

RESEARCH ARTICLE

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Differences in intra-tree variation in spiral grain angle for radiata pine

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Abstract

Background: Spiral grain angle (SGA) is an important factor affecting the distortion and utilisation of solid timber. Little research has investigated how SGA varies at a fine scale within trees and whether this fine-scale three-dimensional variation is similar between genotypes. The objectives of this research were to (i) characterise three-dimensional variation in SGA within stems and clones, and (ii) understand how intra-stem variation in SGA varies between genotypes.

Methods: Detailed measurements of SGA were taken from 12 radiata pine (*Pinus radiata* D. Don) clones. Analyses were undertaken to characterise variation in three dimensions and determine if this variation significantly differed between genotypes.

Results: Spiral grain varied significantly with distance from the pith, showing a sharp initial increase with distance from the pith, followed by a gradual decline. Values of SGA increased significantly with height up the stem, reaching a maximum at ca. 5 m. Circumferential variation in SGA showed no significant trend. There was significant variation in mean SGA between clones; however, the within tree patterns in SGA did not significantly vary between clones.

Conclusion: If further research confirms the uniformity of within tree patterns in SGA between clones this may greatly simplify efforts to model three-dimensional variation in SGA.

Keywords: *Pinus radiata*; Radiata pine; Spiral grain

Background

One of the factors that has the greatest influence on the utilisation of wood from a wide range of species, including radiata pine (*Pinus radiata* D. Don), is lack of dimensional stability caused by spiral grain (Johansson et al. 1994). Spiral grain angle (SGA) is defined as the orientation of fibres (tracheids) with reference to the longitudinal axis of the tree stem. The relatively high values of SGA found in radiata pine (Ormarsson and Cown 2005), particularly in corewood, can cause twist in dry timber, distortion in plywood sheets, surfacing problems during machining (Tsehaye and Walker 1995; Ekevad 2005) and are a major cause of drying degrade in radiata pine and other conifers (Haslett and McConchie 1986; Haslett et al. 1991; Danborg 1994). Cown et al. (1995) reported that twist in radiata pine is responsible

for at least 90% of the instability of affected radiata pine timber produced in fast-grown plantations in New Zealand. Similarly, Sorensson and Lausberg (1996) demonstrated that a decrease in spiral grain in juvenile wood of 3 degrees was sufficient to reduce rejection rates for twist from 12% to 5%, and would save the New Zealand forest industry about \$58 million per annum.

In order to understand whether selective tree breeding can be used to reduce spiral grain angle, research has been undertaken to quantify the heritability of this trait in radiata pine (Burdon and Low 1992; Jayawickrama 2001; Harris 1989; Gapare et al. 2007; Lindstrom et al. 2004). These studies found that the narrow-sense heritability of SGA in radiata pine ranged from moderate to high, which was consistent with research on other conifers such as Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Hansen and Roulund 1998) and Norway spruce (*Picea abies* Karst.) (Costa e Silva et al. 2000). A weak negative correlation between stem diameter and spiral grain has

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also been found indicating there may be some trade off in growth when reducing spiral grain angle through selective breeding (Jayawickrama 2001).

Characterisation of intra-tree variation in spiral grain angle has received considerably less attention in the literature than its genetic variability. In radiata pine, SGA generally declines from the innermost rings to about the 15th ring from the pith (Cown et al. 1991; Xin et al. 1996), while in the longitudinal direction there is generally an increase in SGA with height in the lower stem (Cown et al. 1991; Tsehaye and Walker 1995). Although circumferential variation in SGA has been noted in a single radiata pine stem (Cown et al. 2010) the authors are unaware of any research that has investigated if there is a consistent circumferential influence on SGA for this species between trees. Similarly, little research has investigated how the magnitude of intra-stem variation in SGA differs between genotypes.

Recent advances in measurement techniques (Brännström et al. 2008; Ekevad 2004) now mean that it is possible to assess the three-dimensional pattern of SGA within a stem. This paper reports on a study in which detailed measurements of SGA were made on 12 selected genotypes of radiata pine, aged seven years old. The objectives of this study were to characterise three-dimensional within-stem variation in SGA and identify whether intra-stem variation in SGA varied between genotypes. Given the relatively small number of clones used in this study the objective of this work was not to describe fully the genetic effect but rather understand how intra-tree patterns might vary from genotype to genotype within a current breeding programme.

Methods

Experimental design

Data were collected between July 2008 and March 2009 from a radiata pine clonal variety trial at Esk Forest, Hawke's Bay, New Zealand (latitude 39.274 S, longitude 176.789 E, elevation 180 m). The trial was established in 2001 as an incomplete block, single tree plot design, and consists of 42 plots each containing 48 trees planted at a 4 x 4 m spacing (nominally 625 stems ha⁻¹). The site is in its second rotation of radiata pine. The trial has been pruned in three lifts, occurring between 2005 and 2007, to a height of around 6 m. Hydrated sodium calcium borate hydroxide (Ulexite) was applied in 2005 at a rate of 6 kg ha⁻¹ in response to a foliar boron deficiency but no other applications of fertiliser were made. Over the trial period, this site has had a mean annual rainfall of 1500 mm and a mean annual temperature of 13°C.

Twelve clones were selected (Mike Carson, *pers. comm.*) to span the range of available breeding values for diameter (at breast height), height, wood density, acoustic velocity, dothistroma resistance, branching,

malformation and straightness. Selected clones also covered the range in outerwood densities and stress wave velocities (as assessed using a standing tree instrument). For each clone, two ramets were randomly selected giving a total of 24 trees for measurements.

The mean (and range in brackets) for diameter at breast height, height and crown mass of the selected trees were respectively 20.95 cm (17.6 – 24.3 cm), 13.25 m (11.7 – 16.5 m) and 66.2 kg (29 – 146.2 kg).

Measurements

Each selected tree was felled then cut into sequential, parallel 30-mm discs from the butt to a top diameter of approximately 50 mm. A single disc was retained for spiral grain measurements from each annual growth unit meaning that discs were taken at approximately 1.8 m intervals up each stem from a height of about 0.3 m to a height of 7.6 m – 12.0 m depending on the height of the tree, i.e. from 5 to 8 (average 6.6) discs per tree. These discs were selected to avoid grain deviation around branches. The discs were kiln dried under conditions of 60°C dry bulb/56°C wet bulb to a moisture content of between 18 and 25%. They were then further conditioned at 25°C and 65% relative humidity for 2–3 weeks, resulting in an equilibrium moisture content of approximately 10%. Four equally-spaced, 25-mm-wide, radial strip samples (in the N, E, S and W directions) were cut from each disc.

Spiral grain was measured at 5 mm intervals along each radial strip by exploiting the so-called “T2 effect” (McGunnigle 2009; Marschner et al. 2005; Matthews and Soest 1984). Due to the cellular nature of wood, light specularly reflected from a wooden surface is scattered in amounts that differ with fibre direction. By measuring the relative reflected intensities over a range of directions, the grain orientation vector (usually expressed as a pair of surface and dive angles) can be estimated. Careful surface preparation is critical to the success of this technique, since it relies on the microscopic texture and any preparation that alters the nature of this surface (e.g. sawing) will influence the results (Shen et al. 2000; Eastin and Johnson 1993). For this study, surfaces were first sawn then hand planed with a carefully honed blade.

A red laser (635 nm, 5 mm spot size) was projected at 90° to the longitudinal-radial surface of the radial strips. The laser was moved from pith to bark along each radial sample in 5 mm steps. The raw surface (i.e. deviation from vertical in the longitudinal-radial plane) and dive (i.e. deviation from vertical in the longitudinal-tangential plane) angles were obtained from the specular reflection peaks. A peak-fitting algorithm was used to find peak locations based on the intersection of the maximum slopes. Analyses were carried out on grain values in

relation to distance from the pith – not annual rings as in most previous studies.

Previous experience indicates that tilt correction significantly reduces the observed variation in spiral grain (Cown et al. 2010). Consequently, tilt adjusted values of surface and dive angle were also calculated, where surface angles from adjacent radii were used to adjust the measured dive angles. The tilt adjustment was carried out using the radii averages. The surface angle averages for the N and S radii were adjusted (by rotating the disc mathematically) to make the N and S radii equal and opposite in sign with the corresponding adjustment of measured dive angles in the E and W radii. Similarly E and W radii were used to adjust the N and S dive angles.

The most common convention is to consider the left-hand, or “S” pattern (as viewed from the bark side) as a positive angle and right-hand “Z” pattern as negative (Harris, 1989) and this was adopted for this study.

Analyses

Data were analysed using R (R Development Core Team 2011) and SAS Version 9.2 (SAS-Institute-Inc. 2000). An initial exploratory analysis was conducted using graphical procedures. These were used to examine the raw data, the probability distribution of SGA, and to produce box plots showing within- and between-tree variation in SGA. Means, standard deviations, and skewness and kurtosis parameters were calculated for each tree, and compared between clones using a one-way analysis of variance (ANOVA).

To determine how SGA varied within a typical stem, the following random coefficients mixed effects model was fitted using the MIXED procedure:

$$SGA_{ij} = a_i + b_i h_{ij} + c_i d_{ij} + e_{ij} \quad (1)$$

where, i = tree (1,...,24)

j = sample within tree

SGA_{ij} = grain angle of the ij^{th} sample

h_{ij} = height within stem of the ij^{th} sample

d_{ij} = distance from pith of the ij^{th} sample

In this model, a_i , b_i and c_i were assumed to vary between tree and to be independent identically distributed normal variables with means α , β and γ respectively, and with an unstructured covariance matrix, while e_{ij} is a randomly distributed error term. When fitting this model, the independent variables were standardised by subtracting their approximate mean values. Thus, 50 mm was subtracted from distance from pith, and 3 m subtracted from height within the stem. The effect of this approach was to make the random intercept term correspond roughly to a random mean for each tree. The model was used to test whether grain angle varied

significantly in either the radial or longitudinal directions within a typical stem (by testing whether β or γ differed significantly from zero). Nonlinear and interaction effects were also modelled by adding and testing the significance of quadratic and interaction terms to Model (1).

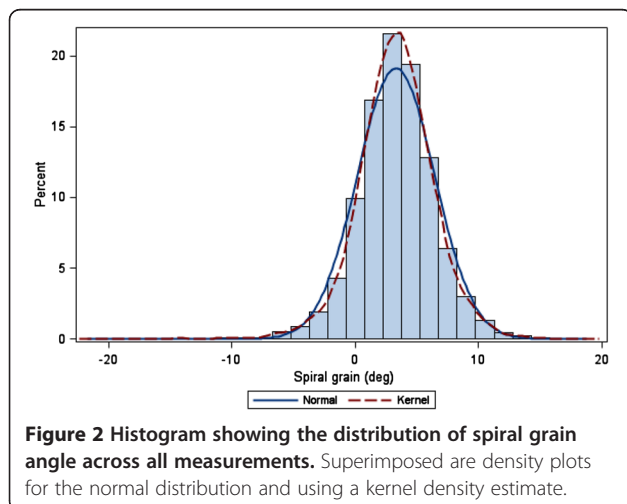
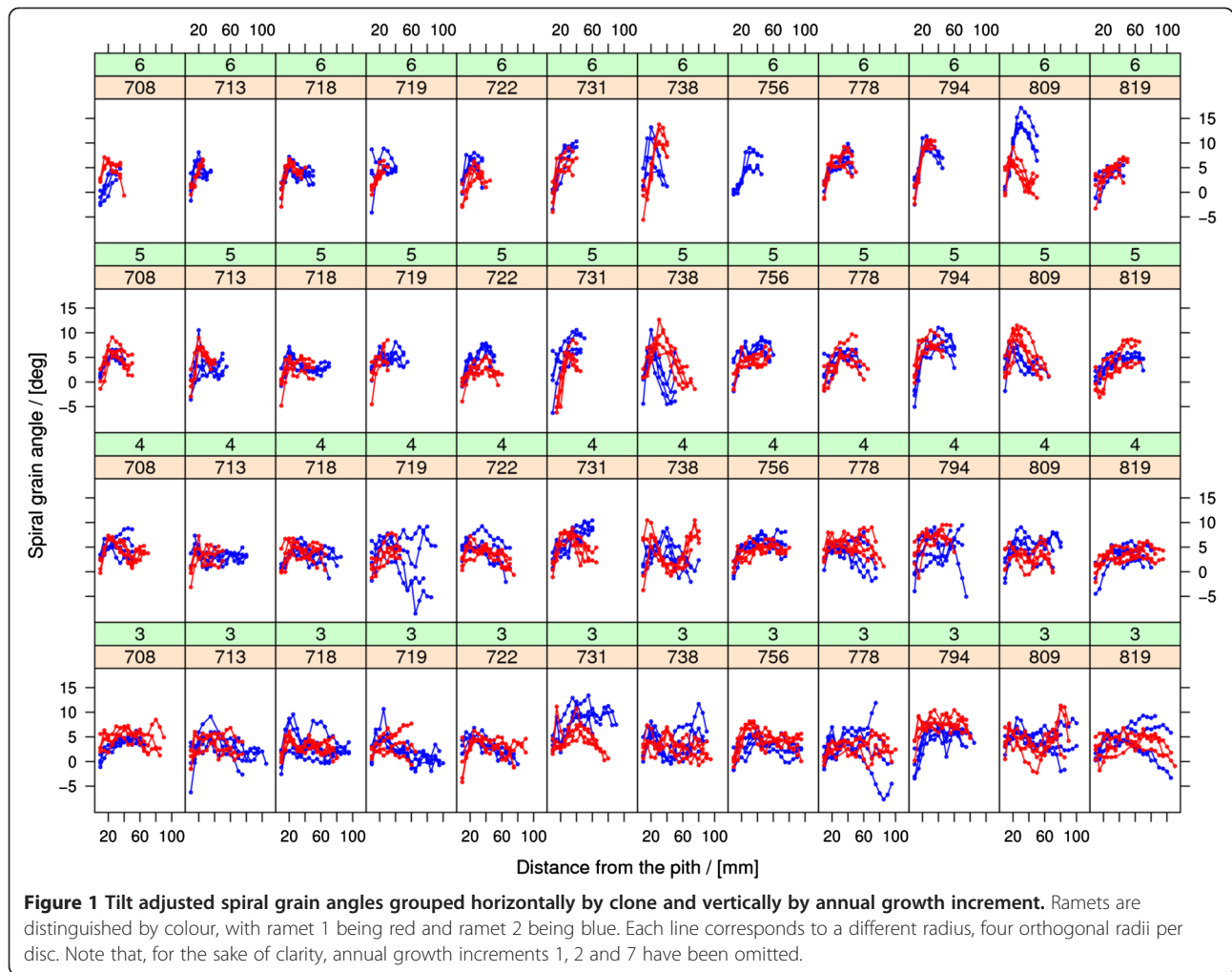
To test for differences in grain angle between circumferential direction (N, S, E, W), mean grain angle was calculated by direction and tree, and a two-way ANOVA fitted with terms for tree and direction.

Results

In general, the two ramets of each clone exhibited similar patterns of SGA (Figure 1) although there were some notable exceptions (e.g. clone 809, growth unit 6). Likewise, the four radii measured on each disc often exhibited similar trends although again there were notable exceptions (e.g. clone 719, growth unit 4, ramet 2). The generally acknowledged average radial trend in SGA, namely near zero close to the pith followed by a rapid increase and subsequent decrease (Lausberg et al. 1995), was found within individual discs (e.g. clone 708, growth unit 5). However, in general, the radial patterns showed a great deal of variability. It is worth noting though that in no case was SGA observed to initially decrease (i.e. become increasingly right-handed).

Overall, SGA was approximately symmetrically distributed with a mean of 3.29°. Compared with a reference normal distribution, the grain angle distribution had long tails, and therefore a high coefficient of kurtosis (Figure 2, Table 1). The extreme values in the tails of the distribution could be largely eliminated by trimming the highest and lowest 0.4% of values from the distribution. All subsequent analyses were performed using both raw and trimmed data, but as results were very similar for both, only the results for the former are reported. Spiral grain angle was an extremely variable property with a coefficient of variation of nearly 100%. Therefore, in order to obtain a robust estimate of the mean value of SGA for a tree or log using this technique, a large number of measurements are required. For example, to achieve an estimate of the mean with a standard error of 10% of this value, 90 measurements would be required. In this study, there were on average 2,800 measurements per tree, ensuring that mean grain angles could be quantified very precisely at both the intra- and inter-tree levels.

Mean values of SGA varied significantly between clones (Table 1). Exploratory analysis of within-tree trends in grain angle indicated a trend of increasing angle with height within stem levelling off above 5 m (Figure 3a), a radial trend showing an increase in grain angle over the first 20 mm followed by a gradual decline (Figure 3b), but no consistent directional effect (data not



shown). Figure 3c shows the variability in grain angle by clone and tree, and demonstrates that the significant clonal differences observed ($P = 0.0026$; Table 1) mostly resulted from several (2 or 3) clones with higher than average values of SGA, with little difference between remaining clones.

Table 1 Distributional statistics of spiral grain angle

Statistic	Value	F-value	P-value
Mean	3.29	5.81	0.0026
Standard deviation	3.13	2.36	0.078
Coefficient of skewness	-0.32	4.60	0.0070
Coefficient of kurtosis	2.58	2.66	0.053

The mean, standard deviation, and coefficients of skewness and kurtosis were calculated for each tree using all measurements and tested for clonal differences. Shown are the mean value for each statistic, and F-values (11 and 12 degrees of freedom) and corresponding P values in tests for clonal differences.

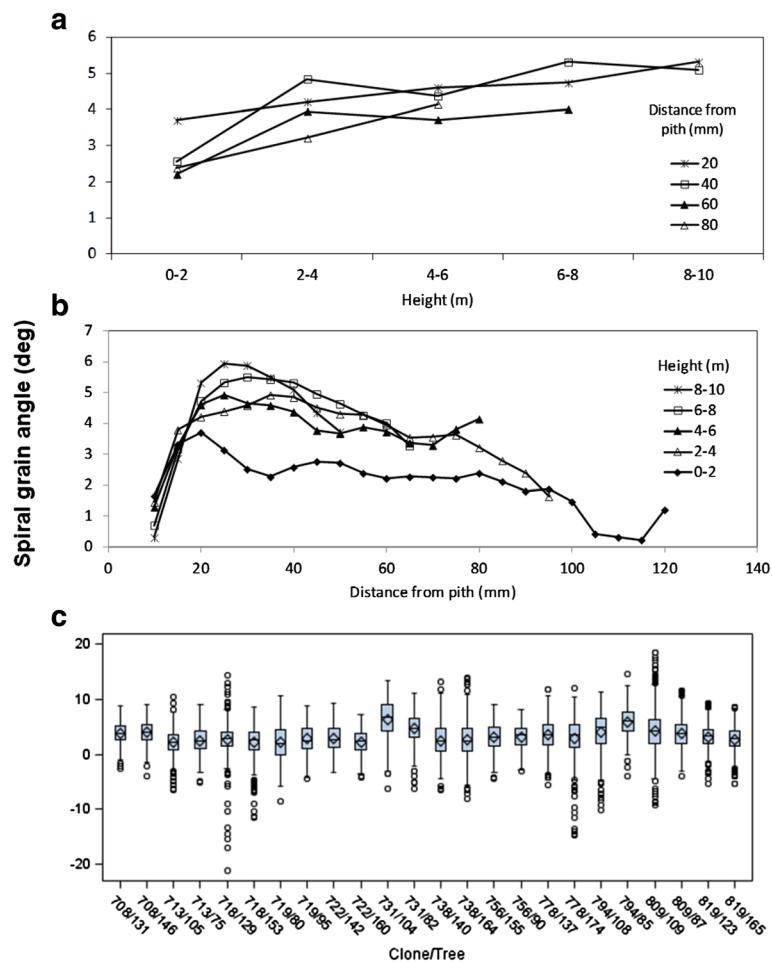


Figure 3 Graphs showing mean spiral grain angle (a) plotted against height in stem (in 2 m height classes) by distance from pith, and (b) plotted against distance from pith (in 5 mm steps) by height class, and (c) box plots showing distributions of spiral grain within clone and tree.

Analysis of variance confirmed that, within a tree, there was no significant difference in SGA between the four radial directions ($F_{26, 69}=0.44, P=0.72$). The effects of the remaining two within-tree directions (longitudinal and radial) were investigated using a random coefficient model similar to Model (1). Because grain angle increased rapidly in the inner 20 mm from the pith (Figure 3b), a strong effect apparent in all 24 trees in the study, measurements made 10 and 15 mm from the pith were excluded when fitting the random coefficient

model. The model fitted to the measurements 20 mm or more from pith had significant terms for height within stem, distance from pith, and squared height (Table 2). A quadratic term for distance from pith and an interaction term between distance and height were tested but found to be not significant ($P>0.05$). Parameters for individual trees were tested for clonal differences. The intercept was found to vary significantly a result in general agreement with the significant clonal differences for mean SGA shown in Table 1. However, the

Table 2 Estimates of parameters for the random coefficient model

Term	Estimate	Std. error	t value (23 d.f.)	P value
Intercept	3.82	0.27	14.31	<0.0001
(Height-3) (m)	0.438	0.052	8.49	<0.0001
(Height-3) ²	-0.0410	0.0075	-5.49	<0.0001
Distance from pith (mm)	-0.0154	0.0044	-3.47	0.0021

Shown are standard errors, t values and corresponding P values.

terms for height and distance from pith and the quadratic height term did not differ significantly between clones. This indicates that clonal effects were confined to differences in the mean value of SGA, and that the within-tree patterns did not vary significantly between these clones.

Predictions for each tree from the model are shown in Figure 4. These show clear trends in mean SGA in both the radial and longitudinal dimensions for the majority of trees. One or two trees showed abnormal patterns but these were from different clones. The model shows a general trend for SGA to decrease linearly with distance from pith (beyond the inner 20 mm), and to increase with height in the lower 5 m of stem and to stabilise beyond this height.

Discussion

Spiral grain angle is a complex wood property and comprises two distinct components that include the grain direction and magnitude of the gradient. The positive (or left handed) mean value of 3.29° found here broadly

agrees with the range found in other studies on radiata pine, where values range from 2.9° to 4.7° (Tsehaye and Walker 1995; Cown et al. 1991; Gapare et al. 2007). Values of SGA found in radiata pine regularly exceed mean values of 2° found for *Pinus taeda* (Zobel et al. 1968), and 1.4° to 2.7° for *Picea abies* (Costa e Silva et al. 2000), but are relatively similar to mean values of 3.6° for *Araucaria cunninghamii* (Eisemann et al. 1990) and 5° for *Picea sitchensis* (Hansen and Roulund 1998). It is worth noting that, for wood utilisation, the mean value is not as important as the variation in SGA as twist results from differential SGA within the same board. The intra-tree variation in SGA was found to be very high, which agrees with results from previous research on the within tree distribution of SGA (Cown et al. 1991).

Consistent with the findings of this study, the high variation in SGA within trees has been shown previously to exhibit certain patterns, but these patterns are known to differ between tree species (Harris 1989; Aebischer and Denne 1996; Bäckström and Johansson 2006; Bannan 1966; Danborg 1994; Elliott 1985; Fujimoto et al. 2006). In trees

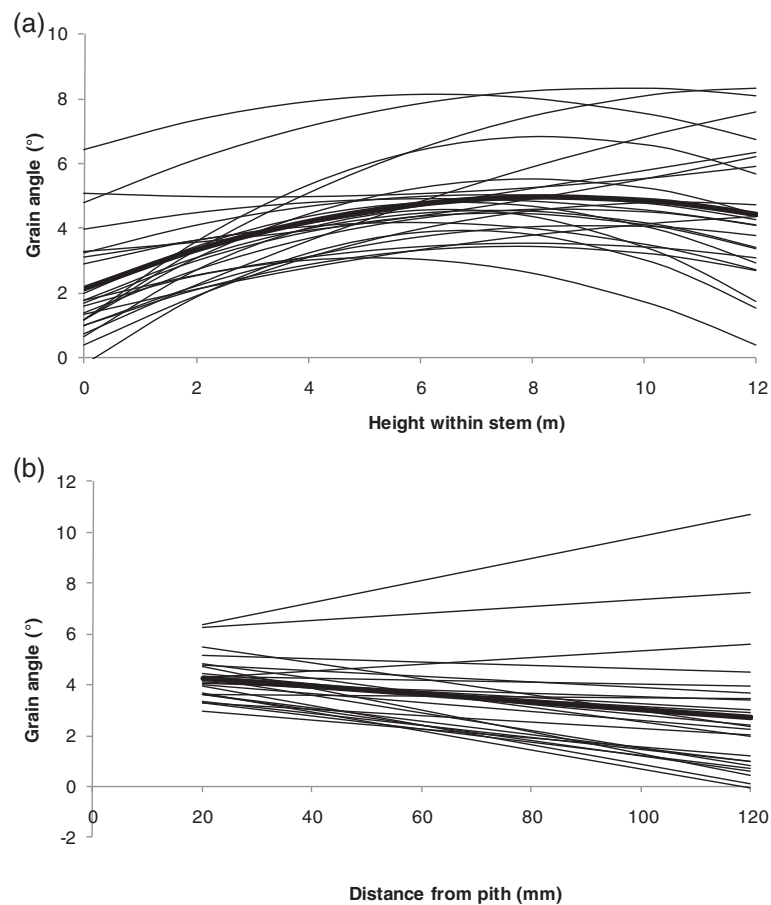


Figure 4 Predicted spiral grain angle from the random-coefficient model with narrow lines representing individual trees, and the bold line representing the mean of all trees. Predictions are shown versus (a) height, at a fixed distance from pith of 50 mm, and versus (b) distance from pith, at a fixed height of 3 m.

sampled from natural forests of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg), the highest values of SGA were found near the outside of the tree, where visible spiral grain causes timber degrade (McBride 1967). In contrast, highest values of SGA in radiata pine usually occur within the juvenile core, declining with distance, or ring number, from the pith (Cown et al. 1991; Tsehay and Walker 1995).

Little systematic variation in SGA has been reported previously in the longitudinal direction (Cown et al. 1991; Tsehay and Walker 1995) although a general small increase with height has been noted. In the current study, a significant increase in SGA was observed to a height of 5 m before it stabilised. These variations between studies may be attributable to the young age of the material studied here, which primarily shows longitudinal variation within the juvenile core, rather than variation over mature stems. This suggests that boards cut from the first log within the juvenile core may be subject to less twist, which agrees with previous sawing studies (Haslett et al. 1991). The age of the samples was too young to detect the normal transition with age from positive to negative values, which occurs after about 15 years (Cown et al., 1991). The results of the present study extend previous research by showing no consistent significant circumferential variation in SGA.

The major advance of this research is that it shows that three-dimensional within-tree variation in SGA pattern does not differ significantly among the clones tested. Further research is needed to confirm this result across a broader range of clones and sites. If found to be correct, this result will greatly simplify any further efforts to model within-tree variation in SGA as clonal effects can be treated as a simple offset in the model intercept. Given the young age of the material studied and the relatively low number of clones used within this study, further research should be undertaken to confirm this result. A tool recently developed (Riddell et al. 2012) will allow more detailed examination of within-tree patterns and eliminate problems associated with sample alignment (with respect to stem axis).

Conclusions

The radial variation in SGA in radiata pine observed in this study was consistent with results from other studies in this and other conifer species. There was no consistent significant circumferential variation in SGA and no significant differences in within-tree patterns in SGA between the clones studied. Differences in SGA between clones were limited to differences in mean values. This uniformity of within-tree patterns of SGA between clones may greatly simplify efforts to model three-dimensional variation in SGA.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

MSW was the primary author. MOK undertook the data analysis. JH designed the study, extracted the raw data and undertook preliminary data analysis. MR constructed the experimental apparatus, surfaced samples, and made measurements. DJC assisted with the study design, writing and literature review. JRM was a secondary author. All authors read and approved the final manuscript.

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