Modelling spiral angle in *Picea sitchensis*[1]

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Abstract

Spiral grain was measured in 128 trees from two different forest plantations of Sitka spruce (*Picea sitchensis*) situated in west and central Scotland. Spiral grain angle was measured for every fifth ring from pith to bark mainly at two heights in each tree. The aim of this study was to develop a model, which would predict accurately enough the degree of spirality of Sitka spruce plantations without the necessity of them being felled. The model constructed included as variables the grain angle and the annual rings taking into account variability between trees and height in trees.

Key words: spiral grain angle, modelling, *Picea sitchensis*

1. Introduction

Spirality is a common characteristic of almost all tree species (Harris 1989). "Spiral grain angle is the angle between the longitudinal wood elements and the axis of the stem" (Harris 1989, p.44) and it is strongly associated with twist in dried timber. It has been experimentally shown that twist is caused mainly by annual ring curvature, spiral grain angle and changes in moisture content (Forsberg et al. 2001). The presence of spiral grain in a tree stem decreases the strength of the wood and causes warp when timber is seasoned (Tian 1995). A large number of factors have been proposed as possible causes of spiral grain, but none explained adequately its occurrence (Tian 1995). This study was initiated to provide basic information concerning the magnitude and pattern of spiral grain in Sitka spruce (*Picea sitchensis*). Using data collected from two different sites in Scotland we constructed a model of grain angle which predicted the degree of spirality accurately enough to be of value to commercial forestry. The model was tested using non-linear mixed model analysis in the software program SAS (SAS Institute Inc.1990).

2. Spiral grain

"Spiral grain is the phenomenon where tracheids in the stem systematically have the same inclination, forming a spiral and causing twisting in dried sawn timber through anisotropic shrinkage"(Harris 1989). It is a common characteristic of both conifers and broad-leaved trees (Tranquart 1995) and is regarded as one of the key properties determining the suitability of wood for use as sawn timber (Raymond 2002). Therefore, it decreases the desirable properties (strength and stiffness) and thereby the value of the timber (Sepúlveda et. al 2003).

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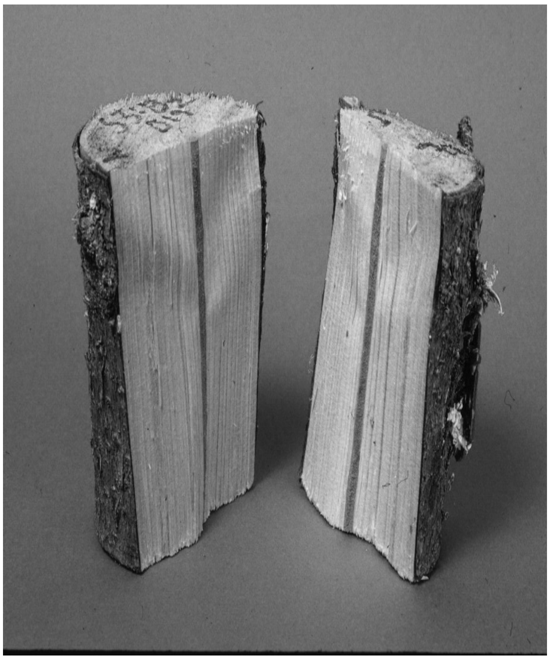
[1] The structure of this paper was based on Journal of Forestry

It is clear from the above discussion that for the wood products used by man, large grain angles are a defect. Nevertheless, it is hard to believe that the processes of natural selection would not have eliminated it by now, or at least reduced it to an occasional feature encountered in isolated trees (Harris 1989) if it had not been beneficial for them. According to Kubler (1991), spiral growth allows water from each individual root to reach around to nearly every branch on the tree, so that if all the roots on one side of the tree die the foliage should survive unharmed. Kubler (1991) also showed that spiral-grained stems and branches bend and twist more when exposed to strong wind therefore offering less wind resistance and being less likely to break.



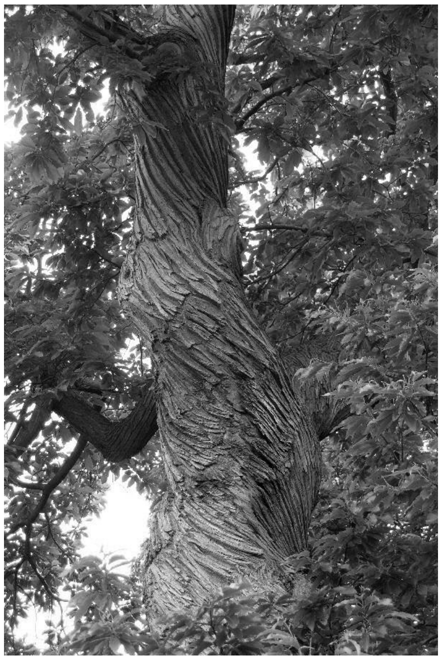


Figure 1: The picture on the left shows a split disc which uncovers the inner spirality [1], and the one on the right displays how spiral grain appears in the external part of the tree [2].

2.1 Environment

Researches have shown that, wind, temperature, nutrient status of soil, rainfall, exposure and altitude have different effects on spiral grain. “However, there is no support for the belief that regular patterns of spirality can be initiated by, or attributed primarily to, any environmental factor” (Harris 1989). A problem occurs when most of these environmental factors have a contradictory affect on spiral grain in different tree species. Therefore, it is possible that there are inherently large differences in grain angle between species, which is unfortunately something we were unable to look at in this project.

2.2 Heritability

Most known aspects of spiral grain are considered in Harris (1989). Despite intensive research, the fundamental cause of spiral grain angle changes in individual trees remains a mystery. According to Harris (1989), there is no strict causal relationship between environmental conditions and fibre direction because grain angle is highly heritable (i.e. under strict genetic control) although its expression may be dependent, at least in part, on the environment. Many scientists agree that even if spiral grain angle is due to several environmental conditions like wind, rainfall, sun and even the rotation of earth the most important factor is heritability.

In the present work, the specific question as to whether spiral grain angle can be predicted accurately enough for practical use without taking into consideration any genetic or environmental factors was addressed.

3. Materials and Methods

3.1 Material

The data were obtained from two different forests situated in the United Kingdom, owned and managed by the Forestry Commission. We worked with data from a total of 128 trees from four different stands. Two of the stands were located at Lochaline in the west of Scotland and the other two at Benmore in central Scotland. Figure 2 displayed were these forests are situated. The key site and stand characteristics are summarised in Table 1. We observed that there were some key differences between the trees from the two locations. Firstly the trees from Lochaline were six years older than the ones from Benmore when they were cut. That is why the mean diameter at breast height (dbh), the mean total height and the mean volume were larger. Moreover the mean hourly wind speed at Lochaline was higher. There were also differences between the two stands at each location, particularly the average slope of the ground.

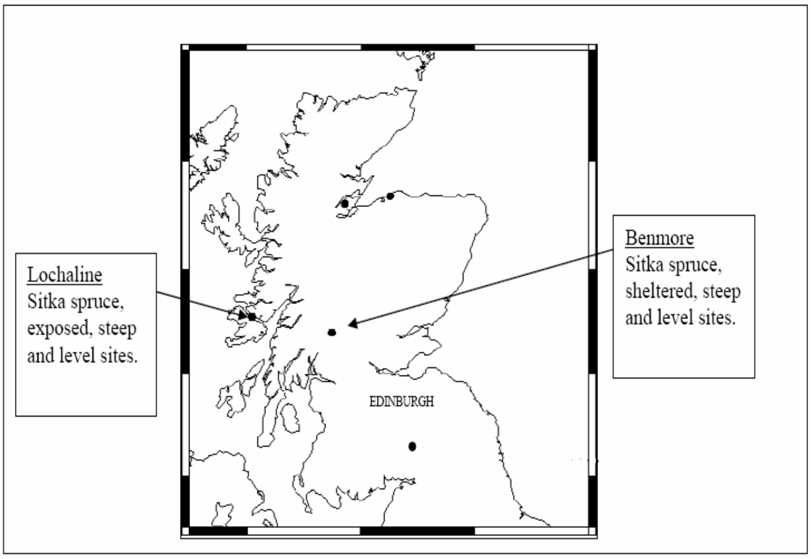


Figure 2: Location of sample stands in United Kingdom (Gardiner et. al 2005)

All data were for Sitka spruce (*Picea sitchensis*) plantation trees (Table 2). Sitka spruce is widely used as a plantation tree in the UK[2] because of its rapid growth on poor soils. It is mostly used for sawn timber. However, the sawn timber from Sitka spruce is often degraded because of twist following kiln drying.

[2] Sitka spruce is also used in other countries e.g. Denmark for the same reasons (Hansen et. al 1998)

	Lochaline NM 605 471		Benmore NN 452 265	
	FR1	FR2	FR3	FR4
Number of live trees per hectare	1360	1476	1443	1712.5
Top Height (m)	26.6	26.9	28.1	24.5
Planting year	1954	1954	1961	1961
Age at felling	48	48	42	42
General yield class	18	18	24	18
Mean dbh (cm)	28.4	26.1	24.6	22.3
Mean tree volume (m^3)	0.69	0.59	0.53	0.38
Average slope (degrees)	3	24	23	6
Mean hourly wind speed (m/s)	7		3.3	

Table 1: Site and Stand Characteristics for Sitka spruce stands (FR1 – FR4) (Gardiner et. al 2005)

3.2 Methods

3.2.1. Measurements

Two discs of 10cm thick were cut at around 4 and 10m height from each tree. The discs were then split in half using a blunt blade to allow the disc to separate along the grain (Figure 3). The angle[3] was measured on the split surface at intervals of five rings from pith to bark. Each measurement was taken across opposite radii for each ring and the mean was calculated to eliminate errors originating from skewness in stem disc arising during crosscutting and sample preparation (Brazier 1965).

Figure 3: The first picture is an instrument which splits the logs in half and the second is a protractor, an instrument that measures spiral grain angle [2].

[3] Grain angle measurements were made using an angle gauge (protractor) which is displayed in Figure 3 (Tranquart 1995).

Table 2[4] showed an example of the tree and disc characteristics used in the analysis. It must be mentioned that not all the characteristics were displayed here. Several others like the relative height and diameter, spacing and ring width were calculated from those displayed in Table 2.

TREE NO	TOTAL HT	DBH	DIAMETER	DISC HT	RING NO	ANGLE
21	24.65	0.246	0.1759	9.86	1	0.25
21	24.65	0.246	0.1759	9.86	6	1.75
21	24.65	0.246	0.1759	9.86	11	0.75
21	24.65	0.246	0.1759	9.86	16	-0.25
21	24.65	0.246	0.2873	3.94	1	1.75
21	24.65	0.246	0.2873	3.94	6	3.25
21	24.65	0.246	0.2873	3.94	11	2.5
21	24.65	0.246	0.2873	3.94	16	1.25
21	24.65	0.246	0.2873	3.94	21	0.25
21	24.65	0.246	0.2873	3.94	26	-0.5

Table 2: This table is a small example of the data used in this project. The four data sets (FR1- FR4) contained information on Sitka spruce characteristics such as total height, diameter at breast height (DBH) and angle measurements at different heights and ring numbers. They also contained other tree characteristics like ring width and spacing which were calculated from the ones mentioned earlier.

3.2.2 Analysis & Modelling

"There are three simple rules for creating a model. Unfortunately, nobody knows what they are." (Haefner & W. Somerset Maugham) (Haefner 1996, p.87)

Initially, we plotted the angles against the ring numbers from pith in order to see if there was any particular trend created. Ormarsson (1995) showed that the slope of the grain angle curve from pith to bark is relevant when modelling twist. Figure 4 demonstrated that a specific shape was observed in the data. This trend showed that juvenile wood is more variable than the mature wood which is found in the outer part of the stem. As one can see in Figure 4, there was an initial increase until a maximum at around the 5th ring and then a steady decrease as the tree became older. Therefore, we could suggest that there was a juvenile wood effect, which was stronger for rings near the pith. As the tree became older the juvenile effect stopped (logarithm) and a gradual decrease followed (exponential) as it reached the bark. Leban (1994) also found that juvenile wood effect consisted in high densities for rings near the pith (ring numbers < 5), followed by a rapid decrease for older cambial ages and a gradual increase.

[4] Table 2 is just an example of the data used in this study. It is not a complete table.

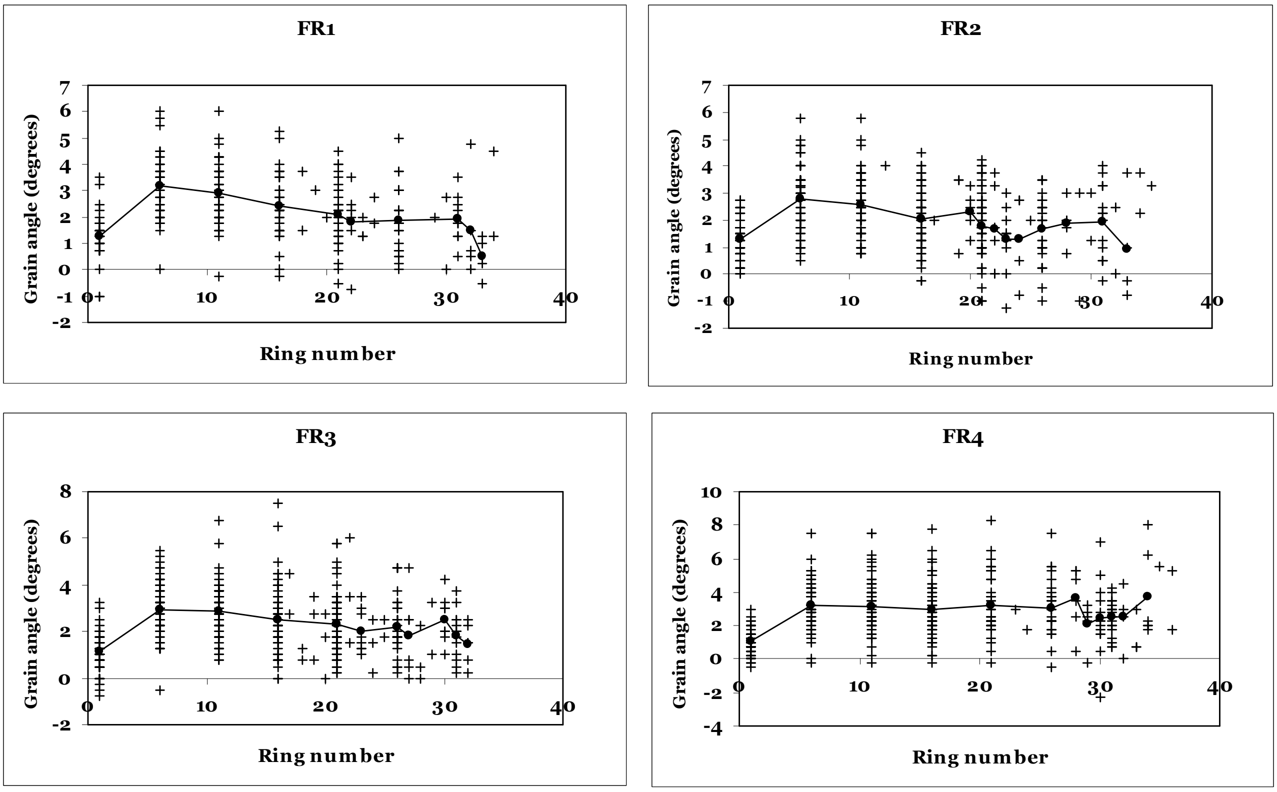


Figure 4: The four graphs showed the actual angle values (cross) against the ring number from pith. Each graph represents one of the four different stands. The smoothed lines joined the mean angles.

The aim of this study was to develop a model that could predict this particular trend; that angle values produced when plotted against annual rings. Thus, the five models used in the analysis were:

- <u>Model 1</u>: $A = (\alpha_1 + \alpha_2 \log(R)) * \exp(-\alpha_3 R)$ was the main model used throughout the analysis

- <u>Model 2</u>: $A = (\alpha_1 + a_2 R) * \exp(-\alpha_3 R)$ was a combination of linearity and exponential decay

- <u>Model 3</u>: $A = (\alpha_1 \log(\alpha_2 R)) * (1 - \alpha_3 R)$ was a similar approach to model 1 with the difference exponential decay was replaced by a linear decay

- <u>Model 4</u>: $A = (\alpha_1 + \alpha_2 R) * (1 - \alpha_3 R)$ two linear models, one increasing, one decreasing

- <u>Model 5</u>: $A = \alpha_1 - \alpha_2 \log(R) + (\alpha_3 - \alpha_4 \log(R)) * D - (\alpha_5 - \alpha_6 \log(R)) * D^2$ was used in order to check whether the generalised equation of Tian et al. (1995) when modelling *Pinus Radiata* could have the same success for Sitka spruce

where A is the spiral grain angle measured in degrees, α_1, α_2, α_3, α_4, α_5, α_6 are parameters, D is the height of the tree were the angle was measured, and R is the ring number from the pith.

The reason for choosing Model 1, except for the fact it had a better fit to the data, was its biological meaning which was explained above. We applied all five models[5] on the data but results are only reported for the first model. By using the mean angle values for each ring number (Table 3) we estimated the values for parameters a_1, a_2 and a_3 (which later on were put as starting values[6] into the different procedures in the software program SAS, (SAS Institute Inc.1990).

Non-linear procedure (NLIN) was applied to estimate a_1, a_2 and a_3 for every tree at every height of the tree (i.e. different model for each tree and height). From the given data no significant relation was found between the parameters and other tree characteristics (Appendix A) so we could not fulfill our initial objective which was to find a model to predict grain angle by using values of tree characteristics that can be obtained without felling, i.e. height or diameter or even the external angle.

3.2.3 The NLMIXED procedure

Since non-linear procedure was not appropriate for our data for reasons stated above, we searched for a method that could take into account tree and tree height variation and also fit a non-linear model. This was achieved by using non-linear mixed procedure[7]. The adjusted Model 1 was:

$$a_{ij} = \left(\alpha_1 + \alpha_2 \log(r_{ij})\right) * \exp\left(-\alpha_3 r_{ij}\right) + u + e_{ij}$$

where a_{ij} represented the j^{th} angle measurement of the i^{th} tree; r_{ij} was the corresponding ring number from the pith; α_1, α_2 and α_3 were the fixed-effects parameters; u was the random-effect[8] parameter assumed to be independent and identically distributed (i.i.d.) $N(0,\sigma^2_u)$, and e_{ij} were the residual errors assumed to be i.i.d $N(0,\sigma^2_e)$ and independent of u.

As we previously mentioned non-linear mixed procedure takes into account tree variation. However, we needed a model that could also take into account the fact that we had, most of the times, angle measurements at different heights of the tree. Due to limitations of this procedure in SAS we could not insert a second random effect, i.e. height. Thus, we grouped the data according to the height the angle measurements were

5 The results of Model 1 are displayed in section 4. Comparison between Model 1 and Models 2-5 is made in section 5.

6 One must consider the initial starting values to put when building the model. We sometimes noticed that when altering the initial values of the parameters the results obtained, differed.

7 "The NLMIXED procedure fits nonlinear mixed models, that is, models in which both fixed and random effects are permitted to have a nonlinear relationship to the response variable" (Wolfinger). This procedure fits the specified nonlinear mixed model by maximizing an approximation to the likelihood integrated over the random effects. The default optimization technique which carries out the maximization is a dual quasi-Newton algorithm. (Wolfinger)

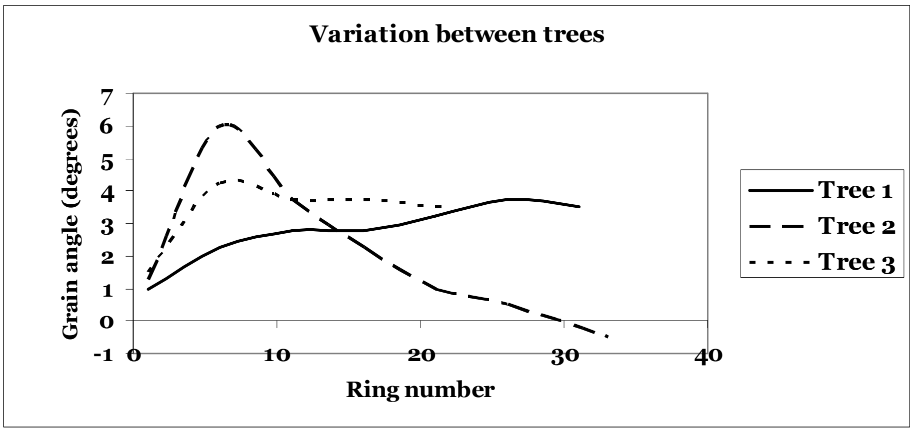
8 Due to lack of bibliography on where the random-effect parameters should be in a model and after several tests by changing the positions of u inside the model we decided that the most appropriate solution was to add the random-effect parameter u in the model linearly.

obtained and created two new datasets. A sub data set for the low (below 6 meters) and one for the high (from 6 to 12 meters) heights[9]. Subsequently, we used this procedure to estimate the global values of the parameters for the new subsets. Those values were then used to validate the model when applied into new data sets obtained from forests at Cloich and Kershope.

To assess the goodness of fit, graphical examinations of the residuals and observations against predicted values were necessary. The UNIVARIATE procedure performs tests for location and normality[10]. When the data are from a normal distribution, all p-values from the tests for normality should be greater than the alpha value (equal to 0.05 by default). Another way of testing normality is by finding the values of standardized skewness and kurtosis, which can be used to determine whether the sample comes from a normal distribution (Statgraphics Plus 5.1, 1994-2001 Statistical Graphics Corp.). Values of these statistics outside the range of -2 to +2 indicate significant departures from normality, which would tend to invalidate any statistical test regarding the standard deviation (Statgraphics Plus 5.1).

4. Results

In the beginning, we plotted the angle values against ring number from the pith (Figure 4) to see if there was any particular pattern created. As we mentioned in section 3.2.2, the four stands illustrated the same pattern, and it was clear that the grain angle was higher near the pith (more than 3 degrees on average) than in the outer part of the disc. In addition, mean angles displayed almost always the same trend. We also noticed that there were large variations both in absolute grain angle and in grain angle pattern between individual trees (Figure 5). Individual trees differed in the age at which a maximum angle was reached and, although the pattern described was the most common, others occurred (Brazier 1967). Most of the trees showed the same general pattern, but some exhibited an unusually large grain angle that persisted longer (e.g. tree 2). Other trees had a fairly constant spiral grain (straight grained) while few others had an increasing grain angle from the centre of the stem outwards (e.g. tree 1).



[9] Notice that when estimating a_1, a_2, a_3 for those two subsets, 'low' and 'high', we did not take into account site variation.

[10] "Normal distributions of the residuals from the model were tested using UNIVARIATE procedure in SAS, and variance of homogeneity, by plots of residuals as a function of predicted values". (Rudemo et al. 1984)

Figure 5: This graph displayed the grain angle against annual ring numbers of three different trees randomly chosen.

We also plotted the 95% confidence intervals of average grain angle for the four datasets FR1-FR4 (Figure 6). The reason for using data up to the 21st annual ring was to examine if there were any differences after removing the effect of age. We observed that as trees became older (21st annual ring) the variation of angle was the highest. That meant that our initial objective was even harder. We not only had variation due to genetics and height within the trees but growth rate and age also seemed to matter.

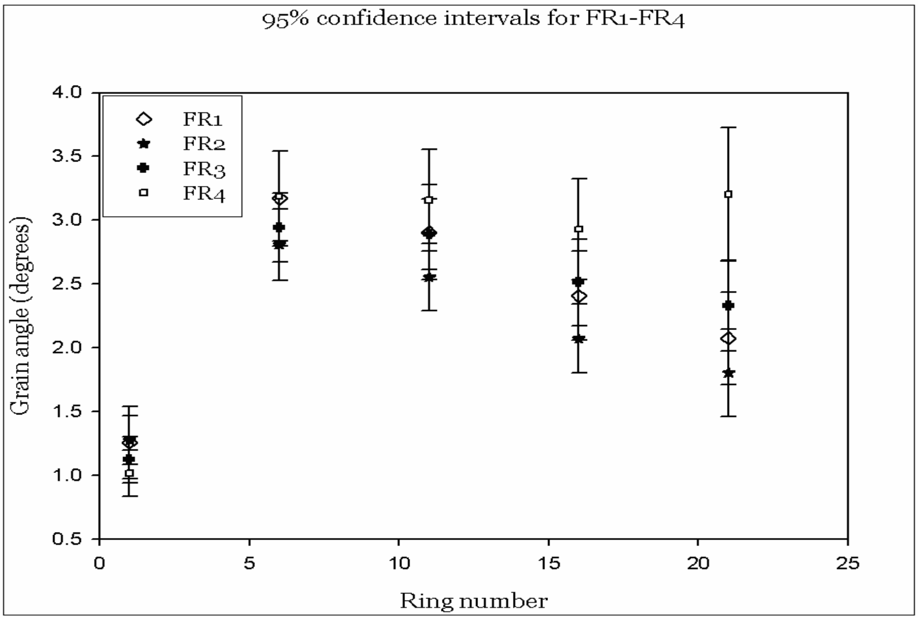


Figure 6: This graph displayed the 95% confidence intervals of the mean angles of FR1-FR4 for ring numbers smaller and equal to 21 (Appendix B)

For reasons stated in section 3.2.3, the four data sets were grouped into 'low' and 'high' height levels. The mean angles displayed in Table 3[11] revealed that the sixth ring number from pith had the largest values for all subsets. In addition, there was a constant decrease, in almost all cases, after the 11th ring number.

Ring No.	FR1 all	FR1 low	FR1 high	FR2 all	FR2 low	FR2 high	FR3 all	FR3 low	FR3 high	FR4 all	FR4 low	FR4 high
1	1.257	1.524	0.906	1.277	1.375	1.169	1.1231	1.052	1.2016	1.016	1.1129	0.917
6	3.171	3.261	3.066	2.81	2.887	2.732	2.942	2.97	2.9141	3.1875	3.398	2.946
11	2.91	3.216	2.528	2.555	2.719	2.391	2.8923	2.947	2.836	3.1573	3.188	3.125
16	2.41	2.534	2.263	2.071	2.141	2	2.5114	2.63	2.383	2.9303	3.109	2.733
21	2.074	2.113	2.017	1.806	1.879	1.707	2.329	2.34	2.313	3.204	3.048	3.604
26	1.864	1.864		1.313	1.375	1.3	2.2155	2.216		3.052	3.052	
31	1.944	1.944		1.654	1.654		1.846	1.846		2.523	2.422	2.792
Total Mean	**2.25**	**2.31**	**2.174**	**2.03**	**2.03**	**2.019**	**2.292**	**2.27**	**2.317**	**2.704**	**2.785**	**2.589**

[11] Table 3 included all subsets for each stand in order to make some observations and assumptions that are mentioned in section 5.

Table 3: Average grain angles from pith to bark for each subset. The total mean value was estimated for every subset. It must be mentioned that not all measurements were included. However, the total mean angle values were calculated from the completed dataset.

In section 3.2 we mentioned that no significant relation was found between parameters a_1, a_2 and a_3 with any other tree characteristic and we also stated the reasons for not choosing non-linear procedure. Instead, non-linear mixed procedure was used to estimate the values of the parameters a_1, a_2 and a_3 taking into account tree and height variability. Table 4 displayed those values which were later used to validate the model in new data sets. It also showed the values of the parameters when applying the model on all data FR1-FR4 (ALL). The values were similar for all three sets of data (low, high, all).

	LOW	HIGH	ALL
a_1	1.247	1.1646	1.199
a_2	3.1398	2.8977	2.9243
a_3	0.0371	0.0405	0.0367
σ^2_u	0.8216	0.6856	0.6978
σ^2_e	0.9739	0.7593	1.0052

Table 4: In this table the estimated values of the parameters are displayed along with the variances of the random effects u and the residuals e.

We wanted to test whether the model could have a better prediction when dealing with the mean angle values. Figure 7 showed that the model approached the mean angles of the first annual rings but failed to do the same in the last annual rings.

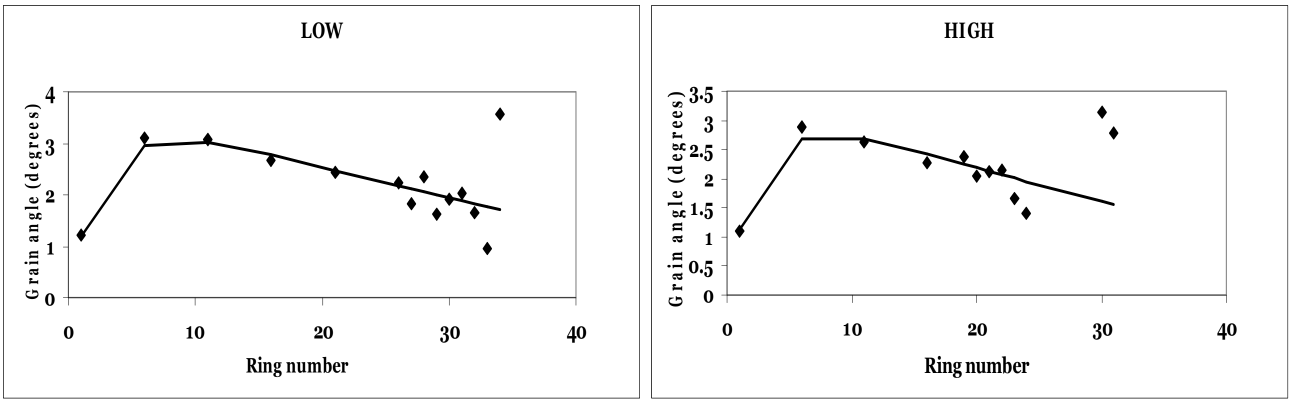


Figure 7: Average grain angle from pith to bark (dots). The line running through them is the fitted model.

4.1 Testing the model with residual plots

We needed to check whether the adjusted model 1 predicted accurately enough the actual angle values (Figure 8). The coefficient of determination for the 'low' group was smaller (R^2=0.6081) than the one for the 'high' (R^2=0.6414). That could imply that when measuring angles at higher heights of the tree the prediction of the spiral grain is slightly better.

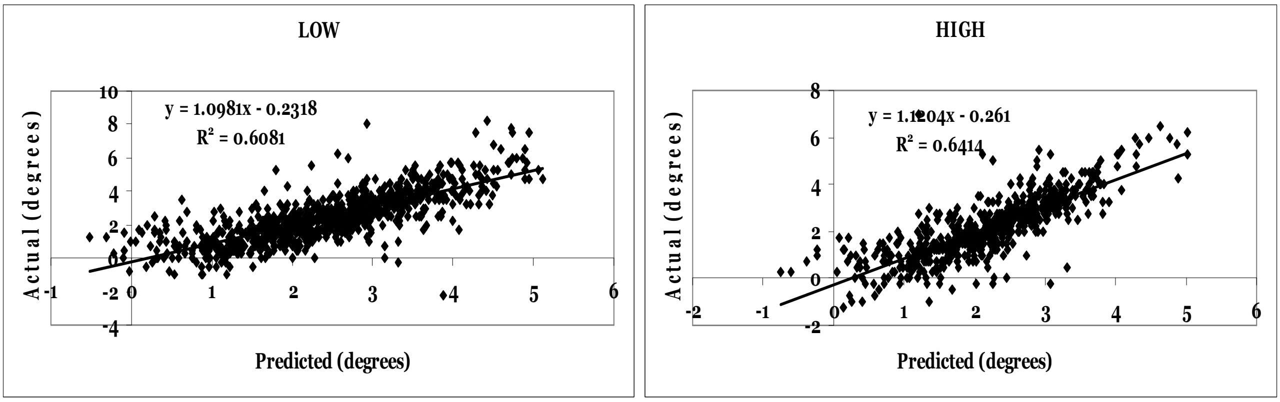


Figure 8: Both graphs displayed the actual versus the predicted angles. The one on the left was for the 'low' and the one the right for the 'high' height groups.

The model was also tested using residual plots. We plotted the residuals against the predicted angles (Appendix C) to observe if any particular shape was created. That would have implied that other variables should have been included in the model. In our case the points were fairly scattered.

Despite the fact that the two histograms (Appendix D) seemed to present populations from normal distributions, the standardized skewness and kurtosis values were not within the range (-2, 2) expected for data from a normal distribution (Table 5). In addition, the p-values[12] were less than the alpha value 0.05 (Appendix E). The reason of those results might be that the angle measurements did not follow normal distribution[13]. Therefore, one could suggest that the model was not initially well designed. Possible transformations[14] of the angle were tested but none of the alterations of the angle variable was normally distributed.

	LOW	HIGH	ALL
Skewness	-0.33	9.12	-0.12
Stnd. Skewness	-3.97	-5.87	-3.29
Kurtosis	4.34	5.74	3.45
Stnd. Kurtosis	26.06	28.08	26.76

Table 5: Values of kurtosis, skewness, standardised skewness and kurtosis of the residuals of 'low', 'high'and the whole dataset (FR1-FR4).

The same procedures were repeated when dividing the four datasets FR1-FR4 into 'low' and 'high' height groups and one can see the results in Appendices F-M. We included

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[12] "You determine whether to reject the null hypothesis by examining the probability that is associated with a test statistic. When the p-value is less than the predetermined critical value (alpha value), you reject the null hypothesis and conclude that the data did not come from the theoretical distribution" (SAS Institute Inc.1990).

[13] One of the initial assumptions when starting modelling was that angles were normally distributed.

[14] The transformations tested were:

$$\log(a), \exp(a), \frac{1}{a}, \frac{1}{\exp(a)}, \frac{1}{\log(a)}, \sqrt{a}, a^2, \frac{1}{a^2}, \frac{1}{\sqrt{a}}, \exp\left(\frac{1}{a}\right), \log\left(\frac{1}{a}\right).$$

those results because it was important to show that when applying Model 1 to each individual stand we could observe that the percentage of explanation of angle variability was higher that the one displayed above. That indicated that stand variability influenced spirality.

4.2 Validation of the model

Data from Cloich (Irvine et al. 1998) and Kershope (Gardiner et al. 1997) forests were used for model validation. The new datasets had significant differences from the data used to build the model (Table 6). For example, the sample size was very small, 12 trees in Cloich forest and 6 in Kershope, compared to the initial dataset of 128 trees in total. In addition, these two forests differed in key site characteristics like average wind speed, slope etc. which might influence grain angle as discussed in section 1. Thus, we expected that the model might not have a good fit. Furthermore, spiral grain is variable and depended on several environmental and genetic factors that were not inserted in the model.

	Cloich NT 206 460	Kershope NY 551 810
Number of live trees per hectare	12	6
Average slope (degrees)	2	4.5
Elevation (m)	400	245
Mean hourly wind speed (m/s)	6.4	4.8

Table 6: Site and stand characteristics for Sitka spruce stands of forests Cloich and Kershope.

Appendix N showed that the trend of the grain angle against the ring number is once again the same as before; starting with an increase until approximately the 8th annual ring and then a constant decrease followed when the tree became older.

We used the values of the parameters a_1, a_2 and a_3 previously calculated (Table 4) in order to obtain the two following models:

- $a_{ij} = (1.3066 + 3.0327\log(r_{ij})) * \exp(-0.037 r_{ij}) + u + e_{ij}$ for the 'low' height group
- $a_{ij} = (1.1326 + 2.9363\log(r_{ij})) * \exp(-0.0384 r_{ij}) + u + e_{ij}$ for the 'high' height group

As one may notice in Appendix N the line of the fitting models followed the trend of the data, but this did not give enough insight into the models usefulness. Due to the unsatisfactory outcome that the model had when applied in the whole datasets of both forests (Appendix O), the model was tested whether it could predict accurately enough the average angles. Figure 9 displayed the response of the models to Cloich data. The prediction only explained approximately 11% of angle variability for the 'low' group and 20% for the 'high' group.

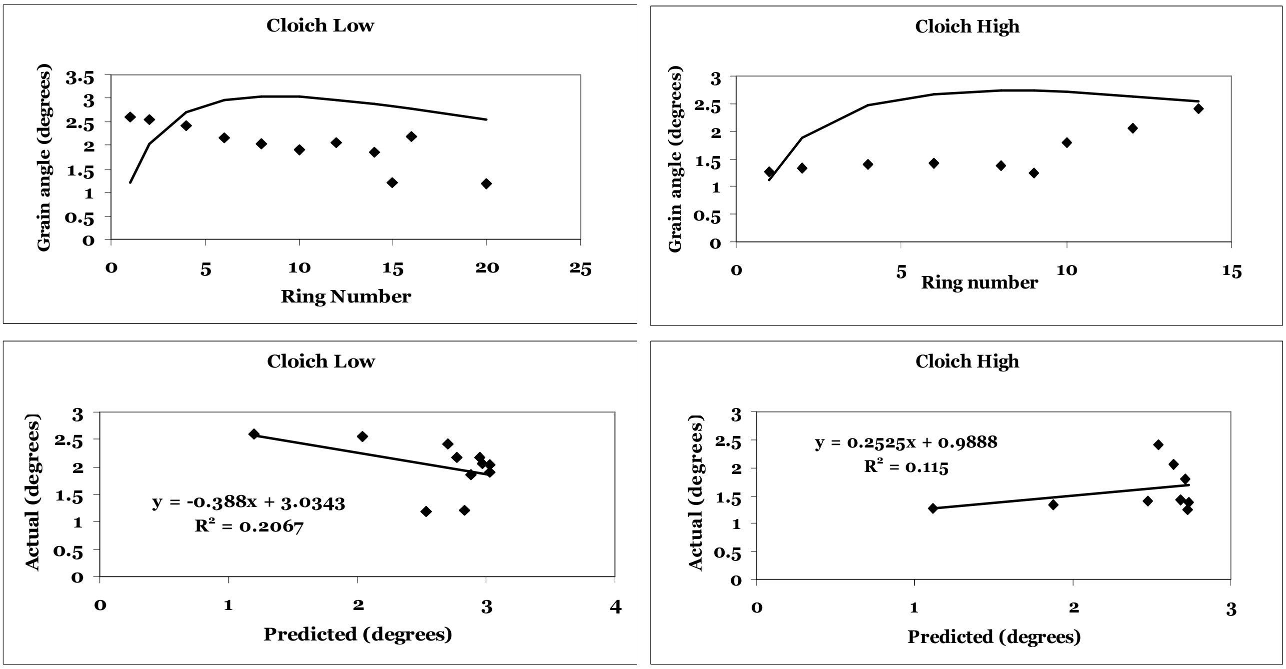

Figure 9: The graphs on top showed the actual average angles (dots) and the corresponding fitted model versus annual rings and the graphs below displayed the predicted versus the actual average angles. All graphs were created from data taken from Cloich forest.

Figure 10 displayed the response of the model to Kershope data. Those results had a more satisfactory outcome since the model explained approximately 39% of angle variability for the 'low' group and 49% for the 'high' group. One of the reasons that we had better results comparing with the ones from Cloich forest might be that we only used trees which had the same spacing as the ones from the initial FR1-FR4 stands.

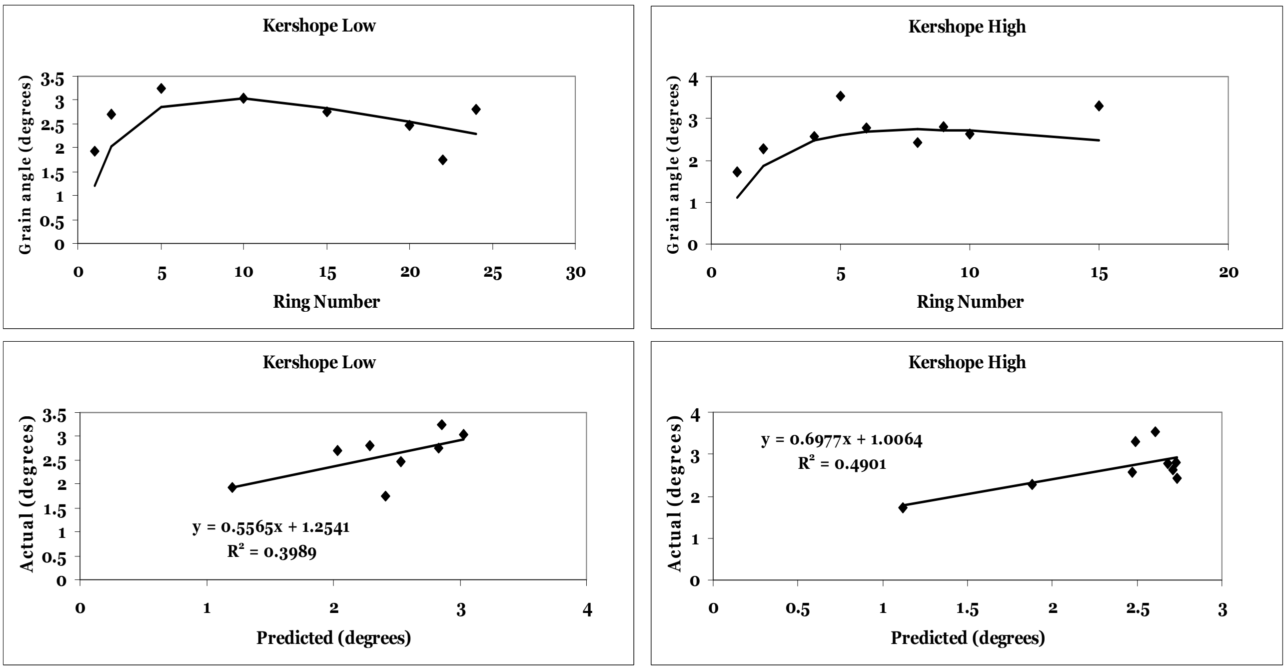

Figure 10: The graphs on top showed the actual average angles (dots) and the corresponding fitted model versus annual rings and the graphs below displayed the predicted versus the actual average angles. All graphs were created from data taken from Kershope forest.

5. Conclusion and Discussion

This research was based on data provided from two forests in Scotland. As discussed in section 3.1 the four stands (FR1-FR4) had significant differences not only in site characteristics but also in environmental conditions. That might have been the reason that grain angle varied from stand to stand. One might say that the mean angles (Table 3) of Lochaline stands (FR1, FR2) should have been substantially greater than the ones of Benmore (FR3, FR4), since Lochaline forest had stronger winds[15]. On the other hand the trees of Lochaline forest were older, so that could have balanced the mean values.

The analysis of the data showed that spiral grain was characterised overall by an initial increase from the pith until reaching a maximum after a few years and a gradual decrease after the 10^{th} annual ring towards zero at the outside of the tree. This was in agreement with Hannrup et al. (2002) and Brazier (1967) who showed that spiral grain of spruce trees has the tendency to increase outwards from the pith until a maximum after a few rings, followed by a gradual decrease. Grain angle was generally higher in the juvenile wood compared with angles in mature wood. This could imply that other interdependent factors may influence spirality. Considering the large variation of grain angle between and even within trees, further analysis is necessary.

"Some models are deemed useful only if they succeed in simulating the essential features of the real system and lead to the prediction of previously unsuspected phenomena or relationships that are subsequently verified" (Kiviat 1967).

The aim of this study was to develop a model, which would predict accurately enough the grain angle of Sitka spruce plantations. Five different models were presented in section 3.2.2. Models 1-4 were suggested based on the observations made on the behavior of spiral grain and Model 5 was proposed in Tian et al. (1995). Non-linear mixed procedure was applied to all five models for both 'low' and 'high' subsets. Selection among competing models can be based on a number of criteria including the Akaike Information Criterion (AIC) and the likelihood test (Wolfinger). Appendix O[16] showed the optimal values of the models' parameters along with the AIC and the coefficient of determination[17] (R^2). Model 1 was selected because it had the highest R^2 values.

Model 1 was used to predict spiral grain in other Sitka spruce plantations. The results were not satisfactory enough. The main reason might be the fact that only the annual ring numbers and indirectly the tree height, through the creation of the 'low' and 'high' subsets, were taken into account. Further examination on relations between grain angle and other tree characteristics, such as diameter, ring width or growth rate, would be the next and most important step when continuing this project. If such relationships were discovered the model would have been more flexible to real life conditions. This research failed to identify such relationships whereas Brazier (1967) found a significant positive relationship between diameter growth and grain angle in Sitka spruce.

[15] Wind was seen by many to be the most likely cause of spiral grain (Harris 1989, p.81)

[16] Models 2 and 3 failed to converge. Model 5 had significantly small R^2 values.

[17] The coefficient of determination (R^2) was found when plotting actual versus predicted grain angles.

Another aspect of future research could be to examine the genetic factors which, according to several scientists, seem to play a significant -if not the most basic- role in the development of spiral grain. Many studies have dealt with clonal trials (Hansen 1998, Hannrup et. al 2002) in order to find a way to reduce spiral grain. Those studies have been concentrated in heritability.

We recommend that in order to construct a model which could help provide better timber quality it is necessary to investigate the influence of a combination of environmental and genetic factors.

Acknowledgements

I would like to thank Dr. Barry Gardiner for his welcome to the Northern Research Station (NRS) of Edinburgh and his help and guidance throughout this work; Dr. Richard Law for his suggestions and assistance rendered to me; Dr. Alexis Achim for his assistance with the modelling and computing part of the project; Dr. Tom Connolly for the statistical advice and Dr. Giorgos Xenakis for his valued opinions and help. I also wish to express my gratitude to my fiancé for his support and inspiration.

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1. Available online at www.forestry.gov.uk/compressionwood; last accessed Aug. 29, 2007.

2. Available online at http://www.theborrows.plus.com/twisted_800.jpg; last accessed Aug. 29, 2007.

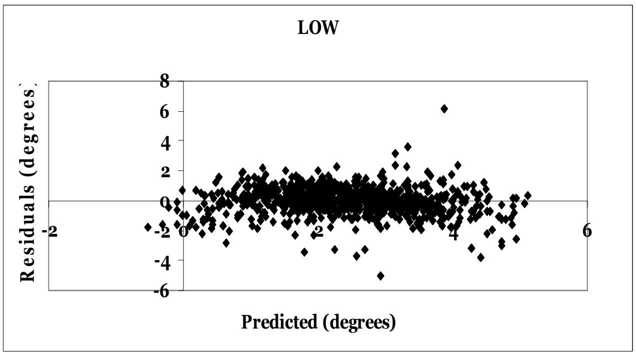
Appendix A: Correlation matrix between the global values (found with NLIN procedure) of the parameters a_1, a_2 and a_3 and other tree characteristics. No significant relation was found.

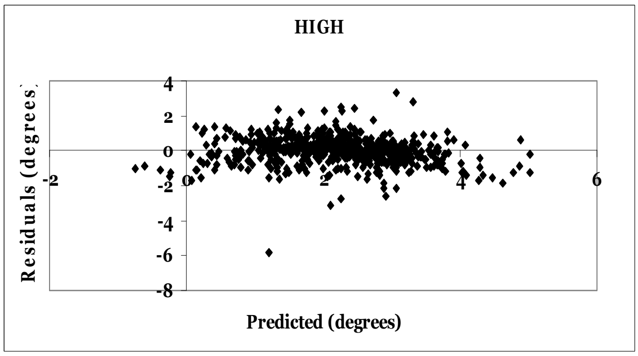
	Total height	Disc height	DBH	Diameter	HOD	Ring No.	Angle	Last angle	Ring width
FR1									
a1	0.1619	0.1034	0.0363	-0.046	0.0147	-0.053	-0.161	-0.126	0.0002
a2	-0.058	0.1361	-0.067	-0.165	0.0194	-0.057	-0.184	-0.197	-0.021
a3	-0.06	0.1398	-0.036	-0.146	-0.009	-0.057	-0.221	-0.289	-0.005
FR2									
a_1	0.1264	-0.122	0.0941	0.237	-0.006	0.0818	0.1917	0.0264	-0.06
a_2	0.0137	0.2048	0.0918	-0.066	-0.067	-0.034	-0.184	-0.428	0.0702
a_3	-0.062	0.263	0.1159	-0.011	-0.128	-0.027	-0.424	-0.734	0.089
FR3									
a_1	-0.047	-0.089	0.18	0.2149	-0.127	0.0104	-0.146	-0.187	0.1602
a_2	0.0906	0.1249	-0.167	-0.226	0.1587	-0.019	0.1939	0.21	-0.146
a_3	-0.097	-0.122	0.1613	0.2272	-0.159	0.0172	-0.229	-0.284	0.1421
FR4									
a_1	-0.152	-0.08	0.0767	0.0909	-0.228	0.0354	0.1531	0.1294	-0.058
a_2	-0.008	-0.06	-0.064	-0.031	0.0507	-0.014	0.2833	-0.49	0.0917
a_3	-0.045	0.1102	0.0375	0.0144	-0.049	-0.022	-0.068	-0.316	0.0566

Appendix B:

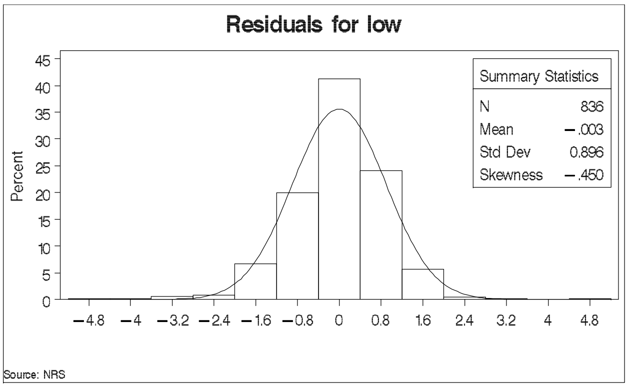
	Ring Number	Average angle	Confidence	Standard deviation	Count
FR1	1	1.25676	0.28	0.87	37
	6	3.17073	0.375	1.22	41
	11	2.90625	0.372	1.2	40
	16	2.40854	0.35	1.147	41
	21	2.07432	0.362	1.122	37
FR2	1	1.27692	0.194	0.797	65
	6	2.80968	0.279	1.121	62
	11	2.55469	0.264	1.079	64
	16	2.07143	0.269	1.09	63
	21	1.80556	0.342	1.284	54
FR3	1	1.12308	0.182	0.75	65
	6	2.94231	0.272	1.12	65
	11	2.89231	0.276	1.136	65
	16	2.51136	0.34	1.398	65
	21	2.32870	0.356	1.334	54
FR4	1	1.0164	0.18	0.717	61
	6	3.1875	0.35	1.39	60
	11	3.1573	0.398	1.588	61
	16	2.9303	0.397	1.581	61
	21	3.20349	0.522	1.747	43

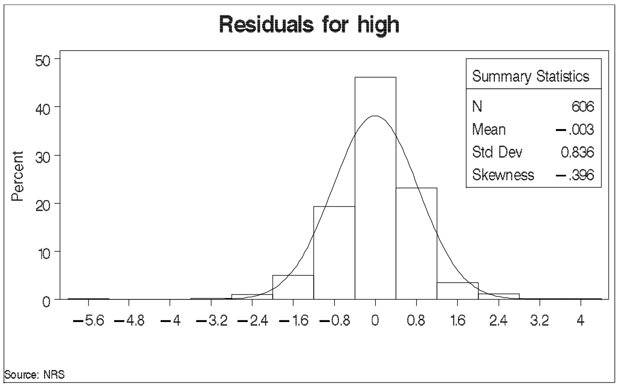
Appendix C: Residuals versus predicted angle values for 'low' and 'high' groups.





Appendix D: Histograms of the residuals for 'low' and 'high' groups.

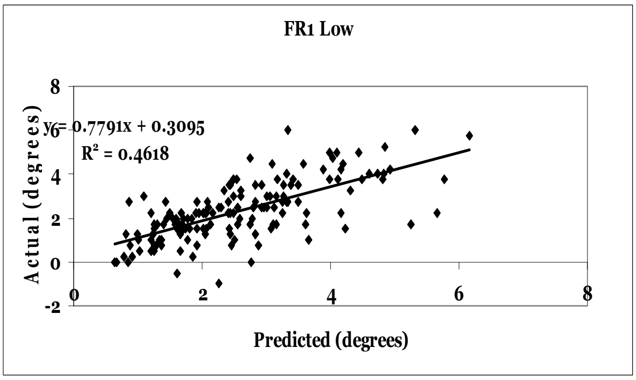


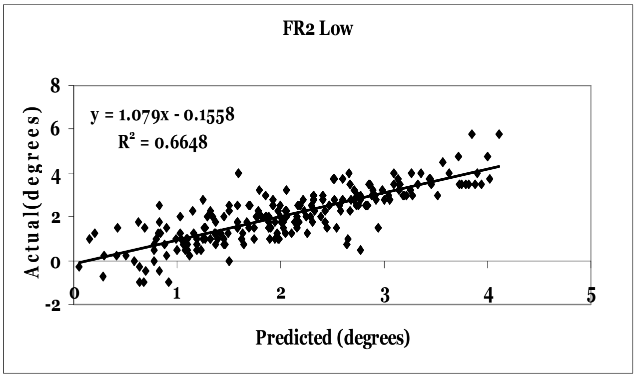


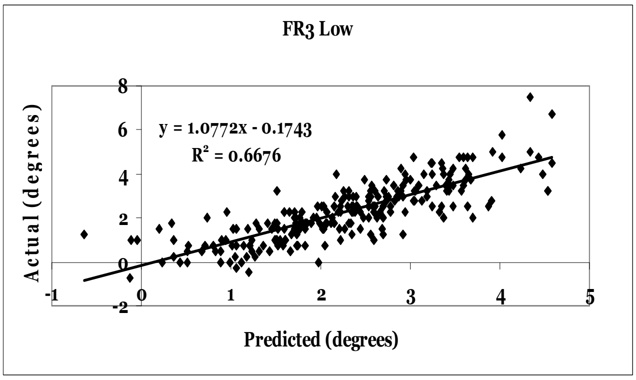
Appendix E: The three normality tests for the residuals of 'low', 'high' and the whole dataset (FR1-FR4).

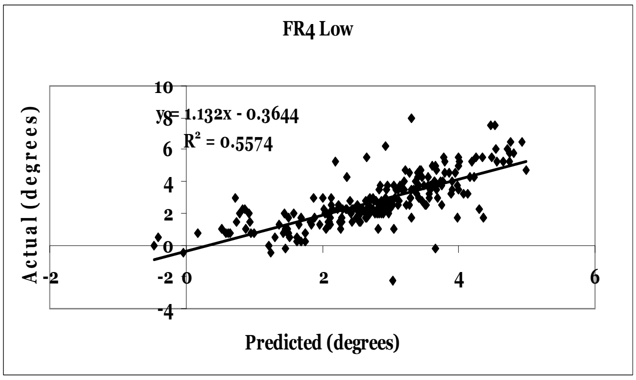
Dataset	Test	Statistic	p-value
Low	Kolmogorov-Smirnov	D 0.06138948	Pr > D <0.01
	Cramer-von Mises	W-Sq 1.02209994	Pr > W-Sq <0.005
	Anderson-Darling	A-Sq 6.20633086	Pr > A-Sq <0.005
High	Kolmogorov-Smirnov	D 0.05581651	Pr > D <0.01
	Cramer-von Mises	W-Sq 0.54955360	Pr > W-Sq <0.005
	Anderson-Darling	A-Sq 3.33390827	Pr > A-Sq <0.005
All	Kolmogorov-Smirnov	D 0.05540446	Pr > D <0.01
	Cramer-von Mises	W-Sq 1.44054657	Pr > W-Sq <0.005
	Anderson-Darling	A-Sq 8.73225480	Pr > A-Sq <0.005

Appendix F: Actual angle values against predicted for datasets with low height angle measurements.

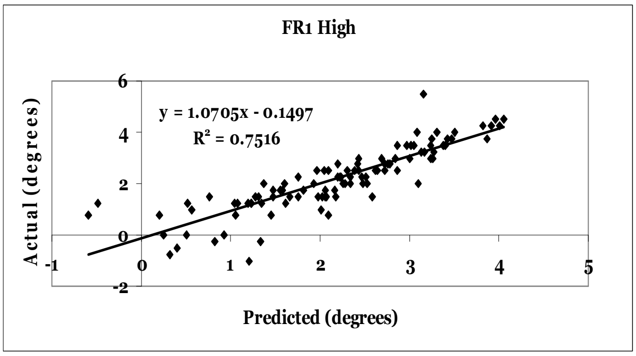


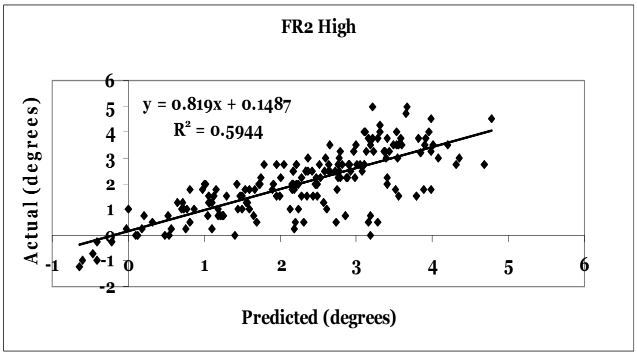


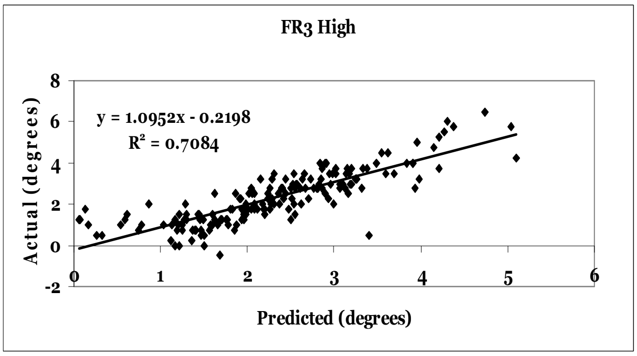


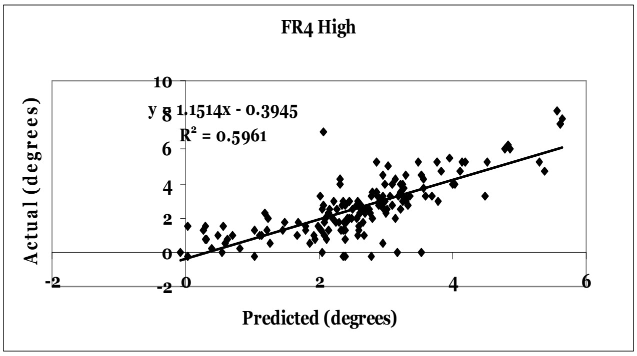


Appendix G: Actual angle values against predicted for datasets with high height angle measurements.

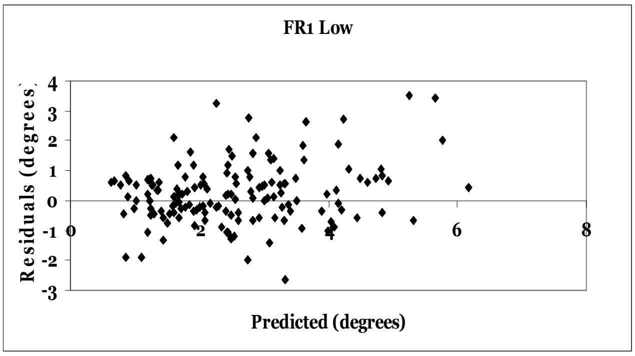


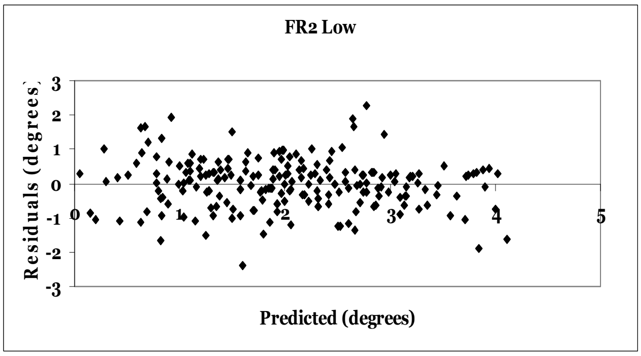


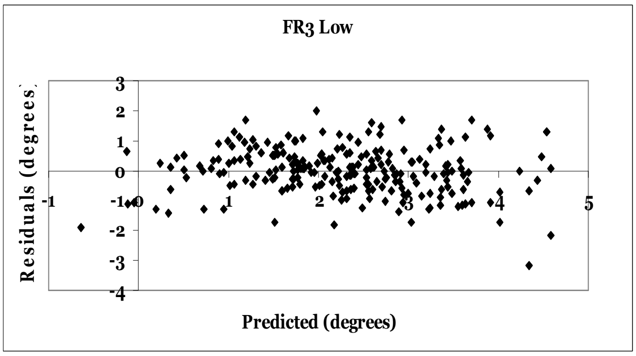


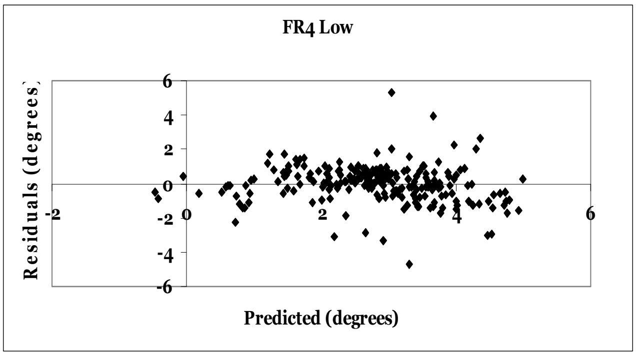


Appendix H: Plots of the residuals against the predicted angle values for the 'low' height datasets.

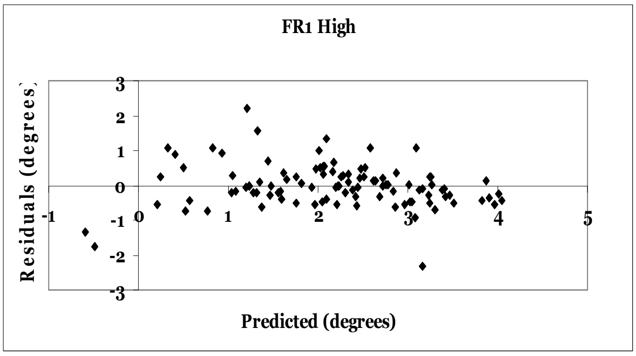


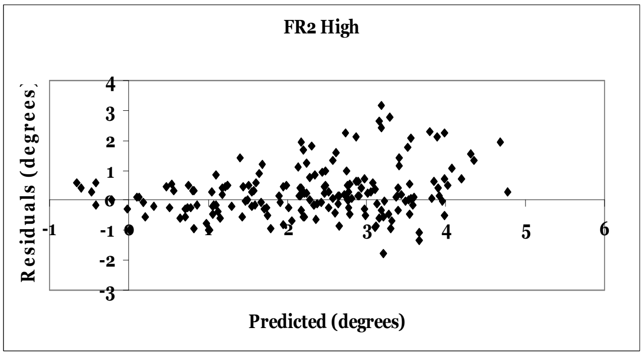


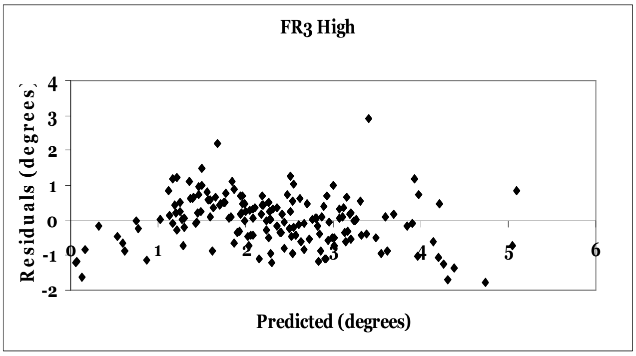


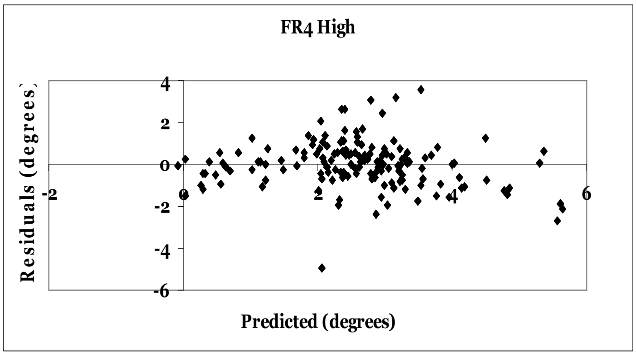


Appendix I: Plots of the residuals against the predicted angle values for the 'high' height datasets.

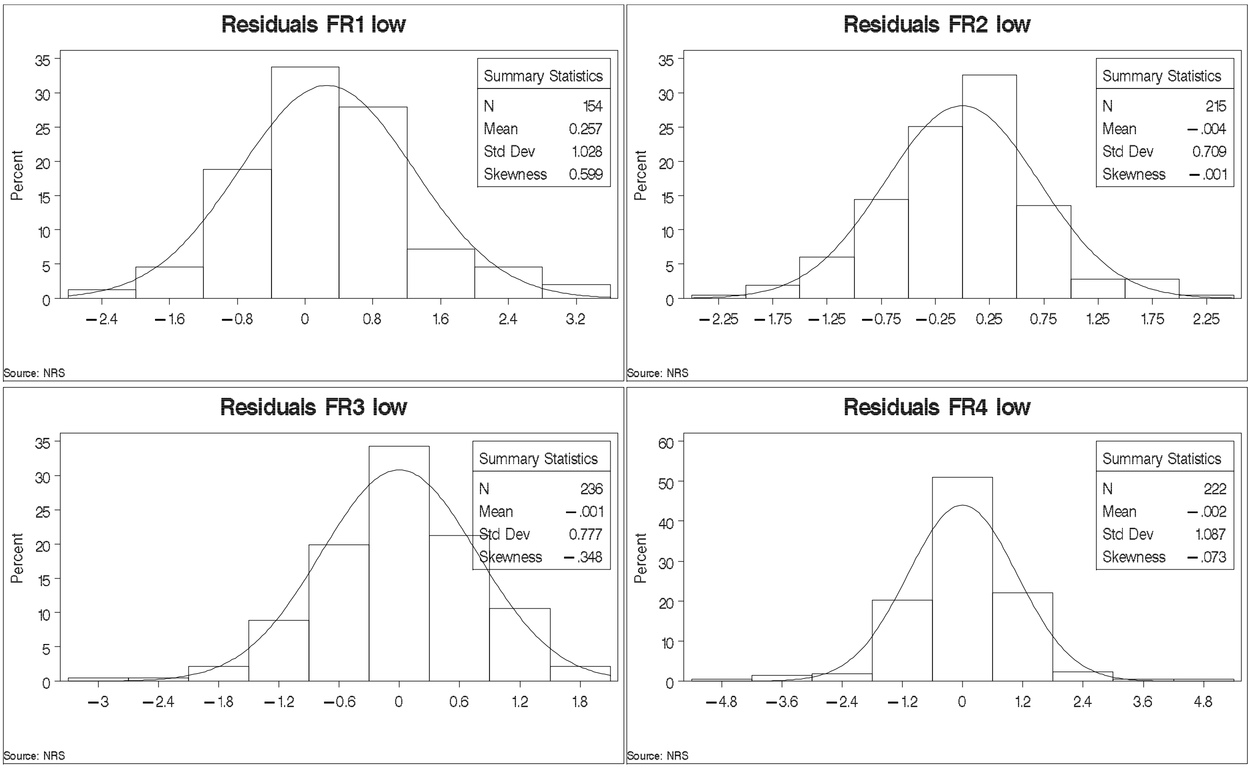




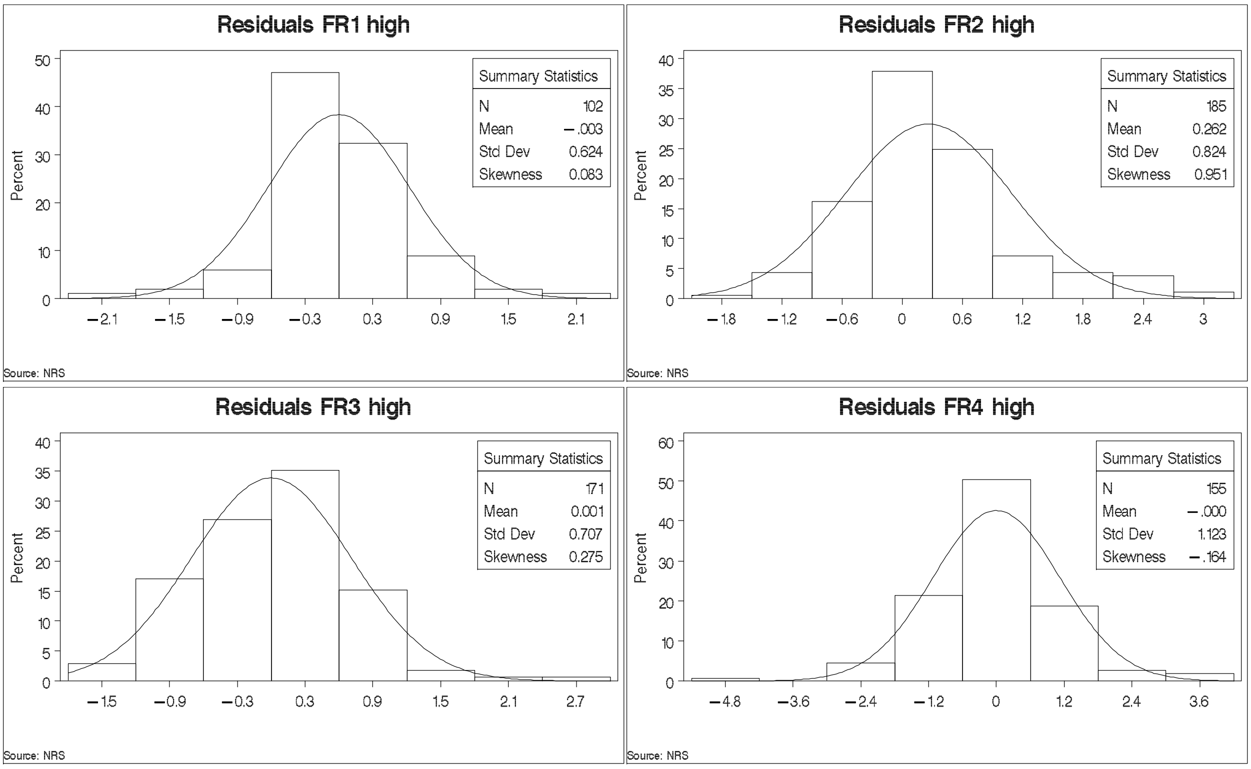




Appendix J: The histograms of the residuals for the 'low' height level datasets.



Appendix K: The histograms of the residuals for the 'high' height level datasets.



Appendix L: The three normality tests for the residuals of all groups of data.

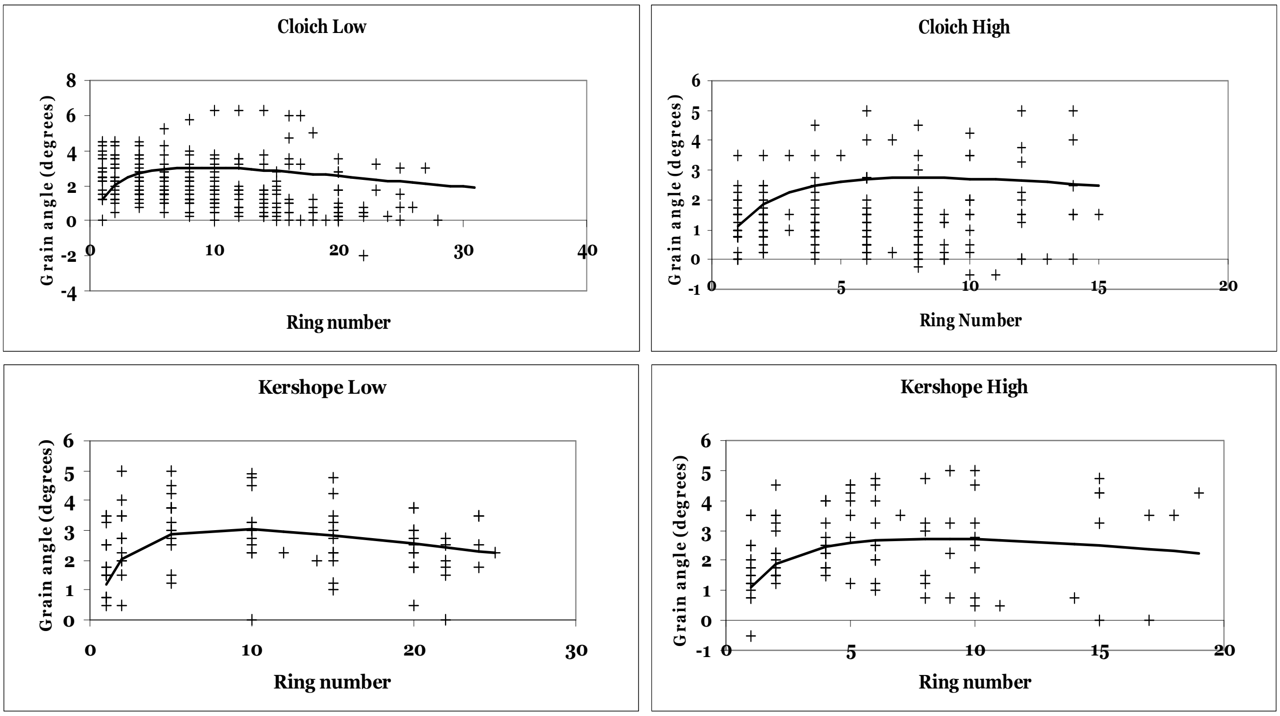
Dataset	Test	Statistic	p-value
FR1 low	Kolmogorov-Smirnov	D 0.09556136	Pr > D <0.01
	Cramer-von Mises	W-Sq 0.24932502	Pr > W-Sq <0.005
	Anderson-Darling	A-Sq 1.59890849	Pr > A-Sq <0.005
FR2 low	Kolmogorov-Smirnov	D 0.06522835	Pr > D 0.024
	Cramer-von Mises	W-Sq 0.16016208	Pr > W-Sq 0.019
	Anderson-Darling	A-Sq 0.91461545	Pr > A-Sq 0.021
FR3 low	Kolmogorov-Smirnov	D 0.04001023	**Pr > D >0.150**
	Cramer-von Mises	W-Sq 0.0758446	**Pr > W-Sq 0.238**
	Anderson-Darling	A-Sq 0.43896925	**Pr > A-Sq >0.25**
FR4 low	Kolmogorov-Smirnov	D 0.08874720	Pr > D <0.010
	Cramer-von Mises	W-Sq 0.44206467	Pr > W-Sq <0.005
	Anderson-Darling	A-Sq 2.89387250	Pr > A-Sq <0.005
FR1 high	Kolmogorov-Smirnov	D 0.09548926	Pr > D 0.022
	Cramer-von Mises	W-Sq 0.22083444	Pr > W-Sq <0.005
	Anderson-Darling	A-Sq 1.47222935	Pr > A-Sq <0.005
FR2 high	Kolmogorov-Smirnov	D 0.1280166	Pr > D <0.01
	Cramer-von Mises	W-Sq 0.61126302	Pr > W-Sq <0.005
	Anderson-Darling	A-Sq 3.60907960	Pr > A-Sq <0.005
FR3 high	Kolmogorov-Smirnov	D 0.0471148	**Pr > D >0.150**
	Cramer-von Mises	W-Sq 0.0535053	**Pr > W-Sq >0.250**
	Anderson-Darling	A-Sq 0.4088222	**Pr > A-Sq >0.250**
FR4 high	Kolmogorov-Smirnov	D 0.07690145	Pr > D 0.024
	Cramer-von Mises	W-Sq 0.21135300	Pr > W-Sq <0.005
	Anderson-Darling	A-Sq 1.3174243	Pr > A-Sq <0.005

The bolded numbers showed were the tests were greater than the alpha value = 0.05. We can observe that the residuals of FR3 low and FR3 high were the only normally distributed.

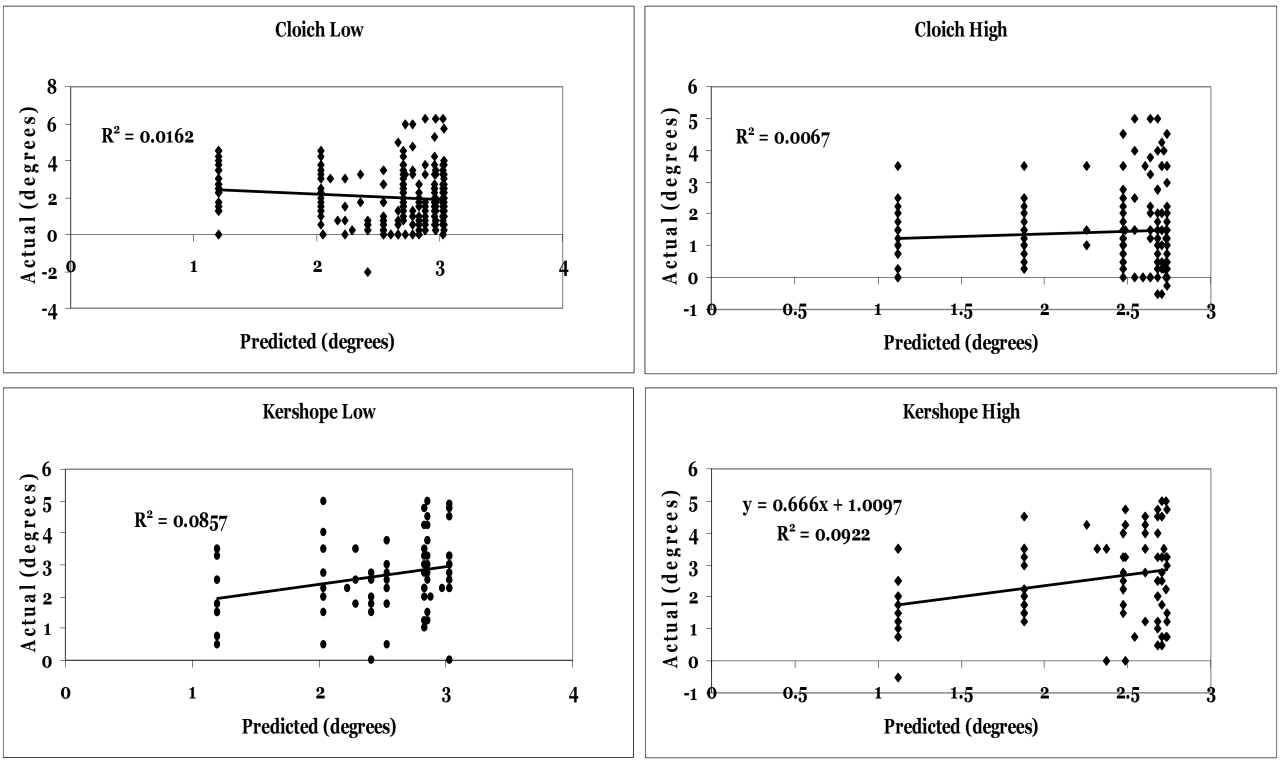
Appendix M: Values of kurtosis, skewness, standardised skewness and kurtosis for the residuals of all subsets.

	FR1 LOW	FR2 LOW	FR3 LOW	FR4 LOW	FR1 HIGH	FR2 HIGH	FR3 HIGH	FR4 HIGH
Skewness	0.599	-0.0006	-0.35	-0.07	0.083	0.95	0.28	-0.16
Stnd. Skewness	3.04	-0.0003	-2.18	-0.44	0.34	5.28	1.47	-0.84
Kurtosis	1.29	0.9	0.82	4.47	2.94	1.34	1.24	2.73
Stnd. Kurtosis	3.26	2.69	2.58	13.58	6.07	3.72	3.3	6.93

Appendix N: Actual angle values against ring number from pith are displayed with a cross sign where the fitted line is the corresponding model.



Appendix O: The first two graphs displayed the actual angles versus the predicted for Cloich trees and the two graphs below for Kershope trees.



Appendix P: The parameter values, the value of the A.I. Criterion and the coefficient of determination R^2 for Models 1-5 for 'low' and 'high' subsets.

	Model 1		Model 2		Model 3		Model 4		Model 5	
	LOW	**HIGH**	**LOW**	**HIGH**	**LOW**	**HIGH**	**LOW**	**HIGH**	**LOW**	**HIGH**
a_1	1.247	1.1646	0.7837			1.4323	-0.9537	-0.8209	1.7187	-1.4616
a_2	3.1398	2.8977	0.5748			2.429	0.07461	0.08786	3.2301	15.3806
a_3	0.0371	0.0367	0.07807			0.01906	0.05652	0.0478	0.42	0.3155
a_4				Optimisation could not be completed.					-1.5496	-2.8848
a_5									-0.7491	5.1619
a_6									0.7975	-0.3239
σ^2_u	0.8216	0.6856	0.8213			-0.9452	-3.3709	-19.1847	-1.6386	-14.061
σ^2_e	0.9739	0.7593	1.0275			0.699	1.1018	0.8102	2.2614	0.08403
AIC	2679.7	1668.7	2721			1263.2	2182.1	1470.4	-7243	$-168e^{4}$
R^2	0.6081	0.6414	0.5845			0.6168	0.522	0.5478	0.057	0.04