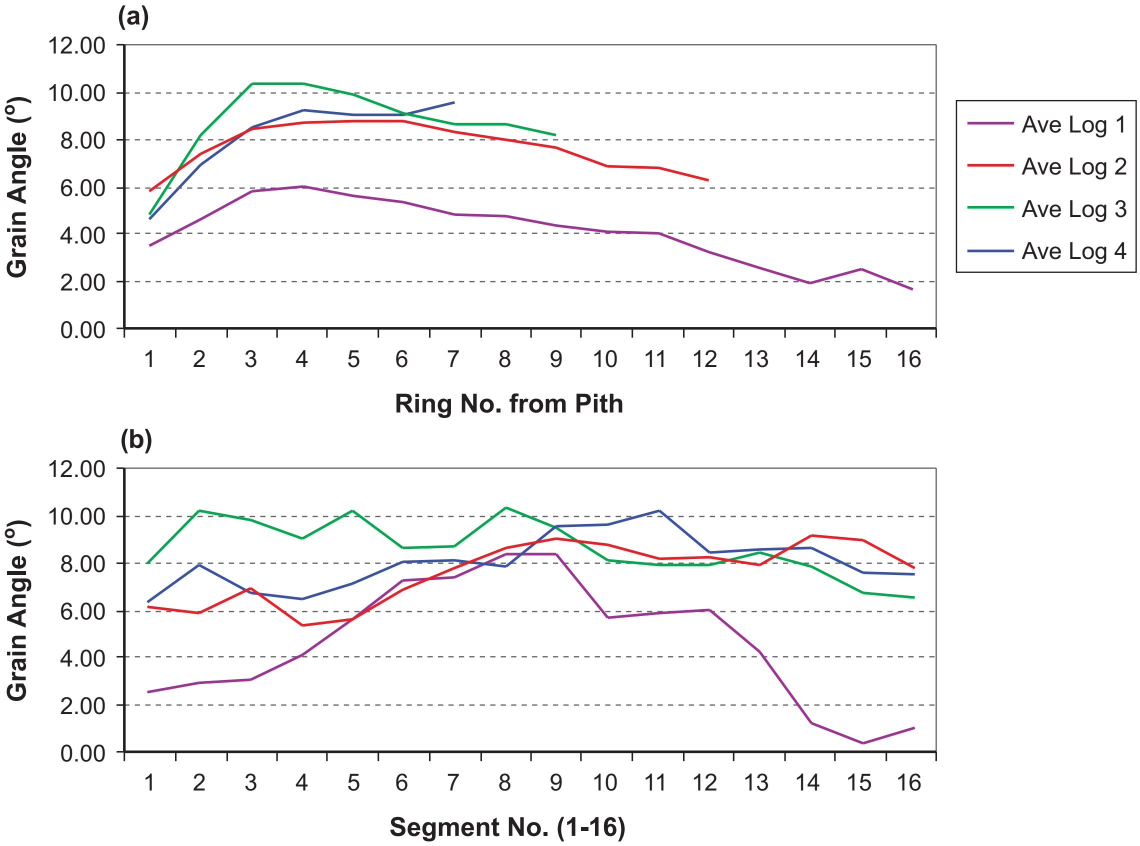
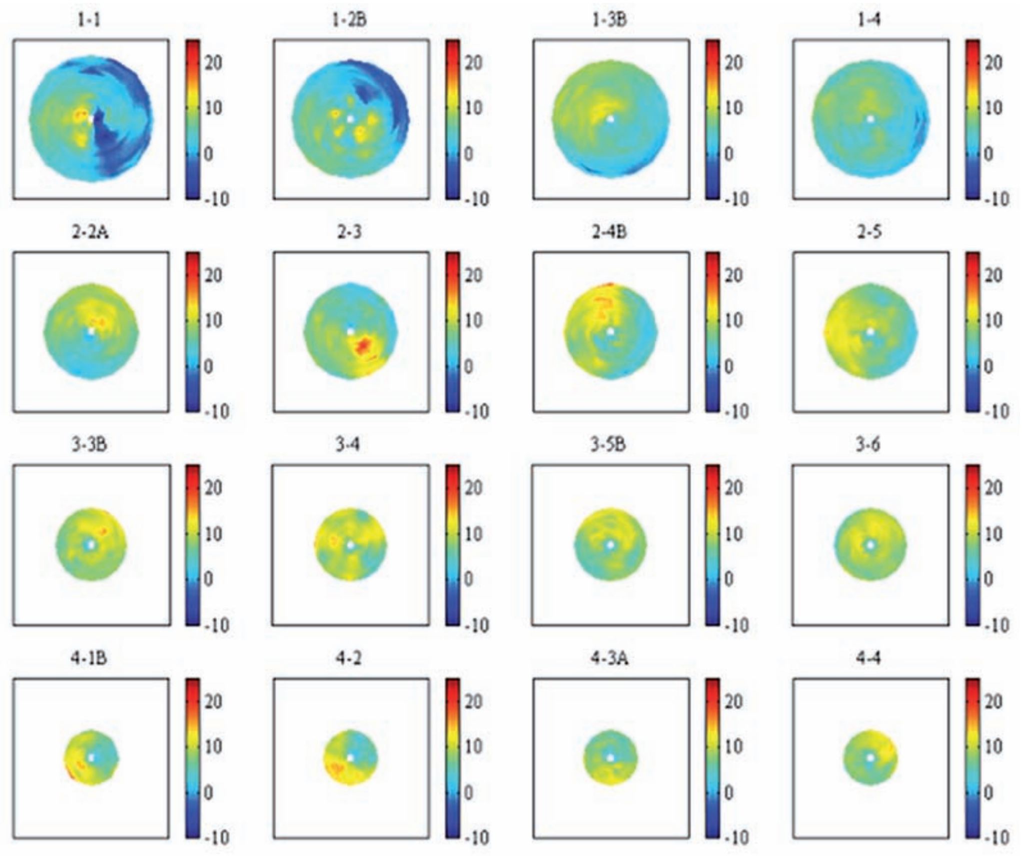
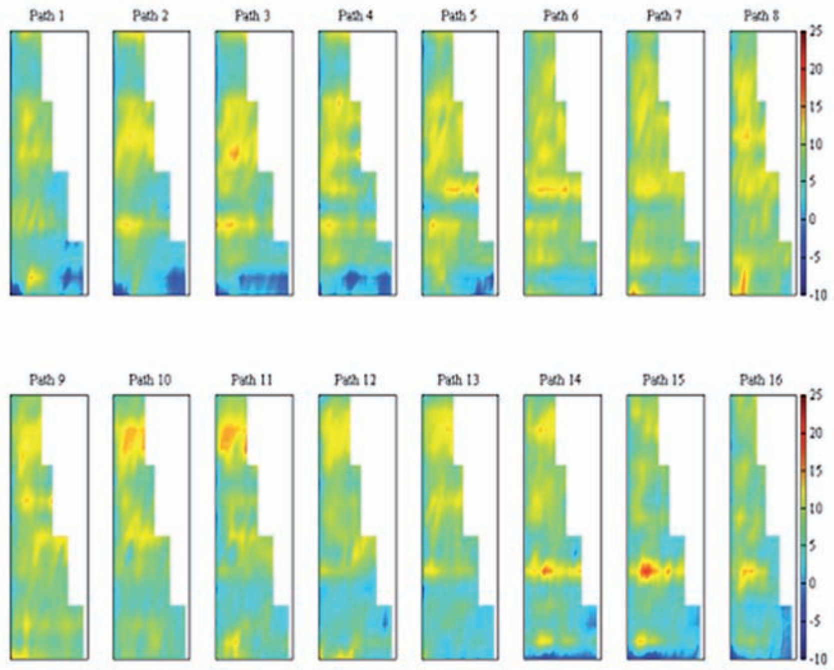


FIGURE 10: Log and Disc average spiral grain angle variation: (a) radial variation; (b) circumferential variation.



negative = Right-handed SGA Note: ignores ring-width variations

FIGURE 11: Stem grain angle (SGA) distributions within individual discs. Numbers related to log and disc numbers for the 16 radial scans.



negative = Right-handed SGA Note: ignores ring-width and disc-height variations

FIGURE 12: Average stem grain angle (SGA) distributions throughout the stem for the 16 radial scans. X-axis reflects radial position from the pith.

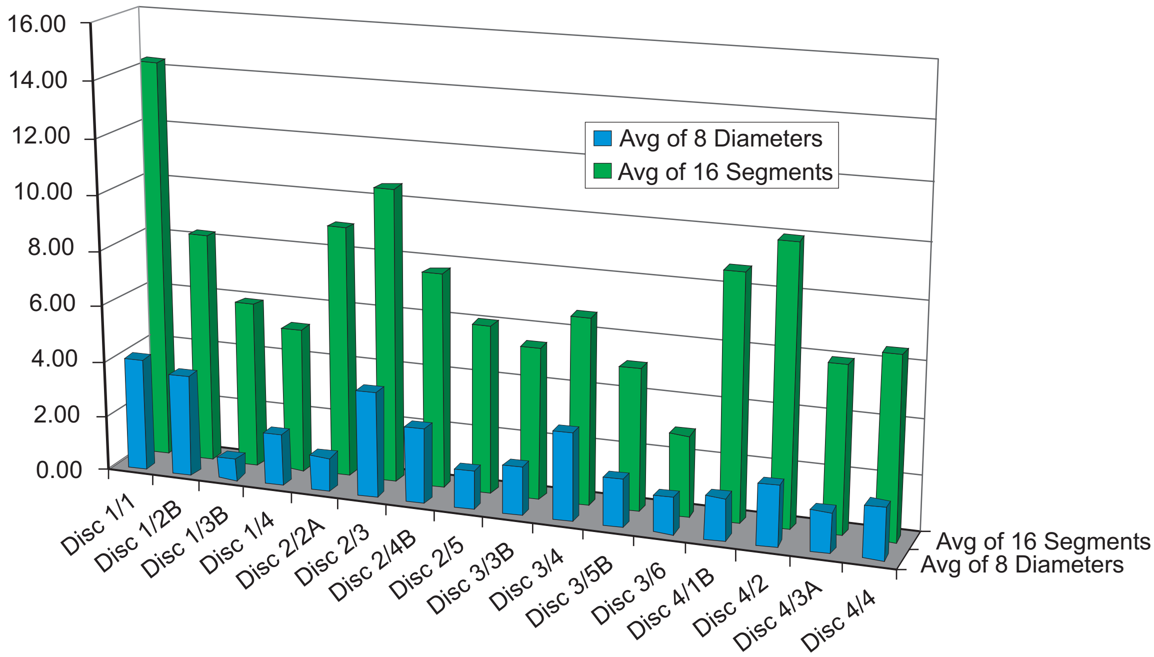


FIGURE 13: Median values using all 16 segments and eight averaged diameters

Both sets of data indicate a pattern of increasing grain angle with log height and show broadly similar circumferential trends around the logs. In the majority of cases, the methods give values less than 2 degrees different for a given log segment, but occasionally (particularly in a small number of contiguous segments of Log 4) values were around 4 degrees different. This was explained by the fact that the laser does not allow for log geometry – sweep will create apparent variability irrespective of the actual spiral grain in the log.

Discussion

This study of a single radiata pine stem documented the degree of variation in grain angles determined using the standard "scribing method" and the log surface grain angles determined using a laser dot scanner. Both approaches confirmed the "generic" patterns of an increase in grain angle with height for this stem, but also quantified the spatial variation radially and circumferentially. Spatial variation may be more important in fast-growing species such as radiata pine compared to slower growing material such as Norway spruce.

Radial variation from pith to bark

This study confirmed that the general pattern of grain angle for radiata pine, described by past researchers (Harris, 1989; Cown et al., 1991; Tian et al., 1995), applied to this stem. The average angle increased rapidly over about 5 rings from the pith to an average of 6 to 10 degrees after which there was a decrease outwards to the bark. Angles tended to increase above the levels found in the lower stem.

Circumferential variation around individual growth rings

Grain angles were shown to be highly variable and vary by several degrees within a matter of millimetres circumferentially. The degree of variation recorded here for radiata pine was much greater than had previously been reported for other species such as ash (*Fraxinus excelsior* L.) or Douglas-fir (Wobst et al., 1994). The results highlight the limitations of studies which only examine single radii or widely spaced disc samples. Even the average values around the stem for individual radii were seen to vary by up to 6 degrees (Figure 10b).

Longitudinal variation within growth rings up the stem

As with circumferential variation, grain angles in the sample stem did not show a strong consistent longitudinal pattern, apart from a decrease from the lowest log to the upper logs. In the sample discs, grain angles above the lowest log were on average 2 degrees greater at equivalent growth rings (Figure 10a).

Effects of branch whorls on local grain angle

In this study, the impact of branches and knots was found to be very localised (Figures 2 & 5). When discs from within 50 mm of visible branch whorls were

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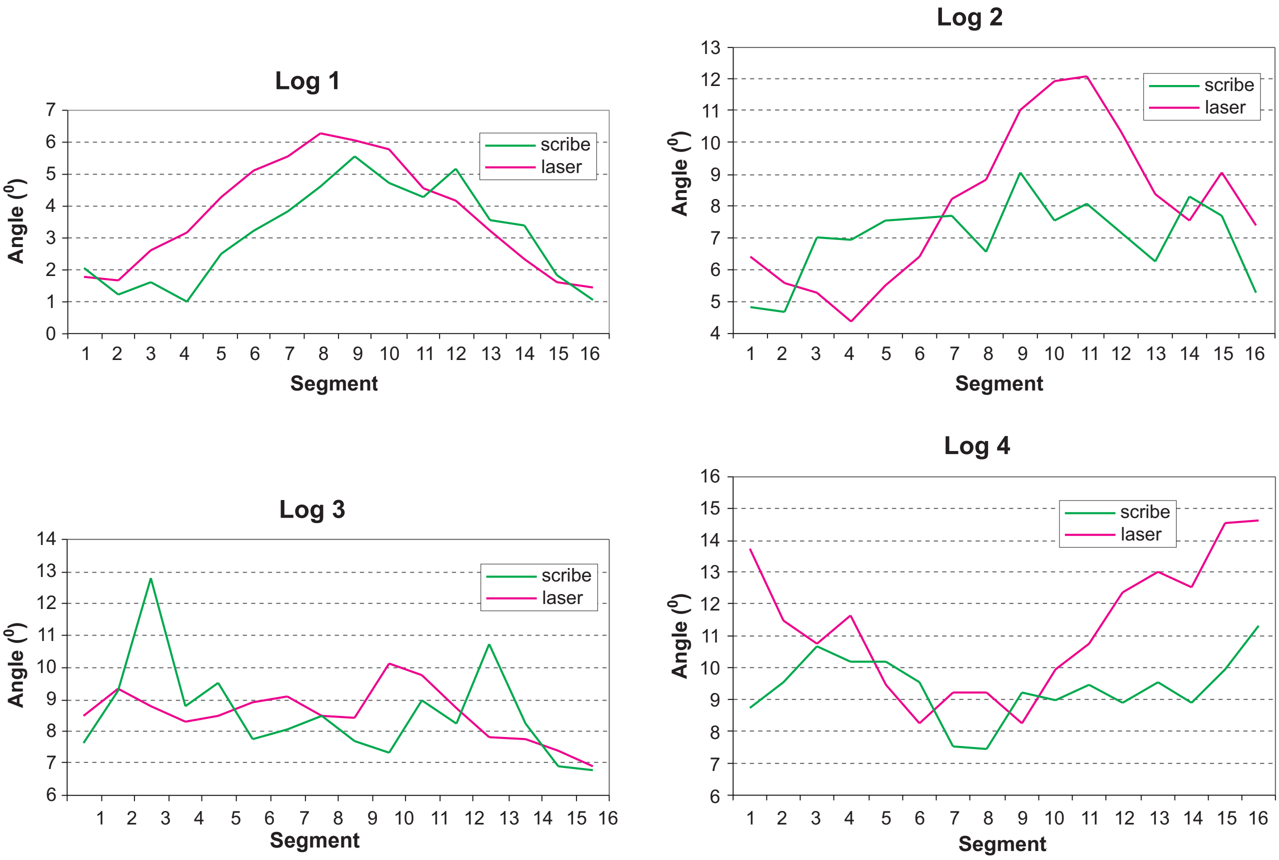

FIGURE 14: Grain angles for each log obtained from scribing and laser scanning

analysed, the effect on grain angle was not obvious (Figures 11 & 12).

Comparison of laser scanning and disc scribing methods

As far as was possible, the disc scribing and log laser dot scanning methods were compared (Figure 14) and found to be similar – the averages were generally within 2 degrees with no obvious bias. Given the visibly observed (Figures 2 & 3) and measured (Figures 7, 8 & 9) spatial variation, it is a moot point as to what can be considered a reasonable level of accuracy. In the authors' opinion, 2 degrees is a very acceptable level.

Implications for sampling tree stems and sawn products.

Given the spatial variation demonstrated here (between growth rings, discs and stem heights), it is not realistic to accurately describe individual stems or logs from small samples such as external scribing or discs. While very precise data may be obtained from small samples, they are not necessarily representative in terms of discs or logs. However, in silviculture and breeding trials, cost-effective sampling is necessary and at the same time must allow for variation from stem sweep, compression wood and branches, as well as apparently random variation. Assessment of spiral grain angles along single radii (as from breast height cores or discs) is not recommended, unless at least 2 radii can be averaged to compensate for "tilt" in relation to the stem axis (as is common current practice). However, the current study has shown that even averaging results across diameters to compensate for disc "tilt" can obscure real variation in radial median values of up to 4 degrees. Using growth ring boundaries as reference points at least provides a biological means of tracking changes and comparing samples. For comparing datasets, the lack of accuracy in individual tree assessments can be somewhat countered by using larger numbers of stems in the sample.

Conclusions

A number of authors have attempted to model spiral grain patterns from small samples (usually discs) in the hope of predicting twist in timber (Tian et al., 1995; Johansson et al., 2001; Gjerdrum et al., 2002; Säll, 2002; Ormarsson & Cown, 2005). While generic trends can be described in this fashion, the usefulness of mathematical functions is limited by the new knowledge that there is considerable variation between samples and most of the variation remains stochastic, i.e. there are both predictable and random elements. Modelling can still be useful in describing general tree patterns for comparing sites, silvicultural treatments and genetic material, but more accurate prediction of timber distortion requires observation of a number of properties on the actual logs and wood products (Johansson & Kliger, 2002). The use of laser-scanning methodology satisfies the requirement to provide cost-effective information on grain angles over large surfaces of logs and timber. Swept logs will show more apparent variation due to geometric considerations of the position of the laser with respect to the log sweep. From a practical point of view, however, laser scanning is currently the most applicable tool for assessing spiral grain on the surfaces of logs and timber, where measures over a large area are required using combination technologies (Bacher, 2008).

This intensive study has provided new information on spatial spiral grain variation within a single radiata pine stem (growth rings, discs and stem heights) and has highlighted the limitations of traditional methods of grain measurement. If the observed variability within a single stem is assumed to be representative of the radiata pine resource as a whole, then traditional sampling and analysis regimes are unlikely to detect all spiral grain variations, and may even impede the understanding of the effects of grain deviation on distortion. Laser dot scanning is seen as a useful addition to the armoury of tools for scanning of wood products.

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