Processing Potential of Lodgepole Pine

Final report

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Forest Research
January 2004

Contents

Executive Summary

- The overall objective of this project was to investigate the factors that had an influence on the fracturing of lodgepole pine in use. The investigations linked three provenances of lodgepole pine that are commonly grown in the UK with conversion at a sawmill and end product universal testing (BS EN 408:1995). This allowed an investigation of the effects of provenance on the strength properties of lodgepole pine.
- Three provenances were selected to represent the type of material generally planted in north Scotland, Longbeach (SLP), Petersburg (ALP) and Terrace (Inland).
- A total of 132 LP trees were selected from two Forestry Research experiments and from these 311 2m logs were obtained. Form, size and branch data were collected on the trees and the logs. The logs were converted into battens of standard dimensions 100*50*2000mm using a commercial cutting pattern. Static bending tests, compression wood and knot area were measured on the battens. Impact tests were conducted on a sub-sample of the battens. Compression wood was also analysed with discs cut from the top and bottom of the logs. Scots pine material was obtained from an experimental site on the Black Isle for comparison.
- The lodgepole pine underperformed for MoE and MoR compared to figures published for the species. It was also consistently weaker than the Scots pine for all strength tests. One exception to this was that Petersburg (ALP) performed as well as SP for impact testing.
- At the site level the mean values for strength parameters were better for battens from Rosarie compared to Shin. This is possibly due to heavier branching on average at Shin compared to Rosarie.
- At the provenance level Longbeach had the highest MoR, Terrace the highest MoE and Petersburg the highest toughness and impact strength. Branching and knot characteristics were the best predictors of MoR, MoE and toughness.
- Fracture type is very strongly linked to provenance and Longbeach is the poorest performer with the highest chance of brash fracture. This is also reflected in the low average impact energy needed to break Longbeach battens compared to other provenances. Compression wood area is similarly strongly linked to provenance and it seems likely that the brash failure is due, in part, to the high levels of compression wood found in the Longbeach battens.
- Due to the very poor form of the Longbeach trees it is impossible to be certain that these findings are characteristic of the provenance, i.e. genetic in character. Straight Longbeach trees would need to be found in order to test this. This work does suggest that although it is possible to cut short straight logs they will still contain compression wood that has been produced due to bends or leaning trees, therefore reducing the overall strength qualities of the provenance.

Introduction

1. Lodgepole pine was planted extensively in Scotland during the 1960s, 1970s and 1980s. The National Inventory of Woodlands estimates that there are 121,060 hectares of lodgepole pine high forest in Scotland, representing 11% of the total high forest resource, and that 87% of this area was planted between 1961 and 1990. 63% of the lodgepole pine resource lies within Highland conservancy, with a further 12% in Grampian conservancy.
2. This study investigated the observation that fresh cut lodgepole pine (*Pinus contorta* Dougl. Ex. Loud.) used as fence posts and pallet wood would fracture abruptly leaving a smooth non-fibrous surface. High levels of failure in use have raised concerns that the lodgepole pine currently being harvested is not suitable for solid wood products such as pallet slats or fencing posts.
3. Complaints from customers about the in-service performance of lodgepole pine apparently started about 3 years ago, and have increased recently. There was no obvious reason for the breakages, such as a large knot, and the timber appeared to be very brittle. Examples of the brittle fracture of fencing posts have been reported in the agricultural fencing market and breaking suddenly once the pallets had been assembled and were in use. There have also been examples of lodgepole pine logs breaking in a similar manner, particularly during debarking, and of boards breaking on the sawmill line.
4. Lodgepole pine is a highly variable species with a large native range covering large areas of North America. Provenance differences in vigour and form are similarly known to be large. The south coastal provenance grows very vigorously in Scotland but displays very poor form. Provenances from further north and inland of the native range tend to grow more slowly but are of better form.
5. It was hypothesised in this study that compression wood was the underlying mechanism for the breakages and that this in turn was a function of poor form. Since provenance has a well known impact on the form of lodgepole pine (LP), differences in performance of wood from different provenances were a key part of the investigation. However, it should be stressed that finding the cause and assessing the full extent of the problem would require an effort that is beyond the scale of this study.

Methodology

6. This work was carried out between June 2003 and January 2004. Two experimental stands of lodgepole pine were selected located at Shin, Inverness forest district and Rosarie, Moray forest district. These were originally established as provenance trials in the same year and using the same seed sources. The experiments are similar in initial spacing and age to the bulk of lodgepole stands currently being harvested in north Scotland. Details of the sites and a summary of their management to date are given in Table 1. Three provenances were chosen for the experiment, Longbeach (South Coastal), Terrace (Inland), Petersburg (Alaskan), as they represent the main commercial provenances of LP timber grown in quantity in the UK.
7. At Shin the experiment was planted as 100 tree plots replicated into three blocks, whereas at Rosarie the layout was 36 tree plots with four blocks. Trees were selected

from all blocks in both sites, 9 trees per plot in Shin and 5 trees per plot at Rosarie. The trees were selected to represent the top quartile in terms of dbh and of average, or above average, form for the plot. One plot of Longbeach provenance at Shin was so badly wind blown that no trees could be extracted. Hence the number of Longbeach trees sampled there was 18 rather than 27.

Table 1: Summary of site characteristics and management at Shin and Rosarie

Description	**Shin 25 P. 70**	**Rosarie 3 P. 70**
Grid Reference	NC 535223	NJ 322487
Soil class	Deep molinia/trichophorum peat (mainly over 1,5m)	Strong iron pan, SE & NE edges of main block merge to surface water gley.
Vegetation	Molinia, Trichophorum, Narthecium, Calluna, E.tetralix & Myrica	Calluna vulgaris.
Elevation	190m – 220m	305-330m.
Rainfall	1120mm – 1250mm	890mm
Exposure	Exposed North-West to South-West	Fully exposed to NE and S-SW
Spacing	1.7m	1.8 x 1.8m.
Treatment	UPR at 376 kg/ha applied broadcast Beat up in 1971 Summer 1973 top dressing with PK mixture broadcast at 575 kg-ha Summer 1979 top dressing with PK at 575kg/ha broadcast Rogue trees removed from several plots May 1984 Lane brashing	UPR applied broadcast at 49kg elemental P/ha. Beat up in 1971 & 1972. Loose plants firmed after wind loosening, summer 1972. Additional soil on leeward side- straightened. Weedings in early years Chemically thinned in 1996
Observations	1980s- effects of defoliating insects noted Poor stem form noted, particularly in Longbeach	1973 noted poor stem form through inability to stabilise early. 1975 noted S. coastal as comparably tall (2m to exp. Mean of 1.6m). 1975 noted incidence of basal bowing/crooked stems (45-73% stems affected). 1976 inspection reports, broken leaders after heavy winds and sandstorms in spring. 1980 S. coastal growing with vigour, but incidence of bowing and blown trees is high. 1981 snow breakages noted in Longbeach.

8. Scots pine was also obtained from a separate spacing experiment located at Findon on the Black Isle for use as comparison material. There were two different experiments

within the stand planted in 1935. One stand was planted at 5500 stems per hectare (1.4 metre spacing) and the other at 1700 stems per hectare (2.4 metre spacing). Subsequent thinning has maintained these initial spacing differences. Four trees were selected from each spacing and 3 logs cut per tree. A top log was selected with a top diameter of ≥16cm, the bottom log from the butt and the third selected at the mid-point between the two.

9. The tree samples were logged into 2.0m sections before being transported to the sawmill for further assessment. Measurements taken at the site, sawmill and I-beam factory are summarised in Table 2.

Table 2: Measurements taken at different stages in the work.

	Forest	**Sawmill**	**I-Beam**	**NRS**
Shin and Rosarie	Log measurement Stem taper, two directions Stem shape Branch diameter, vertical and horizontal Whorl position from butt Spiral grain Log deviations using string	Moisture content Compression wood area Knot area Spiral grain	Batten dimensions Moisture content MoE MoR	Impact testing Moisture Content Disc Analysis
Findon	Log measurement Log end coding Spiral grain	Batten Coding	Compression wood area Knot area Batten dimensions Moisture content MoE MoR	Impact testing Moisture content

10. Details of measurements taken at each stage of the work are summarised in Table 3.

Table 3: A summary of measurements taken during the work

Forest	**Description of measurement**
Marking of trees and logs	A north mark was painted on each tree as a future point of reference. Another paint line marked the concave side of the largest bend and/or the topside of maximum lean (see Appendix 1) Each stem was marked to maximise the log out-turn of 2.0m logs from the available material. Each log was given an identity code to follow the wood from forest to end product.
Spiral grain (degrees)	Two 2-inch squares were cut through the bark to expose the cambium layer on the N and S sides of the stem. The

	spiral grain device was used to record the angle from vertical, and the direction of the grain.
Stem shape using ‘Torpedo boy’ laser. (cm)	A laser set square was used to measure the maximum horizontal deviation of the first 4m of the stem.
Log numbering	Each tree and log was given a unique code to identify its provenance and location on the stem.
Log deviation (cm)	The deviation of each log was recorded using a piece of string attached to both ends of the log and pulled taught. The deviation was measured at the mid-point of the log to the piece of string measured in centimetres (cm). See Appendix 1.
Stem taper (cm)	The diameter of the stem was measured twice using callipers at 1m intervals, maximum diameter and diameter at 90 degrees to max were recorded.
Whorl position (m)	The whorl positions up to 16 cm obd were recorded from the butt to their exact position on the stem.
Branch size (mm)	Branch diameters both vertical and horizontal were recorded using callipers.
Discs	10cm discs were removed from the bottom and top of each of the logs. The height to the bottom of the discs was also recorded (m).
Sawmill	**Description of measurement**
Moisture content (%)	Measured electronically to 0.1%
Batten marking	Each batten was marked with a unique number to trace it back to the provenance and tree number.
Batten dimensions (mm)	The actual length, width and depth of the battens were recorded in millimetres (mm).
Compression wood (%)	Compression wood was estimated by eye and marked on the fresh sawn battens. The area was measured using a transparent grid that fitted over the batten. The grid was sectioned into 100 parts making each part 1%. A smaller grid fitted over this to break it into 0.25%.
Knot area (%)	Knot area was also recorded using the same method as the compression wood.
I-Beam Factory	**Description of measurement**
Modulus of Elasticity and Modulus of Rupture	The battens were tested over a four point bending machine from between 60-90seconds. MoE and MoR were recorded using James Jones’s computer recording system called Windaq. MoE is measured in Newton per mm^2 (N/mm^2). MoR was measured using MPa (Mega Pascal).
Fracture type	Fracture types were recorded after each bending test. 6 types of fracture as described in the ASTM D 143-94 Standard methods of testing 1995 were used.
NRS	**Description of measurement**
Impact Testing (J)	A random selection of battens was tested using a weighted

	pendulum to break the battens. Results were measured in joules. [Mass*gravity*(Ht_1-Ht_2)]. (Ht_1 start height, Ht_2 end height).
Disc analysis (%)	The discs were analysed to ascertain the percentage of compression wood using the colour recognition software, Optimas, further details in Appendix 2.

11. Toughness: was derived from Windaq and provides a measure of the energy used to break the battens (J).

12. Adjusted MoE: due to the differing moisture contents of the battens the MoE values used for the statistical analysis were adjusted to a common moisture content of 18% using the following expression:

$$\mathrm{Ln}\ (\mathrm{MoE}) = \mathrm{Ln}\ (\mathrm{MoE})_{wet} + c(MC_{wet}-MC_{dry})$$

Where c is a constant calculated as 0.0172 for lodgepole pine and 0.021 for Scot pine using values published by BRE (Lavers 1983) and MC is percentage moisture content. Any battens above the fibre saturation point of 27% were assumed to have MC_{wet} = 27 and MC_{dry} was fixed at 18% for all battens.

13. Data collection on a site and provenance basis is shown in Table 4.

Table 4: Distribution of trees, logs and batten by site. Note Findon was a Scots pine stand.

Site	No. Trees	No. Logs	No. Battens
Shin	**72**	**139**	**244**
Longbeach (L)	18	48	76
Petersburg (P)	27	37	75
Terrace (T)	27	54	93
Rosarie	**60**	**172**	**391**
Longbeach (L)	20	68	152
Petersburg (P)	20	42	93
Terrace (T)	20	62	146
Findon	**8**	**24**	**93**
FR5	4	12	39
FR6	4	12	54

Results

14. The data were analysed at different levels. Initially, analysis was undertaken to examine broad mean differences between the logs and battens at the site and provenance level. Then, a more detailed statistical analysis on a batten by batten basis was undertaken to examine factors associated with MoE, MoR, toughness and compression wood. Finally, fracture type was analysed using a probabilistic decision tree method and a refinement made by estimating a “profit” or “loss” for a right or wrong decision.

15. For **MoR**, there were no significant differences between the provenances at Shin or Rosarie. However, battens at Rosarie had a significantly higher MoR than those for Shin (R = 28.2, S = 26.3; $p = 0.057$) and, when both sites are compared, Longbeach had a significantly higher MoR than Terrace (L = 28.42, P = 27.9; T = 25.5; $p=0.040$).

16. For **MoE**, the general trend at both sites was Terrace>> Longbeach> Petersburg but only at Rosarie was this difference significant (T = 7167, L = 6190, P = 6061; p=0.006). However when comparing sites, Rosarie had a significantly higher MoE than Shin (R = 6473, S = 4955 p<0.001).

17. The published figures for lodgepole pine at 13.3% MC are MoR = 79 and MoE = 8100 (Lavers 1983) which are significantly higher than the values found in this work. Lavers figures for Scots pine at 12% MC are MoR = 89 and MoE = 10,000. Compared to the material from Findon the value for MoR is much higher (MoR = 37.1) whereas MoE is the same (MoE = 10,019). This suggests that our methodology underestimates MoR and this is probably due to the fact that whole battens were tested rather than small clears.

18. The percentage of **compression wood** measured on the battens showed highly significant differences between the sites and the provenances (p<0.001) the values are shown in Table 5.

Table 5: Mean percentage compression wood area per batten for sites and provenances (average SED in brackets)

Site	Site mean (1.018)	Longbeach	Petersburg	Terrace
Shin	23.08	35.56	19.34	14.34
Rosarie	16.42	20.92	18.60	9.75
	Provenance Mean (1.247)	28.24	18.97	12.04

19. The analysis of compression wood from discs (Appendix 2) also shows that Longbeach contains significantly more compression wood than the other two provenances when sites are combined (L = 8.89%, T = 4.54%, P = 4.03%; p<0.001). In contrast to the batten analysis, however, the discs showed significantly higher compression wood area for Rosarie compared to Shin (R = 7.14, S = 4.38; p<0.001).

20. **Impact testing** of a sub-sample of the battens indicated both site and provenance differences. At the site level, Rosarie produced stronger battens than Shin but the values for both sites were significantly less (p<0.001) than those for Scots pine battens from Findon (R = 271.5 J, S = 225.5 J; p=0.22: SP = 411.6 J). The provenances followed the same trend at both sites (P>>T>L) with Petersburg being much stronger under impact than the other two provenances (p<0.001) and not being significantly different to the Scots pine (Shin P = 367.7 J, T = 230.1 J, L = 184.7 (T and L, p=ns); Rosarie P = 371.4 J, T = 254.1 J, L = 245.3 J (T and L, p=ns)). The fracture types of the test specimens were also assessed. Petersburg only broke with simple tension fracture type whereas the other two provenances showed both simple tension and brash fractures. Brash fractures accounted for 30.8 % of all fractures for Longbeach and 14.3% for Terrace. The average impact energy for brash fracture was 177.7 J (Longbeach and Terrace) significantly less than 248.0 J for simple tension fracture (Longbeach and Terrace; p<0.001).

21. **Fracture type** was assessed once the battens had been broken during 4-point bending. The data were analysed using a probabilistic decision tree method that aims to provide the best prediction via a series of questions. The system can be weighted to take into account the different value placed on a right or wrong answer, for example predicting a simple tension when in fact the batten fails with a brash fracture is far worse than if the batten fails with a cross grain tension fracture. This analysis showed that provenance

was a better determinate of fracture type than site or percentage compression wood area. If a batten comes from Longbeach it is best to assume that it will break with a brash fracture. The decision tree for site and provenance with no profit matrix is shown in figure 1 and for site, provenance and compression wood with a profit matrix in figure 2.

22. **Branch data** was analysed on a log basis. It was found that the total branch area per log, i.e. the sum of the area of all the branches on the log, was not significantly different between provenances but differed between sites (S = 73.1 cm^2/log, R = 63.3 cm^2/log; p=0.033). The maximum branch diameter per log showed differences between the provenances and between sites. Longbeach had significantly larger branches than Terrace at both sites (Rosarie L = 3.72 cm, T = 3.42 cm; p=0.027: Shin L = 4.24, T = 3.70; p=0.031) but was only significantly larger than Petersburg at Rosarie (Rosarie L = 3.72 cm, P = 3.16 cm; p=0.001: Shin L = 4.24, P = 4.30; p=ns). Comparison between the sites showed that Shin had significantly larger maximum branch size than Rosarie (S = 4.06 cm, R = 3.47 cm; p<0.001). These results indicate that Longbeach had fewer, but larger branches per log length than the other provenances. This was mainly due to the larger interwhorl distance for Longbeach.

23. **Batten knot area**, expressed as the percentage surface area of one side of the batten, showed provenance differences at both sites, the trend being P>T>L. Differences were highly significant (p<0.001) between all the provenances at both sites except Petersburg and Terrace at Shin. Again, Shin showed a larger average knot area compared to Rosarie.

24. **Toughness** showed no significant differences between sites but within each site the trend was P>L>T and the differences were significant (p between 0.025 and <0.001). Petersburg battens were 24% tougher than Longbeach battens from Rosarie and 36% greater when from Shin. Similarly the differences between Longbeach and Terrace battens were 16% at Rosarie and 25% at Shin.

25. Toughness, compression wood, MoE and MoR were further analysed on a batten by batten basis to determine any interactions between them and other data measured on the logs and battens. Analysis was undertaken on a site by site basis since this was a fixed effect. The covariates identified as significant are given in Table 6.

Figure 1. Site & Provenance simple model

Fracture Type 1, 2, 4 & 9
Default profit matrix
500 battens (Minimum sample size 49)
Training 70% - Validation 30%

9		6.1%
4		21.8%
2		13.9%
1		58.2%
Total		
Predict	1	
Correct		58.2%

Provenance

Longbeach

9		4.9%
4		44.3%
2		4.9%
1		45.9%
Total		
Predict	4	
Correct	44.3%	

Site

Shin

9		4.3%
4		34.8%
2		8.7%
1		52.2%
Total		
Predict	1	
Correct		52.2%

Rosarie

9		5.3%
4		50.0%
2		2.6%
1		42.1%
Total		
Predict	4	
Correct		50.0%

Terrace

9		10.6%
4		4.3%
2		19.1%
1		66.0%
Total		
Predict	1	
Correct		66.0%

Petersburg

9		3.5%
4		12.3%
2		19.3%
1		64.9%
Total		
Predict	1	
Correct		64.9%

Fracture types
1 – Simple tension
2 – Cross grain tension
4 – Brash tension
9 - Other

Figure 2. Site & Provenance & CW% Model (2DEEP)

Fracture Type 1, 2, 4 & 9

Defined profit matrix (opposite)

500 battens (Minimum sample size 49)

Profit Matrix

		Prediction			
		9	**4**	**2**	**1**
Truth	**9**	1	-5	0	1
	4	-5	10	-10	-10
	2	1	-5	1	1
	1	1	-5	1	1

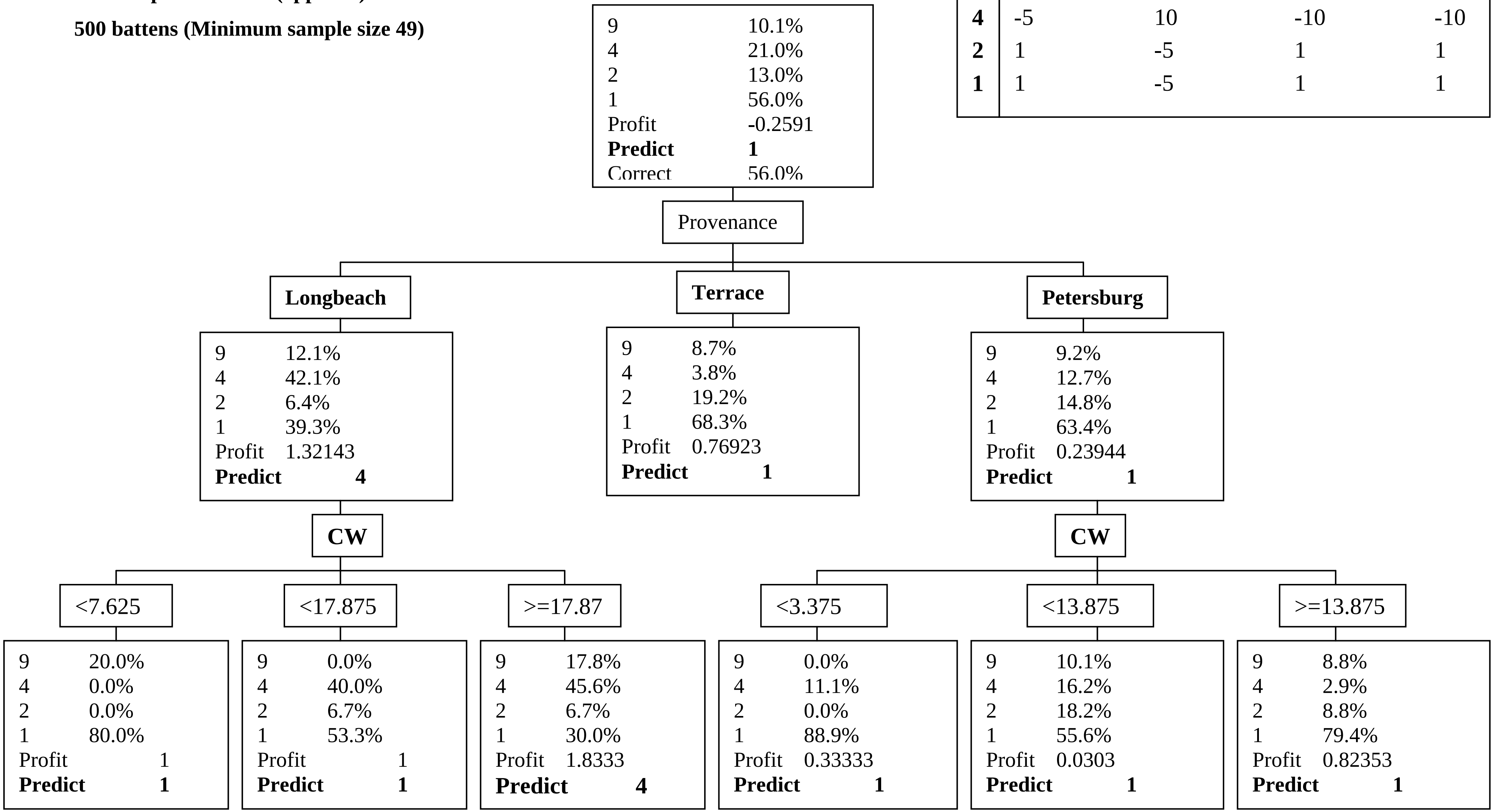


Table 6: Analysis of significant covariates and interactions for MoE, MoR, toughness and compression wood (p values in brackets)

Response	Shin: Significant Covariate	Rosarie: Significant Covariate
MoR	Max branch diameter x prov. (0.020) Batten knot area x prov. (<0.001)	Batten knot area (0.002)
MoE	No. of whorls/log (0.016) Total branch area/log (0.041) Total branch area/log x prov. (0.021) Batten knot area (0.025)	Log deviation (0.027)
Toughness	Provenance (<0.001) Max branch diameter (0.049) Batten knot area x prov. (0.038)	Batten knot area (0.013)
Compression Wood	Provenance (0.001) Total branch area/log (0.015) Total branch area/log x prov. (<0.001) No. of branches/log (0.011)	Provenance (<0.001)

Discussion

26. In general the lodgepole pine material performed more poorly than the published results in Lavers. The Scots pine material was close to the published figures for MoE and therefore this suggests that the testing procedures were compatible with those used by Lavers at BRE. The use of whole battens compared to small clears will have had an effect on MoR. It could also be that Lavers tested maturer lodgepole material than that used here, but the difference between the results is significant.

27. Three of the four measures of batten performance all show a consistent trend when looked at on a site basis. For MoR, MoE and impact energy the battens from Rosarie perform better than those from Shin. For toughness, the mean value for Shin is higher than that for Rosarie but not significantly so.

28. At a provenance level the situation is more complex with Longbeach appearing to have the best MoR, Terrace having the best MoE and Petersburg having the highest impact energy. Interestingly Petersburg battens performed as well as Scots pine when impact tested.

29. Branching and knot characteristics appear to be highly correlated with MoR, MoE and toughness, more so than provenance, and hence lightly branched trees should perform well regardless of provenance for these performance measures.

30. In contrast, impact testing demonstrated strong provenance differences with Petersburg considerably out-performing the other two provenances. Longbeach has a higher number of brash fracture type failures than the other provenances, which is of concern due to the low impact energy needed to break battens with this fracture type.

31. Analysis of fracture type after 4-point bending tests reinforced the picture that provenance is the controlling factor for fracture type and that Longbeach is the most likely to produce battens that fail with a brash fracture. It is interesting to note that knowing a threshold level of compression wood in the batten allows a better split of those Longbeach battens that will fail with brash fracture and those that will not. Higher levels of compression wood are associated with brash fracture and this is

consistent with the results here. The poor form and wind blown nature of the majority of the Longbeach sample trees makes the finding of higher levels of compression wood in the battens of this provenance compared to the others unremarkable. However, it demonstrates that maximising recovery by cutting the bends out does not remove the presence of compression wood over the short 2m log lengths used in this work.

32. In conclusion, it is likely that the poor performance of the material used in this work is due to the fact that it is not full rotation material and hence will contain a higher proportion of juvenile core than that used by Lavers for her work. It is noticeable that material from Shin behaved more poorly than that from Rosarie for MoR, MoE and impact energy, however, due to the lack of site replication it would not be possible to extend these findings to other sites of similar type with any certainty. The fact that the trees were more heavily branched at Shin is a possible explanation why battens from this site performed poorly compared to Rosarie. Fracture type and impact energy, which are measures of batten performance possibly more importantly for the end-user, appear to be more strongly determined at a provenance level. Longbeach performs particularly poorly in this respect. This is likely to be linked to the presence of compression wood, but without being able to test Longbeach battens with low levels of compression wood it is impossible to determine whether the behaviour is predominantly due to provenance, i.e. genetic in character, or a consequence of the growth habit observed at the two experimental sites.

Reference:

Lavers, G.M. 1983 *The strength properties of timber*, Third Edition (revised by G.L. Moore), Building Research Establishment, Garston, Watford.

Appendix 1

Analysis of the orientation of bends in standing trees.

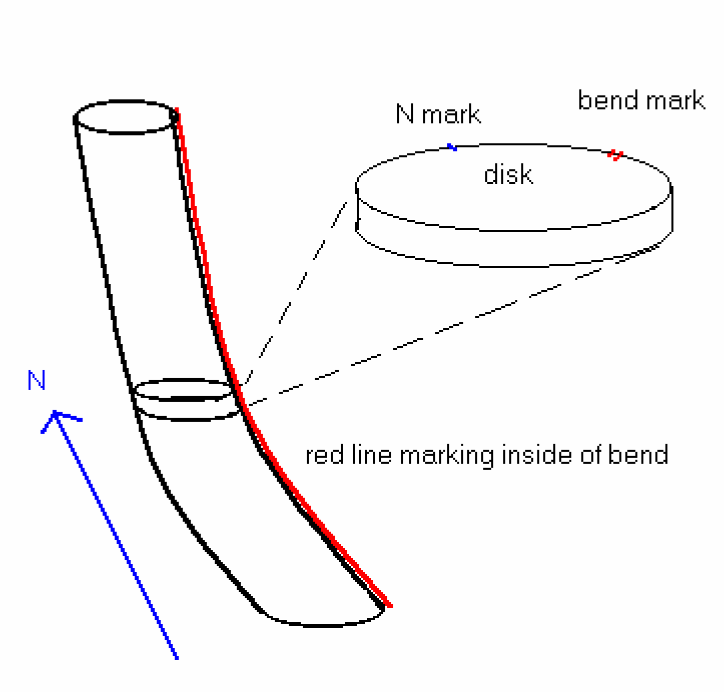
Introduction – The Measurement and Significance of Concave Bearings

This investigation aims to identify and assess patterns in the bending orientation of standing lodgepole pine from Rosarie and Shin. Exposure to external influences such as wind, slope aspect and direction of light transmission tend to be responsible for stem bending and it is intended that the impact of these factors will be studied for each site. A measurement of 'concave bearing' was taken to indicate the orientation of bending stems. This measurement was made on each standing tree in the sample plot, totalling 60 in Rosarie (20 of each provenance) and 69 in Shin (27 trees of Terrace and Petersburg and 15 of Longbeach – 3 trees were lying flat and were not included). The procedure for taking this measurement is outlined below.

Method

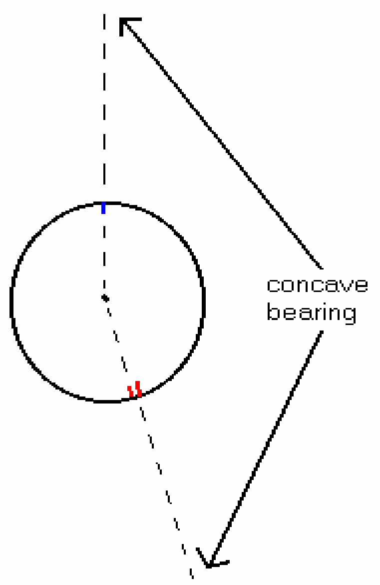
A line was marked down the inner side of the bend, or the upper side of a leaning tree on each sampled standing tree. This mark was transferred to the top face of the disk, which was later scanned (see Figure 1), and used to assess the spatial distribution of compression wood, with reference to the bend (see earlier study).

Figure 1. Defining the Concave Bearing



The concave bearing was registered at the site, as the bearing of a horizontal line extrapolated from the supposed position of the pith, through the mark of the inside bend (Figure 2 shows a 'bird's eye view').

Figure 2. Measuring the Concave Bearing

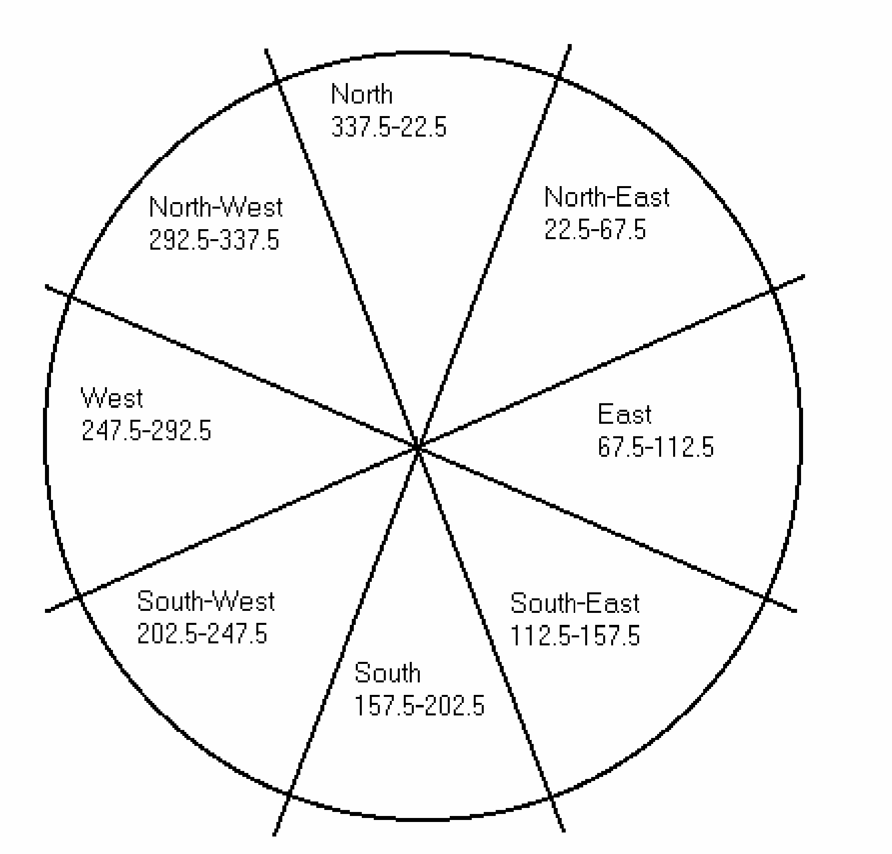


The significance of the concave bearing in studying environmental influences the concave bearing represents the inside of the sweep in the trunk, and indicates the direction in which the stem has grown to compensate against prevailing environmental factors. For example, in a prevailing North wind, or in a stand which is exposed to the North and sheltered in other directions, the stems may be expected to lean towards the South initially, due to the average force of the wind coming from one direction. However, stems tend to respond to this directional force by producing differential growth on the leeward side, often with increased compression wood. Thus the concave bearing could be expected to be in the same direction as the prevailing wind direction. Similarly, on a slope with a Southern aspect, trees would be expected to grow perpendicular to the slope in the early phase of growth and then later trend towards the vertical. Therefore if a sweep did exist in the trunk, it could be expected to display a concave bearing in the North direction.

Results

The distribution of concave bearings was investigated on a site and provenance basis. The compass was divided into 8 equal sectors (North, North-East, East, South-East, South, South-West, West and North-West) and bearings were grouped according to their direction. This is illustrated in Figure 3.

Figure 3. Grouping Concave Bearings into Compass Directions



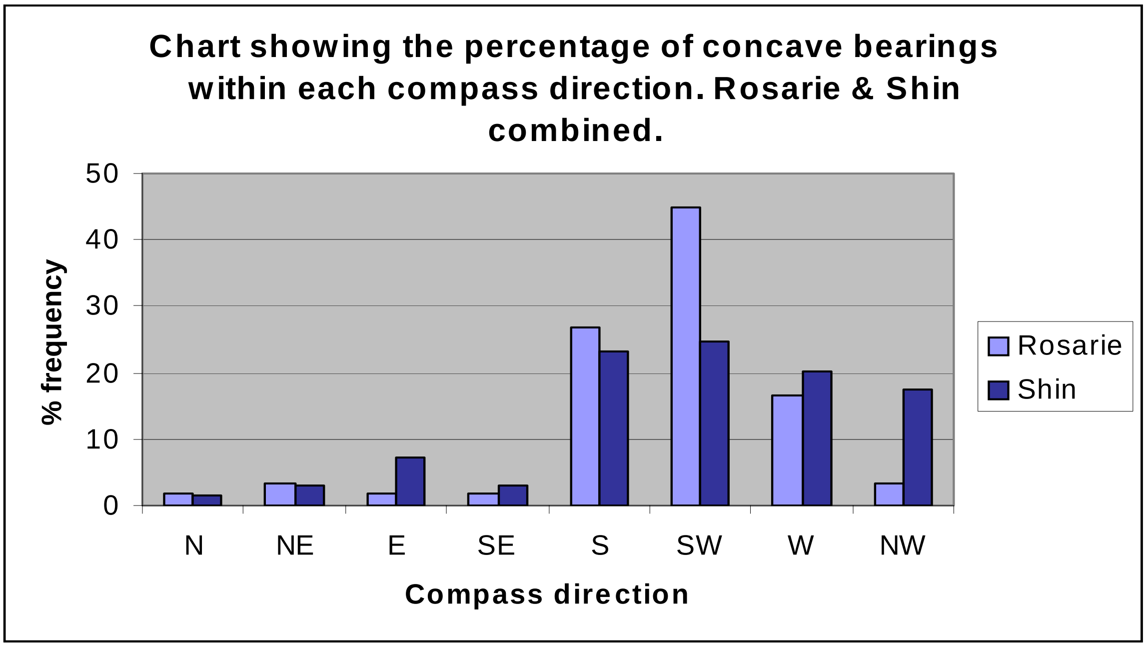
Site-based Results

Table 1 displays concave bearing frequencies for Rosarie and Shin. The percentage data is also displayed (underneath the frequency data) and was calculated as Compass direction frequency/Total number of site samples*100. Figure 4 shows the histograms constructed using the percentage frequency data from Table 1.

Table 1. Frequency table of Concave Bearings and Compass Directions

	N	NE	E	SE	S	SW	W	NW	Totals
Rosarie	1.00	2.00	1.00	1.00	16.00	27.00	10.00	2.00	60
as % of total	1.67	3.33	1.67	1.67	26.67	45.00	16.67	3.33	100
Shin	1.00	2.00	5.00	2.00	16.00	17.00	14.00	12.00	69
as % of total	1.45	2.90	7.25	2.90	23.19	24.64	20.29	17.39	100

Figure 4.



The histogram in Figure 4 shows that, in both sites, the South-West direction has a higher percentage frequency of concave bearings than any other sector. Forty-five percent of the concave bearings from Rosarie lie within this sector, compared to about twenty-five percent in Shin. There is a marked difference between sites in the distribution of concave bearings. Most strikingly, the frequency of Rosarie bearings in any sector other than South, West and South-West is almost negligible. This is in contrast to the Shin samples, where although similar to Rosarie in the sense that the South and West directions are well represented, there is also a significant frequency (17.4%) in the North-West sector, and even a small peak of 7.25% representing the Easterly direction.

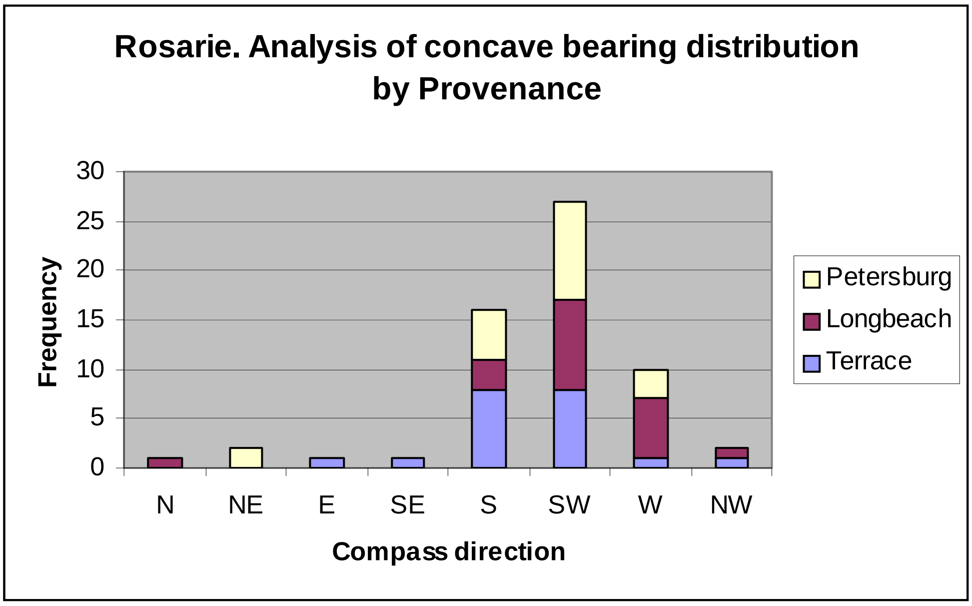
Provenance-based Results

It is important to note here that the sample size for each provenance is relatively small (up to twenty-seven trees) and as such the statistical significance of any apparent trends is not as high as would be afforded by a larger sample size. However, it is intended that these results be used to give some indication of the effect of provenance.

Rosarie

Figure 5 shows an analysis of the frequency of concave bearings within each compass direction, in relation to Provenance for the Rosarie site.

Figure 5.



The provenance-based analysis for Rosarie shows that the three provenances conform to the general pattern described above in the site analysis. However there are certain points of interest, which distinguish the provenances.

Terrace

No standing trees of the Terrace provenance had concave bearings, which fell into the North or North-East sectors. It is also comparatively low in the West sector concave bearings. However, it is the sole contributor to the East and South-East sectors and has more bearings in the Southern sector than either Petersburg or Longbeach.

Longbeach

Longbeach provenance has no trees in this sample with a concave bearing of any Easterly orientation (22.5^{o} – 157.5^{o}). However, it is the sole contributor in the North direction.

Petersburg

Petersburg is well-represented in the South, South-West and West sectors (157.5^{o} – 292.5^{o}) and particularly high in the SW compass direction. However, it is absent from all other sectors apart from the North-East sector, where it is the sole contributor, with 2 standing trees with a concave bearing in this direction.

Shin

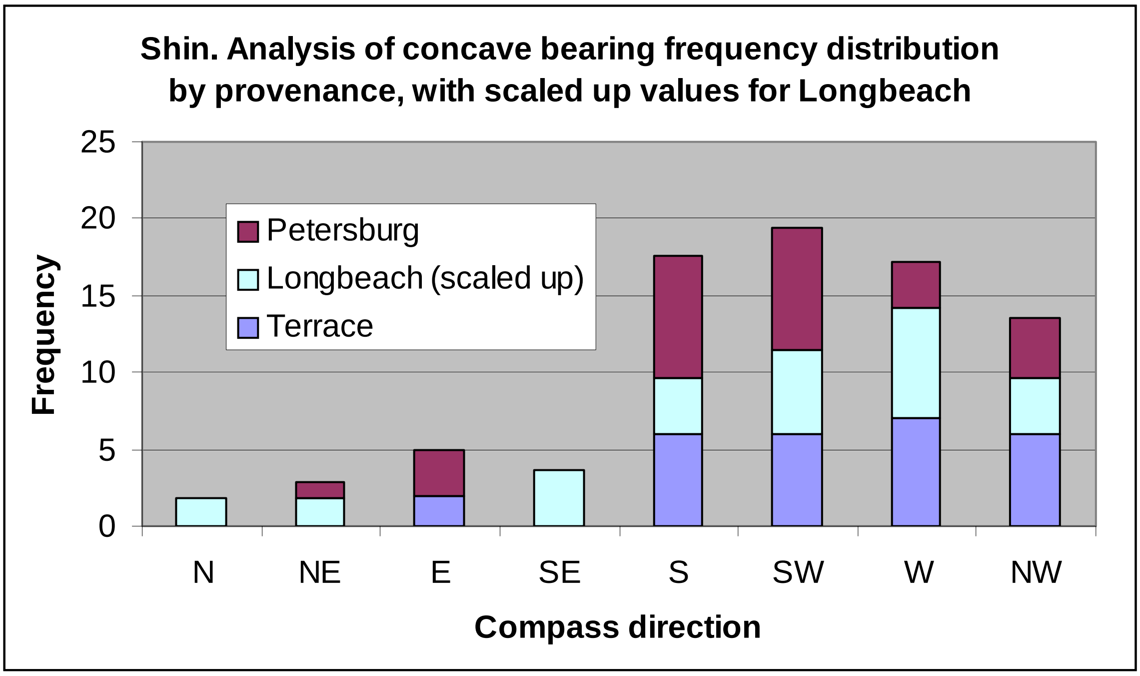
Site constraints in Shin meant that only 18 trees of Longbeach provenance were sampled, in comparison to the 27 sampled for both of the other provenances. Additionally, of the 18 sampled, 3 had been growing horizontally and were therefore lying on the ground. Accordingly, the concave bearing measurements were not taken. This leaves 15 trees with concave bearing measurements in the Longbeach provenance, compared to 27 in the other provenances. Longbeach is therefore under-represented in the sample, and to correct for this, a ‘scaling-up’ factor has been used. This factor was implemented by multiplying the original frequency figures for Longbeach by 27/15, and the results are shown in Table 2 below.

Table 2. Frequency table showing the Provenance-based Compass Directions for Shin

	N	NE	E	SE	S	SW	W	NW	total
Terrace	0	0	2	0	6	6	7	6	27
Longbeach	1	1	0	2	2	3	4	2	15
Longbeach (scaled up)	1.8	1.8	0	3.6	3.6	5.4	7.2	3.6	27
Petersburg	0	1	3	0	8	8	3	4	27

A histogram was constructed from the frequency table, using the scaled-up distribution from Longbeach, and is displayed below.

Figure 6.



Terrace
In Shin, the concave bearings of Terrace provenance are relatively uniform in the South, South-West, West and North-West sectors. Beyond this spread of bearings (157.5^{o} – 337.5^{o}), Terrace is only present in the East sector, where it has a fairly low frequency.

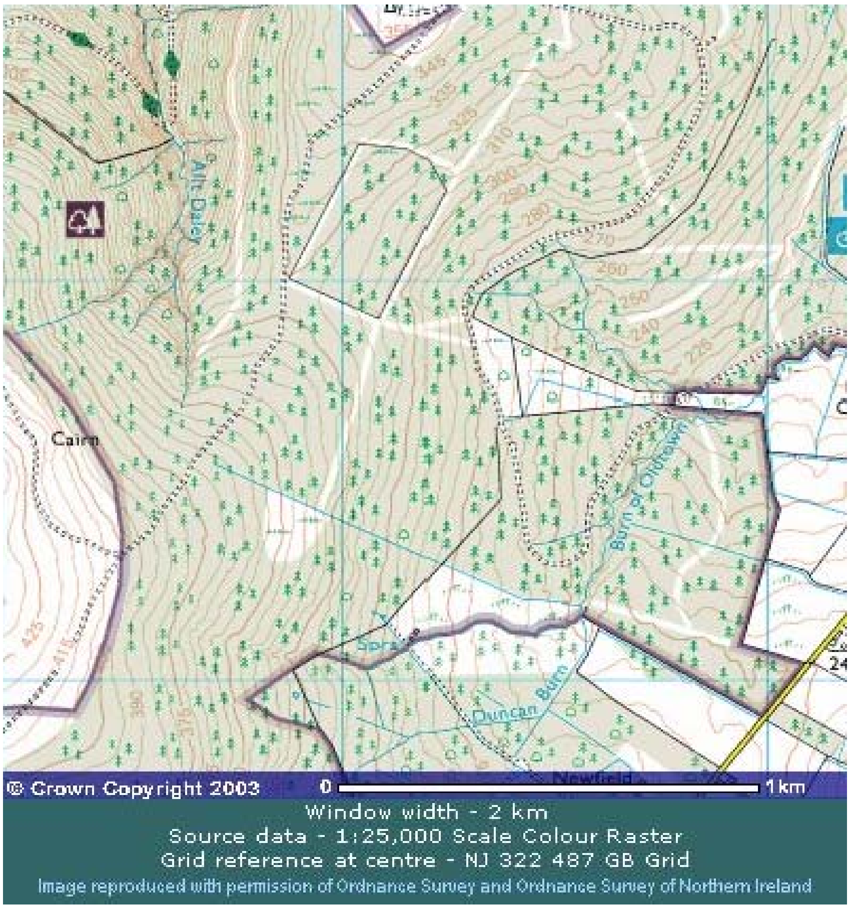
Longbeach
There is a wider distribution of concave bearings of Longbeach provenance than the other provenances and there are concave bearings of Longbeach in every compass direction, apart from due East. The Western sector has the highest representation by Longbeach and also the North, North-East and particularly the South-East sectors are well represented.

Petersburg
Concave bearings from Petersburg samples follow the general pattern, and mainly exist within the South and South-West sectors. Few exist within the West sector and Petersburg is absent in the North and South-East sectors, however, is quite well represented in the East sector.

Discussion

Rosarie
Within Rosarie, 83% of all concave bearings exist within the range between South and West (157.5^o – 292.5^o) and 45% exist within in the South-West sector alone. Most trees are therefore tending to bend at least initially away from the South-West, and then displaying differential growth on the leeward side and tending slightly towards the South West, thus creating a concave sweep in the trunk.
The consistent orientation of bending stems in Rosarie indicates the prevailing influence of external factors. It may be possible to identify and assess these factors through studying a map of the area and the historical site details record.

Figure 7. Map of Rosarie 3PS 70. Scale: 1:25000



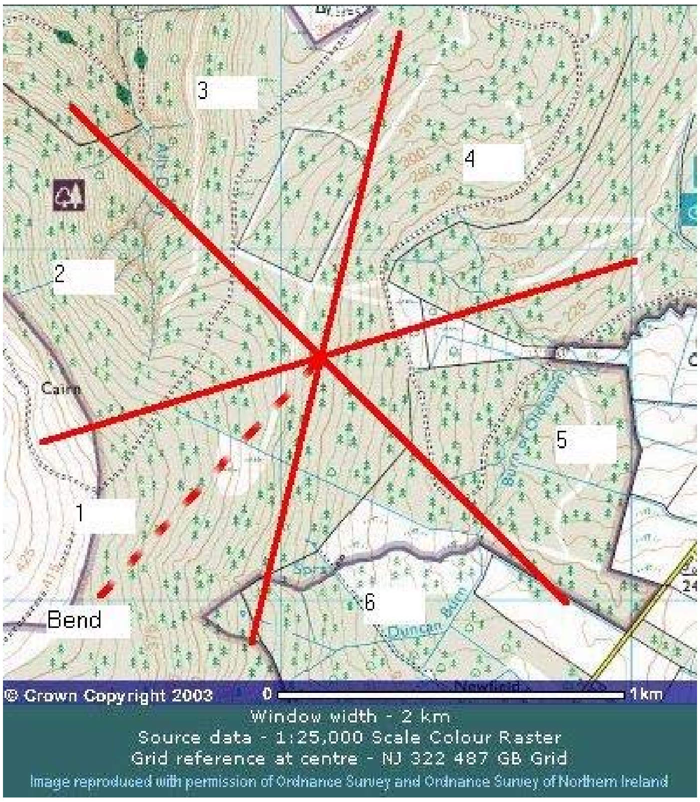
The site details record that the site is fully exposed to the North-East and South to South-West, meaning that winds from these directions will be experienced particularly strongly within the site. The geographical position of the British Isles and the overall meteorological patterns of the Northern Hemisphere combine such that the prevailing wind direction in Britain is south-westerly. The site details record that in 1976 (when the crop was 6 years old) this area suffered particularly heavy winds and sandstorms in spring and in 1980 it was noted that the incidence of blown trees was high. It is apparent therefore from the historical site record that this site has been exposed to heavy winds, particularly from the South to South-West, when the crop was at a vulnerable age. The concave-bearing frequency was highest in both of these directions, therefore it can be concluded that exposure is an important factor in the orientation of stem bending.

The site details note the incidence of snow breakages in Longbeach provenance. The provenance-based analysis for Rosarie (figure 5) shows Longbeach to be the only contributor in the North sector and it could be postulated that this may be linked to snow loading. If snow tends to arrive with a Northerly wind, thus loading the northern side of a tree with snow, it may cause the stem to bend towards the North, giving a concave bearing within the range of North values. However, this may be a slightly tenuous link, as there was only one example of a Longbeach tree with a Northerly concave bearing. Additionally, Petersburg is the sole contributor in the North-East sector (which would also be expected to get loaded with snow), with a bar representing two trees and there is no record of snow-breakages in this provenance. The earlier study of the spatial distribution of compression wood within the stem showed that Rosarie Longbeach had particularly high compression wood percentage values and it is not surprising in the light of this that breakages were more common in this provenance.

The map shows that the contours run North-South in Rosarie, thus creating a slope aspect of due East. There is a relatively uniform spacing of contours and within a 400m section across the sample plot, 13 contours are present, thus giving an average gradient of around 1/6 (contours every 5 metres in non-mountainous terrain). This is relatively steep and it may be expected that some affect on growth would be experienced. On a slope with an Eastern aspect, it would be logical to expect that stems may tend to have a concave bearing in the Western sector. The slope would tend to cause stems to bend towards the East, but the stem would be expected to compensate and attempt to grow vertically, thus resulting in a concave sweep with a West bearing. Figure 4 shows that Rosarie has a substantial number of concave bearings in the Western sector, however, because the Wind is predominantly in the South-West, it would be difficult to separate the effect of exposure and slope aspect.

However, it may be fruitful to link this to the earlier study of the spatial distribution of compression wood in the Rosarie stems. This study showed that sector 5 contained a disproportionately high percentage of compression wood in comparison to Shin (see figure 4.4.2 in the compression wood analysis paper). Figure 8 (below) displays the map of Rosarie with the superimposed impression of the sector divisions used in the compression wood spatiality study. The line from the pith to the concave bearing is represented by the broken red line and is aligned in the SW sector, as in 45% of stems in Rosarie. This superimposition places the fifth sector in an easterly direction, matching with the slope aspect for this site. The compression wood spatiality study showed that compression wood tended to be formed in sector 4, directly opposite the concave bearing mark, and it can now be seen that this may be predominantly the effects of wind exposure in this site. Trees tend to be exposed to their SW side, and thus lay down compression wood in the NE sector in an attempt to grow more vertically. However, the factor causing heavy compression wood deposition in sector 5 of Rosarie, is proposed to be slope aspect, rather than exposure (as the sample plot is not exposed to the West): compression wood is lain down on the East side of trees such that they grow vertical, rather than perpendicular to the gradient of the slope.

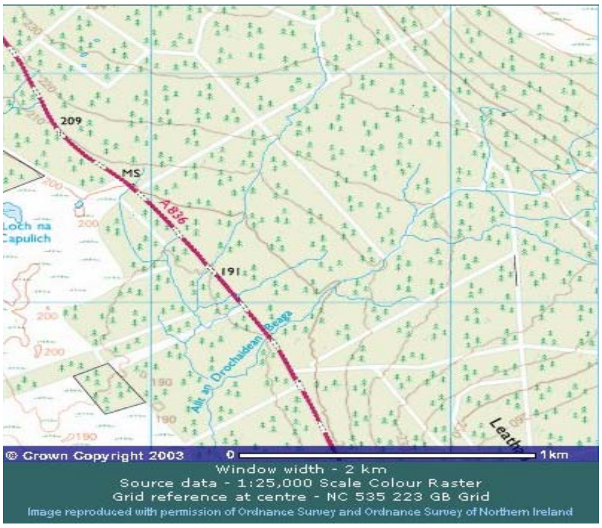
Figure 8. Map of Rosarie with superimposed sectors



Shin

As with Rosarie, concave bearings in the South-West compass direction are the most prevalent in Shin, encompassing 24.6% of concave bearings. However, Shin displays a broader frequency distribution of concave bearings than Rosarie, with the South, West and North-West sectors, also relatively high and all within 7 percent of the South-West sector (see figure 4 above). Just as consistent patterns of stem-bending were linked to environmental influences in Rosarie, the effect of the external influences can be investigated for Shin.

Figure 9. Map of Shin. Scale: 1:25 000



The site details record that Shin is exposed from the North-West to the South-West. As this coincides broadly with the sectors in which there is a high frequency of concave bearings, it could be proposed that exposure is the main causal factor in the direction of stem bending. The only slight anomaly in this analysis is the existence of many concave bearings within the South sector, which is not exposed according to the record. However, in Britain the prevailing wind direction tends to be in a Southerly or South Westerly direction, and therefore, even if the site is not particularly exposed to the South, it will still experience winds from this direction.

The effects of slope aspect in bending in trees in Shin can be eliminated for the main part, as the map below (figure 9) shows that the gradient of the slope is very small, at around 1/28. Therefore slope aspect wouldn't be expected to be a major factor in stem form or compression wood orientation.

Very little is mentioned in the Shin site record about the differences in form between the provenances selected for this analysis. Figure 6 shows that although there are differences between provenance in concave bearings displayed, these are not very significant, each provenance broadly displaying the form of the combined provenances. However, one point of note may be the existence of concave bearings of Longbeach in all directions, whereas Terrace and Petersburg are more constrained to bearings between North-West and South.

The effect of defoliating insects is noted during the mid 1980s and it is possible that this reduced the potential for snow loading in the site, which is the postulated cause of some bending in Rosarie.

Appendix 2

2. Aims of investigation into Lodgepole Pine timber quality

2.1 To accurately identify compression wood using image analysis software. This will involve an investigation into the relationship between mean green value of the scanned disk images and a defined threshold value to classify compression wood using *Optimas*.
2.2 To investigate the relationships between site, provenance and mean disk to log ratio, as an indicator of stem form.
2.3 To make comparisons between the mean percentage compression wood present in sites Rosarie and Shin and between provenances therein, Petersburg, Longbeach and Terrace.
2.4 To investigate the spatial distribution of compression wood with reference to the line of bend in the trunk and make comparisons between sites and provenances in this respect.
2.5 To investigate the relationship between levels of compression wood in the first disk and that present in the rest of the tree.

3. Methodology

3.1 Disk Preparation and Scanning

Standing trees from Rosarie and Shin were assessed. The orientation of the stem to North and an indication of the line of bend were marked on the standing trees. If the tree had a significant bend, a line was marked down the concave (inner) side of the bend, and if the tree was leaning, the upper side of the stem was marked with such a line. Disks were cut from the marked stems at recorded heights from the base. The north and bend markings were duplicated on the horizontal plane of the disks and they were placed in cold storage.
For a short time (less than 1 hour) prior to scanning, the disks were allowed to thaw and the upper side was washed with warm water to clean up the scanning surface.
Using a flatbed scanner, the disks were scanned according to a set the protocol.

3.2 Analysis of Disk Image using *Optimas*

Images were analysed according to the analysis protocol. This provides measurements of:

- Mean green value of normal wood in the disk.
- Compression wood threshold formulation (Rosarie).
- Percentage area of compression wood present on disk surface.
- Sectorial breakdown of compression wood, with reference to the marked bend.

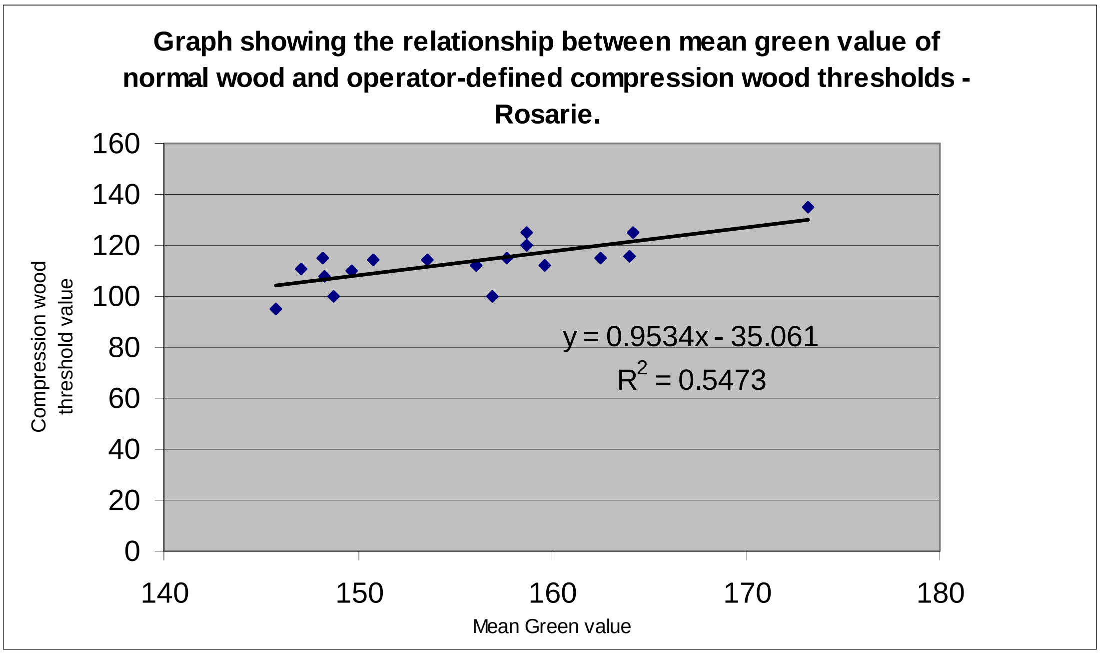
4. Results

4.1 Relationship between Mean Green value and Compression Wood Threshold

Previous work on compression wood in *Picea sitchensis* made use of image analysis software (*Optimas)* for the classification of compression wood in scanned images of disks. *Optimas* requires the input of a threshold value in order to classify compression wood and normal wood. Previous studies have shown that this threshold value is related to the mean green value of normal wood. This relationship takes a linear form and can be described by the equation $y = mx + c$.
It was proposed that a similar relationship may relate threshold values to mean green values in lodgepole pine, and this was investigated on a site basis. Using the methods outlined in appendix 2, mean green values were calculated and threshold values assigned by an operator, matching compression wood detected by eye to that classified by the software. This was done with a random sample of 6 disks from each provenance (18 in

total), and the resulting relationship for the Rosarie site is shown below in figure 4.1.1. For continuity and the reduction of error, the same operator was responsible for the analysis of Rosarie and Shin samples.

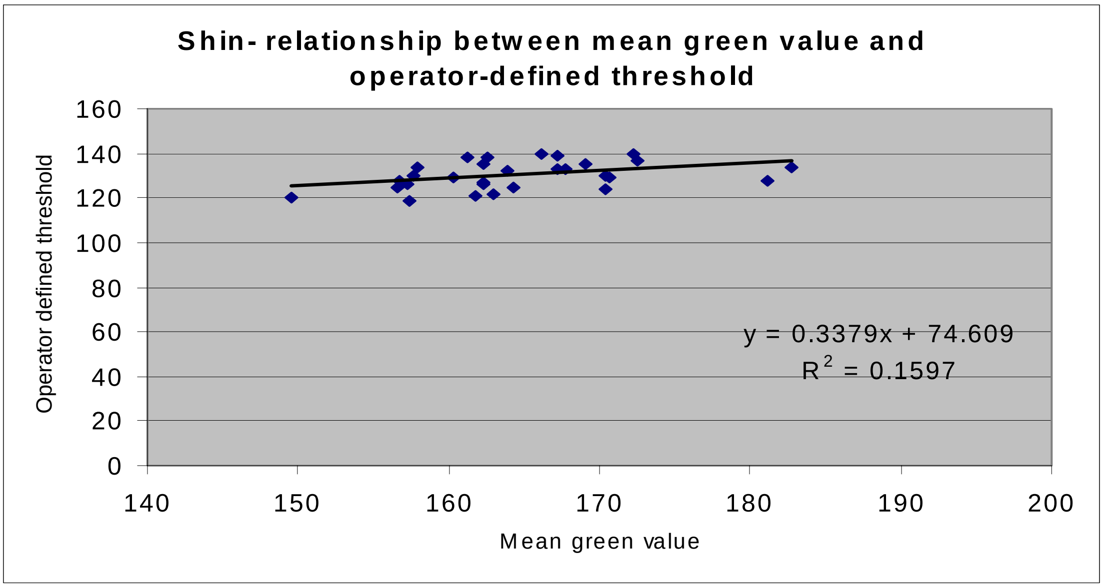
Figure 4.1.1



For Rosarie, it was deemed that the relationship was robust enough (r^2 = 0.5473) to proceed and calculations of threshold values based on the mean green values of normal wood were made for each disk. Throughout the analysis, the operator assigned a threshold using the derived formula ($y = 0.9534x – 35.061$), although this was occasionally altered slightly (within 10% of formulated threshold) to accurately reflect the operator's detection of compression wood in the disk.

For the Shin site, it was noted that there was a much less robust relationship between mean green value and threshold values (r^2 = 0.1597) (figure 4.1.2.), therefore each threshold was defined independently of the mean green value, according to the operator's detection of compression wood.

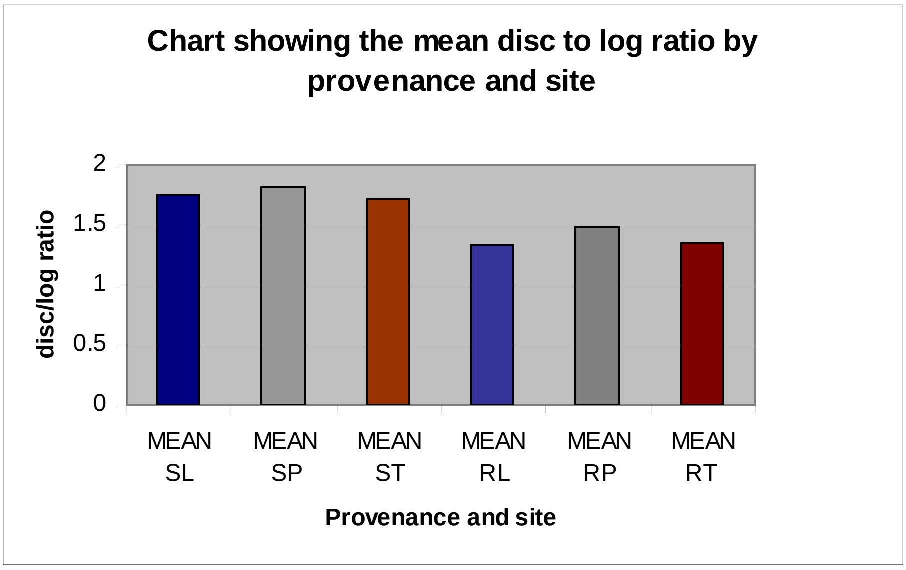
Figure 4.1.2



4.2 Effect of Site & Provenance on mean number of disks per log

Figure 4.2.1 shows the mean disk/log ratios, displayed by provenance and site. It is clear that all the Rosarie figures are lower than those from Shin (mean ratio Rosarie = 1.39, Shin = 1.76). Additionally Petersburg provenance has a particularly high disk/log ratio. The closer the ratio is to one, the better the form of the tree, as disks were taken regardless of the stem form, but logs were taken at reasonably straight sections. Therefore Shin as a site and Petersburg provenance perform badly in this indicator of stem form.

Figure 4.2.1

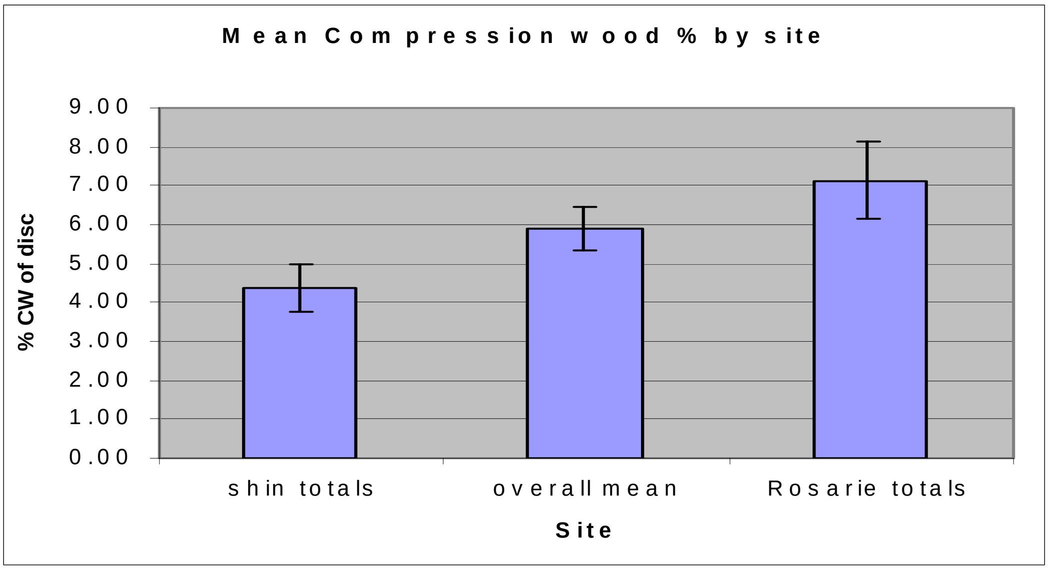


4.3 Compression Wood and the effects of Site and Provenance

4.3.1 Effect of Site on Compression Wood

The results show that the mean compression wood per disk was considerably higher in Rosarie than in Shin (7.14 compared to 4.38). Note that error bars represent 95% confidence limits.

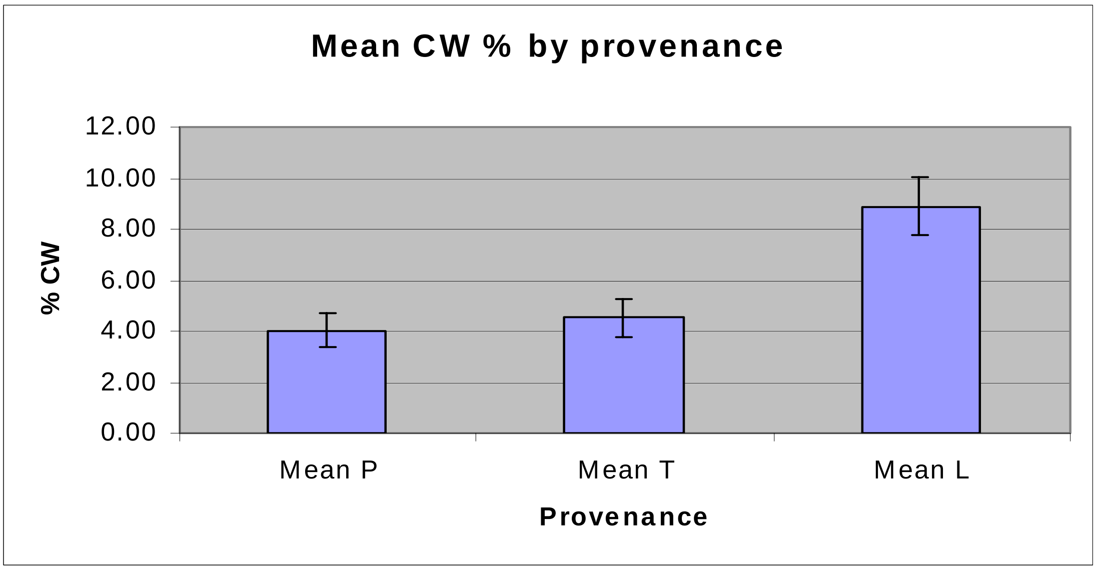
Figure 4.3.1



4.3.2 Effect of Provenance on Compression Wood

As would be expected, provenance has a demonstrable effect on compression wood. The mean compression wood per disk in Longbeach provenance is considerably higher (almost double) than that of either Terrace or Petersburg, whilst Terrace is slightly higher than Petersburg (figure 4.3.2). Note that error bars represent 95% confidence limits.

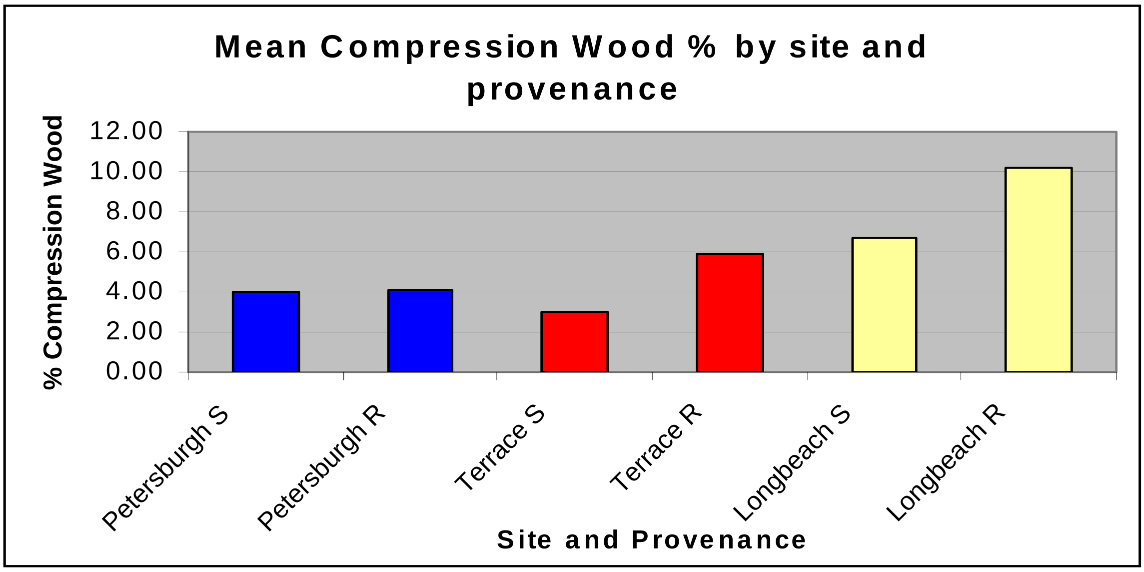
Figure 4.3.2



4.3.3 Combined effects of Provenance and Site on Compression Wood

Figure 4.3.3 shows the mean compression wood percentage per disk to be highest in Longbeach provenance trees at the Rosarie site. This is as would be expected from the past two results (figure 4.3.1 & 4.3.2). Shin Terrace trees have the lowest mean compression wood content, whilst the Petersburg provenance from both sites is consistently low in compression wood.

Figure 4.3.3

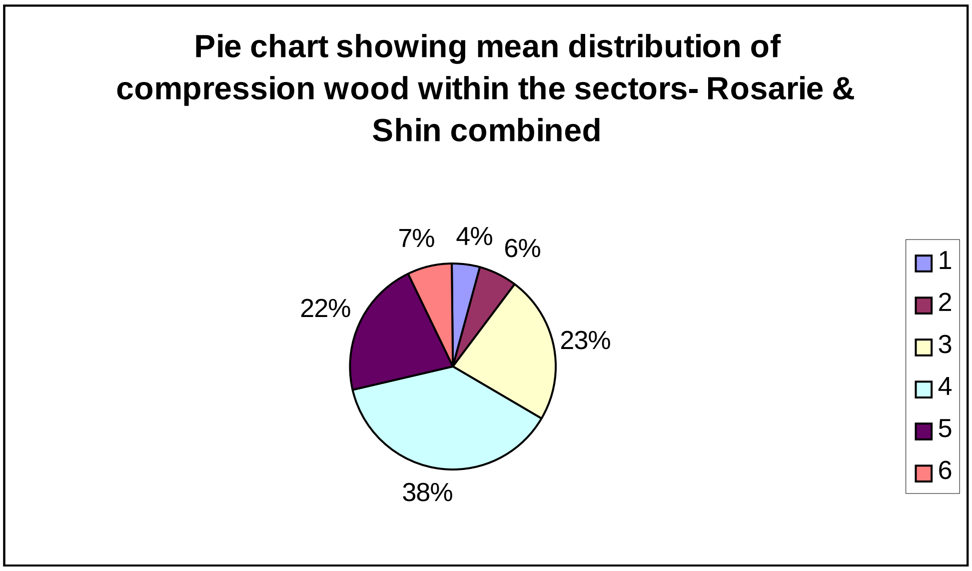


4.4 Spatial distribution of compression wood within the trunk.

4.4.1 General Results

Appendix 2, figure. 3 shows the method of analysis of spatial distribution of compression wood within the disks. The numbering of the sectors places sector 1 over the concave bend mark and continues clockwise around the circle, such that sector 4 is directly opposite the mark. The results show that, on average, over both sites and for all provenances, compression wood is most prevalent in sector 4 directly opposite the bend (38%) and is also high in sectors 3 and 5. In sectors 1, 2 & 6 on the inside of the bend, the compression wood load is extremely low (see Figure 4.4.1).

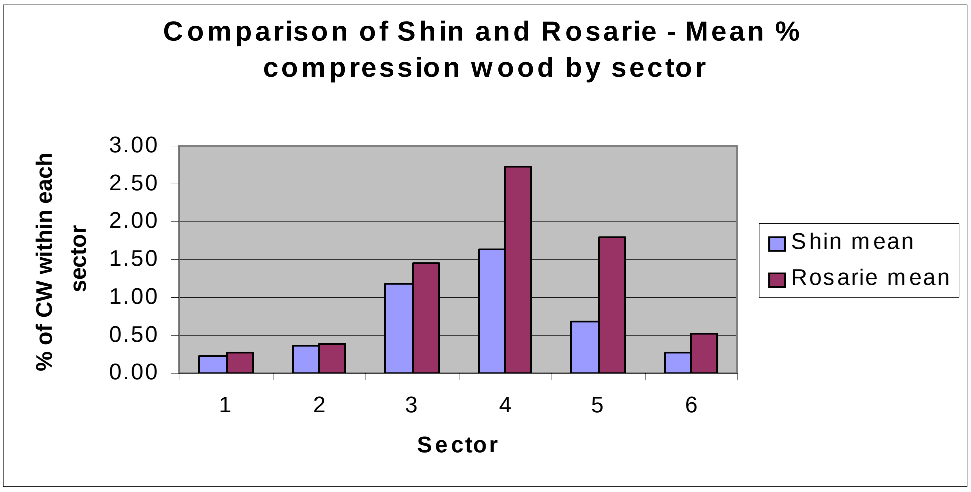
Figure 4.4.1



4.4.2 Effects of site on Compression Wood distribution within the stem

As was noted earlier, Rosarie has a higher mean percentage compression wood than Shin (figure 4.3.1), and this result is reflected in the sectorial analysis. The heavy distribution of compression wood opposite the bend (sector 4) is also reflected in these results. Figure 4.4.2 shows that each sector in Rosarie has a consistently higher mean percentage compression wood than the corresponding sector in the site at Shin. Another point of note is the particular difference between Rosarie and Shin in sectors 4 and 5, where the mean Rosarie value is more than double (in the case of sector 5) the Shin mean.

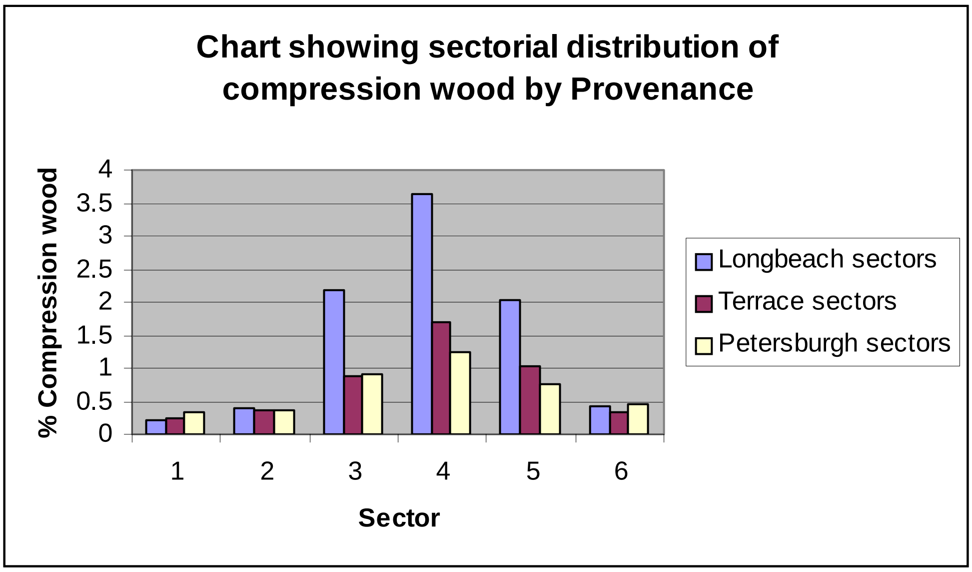
Figure 4.4.2



4.4.3 Effects of Provenance on Compression Wood distribution within the stem

Figure 4.3.2 demonstrated the particularly high levels of compression wood in Longbeach Provenance, and this is reflected in the sectorial analyses (see Figure 4.4.3). However, it is also important to note from this histogram (figure 4.4.3) that Longbeach only exceeds the other provenances in sectors 2, 3, 4 & 5 (and only in sector 2 by a small margin). Petersburg has a higher mean compression wood value in sectors 1 and 6.

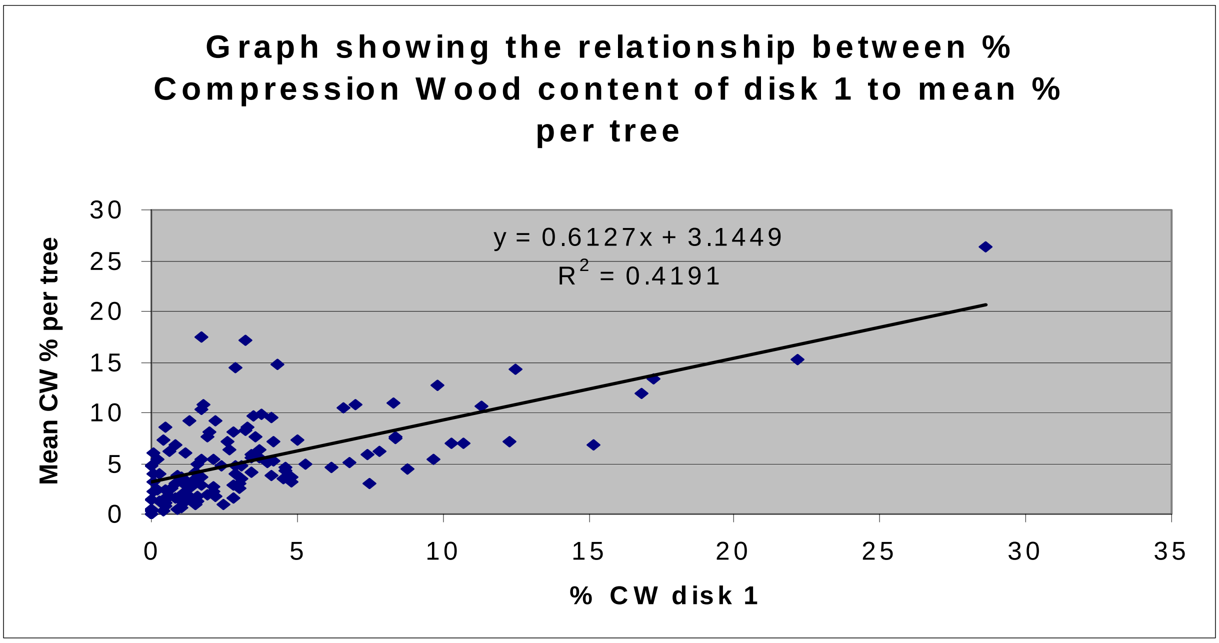
Figure 4.4.3



4.5 The relationship between Compression Wood percentage in the lowest disk and the mean compression wood of all disks in the tree.

An investigation of the relationship between the percentage compression wood in the lowest disk of a tree and mean compression wood percentage for the complete tree was undertaken. Figure 4.5 shows the resultant relationship using the analysis from all the trees in both sample sites, Rosarie and Shin. As would be expected, the relationship is positive, however the r^2 value is relatively low (0.4191) and particularly for low values of compression wood in disk 1 (x axis), the variance is high (see figure 4.5).

Figure 4.5



5. Conclusions

5.1 Relationship between Mean Green value and Compression Wood Threshold

It was desirable, from both an efficiency and consistency point of view, to employ a formula to construct threshold values to identify compression wood through *Optimas*. The Rosarie samples proved amenable to threshold construction by this means, but the Shin samples appeared to display no meaningful relationship between mean green value of normal wood and compression wood thresholds. This discrepancy between sites could be the result of site characteristics, for example different mineral properties of the soil causing different wood colouration. Alternatively this may result from slight differences in disk preparation, for example, the Shin disks may have been left before cold storage for a longer period than the disks from Rosarie, and the water content at scanning may have been slightly different, thus the colour properties would have been affected. Although this raises interesting questions about cross-site comparisons of compression wood formation and detection, the methods for analysis in this project have aimed to reduce possible error in detection due to this discrepancy. The most important of these was the continuity of operator running the *Optimas* analyses, such that there was a high degree of continuity in eye-detected compression wood. Additionally, the flexibility of the method used for detection in Rosarie was also important. Although a threshold was always calculated using the formula, this was altered according to the operator's detection, if required.

5.2 Effect of Site & Provenance on mean number of disks per log

Straightness and diameter are crucial factors in log selection. Thus the number of logs extracted from a tree gives an indication of stem form. The ratio constructed in this analysis relates mean disk numbers to mean log numbers for sites and provenances. Disks were taken regardless of stem form, at regular intervals, therefore the ratio of disk/log gives an indication of stem form, which can be used in relation to compression wood analyses. The results show that Shin site and Petersburg provenance have particularly high disk/log ratios and this indicates their poor stem form. It is however, interesting to compare these results with those from the compression wood analysis which show Petersburg and Shin to be particularly low in compression wood (see results 4.3). As compression wood is also linked to stem form, these results are slightly unexpected. However, they represent two different ways of examining stem form, from an internal and external perspective and it is perhaps pertinent to note that these different analyses yield very different results.

5.3 Compression Wood and the effects of Site and Provenance

Rosarie disks appear to display on average, 2.76% more compression wood than Shin and site peculiarities therefore appear to be fairly important. Since compression wood is associated with bending, it would perhaps be interesting to investigate the mean straightness of trees in both sites and thus draw conclusions as to what, more specifically, in each site is responsible for the compression wood prevalence.

Longbeach has a mean compression wood percentage around twice that of Terrace or Petersburg (figure 4.3.2), using combined data from Rosarie and Shin. Provenance evidently has a large effect on compression wood prevalence, and it is apparent that the economic resource of Longbeach timber is compromised heavily by compression wood. As would be expected from site-based results, the combination of Longbeach provenance on Rosarie site gives the highest percentage area compression wood of any site-provenance combination (see figure 4.3.3). As with the effects of site (above), it would be fruitful to investigate the bending tendencies of Longbeach provenance, particularly at Rosarie.

5.4 Spatial distribution of compression wood within the trunk.
Sectorial analyses of compression wood distribution within the trunk support the physiologically-based expectation that compression wood is laid down on the outside of a bending stem. Using data from both sites and all three provenances, figure 4.4.1 clearly shows the heavy loading of compression wood into sectors 4 in particular and 3 and 5 more generally. In fact, 83% of mean compression wood within the sample stems exists in the semi-circle orientated towards the outside of the bend, if the circle is divided with a line parallel (through the pith) to the tangent of the bend mark. Of this 83%, just under half (38%) exists in sector 4.

The influence of site on these results is as would be expected given that Rosarie has a higher mean percentage compression wood; accordingly each sector has a higher loading of compression wood (see figure 4.4.2). In particular sectors 4 and 5 contain a high degree of compression wood. If this is a significant result, it would appear that the orientation of compression wood with relation to the bend differs slightly between Shin and Rosarie.

Figure 4.4.3 shows Longbeach to display a dramatically higher loading of compression wood in sectors 3, 4 and 5 than Terrace or Petersburg. These sectors represent the semicircle towards the outside of the bend and the other sectors show very little difference between provenances, with Petersburg slightly higher in sectors 1 and 6. This suggests that the association of compression wood content with provenance may be a function of the provenance's susceptibility to bending, rather than provenance *per se*. Further analyses incorporating the angle of bend in the Longbeach provenance in comparison to that of Terrace and Petersburg would perhaps yield further information regarding provenance and its relationship to mean compression wood content.

5.5 The relationship between Compression Wood percentage in the lowest disk and the mean compression wood of all disks in the tree.

Methods for the easy detection of compression wood in forest stands would be useful to the forest industry, as compression wood has demonstrable effects on the economic utility of harvested timber. We have demonstrated that a relationship does exist, as would be expected, between the compression wood content of the lowest disk (disk 1) and that observed in the remainder of the disks from one tree. However, the variance is relatively high in this relationship and is particularly confounded by low compression wood values in the basal disk. The linear equation does not pass through the origin and this shows that if compression wood is present in a stem, it may not necessarily be present (and thus easily detectable) in the basal disk.